Wavefront Sensing, Control and PSF calibration

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Effort goals

Early Stage Innovation program: we are working at the low end of TRL scale

Wavefront sensing and control for centrally obscured and segmented apertures

- Coronagraph design for "unfriendly apertures"
- Efficient sensing and control of cophasing errors using starlight
- PSF calibration

Future large space telescopes WILL be segmented and/or centrally obscured

Our effort is aimed at identifying approaches for high contrast imaging and wavefront sensing for future (beyond WFIRST) NASA missions

Coronagraph design

PIAACMC coronagraph

We adopt PIAACMC for this study, as it can be designed for (almost) any aperture geometry without significant loss in throughput, IWA or contrast. The focus of our study is NOT coronagraph design, but wavefront sensing/control approaches. HOWEVER, we do need a coronagraph model to test/validate WFS concepts.

Application to other coronagraphs

Results/techniques presented are not coronagraph-specific and can be applied to any coronagraph.

Application to other Telescope Apertures

Results/techniques presented are not aperture-specific and can be applied to any Telescope (WFIRST included).

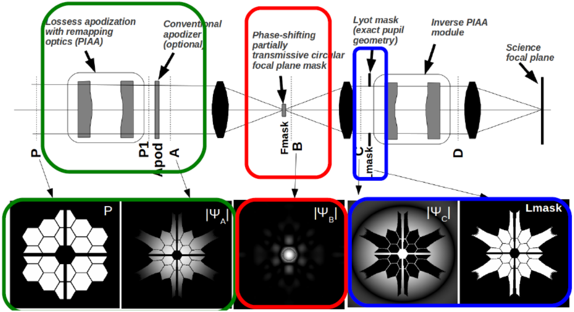
PIAACMC principle

How does PIAACMC work ?

Combines 3 techniques :

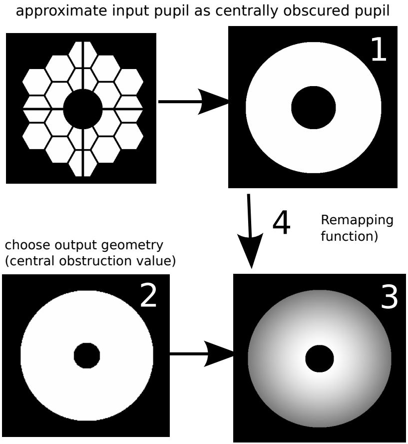
- Lossless apodization with PIAA optics (beam shaping)
- Phase mask coronagraphy (focal plane mask is phase-shifting)
- Lyot coronagraphy (Pupil plane Lyot mask removes starlight)

→ starlight rejection achieved by **destructive interference** between light that passes through the focal plane mask and light that passes outside the focal plane mask



PIAACMC design process: initial remapping function

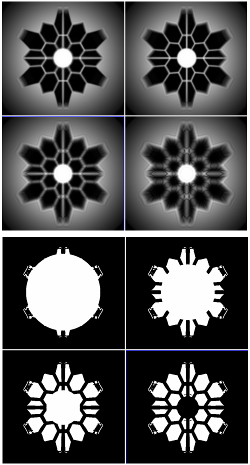
Define initial remapping function



1. Approximate pupil as centrally obscured geometry
2. Choose a circular centrally obscured output pupil
3. Compute generalized prolate spheroidal function for output pupil geometry
4. Compute circular remapping function

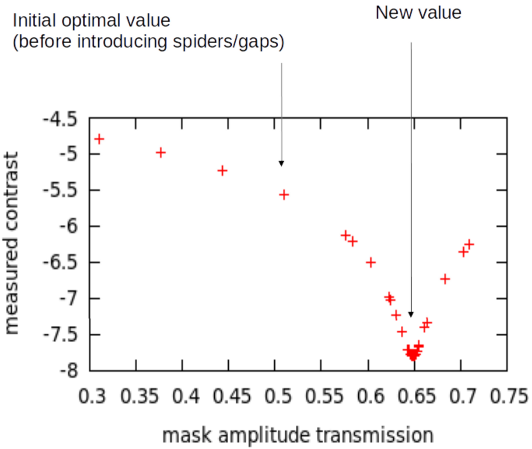
PIAACMC design process: Lyot stops

Compute Lyot stop(s)



