Strategic Astrophysics Technology

Milestone #3 Final Report

Linear Wavefront Control PSF Calibration

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Executive Summary

The milestone completion described in this document is part of the NASA-funded effort “Linear Wavefront Control for High Contrast Imaging”, which is aimed at improving the efficiency, sensitivity, and reliability of wavefront control for exoplanet imaging.

As discussed in the previous completion report for Milestones 1 and 2, imaging planets in reflected light, a key focus of future NASA missions, requires advanced wavefront control to maintain a deep, temporally correlated null of stellar halo, called a dark hole (DH). Linear Dark Field Control (LDFC) is a wavefront stabilization technique that uses bright starlight outside the science band to stabilize a deep null in a coronagraphic science band image.

Results presented in this document are aimed at completing LDFC milestones #3 (MS3) defined in the LDFC Milestone #2 and Milestone #3 white paper:

MS3: **“Demonstrate a 10x gain in contrast by post-processing using LDFC telemetry, reaching a post-processed contrast level below 1e-8.”**

Telemetry refers to measured starlight (intensity on detector(s)) other than in the high contrast area. This can be light captured by a wavefront sensor to drive an active control loop. For this milestone, telemetry refers to out-of-band light within the geometrical dark hole area, but at a different wavelength from the high contrast (science) spectral band.

MS3 (LDFC PSF calibration) builds upon LDFC MS2 (Spectral LDFC), and was conducted using the same laboratory setup. MS2 and MS3 dataset also overlap, as MS3 has been validated using the same images as used for some of the MS2 demonstrations.

Eight (8) datasets were processed as part of MS3 demonstration, with raw contrast spanning the 6e-9 to 6e-8 range.

For each dataset, a series of 100 to 400 consecutive high contrast area frames were reconstructed using LDFC telemetry, and subtracted from the measured frames. These are the ***post-processed frames***.

We report both the temporal standard deviation (precision) and the average (accuracy) of the post-processed frames. We find that the post-processing precision approaches the 1e-9 contrast limit imposed by camera noise and photon noise. ***The photon and readout noise were too high to demonstrate a 10x contrast stability on individual frames, as was specified in the milestone***.

For each dataset, we combined consecutive frames in an observation, allowing for photon and readout noise to average below the MS3 stated goals. We demonstrated **post-processed image contrast values between 1.37e-9 to 1.18e-10**, which is **13.25x to 95.69x deeper than the corresponding raw contrast levels**.

SAT Description

Background and Motivation

LDFC is a contrast stabilization technique, aimed at maintaining a deep contrast area in the science focal plane after it has been established by a speckle nulling technique. The background and motivation for LDFC's contrast stabilization are described in the LDFC MS2 completion report.

Our NASA-funded SAT effort is aimed at validating both spatial and spectral LDFC, as well as demonstrating that LDFC telemetry (bright field pixel values) can serve as the input for PSF calibration (Guyon et al. 2021, Guyon et al. 2022) .

This document presents results for Milestone 3 (MS3), which was formulated in the MS#2 and MS#3 whitepaper, and focuses on LDFC-based PSF calibration.

Definitions

A dataset is a series of consecutive frames (individual camera exposures) alternating between a dark hole frame (noted **PSF**) and a bright field frame (noted **WFS**). A subset of consecutive frames (typically the middle third of the dataset sequence) is chosen to be the ***observation*** (noted **SIG**) over which the dark hole frames are reconstructed, with the remaining time samples adopted for calibration (noted **CAL**).

A **frame** refers to an individual camera readout, while an **image** refers to the average of frames over the observation.

Contrast values are measured in the dark hole (DH), an area from 3.5 λ_{sci}/D to 8 λ_{sci}/D for a 170 degree angle. Contrast values are derived from an intensity image normalized to the peak intensity of the star PSF in the absence of a focal plane mask. This is referred to as the normalized intensity (NI) image.

The **raw contrast value** is the average value of the NI over the DH area, averaged over the observation.

A **post-processed frame** is the difference between a measured NI dark hole frame and its reconstruction.

The **post-processed image** is the average of post-processed frames over the observation.

The **post-processed image contrast value** is the spatial root mean square (RMS) value of the post-processed image over the DH area. This quantity is indicative of the observation detection limit.

The **post-processed contrast precision** is the average, over the observation, of the spatial root mean square (RMS) value of the post-processed frame over the DH area.

Experimental Overview & Algorithm

We conducted the demonstration of LDFC PSF calibration using the Decadal Survey Testbed 2 (DST2) (Noyes et al 2023), located at NASA's High Contrast Tested Facility (HCIT). The DST2 hardware and configuration were identical for both MS2 and MS3 validations, and are described in the MS2 completion report.

The following MS2 completion report sections are applicable to this report:

- Laboratory Setup
- Creating the dark hole region
- Linearity in the sensing band
- Calibration
- Wavefront sensing and control loop

MS3 was conducted using images acquired as part of MS2 validation, as shown in Fig 1.

