DIRECT DETECTION OF EXOPLANETS USING TUNABLE KERNEL-NULLING

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In a nutshell 🥜

This thesis aim to enhance nulling interferometry for exoplanet detection using a four-telescope architecture named Kernel-Nuller. By integrating 14 active phase shifters, we aim to mitigate phase aberrations caused by manufacturing defects. An algorithm is developed to optimize device performance, validated through simulations and lab experiments. A second phase consist in analyzing intensity distributions produced by Kernel-Nuller and applying statistical tests and machine learning to extract science information. This poster present the preliminary results.

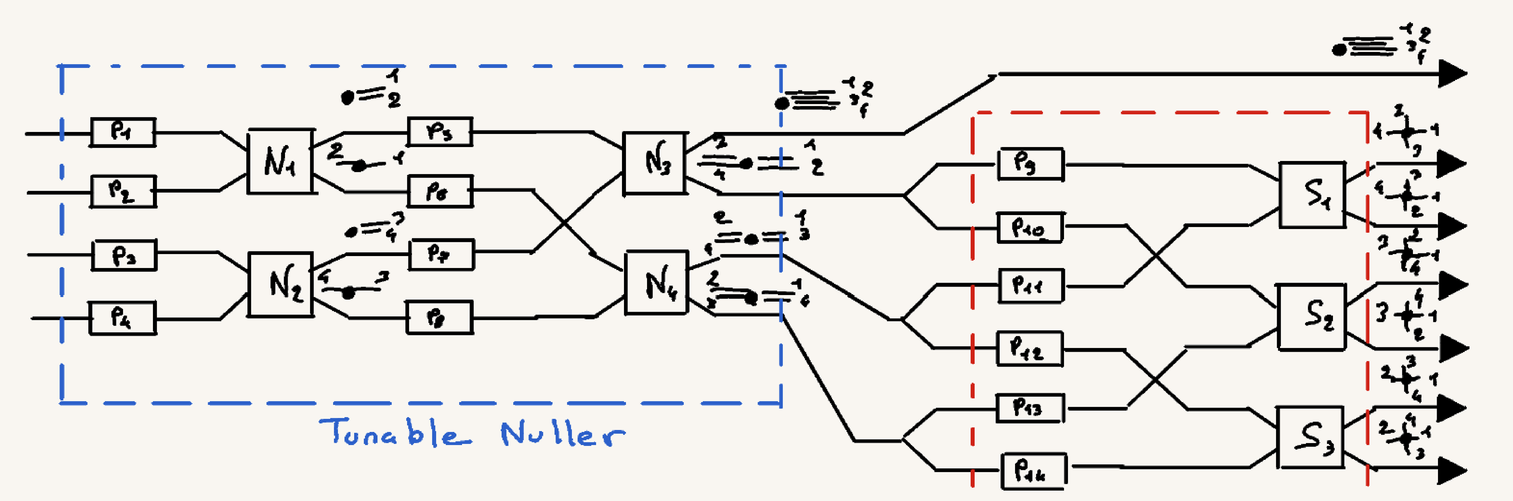

Figure 1: Scheme of our Kernel-Nulling architecture

Nulling interferometry 〰️

On the VLTI

This technique consist in taking advantage of the angular separation and the coherence properties of the light to destroy the star light and combine the planet light in the same process. Our approach enhance this principle by introducing « Kernels » which combine the light from 3 telescopes [1] or more to be less sensitive to low order phase aberrations and asymmetries [2] the output to better constrain the planet position.

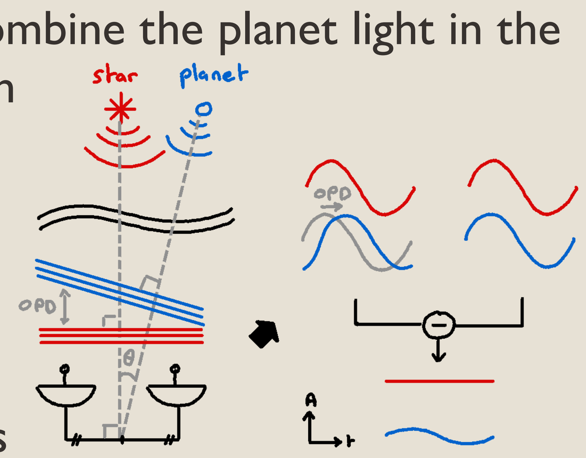

Figure 2: Concept of nulling. The signals are placed in phase opposition to destroy the on-axis source and let pass the light from nearby objects

