The High Order Test Bench: Evaluating High Contrast Imaging Concepts for SPHERE and EPICS

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The High Order Test bench (HOT) is an adaptive optics facility developed at ESO to test high contrast imaging instrument technologies and concepts. HOT reproduces realistically in the laboratory the conditions encountered at a telescope, including turbulence, high order adaptive optics correction and coronagraphy. Experiments carried out with HOT will be discussed mainly in the context of the SPHERE instrument.

Around the end of 2011, the SPHERE instrument (Beuzit et al., 2008) for the ESO Very Large Telescope (VLT), dedicated to direct imaging and spectroscopy of self-luminous giant planets, will be on its way for integration and tests at the Laboratoire d'Astrophysique de Grenoble (LAOG), followed by installation at Paranal. The High Order Test bench (HOT) is a high-contrast imaging adaptive optics bench developed at ESO in collaboration with Durham University and Arcetri with the support of the European Framework Programme 6 Opticon JRA1. It is a key tool for enabling technologies and concepts, and probing crucial aspects of high contrast imaging instruments such as SPHERE or EPICS (for the European Extremely Large Telescope). HOT reproduces realistically in the laboratory the conditions encountered at a telescope (for example, the VLT), including turbulence generation, a high order adaptive optics system and near-infrared (NIR) coronagraphs. We present recent results obtained with HOT, efficiently combining extreme adaptive optics, coronagraphy and differential imaging techniques (spectral and polarimetric). Results will be particularly discussed in the context of SPHERE.

Design and characteristics of HOT

Direct detection and characterisation of faint objects around bright astrophysical sources is challenging due to the high flux ratio and small angular separations. For instance, self-luminous giant planets are typically 10^6 times fainter than the parent star in the NIR. Virtually all high contrast instrument concepts for large ground-based telescopes dedicated to the search for extrasolar planets use a combination of a high order (or eXtreme) adaptive optics (XAO) system and advanced starlight cancellation techniques such as coronagraphy. While an XAO system corrects the scattered light for optical aberrations introduced by the atmospheric turbulence and the instrument, a coronagraph reduces the starlight diffracted by the telescope in the image plane.

HOT is a high contrast imaging adaptive optics bench, which implements an XAO system, star and turbulence generator, mimicking conditions at a telescope realistically, and provides a large panel of coronagraphs. It provides ideal conditions to study XAO and coronagraphy. HOT is installed at ESO Headquarters on the

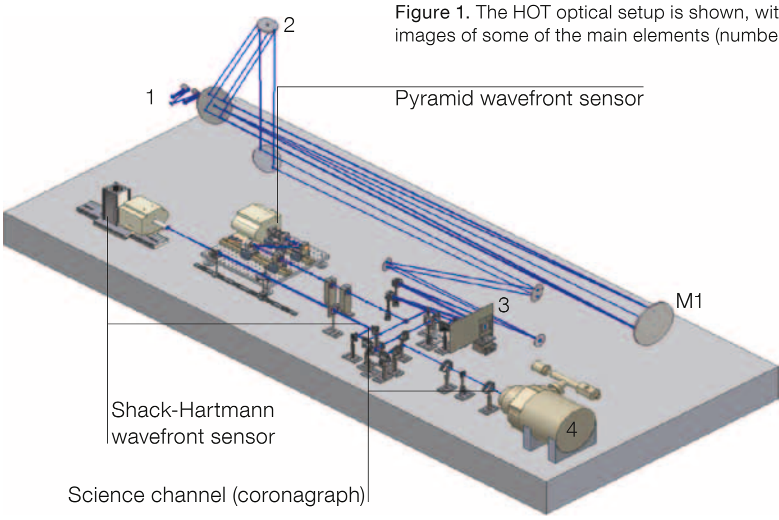
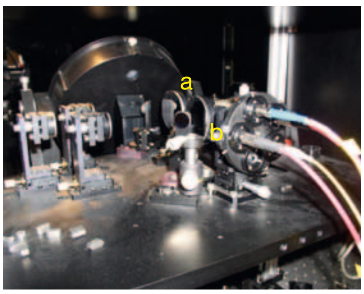
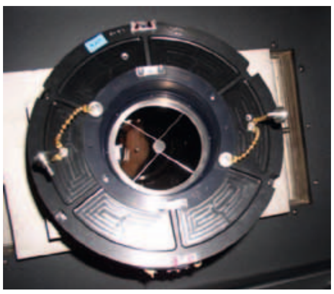


