Real-Time Estimation and Correction of Quasi-Static Aberrations in Ground-Based High Contrast Imaging Systems with High Frame-Rates

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Introduction

The success of ground-based, high contrast imaging for the detection of exoplanets in part depends on the ability to differentiate between quasi-static speckles caused by aberrations not corrected by adaptive optics (AO) systems, known as "non-common path aberrations" (NCPAs), and the planet intensity signal. Frazin (2013, ApJ) introduced a post-processing algorithm demonstrating that simultaneous millisecond exposures in the science camera and wavefront sensor (WFS) can be used with a statistical inference procedure to determine both the series expanded NCPA coefficients and the planetary signal. The algorithm can be summarized as follows:

Focal plane intensity can be written as:

Eq. 1) $I(\boldsymbol{\rho},t) = u_\bullet^2\, i_p(\boldsymbol{\rho},t) + A(\boldsymbol{\rho},t) + \mathbf{a}^\dagger\mathbf{b}(\boldsymbol{\rho},t) + \mathbf{b}^\dagger(\boldsymbol{\rho},t)\mathbf{a} + \mathbf{a}^\dagger C(\boldsymbol{\rho},t)\mathbf{a}$

$u_\bullet$ is the field amplitude of the planetary signal, i_p is related to the planetary intensity, **a** is a vector of static aberration coefficients, A is intensity only depending on AO residual ($\varphi_r(\mathbf{r})$) speckles, C depends on the static aberration ($\varphi_u(\mathbf{r})$) modulated by the AO residual, and **b** depends on the mixing of both effects.

Decompose Quasi-static NCPA: $\varphi_u(\mathbf{r}) = \Sigma a_k \Psi_k(\mathbf{r})$ from k = 1 to K, with $\Psi_k(\mathbf{r})$ being the functions in the search basis

Consider N locations $\{\rho_1, \ldots, \rho_N\}$ one desires to know if there is a planet and how bright it is, and T exposures synced with AO system WFS measurements:

- $\mathbf{y} = \mathbf{Hx}$ linear system form
- $\mathbf{y} = [\mathbf{y}_1; \ldots; \mathbf{y}_T]$, where each $\{\mathbf{y}_j\}$ is $I(\boldsymbol{\rho}_n,t_j) - A(\boldsymbol{\rho}_n,t_j)$
- $\mathbf{H} = [\mathbf{H}_1; \ldots; \mathbf{H}_T]$, where $\{\mathbf{H}_j\}$ is $[i_p(\boldsymbol{\rho}_n,t_j) \quad \mathbf{b}^T(\boldsymbol{\rho}_n,t_j) \quad \mathbf{b}^\dagger(\boldsymbol{\rho}_n,t_j) \quad \mathbf{c}^\dagger(\boldsymbol{\rho}_n,t_j)]$

Solve for $\mathbf{x} = [u_\bullet^2;\ \mathbf{a};\ \mathbf{a}^*;\ \{\mathbf{a}_k\mathbf{a}_l^*\}]$ using a linear solver

Verifying and Exploring the Algorithm

The first steps were to recreate and verify the results of the Frazin Algorithm (FA). With this done, several simulated experiments were run to probe the accuracy of the resulting estimation of the NCPA after a given number of measured exposures versus factors such as strehl ratio, overall strength of the NCPA, and the number of functions ($\Psi_k(\mathbf{r})$) included in the search basis set.

