Laboratory Demonstration of Spatial Linear Dark-Field Control for Imaging Extrasolar Planets in Reflected Light

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Abstract

We present the first laboratory tests of Spatial Linear Dark Field Control (LDFC) approaching raw contrasts (5e-7) and separations (1.5–5.2 lambda/D) needed to image jovian planets around Sun-like stars with space-borne coronagraphs like Roman-CGI and image exo-Earths around low-mass stars with future ground-based 30m class telescopes. In four separate experiments and for a range of different perturbations, LDFC largely restores (to within a factor of 1.2–1.7) and maintains a dark hole whose contrast is degraded by phase errors by an order of magnitude. Our implementation of classical speckle nulling requires a factor of 2–5 more iterations and 20–50 DM commands to reach contrasts obtained by spatial LDFC. Our results provide a promising path forward to maintaining dark holes without relying on DM probing and in the low-flux regime, which may improve the duty cycle of high-contrast imaging instruments, increase the temporal correlation of speckles, and thus enhance our ability to image true solar system analogues in the next two decades.

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MOTIVATION: WHY LDFC?

Directly detecting and characterizing the spectrum of an Earth-like planet with a future space mission requires suppression of noisy, scattered halo of starlight better by a factor of 10^{10}. While high-contrast imaging testbeds simulating space-based high-contrast imaging have demonstrated significant progress towards this goal, *maintaining* this dark hole (DH) requires extremely precise stellar halo measurements. If the halo itself is dark/low in flux because focal-plane wavefront control (FPWFC) methods like EFC are applied in the first place), the DH can degrade due to dynamic aberrations. Furthermore, by *modulating* the deformable mirror (DM) to determine and update the estimate of the electric field, FPWFC methods like EFC *perturb* science exposures, potentially limiting exposure times and the effectiveness of post-processing methods to further remove the stellar halo.

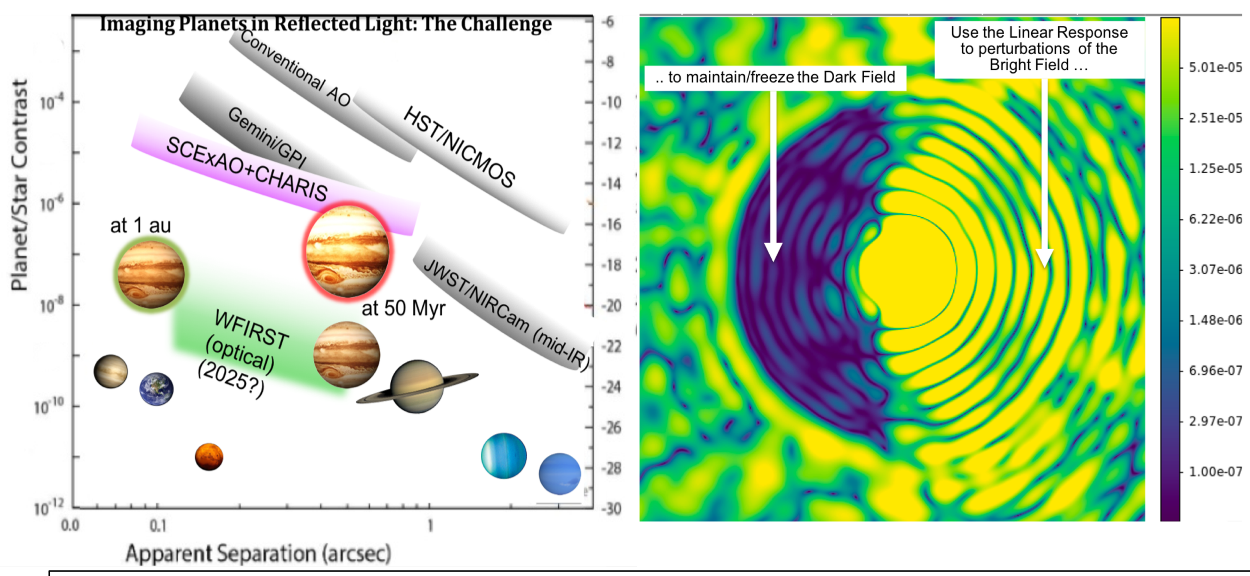


Fig. 1 – Imaging solar system-like planets requires maintaining a static dark hole (shown as "the dark field" or DF). LDFC utilizes the linear response of the region outside the dark hole which has far larger signal (the ``bright field" or BF) to wavefront perturbations that affect both the BF and the DF ([1], [2]). LDFC does not require modulation.

