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ABSTRACT

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 (ApJ, 2013) 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. We demonstrate, via simulation, that using this algorithm in a closed-loop AO system, real-time estimation and correction of the quasi-static NCPA is possible without separate deformable mirror (DM) probes. Thus the use of this technique allows for the removal of the quasi-static speckles that can be mistaken for planetary signals without the need for new optical hardware, improving the efficiency of ground-based exoplanet detection. In our simulations, we explore the behavior of the Frazin Algorithm (FA) and the dependence of its convergence to an accurate estimate on factors such as Strehl ratio, NCPA strength, and number of algorithm search basis functions. We then apply this knowledge to simulate running the algorithm in real-time in a nearly ideal setting. We then discuss adaptations that can be made to the algorithm to improve its real-time performance, and show their efficacy in simulation. A final simulation tests the technique's resilience against imperfect knowledge of the AO residual phase, motivating an analysis of the feasibility of using this technique in a real closed-loop Extreme AO system such as SCExAO or MagAO-X, in terms of computational complexity and the accuracy of the estimated quasi-static NCPA correction.

Keywords: High contrast imaging, Extreme adaptive optics, Active speckle control, Quasi-static speckles, Exoplanets

1. INTRODUCTION

Eliminating quasi-static non-common path aberrations (NCPA) not seen by the AO system is an important step to improving the capability of ground-based, high contrast imaging systems to detect exoplanets. In Frazin 2013,[1] the author proposed a means to post-process millisecond science camera exposures simultaneously obtained with WFS measurements of the AO residual phase (ϕ_r) to estimate any quasi-static NCPA phase (ϕ_u) upstream of the coronagraph in a high contrast imaging system, as well as any present planetary emission in the science frames. To review, the Frazin Algorithm (FA) is advantageous because of its exploitation of the fact that the AO residual

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phase provides a new phase in the pupil plane at each exposure, and provides a statistically independent phase screen which modulates the quasi-static speckles in a new way every "atmospheric clearing time," τ_c (Macintosh et al. 2005).[2] This means that the rapidly changing AO residual speckles can be used as a probe to estimate the quasi-static NCPA because with each passing millisecond, more diversity in the observations is achieved. In equation form, the science camera intensity can be written as:

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

where $\boldsymbol{\rho}$ is a vector of pixel locations, $u_\bullet$ is the planet field amplitude, $u_\bullet^2 i_p$ is the planetary point spread function (PSF), $\mathbf{a}$ is a vector of quasi-static aberration coefficients, $\mathcal{A}$ is the intensity only depending on the AO residual speckles (ϕ_r), $\mathbf{C}$ depends on the quasi-static aberration (ϕ_u) as modulated by ϕ_r, and $\mathbf{b}$ depends on the mixing of both ϕ_r and ϕ_u. ϕ_u is then decomposed into a "search" basis set with no orthogonality restriction as:

$$\phi_u(\mathbf{r}) = \sum_{k=1}^{K} a_k \psi_k(\mathbf{r})\,, \tag{2}$$

where a_k are the individual elements of $\mathbf{a}$ from above, and ψ_k are the functions in the search basis the algorithm fits the quasi-static NCPA to. Considering N pixel locations $\boldsymbol{\rho} = \{\rho_1, ..., \rho_N\}$ in a single exposure from the science camera, $I(\boldsymbol{\rho}, t_i)$, one desires to know if there is planet emission, and T total millisecond exposures synchronized with WFS measurements of ϕ_r, $\mathcal{A}(\boldsymbol{\rho}, t_i)$, $\mathbf{b}(\boldsymbol{\rho}, t_i)$, and $\mathbf{C}(\boldsymbol{\rho}, t_i)$ are computed using FFTs following the equations given by Frazin,[1] and the following linear system model:

$$I(\boldsymbol{\rho}, t) - \mathcal{A}(\boldsymbol{\rho}, t) = u_\bullet^2 i_p(\boldsymbol{\rho}, t) + \mathbf{a}^\dagger \mathbf{b}(\boldsymbol{\rho}, t) + \mathbf{b}^\dagger(\boldsymbol{\rho}, t)\mathbf{a} + \mathbf{a}^\dagger \mathbf{C}(\boldsymbol{\rho}, t)\mathbf{a}\,, \tag{3}$$

is used to set up an inverse problem as:

$$\mathbf{y} = \mathbf{H}\mathbf{x}\,, \tag{4}$$

where

$$\mathbf{y} = [\mathbf{y_1};\, ...\, ;\, \mathbf{y_T}]\ , \{\mathbf{y_i}\} = I(\boldsymbol{\rho}_\mathbf{n}, t_i) - \mathcal{A}(\boldsymbol{\rho}_\mathbf{n}, t_i)\,, \tag{5}$$

$$\mathbf{H} = [\mathbf{H_1};\, ...\, ;\, \mathbf{H_T}]\ , \{\mathbf{H_i}\} = \Big[i_p(\boldsymbol{\rho}_\mathbf{n}, t_i) \qquad \mathbf{b}^T(\boldsymbol{\rho}_\mathbf{n}, t_i) \qquad \mathbf{b}^\dagger(\boldsymbol{\rho}_\mathbf{n}, t_i) \qquad \mathbf{c}^\dagger(\boldsymbol{\rho}_\mathbf{n}, t_i)\Big]\,, \tag{6}$$