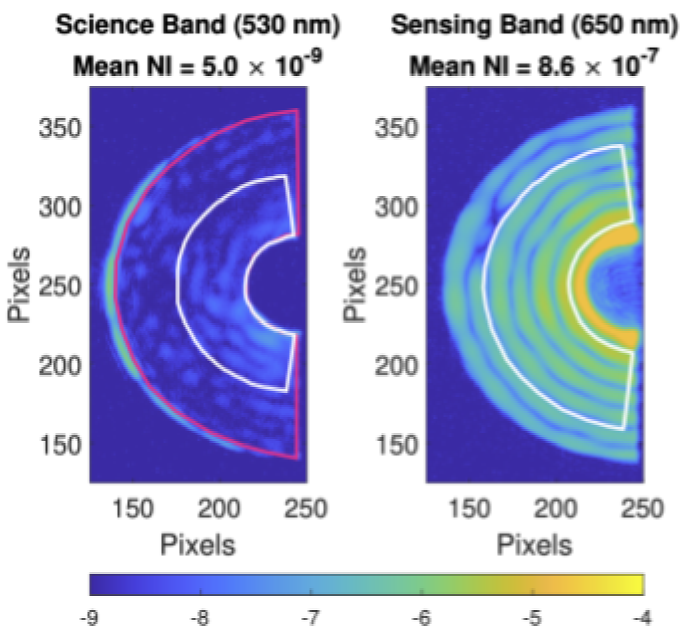

Fig 1: Science band (left) and Sensing band (right) used for MS2 and MS3 validations. The full sensing band (right) and science band (left) frames are used respectively as the input and output to the PSF reconstruction.

Robustness to Incoherent Source(s) in Sensing Band

We discuss in this section the potential effect of incoherent sources (faint companions, exozodiacal dust) in the sensing band on the science band reconstruction.

The PSF calibration relies on coherent mixing with bright starlight to measure wavefront errors, similarly to LDFC. The process is therefore relatively immune to incoherent sources in the sensing band images, as these will not interfere with starlight and therefore will not generate a strong signal.

A background target will add incoherently to starlight in the sensing band, while a wavefront error would add coherently. We note the sensing band contrast ***Cwfs***. A wavefront error (coherent speckle) of contrast ***dCwfs*** in the science band will create in the sensing band a signal:

WFSsignal = (sqrt(Cwfs)+sqrt(dCwfs))^2 - Cwfs

This equation considers the complex part of dCwfs that is aligned with Cwfs (same complex amplitude phase). The orthogonal component is ignored, as it does not contribute to coherent mixing.

Under the approximation dCwfsi << Cwfs, the WFS signal (change is sensing band intensity) is:
WFSsignal ~ 2 sqrt(Cwfs) sqrt(dCwfs)
The coherent speckle is estimated from the WFS signal:
dCwfs ~ WFSsignal^2 / (4 Cwfs)

The concern is that WFSsignal could be an unknown incoherent (real) source, which would create a dCwfs error (unit: contrast) in the reconstructed science image.

For example, if the sensing band contrast is Cwfs=1e-6, and a real source is at the 1e-8 level (misinterpreted as a WFSsignal), the corresponding science band PSF reconstruction error would be:
dCwfs = (1e-8)^2 / 4e-6 = 2.5e-11

The table below explores a wider range of possible effects.

Sensing band contrast Cwfs	Added (real source) incoherent source contrast	PSF reconstruction error in science band
1e-6	1e-8	2.5e-11
1e-6	1e-9	2.5e-13
1e-7	1e-8	2.5e-10
1e-7	1e-9	2.5e-12
1e-8	1e-9	2.5e-11
1e-8	1e-10	2.5e-13

In this demonstration, the sensing band contrast is 8.6e-7. A 1e-8 incoherent source in the sensing band will lead to a 3e-11 change in the science band reconstruction.

Notations

	CAL (calibration set)	SIG (reconstruction set)
measured WFS (bright field)	**CAL/WFS**	**SIG/WFS**

measured PSF (dark field)	**CAL/PSF**	**SIG/PSF**
reconstructed PSF	N/A	**REC/PSF**
reconstruction residual	N/A	**RES/PSF = SIG/PSF-REC/PSF**

Bright field images are noted **WFS** (for wavefront sensing), and dark field images are noted **PSF** (for point spread function). They are collected as pairs, consisting of nearly simultaneous WFS and PSF frames, with the intent that the WFS and PSF frames of a pair correspond to the same wavefront disturbance. The aim of MS3 is to reconstruct the PSF (reconstruction output: REC/PSF) from SIG/WFS, such that REC/PSF is as close as possible to the measured SIG/PSF. For convenience, we also define the reconstruction residual as REC/PSF=SIG/PSF-REC/PSF.

For MS3, approximately 1000 pairs of WFS-PSF frames are collected. For clarity, the table below illustrates a sequence of 9 such pairs, with time running from left to right. Colored cells indicate a camera exposure is acquired. The first 3 pairs and last 4 pairs are used for calibration (CAL), and the 4th and 5th pairs are in the reconstruction set (SIG).

	CAL						**SIG**				**CAL**							
WFS	1		2		3		4		5		6		7		8		9	
PSF		1		2		3		4		5		6		7		8		9

For this example CAL frames are noted (1-3;6-9), and SIG frames are noted (4-5), with CAL#=7 (number of calibration frames) and SIG#=2 (number of SIG frames).

Linear-Quadratic Model

The LDFC-based PSF reconstruction process assumes that the bright field (sensing band) responds linearly to small wavefront perturbations, while the dark hole area (dark field) responds quadratically to the same perturbations. This model is the same as used for high contrast stabilization by LDFC, as described in the MS2, and has been validated experimentally (Fig 2).