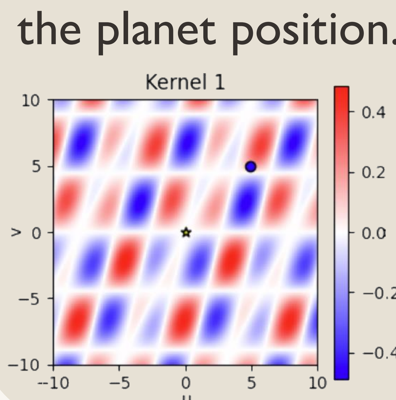

Figure 3: Transmission map of one of the Kernels obtained using the 4 telescopes of the **VLTI**. The transmission zones and blind bands are directly derived from the telescopes position. By rotating the baseline, we can get a modulated signal from which we can precisely constrain the planet position. (cf. "Parallactic diversity" block)

Thermo-optic phase shifter 🌡️

Coming from telecom technologies, the thermo-optic phase shifters consist in heating a fiber core using an electrode to increase the optical index and then induce an artificial **OPD**. Thanks to the compactness of such systems, the heat transfer is fast enough to have response time of about $1\ ms$. These shifters have been designed to work optimally at $\lambda = 1.65\ \mu m$

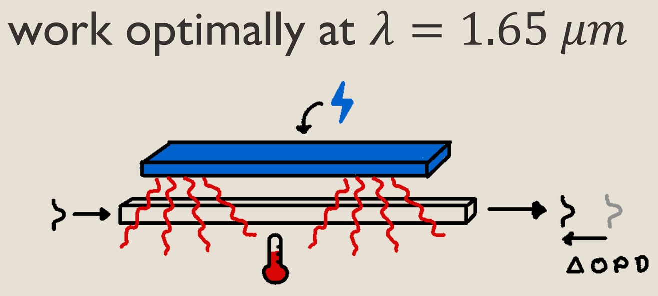

Figure 4: Scheme of thermo-optic phase shifter

Active optical components 💡

The idea of our architecture is to combine the nulling interferometry with the phase shifter technologies to make an active optical component that can be calibrated to compensate the phase aberration induced by the manufacturing defects.

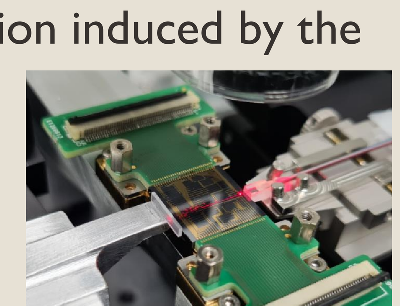

Figure 5: Picture of the waffle that contain several prototype architectures of Kernel-Nuller. The overall component size is comparable to a 1 cent coin.

Calibration algorithm

To find the best phase shifts to introduce, I proposed an algorithm inspired from dichotomy and gradient descent that accept or reject steps in the parameter space according to the bright $M_1 = B$ and dark asymmetry $M_2 = |D_1 - D_2| + |D_3 - D_4| + |D_5 - D_6|$ metrics. B and D are respectively the bright and darks output intensities.

