Linear Dark Field Control (LDFC)

Bright ("unwanted") starlight should be used in a linear control loop and for PSF calibration

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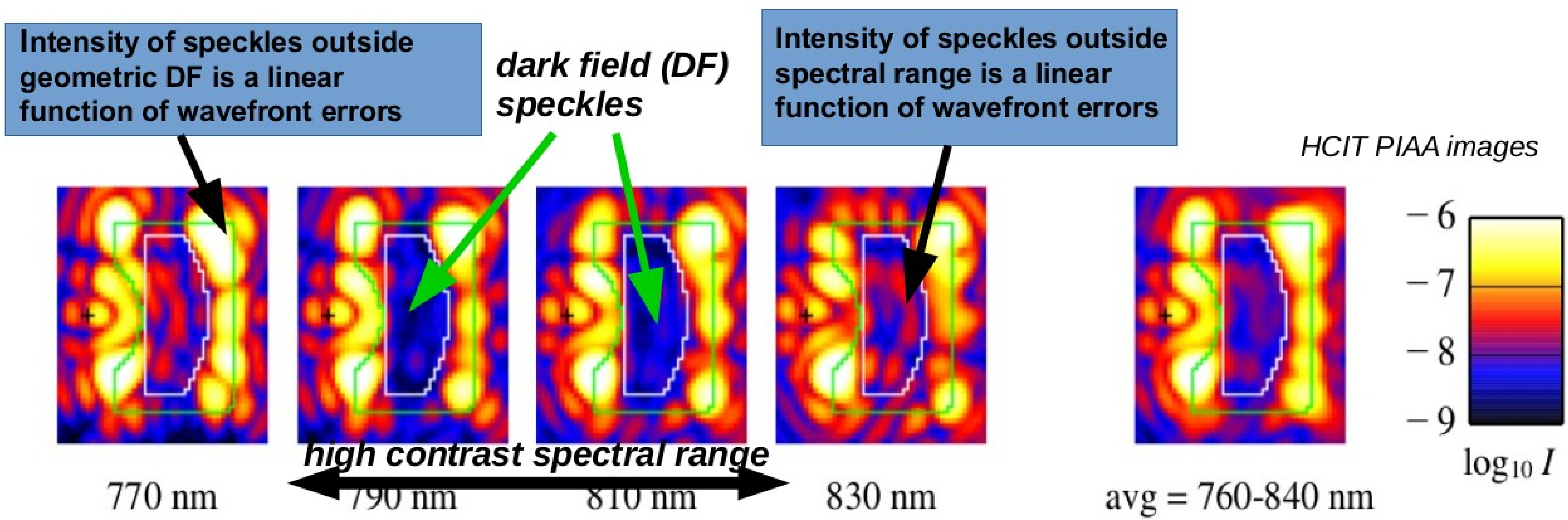
The series of images below shows intensity as a function of spatial coordinate (x,y) and wavelength (lambda) obtained with the PIAA coronagraph at the JPL high contrast imaging testbed.

The **DARK FIELD (DF)** is the area in (x,y,lambda) space over which starlight is removed.
The **BRIGHT FIELD (BF)** is the area outside the dark field.



