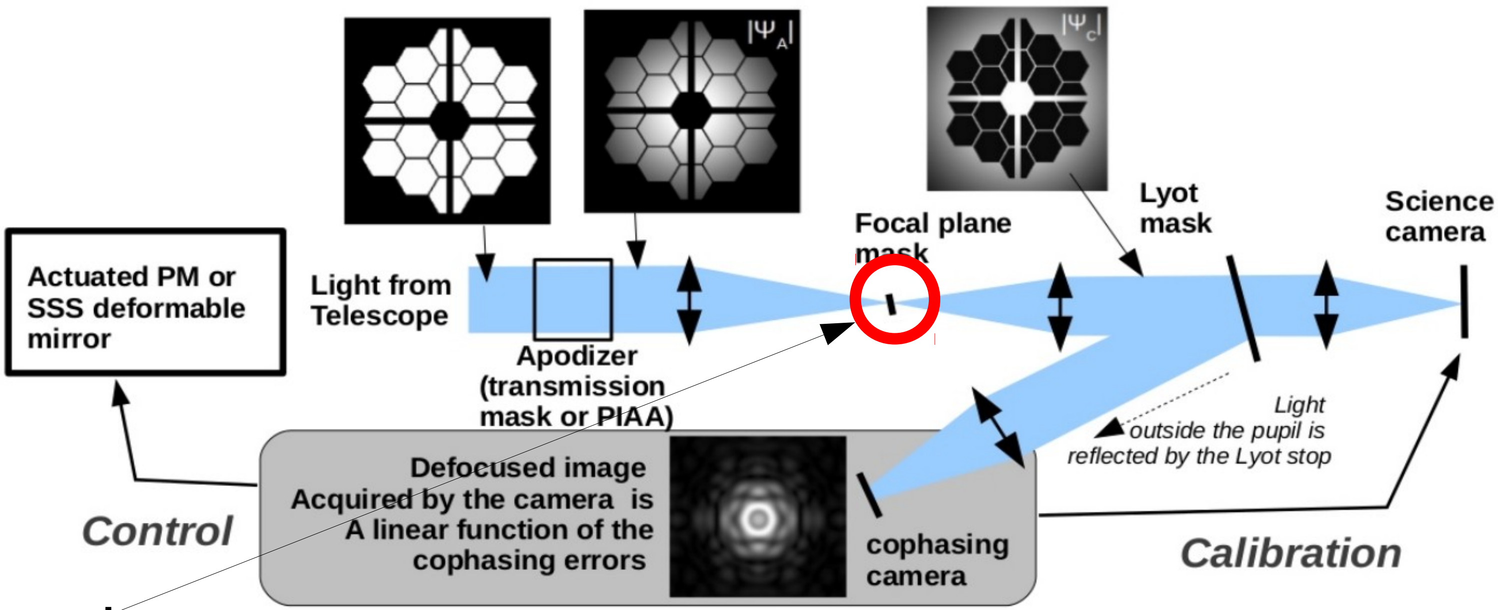
LOWFS: sensing and control

Design approach: use light rejected by coronagraph



Phase-shifting mask

Modulates the light in such a way as to cause it to fall completely outside the Lyot stop mask (by causing complete destructive interference inside the Lyot stop)

→ Almost ALL starlight is directed to LOWFS camera, for optimal LOWFS sensitivity and calibration

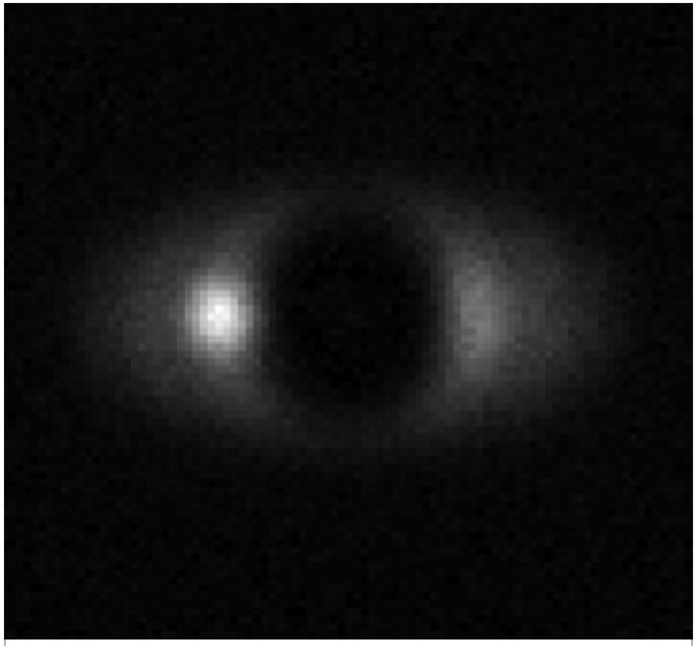
→ The interaction between PSF and focal plane mask (diffraction) creates a diffraction pattern that is strongly dependent on low order aberrations, yielding a LOWFS response that is largely free of non-common path errors: TT is measured as a pattern shape, NOT a photocenter on a reflected spot