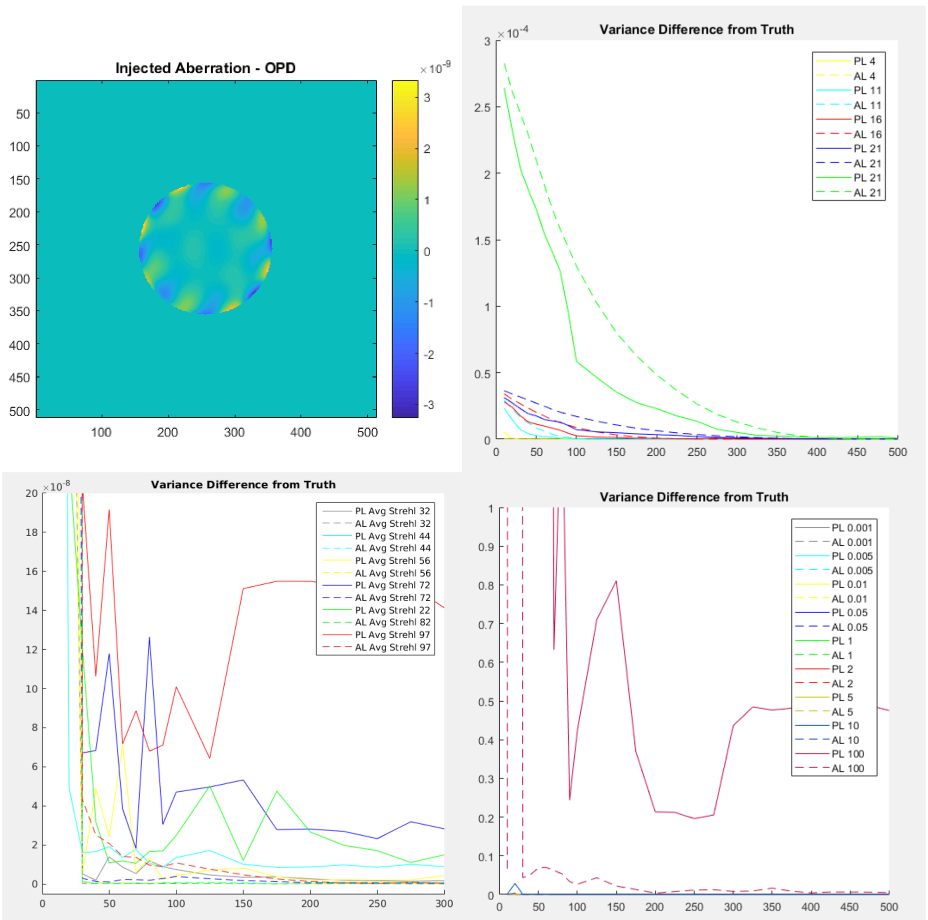

Fig 1. Algorithm Convergence Rates

At each exposure measured, the Frazin Algorithm is used to generate an estimate of the NCPA using the pixel location an artificial planet is injected (PL) and using all the pixels in the search region (AL). This estimate is then subtracted from the true NCPA, and the variance across the pupil is measured.

Top Left: Injected NCPA

Top Right: Variance vs. Exposure vs. Number of search Basis functions

Bottom Left: Variance vs. Number of Exposures vs. Average Strehl Ratio

Bottom Right: Variance vs. Number of Exposures vs. Strength of NCPA

Simulating the FA in Real Time with Ideal Conditions

Simulations using the ideal coronagraph, ideal wavefront sensor, no noise in measurements, phase only aberrations for the atmospheric effects and the NCPA, and an injected planet PSF are run to feed focal plane intensity frames into the FA. Every 150 exposures, the FA generates an estimate of the NCPA and applies a correction.

