Advanced Speckle Sensing for Internal Coronagraphs

Technology Demonstration for Exoplanet Missions (TDEM)

Charley Noecker (BATC)

Stuart Shaklan, Brian Kern, Amir Give'on (JPL/Caltech)

Ruslan Belikov (NASA-Ames)

Jeremy Kasdin (Princeton)

Goal of the study

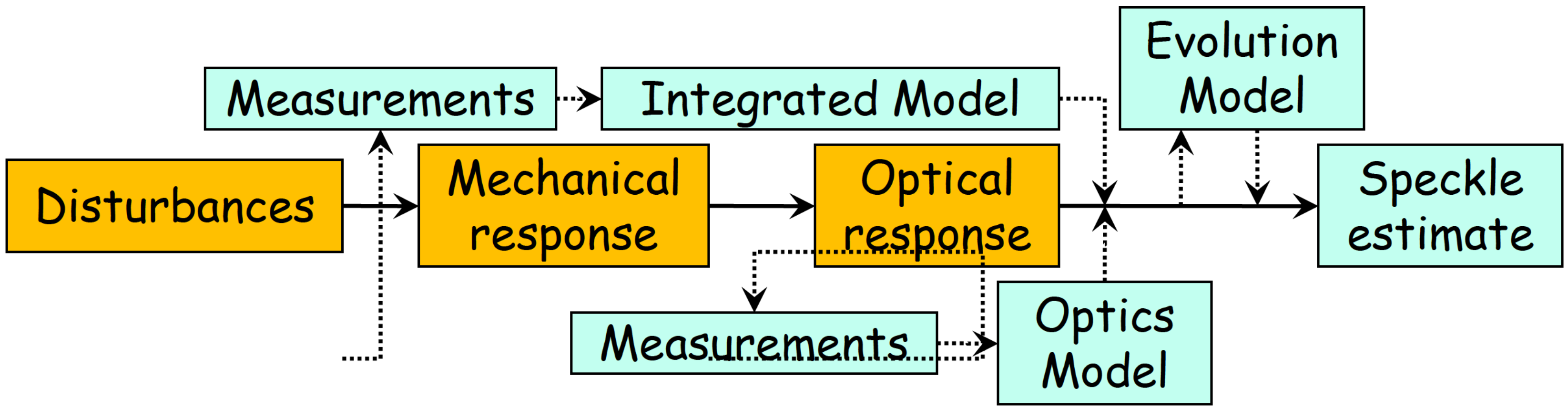
- Develop coherent methods for measuring starlight speckles in an internal coronagraph
  - Calibration and subtraction
  - Correction with the DM
- Concentrate on accurate <u>measurement</u> of speckles, not on <u>control</u>
  - Focused on quick calibrations between science integrations

- Coherent methods offer the possibility of quick measurement
  - Can be limited mainly by shot noise in speckle brightness, almost independent of zodi and other backgrounds
  - 1 ksec instead of 30-150 ksec
- Quick measurement enables relaxed optical stability requirements
  - Allows quick alternation between calibration and science observations
  - Allows shorter time scales for "passive" wavefront stability

How speckles threaten the science

- Coronagraphs suppress the stellar light by a factor 10^{10} or more
- Residual speckles are caused by optical imperfections that allow starlight to leak into the science image
- Speckles are a sensitive position-and-time-varying contribution; other light sources (exozodi, background galaxies) are stable
- Uncertainty in the contribution of starlight in the image plane sets a floor for the faintest planets that can be identified

Speckle image, maybe animated with "boiling" speckles



Why Coherent Speckle Detection (CSD) is helpful

- Speckles are roughly as faint as planets
  - Small static speckle fields help limit the impact of dynamic speckle fields
- Speckle brightness is buried in local zodi and exozodi backgrounds
  - Long integration times for calibration
  - Long procedure times for speckle identification and control
  - Stringent stability requirements across the time between calibrations

$$I_{LZ} + I_{EZ} + I_S \qquad (I_{LZ} + I_{EZ}) >> I_S \qquad I_R > (I_{LZ} + I_{EZ})$$