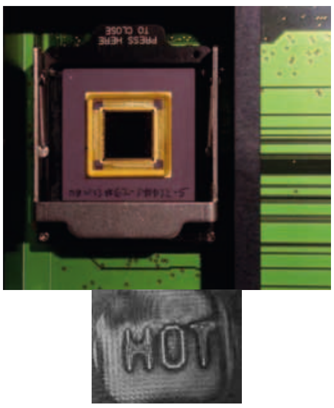
Figure 1. The HOT optical setup is shown, with images of some of the main elements (numbered).



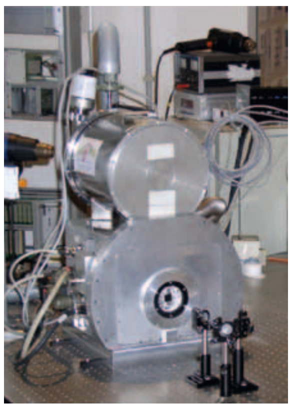
1 Turbulence generator
a Screens
b Source



2 Bimorph deformable mirror
VLT-pupil



3 Electrostatic deformable mirror



4 Infra-red test camera

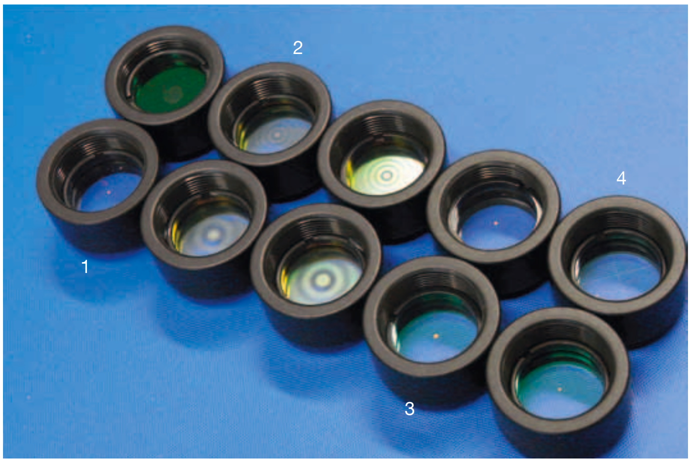


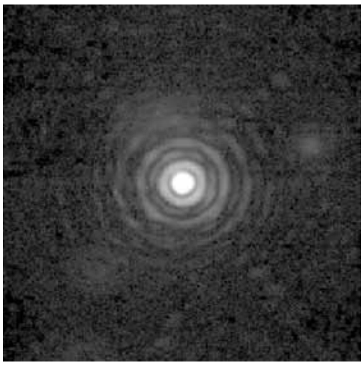
Figure 2. A selection of the various coronagraphic masks manufactured for HOT are shown.

1 Apodised Pupil Lyot Coronagraph (APLC)

2 Band-Limited Coronagraphs (BLC)

3 Lyot Coronagraphs (LC)

4 Four-Quadrant Phase Mask (FQPM)



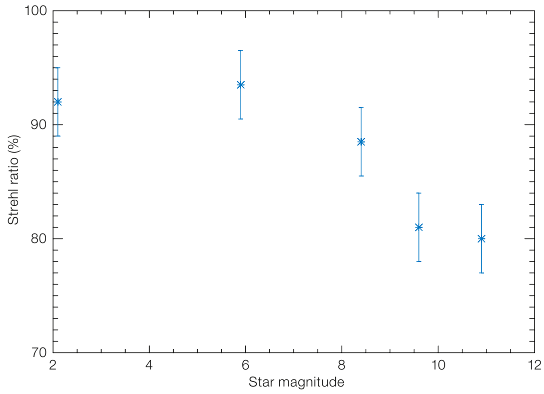


Figure 3. Left: XAO corrected PSF in *H*-band under 0.5-arcsecond seeing, Strehl ratio > 90 %. Right: Strehl ratio performance as a function of the *H*-band stellar magnitude.