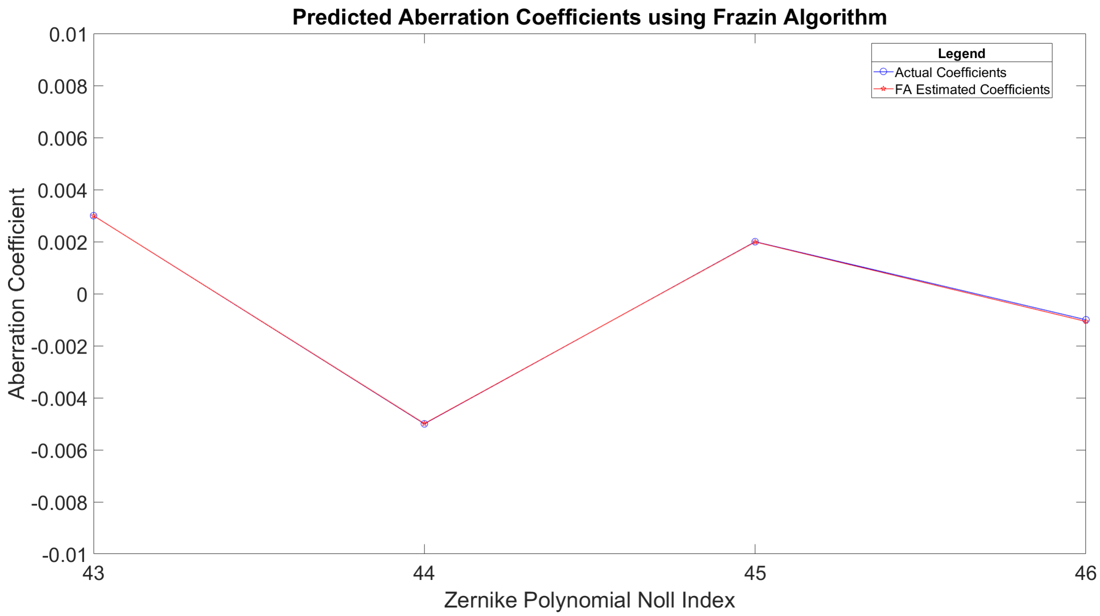
and

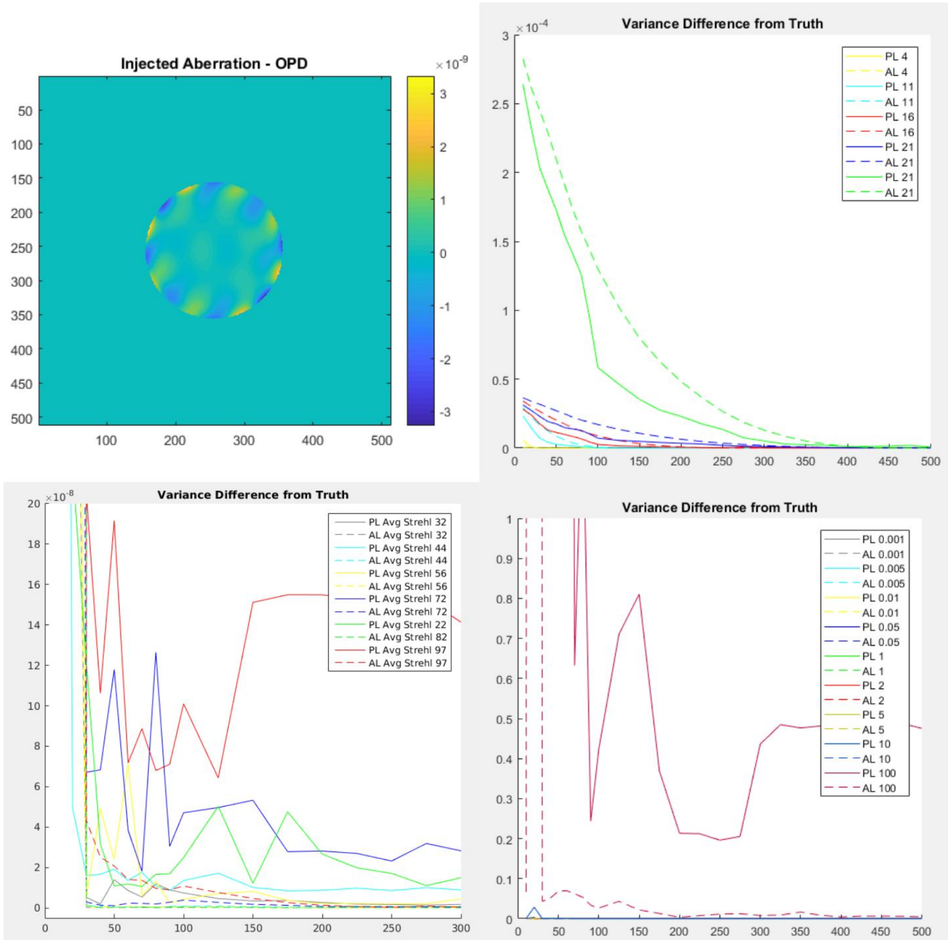
$$\mathbf{x} = \left[u_\bullet^2; \mathbf{a}; \mathbf{a}^*; \{\mathbf{a}_k \mathbf{a_l}^*\}\right] \tag{7}$$

$\mathbf{x}$ is then solved for to produce an estimate of the planetary field amplitude and the coefficients of the search basis set functions. The methods described below aim to take these equations and compute them in real-time using data streams from a science camera and WFS, as opposed to post-processing. Achieving this would allow for real-time estimations of the slowly evolving NCPA to be generated, and applied to a DM or DMs to correct for them, thus eliminating the quasi-static speckles one might mistake for a planetary signal.

2. VERIFYING THE FRAZIN ALGORITHM

In order to better understand the feasibility of running the Frazin Algorithm (FA) in real-time, a simulation is set up in order to both verify that the algorithm works as described, and explore its parameter space. Using a simple Fraunhofer diffraction model, we perform plane-to-plane propagations between elements of a kHz AO system which includes an ideal WFS, an ideal coronagraph, and a noiseless detector. A model of the atmosphere is constructed using AtmosphericTurbulenceSimul (see https://github.com/oguyon/AtmosphericTurbulenceSimul). This models a seven layer atmosphere, with each layer at various altitudes and wind vectors, and uses Fresnel Propagation between the layers to collapse the effects into a single phase screen with an average seeing of 0.65 arcseconds at 500nm, at 1 millisecond time steps. Only the phase effects are used in this simulation, leaving amplitude effects for a later study, knowing the algorithm is designed to handle them. A bright planewave (1e10 photons per millisecond per square meter) to model starlight is sent through the atmosphere model, and is incident upon an eight meter diameter telescope pupil. Here, an ideal WFS measurement is taken to measure ϕ_r, and then a phase only NCPA (ϕ_u) that consists of the sum the high order Zernike polynomials Z43-Z46