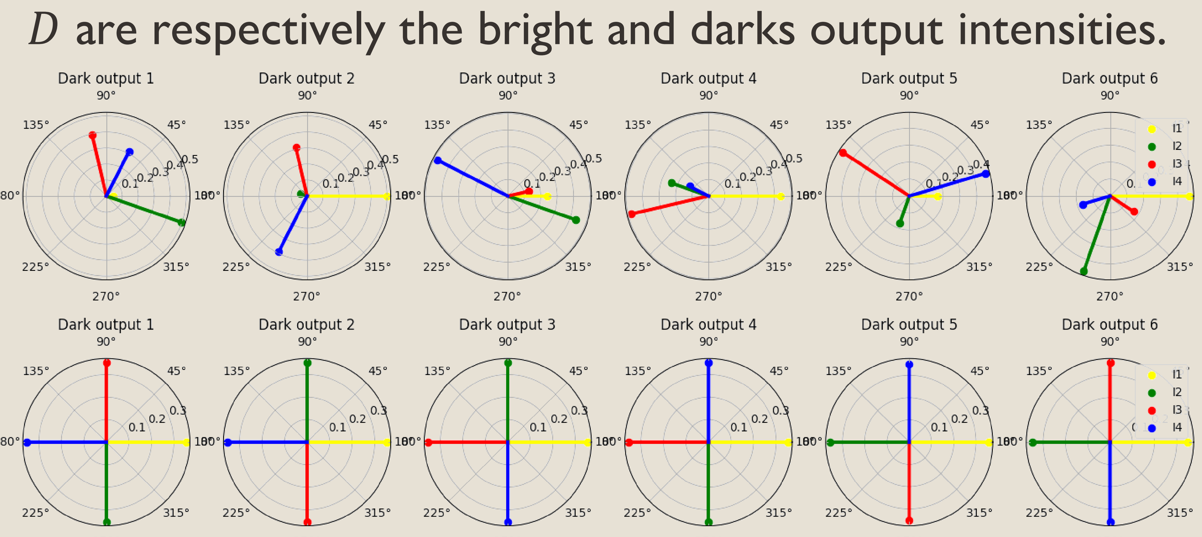

Figure 6: phase and amplitude of the 4 input signals on the 6 dark outputs before (top) and after (bottom) the calibration process

Distribution analysis 📊

By introducing input phase aberrations, the system is not able to perfectly cancel the star light. By multiplying the observation, we obtain such distribution:

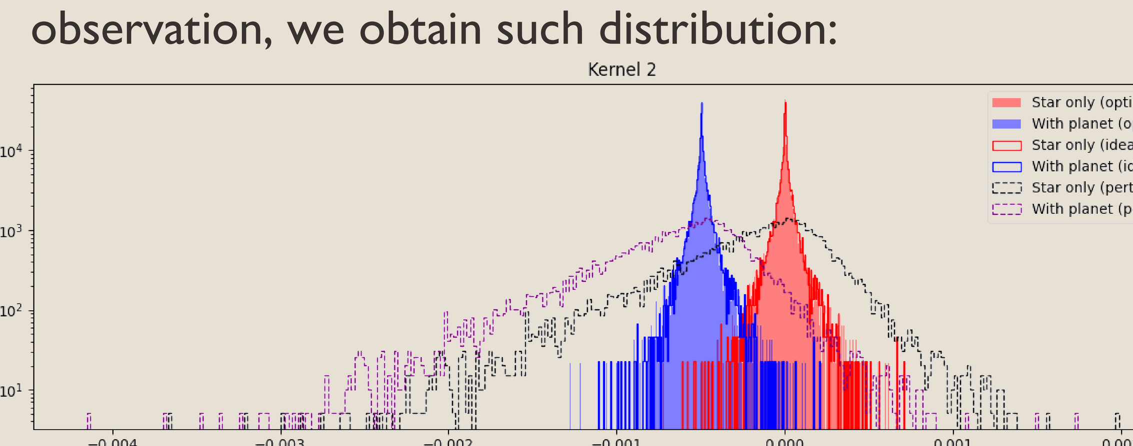

Figure 7: Intensity distribution obtained on a kernel output (with an extremely bright planet to clearly show the distribution shift)

The presence of an exoplanet in the field of view result in a shift of the distribution. The more the planet will be bright, the more the shift will be pronounced. In practice, both distribution are almost indistinguishable. We then test several estimators to retrieve the true value of the signal and then estimate the probability of detection.