Table 1. A comparison of the main parameters of HOT and SPHERE (13 m/s wind speed assumes Paranal standard atmospheric conditions).

	Parameter	HOT	SPHERE
General	Seeing (arcseconds)	0.5	–
	Wind velocity (m/s)	1.3	~ 13
AO System	AO speed frequency (Hz)	80	1200
	AO system bandwidth (Hz)	3.5	100
	Deformable mirror actuators	32 × 32	41 × 41
	SHWFS subapertures	31 × 31	40 × 40
	Pixels per subaperture	4 × 4	6 × 6
	Inter-actuator pitch (μm)	340	4500
	Mechanical stroke (μm)	1.53	5
	AO cut-off frequency (arcseconds)	0.6	0.8
IR Path	Pupil plane diameter (mm)	3	18
	Pupil-stop plane diameter (mm)	3	10
	F number	F/48	F/40
APLC	Mask diameter (λ/D)	4.5	4.0/5.2
	Inner working angle (arcseconds)	0.09	≤ 0.1

Multi Application Curvature Adaptive Optics (MACAO) test bench (the MACAO test bench was initially developed for the assembly, integration and testing of the ESO multi-application curvature AO systems for the VLT Interferometer), and includes several critical components as shown in Figure 1:
- a turbulence generator with phase screens to simulate real seeing conditions;
- a VLT-pupil mask installed on a tip-tilt mount;
- a 60-bimorph large stroke deformable mirror correcting for static aberrations;
- a 32 × 32 micro-deformable mirror — an electrostatic MEMS (micro-electronic-mechanical system) device correcting for dynamic turbulence;
- a beam splitter transmitting the visible light to a wavefront sensor (WFS), either with a Shack–Hartmann WFS (SHWFS), or a pyramid concept WFS (PWFS), while the infrared light is directed towards the coronagraph and the Infrared Test Camera (ITC) that employs a 1k × 1k pixel HAWAII detector; and
- the ESO SPARTA real-time computer.

All the optics are set up on a table with air suspension in a dark room and are fully covered with protection panels that form a nearly closed box.

After the generation of the dynamical aberrations, the output f/16.8 beam is transformed into an f/51.8 beam by a spherical on-axis mirror (M1), and directed towards the pupil plane located at about 1010 mm above the table level, with its axis tilted at 13.26°, as in the VLT Coudé train. Then relay optics prior to the beam splitter make use of flat and spherical mirrors to produce an f/50 telecentric beam. All the relay optics in the IR-path include IR achromatic doublets. The SHWFS, developed by the University of Durham, provides a plate scale of 0.5 arcseconds/pixel with 31 × 31 subapertures, each one sampled by 4 × 4 pixels of a 24 μm pixel L3-CCD (Andor camera, readout noise < $1e^-$). The SHWFS real-time computer is an all-CPU architecture. The PWFS built by Arcetri is formally equivalent to the Large Binocular Telescope wavefront sensor optical design, and consists of a double refractive pyramid modulated by a tip-tilt mirror, combined with an L3CCD-camera. Two pupil samplings are available depending on the final camera lens; a low sampling mode (31 × 31 subapertures); and a high sampling mode with 48 × 48 subapertures. The PWFS uses a dedicated all-CPU real-time computer.

In collaboration with the Paris Observatory (LESIA), several coronagraph concepts were manufactured for HOT (as shown in Figure 2): Apodised Pupil Lyot Coronagraph (APLC); Band-Limited Coronagraphs (BLC); Lyot Coronagraphs (LC); and a Four-Quadrant Phase Mask (FQPM). All of them, except for the BLC, are SPHERE-like coronagraphs. In its standard operational coronagraphic mode, HOT uses an APLC that combines pupil apodisation and a hard-edge opaque focal plane mask.

Although HOT was not meant to be a SPHERE demonstrator, it is, in some aspects, similar to SPHERE. In Table 1 we compare HOT and SPHERE at different levels of their design.

