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Extreme AO for extrasolar planet detection with ELTs: application to OWL

T. Fusco[1], C. Verinaud[2], G. Rousset[3], J.-L. Beuzit[4], M. Kasper[2], D. Mouillet[5] and N. Hubin[2]

[1]ONERA, BP 72, 92322 Chatillon Cedex, France
[2]ESO, Karl-Schwarzschild-Straβe 2, Garching, D-85748 Germany
[3]LESIA, Observatoire de Paris, 5 Place Jules Janssen 92195 Meudon, France
[4]LAOG, Observatoire de Grenoble, B.P. 53, 38041 Grenoble, France
[5]Observatoire Midi-Pyrénées, B.P. 826, 65008 Tarbes, France

Abstract. The detection of telluric extra-solar planets implies an extremely high contrast long exposure imaging capability at near-infrared and probably visible wavelengths. We present here the core of any Planet Finder instrument which is the extreme AO sub-system. The level of AO correction directly impacts on the exposure time required for planet detection. The extreme adaptive optics system has to correct for the perturbation induced by the atmospheric turbulence as well as for the internal aberrations of the instrument itself. An example of application is proposed in the frame of the EPICS project (XAO system for the ESO OWL telescope).

Keywords. ELT, Extreme AO, coronagraphy, exoplanet imaging

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1. Introduction

Direct detection and spectral characterization of exo-planets is one of the most exciting but also one of the most challenging area in the current astronomy. "Planet Finder" systems under design on ground-based 10m-class telescopes (Beuzit 2005, Fusco 2005a) should allow astronomers to detect Jovian-like planets, in a few years, around stars aged <1 Gyr. The extension of such instruments for future Extremely Large Telescope (30 to 100m class) is an extraordinary challenging, but exciting bet. From the ground, the core of any high contrast instrument is an extreme adaptive optics (XAO) system correcting for the perturbation induced by the atmospheric turbulence as well as for the internal aberrations of the instrument itself.

2. AO loop performance in the focal plane

Achieving the final contrast required for extrasolar planet detection (typically 10^{-6} to 10^{-8}) leads to the use of an extreme AO system, a very efficient coronagraph device as well as imaging concepts allowing the calibration (and thus to cancel out) of all residual uncorrected defects. The optimisation of the coronagraph device as well as the imaging technique is beyond the scope of this paper. In the following, we will suppose that the main detection limitation is brought by the AO residual uncorrected wavefront (that is, that the internal coronagraph defects can be neglected).

Unlike classical AO systems, residual variances or Strehl ratios are not sufficient anymore to optimize the system and to derive the pertinent trade-offs. They have to be replaced by a more accurate parameter which can provide information on the coronagraphic image shape in the focal plane. The purpose of the coronagraph is to remove the coherent light coming from the on-axis guide star (GS). Therefore one can analytically define a "perfect coronagraph" using the following equation:

$$C(\rho) = \left\langle \left| \mathrm{FT} \left[P(r)A(r)e^{i\varphi_{res}(r)} - \sqrt{\exp\left[-\sigma^2_{\varphi+\log(A)}\right]}\; P(r) \right] \right|^2 \right\rangle \tag{2.1}$$

where $\langle . \rangle$ stands for a statistical average and with $A(r)$ the wavefront amplitude, $\varphi_{res}(r)$ the residual phase after AO correction, $P(r)$ the pupil function and $\sigma^2_{\varphi+\log(A)}$ the residual variance gathering phase and log-amplitude effects. When only a partial correction is performed, the coherent peak is removed and only the incoherent light (the residual uncorrected speckles) remains. In that case, it is easy to show that, as a first approximation (first order expansion) the coronagraphic image is proportional to the residual phase power spectral density.

The final performance of the instrument depends on the science detector calibration (flat-field) and on the level of sky background etc. Nevertheless, the ultimate limit is given by the photon noise level. In that case, one can show that the total integration time required to achieve a given signal-to-noise ratio (SNR, between planet signal and star residual light) is directly proportional to the shape of C_{res} as shown in Equation 2.2

$$T_{int} = \sqrt{2} * \frac{SNR^2 * C_{res}(\rho) * N_s}{D^4 * S^2 * N_p^2} \tag{2.2}$$

where N_p (resp. N_s) is the number of photons per m^2 and per s on the telescope pupil for the planet (resp. the star). S stands for the Strehl ratio and D the telescope pupil diameter. It is interesting to note that the integration time decreases as D^4 for a given contrast.