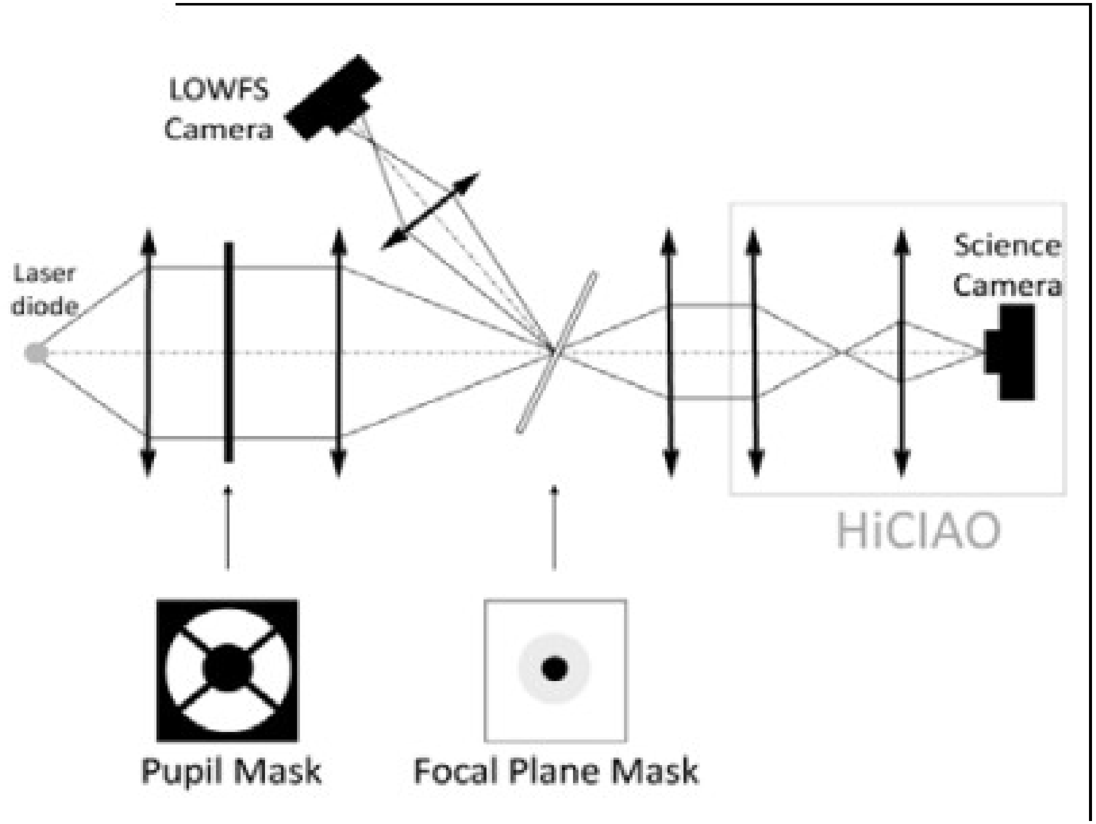
→ Almost ALL starlight is directed away from pupil, yielding a high throughput, high contrast coronagraph

Low-order WFC

Problem: planets at small separation look very similar to pointing error signature

Solution: measure real-time pointing inside coronagraph using starlight, for both correction and calibration