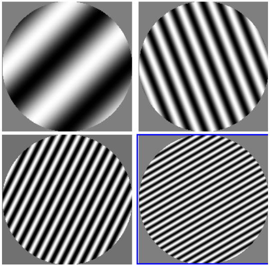
1. Propagate aperture through system, itegrate over bandpass (4 planes shown on the left)
2. Identify which parts of the pupil are "sharp" at each plane
3. Run non-linear optimizer to find shapes and locations of Lyot stops that maximizes throughput while minimizing transmitted starlight

PIAACMC design process: Optimize focal plane mask transmission



PIAACMC design process: Optimize PIAA mirrors shapes

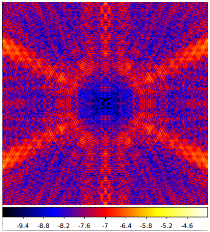
PIAA mirrors perturbation modes

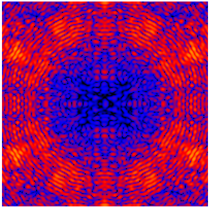


1. Compute focal plane complex amplitude Jacobian against modal changes to PIAA mirror shapes
2. Compute pseudo-inverse of Jacobian for different regularization parameters
3. Perform linear scan along directions defined by pseudo-inverses
4. Repeat process until convergence

PIAACMC design process

Focal plane on-axis PSF

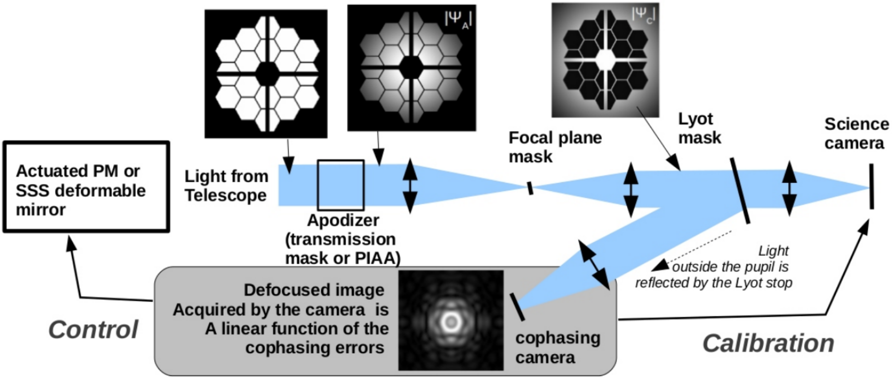




The steps described above are executed several times in a loop, due to coupling between PIAA mirror shapes, focal plane mask transmission and Lyot stop design