Spatial Linear Dark Field Control (LDFC) is a promising wavefront control method that can maintain a static, deep DH that is first generated from FPWC methods ([2]).

Mathematical Premise Behind LDFC

Electrical Field in image plane = initial pupil plane field + small change in complex amplitude induced by DM (1); resulting intensity is given by three terms (2, 3)…

$$E_t \approx E_0 + E_{DM} \quad (1)$$

$$I_t = |E_t|^2 \quad (2)$$

$$I_t \approx |E_0|^2 + |E_{DM}|^2 + 2\langle E_0, E_{DM}\rangle \quad (3)$$

In the DF, intensity is dominated by DM term (4); in BF, the initial field dominates (5)

$$|E_{DM}|^2 \gg |E_0|^2 \quad (4)$$

$$|E_0|^2 \gg |E_{DM}|^2 \quad (5)$$

Signal used by LDFC to drive DF back to its initial state is (6)

$$\Delta I_t = I_t - I_{ref} \approx 2\langle E_0, E_{DM}\rangle \quad (6)$$

DM shape that restores deep DH is then (7), where M is the pseudo-inverse of the Response Matrix (i.e. Control Matrix)

$$u_t = -(M^T M)^{-1} M^T \, \Delta I_{t,n} \quad (7)$$

SETUP

To provide first empirical test of LDFC, we used the Ames Coronagraph Experiment (ACE) laboratory at NASA-Ames Research Center.

Experimental Setup:

S1FC635 laser centered on ~635nm; ~1nm bandpass; PIAA coronagraph
One-sided dark hole created using Speckle Nulling ([3]) using an implementation of the Gerchberg-Saxton method for phase retrieval ([3])
Starting contrast of ~1e-3--1e-4, final DH contrast of ~5 to 8e-7 (1.2-4.5 lambda/D)

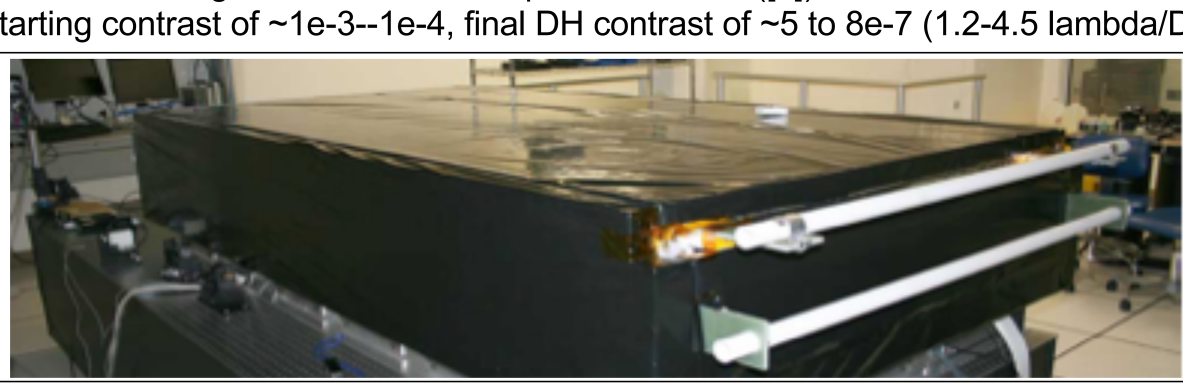


Fig 3 – ACE lab setup

Methods

Response and Control Matrix Calculations and Wavefront Control Loop

- We calculate the LDFC Response Matrix (RM) by poking *m* actuators and recording the intensity over *n* BF pixels using two different patterns, a and b:
RM(n,m) = 0.5*[(I_{a1}-I_{a2})+(I_{b1}-I_{b2})]/2*$ampl_{poke}$
- We compute the Control Matrix (CM) as the pseudo-inverse of the RM using eigenvalue truncation, typically at 250—300 modes (out of 1024)