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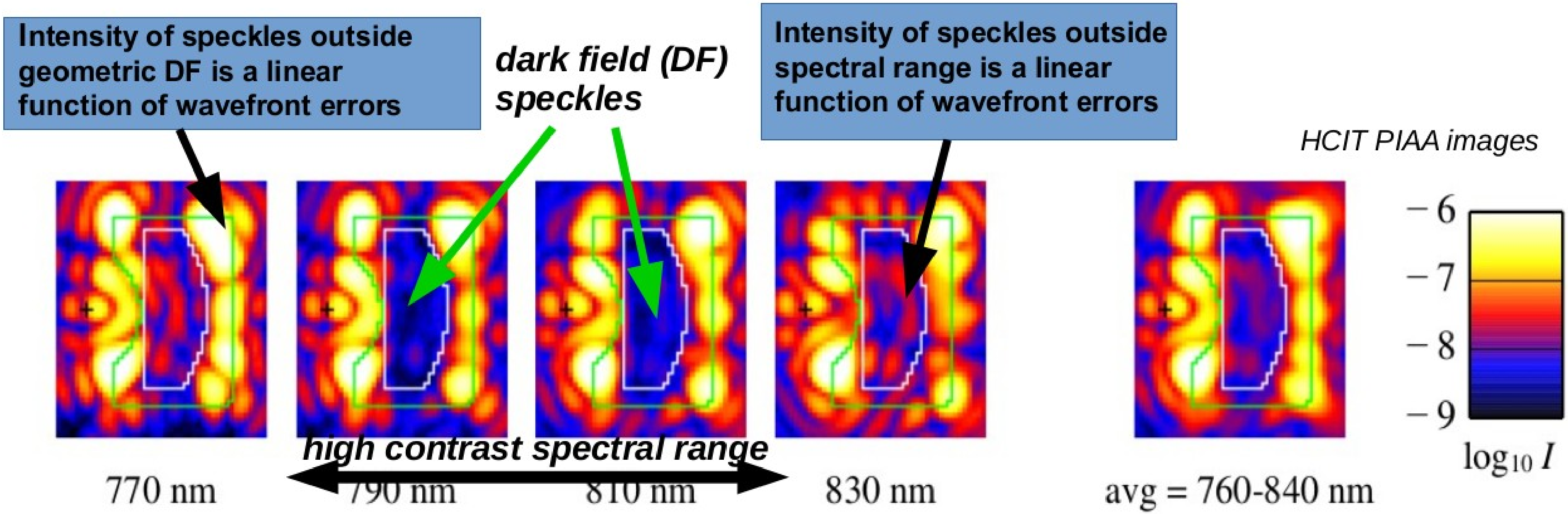
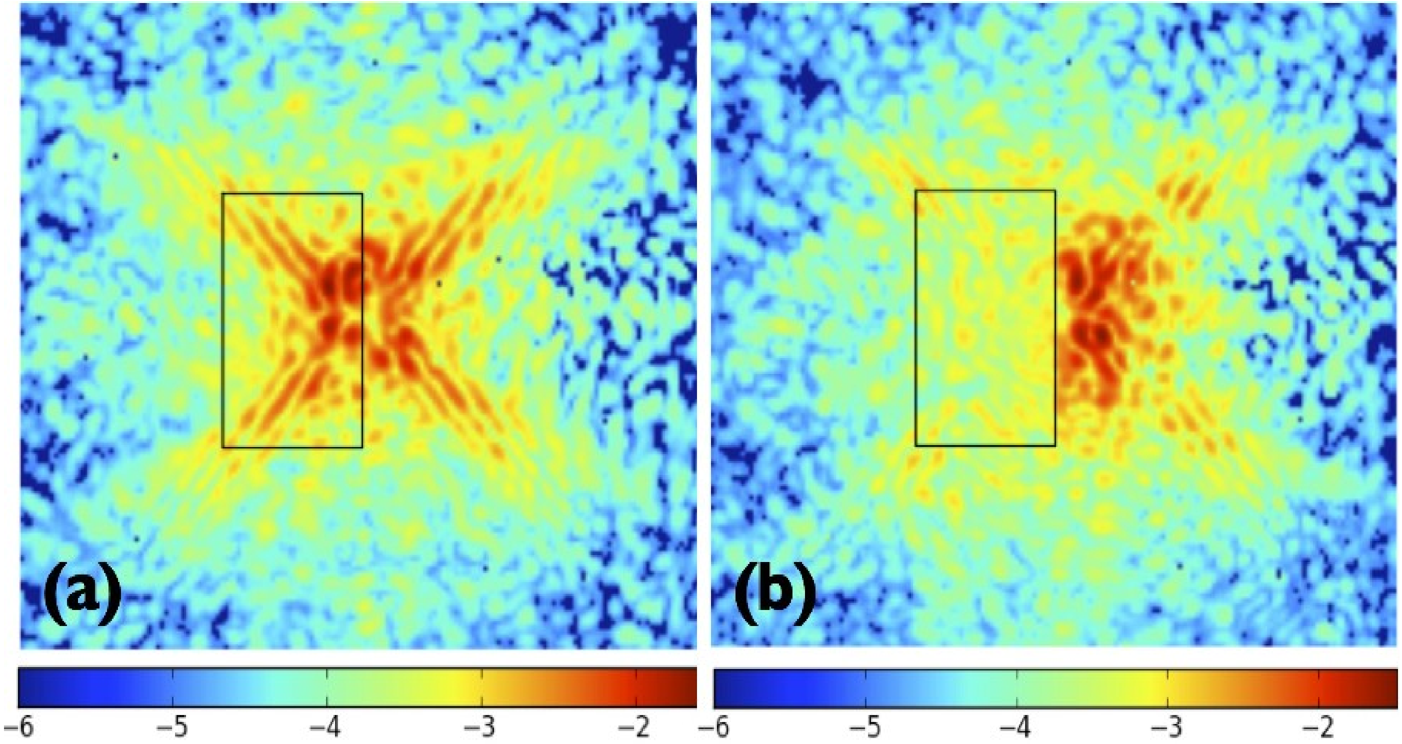
Speckle intensity in the DF are a non-linear function of wavefront errors
→ current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

