Millisecond Exposures in Ground-Based Exoplanet Imaging

Richard A. Frazin

University of Michigan

ms exposures are the only thing that can find planets within $\approx 3\ \lambda/D$ of the star because differential imaging does not.

Least controversial motivation to study millisecond focal plane sensing:

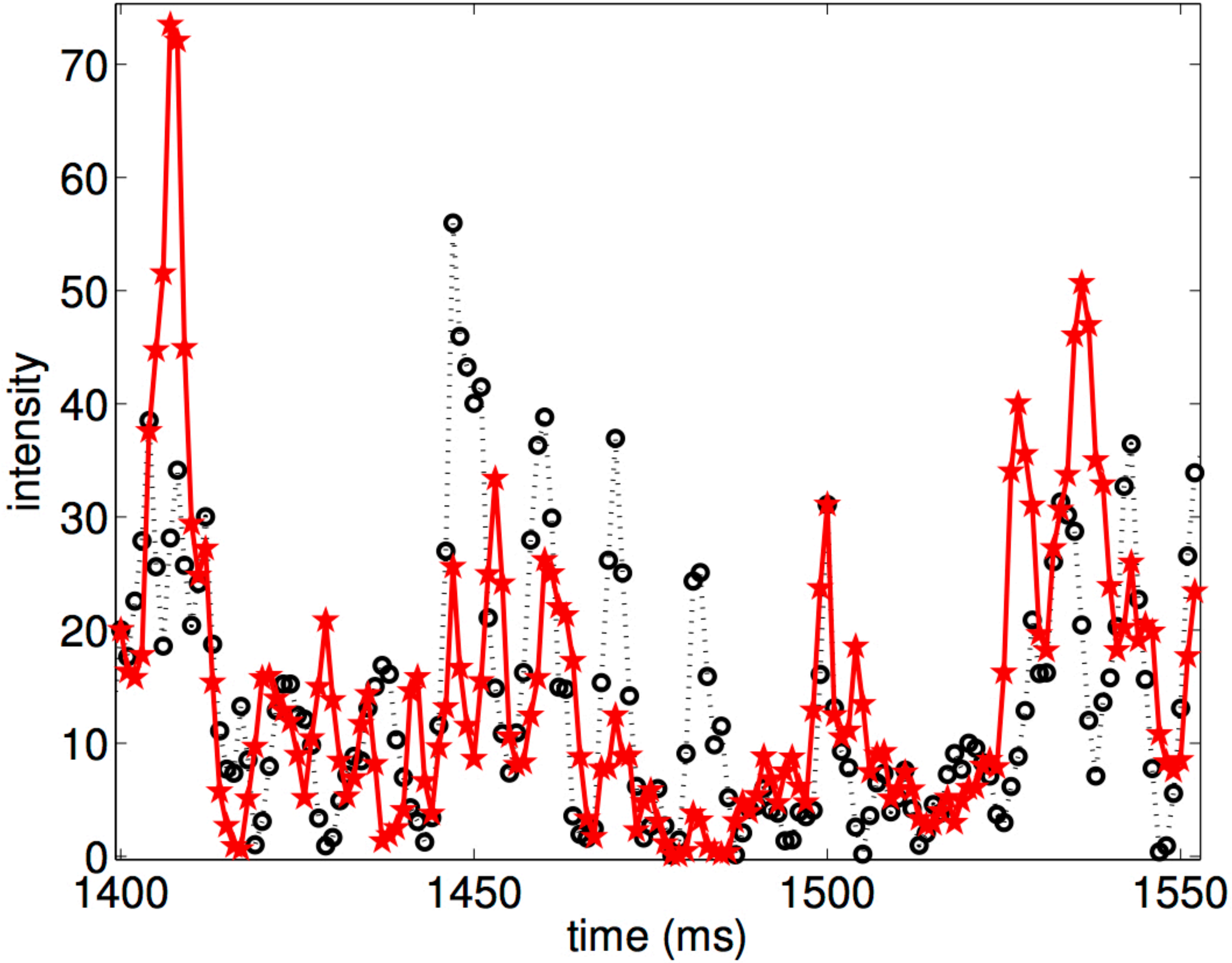
SELEX and MKIDS near-IR detectors!