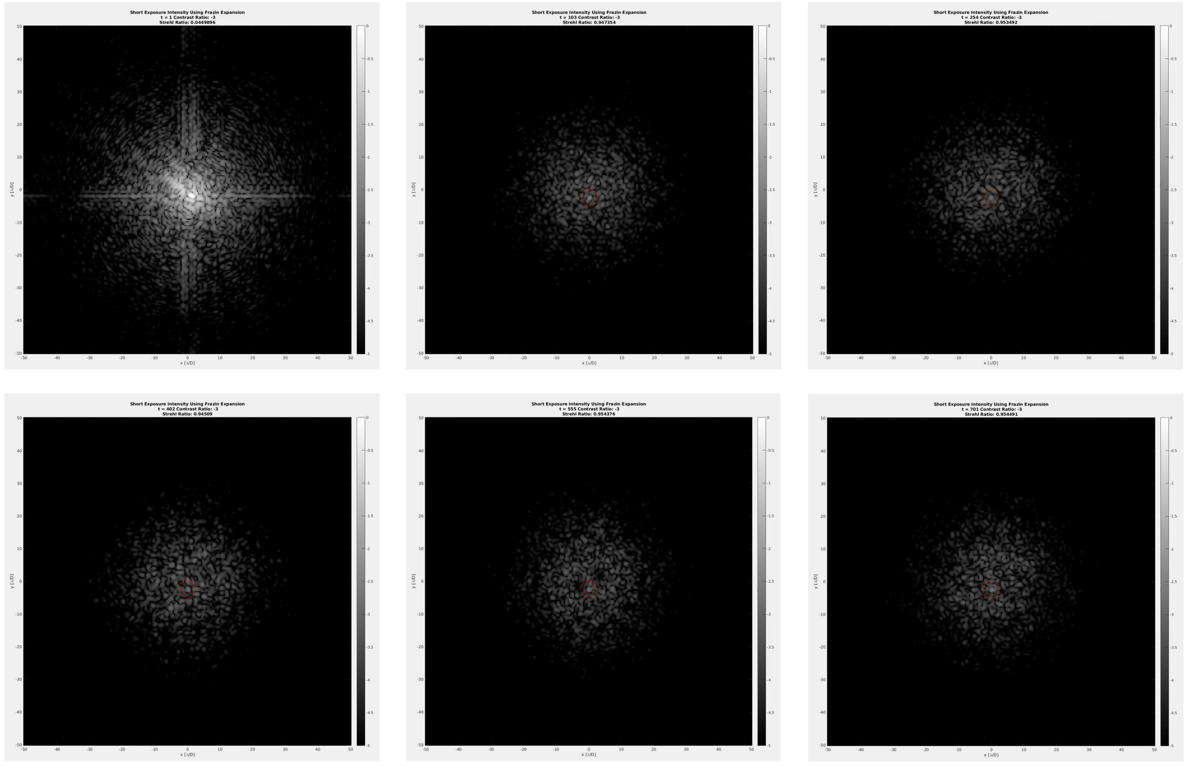

Fig 2. Frames from Ideal simulation showing the removal of a Static NCPA

Top left:	Starting intensity before the AO system turns on
Top middle:	AO loop is closed, revealing speckle pair caused by NCPA. A planet sits underneath the circled speckle.
Top right:	Frame just after first FA generated correction. The speckle pair is reduced, seen by the fact that the top speckle has mostly faded from view
Bottom row:	Subsequent frames corresponding to FA generated corrections. The speckle pair is not visible, leaving behind the planet PSF. The FA loop is closed.

Adapting the Algorithm for Real-Time Use

In order to use this algorithm in real-time, it must be made more computationally efficient. To accomplish this, Eq. 1) is remapped so that $\mathbf{y} = \mathbf{Hx}$ no longer produces estimates of the planetary signal, seen in Eq. 2.

Eq. 2) $I(\boldsymbol{\rho},t) - A(\boldsymbol{\rho},t) - u_\bullet^2\, i_p(\boldsymbol{\rho},t) = \mathbf{a}^\dagger\mathbf{b}(\boldsymbol{\rho},t) + \mathbf{b}^\dagger(\boldsymbol{\rho},t)\mathbf{a} + \mathbf{a}^\dagger C(\boldsymbol{\rho},t)\mathbf{a}$

We have named this the Real-Time Frazin Algorithm (RTFA), and assume that i_p is zero in order to remove estimating any planetary signal from the algorithm (See Figure 3 for analysis).