- Coherent techniques produce large interference cross-terms, which rise above the background
  - Relative phase information is also available
- Shot-noise limit for integration time drops with increasing E_R:

$$\frac{SNR^2}{I_S}\left(1 + \frac{I_{LZ} + I_{EZ}}{I_R}\right)$$

Shot noise limit with zero background → I_S

Ratio of zodi backgrounds to reference beam intensity → I_R

$$\frac{\tau_R}{\tau_0} = \frac{1}{4}\left(\frac{I_S}{I_{LZ} + I_{EZ}} + \frac{I_S}{I_R}\right)$$

Ratio of integration times with and without a reference beam

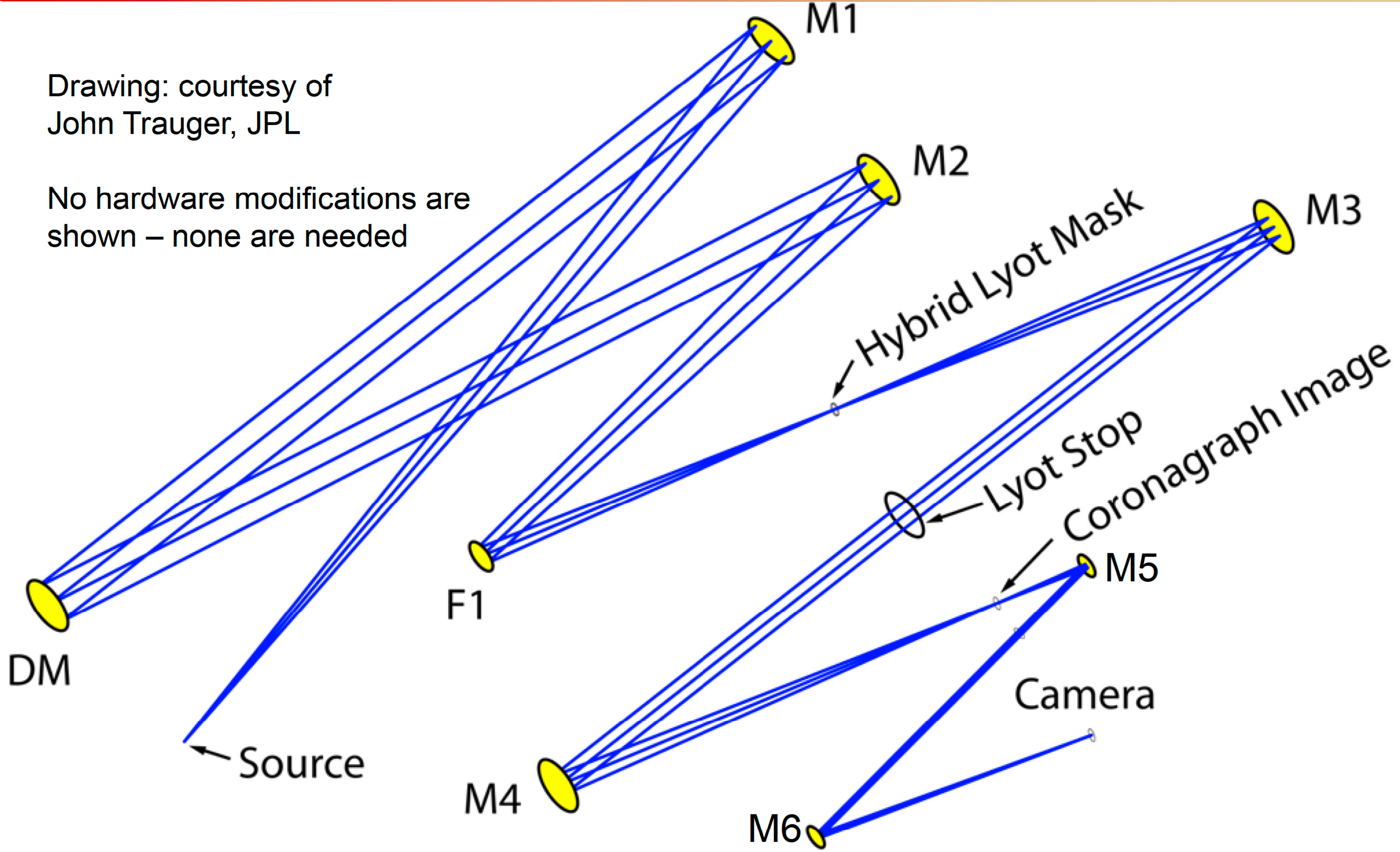
Two CSD techniques considered

- Phase-diverse CSD
  Use the deformable mirror to create the reference field E_R
  - Closely related to electric field conjugation (EFC) technique for WFSC