1. Optimize Lyot stop
2. Optimize focal plane mask transmission
3. Optimize PIAA shapes

LOWFS Principle



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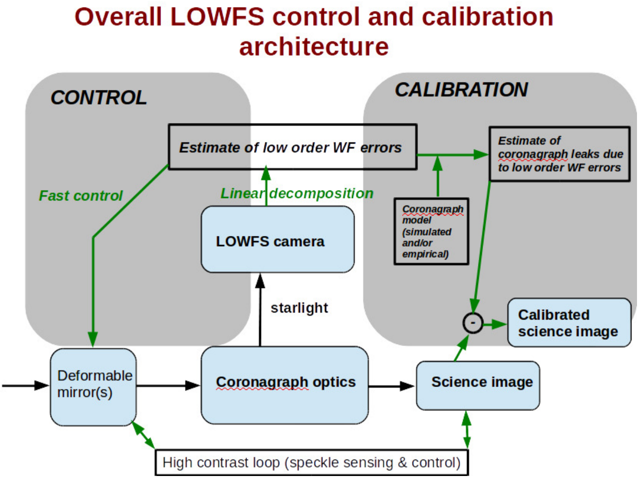
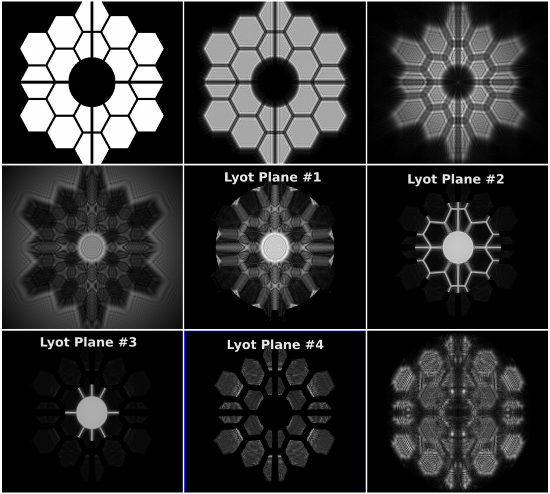
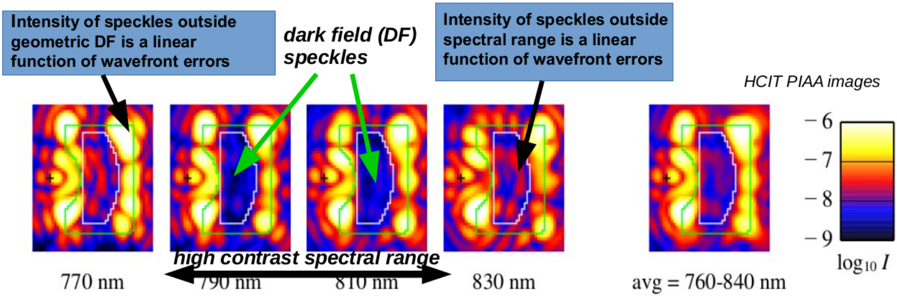


LOWFS for segment cophasing



In segmented apertures, much of the signal is containted in the Lyot stop, in gaps between segments.
→ Refracting focal plane mask + Reflecting Lyot stop is prefered solution to avoid confusion between low-order modes and segment co-phasing errors.

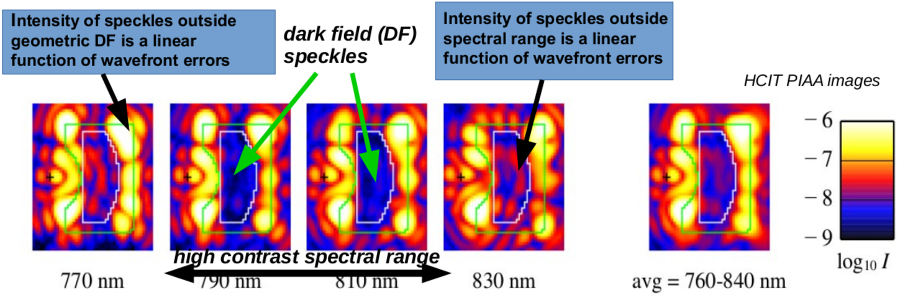
Speckle intensity linearity



Dark field speckles sensing requires non-linear multi-probe sensing

Speckle intensity inside dark field is non-linear (quadratic + cross terms) function of wavefront errors.