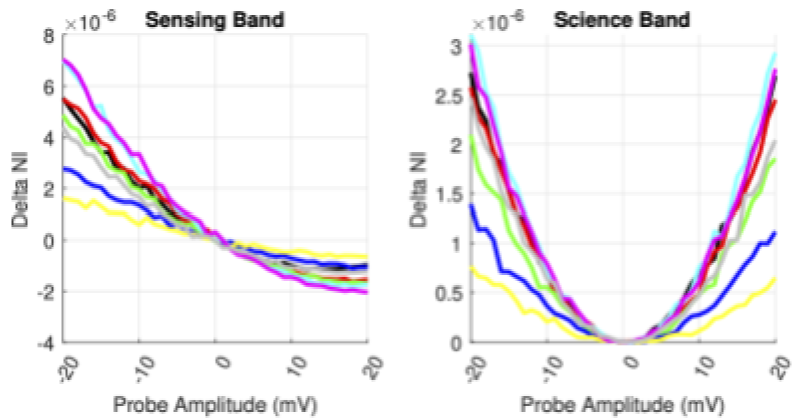

Fig 2: Experimental validation of the linear (left) and quadratic (right) focal plane instensity response to small perturbations respectively in the sensing band (left) and science band (right). Here, the sensing band is the LDFC bright field, and the science band is the LDFC dark field.

Under the assumption that WFS frames are a linear function of hidden variables (wavefront coefficients), and the PSF frames are a quadratic function of the same hidden variables, the WFS frames can be expressed as a linear combination of WFS modes, and the PSF frames can be expressed as a linear combination of PSF modes, such that there is a quadratic relationship between the coefficients of the WFS decomposition and the coefficients of the PSF decomposition.

The quadratic mapping is expressed by quadratic expansion of the WFS decomposition vector as shown in Fig 3 (right panel), expanding the **LIN vector** into the **QUAD vector**.

There exists a set of ***PSF modes*** such that each measured CAL/PSF frame is obtained by multiplying ***PSF modes*** by this ***QUAD vector***. To calibrate the PSF reconstruction, the PSF modes corresponding to the WFS modes must be computed.

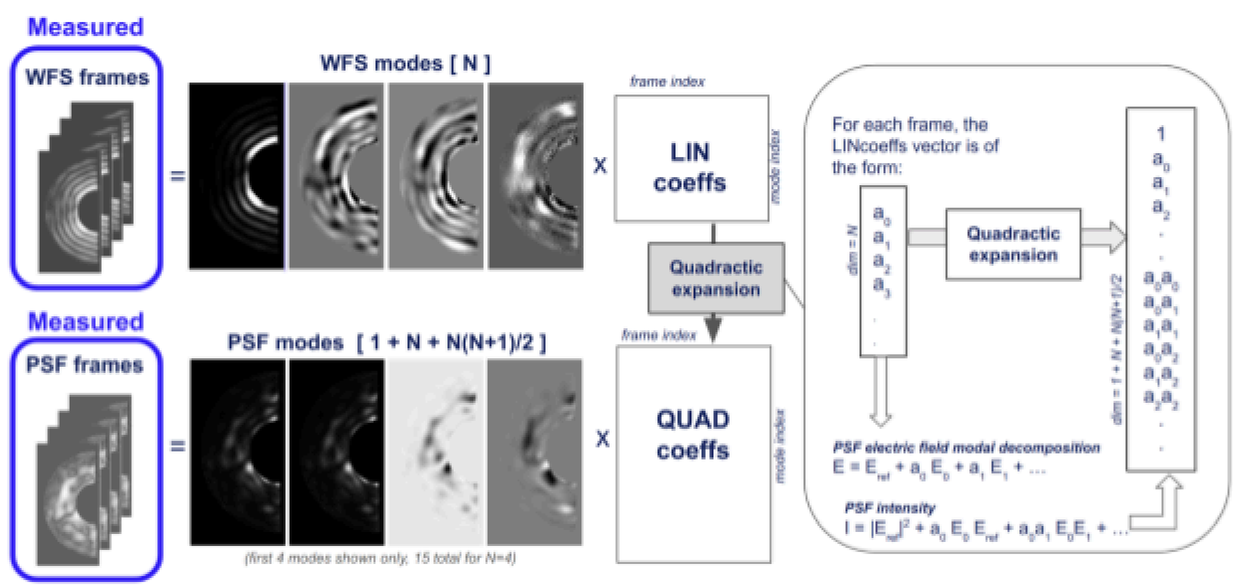

Fig 3: Calibration for PSF reconstruction algorithm - overview. The set of WFS frames (= bright field) is decomposed by principal components analysis (PCA) as a linear sum of WFS modes. The coefficients of this decomposition, for each frame, are quadratically expanded into a longer vector. The set of such vectors (QUAD coeffs) encodes the measured PSF frames (= dark hole frames), but with unknown modes (PSF modes), which are derived by linear regression from the measured SIGnal frames and the QUAD coeffs. Notation are simplified here, with "CAL/" omitted for clarity.

Calibration

The calibration process, shown in Fig 3, is aimed at constructing a mapping from WFS to PSF frames constrained by the linear-quadratic model. To “learn” this mapping, pairs of measured CAL/WFS and CAL/PSF frames are used.