  - Adds no hardware to the testbed
- Mach-Zehnder CSD
  Use a separate beam path to capture and craft the reference field
  - Pickoff at coronagraph field occulter
    - Capture starlight from the PSF core that is blocked by the CFO
    - Collimate, mask, attenuate, and focus a beam made from this light
    - Transport it to a beam combiner just before the science CCD
  - Pickoff at Lyot plane
    - Capture diffracted starlight from the bright ring at the Lyot plane
    - Collimate the spherical wave → off-axis plane wave at science CCD
    - Requires only pinholes in Lyot mask, with selector "shutters"
    - Equivalent to Baudoz's Self-Coherent Camera (SCC)

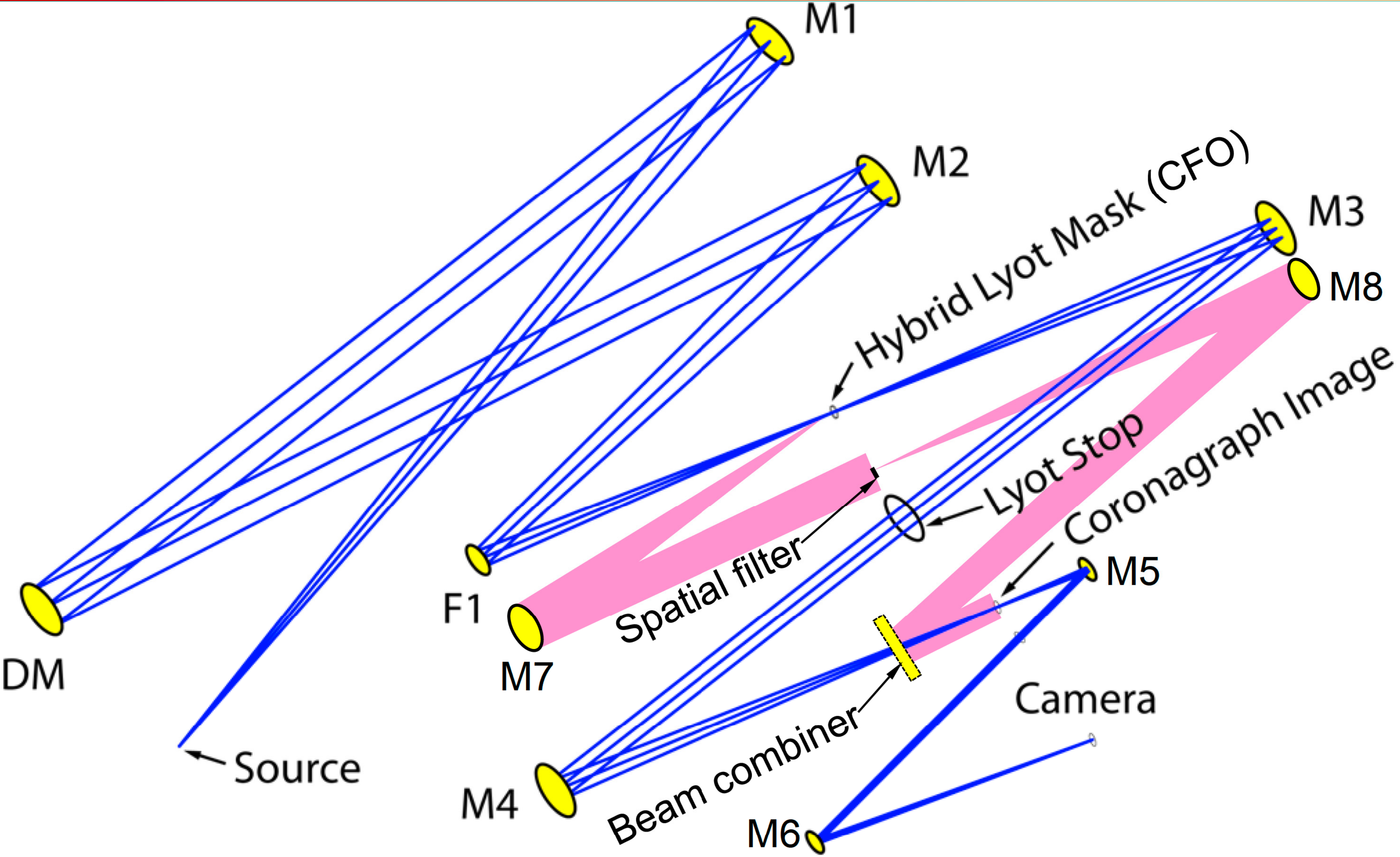
Phase-diverse CSD
Reference beam by DM actuation