Capable of kHz readout rates and have sub-electron read noise. Need to explore how they can be applied.

What happens on ms time-scales?

- At the center of a planet's Airy disk, the AO system holds its intensity nearly constant
- At the center of a planet's Airy disk, the stellar intensity is fluctuating wildly.
- The ms fluctuations of the speckle light encode information about the aberrations, carrying a tremendous amount of information about them
- This information is readily available since the residual phase is measured by the WFS.

Illustration of Available Info: Vibration Detection with FP Sensing



Frazin,
SPIE 2014

- Turbulent modulation of speckle caused high frequency vibrations. Red: 10 Hz Black: 100 Hz.

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UTILIZATION OF THE WAVEFRONT SENSOR AND SHORT-EXPOSURE IMAGES FOR SIMULTANEOUS ESTIMATION OF QUASI-STATIC ABERRATION AND EXOPLANET INTENSITY

Richard A. Frazin
Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI 48109, USA; rfrazin@umich.edu
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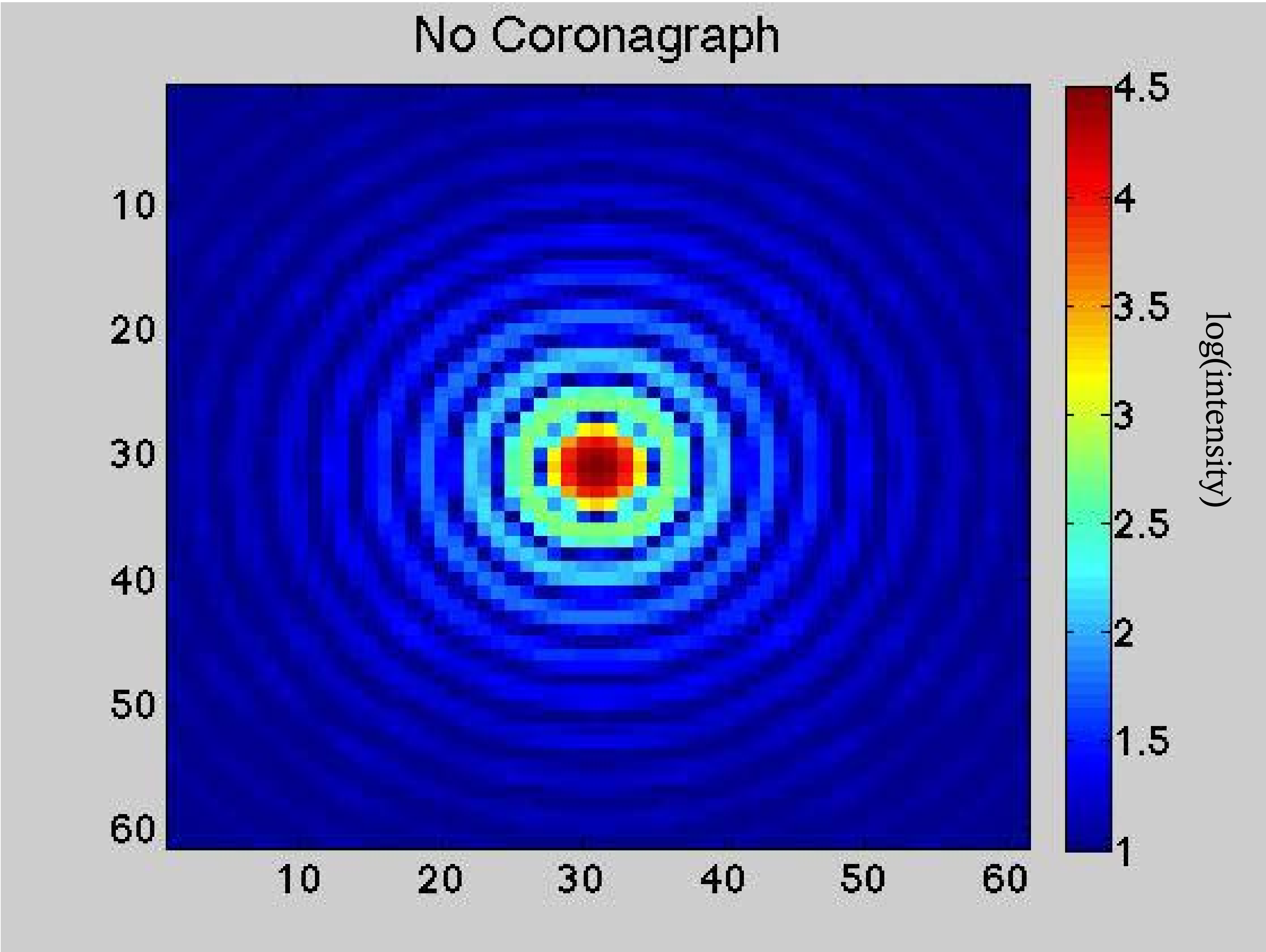
ABSTRACT