Subaru testbed results

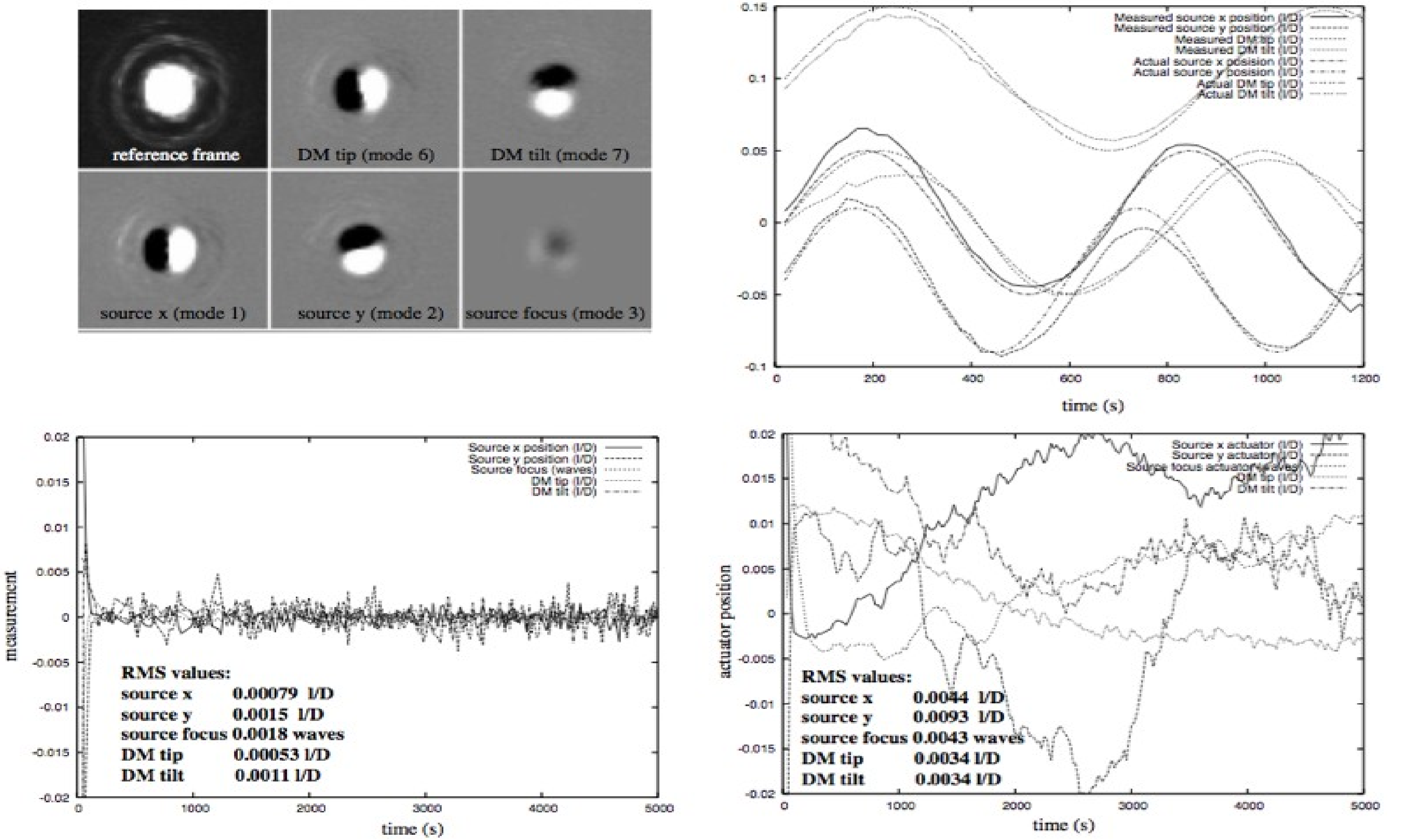
