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Calibration of Residual Speckle Pattern in a Coronagraph

Michael Shao[1], Joseph J. Green[1], Benjamin Lane[2], James Kent Wallace[1], Bruce Martin Levine[1], Rocco Samuele[3], Shanti Rao[1], and Edouard Schmidtlin[1]

[1]Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Drive,
Pasadena, CA 91109, USA, email: Michael.Shao@jpl.nasa.gov

[2]Center for Space Research, Department of Physics, Massachusetts Institute of Technology.
Cambridge, MA 02139, USA

[3]Northrop Grumman Space Technology, One Space Park, Redondo Beach, CA 90278, USA

Abstract. Ground and space based coronagraphs have been proposed to suppress the light of the star so a planet nearby can be imaged. But even when starlight has been suppressed by 10^{10}, the residual starlight is as bright as the planet, and must be subtracted to $2 * 10^{-11}$ for a 5 sigma detection of the planet. For a ground based AO coronagraph, the problem is even more severe. Typically suppression of starlight to 10^{-5} of the star is possible and the residual speckle pattern must not have any "bumps" that mimic a planet at $10^{-7} - 10^{-8}$. This paper describes a speckle calibration approach that measures the electric field of the light after it exits the coronagraph, in order to estimate the speckle pattern in the image plane. This technique makes use of the coherence of star light or rather the incoherence of starlight to planet light, and has very significant advantages compared to other techniques.

For a space based coronagraph, an alternative approach is to rotate the telescope /coronagraph and subtract two images. The calibration interferometer described here has the advantage that the temporal stability of the system can be relaxed by several orders of magnitude. For a ground based AO coronagraph system this approach has none of the serious limitations of the techniques based on the radial expansion of the speckle pattern with wavelength and enables ground based AO coronagraphs to approach the photon limit rather than the atmospheric limit. The calibration interferometer is being built for a NASA sounding rocket experiment by BU, JPL, MIT, and GSFC (PICTURE) with a 50cm telescope and a nulling coronagraph to be launched in 2007. It is also part of a design study for an extreme AO coronagraph for the Gemini Telescope, and a conceptual study of an extreme AO coronagraph for the TMT.

Keywords. coronagraph, direct detection of planets, nulling interferometer.

1. Introduction

Removal of the residual speckle pattern after a coronagraph is essential for direct detection of planets whose flux is at or below the residual speckle level. If the average flux after a coronagraph is say 10^{-10} and the speckles amplitudes have a Gaussian distribution with a variance of $\approx 10^{-10}$, then in a typical image with a 30*30 airy spot field of view, there will be $\approx$45 speckles brighter than $2 * 10^{-10}$ and $\approx$3 speckles brighter than $3 * 10^{-10}$. A clear detection of a planet at 10^{-10} means the fluctuation in the background has to be significantly smaller than 10^{-10}, typically $\approx 2 * 10^{-11}$.

Many techniques have been proposed to "subtract" the speckle pattern. One is based on assuming the speckle pattern is stable while the telescope is rotated about the line of sight. The main drawback of this approach is that it requires extreme stability. If we

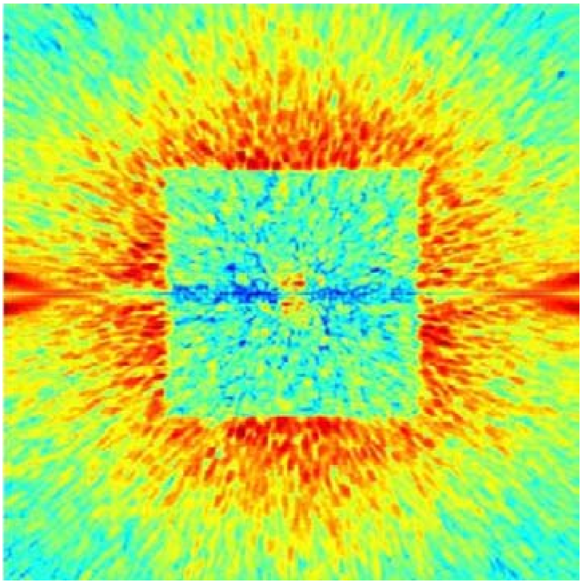

Figure 1. TPF-C simulation of residual speckles in white light.

want a speckle pattern of intensity $\approx 10^{-10}$ to be stable to $\approx 10^{-11}$ for 2–4 hrs, we are asking for the wavefront of the telescope to be stable to a few picometers for 2–4 hrs. For ground base extreme AO coronagraphs this approach doesn't work at all. A 2nd approach that has been proposed is to use the radial smearing of the speckle pattern with wavelength. This approach works if the imperfections in the wavefront are due to phase and amplitude errors in the pupil. But for a coronagraph looking at Earths, deformable errors will remove most of the errors at the telescope pupil and residual errors that form the 10^{-10} speckles will in general not originate at the pupil, and will not smear radially with wavelength.