Predicted Aberration Coefficients using Frazin Algorithm
Legend
Actual Coefficients
FA Estimated Coefficients
Aberration Coefficient
Zernike Polynomial Noll Index
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
43
44
45
46


Injected Aberration - OPD
×10^-9
Variance Difference from Truth
×10^-4
PL 4
AL 4
PL 11
AL 11
PL 16
AL 16
PL 21
AL 21
PL 21
AL 21
Variance Difference from Truth
×10^-8
PL Avg Strehl 32
AL Avg Strehl 32
PL Avg Strehl 44
AL Avg Strehl 44
PL Avg Strehl 56
AL Avg Strehl 56
PL Avg Strehl 72
AL Avg Strehl 72
PL Avg Strehl 22
AL Avg Strehl 82
PL Avg Strehl 97
AL Avg Strehl 97
Variance Difference from Truth
PL 0.001
AL 0.001
PL 0.005
AL 0.005
PL 0.01
AL 0.01
PL 0.05
AL 0.05
PL 1
AL 1
PL 2
AL 2
PL 5
AL 5
PL 10
AL 10
PL 100
AL 100

reduces ϕ_r, even possibly to the point of the NCPA becoming the dominant aberration present in the wavefront, reducing the efficiency of the FA. The convergence plots for this analysis can be seen in the lower right of Figure 2. Again, the expected behavior is present. However, a vast difference in the convergence between the PL and AL methods is also present. The AL method curves remain smoother, but converge very quickly to lower variance difference values than the PL method curves. The PL method in this case seems to become very unreliable, suggesting that an individual pixel estimate requires more time to converge to the true value with higher Strehl, but the average of all the individual pixel estimates in the search region maintains the precision we expect to see in fewer exposures.

The final dependence that is examined is the strength of the NCPA that is being looked for. In this case, a scale factor is applied to the injected NCPA in the simulations. The scale factor of one is what is pictured in the top left of Figure 2. The other scale factors used can be found in the legend of the bottom right frame of Figure 2. The expected behavior is that the FA will perform better for smaller aberrations, and degrade quickly as the scale becomes larger because the construction of the algorithm uses only up through the quadratic terms of the Taylor expansion. What is seen in Figure 2 shows this to be the case. All of the small aberrations (scale less than 100) converge on a scale that is orders of magnitude faster than the largest aberration analyzed. Using a scale factor of 100 represents an aberration strength on par with one wavelength in OPD, which falls outside of the small aberration assumption used to justify throwing away the terms of the expansion larger than the quadratic term. The same behavior that is observed comparing the PL and AL methods in the case of the Strehl ratio examination is present in this test as well.

Having now examined numerous different simulated experiments in probing the algorithm, and finding that it converges and provides very accurate estimates in all the cases it is expected to, we confirm the validity of the FA. It is also clear that the AL method should be used for future work with the FA in order to obtain estimates of the aberration coefficients and planet amplitude with the quickest, most stable convergence. With a greater understanding of the FA and its behavior, we move on to simulate its use in a real-time, integrator control loop to correct the NCPA.

