Visible extreme adaptive optics on extremely large telescopes: Towards detecting oxygen in Proxima b and analogs

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Requirements for Detecting Oxygen

Goal: Detection of the oxygen A-band in the atmosphere in Proxima b (centered at 765nm; 10nm bandwidth; 1e-7 contrast) within a single night of observation with the E-ELT. High-spectral resolution (R= $2 \cdot 10^6$) observations are required to separate the Oxygen lines from Earth's telluric lines. The instrument will need simultaneous spectra of the star and planet for removing residual star light.

Signal-to-noise: Because HRS (high resolution spectroscopy) is a photon-noise limited post-processing algorithm, SNR is calculated with:

$$\mathrm{SNR} = \frac{\eta T_p C F_s}{\sqrt{F_s K}} = \eta C T_p \sqrt{F_s / K}. \quad (1)$$

with efficiency of the post-processing η, throughput of the planet T_p, contrast between planet and star C, stellar flux F_s, and achieved raw contrast K. The main drivers for the SNR are η, T_p, and K.

Contrast requirement: $3 \cdot 10^{-5}$ at 10 λ/D to achieve SNR=5 in 4 hours of exposure time with HRS on the E-ELT.

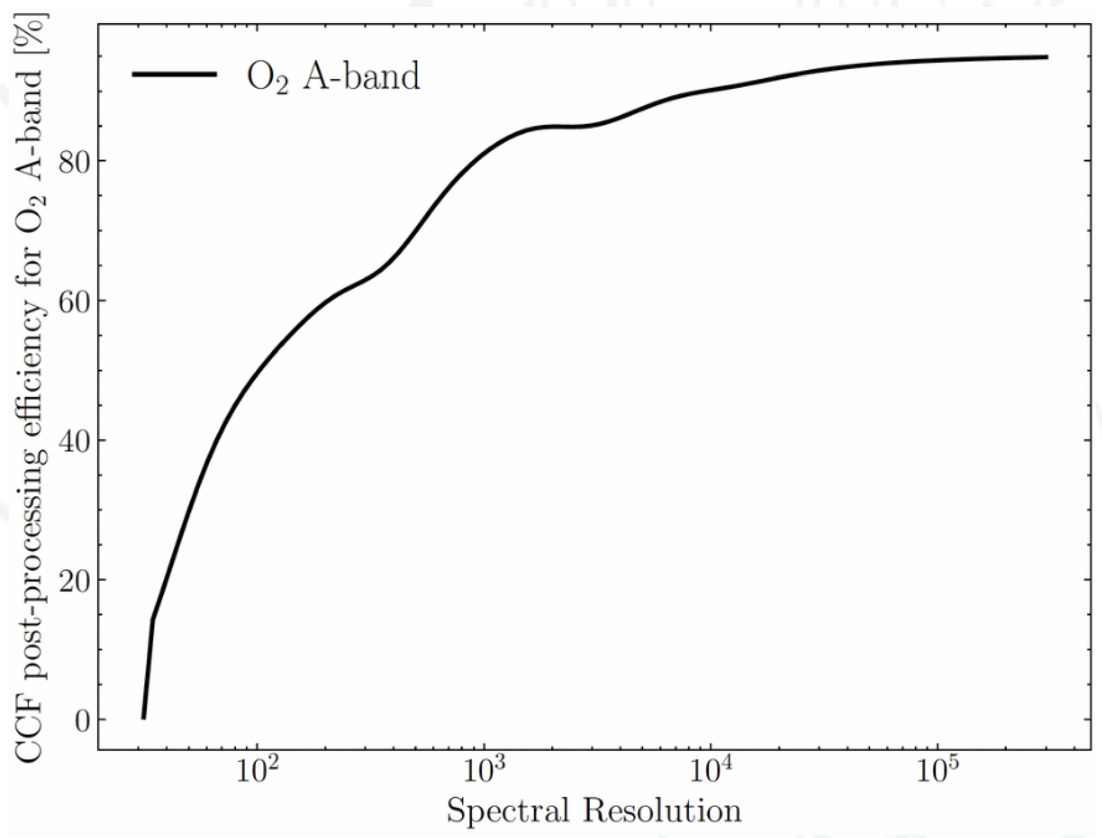

Figure 1: The efficiency of HRS post-processing (in this case we use a cross correlation function) as a function of spectral resolution. The efficiency converges to 95% around $R = 10^5$.