The steps to the calibration are:

1. Perform a modal decomposition of the CAL/WFS frames, using principal component analysis. Each CAL/WFS frame is then expressed as a linear sum of ***WFS modes***. The coefficients of this linear decomposition are a vector noted [a_0, a_1, a_2, .. a_{N-1}], with **N** the number of linear WFS modes kept. To choose **N**, it is increased until a performance plateau is reached, where increasing #LINm no longer improves PSF reconstruction.
2. Perform a quadratic expansion of the LIN vector [a_0, a_1, a_2, .. a_{N-1}], to the QUAD vector by adding to the vector all possible cross products [a_0a_1,.....] and squares [a_0a_0, ..], as well as the unity constant. The expanded vector has 1+N+N(N+1)/2 terms.
3. The PSF modes are estimated by linear regression. A SVD-based pseudo-inverse of the QUAD coefficients matrix is multiplied with the measured CAL/PSF frames. The number of modes kept in the SVD is denoted ***#QUADm***, chosen to regularize the pseudo-inverse. Note that #QUADm < 1 + N + N(N+1)/2, so the PSF modes are not linearly independent.

The mapping from WFS frames to PSF frames is encapsulated in the ***WFS modes*** and ***PSF modes***.

Example Modes

The WFS and PSF modes for LDFC run 204 are shown in Figures 4 and 5.

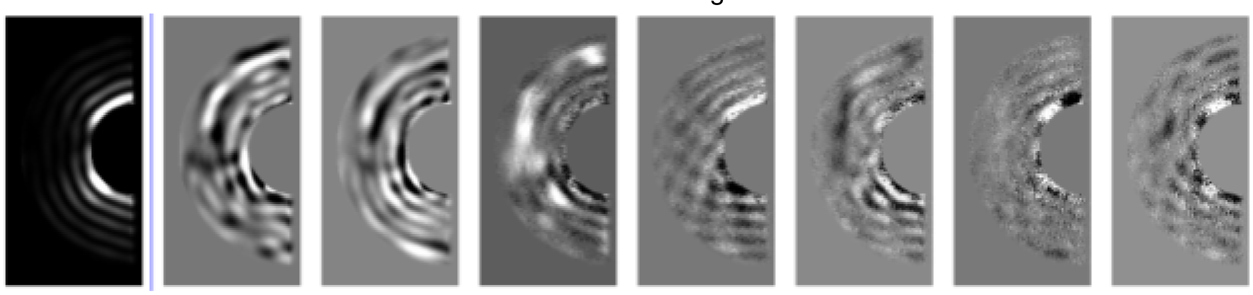

Fig 4: First 8 principal components of the set of calibration WFS frames for LDFC run 204. The first N=4 components are adopted as the WFS modes.

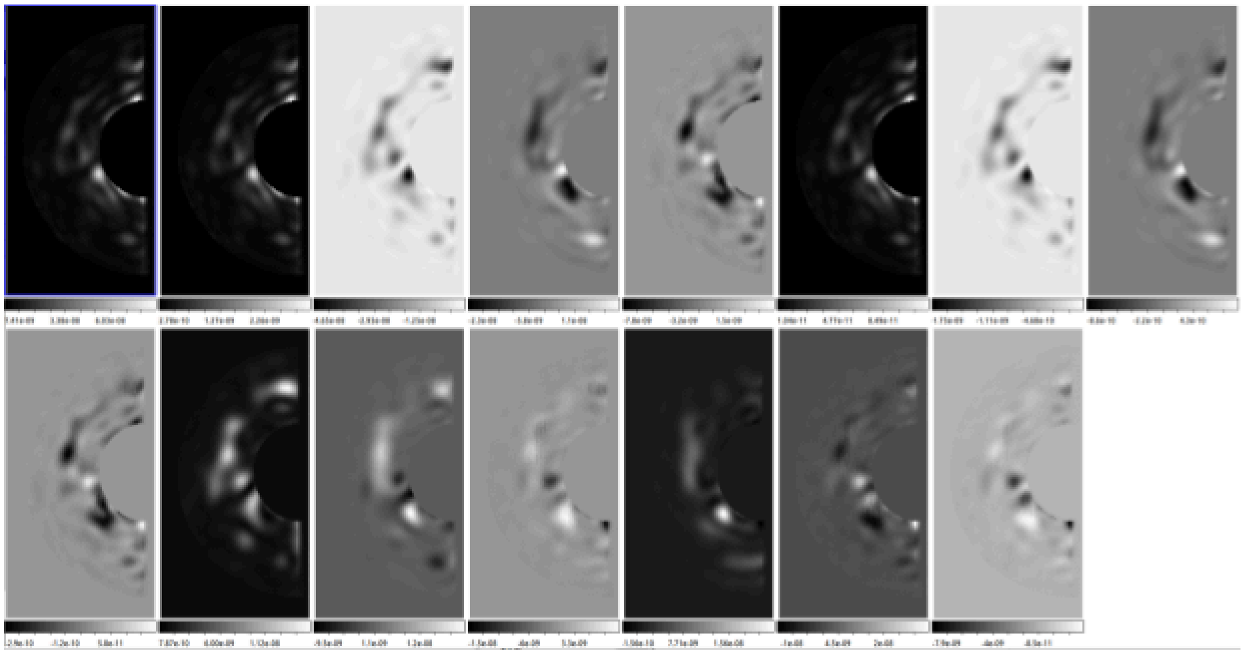

Fig 5: PSF modes for LDFC run 204, for N=4 linear WFS modes. The 15 PSF modes (= 1+N+N(N+1)/2) are obtained by multiplying the pseudo-inverse of the QUAD coefficient matrix (keeping 8 singular values) with the PSF frames. PSF modes are linearly coupled.