RESULTS:

We obtained the first closed-loop lab demonstrations of LDFC at a contrast level relevant for imaging planets in reflected light

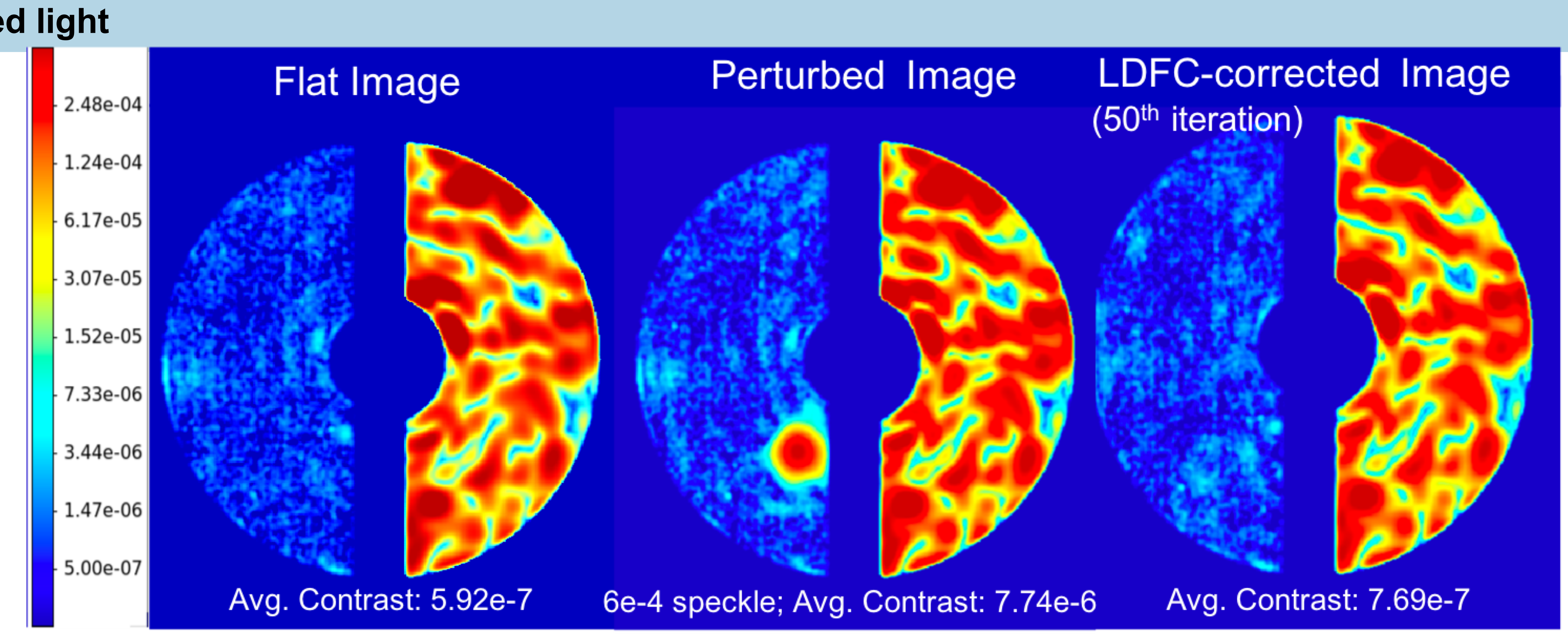
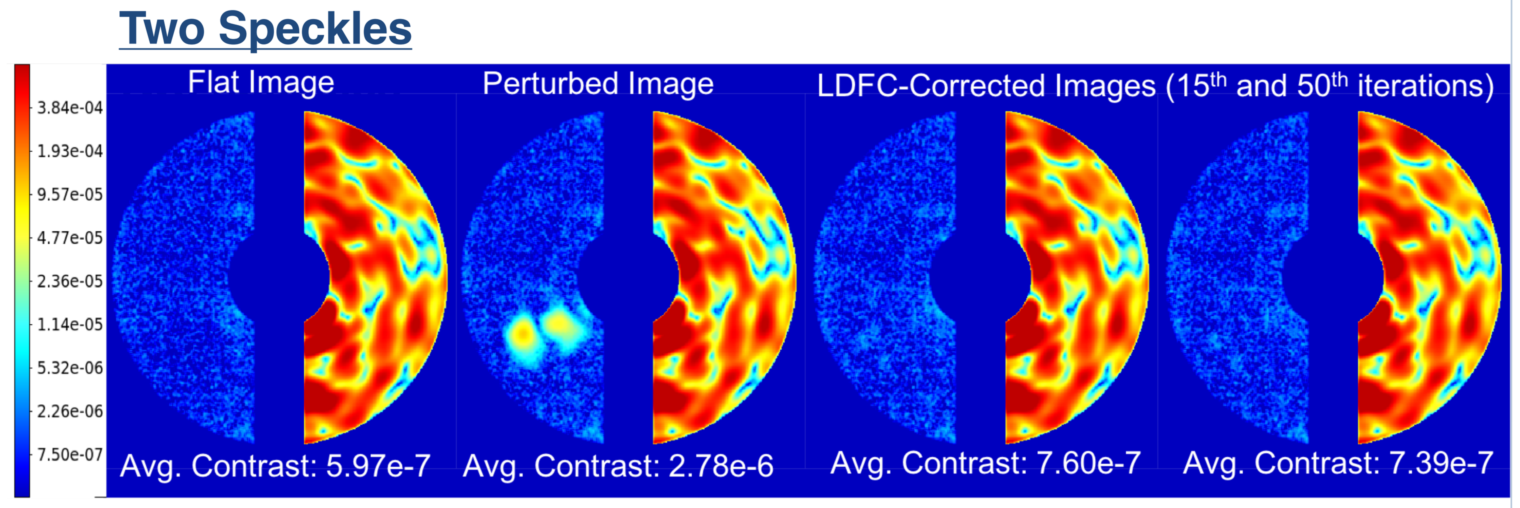