AO closed-loop results

During all experiments presented in the following, the XAO system was operating with the SHWFS, under 0.5 arcsecond seeing with 1.3 m/s wind speed. The SHWFS closed-loop runs at 80 Hz using 600 modes for the modal reconstruction on an 8-metre pupil. In these conditions, we were able to demonstrate that XAO can produce very well-corrected images, delivering *H*-band Strehl ratios above 90 % (see Figure 3) at high flux (stellar magnitude 5). Evolution of the Strehl ratio as a function of the stellar magnitude obtained with HOT is presented in Figure 3 (right).

Coronagraphic runs

Point spread function (PSF) and APLC raw images recorded during the experiment in *H*-band are shown in Figure 4. The AO-corrected and apodised PSF (left) reveals the diffraction pattern of the VLT pupil owing to the high 90 % Strehl ratio. As a consequence of the apodiser presence, the intensity of the PSF wings is reduced; otherwise the wing of the PSF would be better defined in the image according to the level of the AO-correction. The AO cut-off frequency identified in the image with a dashed-white circle is localised as expected at 0.6 arcseconds. Its position in the field is clearly identified in the coronagraphic image owing to the slope of the intensity in the speckle field at 0.6 arcseconds offset from the centre. Outside the inner domain defined by the AO cut-off frequency, the AO system cannot measure or correct the corresponding spatial frequencies. The APLC image demonstrates starlight attenuation, and exhibits atmospheric speckles with lower intensity in the AO-correction domain. For the sake of clarity, ghosts originating from reflections in the optical system have been identified with white arrows. A radial trend in speckle intensity is observable in the image: speckles closer to the centre of the image are brighter. The central part of the APLC image is dominated by diffraction residuals and pinned speckles. These pinned bright speckles localised at the position of the diffraction rings, originate from random intensity fluctuations — residual speckles produced by aberrations left after the AO correction — amplified by the coherent part of the wave. Contrasts of 1×10^{-3} at 0.1 arcseconds, and 9×10^{-5} at 0.5 arcseconds have been demonstrated with the APLC. All the various coronagraphs available on HOT (Figure 2) have been tested in the same way, and deliver roughly similar performances.

Spectral and polarimetric differential imaging runs

Ground-based instruments with adaptive optics, such as SPHERE, require significant speckle attenuation to achieve star–planet contrast of 10^{-4}–10^{-7}. Instrumental errors and errors in the wavefront due to imperfect optics are expected to produce a limiting speckle noise floor. Among the instrumental speckle suppression techniques prepared for SPHERE, the Spectral Differential Imaging (SDI) and the Polarimetric Differential Imaging (PDI) techniques can be tested on HOT. These techniques rely on either the spectral characteristics of the planet (e.g., methane absorption feature) or the polarimetric *a priori* assumptions on the planet signal (i.e. light reflected by a planet is polarised, typically by about 10 %, while the stellar light is almost unpolarised).

In its current design, HOT does not allow simultaneous images to be taken since the IR-path is made with only one optical channel, so a sequential series of two images has to be made. Therefore SDI runs are carried out as a non-simultaneous spectral differential imaging mode. SDI is carried out using subtraction of