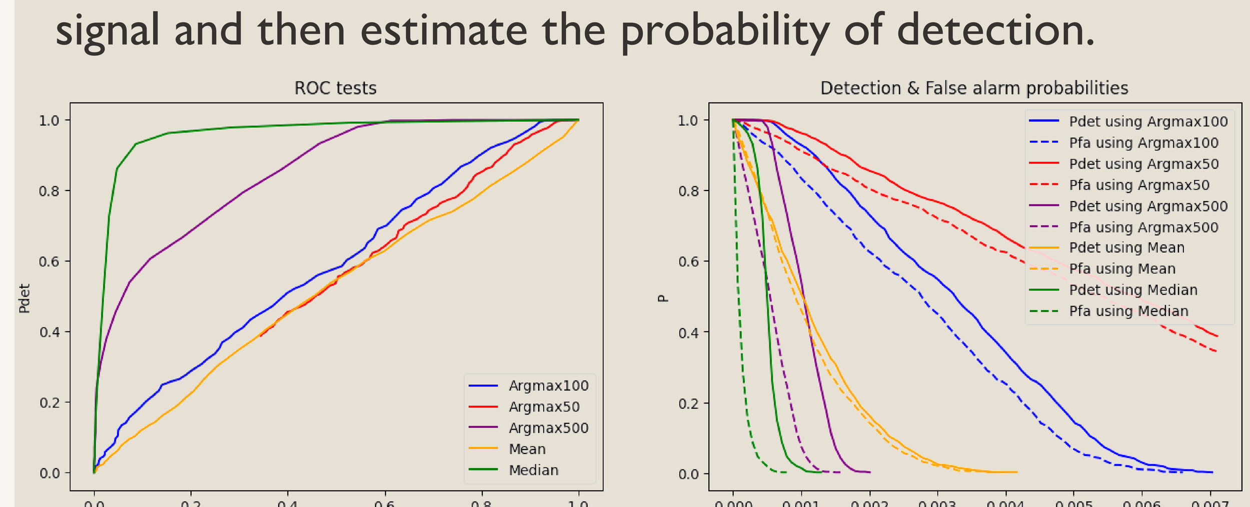

Figure 8: **ROC** test to estimate the confidence of detection regarding to the probability of false alarm.

Parallactic diversity 🔄

Taking advantage of the earth rotation, the kernel distribution will shift according to a known modulation. For each kernel output, one fit this modulation to the data points, giving the position and contrast of the potential object. By averaging all these parameter and computing a global fit, we can then see if this last one is well correlated to each kernel modulation.

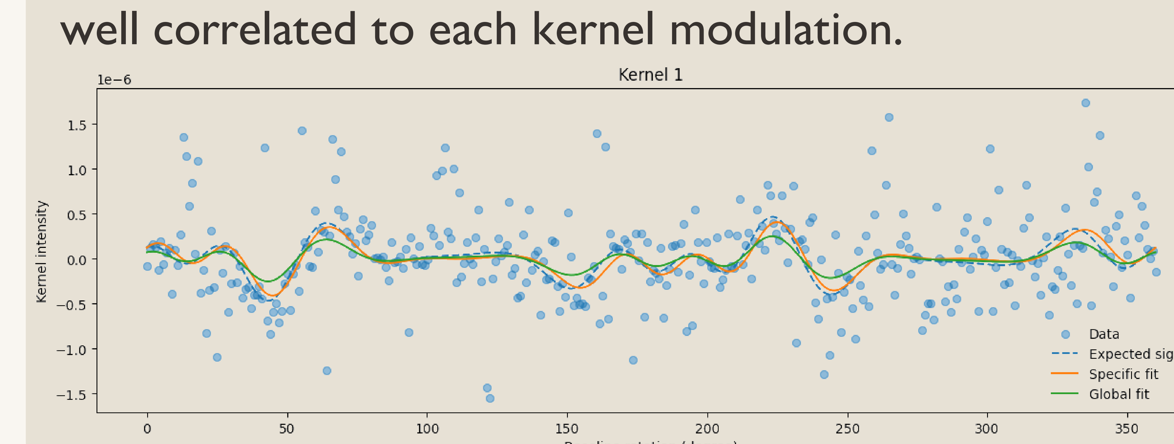

Figure 9: Kernel modulation & fitting

On-sky contribution 🌠

By weighting the kernel transmission map by the output intensity and integrating it over the parallactic angle, we can dress a map of the source of input light. By cumulating the 3 maps, one can constrain precisely which part of the sky contributed the most to the data we have. Thus, this process reveal the approximative object location, spreaded by the input phase aberrations.