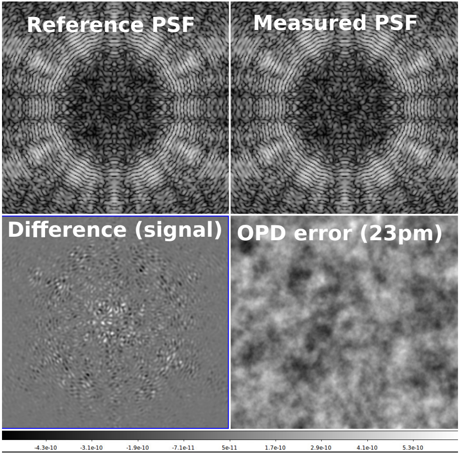
Speckle intensity linearity



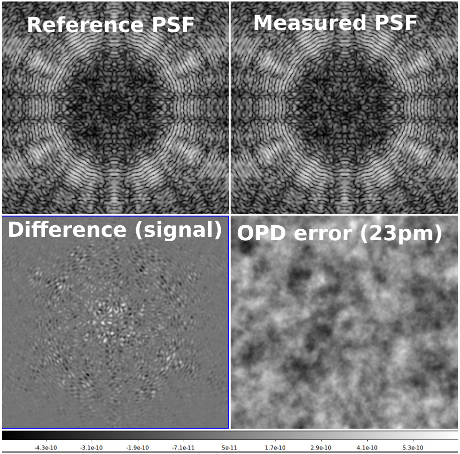
Bright field speckles

Bright speckles intensity outside dark field is LINEAR function of wavefront errors.

LDFC loop principle

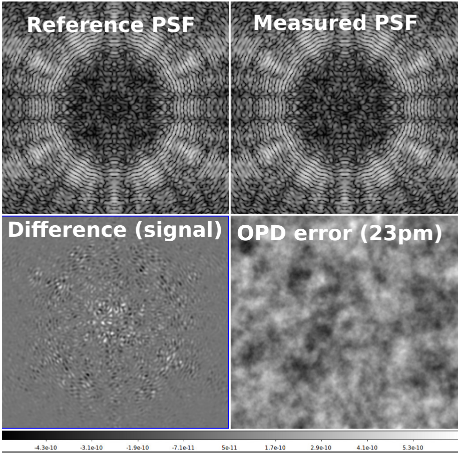


LDFC loop principle



1. Take an image

LDFC loop principle



1. Take an image
2. Subtract reference: this is your signal

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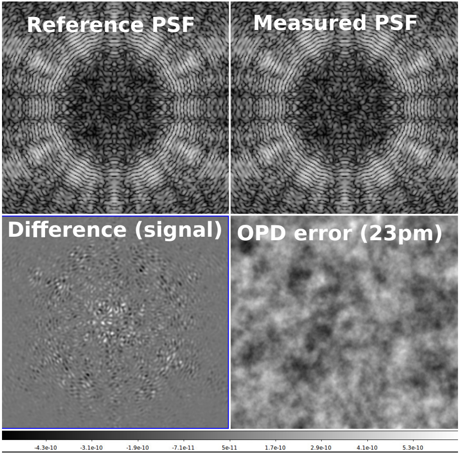

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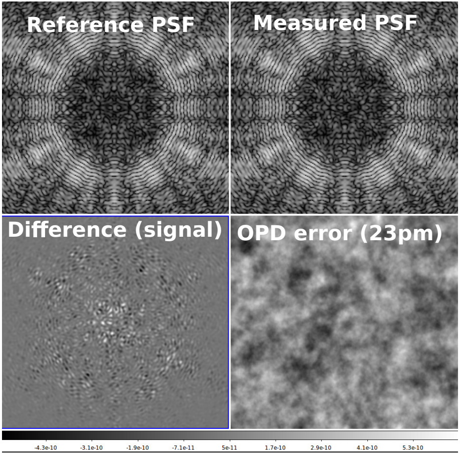

1. Take an image
2. Subtract reference: this is your signal
3. Multiply signal by reconstruction (control) matrix
4. Apply DM correction

Advantages: faster, more sensitive and robust

EFC

LDFC

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- Requires ≈4 images

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- Single image

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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

LDFC speed and detector requirements

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

Optimal bright speckle level is around 1e-5 to 1e-6.
Control bandwidth $\approx$ 10mn (vs. several hrs for EFC).