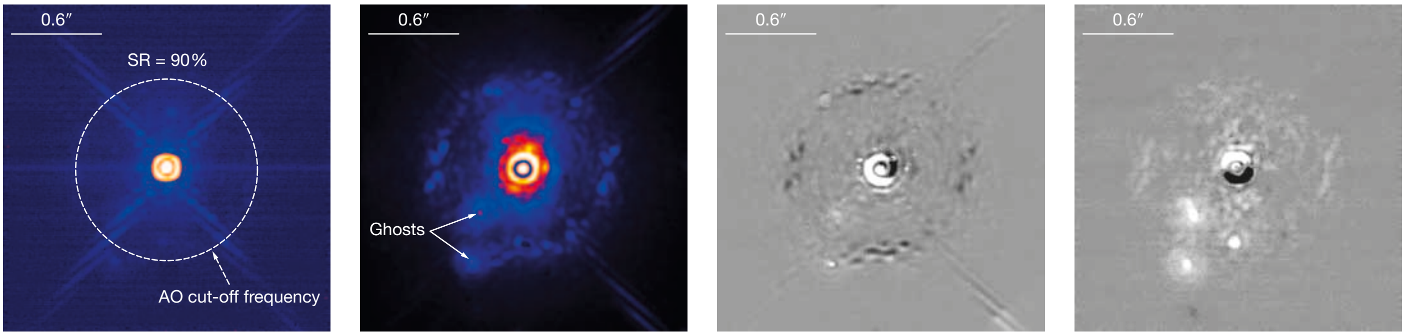


Figure 4. From the left to the right: *H*-band AO-corrected and apodised PSF, raw APLC image, SDI image, and PDI image. The arbitrary false colour distribution and image dynamic have been chosen to enhance the contrast for the sake of clarity.

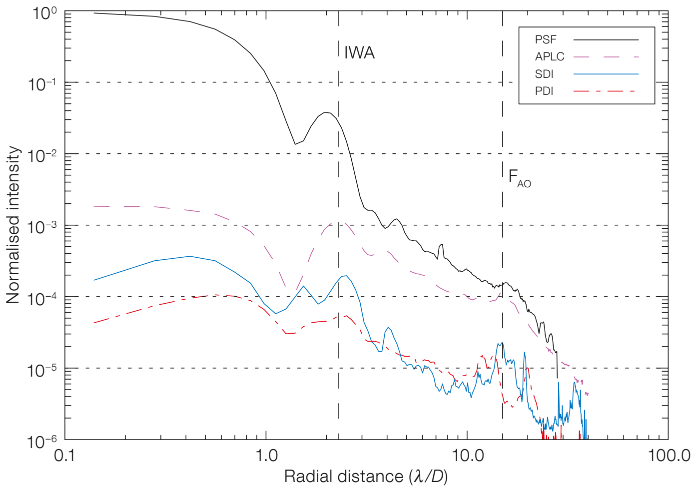


Figure 5. Azimuthally averaged contrast profiles: PSF (black), raw coronagraphic image (purple), SDI (1σ, blue), and PDI (1σ, red). IWA stands for the coronagraph inner-working angle, i.e. angular separations beyond which science can be carried out.

sequential coronagraphic images made with closely spaced narrowband filters around 1.6 µm (H1 filter centred at 1.56 µm with FWHM 55 nm, and H2 filter centred at 1.60 µm, FWHM 64 nm), while a PDI run is performed by the subtraction of two coronagraphic images with orthogonal polarisation states using a NIR linear polariser.

We have carried out these differential-imaging tests under 0.5 arcsecond seeing, efficiently corrected by the AO system to a 90 % Strehl ratio. Figure 4 presents in *H*-band (from left to right) the PSF, the APLC coronagraphic image, and finally the SDI and PDI images. Corresponding contrast profiles are presented in Figure 5. SDI and PDI yield very similar performance (the PDI image exhibits an additional ghost, originating from the polariser components). In both cases, the improvement over that of the raw APLC image contrast is about a factor 22 at 0.1 arcsecond offset and 20 at 0.5 arcseconds. Images exhibit quasi-static speckles that are, in principle, stable on timescales of minutes to hours. At this level of contrast a fair agreement with SPHERE simulations (Boccaletti et al., 2008) is already demonstrated. Investigations are being carried out to identify the source of limitation in the delivered contrast in SDI/PDI images (e.g., speckle stability, calibration issues, etc.).