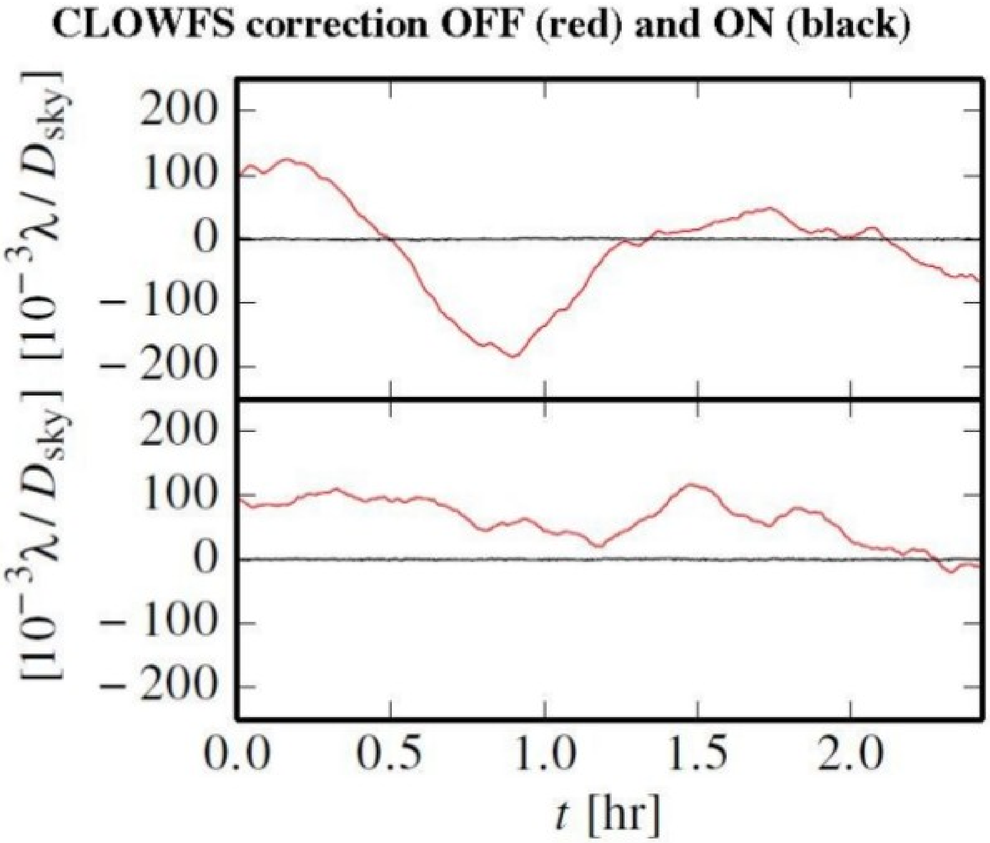
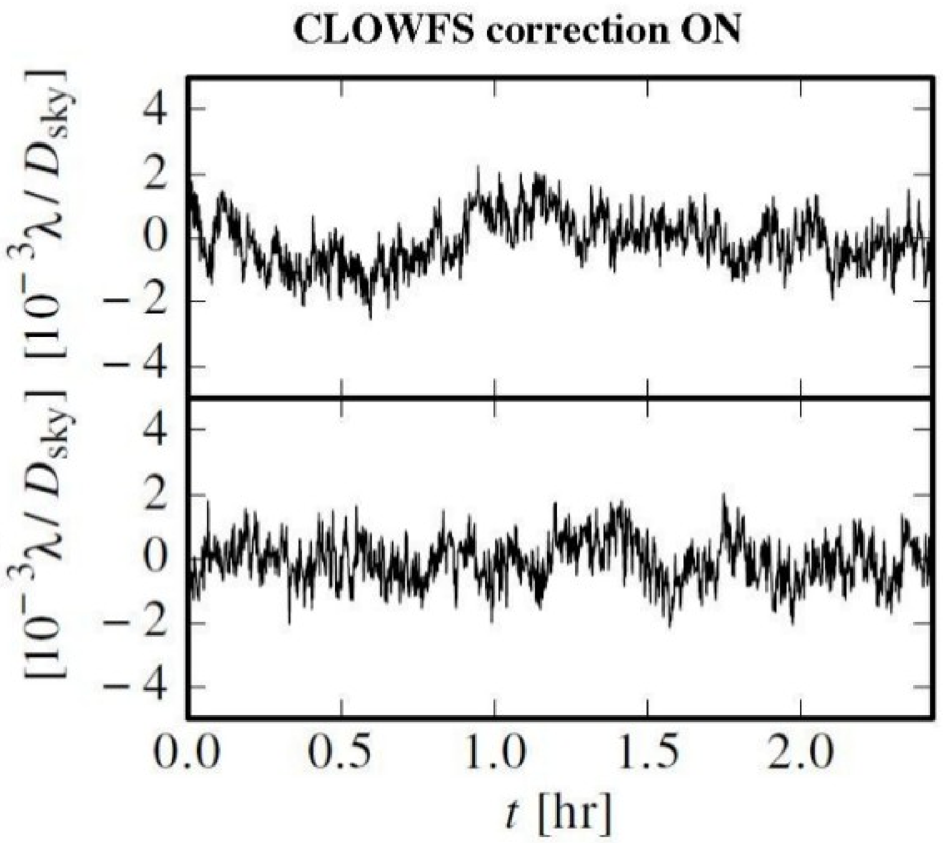


Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. The measured amplitudes match very well the sine-wave signals sent to the actuators, and the CLOWFS is able to accurately measure all 4 modes shown here with little cross-talk. Since this measurement was performed in open loop, the measurement also include unknown drifts due to the limited stability of the testbed. Bottom left: Closed loop measurement of the residual error for the 5 modes controlled. The achieved pointing stability is about 10^{-3} λ/D for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.

HCIT LOWFS results

See Brian Kern's talk





Temporal bandwidth estimate

Assumptions:

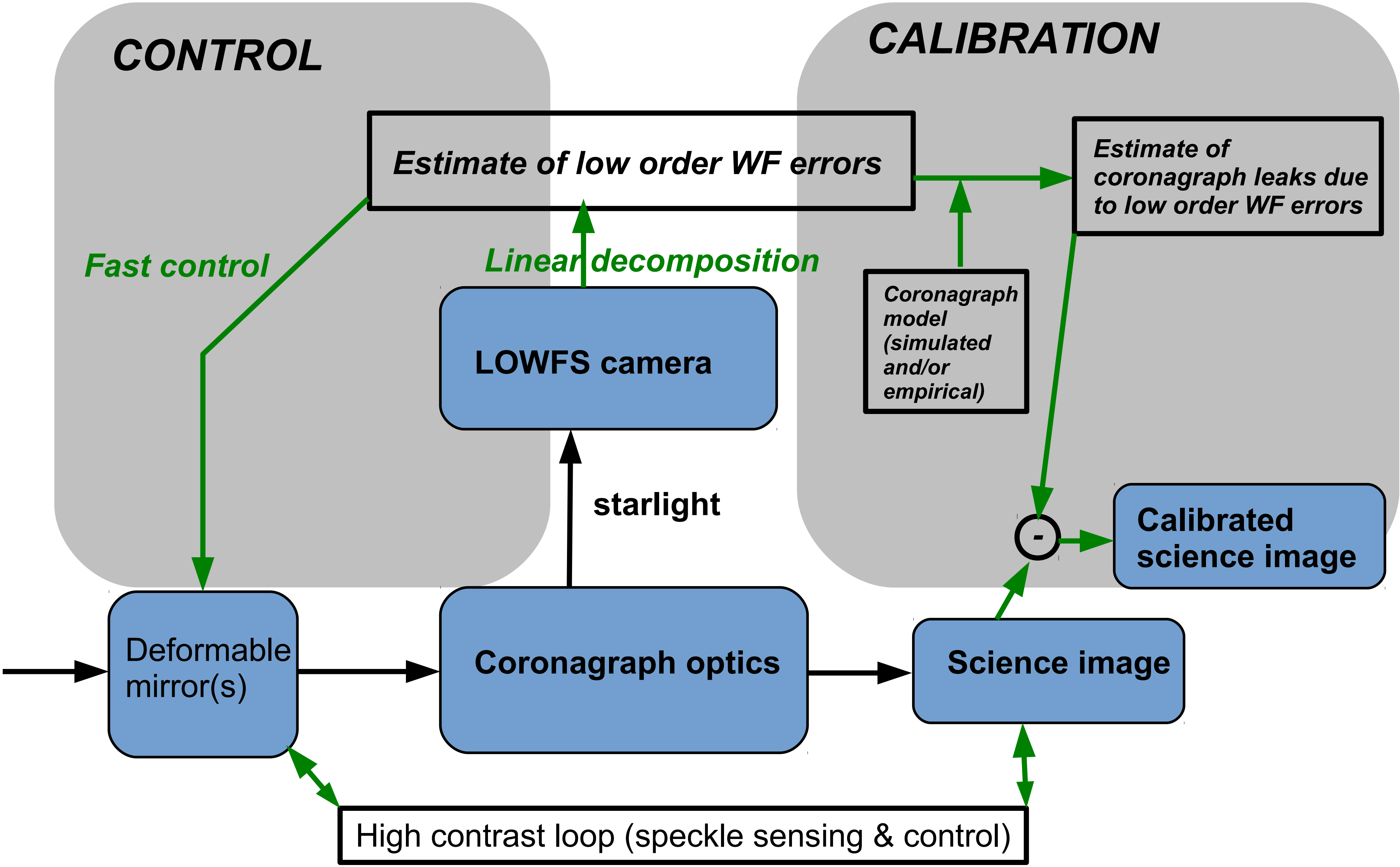
- Simple integrator controller, with a gain between 0 and 1 (no PID, no Kalman filter, no on-board processing of PSDs to optimize loop controller)
- CCD camera, 10 MHz pixel readout rate max, 5e- RON
- LOWFS is 5x5 pix, readout frame area is 30x30 pix → 10 kHz max frame rate
- LOWFS is taking diffracted starlight from Lyot stop (as done on SCExAO) to eliminate non-common path errors, and offer high efficiency
- Star is mV=5, 50% bandpass (LOWFS before filter), 20% system efficiency -> 2e8 ph/s -> 4e6 ph/s/pix

