National Aeronautics and Space Administration

Advancing space-based exoplanet imaging with photon-counting image processing

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Objectives

The photon arrival time distributions for exoplanets and speckles are sufficiently distinct in ground-based high-contrast data to enable effective discrimination (Gladysz & Christou 2008; Meeker 2018; Steiger 2021). The Stochastic Speckle Discrimination (SSD) technique in Figure 1 specifically assumes that speckle intensity distributions will follow a Modified Rician (MR) form, and fits the histogram of speckle intensities from many short exposures with a MR function, extracting the skewness as a metric for the contribution of planet light . Additionally, speckle spatio-temporal coherence can also be a useful tool for studying atmospheric statistics and instrumental error sources directly from the science image plane without requiring non-common-path sensing or external telemetry. The difference in arrival time statistics between exoplanets and speckles is expected for speckles induced by atmospheric turbulence as well as speckles induced by instrumental drifts. Our objective was to explore the use of time domain processing techniques such as SSD for space-based exoplanet imaging data to improve detection limits, or serve as a useful diagnostic tool

Background

- photon arrival times for exoplanets, speckles, and other noise sources should follow different distributions, providing a means to discriminate between sources
- The advent of photon-counting detectors for use in ground-based high-contrast instruments has led to renewed interest (and successful demonstration) of techniques that use these statistical differences to separate exoplanets from speckles.
- For this study we used the Roman-CGI OS9 simulated observing scenario

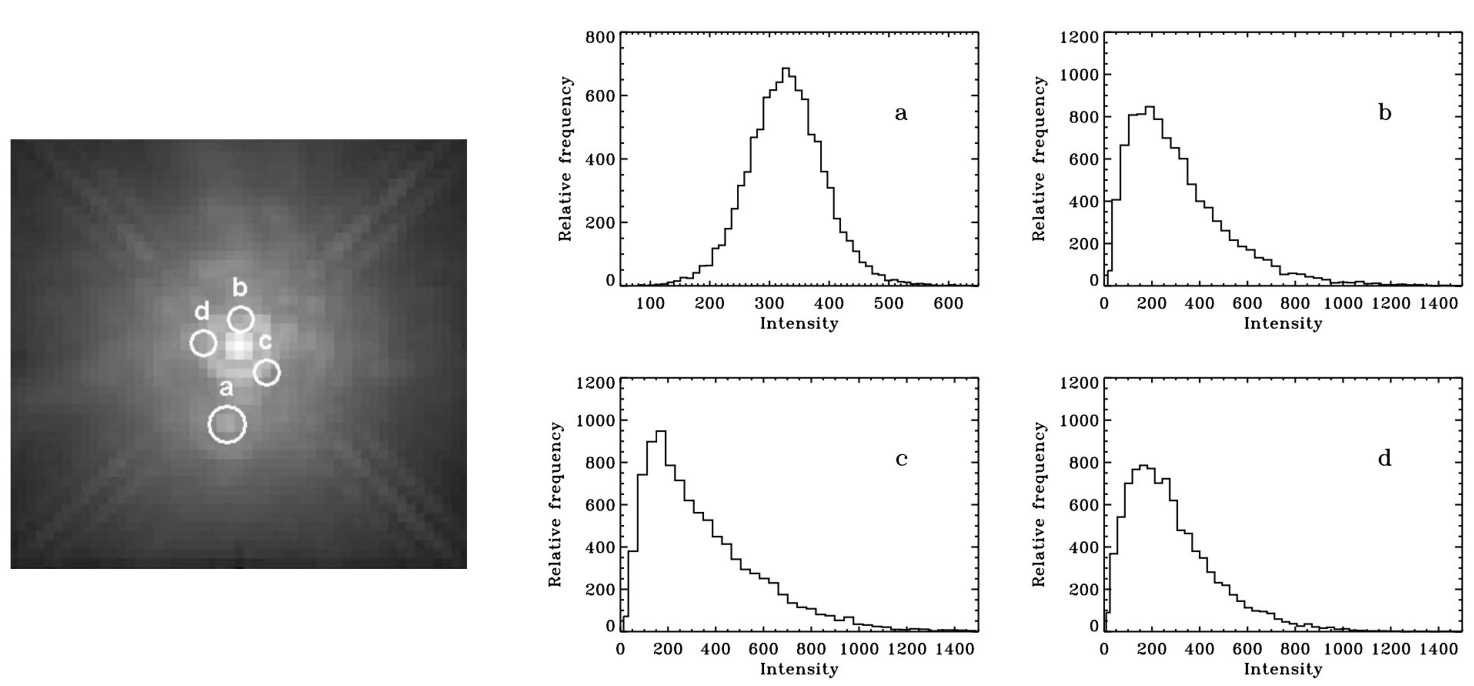

Figure 1. Illustration of the SSD technique from Gladysz and Christou, 2008. Speckles are expected to have a modified rician (MR) intensity distribution, skewed right, while on-axis PSFs have been shown to have a left skewed distribution in AO corrected images