In the SPHERE instrument, in order to push the detection threshold further down, calibration procedures such as the use of a reference star, or the comparison between two angular positions (angular differential imaging technique, ADI) will be implemented, with the goal of delivering a 10^{-5} and 5×10^{-7} 5σ detectability at 0.1 and 0.5 arcsecond offsets respectively. The results obtained with HOT and presented above provide confidence for achieving such challenging contrast requirements. The 1σ contrast obtained in the laboratory at 0.1 and 0.5 arcseconds (prior to application of the ADI technique) translated to a 5σ contrast is two orders of magnitude (a factor of 25 and 45 respectively) away from the corresponding SPHERE goal requirements (after SDI and ADI) at the same angular separation. Table 2 compares SPHERE, the Gemini Planet Image (GPI) and the High Contrast Instrument for the Subaru next generation Adaptive Optics (HiCIAO) contrast goals to that obtained with HOT. GPI and HiCIAO are the US and Japanese counterparts of SPHERE developed for the Gemini and Subaru telescopes re-spectively. Accounting for system differences, the agreement between these experimental results and the expectations from SPHERE, or GPI at similar level of contrast, is fairly good, while HiCIAO contrast goals are already met.

Table 2. Contrast goals (5σ) of several planet-finder instruments compared to results obtained with HOT.

System	Inner Working Angle (IWA) (arcseconds)	Contrast at 0.1 arcseconds	Contrast at 0.5 arcseconds	Telescope
HOT (w/ SDI or PDI)	0.09	2.5×10^{-4}	2.2×10^{-5}	–
HiCIAO (w/ SDI)	0.1	2.0×10^{-4}	2.0×10^{-5}	Subaru
SPHERE (w/ SDI & ADI)	≤ 0.1	10^{-5}	5.0×10^{-7}	VLT
GPI (w/ SDI & ADI)	0.2	–	10^{-7}	Gemini

From SPHERE to EPICS

Among the various experiments carried out with HOT, we were able to demonstrate that XAO can produce very well-corrected images, delivering *H*-band Strehl ratios above 90 %. SHWFS and PWFS have been compared, including their behaviour with respect to different error sources during calibration, showing an advantage for PWFS (Aller Carpentier et al., 2008; Pinna et al., 2008). We have successfully developed and validated a new technical solution for manufacturing components with spatially varying transmission (e.g. APLC, BLC), the so-called microdot masks (Martinez et al., 2009). These masks have now been selected for SPHERE, solving issues raised by a previous approach.

Accounting for the system differences (e.g., deformable mirror (DM) actuator number), we have demonstrated a fairly good agreement between experimental coronagraphic results and the expectation from SPHERE (Martinez et al., 2010). Finally, a speckle-nulling technique, using a single DM to sense and correct the static speckles directly in the coronagraphic image is being implemented and tested with HOT, opening up the possibility of reaching higher contrast by overcoming the limit imposed by remnant speckles in the coronagraphic image.

A new pupil mask (E-ELT-like) has been recently installed on HOT in place of the VLT one. With this configuration we have demonstrated the ability of the APLC to accommodate the large central obscuration and configuration of the spider arms, as well as testing another promising concept, the Dual Zone phase mask (DZ) in collaboration with the Marseille Observatory (LAM). The DZ is a potential second generation SPHERE coronagraph. All these experiments provide useful information and feedback for both the SPHERE and EPICS consortia. SPHERE is currently under construction and due at the VLT in 2011, so in the near future HOT will obviously be more oriented towards EPICS. For instance, the baseline XAO wavefront sensor of the EPICS instrument for the E-ELT is a roof-pyramid concept. This modified PWFS has been extensively studied by simulation and demonstrates improved behaviour (Korkiakoski & Vérinaud, 2010). A proof-of-concept is at this stage necessary, and HOT could provide the required environment to design and implement such a sensor. Among the other potential experiments that can be performed with HOT, the so-called “island effect” is of a great interest: the partial or complete coverage of the wavefront sensor subapertures by the dark zones created by the secondary mirror supports (spider arms) on the pupil. This issue is particularly important in the case of the E-ELT, and can easily be addressed by experiment with HOT.

The High Order Test bench is thus a unique and versatile ESO key tool to enable technologies and concepts, and to address crucial aspects of the forthcoming and future generation of high contrast imaging instruments.

Acknowledgements

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Colour-composite image of the central part of the young Galactic stellar cluster RCW 38 formed from *J*, *H* and *Ks* filter images taken with the VLT NACO adaptive optics instrument. The image, which is about 1 arcminute in size, is centred on the binary O star RCW 38 IRS2 and reveals many lower mass protostar candidates. See eso0929a for more details.