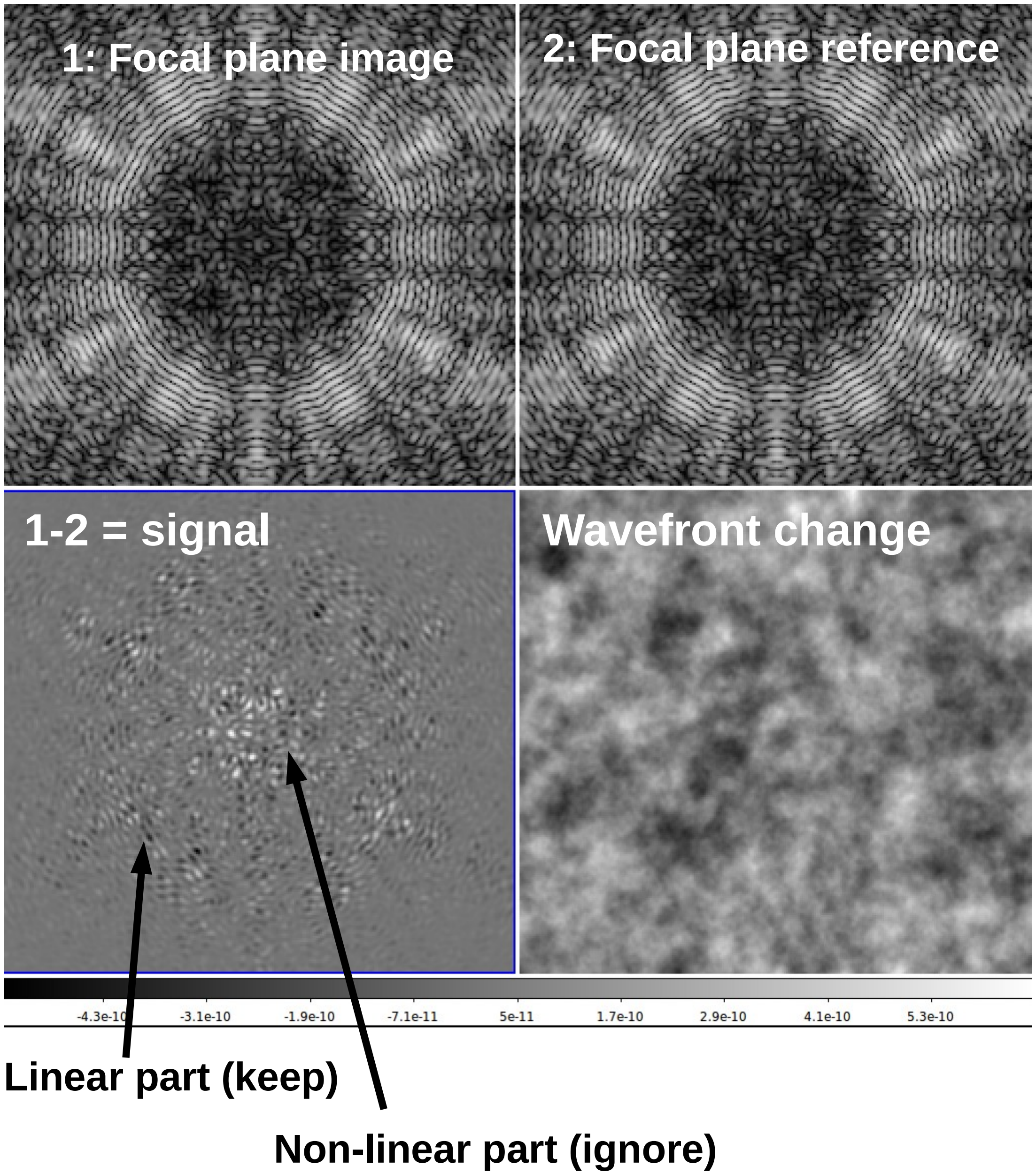
Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF



Bright field speckles in ½ field dark hole



LDFC steps



STEPS:

- Take an image
- Subtract reference: this is our signal
- Multiply signal by reconstruction (control) matrix
- Apply DM correction

LDFC vs. EFC

LDFC improves wavefront control loop speed by ~20x (more starlight is used for the measurement) and does not require DM modulation.
Linear loop is simpler, more robust that state of the art.

