Linear Wavefront Control for High Contrast Imaging

Milestone #1 White Paper

10x raw contrast stability gain at <1e-5 raw contrast

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Introduction, Background

The milestone 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. The LDFC technique is introduced in two previously published papers, covering respectively the spectral [1] and spatial [2] variants of the technique.

We will develop and demonstrate in the laboratory a new approach to focal plane wavefront control based on linear sensing and control of bright regions of the diffracted and scattered starlight halo rather than the current non-linear iterative techniques which require probing with a DM. Our approach, referred to as Linear Dark Field Control (LDFC), will simultaneously improve the speed and sensitivity of wavefront control and provide the telemetry required for PSF post-processing calibration.

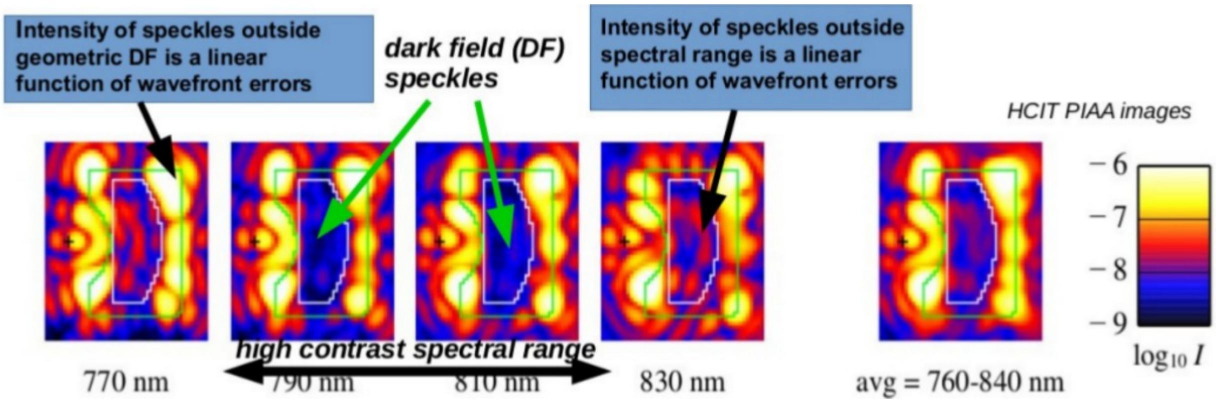


Fig 1: Laboratory coronagraph images illustrating LDFC signal. The images were acquired at the High Contrast Imaging Testbed (HCIT) with a Phase-Induced Amplitude Apodization (PIAA) coronagraph. The contrast ratio is deepest within the control band, and quickly increases outside the spectral band and outside the field mask. The associated light responds linearly to small wavefront perturbations, and is the signal input for LDFC.

LDFC uses starlight that is falling outside the high contrast region (Fig 1) to drive a linear control loop aimed at “freezing” the wavefront state. This bright light (referred to as the ***bright field – BF***) is abundant relative to the much smaller amount of light in the high contrast region (referred to as the ***dark field – DF***). It responds linearly to small wavefront errors, allowing a linear control loop to operate at higher speed and sensitivity than possible with conventional wavefront control schemes relying on measurements in the high contrast region.

1. LDFC Algorithm Description

The Linear Dark Field Control (LDFC) wavefront stabilization loop for high contrast imaging is defined by the following key properties :

- [LDFC-requ1] Does not require runtime DM probing for wavefront sensing.
- [LDFC-requ2] Relies on focal plane images for wavefront sensing.

- [LDFC-requ3] Uses a linear relationship between sensing input and control output
- [LDFC-requ4] Uses pixels outside (in spatial and/or spectral dimensions) the high contrast area for wavefront sensing input

LDFC is a wavefront stabilization technique, but is not suitable to iteratively build a dark hole, so it is foreseen that the two approaches would be used alongside. Once a dark hole is established, LDFC may be used as the sole control loop, or can run in addition to other control loop(s). If another control loop is running in addition to LDFC, we will ensure their independence by linear separation of control space (each loop controls a set of wavefront modes that is orthogonal to other control sets), or by setting up a master-slave relationship, where the slave loop offsets the convergence point of the master loop.

