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K-STACKER: PUSHING THE BOUNDARIES OF HIGH-CONTRAST IMAGING - A COMPREHENSIVE REVIEW OF RECENT RESULTS

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Abstract. Keplerian-Stacker is a pioneering multi-epoch algorithm designed to combine numerous observations while taking into account the orbital motion of potential exoplanets to enhance the final detection threshold. K-Stacker has been used on several surveys (SHINE, NEAR-VISIR, SPHERE-ZIMPOL) containing multiple observations on single targets. Beyond the algorithm, we also suggest that K-Stacker should be seen as a novel observational strategy, leveraging multi-epoch observations to extract orbital parameters of the sought-after planets while minimising the total exposure time, thereby optimizing the use of future E-ELT instruments (HARMONI, METIS, PCS, etc.). At shorter wavelengths and/or for shorter separations (e.g. the observations of Jupiter-like planets or Earth twins with the upcoming Roman Space Telescope or the Habitable World Observatory), multi-epoch recombination will become an essential requirement, and K-Stacker provides a first step towards ensuring the success of those future observatories.

Keywords: High Contrast Imaging, Data Analysis, Adaptive Optics, High Angular Resolution, Dynamical Evolution and Stability, Earth and Planetary Astrophysics, Instrumentation and Methods for Astrophysics, eps Eri b, Alpha Cen

1 Introduction

Males et al. (2013) conducted an initial analytic study showing that planets in the habitable zone around nearby stars (1-10 pc) would move more than one Full Width at Half Maximum (FWHM) of a typical 30 m telescope near-infrared Point-Spread Function (PSF) during the time required for their detection (> 10 hours). K-Stacker represents a pioneering attempt to solve this problem of multi-epoch recombination (Le Coroller et al. 2015). This algorithm is designed to combine multiple observations in which a potentially undetected planet is moving along its orbit, by optimizing a likelihood function written as:

$$\log(L)(\mathcal{O}) = \frac{1}{2}\frac{\left(\sum_{i=0}^{n}\frac{S_i(\mathcal{O})}{\sigma_i(\mathcal{O})^2}\right)^2}{\sum_{i=0}^{n}\left(\frac{1}{\sigma_i(\mathcal{O})}\right)^2} - \frac{1}{2}\sum_{i=0}^{n}\left(\frac{S_i(\mathcal{O})}{\sigma_i(\mathcal{O})}\right)^2 \tag{1.1}$$

where $S_i(\mathcal{O})$ is the signal in image i at a position corresponding to set of orbital parameters $\mathcal{O}$, and $\sigma_i^2(\mathcal{O})$ the noise variance at this same position.

In this Equation, the first term corresponds to the log-likelihood of having a planet in the data, while the second term is the log-likelihood of not having any planet in the data (null-hypothesis). In K-Stacker, only the first term of this likelihood is used to search for planets.

Another example of likelihood can be derived from the Bayesian framework for direct exoplanet detection proposed by Ruffio et al. (2018).

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2 Review of recent results and future observations

2.1 Review of recent results

The ability of an algorithm such as K-Stacker to detect planets with very low Signal to Noise Ratios (SNR), typically < 2 in each image, was demonstrated through a large blind test on simulated SPHERE images by Nowak et al. (2018). Nowak et al. (2018) has also shown that an $\mathrm{SNR}_{\mathrm{KS}} > 7$ allows to claim a true detection with high confidence (i.e., small rate of false alarm). We applied K-Stacker for the first time on real observations (IRDIS and IFS-SPHERE) in Le Coroller et al. (2020). In this paper, we have demonstrated that the SNR enhancement achieved through K-Stacker recombination closely approximates the optimal value, which is the square root of the number of combined observations. Additionally, we confirmed that the detection threshold is approximately $\mathrm{SNR}_{\mathrm{KS}} \approx 7$.

An other important result of Le Coroller et al. (2020) has been to show that K-Stacker is therefore also an algorithm that allows for the extraction of orbital parameters of planets directly from observation images, instead of relying on the astrometry of detections as commonly used by MCMC methods. Indeed, K-Stacker yields orbital parameters that are consistent with literature values on β Pictoris b and HD 95086 b. In the case of HD 95086, the companion b was nearly undetectable in the H-band (with $S/N \approx 3$ at one epoch), but K-Stacker enhanced its signal to noise to $\mathrm{SNR}_{\mathrm{KS}} = 10$, demonstrating the full potential of this algorithm.

In 2022, we re-detected the companion C1, initially discovered in the mid-IR (11.2 microns) by the VISIR-NEAR team (Wagner et al. 2021), located in the habitable zone of Alpha Cen A. We demonstrated that even at 11 microns (i.e., with a large FWHM-PSF) and within the shortest possible observation period with the VLT-UT4 (80 hours of observations conducted in just one month), 25% of orbits (eccentric and/or close to the mask) result in an orbital motion of more than one PSF. For these high-displacement orbits, K-Stacker provides approximately a 30% gain compared to simple co-addition, making it indispensable to ensure no planets are missed.