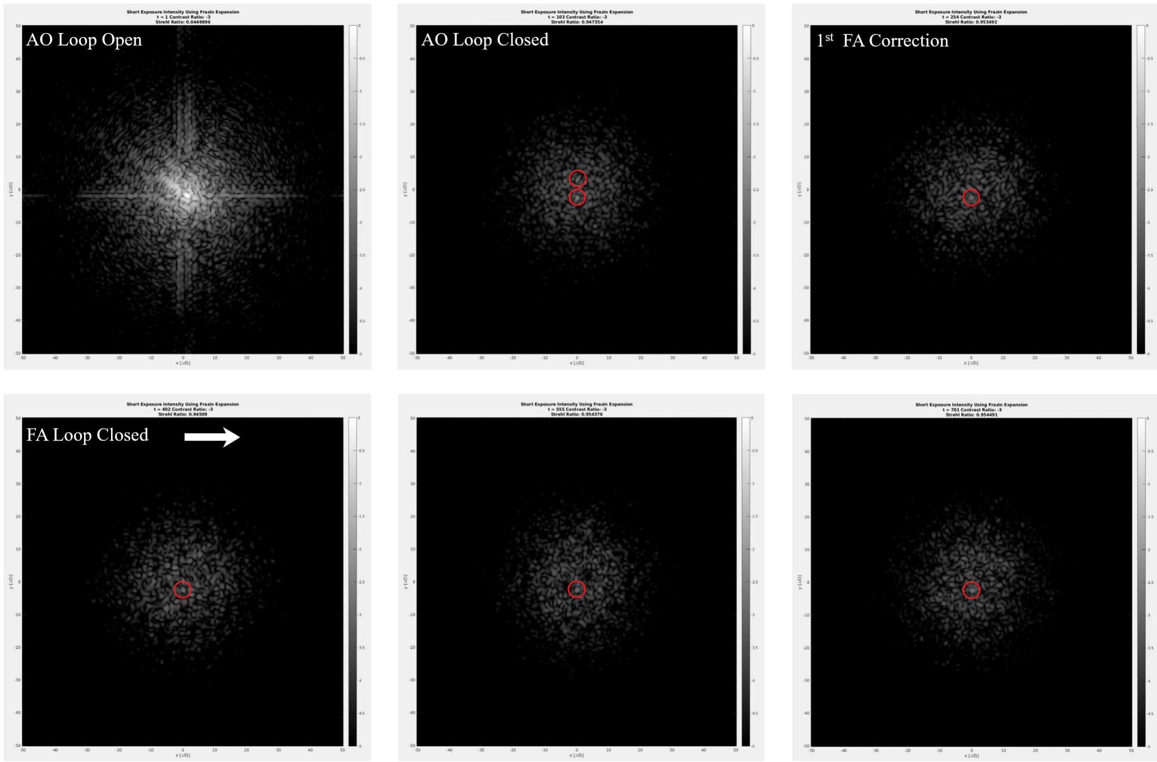
3. SIMULATING THE FRAZIN ALGORITHM IN REAL-TIME

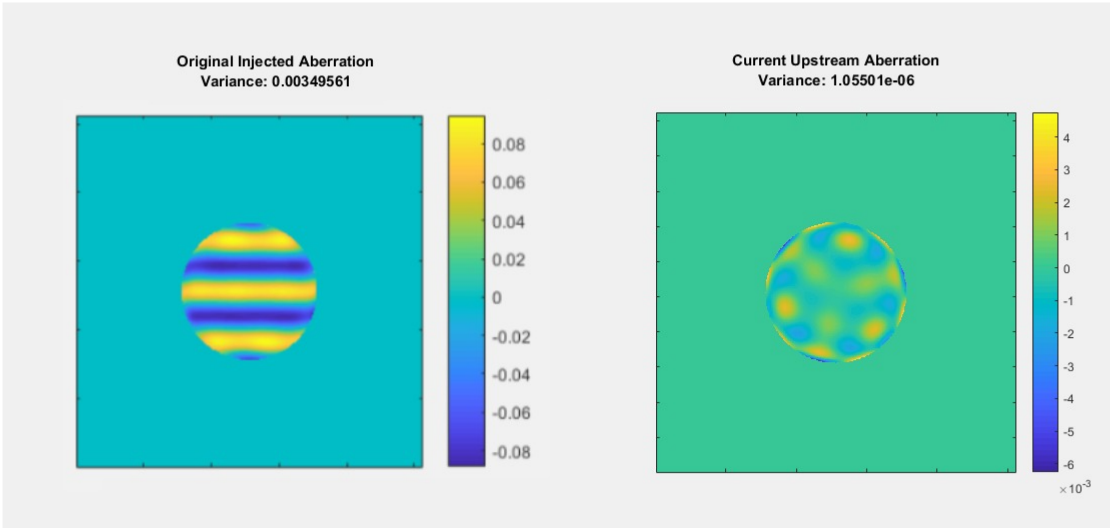
In order to simulate the FA in real-time, several assumptions are necessary. Again, the ideal coronagraph, ideal WFS, ideal science camera, and the same phase only model of the atmosphere are chosen, but in order to truly demonstrate the real-time capability, a new static NCPA is constructed. This NCPA is chosen to be a phase only cosine mode to create a vertical speckle pair in the science camera image plane, that is perturbed by the same Zernikes (Z43-Z46) as used before. The cosine mode is chosen to place the speckle pair such that one of the speckles lies directly on top of an injected planet PSF. The AO system is manipulated to maintain a very high averaged Strehl ratio of about 0.95 across the length of time the simulation is run. This is done so that the ideal coronagraph model performs better, allowing the planet