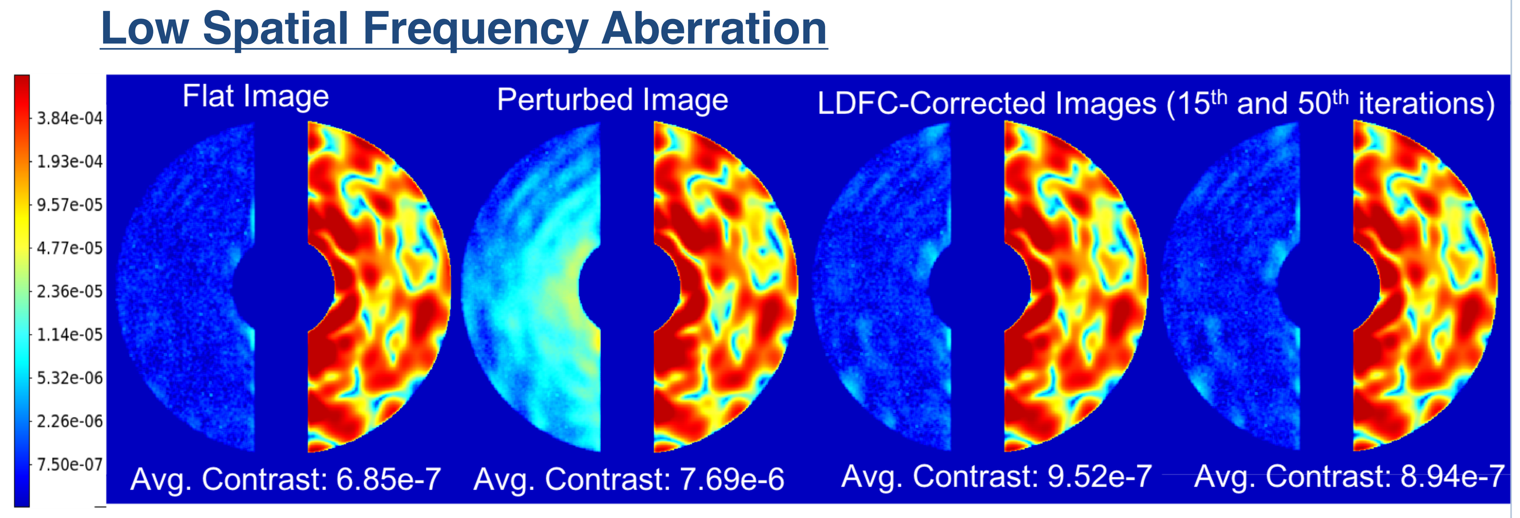
Fig 4 – Demonstration of LDFC. After producing a 5.9e-7 dark hole, we introduced a sine wave perturbation to produce a pair of 6e-4 speckles, degrading the average contrast to 7.7e-6. After 15 iterations our LDFC loop nulls the speckles and returns the dark hole to near nearly its original state. The dark hole stays frozen through 125 iterations.