Drawing: courtesy of
John Trauger, JPL

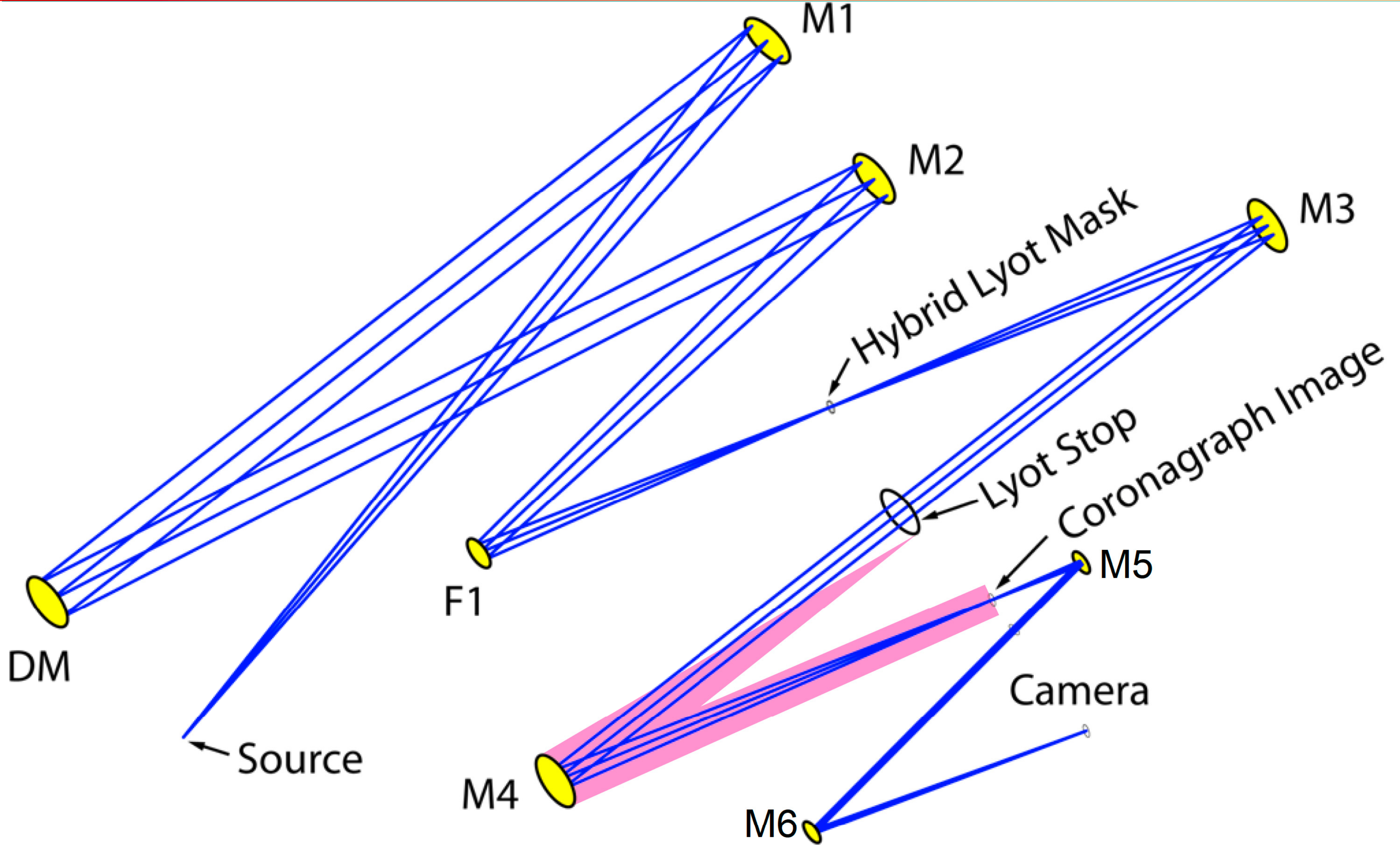
No hardware modifications are
shown – none are needed