10 kHz frame rate: 400 ph/pix/exposure, which is OK for RON
single measurement precision at 10 kHz (photon noise):
2/sqrt(2e4) rad = 0.014 rad RMS = 1/112 lambda/D = 0.42 mas
→ Loop should run at full speed, gain ~1. We assume gain = 0.5 (1.0 for HCIT)

Photon noise contribution = 0.27 mas RMS
0 dB point in transfer function at ~500 Hz
Rejection at 50 Hz = 10x, Rejection at 5 Hz = 100x

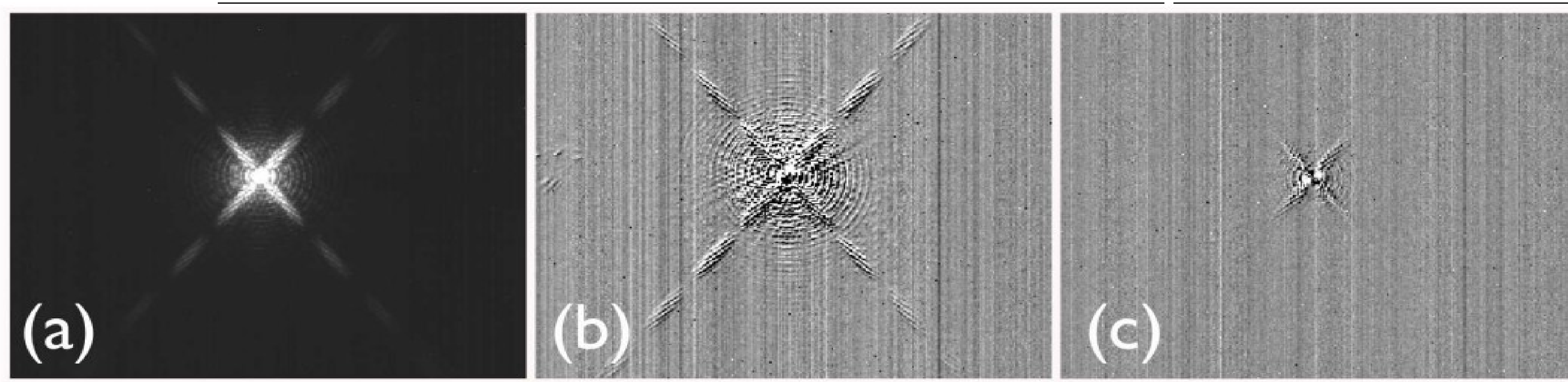
LOWFS: telemetry

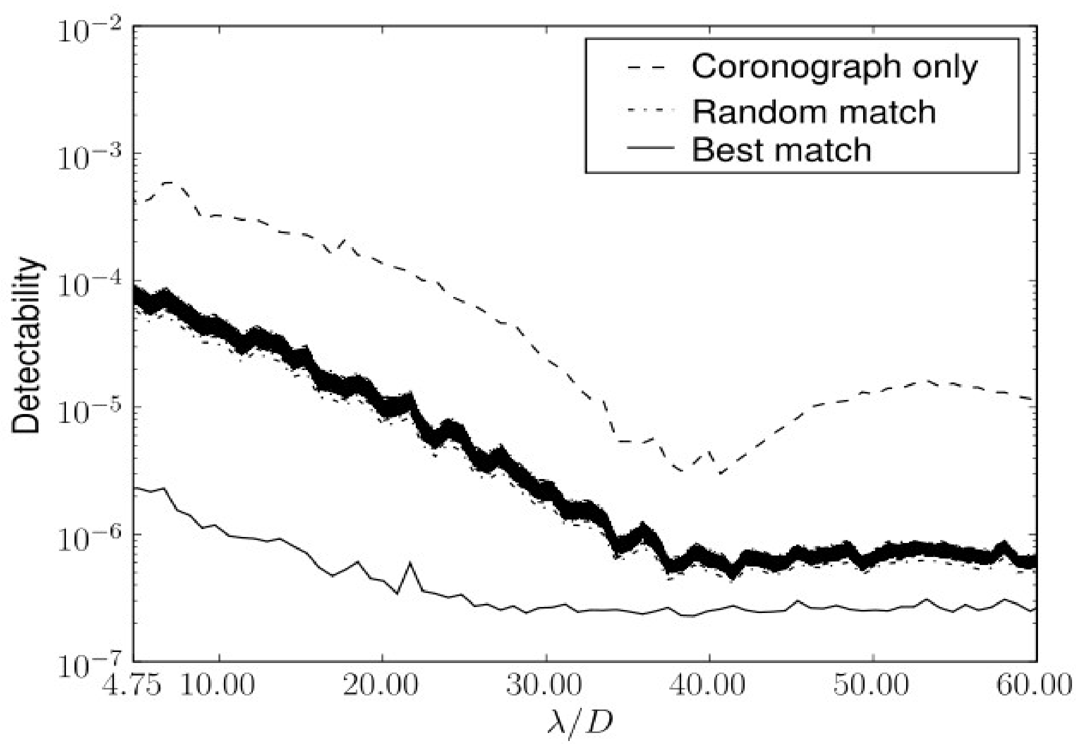
Overall LOWFS control and calibration architecture



Coronagraph leaks calibrated to 1% in SCExAO (Vogt et al. 2011)

Co-added science image | Standard PSF subtraction | MMA





Building the "dictionary"

Problem: Flux in science image << flux in LOWFS
→ associating a single LOWFS image to a single science image is not possible

Solutions:

(1) Pseudo long exposure
Use noise-free (EMCCD) detector in science channel
Group LOWFS frames by similarity
Coadd large number of corresponding science images to build dictionary
Requires large on-board data storage and computation

(2) Linear algebra solving
Record short LOWFS exposures ($L_{i,j}$) and long science camera exposures (S_i)
$S_i = sum_j(S_{i,j})$
Dictionary : $L_{i,j} \leftrightarrow S_{i,j}$
After grouping $L_{i,j}$ by similarity, a dictionary L entry is built (L_k)
L_k can be written as linear sum of $L_i = sum_j(L_{i,j})$
→ corresponding dictionary enty S_k is the same linear sum of S_is