Reconstruction

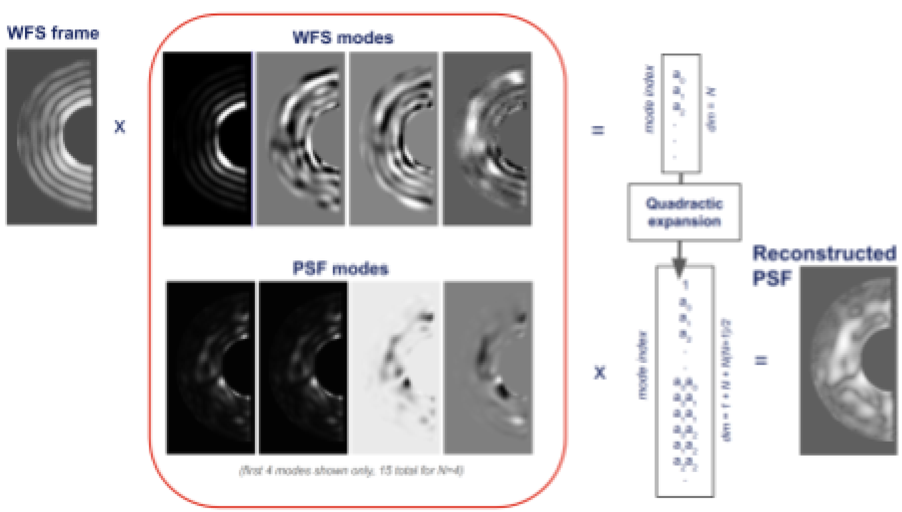

Fig 6: PSF reconstruction process.

PSF reconstruction is done by:

1. Decomposing the SIG/WFS frame as a linear sum of the WFS modes (LIN vector)
2. Performing the quadratic expansion of the LIN vector to the QUAD vector
3. Multiplying the QUAD vector with PSF modes

PSF reconstruction is done by decomposing the input WFS frame on the WFS modes basis, expanding the corresponding LIN vector to a QUAD vector, and expanding using the PSF modes. The process, shown in Fig. 6, allows for fast reconstruction of each PSF frame.

Experimental Results

LDFC Datasets

Eight (8) spectral LDFC PSF calibration experiments were conducted as part of MS3. Table A lists, for each dataset:

- **col #1: LDFC label** follows the same labeling used for LDFC MS2. Unless otherwise noted, the LDFC-on frames are used (LDFC loop running). The second entry in the table uses frames without LDFC correction applied.
- **col #2: CAL frames:** Calibration frames, listed as one or two intervals. For example, “1-100” indicates that frames 1, 2, … 99, 100 are part of the calibration set.
- **col #3: SIG frames (SIG#/CAL#):** Signal frames, listed as an interval. The total number of signal frames (**SIG#)** and calibration frames (**CAL#**) are also listed.
- **col #4: #modes #LINm/#QUADm:** Number of linear and quadratic modes used for the lin-quad mapping.
- **col #5: Raw contrast:** Raw contrast in the dark field. This is the average contrast value within the high contrast area.
- **col #6: PSF subtraction <SIG/PSF>-<CAL/PSF>:** This is the PSF subtraction residual for the standard PSF subtraction scheme, where the average of calibration PSF frames is subtracted from the average of signal PSF frames. This value is representative of the optimal PSF subtraction without use of LDFC telemetry.

TABLE A					
LDFC label	CAL frames	SIG frames (SIG# / CAL#)	#modes #LINm / #QUADm	**Raw contrast**	PSF subtraction <SIG/PSF> - <CAL/PSF>
204	1-800;1201-2000	801-1200 (**400**/1600)	4/8	1.07e-8	6.38e-9
204/off	1-800;1201-2000	801-1200 (**400**/1600)	16/64	6.38e-9	1.89 e-10
205	1-800;1201-2000	801-1200 (**400**/1600)	16/32	2.05e-8	3.19e-9
206	1-300;401-577	301-400 (**100**/477)	8/8	4.42e-8	8.74e-9
208	1-400;601-1000	401-600 (**200**/800)	8/32	2.08e-8	1.09e-9
209	1-50;151-200	51-150 (**100**/100)	8/64	2.10e-8	1.34e-9
210	1-50;151-200	51-150 (**100**/100)	8/8	2.11e-8	1.06e-9
211	1-400;601-934	401-600 (**200**/734)	8/32	5.53e-8	2.96e-8

PSF reconstruction quality - Temporal Statistics

For each dataset, each SIG/PSF frame is reconstructed from the corresponding SIG/WFS frame. Statistics for the residual RES/PSF=SIG/PSF-REC/PSF post-processed residual frames contrast are shown in table B:

- **col #1: LDFC label**
- **col #2: Raw contrast:** Raw contrast in the dark field.
- **col #3: Raw contrast stability:** For each pixel within the dark field, the temporal standard deviation is measured across the raw SIG/PSF frames. The spatial RMS of this quantity over the dark field is reported here.
- **col #4: Post-proc contrast stability**: Same computation as above for the RES/PSF frames instead of the SIG/PSF frames .
- **col #5: Readout & photon noise**: This is the contribution of camera noise and photon noise to the contrast stability measurements. This quantity indicates the limit to post-proc contrast stability assuming perfect reconstruction of the PSF.
- **col #6: Contrast stability gain**: ratio of raw contrast stability over post-proc contrast stability.