with a contrast ratio of 10^{-3} to become visible in the science camera image plane if the NCPA is corrected. The simulation computes the intensity at the science camera image plane for each millisecond exposure and the calculations required by the FA before moving on to the next exposure. This means an assumption is made that the computer running the FA is capable of finding each exposure's contribution to $\mathbf{y}$ and $\mathbf{H}$ as fast as exposures are taken. This also makes the assumption that the WFS readout of ϕ_r is exactly simultaneous with the science camera readout. While both of these assumptions are easily violated in real life observations, they are fine to make in this case as a proof of concept that the FA can be run in real-time. They both, however, inform the feasibility of the technique overall, and will be examined in a later study.

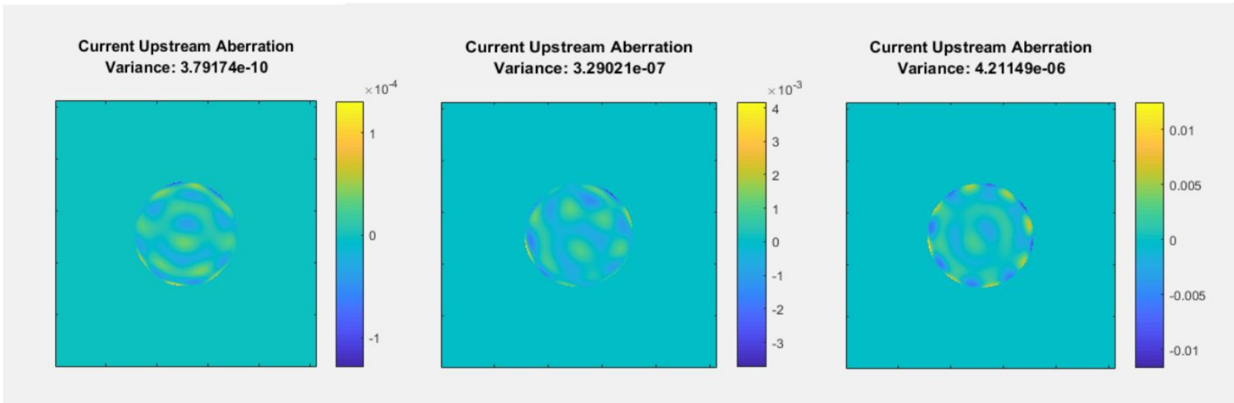
3.1 RUNNING THE BASE ALGORITHM IN REAL-TIME