Heretofore, the literature on exoplanet detection with coronagraphic telescope systems has paid little attention to the information content of short exposures and methods of utilizing the measurements of adaptive optics wavefront sensors. This paper provides a framework for the incorporation of the wavefront sensor measurements in the context of observing modes in which the science camera takes millisecond exposures. In this formulation, the wavefront sensor measurements provide a means to jointly estimate the static speckle and the planetary signal. The ability to estimate planetary intensities in as little as a few seconds has the potential to greatly improve the efficiency of exoplanet search surveys. For simplicity, the mathematical development assumes a simple optical system with an idealized Lyot coronagraph. Unlike currently used methods, in which increasing the observation time beyond a certain threshold is useless, this method produces estimates whose error covariances decrease more quickly than inversely proportional to the observation time. This is due to the fact that the estimates of the quasi-static aberrations are informed by a new random (but approximately known) wavefront every millisecond. The method can be extended to include angular (due to diurnal field rotation) and spectral diversity. Numerical experiments are performed with wavefront data from the AEOS Adaptive Optics System sensing at 850 nm. These experiments assume a science camera wavelength λ of 1.1 μ, that the measured wavefronts are exact, and a Gaussian approximation of shot-noise. The effects of detector read-out noise and other issues are left to future investigations. A number of static aberrations are introduced, including one with a spatial frequency exactly corresponding the planet location, which was at a distance of $\approx 3\lambda/D$ from the star. Using only 4 s of simulated observation time, a planetary intensity, of ≈ 1 photon ms^{-1}, and a stellar intensity of $\approx 10^5$ photons ms^{-1} (contrast ratio 10^5), the short-exposure estimation method recovers the amplitudes' static aberrations with 1% accuracy, and the planet brightness with 20% accuracy.