EFC

- Requires ≈4 images

LDFC

- Single image

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- Maintains dark field during measurement: 100% duty cycle

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- Single polarization
- Non-linear loop (convergence, computing power)

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- Dual polarization (if detector(s) allow)
- Linear loop: simple matrix multiplication

Application to NASA missions

We assume here:

- 2.4m telescope, 10% efficiency, 400nm-900nm LDFC bandwidth
- 1e-9 contrast dark field speckle sensing, $m_V = 5$ star
- 1e-8 incoherent background (zodi + exozodi + detector)

0.2 ph/sec/speckle, 2ph/sec for background.

Bright speckle level	Relative modulation	Absolute change	1mn SNR	Camera dynamical range
1e-4 (20000 ph/sec)	0.6%	6.3e-7 (127 ph/sec)	7.0	1e5
1e-5 (2000 ph/sec)	2%	2.01e-7 (40.2 ph/sec)	7.0	1e4
1e-6 (200 ph/sec)	6%	6.43e-8 (12.86 ph/sec)	7.0	1000
1e-7 (20 ph/sec)	21%	2.1e-8 (4.2 ph/sec)	6.9	100
1e-8 (2 ph/sec)	73%	7.3e-9 (1.46 ph/sec)	5.65	10
1e-9 (0.2 ph/sec)	300%	3e-9 (0.6 ph/sec)	3.13	1

Case study for WFIRST:

LDFC control bandwidth is 10mn, compared to several hr for state of the art EFC

Key benefits:

- LDFC enables close loop aberration control on science targets, as opposed to the current "set and forget" scheme → deeper contrast can be maintained, and system can be more resilient to small wavefront changes
- LDFC is also a powerful aid to PSF calibration. During science exposures, LDFC images provide live telemetry of wavefront changes.

LDFC is particularly well suited to track cophasing errors on a segmented aperture, using diffraction features created by segments

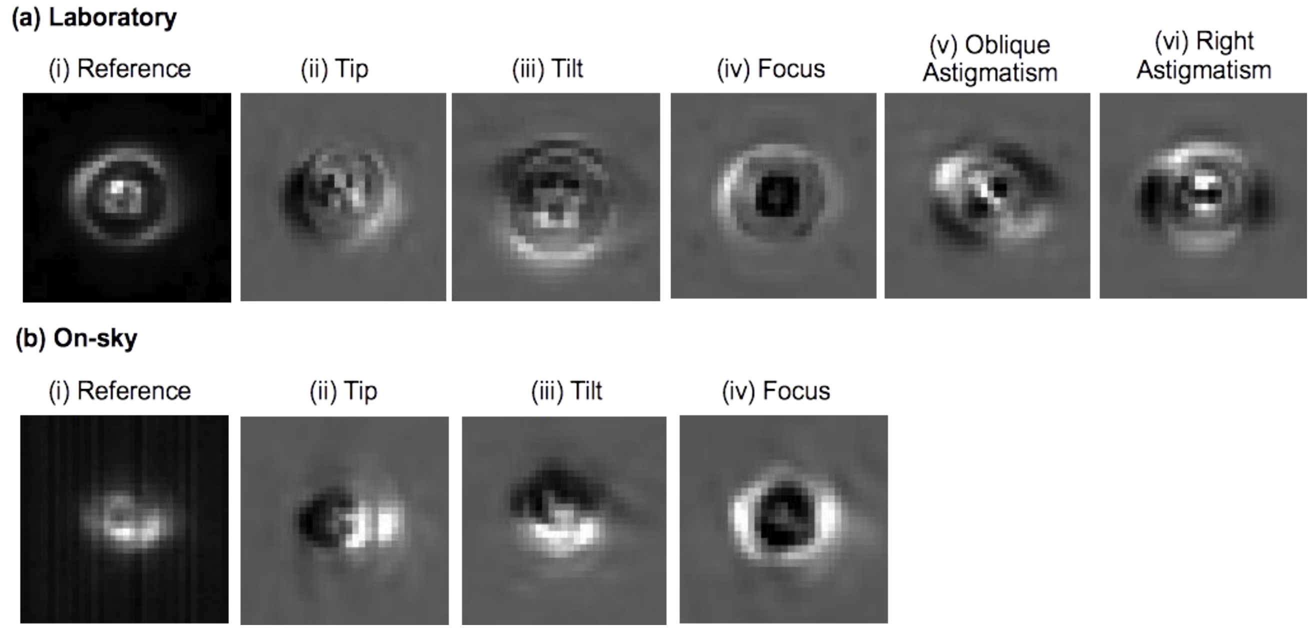
Observation mode

EFC + LDFC calibration on bright source, LDFC on science target:

(1) Perform EFC on bright target
(2) Record bright speckles after EFC converges: this is the reference
(3) Modulate DM actuators, record response matrix
(4) Point to “faint” science target
(5) Close LDFC loop to match reference
(6) Optional: Run slow EFC in background, while LDFC is running