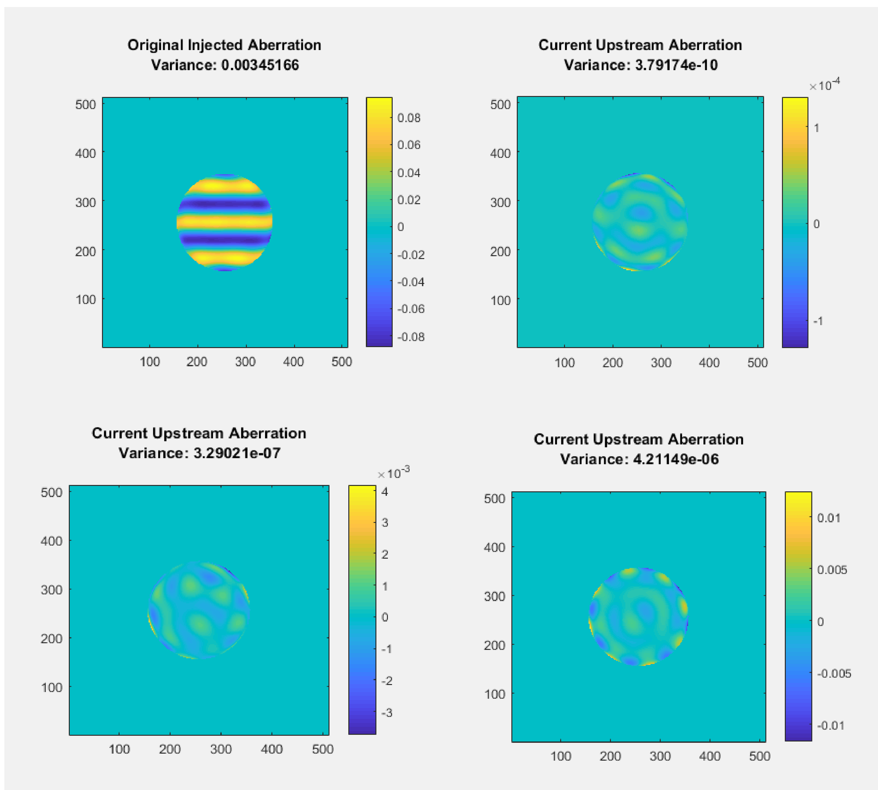

Fig 3. RTFA Results with various contrast ratio planets present in Focal Plane

Each frame shows the NCPA present. The variance across the pupil is given above each frame. In all cases, the RTFA algorithm assumes i_p is zero at all pixels

Top left: Injected NCPA at beginning of simulation

Top right: No planet present in focal plane

Bottom left: Planet at 10^{-3} contrast ratio to star present in focal plane

Bottom right: Planet at $10^{-2.5}$ contrast ratio to star present in focal plane

Simulating the RTFA with Imperfect Knowledge of the AO Residual

In order to determine the effects of a real world AO system, the simulations are re-evaluated using low-order estimations of the AO residual in place of ideal WFS measurements

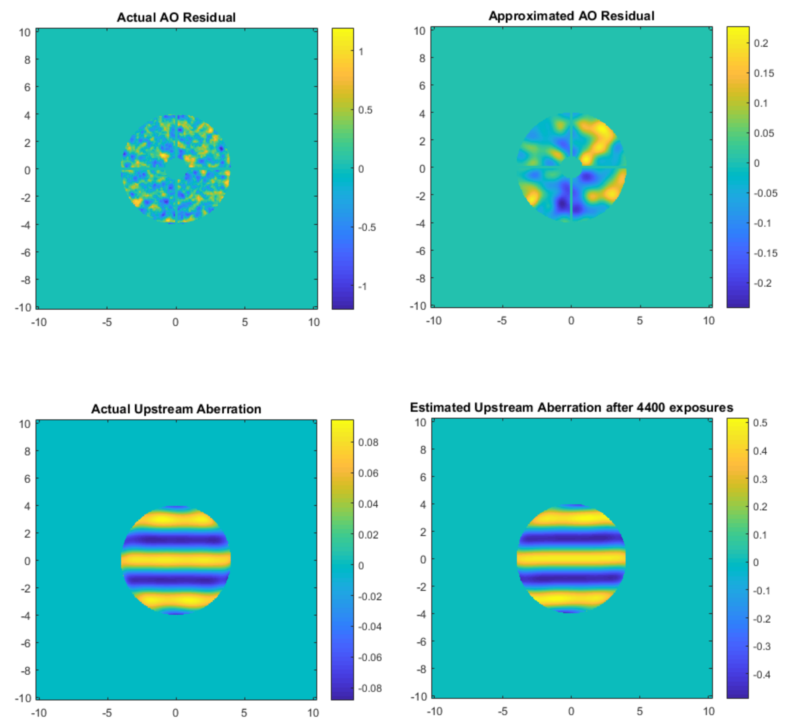

Fig 4. Converged RTFA estimate of NCPA using imperfect AO Residual in the algorithm

The effect of using imperfect knowledge of φr(r) is that it takes more exposures for the estimate to converge, and there is a scale factor error that occurs.