TABLE B					
	TIME-AVERAGED (long exposure contrast level)	**STANDARD DEVIATION (contrast stability within SIG) No temporal or spatial binning**			
LDFC label	**Raw contrast**	**Raw contrast stability**	**Post-proc contrast stability**	**Readout & photon noise**	**Contrast stability gain**
204	1.07e-8	**3.50e-9**	**1.74e-9**	**1.19e-9**	**2.01**
204/off	6.38e-9	**7.31e-10**	**7.26e-10**	**9.49e-10**	**1.01**
205	2.05e-8	**3.34e-9**	**2.13e-9**	**1.43e-9**	**1.57**
206	4.42e-8	**2.61e-9**	**1.67e-9**	**1.67e-9**	**1.56**
208	2.08e-8	**1.56e-9**	**1.10e-9**	**1.20e-9**	**1.42**
209	2.10e-8	**1.00e-9**	**1.02e-9**	**1.26e-9**	**0.98**
210	2.11e-8	**1.12e-9**	**1.04e-9**	**1.19e-9**	**1.08**
211	5.53e-8	**5.57e-9**	**1.89e-9**	**1.83e-9**	**2.94**

The post-proc contrast stability is, for all datasets, within 50% of the readout and photon noise limit. The measured contrast stability gain (col #6) is moderate (factor 3 or less) because the inherent PSF variability (column #3) is within a factor 3 of the readout and photon noise limit (column #5).

The contribution of readout and photon noise (col #5) is computed by high-pass spatial filtering of the highly oversampled raw frames, while the contrast stability metrics (cols #3 and #4) are measured across the time dimension. The col #5 values therefore include flat fielding errors at high spatial frequencies, as well as isolated warm pixels, while these static effects are not included in cols #3 and #4. This explains why, for LDFC label 209 and 210, the post-proc contrast stability appears lower than the readout & photon noise limit.

For most of the dark field, for each frame, the post-processed residual is comparable to the readout and photon noise limit. **The narrow gap (~2x) between raw contrast stability and readout & photon noise does not allow for MS3 goal (10x contrast improvement) to be validated on individual frames. The 10x contrast improvement can be validated when considering images instead of individual frames.**

PSF reconstruction quality - Observation Residual Contrast

We report here observation-level contrast levels and residuals, representative of exoplanet observations spanning multiple camera exposures. Results are combined in table C:

- **col #1: LDFC label**
- **col #2: Raw contrast:** Raw contrast in the dark field.
- **col #3: PSF subtraction <SIG/PSF>-<CAL/PSF>:** This is the PSF subtraction residual for the standard PSF subtraction scheme, where the average of calibration PSF frames is subtracted from the average of signal PSF frames. This value is representative of the optimal PSF subtraction without use of LDFC telemetry.
- **col #4: PSF subtraction <SIG/PSF-REC/PSF>:** This is the PSF subtraction residual for the LDFC-based PSF calibration scheme. From each signal frame SIG/WFS, a reconstructed frame REC/PSF is computed. The subtracted frames (RES = SIG/PSF - REC/PSF) are then averaged.
- **col #5: Readout & photon noise limit**: Estimated from the single frame noise limit, divided by the square root of number of SIG frames. This is the value expected for ideal PSF subtraction, where only readout and photon noise would be present.
- **col #6: Contrast gain**: This is the contrast gain offered by LDFC-based PSF subtraction, defined as the raw PSF contrast divided by the postproc contrast.
- **col #7: Contrast gain over PSF subtraction**: Ratio of col #3 over col #4. This represents the relative contrast gain over a conventional PSF subtraction

TABLE C						
	TIME-AVERAGED OVER OBSERVATION (long exposure contrast level)					
LDFC label	**Raw contrast**	PSF sub. SIG-CAL	**postproc contrast** SIG-REC	**Readout & photon noise limit**	**Contrast gain**	**Contrast gain over PSF subtraction**
204	1.07e-8	6.38e-9	**8.06e-10**	5.95e-11	**13.25**	**7.92**
204/off	6.38e-9	1.89e-10	**1.18e-10**	4.75e-11	**53.89**	**1.60**
205	2.05e-8	3.19e-9	**7.48e-10**	7.15e-11	**27.45**	**4.26**
206	4.42e-8	8.74e-9	**4.62e-10**	1.67e-10	**95.69**	**18.92**

208	2.08e-8	1.09e-9	**4.62e-10**	8.49e-11	**45.05**	**2.36**
209	2.10e-8	1.34e-9	**9.57e-10**	1.26e-10	**21.92**	**1.40**
210	2.11e-8	1.06e-9	**7.10e-10**	1.19e-10	**29.76**	**1.49**
211	5.53e-8	2.96e-8	**1.37e-9**	1.29e-10	**40.38**	**21.61**

The post-proc contrast residual (col #4) is the most relevant quantity to contrast detection limit over the observation, and is highlighted (boldface) in the table, as well as the corresponding contrast gain (col #6) over raw contrast.

For each of the 8 datasets, the post-processing residual is below 1/20x of the raw contrast. The post-processing residual is also lower than the conventional PSF subtraction residual (col #3), by factors ranging from 1.40x to 21.61x.

An example PSF reconstruction is shown in Fig. 7, comparing standard PSF subtraction (top) to LFDC-based PSF reconstruction (bottom). The raw contrast in this dataset is 1.07e-8, with post processing improving the contrast 13.25x to 8.06e-10. Out of the 8 dataset processed, this was the one yielding the smallest contrast gain.

Fig. 8 shows a more significant (53.89x) contrast gain, obtained on data label 204/off (second entry in Table).