LDFC can correct different types of perturbations

Two Speckles



Low Spatial Frequency Aberration



Complex Aberrations

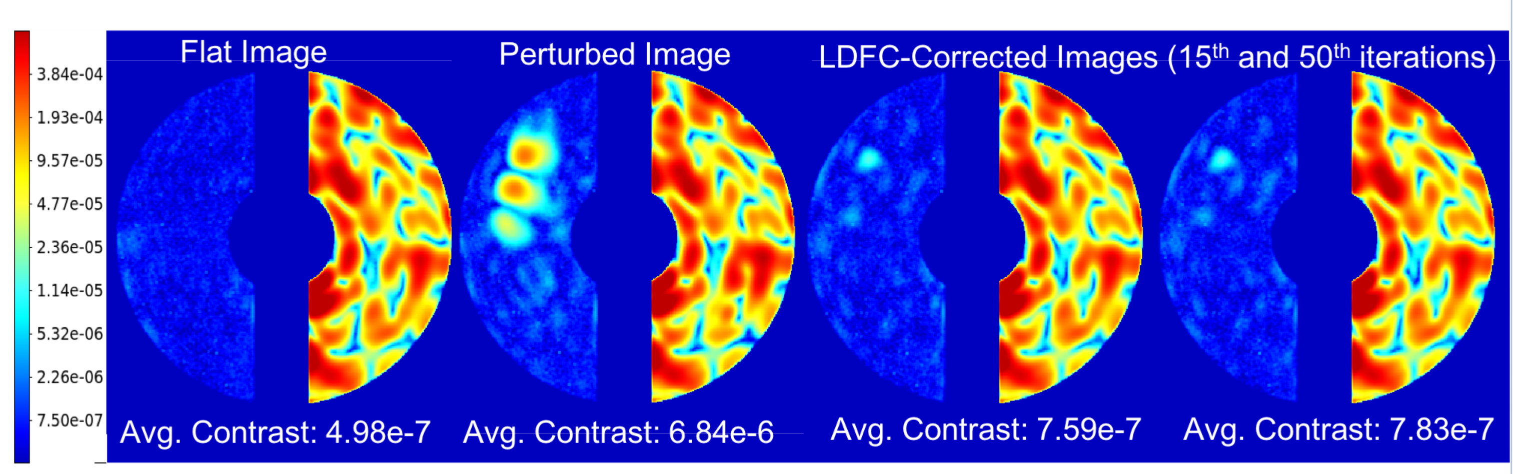


Fig 4 – Performance of LDFC for a range of different aberrations