Limits of Current Optical HCI Instruments

SPHERE/ZIMPOL, SCExAO/VAMPIRES and MagAO-X report raw contrasts on the order of $\sim 10^{-3}$ at 100 mas. The leading limitation in all systems are non common path aberrations (NCPA) which can be both static and quasi-static. The NCPAs can be dealt with by using dark hole digging algorithms [1, 2, 3]. These have been proven to remove quasi-static aberrations to within $5 \cdot 10^{-9}$ in the lab [2] and $1 \cdot 10^{-6}$ on-sky [1]. Atmospheric speckles are then the ultimate limiting factor.

Instrument	Contrast	Wavelength	Seeing	Ref
SPHERE/ZIMPOL	1e-3	I'	0.9"	[4]
SCExAO/VAMPIRES	5e-3	750 nm	0.55"*	[5]
MagAO-X	2e-3	I	0.75"	Priv.com.

Table 1: State of the art for visible AO performance on large (8 meter class) telescopes. *The seeing for this measurement was not recorded so we have provided the median seeing for the Maunakea Summit.

Abstract

Looking to the future of exo-Earth imaging in visible light from the ground, core technology developments are required in visible extreme adaptive optics (exAO) to enable the observation of atmospheric features on rocky planets in this spectral range. UNDERGROUND (Ultra-fast AO techNology Determination for Exoplanet imageRs from the GROUND), a collaboration built at the Optimal Exoplanet Imagers Lorentz Workshop, aims to: (1) isolate Oxygen detection in Proxima b and analogs as an informative science case for high-contrast imaging and spectroscopy, (2) overview the state of the field with respect to visible exoplanet imagers, and (3) identify key technologies that require further development.

Wavefront Error Budget

Our contrast requirements result in an allowable wavefront error of 80 nm total or 0.4 nm at 5 λ/D. However, keeping Strehl as high as possible is also vital to maximize coronagraphic throughput. From there we build an AO error budget to reach this goal. This provides us with a starting point for the design as wavefront error does not directly translate to contrast.

Error term	1kHz	2kHz	5kHz
Fitting Error	38.92	38.92	38.92
Servo-lag Error	29.47	14.87	5.97
Total residual wavefront Error	48.8	41.7	39.38
SR (Marechal approx)	85%	89%	90%

Table 2: RMS (root mean square) wavefront error in nm for major error terms as we vary the control speed. Assuming a 39m telescope, natural guide star (not limited by SNR/guidestar magnitude), 0.5" seeing, effective wind velocity of 10 m/s, 200 actuators across the pupil, and loop delay of 1 frame, at 750 nm.