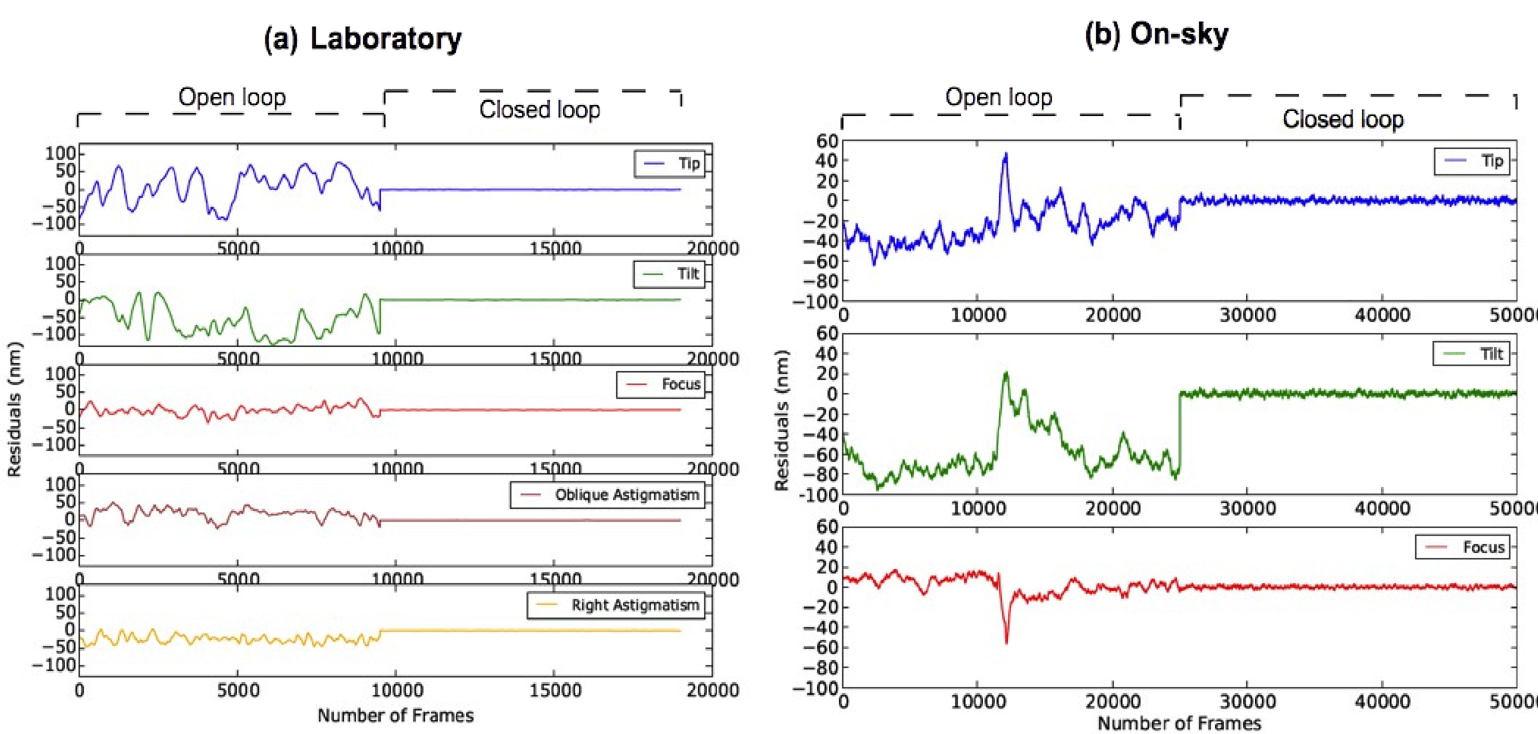
LDFC stability condition
Holding bright speckles static (LDFC) will maintain dark hole as long as relationship between bright and dark speckles is constant (analogous to G-matrix stability requirement): this is likely to hold for long periods of time