LDFC limitations
- LDFC is a **differential** sensing technique that cannot by itself drive the system to a high contrast state. It is only a wavefront stabilization technique.
- A **null space** may exist: not all wavefront modes can be sensed, and some of the unseen modes can negatively impact contrast.
- **Non-stationarity** of the relationship between bright field, wavefront state and dark hole illumination can build up over time and render LDFC’s calibration stale.

A key goal of our activity will be to quantify the null space and calibration non-stationarity, as these two effects are likely to limit LDFC’s performance, and they are currently poorly understood.

2. Milestone Description and Rationale

Demonstrate that wavefront stabilization by LDFC achieves at least a 10x gain in raw contrast in the presence of dynamic wavefront aberrations. The contrast gain shall be measured over a focal plane area covering at least 10 sq l/D, and at a raw contrast (post-LDFC) below 1e-5.

This is the first of a series of milestones aimed at validating the LDFC approach. This initial milestone focuses on demonstrating a relative stabilization gain (in the presence of injected disturbances) and at establishing the LDFC framework for high contrast imaging. Our initial focus is not to demonstrate high contrast level, so we choose a modest 1e-5 raw contrast value, deemed sufficient to validate the LDFC function. The scoring area requirement is also modest, at 10 squ-l/D area (area of a square of 3.3 l/D on a side), and is not constrained by IWA or OWA. Much of the effort toward reaching MS#1 will go toward building the software framework for LDFC operation and analysis.

Injected disturbances will consist of dynamic pupil plane or near-pupil plane optical pathength differences added by way of a deformable mirror. The disturbances will be within the LDFC measurement space and will not purposely include wavefront modes that are within the technique’s measurement null space.

MS#1 may be achieved with spatial and/or spectral LDFC variants. The LDFC algorithm is agnostic about the nature of the input pixels (location, wavelength), so this initial demonstration does not rely on a specific flavour of LDFC. Appendix A provides background information on the planned testbed work and associated optical configurations.

Experience acquired toward securing this milestone will guide future more challenging LDFC demonstration to be performed at deeper contrast. We expect to be able to complete MS#1 in air at the SCExAO, MagAO-X and/or Ames testbeds, while deeper contrast will likely only be attainable at HCIT, and possibly at Ames.

3. Stability Conditions and Algorithm

For all measurements, the raw contrast in the scoring area shall be <1e-5 (average) without LDFC and without the added dynamic disturbances. Wavefront errors will be applied to demonstrate the LDFC gain, and the exact same sequence of aberrations shall be introduced for the ON and OFF tests to be compared.

4. Statistical Requirements

This section describes **requirements** associated with the measurement.

The raw contrast (defined in section 5) shall be measured as the surface brightness averaged over a fixed area covering at least 10 squ-l/D. The scoring area shall be within the primary control region of the deformable mirror(s).

The measurement statistical requirements are as follows:
- Measurements must be performed over a set of >100 consecutive focal plane images.
- The reported ***per-frame raw contrast value*** will be the average raw contrast within the scoring area.
- The measurement noise on the per-frame raw contrast value, due to photon and readout noise, must be <1e-6 raw contrast in the LDFC ON frames. We note that the corresponding noise may be higher in the LDFC OFF frames due to added photon noise.
- The reported ***measurement set raw contrast value*** will be the average of the per-frame raw contrast between all 100 frames. No frame can be excluded from the measurement.

The >100 frames constitute a ***measurement set***.

A minimum of three measurement sets meeting the 1e-6 raw contrast measurement noise requirement shall be acquired. For each set, a separate set must be taken in the same conditions with LDFC=OFF to measure the comparison contrast. For each of the 3 pairs, the ratio of average raw contrast values between OFF and ON shall exceed 10x.

The statistical distribution of contrast values will be compiled and be part of the milestone validation dataset.

5. Calibration and Measurement Steps

This section describes a likely (non-binding) sequence of calibrations and measurements to meet the statistical requirements detailed in the previous section. It is provided here for information, but is not part of MS#1 requirements.