Limitations

Fundamental limits to LDFC technique:

- Photon noise
- Null Space: wavefront errors that affect dark field WITHOUT changing the bright field.
- 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.

Observation mode

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

LDFC stability

Holding bright speckle 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.

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6. Optional: Run slow EFC in background, while LDFC is running

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LDFC for improving DM calibration issues

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

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

Alternative schemes:

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Alternative schemes:

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- 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

Implementation - known issues

Pixel value thresholding

Faint pixels do not respond linearly to wavefront errors: only pixels above a threshold should be considered. Threshold value set by wavefront sensing range.

Image registration

LDFC's signal is small in relative terms (typically 1e-1 to 1e-2), and an equally small signal can be created by image motion on the detector. Image motion should be tracked/controlled if optical system is not sufficiently stable.

Why self-calibration ?

Notations:

- x, y: spatial coordinates in focal plane
- A: Complex amplitude in focal plane (after coronagraph)
- X: DM(s) actuator values
- SRM: System Response Matrix

At high contrast/small wavefront errors ($X < 1 rad$):

$$A[x, y, \lambda] = A_0[x, y, \lambda] + SRM[x, y, \lambda, act_{DM}] \times X[act] \quad (1)$$

High contrast wavefront control process:

1. Measure current complex amplitude A_i using SRM to estimate focal plane probes.
2. Find DM correction Xc_i to minimize $A_{i+1} = A_i + SRM\, Xc_i$. To do this, we compute the control matrix CM (pseudo-inverse or regularized inverse of SRM), and $Xc_i = -g\, CM\, A_i$). g is the loop gain (scalar or vector).

If *SRM* were perfectly known :

- Wavefront estimations would be limited by photon noise
- Wavefront loop would converge very fast (in 1 single iteration if complex amplitude linearity holds), as we could perform loop iterations in the computer to converge prior to applying DM correction.

SRM-related errors

The top candidate for slow/poor convergence in lab (and on-orbit) is poor knowledge of system response matrix.

Current approach

Use system model to COMPUTE system response matrix (linear relationship between DM commands and focal plane complex amplitude)

Limitations, risks:

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Limitations, risks:

- Model can be innacurate due to unknowns (WF errors, geometry mismatch)
- System response can change over time: coating degradation, particules, DM aging, misalignments (launch)

Initial concepts/ideas (which did not work) show why this is challenging

Brute force approach
Conceptually, one may issue a large number of (random ?) DM states X k , measure the corresponding images $I_k = |A_0 + A_k|^2$ and solve for the full SRM. This brute force approach suffers from 3 problems:

1. The underlying complex amplitude A 0 changes with time during the long measurement sequence
2. This is computationally VERY challenging (non-linear, many variables, noise behavior)
3. Poorly known/constrained measurement null space... How to choose the X_k s ?

Initial concepts/ideas (which did not work) show why this is challenging

Matrix evolution approach
During closed loop, take more measurements than required to solve for A_i.
For example, 6 probes instead of 3-4. Use the extra constraint to gently evolve SRM by computing the derivative of each SRM element against residual fit quality.
This works (tested in lab and in simulation), but it is EXTREMELY SLOW. Requires $\approx$ 1e6 loop iterations to make a significant improvement to SRM: not practical.

Suggested approach

Break problem is small groups of n actuators (n-plets), n = 2, 3 or 4.

- Treat each n-plet separately, solving for corresponding n columns of RM and underlying complex field A_0
- Within each n-plet, treat pixels separately to keep computations light and parallel
- Assemble full *SRM* with overlapping n-plets

For each n-plet: Set DM actuators to -stroke, 0 and +stroke (- 0 and +), and measure image for each possible combination:

—, –0, –+, -0-, -00, -0+, -+-, ... , +++

3 n images = 3 n measurements for each image pixel

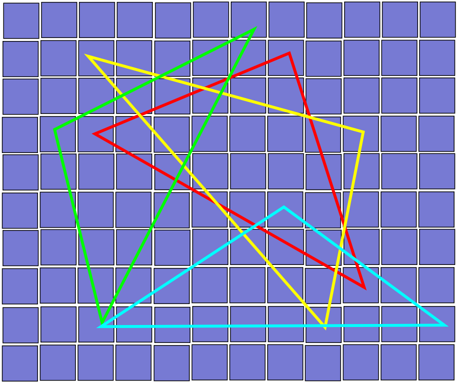
Suggested approach: measurement speed

Example:

- DM stroke = 0.1 rad yields 100 ph/s/speckle on Sirius (10% efficiency, 10% bandwidth)
- Two DMs, each 64x64 actuators, 4000 total actuators illuminated
- 2000 3-plets required to cover all actuators + overlap
- Each 3-plet = 27 images 54000 images total = 15hr at 1sec per image

N-plets

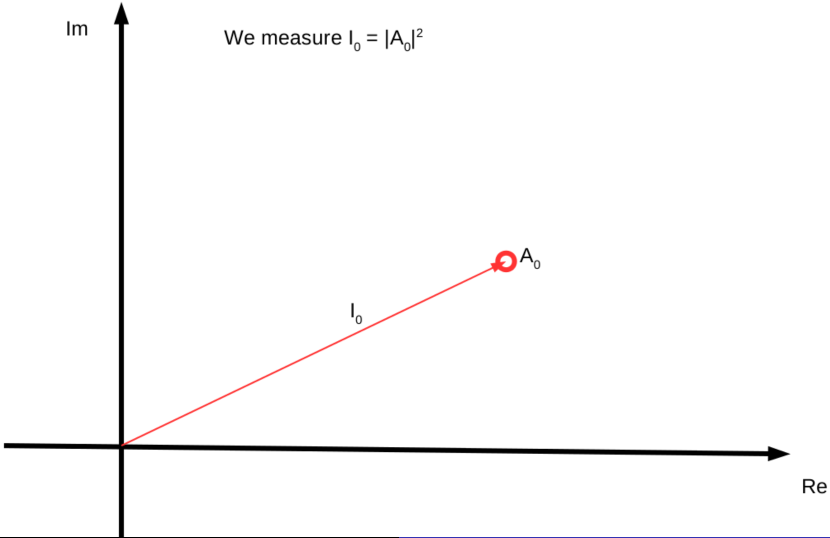
DM triplets



DM actuators

Define sets of N actuators (N-plets) covering all illuminated DM actuators. N-plets can overlap (share actuators).

Single pixel measurement



Single pixel measurement, n = 1

We measure:

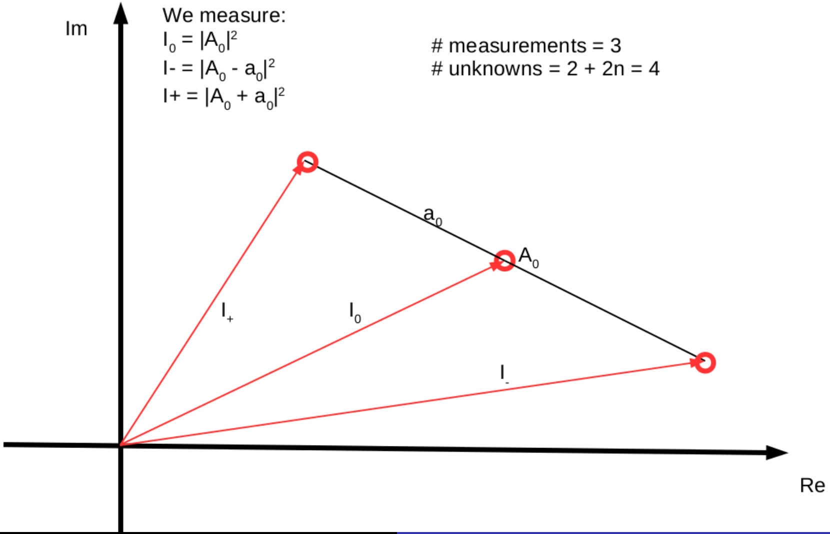
$I_0 = |A_0|^2$

$I- = |A_0 - a_0|^2$

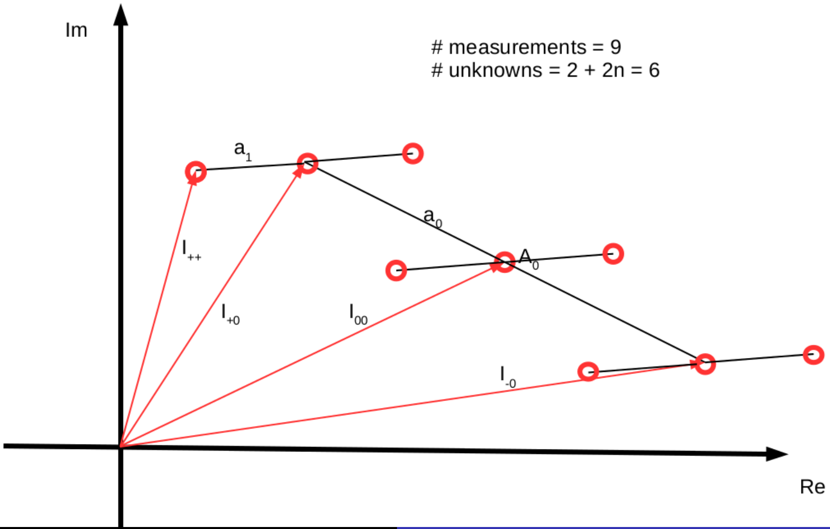
$I+ = |A_0 + a_0|^2$

measurements = 3

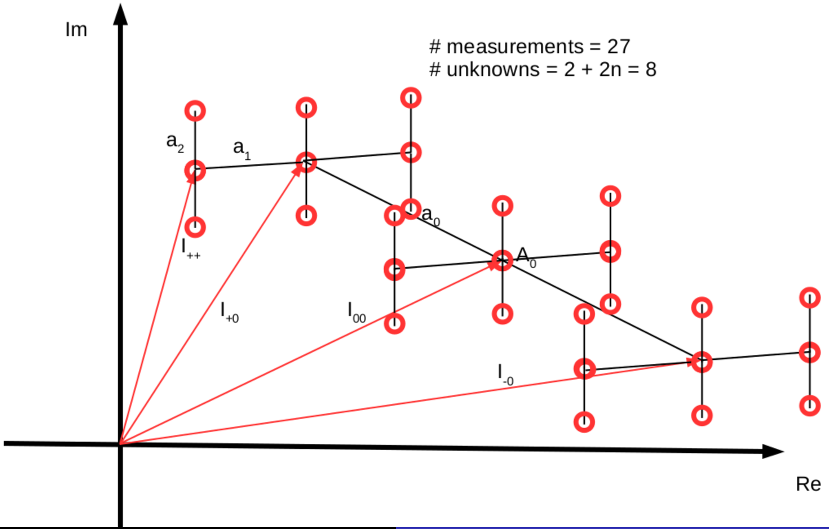
unknowns = 2 + 2n = 4



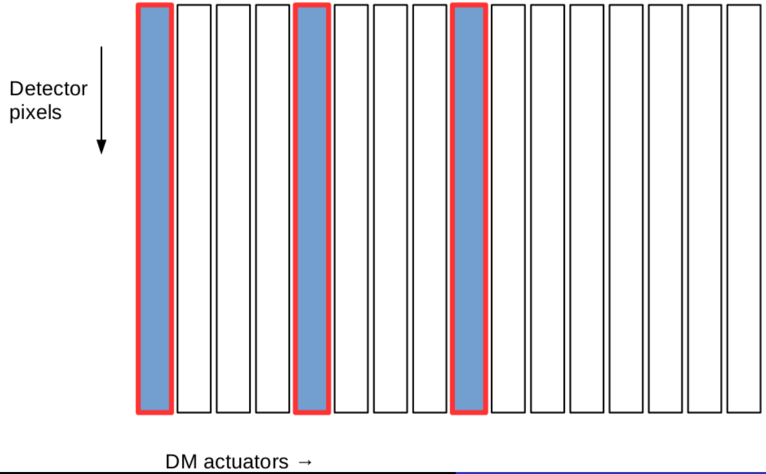
Single pixel measurement, n = 2



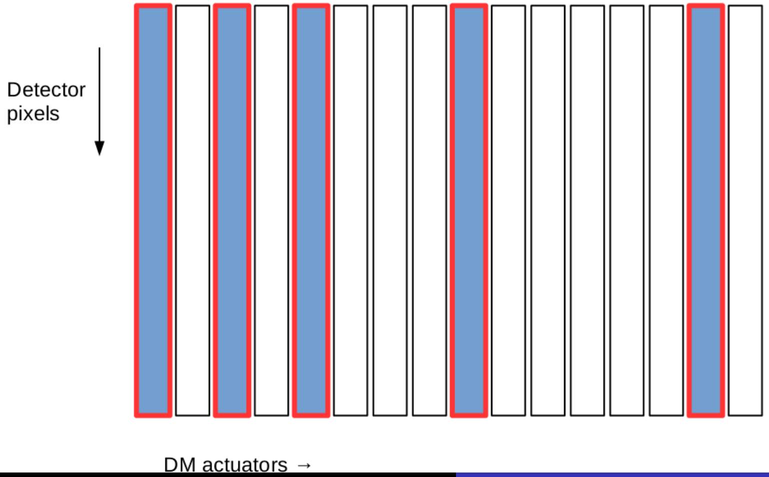
Single pixel measurement, n = 3



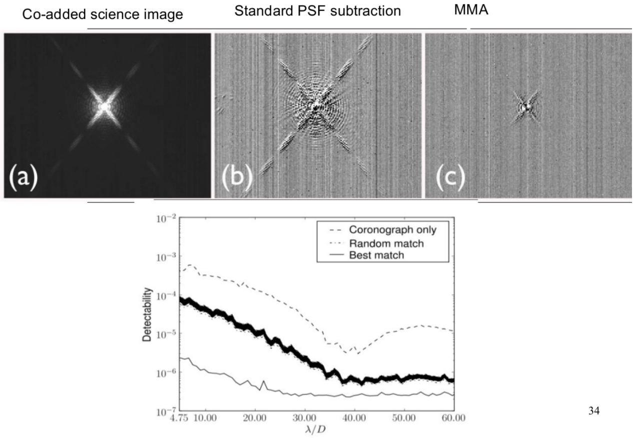
Filling in the RM, 3-plet #1



Filling in the RM, 3-plet #2



PSF calibration: LOWFS



Using LOWFS frames (analogous to bright speckles in LDFC) improves PSF substraction by 30x. (Lab Demo, Vogt et. al 2011)

PSF calibration: LDFC

Bright speckle field tells us what the dark speckle field is:
bright speckle field $\rightarrow$ *dark speckle field*

This can be done in several ways:

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This can be done in several ways:

1. Explicitely estimate WF errors to compute dark speckle field
2. Statistical approach (as shown in previous slide): match bright speckle field images with corresponding dark field images
3. Exploit linearity between bright speckle INTENSITY and dark speckle COMPLEX AMPLITUDE → build from telemetry a time sequence of complex amplitude in dark field (and use this complex amplitude as probe for slow residual speckles ! - see Codona et al. work)

Conclusions

- Linearity is your friend
- Do not throw away light: stellar photons are very useful
- LDFC null space should be mapped for AFTA: how well will it work ?
- PSF calibration should be evaluated alongside LDFC
- We need help: try it, break it, fix it, improve it (we need to test these concepts in lab !)