Other LOWFS-inspired concepts

Motivations

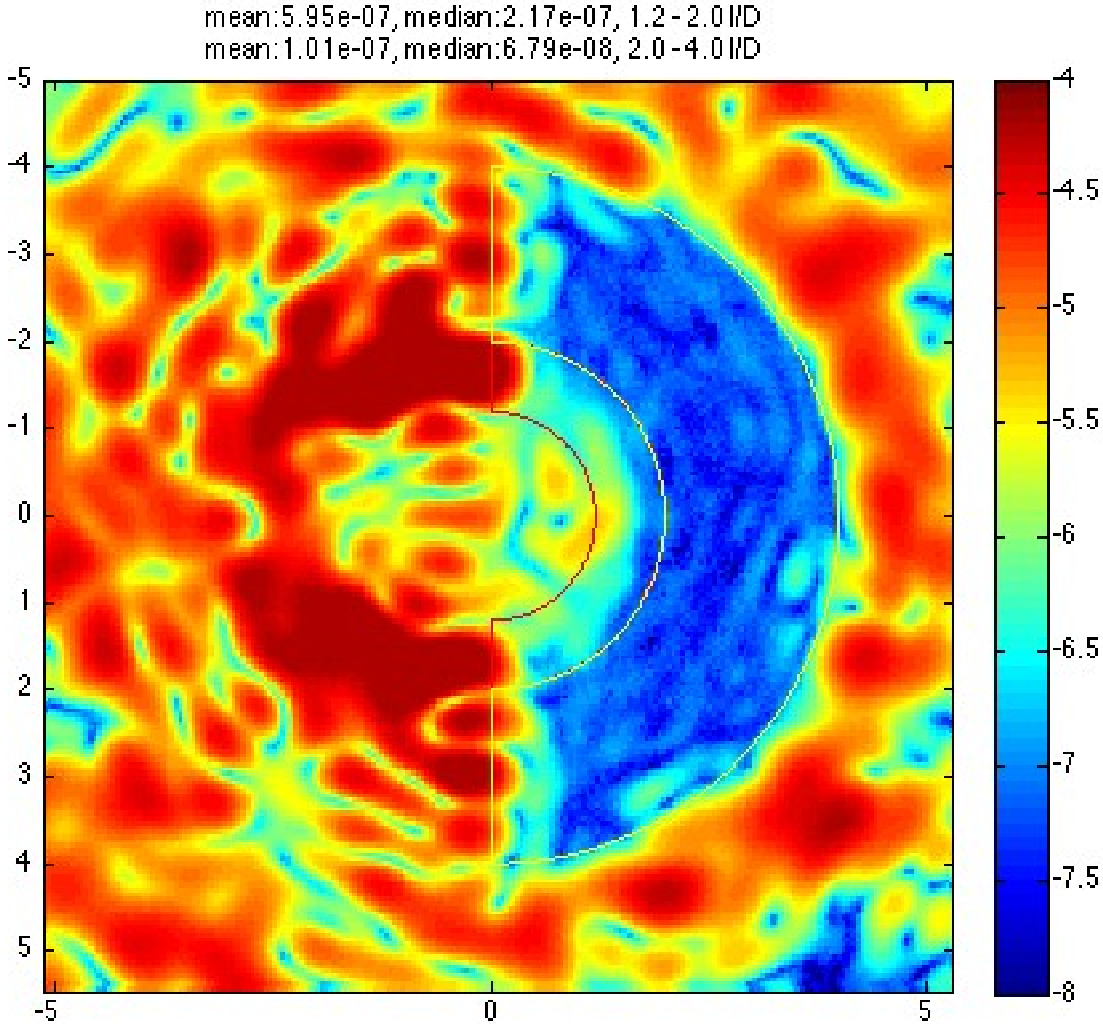
LOWFS is only useful for low-order aberrations
Can unused starlight be used to also control mid-spatial frequencies ?

What does it take to maintain dark hole ?
  DM probes (minimum of 3, plus unprobed image): >4 images
  → process is slow and inversion is prone to DM calibration errors

If dark hole could be maintained without probes, temporal bandwidth could be increased

Two concepts:
  (1) use light outside dark hole
  (2) use out-of band light
Benefits:
  DM commands derived from single image
  Strong coherent coupling: easy to overcome readout noise, zodi

Using light outside dark hole & outside spectral band



Light outside dark hole is ~5 orders of magnitude brighter than inside dark hole

→ intensity is a linear function of wavefront errors on essentially all pixels outside dark hole (as opposed to quadratic)

Std linear algebra AO control (response, control matrix, SVD, modal control)

MAIN STEPS:

Response matrix acquisition by poking DM(s) actuators
→ pseudo-inverse → control matrix

Intensity is also a linear function of wavefront errors on essentially all pixels outside spectral band

Using light outside dark hole: segmented apertures

Outer diffraction structures encode cophasing errors that have impact on dark home