The TPF-C project did a simulation of their coronagraph, shown in figure 1. The main feature is the dark hole. Outside the darkhole, these speckles are cause by wavefront errors at spatial frequencies that can not be corrected by the deformable mirror. These originate mostly from errors in the telescope optics (at a pupil) and they show the characteristic radial smearing with wavelength. Inside the dark hole, almost all the wavefront errors at a pupil have been removed and those speckles some times do and other times don't show radial smearing with wavelength.

A third technique for removing the residual speckle pattern has been called differential imaging. This technique relies of the target (e.g. planet) having a strong spectral feature, such as the methane band in the near IR. If we don't change wavelengths very much, the speckle features should be identical, and the difference between an "in band" and out of band image can show the presence of the planet. This technique has two drawbacks, one is it can't be used for Earthlike planets (which may not have a strong methane feature) and the images are limited to rather narrow bandwidths limiting SNR.

The speckle subtraction approach described here has none of the drawbacks of the above approaches. It doesn't require extreme wavefront stability (picometers) over hours only over fractions of a second. It can be used over a moderate bandwidth (10%–20%) and not just a <1% bandpass. It can be used for space based or ground based coronagraphs. The concept is based on the coherence of the speckle pattern with starlight. The planet light is incoherent with the starlight.

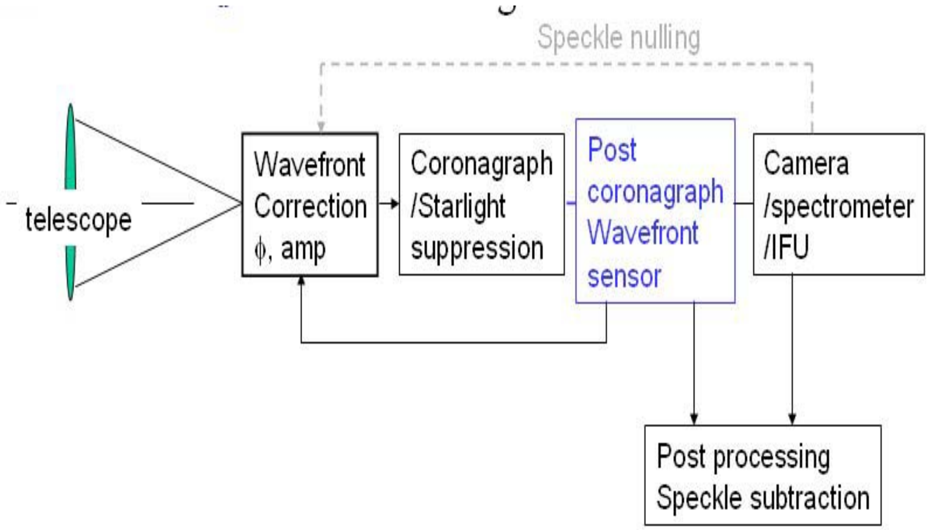

Figure 2. A block diagram of coronagraphic system.

2. Post Coronagraph Wavefront Sensor/Speckle calibration system

A block diagram of the coronagraphic system is show in figure 2. A post coronagraph wavefront sensor (PCWS) is placed between the coronagraph and the science camera/spectrometer. This wavefront sensor measures the electric field of the light that has not been suppressed by the coronagraph, typically because the amplitude and phase errors were not perfectly corrected. The PCWS is used in real time to control the deformable mirror(s) to correct phase and amplitude. The more important use is in post processing. The E-field of the light after the coronagraph in the pupil can be Fourier transformed and squared to yield the speckle pattern of the scattered light in the science camera.