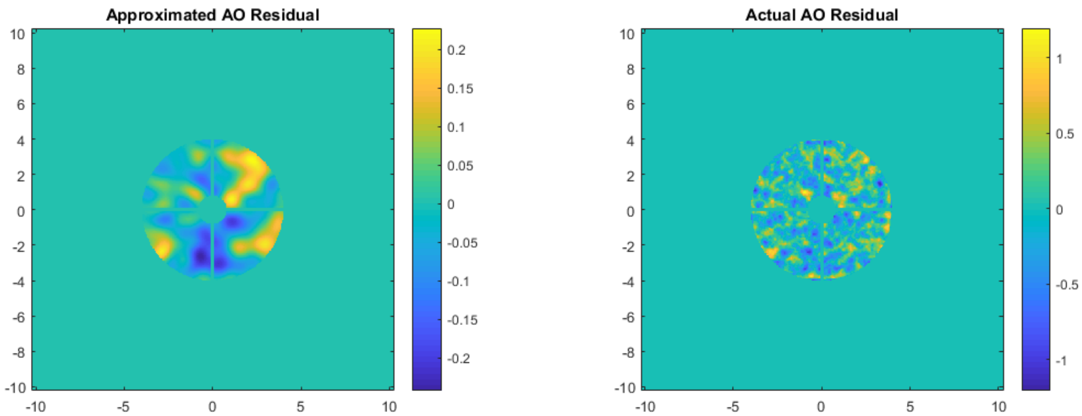
To implement the FA as a real-time control algorithm, the standard AO control technique of an integrator is chosen due to its proven robustness in the field. Equation 8 displays the formulation of the FA real-time loop integrator:

$$(\hat{\psi}_{DM})_n = (\hat{\psi}_{DM})_{n-1} + g_{FA} \frac{(\hat{\phi}_u)_n}{k} \,, \tag{8}$$

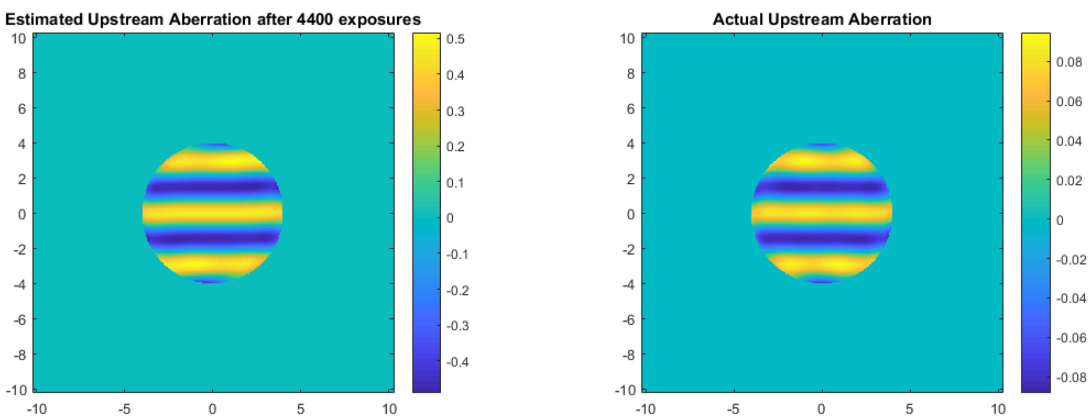

AO Loop Open
AO Loop Closed
1st FA Correction
FA Loop Closed


Original Injected Aberration
Variance: 0.00349561
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
Current Upstream Aberration
Variance: 1.05501e-06
4
3
2
1
0
-1
-2
-3
-4
-5
-6
×10^-3


Current Upstream Aberration
Variance: 3.79174e-10
×10^-4
1
0
-1
Current Upstream Aberration
Variance: 3.29021e-07
×10^-3
4
3
2
1
0
-1
-2
-3
Current Upstream Aberration
Variance: 4.21149e-06
0.01
0.005
0
-0.005
-0.01



All x and y Axes are Pupil Coordinated in Meters



and then run it on-sky at Subaru Coronagraphic Extreme Adaptive Optics system (SCExAO)[4] and Magellen AO (MagAO). Further in to the future, the RTFA will be modified to run at MagAO-X[5] and SCExAO using MKIDs[6] as the science detector. Wavelength resolution in the science camera will provide more diversity to the data being supplied to the algorithm, allowing for more robust performance in terms of accuracy and convergence rate.

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