Finally, despite the movement of the radial velocity planet Epsilon Eridani b along its Keplerian orbit during the observation period, we successfully combined 40 hours of data obtained with SPHERE-ZIMPOL (Tschudi et al. 2024). The probabilistic detection map. (Fig. 1), published in Tschudi et al. (2024) illustrates that the detection of epsi Eri b, with an approximate radius of 0.8 Jupiter radii, was not achievable in the 12 SPHERE-ZIMPOL observations. Although Epsilon Eridani b was not detected by K-Stacker, this integration achieved an unprecedented contrast ratio of 10^8.

2.2 Keplerian Stacker algorithms: A necessity for future observations

These observations conducted on Epsilon Eridani with SPHERE-ZIMPOL closely aligns with the future scientific objectives of the Roman Space Telescope. Indeed, the RST will also aim to detect known radial velocity Jupiter around nearby stars in visible light. Our work demonstrates that a recombination algorithm like K-Stacker will be essential for summing the 100 hours of observations necessary for the Roman Space Telescope to achieve a contrast greater than 10^8.

Future high-contrast imaging observations with ground-based telescopes (E-ELT) and space observatories (Roman Space Telescope and Habitable World Observatory) will aim to probe planet populations near the ice line at 2-5 AU. These planets will move more than one FWHM-PSF of these telescopes during the time required for their detection. In this context, several international teams are now actively developing multi-epoch algorithms for Orbital Differential Imaging.

Recently, Octofitter, a new algorithm for Keplerian recombination (Thompson et al. 2023), has been introduced, implementing an MCMC approach on a likelihood function for direct imaging data defined in Ruffio et al. (2018). This approach tries to extract unbiased orbital parameters and allows to combine direct images with radial velocity and proper motion anomaly, even without a confirmed detection in any single epoch.

An important parameter that must be evaluated for these technics of de-orbiting observations is the signal to noise threshold of detection. The PACOME algorithm (Dallant et al. 2023) apply a multi-epoch algorithm to PACO reductions. In order to provide robust detection limit, PACO algorithm (Flasseur et al. 2018) statistically captures the spatio-temporo-spectral correlations of the data with a weighted multi-variate Gaussian model whose parameters are estimated, in a data-driven fashion, at the scale of a patch of a few tens of pixels. Recently, we compared a PACOME reduction with a K-Stacker plus ASDI-PCA reduction on HARMONI simulated images (Le Coroller et al. 2024). The results were similar at most separations. Both algorithms employ very distinct and complementary mathematical approaches (noise modelling vs. PCA technique). Therefore, confirming detections using both methods would provide greater reliability.

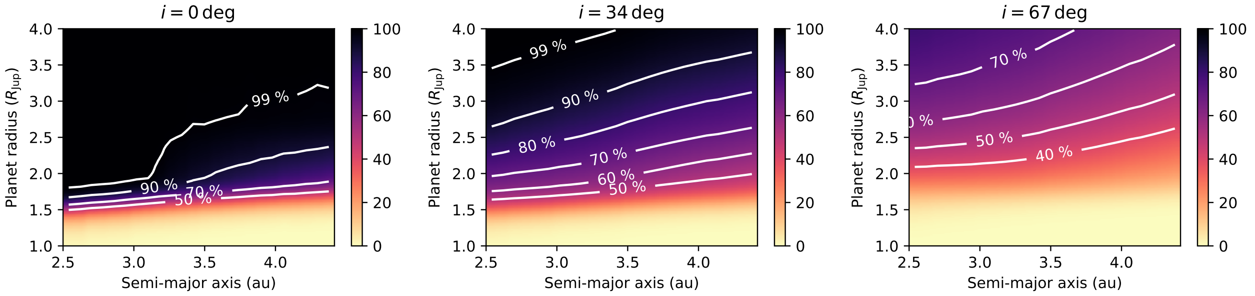

Fig. 1. Detectability of planets around epsi Eridani for which a planet of given radius would have been detected by K-Stacker, for 3 different values of the inclination. The inclination has a significant impact on the detectability of planets, due to the influence of the phase angle on the polarization contrast.

3 Conclusions

The K-Stacker approach significantly improves the detection limits of direct imaging techniques. We have demonstrated that K-Stacker allows the combination of multiple observations even if the planet moves along its orbit during this period and remain undetectable (SNR < 2) at each epoch. More than a simple algorithm, K-Stacker potentially introduces a new observational strategy in high-contrast imaging. Long observations could broken into shorter ones, and performed under the best atmospheric turbulence conditions (in service mode), enabling the highest contrasts and extraction of orbital parameters with minimal total exposure time. Furthermore, K-Stacker allows to resume an observation at a later time, even if it has to be stopped due to technical issues or weather degradation. This is a potential advantage over more classical approaches to imaging, especially considering the value of an observing time on the next-generation observatories (e.g. the E-ELT). We present a practical implementation of K-Stacker, which allows, for example, to probe planets smaller than 2 Jupiter radii in the Epsilon Eridani region at less than 4 AU, using the SPHERE ZIMPOL instrument. We demonstrate that ODI algorithms, such as K-Stacker, will be indispensable for the success of future space missions like RST and HWO. K-Stacker is accessible on GitHub * and can be easily installed as a Python package via [pip install]. It works with any high-contrast reduced images (PCA-ASDI, TLOCI, etc.). Our team regularly enhances the code to improve computational efficiency and the statistical analysis of the outcomes. Contact us, if you would like we run K-Stacker on your multi-epochs data.

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