The PCWS can be implemented as a machzender interferometer shown in figure 3 below. If the coronagraph is a "nulling interferometer", the "bright" output port of the nuller is spatially filtered (with a pinhole) and interfered with $\approx$50% of the light from the "dark" output port with a phase shifting type machzender interferometer. If the coronagraph suppresses all but $\approx 10^{-7}$ of the light, and that light is spread over $\approx$1000 airy spots/pixels in the science focal plane, the average scattered starlight is $\approx 10^{-10}$ of the original star in each airyspot/pixel. In the pupil plane however, the average flux is $0.5 * 10^{-7}$ in the "dark" arm of the machzender interferometer and $\approx$1.0 in the bright arm.

3. Post Coronagraph Wavefront sensor SNR

This is not the first time a machzender interferometer has been suggested for use behind a coronagraph. By using the full starlight flux in the "reference" arm, there is a significant SNR advantage over alternative post coronagraph wavefront sensing schemes. We are trying to in effect measure the flux of speckles that are 10^{-10} the brightness of the star. The measurements of these speckles have added noise, from CCD dark current, CCD read noise, and for a space coronagraph, local and exo-zodi contamination. But none of these additional noise sources are "coherent" with the starlight in the reference

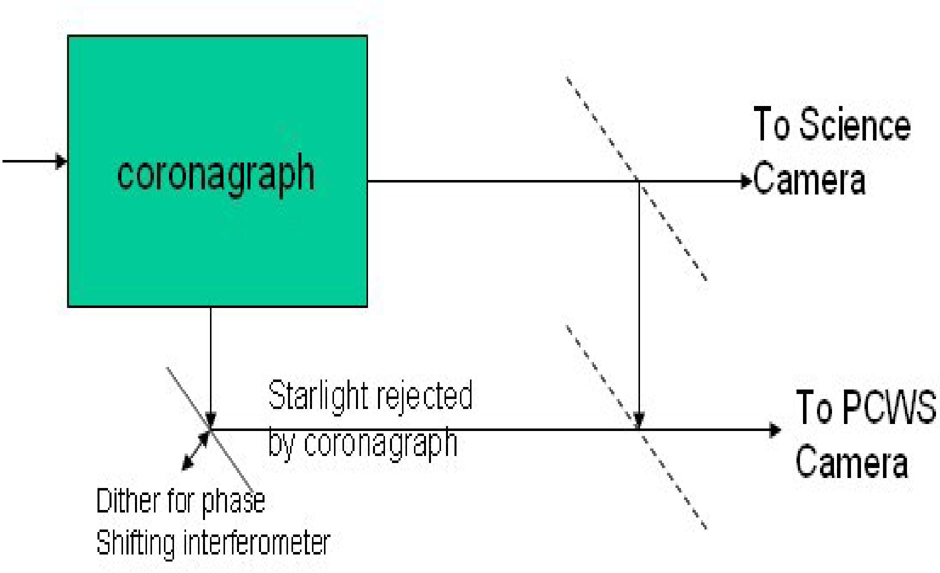

Figure 3. A post coronagraph wavefront sensor (PCWS).

arm of the interferometer. Taking the intensity of the two interfering beams as roughly 1.000 and $0.5 * 10^{-7}$, the fringe amplitude is $\approx 1.0 * fringeVis$ or $4.47 * 10^{-4}$. If the reference beam were attenuated to $5 * 10^{-8}$ to match the "dark" arm, the fringe amplitude would be 10^{-7}. At 10^{-7} CCD dark current, local/exo-zodi would dominate the SNR. The "unbalanced" machzender in a TPF-C mission would reduce the integration time needed for wavefront sensing by about a factor of 100 (from ≈2 hrs to ≈1 minute to measure). The measurement of the post coronagraph wavefront is now limited by photon flux at the dark output of the coronagraph, rather than other larger noise sources such as local/exo-zodi or detector noise.

4. Summary

The PCWS also provides a method for measuring the speckle pattern in a ground based extreme AO system, in a way that is limited only by photon statistics instead of speckle statistics. This makes ground based detection of "normal" Jupiters potentially possible, if they are 1–1.5 AU from the parent stars with contrast of $\approx 10^{-8}$ or better.

In space this approach will be demonstrated in the PICTURE project, a sounding rocket experiment designed to look for a possible planet around E. Eri and scheduled for launch in early 2007.

This concept is also used in a design study for the TPF-C mission, one of 5 funded studies of instrument concepts for the TPF coronagraph mission.