Tunable Kernel Nulling for High-Contrast Exoplanet Imaging

From Theory to Experimental Validation

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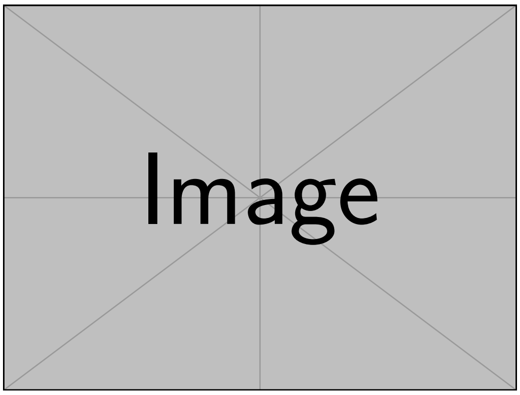
A thesis presented for the degree of
Doctor of Philosophy



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December 22, 2025

Abstract

The direct detection of exoplanets requires overcoming extreme contrast ratios between the star and its companion. This thesis presents the development of Tunable Kernel Nulling, a robust interferometric technique. We introduce theoretical models, the `PHISE` simulation framework, and experimental results from the `PHOBos` test bench.

Contents

Chapter 1

Introduction

1.1 Context: The Quest for Other Worlds

The detection and characterization of exoplanets is one of the most dynamic fields in modern astronomy. Since the discovery of 51 Pegasi b (Mayor and Queloz, 1995), thousands of exoplanets have been detected, revealing a staggering diversity of planetary systems. However, the majority of these detections rely on indirect methods such as radial velocity or transit photometry. While these techniques provide valuable information on the mass, radius, and orbital parameters of planets, they are often limited in their ability to characterize the atmosphere and composition of these distant worlds directly.

High-contrast imaging, or direct imaging, aims to spatially resolve the planet from its host star. This is a formidable challenge due to the immense brightness contrast between the star and the planet (ranging from 10^{-3} for young giant planets to 10^{-10} for Earth-like planets) and the small angular separation involved (often less than a fraction of an arcsecond).

1.2 The High-Contrast Imaging Problem

The fundamental limit to direct imaging is not merely the diffraction limit of the telescope, but the presence of optical aberrations caused by the Earth's turbulent atmosphere or imperfections in the telescope optics. These aberrations create a "speckle halo" that can mimic or obscure faint planetary signals. To overcome this, specific instrumentation strategies are required.

1.3 Current Limitations and Challenges

1.3.1 Coronagraphy

Coronagraphy relies on blocking the starlight using a focal plane mask or pupil apodization. It typically requires a single, continuous aperture and is extremely sensitive to low-order wavefront errors (tip-tilt). While highly effective in space (e.g., JWST) or with extreme adaptive optics (e.g., VLT/SPHERE), it faces challenges at very small inner working angles (IWA).

1.3.2 Classical Interferometry

Long-baseline interferometry (e.g., VLTI) allows for high angular resolution by combining light from multiple telescopes. However, classical visibility measurements often lack the dynamic range required for high-contrast detection due to calibration errors and phase noise limiting the precision.

1.3.3 Nulling Interferometry

First proposed by Bracewell (Bracewell, 1978), nulling interferometry aims to destructively interfere the starlight while constructively interfering the planet light. This requires extremely precise path length control to maintain the "null" depth. In practice, instrumental drifts and residual phase errors limit the stability and obtainable contrast of ground-based nullers.

1.4 A Robust Solution: Kernel Nulling

To address the limitations of classical nulling, the concept of **Kernel Nulling** (KN) has been proposed (Martinache and Ireland, 2018). KN leverages the idea of phase closure (used in closure phase) but applies it to the context of nulling. By forming linear combinations of the combiner outputs that are insensitive to second-order phase errors, KN provides observables that are robust against instrumental aberrations.

This thesis focuses on the development of **Tunable Kernel Nulling**, bringing the concept from theoretical formulation to experimental validation using integrated photonics. We introduce the design of reconfigurable beam combiners capable of adapting to different observing conditions and optimizing the nulling efficiency.

Chapter 2

Theoretical Foundations

2.1 Optical Interferometry and Nulling

Optical interferometry combines light from multiple apertures to achieve high angular resolution. The fundamental observable is the complex visibility, related to the spatial frequency content of the source via the Van Cittert-Zernike theorem.

2.1.1 The Bracewell Nuller

Proposed by Bracewell, 1978, the nulling interferometer aims to cancel the starlight by adjusting the phases of the combined beams such that they interfere destructively on axis (where the star is located) and constructively off-axis (where the planet is). For a two-element interferometer, the transmission map $T(\theta)$ is given by:

$$T(\theta) = \sin^2\left(\frac{\pi B\theta}{\lambda}\right) \tag{2.1}$$

where B is the baseline and λ the wavelength.

2.1.2 limitations of Classical Nulling

Ideally, the null depth is infinite. In practice, it is limited by instrumental defects, primarily piston errors (phase delay differences) and intensity mismatches. These residual errors result in "stellar leakage" which drowns out the planetary signal.

2.2 Kernel Nulling

2.2.1 Matrix Formalism

An interferometric beam combiner can be described by a linear transfer matrix $\mathbf{M}$ linking the input complex amplitudes $\mathbf{E}_{in}$ to the output fields $\mathbf{E}_{out}$:

$$\mathbf{E}_{out} = \mathbf{M} \cdot \mathbf{E}_{in} \tag{2.2}$$

The detected intensities are $\mathbf{I} = |\mathbf{E}_{out}|^2$.

2.2.2 Robustness to Aberrations

Martinache and Ireland, 2018 introduced the concept of **Kernel Nulling** (KN). By forming specific linear combinations of the output intensities (kernels), one can construct observables that are insensitive to second-order phase perturbations. If $\mathbf{K}$ is the kernel matrix such that $\mathbf{K} \cdot \mathbf{A} = 0$ (where $\mathbf{A}$ describes the first-order response to phase errors), then the kernel-nulls $\mathbf{k} = \mathbf{K} \cdot \mathbf{I}$ are robust against small phase ocillations, stabilizing the null depth.

2.3 Photonic Beam Combiners

Integrated photonics offers a compact and stable platform for interferometry.

2.3.1 Multi-Mode Interferometers (MMI)

MMI devices are based on the self-imaging principle in multi-mode waveguides (Soldano and Pennings, 1995). Light injected into a wide multimode region excites multiple modes which propagate with different phase velocities. At specific distances along the propagation axis, these modes interfere to reproduce the input field or form multiple images. For a $N \times M$ coupler, the transfer matrix is determined by the device geometry, enabling the design of complex mixing functions required for Kernel Nulling.

2.4 Tunable Kernel Nulling

To maximize the scientific yield, the beam combiner must be adaptable. By integrating active phase shifters (e.g., thermal heaters) on the photonic chip, one can effectively "tune" the transfer matrix $\mathbf{M}$ in real-time. This allows for:

- Calibrating fabrication errors.
- Switching between different observing modes (e.g., varying the nulling baseline).
- Optimizing the kernel response for specific target geometries.

This thesis investigates the implementation of such tunable architectures.

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