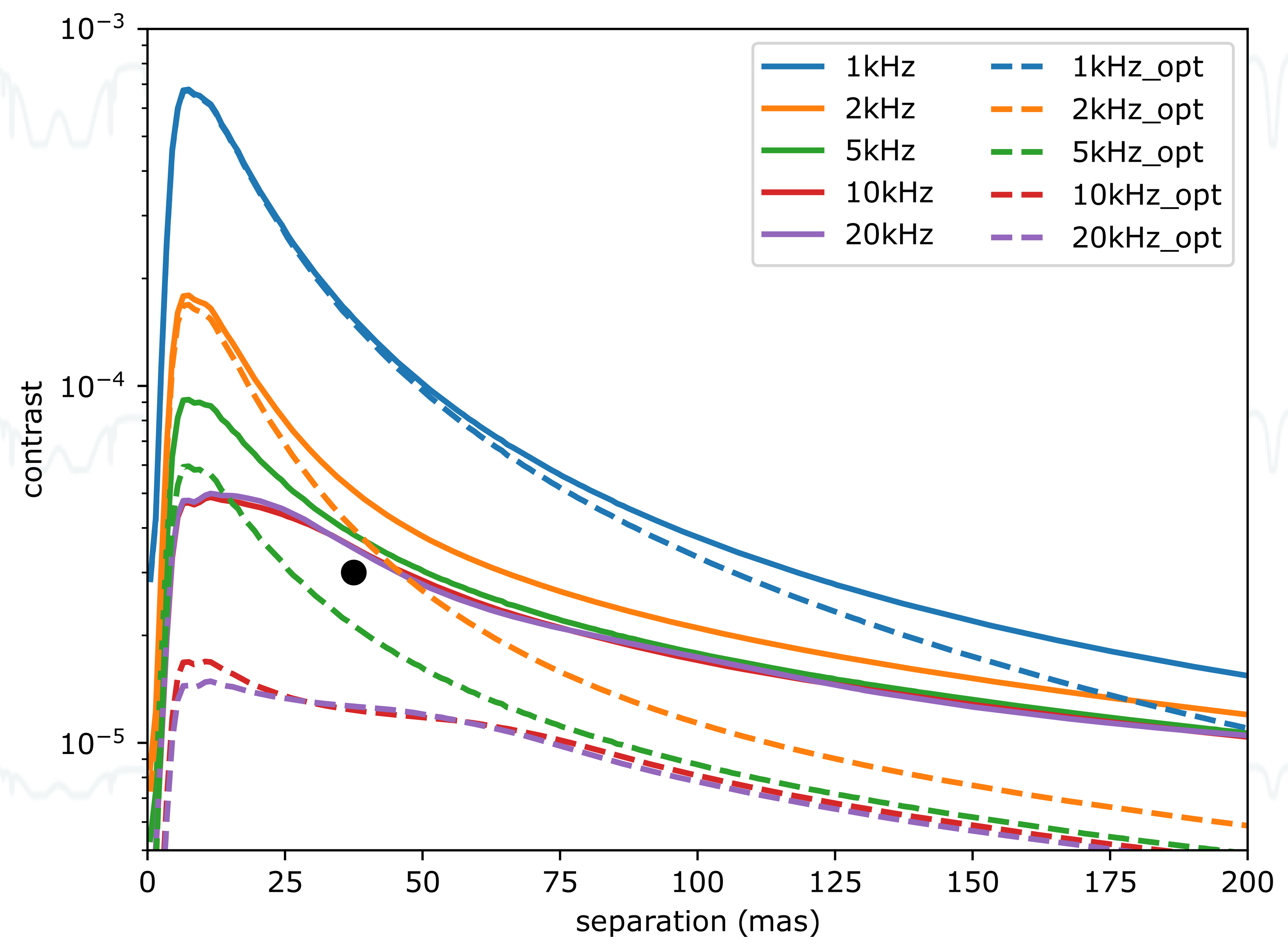

Figure 2: *The contrast for various (1, 2, 5, 10, and 20 kHz) loop speeds with a comparison of the pyramid wavefront sensor (PWFS) and an optimal WFS. The black dot illustrates the contrast requirement for the detection of Oxygen on Proxima Centauri b. Note that to reach our contrast goal we need 5kHz AO with an optimal WFS (the green dashed line.)*

Proposed Instrument Architecture

Figure 3 shows our proposed UNDERGROUND instrument architecture. In particular we highlight the following elements.

Optimal WFS at 5 kHz: We need a high-speed high-order optimal wavefront sensor that will control the eXAO deformable mirror. This could be an optimized ZWFS [6] or the optimal PIAA-ZWFS [7]. This system requires a detector that can run 240x240 pixels at 5 kHz with sub-electron read-noise, which requires future technology development.

NCPA Control: The NCPAs will be controlled by a WFS that is integrated into the coronagraph. This could be a ZWFS integrated within a Lyot-style coronagraph [7,8,9].

High Resolution Spectroscopy: There are several attractive solutions for high-resolution multi-object spectrographs, especially if only a small narrow wavelength range is required. A promising one is the VIPA-style spectrograph that can achieve high throughput and resolution in a compact design [10].

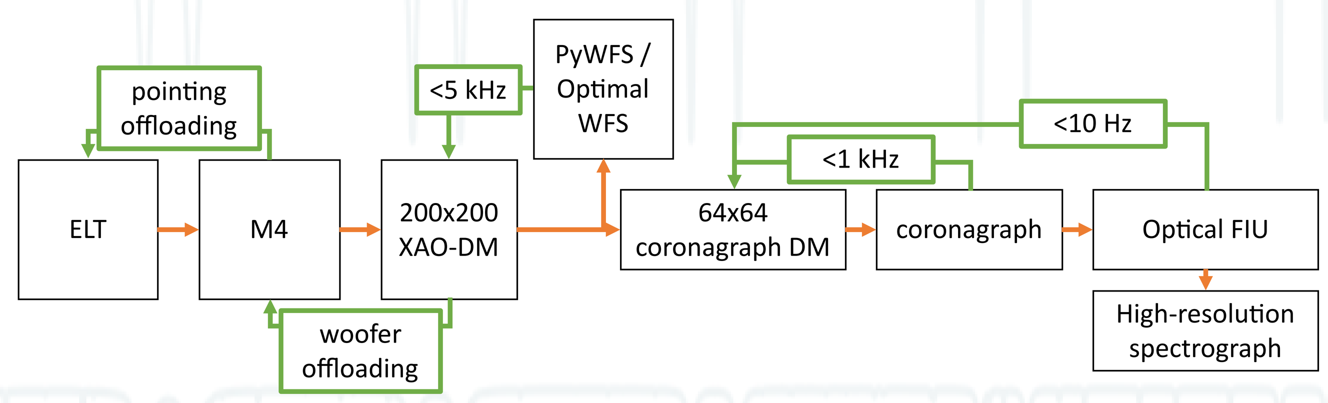

Figure 3: A schematic of the proposed UNDERGROUND instrument setup.

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