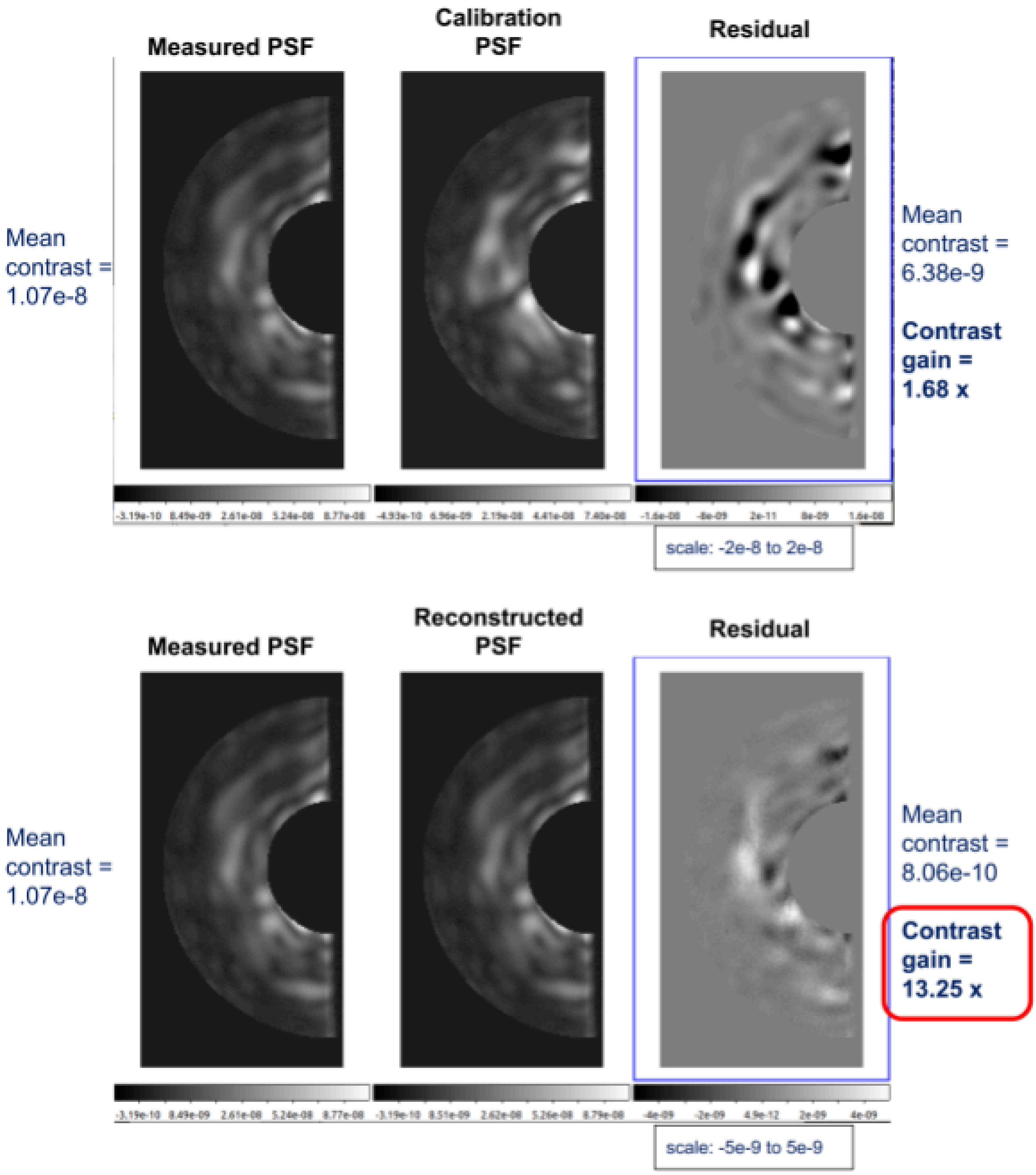

Fig 7: PSF reconstruction for LDFC label 204.
Conventional PSF reconstruction (top), using the average of all CAL/PSF frames (noted "Calibration PSF", middle row) for PSF subtraction. The contrast gain is modest (1.68x) due to PSF variability between the CAL and SIG sets.
The LDFC-based PSF reconstruction (bottom), using WFS/SIG frames to reconstruct PSFs, yields a 13.25x contrast gain. The reconstructed PSF (middle) is nearly identical to the measured PSF. The residual image is displayed here with a different brightness scale.