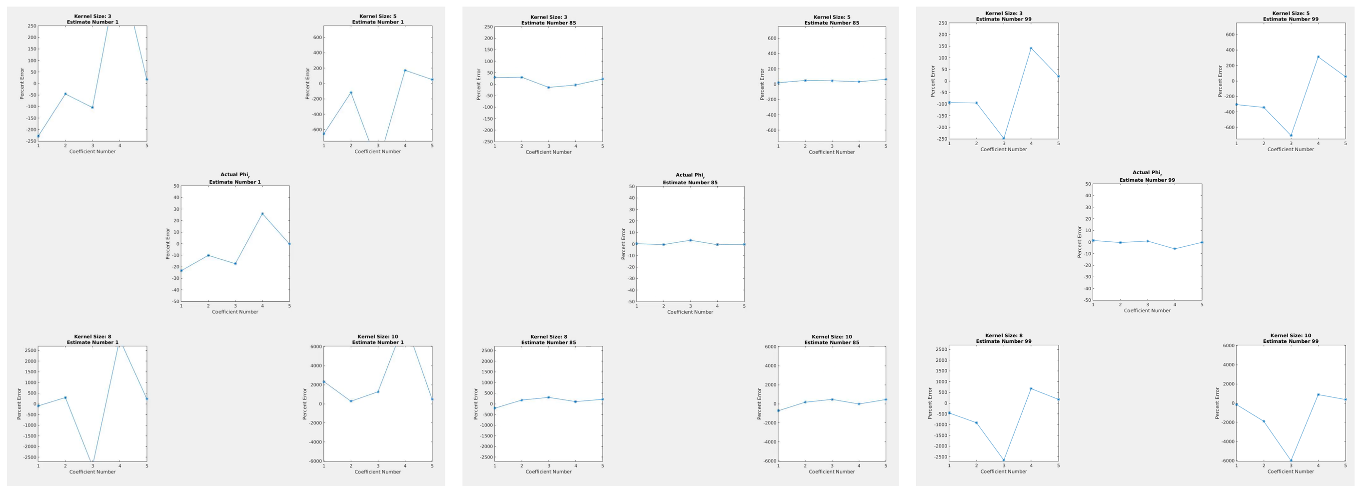

Fig 5. Percent Error of estimated NCPA basis function coefficients for various low-order estimations of the AO residual, at three different times in the simulation

Left group:	Percent error at the very first estimate using 50 exposures
Middle group:	Percent error at the point of best convergence using 4250 exposures
Right group:	Percent error at final estimate using 5000 exposures

Video Links

1. Video of FA simulation in Real Time with Ideal Conditions: https://youtu.be/ALs6qRBSI-8
2. Video of simulation using RTFA (Eq. 2 mapping): https://youtu.be/gLsXRDwlK2M
3. Video representation of Figure 5: https://youtu.be/QyFSnPnn2hc

Future Plans

In order to proceed, several future steps are suggested to be followed:

1. Refine Simulations to include WFS reconstruction, Noise in focal plane and WFS intensity frames, and quasi-static evolution of the NCPA following predicted speckle lifetimes
2. Mathematical Treatment of the use of WFS reconstructed AO Residuals
3. In lab verification of the RTFA
4. On-Sky testing of the RTFA

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References

1. Frazin, RA., "Utilization of the Wavefront Sensor and Short-exposure Images for Simultaneous Estimation of Quasi-static Aberration and Exoplanet Intensity,'' The Astrophysical Journal, vol. 767, article id. 21 (2013).