Initial setup

The high contrast imaging system (HCIS) will be driven to produce a high contrast area in the focal plane, referred to as the dark hole (DH), using a non-LDFC iterative approach (EFC, speckle nulling).

The HCIS includes at least one deformable mirror, and includes optical masks necessary to reach high contrast. At least one focal plane imaging camera will acquire images. One or several WFC loop(s) may be deployed, independently of LDFC, to maintain the desired raw contrast level. For example, a coronagraphic low-order WFS may be required to maintain alignment.

Contrast calibration

Images will be contrast-calibrated so that each frame can be scaled to a raw contrast map. Raw contrast is defined here as image surface brightness relative to the un-occulted peak surface brightness of the PSF core. In a Lyot-type coronagraph architecture, the un-occulted PSF core used as raw contrast reference is obtained with the Lyot stop(s) in and the focal plane mask out. Contrast calibration during the LDFC measurement sequences will be performed by measuring the surface brightness of fiducials, which could be added (by means of a pupil plane phase modulation) if the original coronagraphic PSF does no include sufficiently bright fiducials.

LDFC calibration

The LDFC calibration consists of a LDFC reference and a LDFC response matrix. The reference is the nominal bright field (BF) intensity image that the LDFC loop is driven to maintain. The response matrix encodes the derivative of the BF against each DM actuator. LDFC calibration is measured by poking the DM with modes, and recording the corresponding BF images.

The LDFC calibration may be obtained as follows:

- A basis of LDFC DM control modes is defined. The number of such modes is ***n***.
- The LDFC reference array, a vector of ***m*** elements (number of pixels in the BF), is initialized to zero
- For each DM control mode index -1<k<n, two BF images are acquired: one image with the DM control mode poked with a small positive amplitude +a, and one with an amplitude -a.
- For each DM control mode, the linear response is computed as (I(+a)-I(-a))/(2a) and written in the k-th column of the LDFC response matrix. The average of the two images

(I(+a)+I(-a))/(2n) is additively added to the LDFC reference vector.

LDFC control matrix computation and null space measurement

A regularized pseudo-inverse of the response matrix (RM) is computed and used as the linear control matrix for LDFC operation. A singular value decomposition (SVD) will be performed to reveal the measurement null space and compute the pseudo-inverse.

LDFC loop operation

The BF is extracted from each camera image, and multiplied by the CM to produce an estimate of the DM displacement that should be additively applied to drive the BF to its reference. The corresponding DM command is multiplied by a control loop gain and then added to the DM. These steps are repeated in a loop of at least 100 iterations.

Two consecutive close-loop tests will be performed: first, with no disturbances injected, and then with disturbances injected. As previously noted, the disturbances injected will be within the LDFC measurement space and will avoid the null space.

LDFC calibration stability

To properly function, LDFC requires that the linear relationship between bright field intensity and wavefront aberrations be static in time. It is not known how valid this assumption is, and how long the LDFC calibration will hold. To mitigate and explore this limitation, we will measure on a best effort basis a number of LDFC responses over various timescales. Software tools will be deployed to make the measurement as rapidly and as efficiently as possible.

6. Reporting Requirements

The milestone data package will include a narrative report discussing how each elements of the milestone was met, including appropriate tables and summary charts.

The milestone data package must:

- provide quantitative evidence that the milestone performance goals have been met
- provide measurements and analysis of the LDFC null measurement space
- provide measurements and analysis of the LDFC calibration stability over time
- provide estimate of effects associated with multiple control loops running simultaneously (when applicable)

All raw data and calibrations will be made publicly available for independent review, for a period covering at least the duration of this effort. All analysis tools will also be publicly available for review and for use by other groups. Source code will be released under (a) open-source license(s) to the extent possible, in compliance with US regulations.

7. TRL, Expected Schedule and Future Milestones (tentative)

We expect MS#1 to be completed by end of calendar year (Dec 2019).

We envision two additional milestones as part of our effort:
MS#2: ***Achieve 10x contrast stability gain over 8hr at <1e-7 raw contrast***
Expected completion by Dec 2020
MS#3: ***Achieve 1e-10 contrast stability over 24hr without DM probing***
Expected completion by Dec 2021.

MS#2 and MS#3 will likely require use of the HCIT at JPL.