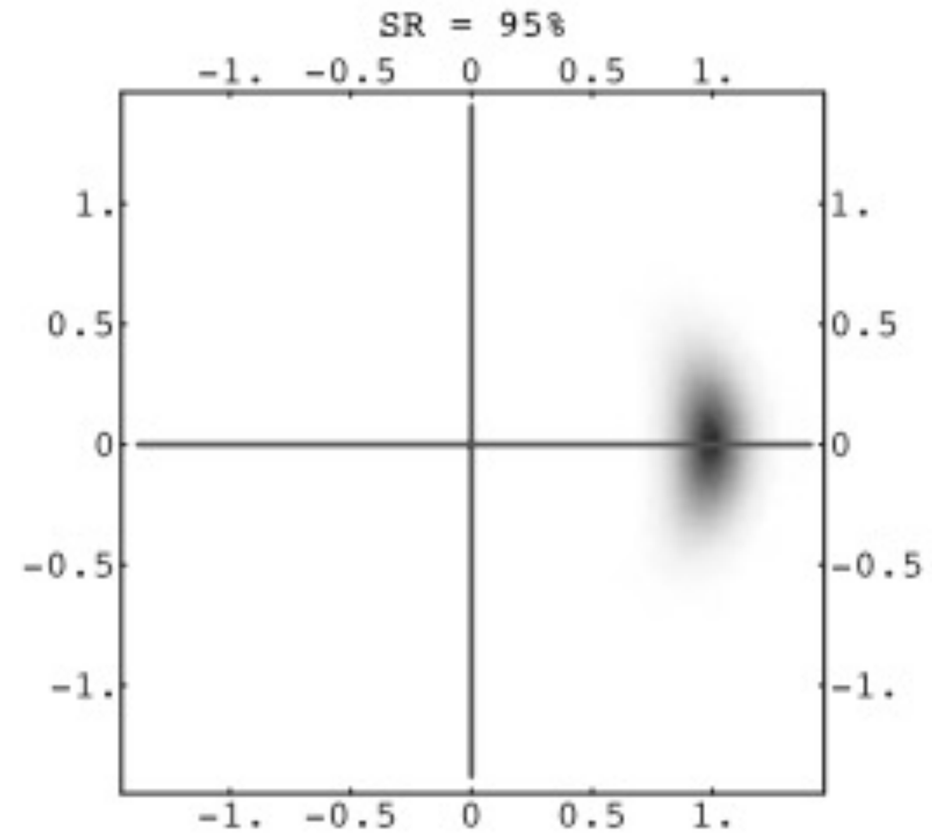

Figure 3. A simulated PDF of pupil plane complex amplitude from Soummer et al 2007 for the case of extreme AO correction

Approach and Results

- Start with noiseless OS9 dataset with perfect resolution of speckle intensity variations, apply photon noise
- Apply SSD using known pipeline developed for photon counting detectors; explore more general 2-point comparison tests as well
- Both yield some intriguing results, but don’t reliably pick out planets
- To better understand why, measured speckle lifetimes directly using auto-correlation of speckle lightcurves and compare to observing timescales.
- While enough photons are collected within a speckle lifetime, not enough speckle lifetimes are sampled over a full observation to resolve the intensity statistics, owing to the very long speckle lifetimes.