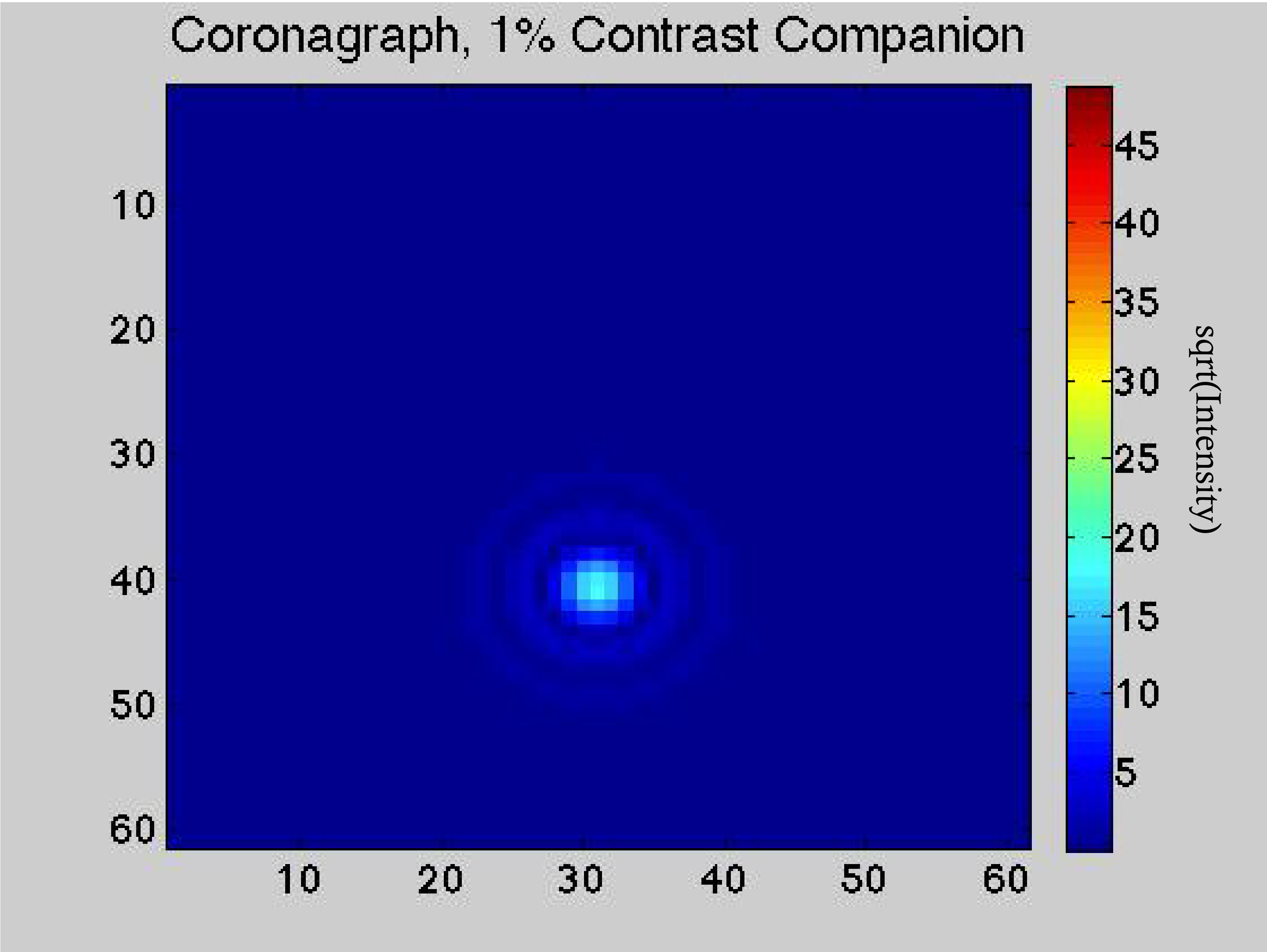
My Coronagraph Simulations

- I started with a series of 4000 measured wavefronts from the AEOS AO system (thanks to Lewis Roberts at JPL)
- Then I simulated how a simple stellar coronagraph would respond to these wavefronts
- I included “unknown” aberration in the optical system, including a sinusoidal term with a spatial frequency that placed a speckle exactly over the simulated planet.