We assess that LDFC is currently at TRL3 (Analytical and experimental critical function and/or characteristic proof-of-concept). MS#1 will not advance the technique TRL, as reaching TRL4 would require the software to “establish interoperability” and woud require “performance in the relevant environment predicted”. The goal of MS#1 is to demonstrate and document “limited functionality to validate critical properties and predictions using non-integrated software components”, and will meet TRL3 exit criteria.

APPENDIX A
LDFC experiment plans

For MS#1, we are pursuing six LDFC experiments in parallel, spanning 3 air testbeds. They are described in this section. Although we expect several of the experiments to meet the MS#1, our MS#1 validation report will select data from a single experiment, to be chosen by the LDFC team to best represent the goals of MS#1.

Why multiple experiments ?

A key open question for LDFC operation remains the size of the null space. Wavefront changes within the null space cannot be sensed by LDFC and will remain uncontrolled. The main rationale behind conducting multiple LDFC experiments in parallel is that we need to understand how optical configuration affects null space. For MS#1 validation, the LDFC test offering the smaller null space and meeting the milestone goals will be selected. Due to our current poor understanding of LDFC null space, it would be too risky to commit to one of the experiments as of today: null space and contrast stability for each of the configurations first needs to be measured.

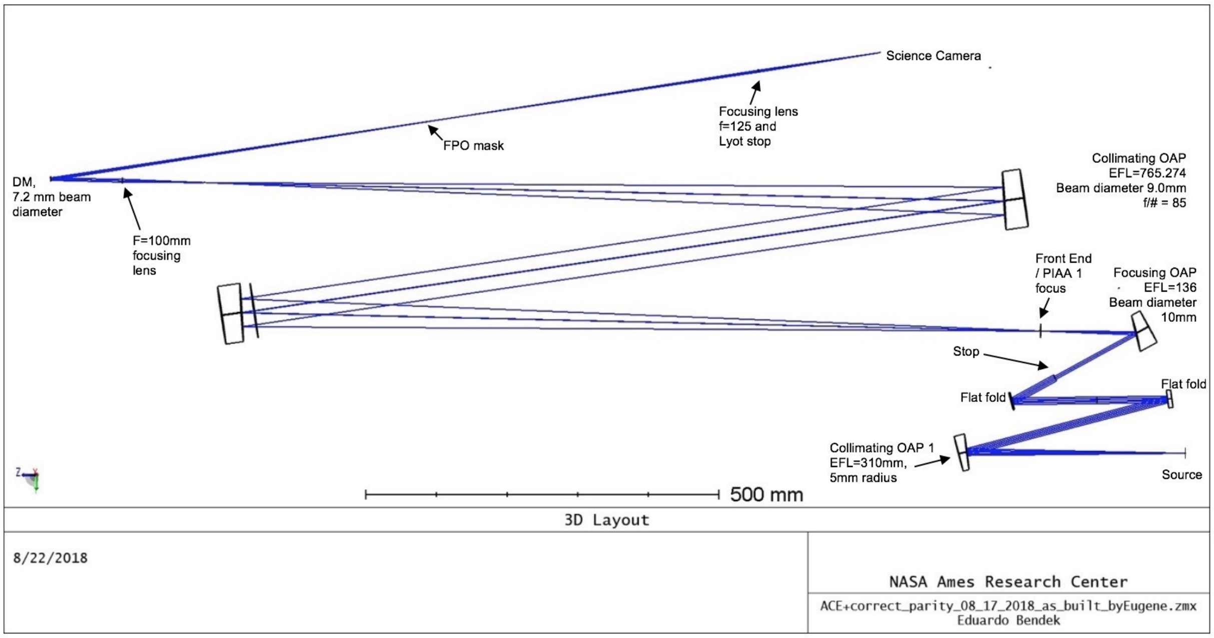
Software support for SCExAO and MagAO-X testbeds

While the Ames testbed will focus on a single LDFC experiment (EXP #1), the SCExAO and MagAO-X testbeds will explore multiple optical configurations. To support these multiple experiments, we are developing a high-level LDFC software framework that can be directly applied to all experiments. The software transparently adapts to spectral and spatial LDFC variants with no change other than minor setting of configuration parameters. The goal of this software effort is to minimize work associated with running multiple LDFC configurations, and ease result comparison between the configurations.