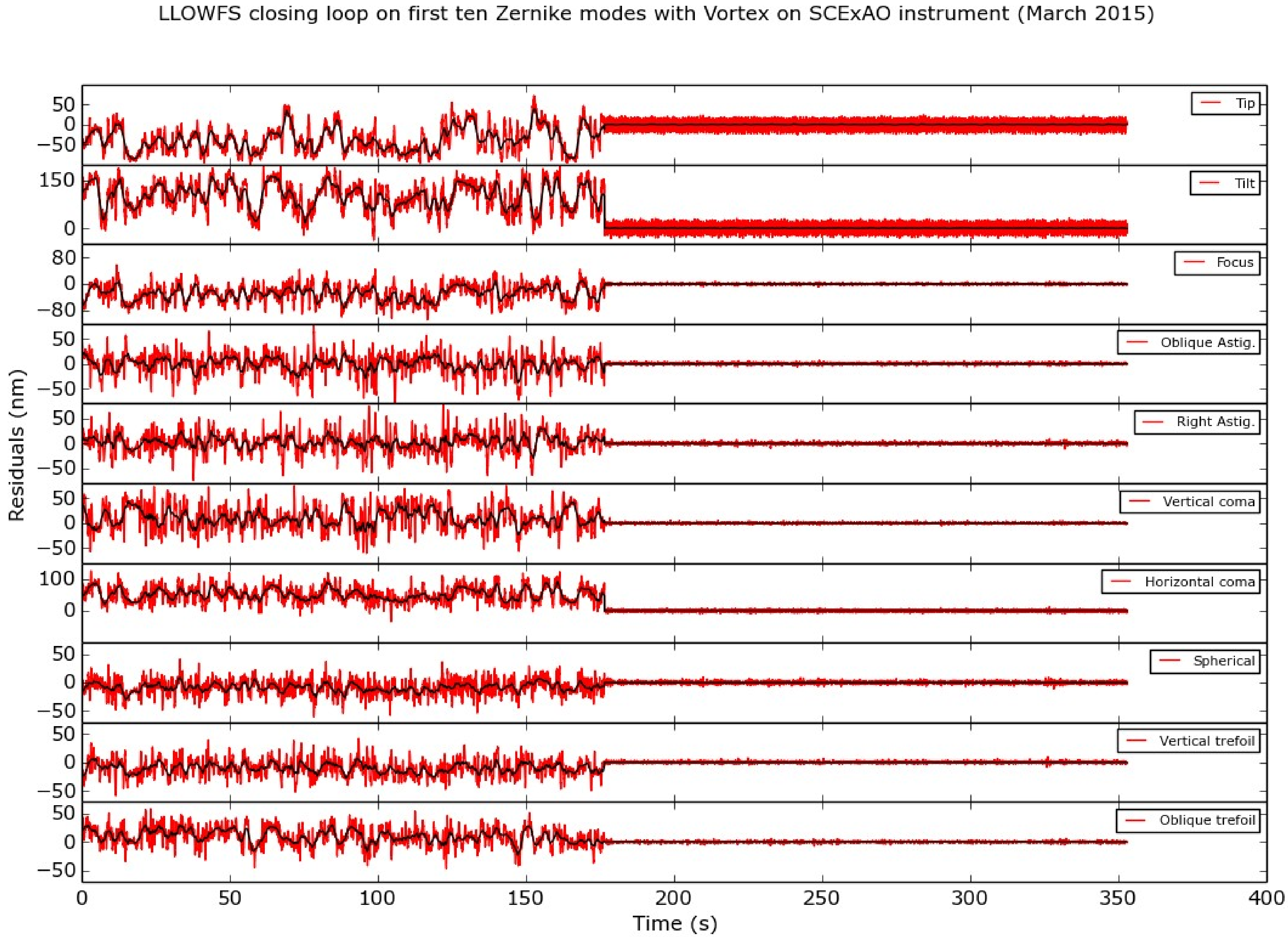
LDFC ↔ LOWFS



Response Matrix

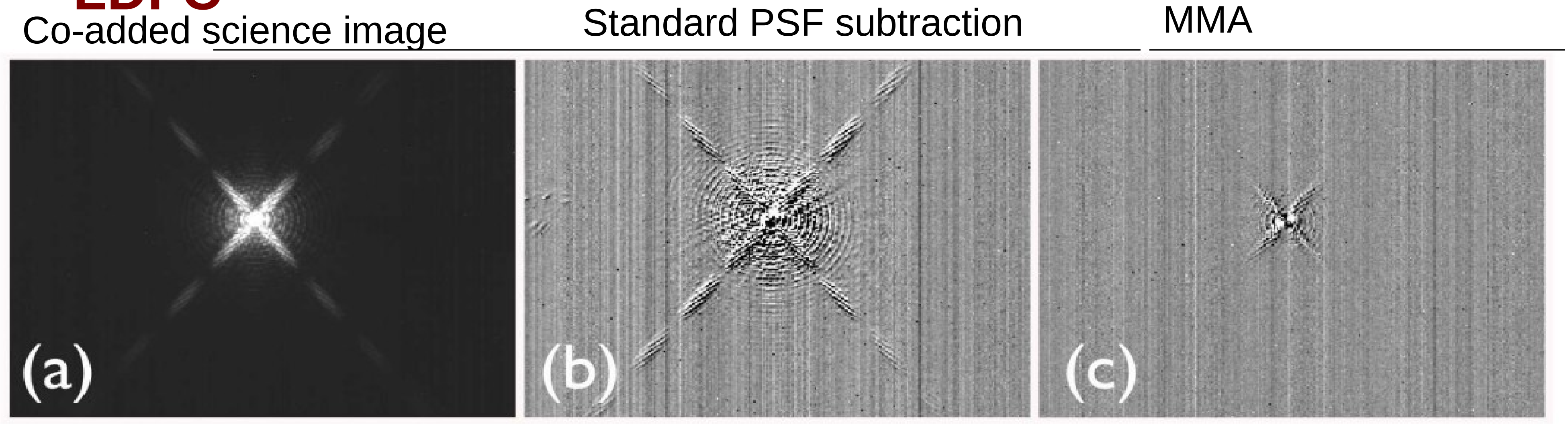
Residuals

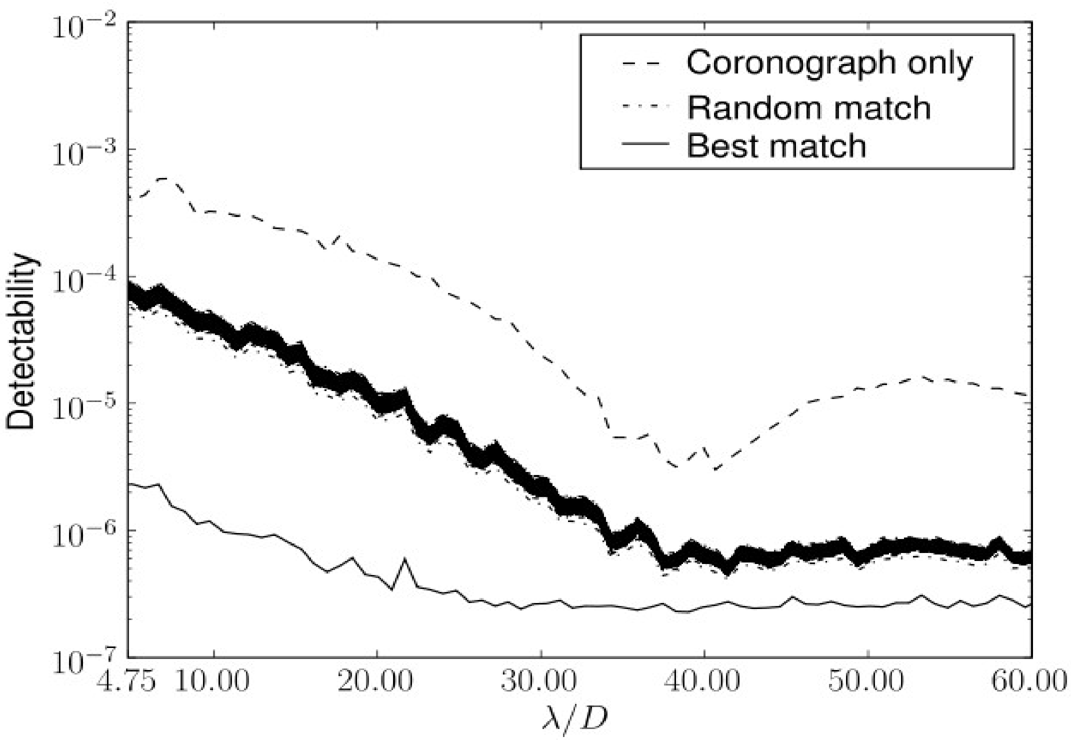




Ref: Singh et al. 2015 (in prep)

Using telemetry from LOWFS and speckle control can greatly improve PSF calibration → same benefit with LDFC





PSF calibration improved ~10x using LOWFS telemetry (Vogt et al. 2011)

Speckle noise

After all correction, calibrations, differential imaging :

$$\text{DETECTION CONTRAST LIMIT} = \sqrt{\frac{\text{SPECKLE INTENSITY LEVEL}}{\text{Exp. time / SPECKLE COHERENCE TIME}}}$$

Time scales:

- **Photon noise in science camera photon arrival rate**
- **Photon noise in WFS: AO loop speed**
- **Atm turbulence: wind crossing time D/v**
- **Optics, telescope: minutes, hours, days**

Chromatic and time lag speckle:
1e-5 speckles, lasting 5s → 14h to get to 1e-7 contrast