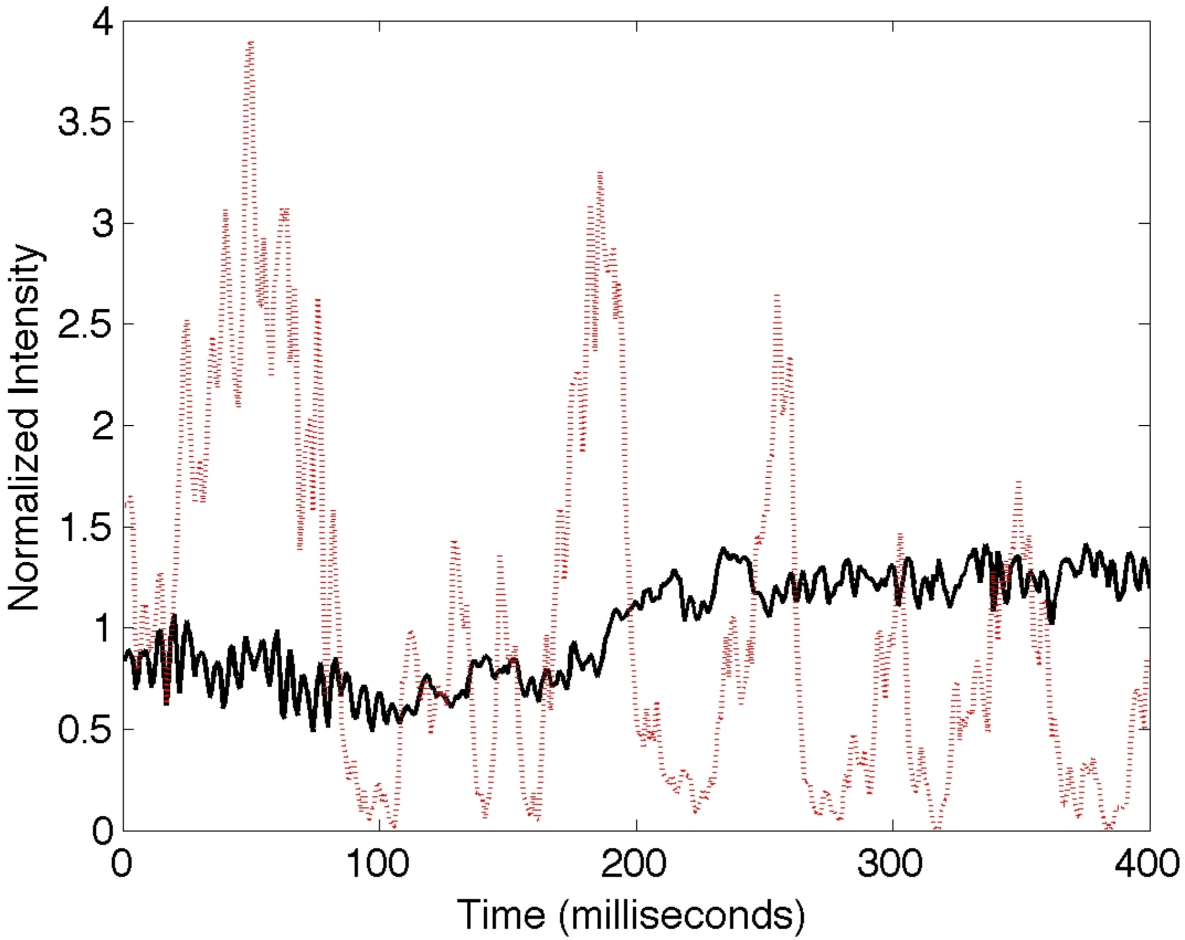
Movie: No Coronagraph



Coronagraph (Companion 1%)



Coronagraph Simulations



Red: stellar speckle intensity (normalized at planet position. Black: Planet intensity (normalized) at same position.

I demonstrated this effect analytically using physical optics arguments in my 2013 ApJ.

Q: How do you use the ms information?

A: large-scale regression

Comprehensive Solution: Statistical Inference

- I showed mathematically that the wavefront sensor data stream and millisecond exposures can be used to simultaneously determine the aberrations and the planetary image self-consistently.
- Later, I demonstrated that this approach can take into account subtle effects of polarizing elements (e.g., mirrors) in the telescope

Statistical Inference

$$\underbrace{I(\rho_{ij}, t_k)}_{\text{pixel value}} = \underbrace{n(\rho_{ij}, t_k)}_{\text{noise}} + \underbrace{\mathcal{A}(\rho_{ij}, t_k) + \mathcal{F}(\rho_{ij}, t_k) \cdot \boldsymbol{p} + \mathcal{B}(\rho_{ij}, t_k) \cdot \boldsymbol{a} + \mathcal{G}(\rho_{ij}, t_k) \cdot \boldsymbol{g}}_{\text{system model containing wavefront information}}$$

variable	status	description
$I(\rho_{ij}, t_k)$	measured	science camera intensity at pixel (i, j) in frame k
n	modeled	random process describing noise in measurements
$\boldsymbol{p}$	inferred	coefficient vector specifying planetary image
$\boldsymbol{a}$	inferred	coefficient vector of NCPA functions (inc. WFS bias)
$\boldsymbol{g}$	inferred	uncalibrated WFS gain coefficient vector
$\mathcal{A}$	modeled	atmospheric speckle image
$\mathcal{F}$	modeled	atmospheric speckle convolution kernel
$\mathcal{B}$	modeled	function to describe NCPA speckles
$\mathcal{G}$	modeled	function for uncalibrated WFS gains