[CONF #1] Spatial LDFC, Lyot type coronagraph, visible light [NASA Ames testbed]

Starlight suppression	PIAA-type coronagraph with opaque focal plane mask
Wavelength range	Monochromatic 629nm (BW < 1nm)
Dark Field	Focal plane dark hole, 2e-7 to 3e-7 raw contrast
Bright Field	Focal plane, side opposite to dark hole. 1e-4 to 1e-5 raw contrast
Actuation	32x32 MEMS DM
Sensor (BF)	Visible camera (Silicon)
Sensor (DF)	Visible camera (Silicon)
Calibration speed	7 hr for several 100s modes

Dynamical range: The Ames testbed PSF bright field is approximately 10x brighter than the target LDFC demonstration contrast, so the native camera sensor dynamical range will be sufficient to make the measurements provided that the exposure time is adequately chosen. We expect that a moderate amount of averaging between frames may be needed.



NASA Ames testbed layout.

[CONF #2] Spatial LDFC, Lyot type coronagraph, near-IR light [SCExAO]

Starlight suppression	Lyot type (PIAA, PIAACMC, Vortex, or Classical Lyot)
Wavelength range	1.55um, Narrow to intermediate band (BW < 20%)
Dark Field	Focal plane dark hole
Bright Field	Focal plane, side opposite to dark hole
Actuation	50x50 MEMS DM
Sensor (BF)	Near-IR camera InGaAs photodiodes, ~5 kHz @ 128x128
Sensor (DF)	Near-IR camera InGaAs photodiodes, ~5 kHz @ 128x128
Calibration speed	1 sec for ~1500 modes. Multiples calibrations to be averaged for improved SNR

Dynamical range: In this coronagraphic test, the PSF bright field is approximately 10x to 50x brighter than the target LDFC demonstration contrast. The native camera sensor dynamical range over a single frame will not be sufficient to fully overcome dynamical range, so a few consecutive frames will be averaged.

[CONF #3] Spatial LDFC, vector Apodizing Phase Plate (vAPP), near-IR light [SCExAO]

Starlight suppression	Vector Apodizing Phase Plate (vAPP) + optional field ND mask
Wavelength range	1.55um, Narrow band (BW < 10%)
Dark Field	One of the two focal plane vAPP dark hole
Bright Field	Focal plane, both vAPP bright PSF areas
Actuation	50x50 MEMS DM
Sensor (BF)	Near-IR camera InGaAs photodiodes, ~5 kHz @ 128x128
Sensor (DF)	Near-IR camera InGaAs photodiodes, ~5 kHz @ 128x128
Calibration speed	1 sec for ~1500 modes. Multiples calibrations to be averaged for improved SNR

Sensor dynamical range: In this configuration, the central starlight is not masked, and the bright fied is 4x brighter than the native PSF, so there is serious dynamical range concern. A mitigation option is to deploy a field ND mask to attenuate the bright field relative to the dark field. Another option is to perform aggressive averaging and therefore make the measurements at slower effective speed.

[CONF #4] Spatial LDFC, vector Apodizing Phase Plate (vAPP), visible light [MagAO-X]

Starlight suppression	Vector Apodizing Phase Plate (vAPP) + optional field-splitting mirror
Wavelength range	656 nm, Narrow band (BW < 10%)
Dark Field	One of the two focal plane vAPP dark hole
Bright Field	Focal plane, both vAPP bright PSF areas
Actuation	50x50 MEMS DM
Sensor (BF)	EMCCD camera, ~500 Hz at 128x128
Sensor (DF)	EMCCD camera, ~500 Hz at 128x128
Calibration speed	10 sec for ~1500 modes. Multiples calibrations to be averaged for improved SNR

Sensor dynamical range: LDFC will be implemented in two was on MagAO-X to mitigate dynamical range. The most conventional way is to use the science focal plane cameras, a pair of Princeton Instruments EMCCDs. A beamsplitter sends light in a 10 nm bandpass centered on H-alpha to one camera, and a nearby 10 nm continuum region to the other. The cameras can be read at high speed (33 fps full 1024x1024 frame, faster in subwindows) and have low readout noise (< 0.5 e). A second mode of LDFC is implemented using a reflective focal plane mask (FPM), which passes the "dark hole" of the vAPP to the science cameras but reflects the bright field to an Andor 512x512 EMCCD camera. This significantly increases the dynamic range of the system (by integrating on the science cameras) while allowing for high-speed LDFC on the separate sensor.