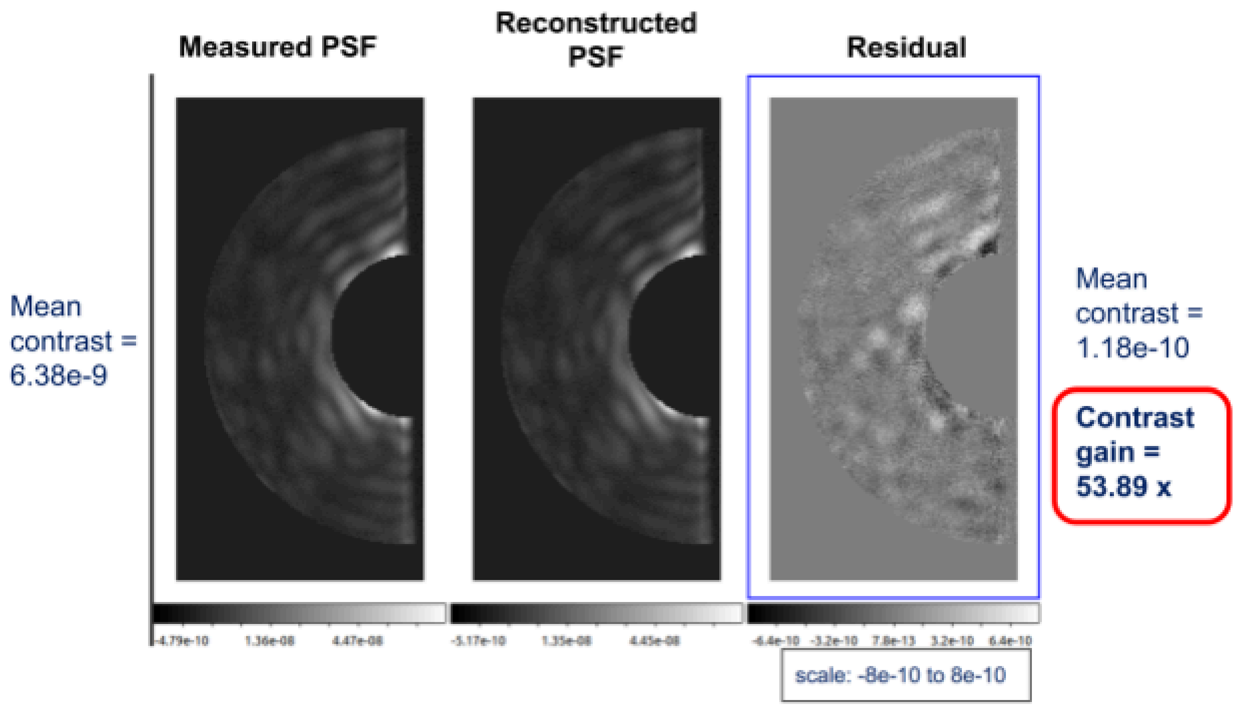

Fig 8: Label 204/off LDFC-based PSF reconstruction (center) and subtraction (right). The contrast gain is 53.89x.

Addressing Specific Milestone 3 Requirements

- **Demonstrate a 10x contrast gain by use of LDFC telemetry reaching a post-processed contrast below 1e-8.** For each of the experiments this level of performance was exceeded, with contrast gains ranging from 13.25x to 95.69x, reaching contrast ranging from 1.37e-9 to 1.18e-10 (see Table C).
- **The 10x gain on per-frame contrast stability could not be demonstrated due to readout and photon noise levels in each frame** (see table B).
- **Measurements will be performed at a wavelength within the 400 nm to 1700 nm range** : For each experiment, the science center wavelength was set to 530 nm with a 1% bandwidth and the sensing center wavelength was set to 650 nm with a 1% bandwidth.
- **Measurements will be performed over an area of at least 10 sq-λ/D:** Measurements were performed over an area in excess of 200 sq-λ/D from 3.5 λ_{sci}/D to 12.4 λ_{sci}/D for a 180 degree DH.

Conclusion

Summary of Results

A PSF reconstruction algorithm was developed leveraging the bright field's linear response and the dark field's quadratic response to wavefront perturbations. This linear-quadratic approximation allows for a small training set to constrain the WFS to PSF relationship, as demonstrated by the smallest datasets (200 frames total).

Eight (8) datasets were processed as part of MS3 demonstration. The contrast gain ranges from 13.25x to 95.69x, reaching contrast levels 1.37e-9 to 1.18e-10, exceeding milestone requirements.

Changes between Milestone Whitepaper and Final Report

The contrast gain was demonstrated at the observation level, but not at the frame level due to readout and photon noise levels.

The observation-level contrast is a relevant metric for science observations, as exoplanets would be revealed from a collection of consecutive raw frames to accumulate signal over a period of time. The achieved contrast gains reported in this document are in part due to this averaging of multiple realization of speckle noise. We also compare our post-processing residual contrast to a conventional PSF subtraction approach where science observation frames are averaged prior to a PSF reference subtraction. The relative gain offered by our PSF reconstruction approach then ranges from 1.40x to 21.60x, with two out of the eight datasets above the 10x gain level.

Future work

PSF subtraction residuals were not limited by photon noise (see table C, cols #4 and #5), so algorithmic refinements could potentially further improve post-processing contrast residuals. A limitation of the MS3 datasets on DST2 is that WFS and PSF frames could not be acquired simultaneously, so small variation in wavefront state between the two frames can contribute to PSF residuals. Future tests should use hardware configurations where WFS and PSF are simultaneously acquired, and should also explore a wider range of WFS options for PSF calibration.
These PSF reconstruction activities will continue as part of a new NASA-funded SAT grant.

References

- **“The decadal survey testbed 2: A technology development facility for future exo-earth observatories,”**, Noyes, M. R., Allan, G. W., Walter, A., Ruane, G., and Riggs, A. E. D., in [Techniques and Instrumentation for Detection of Exoplanets XI], (2023)
- "***High contrast imaging at the photon noise limit with self-calibrating WFS/C systems***", Guyon, Olivier et. al.; Proceedings of the SPIE, Oct 2021, https://arxiv.org/abs/2109.13958
- "***High contrast imaging at the photon noise limit with WFS-based PSF calibration***", Guyon, Olivier et. al.; Proceedings of the SPIE, Aug 2022, https://arxiv.org/abs/2208.01806