WFS noise speckle:
1e-4 speckles, lasting 1ms →17mn to get to 1e-7 contrast

Speckle noises

Slow speckles (SLO)
Due to optics, NCPEs
1e-5 contrast
~10 mn timescale

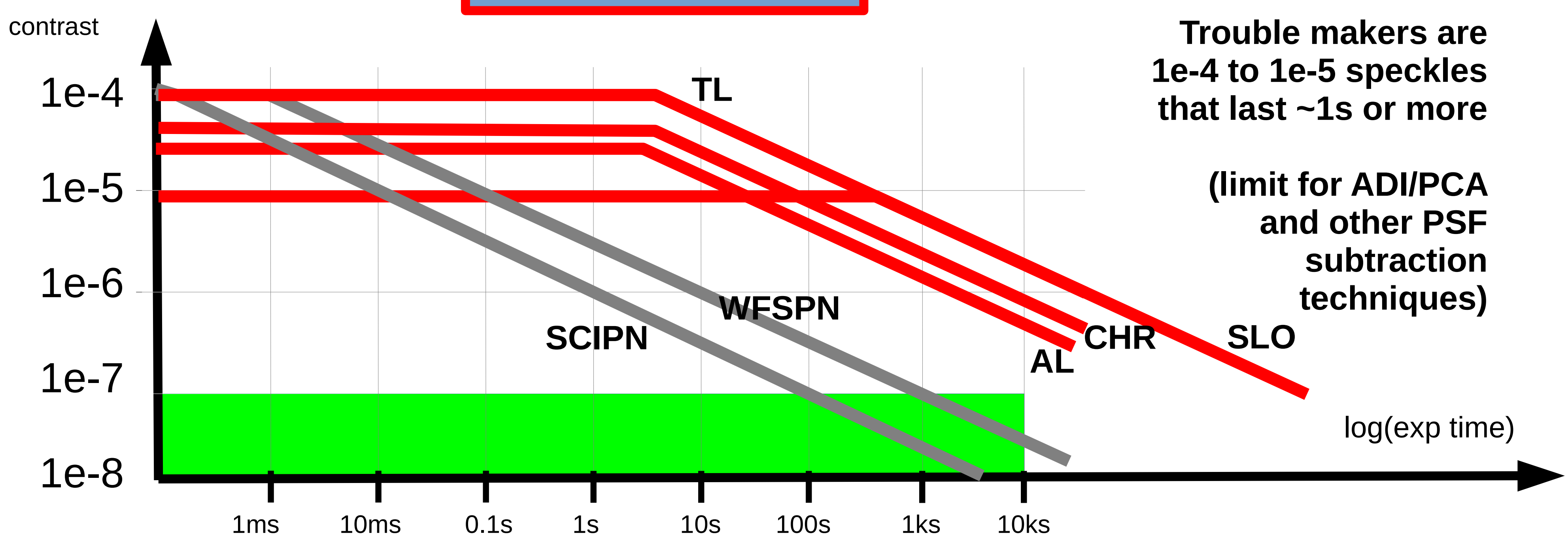
WFS Aliasing (AL)
Aliasing within WFS
few x1e-5 contrast
D/v timescale

WFS photon noise (WFSPN)
Photon noise in WFS
1e-4 contrast
T_{WFS} timescale

Time Lag (TL)
Due to finite AO loop speed / time delay
1e-4 contrast
D/v timescale

Chromaticity (CHR)
Due chromaticity between WFS and science instrument
few x1e-5 contrast
D/v timescale

Science photon noise (SCIPN)
Photon noise in science image
1e-4 contrast
Photon arrival rate timescale (>kHz)



Limitations

Fundamental limits to LDFC technique:

- Photon noise
- Null Space: wavefront errors that affect dark field WITHOUT changing the bright field will not be sensed
- Incoherent background (disk, background stars)

Null space is large if LDFC only uses spatial dimension with 360 deg dark hole, but shrinks to nearly zero if wavelength dimension is also used: It is very difficult to create a wavefront error that ONLY changes complex amplitude in the nulled spectral band.

LDFC for improving DM calibration issues

How to ensure that the DM probes have been properly applied ?

Execute following loop, ≈ 10x faster than EFC probing:

1: Apply DM probe
2: Measure DM probe using LDFC
3: Update DM probe

Alternative schemes:

- Define LDFC probes instead of DM probes
- Do not execute loop, but infer from LDFC what actual probes are to assist with wavefront measurement
- Use LDFC measurement for slow background task that updates DM calibration model

Conclusions

LDFC allows efficient wavefront “freeze” and complements EFC. Both LDFC and EFC should work simultaneously

Can relax WF stability requirement by ~20x

Simpler and more robust that EFC, does not impact science frames

Strong benefit for PSF calibration

Under evaluation for WFIRST and ground-based systems
Impact on instrument design (IFS, filters, masks)

LDFC is extension of LOWFS concept: use starlight that the science doesn't need for WFS

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