MagAO-X is a coronagraphic extreme-AO system with significant hardware and software heritage from SCExAO. MagAO-X is optimized for visible and near-IR observations of exoplanets, especially at H-alpha (656 nm). The coronagraph in MagAO-X is a vector apodizing phase plate (vAPP), which provides excellent LDFC capabilities [2]. MagAO-X uses CACAO for its real-time AO control software, sharing all of the capabilities of SCExAO.

[CONF #5] Sprectral LDFC (visible – nearIR), Lyot type coronagraph [SCExAO]

Starlight suppression	Lyot type (PIAA, PIAACMC, Vortex, Classical Lyot)
Wavelength range	Sensing: 600-800nm. Control: 1550nm
Dark Field	One of the two focal plane vAPP dark hole
Bright Field	Focal plane PSFs (two cameras), full 360deg field
Actuation	50x50 MEMS DM
Sensor (BF)	EMCCD camera, ~500 Hz at 128x128
Sensor (DF)	Near-IR camera InGaAs photodiodes, ~5 kHz @ 128x128
Calibration speed	10 sec for ~1500 modes. Multiples calibrations to be averaged for improved SNR

Sensor dynamical range: Two different cameras are used for sensing and scoring, so there is no dynamical range concern in this configuration.

[CONF #6] Sprectral LDFC (visible – nearIR), vector Apodizing Phase Plate (vAPP) [SCExAO]

Starlight suppression	Vector Apodizing Phase Plate (vAPP)
Wavelength range	Sensing: 600-800nm. Control: 1550nm
Dark Field	One of the two focal plane vAPP dark hole
Bright Field	Focal plane PSFs (two cameras), full 360deg field
Actuation	50x50 MEMS DM
Sensor (BF)	EMCCD camera, ~500 Hz at 128x128
Sensor (DF)	Near-IR camera InGaAs photodiodes, ~5 kHz @ 128x128
Calibration speed	10 sec for ~1500 modes. Multiples calibrations to be averaged for improved SNR

Sensor dynamical range: Two different cameras are used for sensing and scoring, so there is no dynamical range concern in this configuration.

LIST OF ACRONYMS

BF: Bright Field
BW: Bandwidth
CM: Control Matrix
DF: Dark Field
DM: Deformable mirror
EFC: Electric Field Conjugation
HCIT: High Constrast Imaging Testbed
HCIS: High Contrast Imaging System
IWA: Inner Working Angle
l/D : lambda over Diameter
LDFC : Linear Dark Field Control
MagAO-X: Magellan Adaptive Optics - Extreme
MEMS: Micro-Electro-Mechanical Systems
NASA: National Aeronautics and Space Administration
ND: Neutral Density
OWA: Outer Working Angle
PIAA: Phase-Induced Amplitude Apodization
PSF: Point Spread Function
RM: Response Matrix
SCExAO: Subaru Coronagraphic Extreme Adaptive Optics
SNR: Signal-to-Noise Ratio
TRL: Technology Readiness Level
vAPP: vector Apodizing Phase Plate
WFS: WaveFront Sensor

References

[1] “Spectral Linear Dark Field Control: Stabilizing Deep Contrast for Exoplanet Imaging Using out-of-band Speckle Field” Guyon, Olivier; Miller, Kelsey; Males, Jared; Belikov, Ruslan; Kern, Brian, eprint arXiv:1706.07377

[2] “Spatial linear dark field control: stabilizing deep contrast for exoplanet imaging using bright speckles” Miller, Kelsey; Guyon, Olivier; Males, Jared, Journal of Astronomical Telescopes, Instruments, and Systems, Volume 3, id. 049002 (2017).