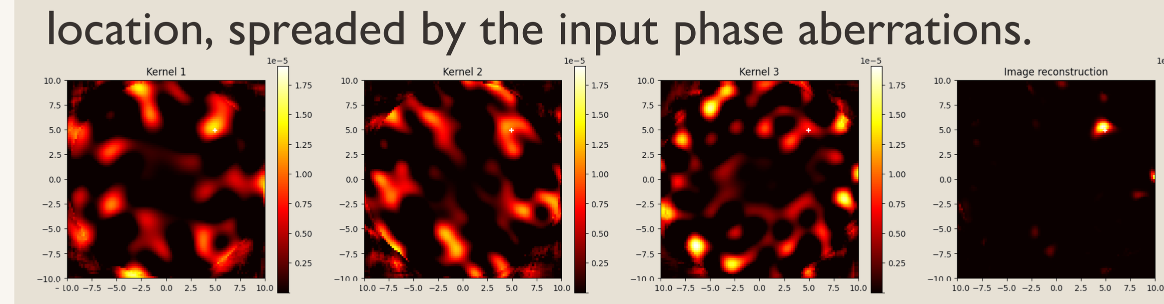

Figure 10: Repartition of on-sky contributions and cumulation of these maps to reveal the object location.

Discussions & prospects 💬

These promising results are mitigated by the persistent sensibility to high order phase aberration. A contrast of 10^{-6} require an **AO** correction that bring phase aberrations below $\lambda/100$ **RMS**. Also, two of the main prospects will consist to make these simulations chromatic and confirm these results on a test bed.

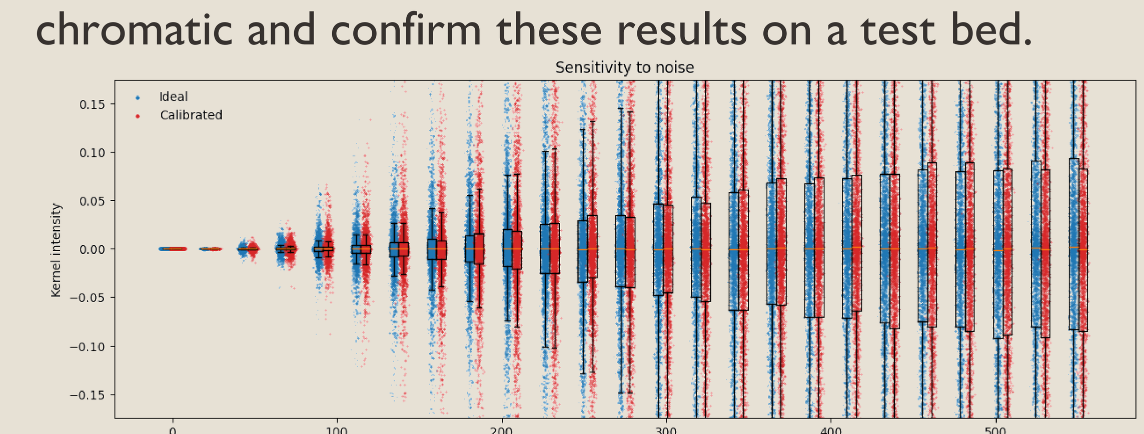

Figure 11: Evolution of kernel distribution spread according to the input phase aberrations.

References 📜

1. Cvetojevic, N. et al. *"3-beam self-calibrated Kernel nulling photonic interferometer"* (2022). Preprint at http://arxiv.org/abs/2206.04977.
2. Martinache, Frantz, et Michael J. Ireland. *"Kernel-Nulling for a Robust Direct Interferometric Detection of Extrasolar Planets"*. Astronomy & Astrophysics 619 (2018): A87. https://doi.org/10.1051/0004-6361/201832847.

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Glossary 📖

AO: Adaptative Optics
OPD: Optical Path Difference
RMS: Root Mean Square
ROC: Receiver operating characteristic
VLTI: Very Large Telescope Interferometer