3. Balance of the error budget

The whole AO study is based on the balance of an error budget. Therefore, the global error budget for the AO system can be summarized as follow:

$$C_{res} = \underbrace{C_{scint} + C_{chrom} + C_{refrac}}_{\text{atmospheric limitation}} + \underbrace{C_{fit} + \underbrace{C_{temp} + C_{alias} + C_{noise}}_{\text{low order residual error}}}_{\text{AO loop residual error}} + \underbrace{C_{calib} + C_{aberr}}_{\text{calibration error}} \tag{3.1}$$

The time variable terms mainly impact on the final integration time of the system since it increases the level of the long exposure coronagraphic image. It includes :

• The atmospheric limitations which gather all the errors due to propagation effects (scintillation, refraction index chromaticity, diffraction, anisoplanatism and differential refraction effects).

• AO loop residual error gathers the fitting error (high order modes not corrected by AO, i.e. frequencies higher than the AO spatial cut-off frequency); aliasing error which can be reduced using focal plane filtering before the WFS device (Poyneer 2004, Fusco 2005b); temporal error which depends on each AO component and on turbulence characteristics; WFS measurement error which depends on the WFS type and design, the number of photons per sub-aperture and per frame, the detector characteristics and the ratio between imaging and WFS wavelengths (Fusco 2004, Vérinaud 2005b).

On the other hand, the persistent speckles represent the ultimate limitation of the detection process. They have to be minimized in order to achieve the level of detectivity compatible with direct planet detection. This highlights the importance of AO loop calibration (interaction matrix and reference slopes) and of the non-common path

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aberrations (NCPA) measurement and pre-compensation (Sauvage 2005). However, some speckles that are due to systematic differential chromatic errors (see Cavarroc 2005) will remain. Thus, to attain the goal contrast, the XAO system must be supported by an extremely accurate control of systematic errors of the order of one nanometer or less.

In addition, a clever image post-processing techniques has to be considered in order to deal with the residual persistent speckles and to extract the planet signal from among them. For a given diameter size one wants to optimize C_{res} in order to obtain the best possible detectivity level of the whole system.

The optimization of this error budget will be performed, keeping in mind three main criteria:

• The corrected area, i.e. the focal plane area where the image contrast is significantly improved by the AO system. It mainly drives the choice of the number of actuators (the correction area is equal to λ_{im}/d in diameter, where d is the actuator spacing).

• The detectivity level, i.e. the capability of the whole system to detect the planet signal. On one hand, this level is affected by the AO loop errors (temporal, noise, aliasing...) which evolve rapidly with time (dynamic terms) and can be calibrated using differential imaging and a reference PSF. Therefore reducing these terms allows one to gain, mainly in terms of integration time. On the other hand, it can also be degraded by the telescope and the system high spatial frequencies and non-common path aberrations which slowly evolve with time (quasi-static terms) and represent the ultimate limitation for the differential imaging and reference PSF subtraction techniques.

• The system sensitivity. This criterion is driven by the number of stars to be observed, but stronly depends on the detectivity level and the corrected area size. Indeed, the larger the corrected area the smaller the available flux per individual measurement zone (subaperture in the case of a SH device for instance). In addition, increasing the detectivity level implies a reduction in terms of temporal and noise errors, which leads to a faster system working on brighter guide stars for wavefront sensing.

4. Example of trade-offs: the EPICS project

The Earth-like Planets Imaging Camera and Spectrograph (EPICS) is a concept study of a Planet Finder instrument for the OWL 100-m telescope. The primary science goal, the detection of Earth-like planets in the habitable zone, calls for extremely challenging requirements: 10^{-10} contrast at 50 mas separation in the Near-infrared (NIR). To reach this contrast, the halo rejection by the AO system after coronagraphy must be very efficient and the trade-offs presented above are of huge importance. A detailed description of EPICS can be found in reference (Vérinaud 2005a). The EPICS XAO system is summarized in Fig. 1. Some of the main trade-offs that have been made for EPICS are:

• The instrument is supposed to work simultaneously in the in the R, J and H bands. In order to mitigate the effects of the chromaticity of index refraction the wave-front sensing is done in the I band.

• A very efficient and fast correction is needed very close to the star at limiting magnitudes of 7 to 9 depending on the star spectral type (G, K and M stars): the use of a Pyramid sensor (Vérinaud 2005b) permits one to limit the noise propagation on low spatial frequencies and thus to keep the halo at a sufficiently low level for separations less than 0.1 arcsec. The high Strehl ratio obtained at the wave-front sensing wave-length (about 80% in I-band) should also mitigate some non-linearity issues of the pyramid sensor.