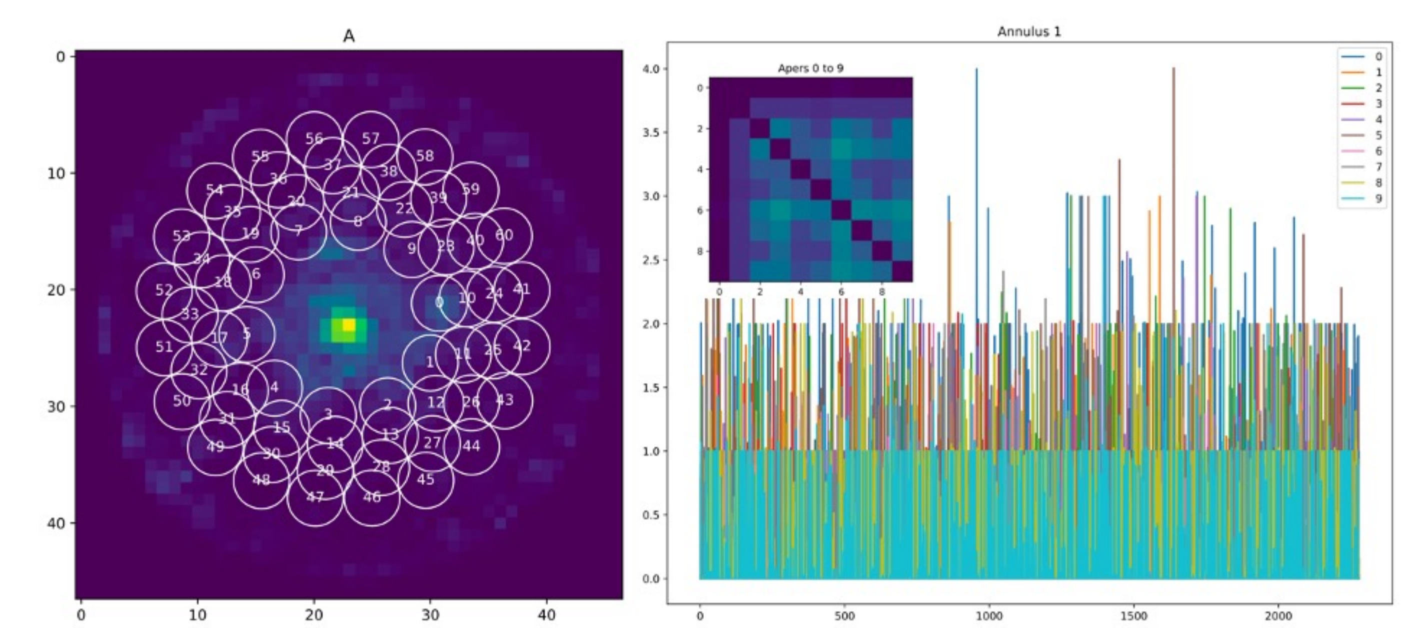

Figure 2. Median image of all 5s frames from the Roll A in the Roman CGI OS9 simulated dataset, tiled with an example of aperture placements. Associated lightcurves from the first annulus is shown on the right. Inset is an example of the 2-D Kolmogorov Smirnov map comparing all pairs of apertures in Annulus 1.

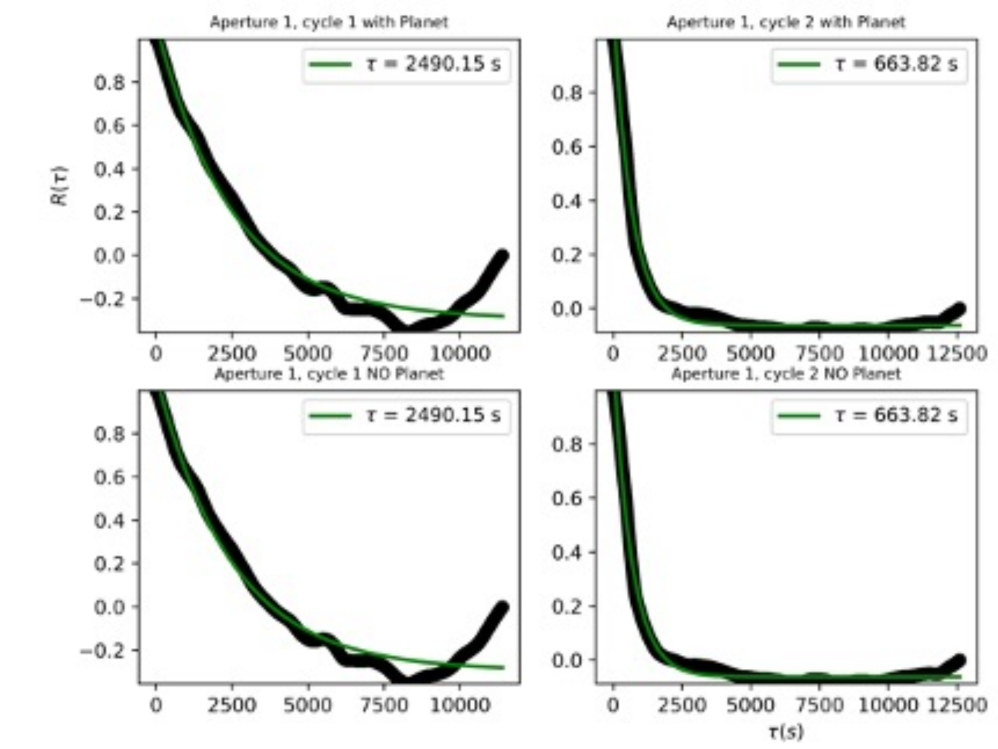

Figure 4. Exponential fit to the auto-correlation function of a given aperture’s lightcurve can be used to extract an estimate for the speckle lifetime within that aperture.

Significance/Benefits to JPL and NASA

- speckle removal with these types of statistical techniques will likely be of limited utility for space-based high contrast imaging unless it is discovered that speckle lifetimes are considerably shorter (~10x) than in this simulated dataset.
- Even then, a criterion must be met that >>1 photon per speckle arrives per speckle lifetime to not be dominated by Poisson noise
- These techniques are still of interest for ground-based high contrast science as the next generation of planet finders that prioritize photon counting detectors are developed
- The direct study of speckle spatio-temporal correlations from the science image plane may also be of interest for the field of optical comm
- All code used for this effort is available on JPL github.

References
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