LDFC may be more efficient than standard DM probing methods like Speckle Nulling

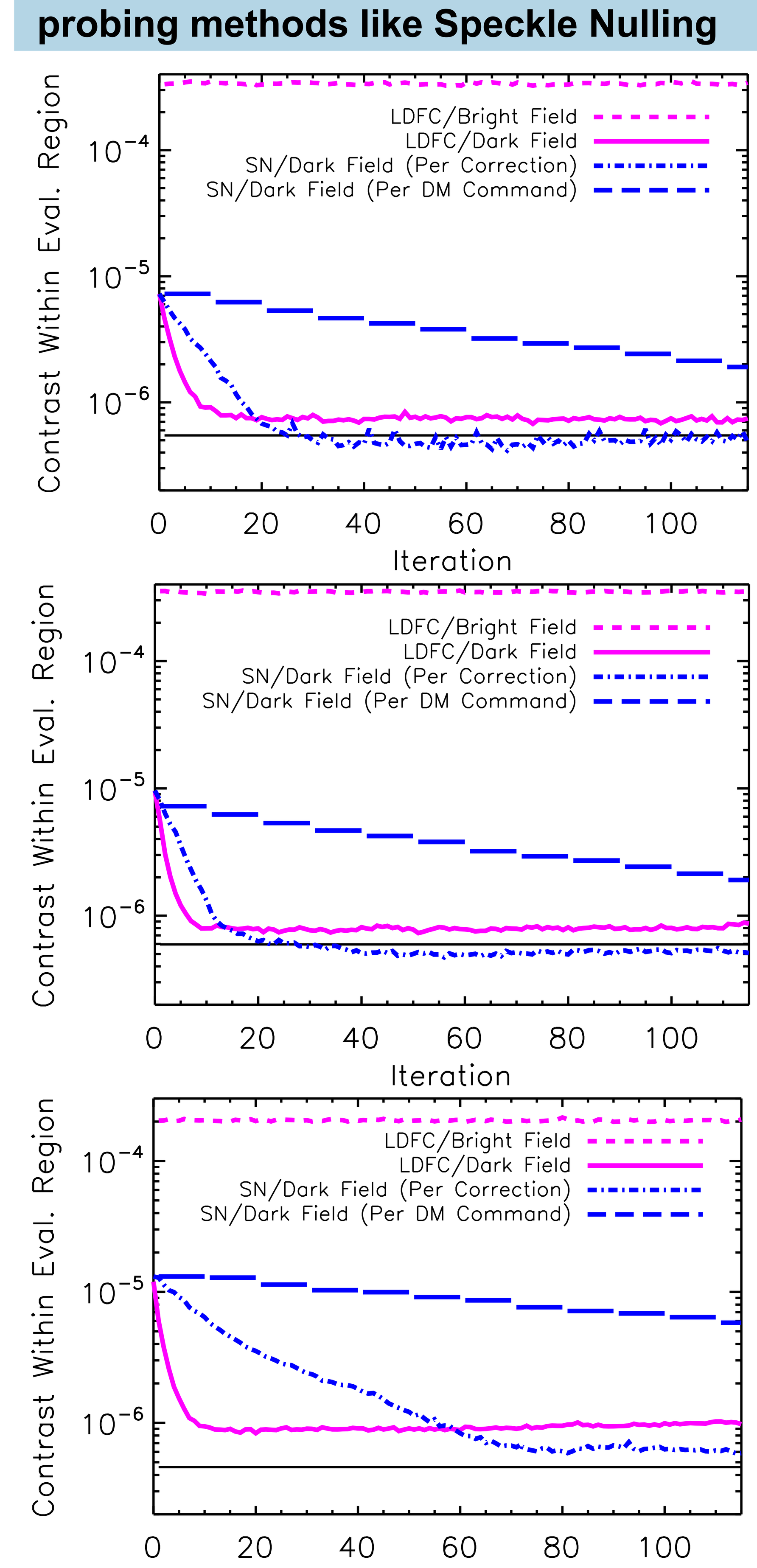


Fig 5 – Efficiency and stability of LDFC vs. Classical Speckle Nulling

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