• A multi-stage AO system is proposed for EPICS: the control of a very high number of modes (1.7×10^5) at 3 KHz, using a Pyramid sensor for which no fast reconstruction

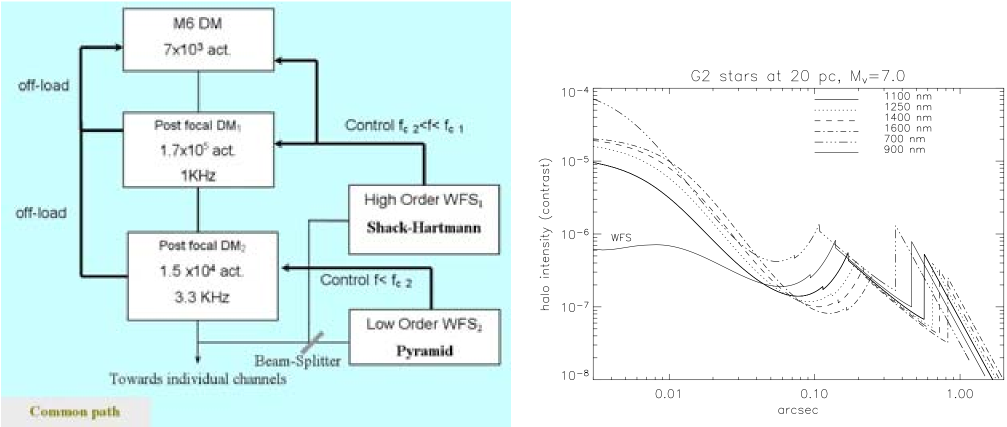

Figure 1. Left: EPICS XAO concept. M6 is the OWL ground conjugated adaptive mirror and is used here for off-load of large amplitude errors. Right: Halo intensity from AO residuals for different wave-lengths. Perfect coronagraph. Seeing: 0.5 arcsec. Coherence time: 4 ms.

algorithms do yet exist, revealed to be extremely demanding in terms of computing power. A first stage (reduced bandwidth, but large number of actuators) AO system based on a Shack-Hartmann with a Fourier reconstructor running at 1 KHz permits to control the high order modes in order to get the required Strehl ratio. Then a second stage (high bandwidth but smaller number of actuators) based on a Pyramid sensor with classical matrix-vector multiplication reconstructor, and controlling only the low spatial frequencies (1.5×10^4 modes) permits to reject the halo further for separations less than about 0.1 arcsec.

As seen on Fig. 1 (right) the instantaneous contrast delivered by the AO and the coronagraph will at best only be of about 10^{-7} at 0.1 arcsec separation. To attain the goal contrast of 10^{-10}, differential imaging and long exposures are needed.

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Discussion

ELLERBROEK: Can you comment upon the tolerances on segment alignment **and figure** errors which are required to obtain contrast ratio or 10^6 to 10^{10} in an EXAO System on an ELT?

VERINAUD: We expect to have about 20 nm rms in tip-tilt and piston after phasing. This error is indeed insufficient to get a high enough contrast. The second stage of the XAO system (pyramid-base 100×150) should be able to compensate for the Fourier components creating speckles in the critical corrected area (20 - 200 mas). Preliminary simulation show that in this corrected area the contrast can be pushed down to less than 10^{-9}. Concerning the segments mis-figure, we are concerned by turned down edges that we haven't studied yet the effect on XAO. Longer spatial frequency errors (curvature, astigmatism) will be corrected by the high sampling of the wave front (20cm).

CRAMPTON: How soon will your 'testbed' instrument provide results that will be useful to inform the design of an ELT planet finder?

VERINAUD: In the frame of 2 years we'll have valuable results coming from the HOT experiment at ESO built for XAO and coronography tests. In addition we will benefit from the developments in the frame of VLT-PF.

ZINNECKER: Would you care to comment on the independent study by Alain Chelli recently published in Astronomy and Astrophysics?

VERINAUD: Even though we didn't make an analysis as detailed as the one of A. Chelli on speckle noise, the integration times we obtain are compatible with Alain's results.

MCCAUGHREAN: What have you assumed for the static errors across the individual mirror segments in the ELT? These can have a significant impact on the final Strehl ratio, as we see for JWST, and a high Strehl is vital to get good coronography which you require/assume. JWST is spending a lot of money on figuring just 18 segments: ELTs will have many, many more.

VERINAUD: The primary mirror segments are spherical, so a good error figure can be achieved. The main concern is, however, turned down edges, and we haven't studied yet the effect on XAO and coronography. Thanks to the high order AO system (20cm sub-aperture size), we expect to connect most of the speckles polluting the FoV in the connected area.