Mach-Zehnder CSD
Reference beam from pickoff at CFO



Mach-Zehnder CSD
Reference beam from pinhole at Lyot Stop



Methods chosen

- Phase-diverse CSD
  - Advance the use of EFC principles for speckle field measurement and speckle intensity estimation
  - Requires advances in reference field calibration → DM calibration

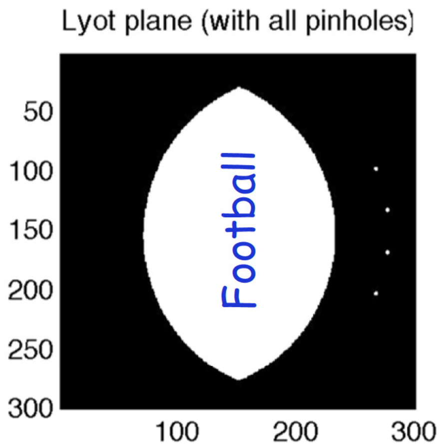
- Mach-Zehnder CSD with pinholes at Lyot Stop
  - Simple implementation in HCIT
  - Reproducibility & stability of reference beams in amplitude and phase
  - Cross-calibration procedure

This time we did not select MZ-CSD with pickoff at CFO, due to our schedule challenges and its added complexity.

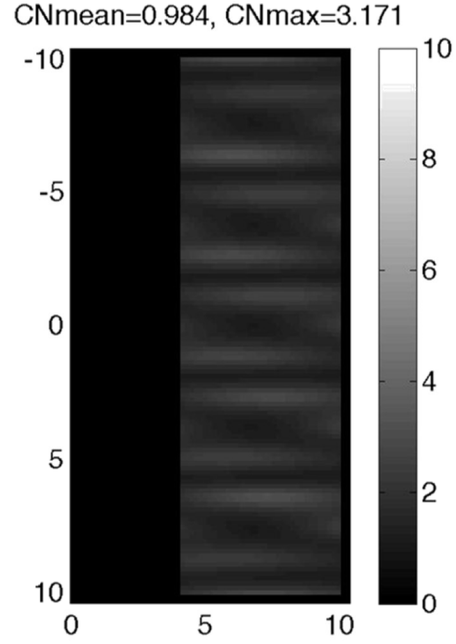
But it has some advantages that warrant follow-up work on this technique

MZ-CSD Pinhole layouts

- Pinholes arranged around the rim of the reimaged pupil (bright rings)
- Planet re-imaging optic then collimates the pinhole light
  ➔ each pinhole produces a plane wave at the science CCD
- Analysis of speckle images taken with each of 4 reference beams determines the speckle amplitude & phase in each pixel
  - Successfully demonstrated with synthetic data
- Some reference beams can yield near-degenerate information at some pixels, due to low-leverage arrangement of their phases
  - High condition number for a solution in that pixel
  - Manageable by selection of pinhole positions
- A workable layout of pinholes has been chosen



Condition Number vs. position in image (λ/D)



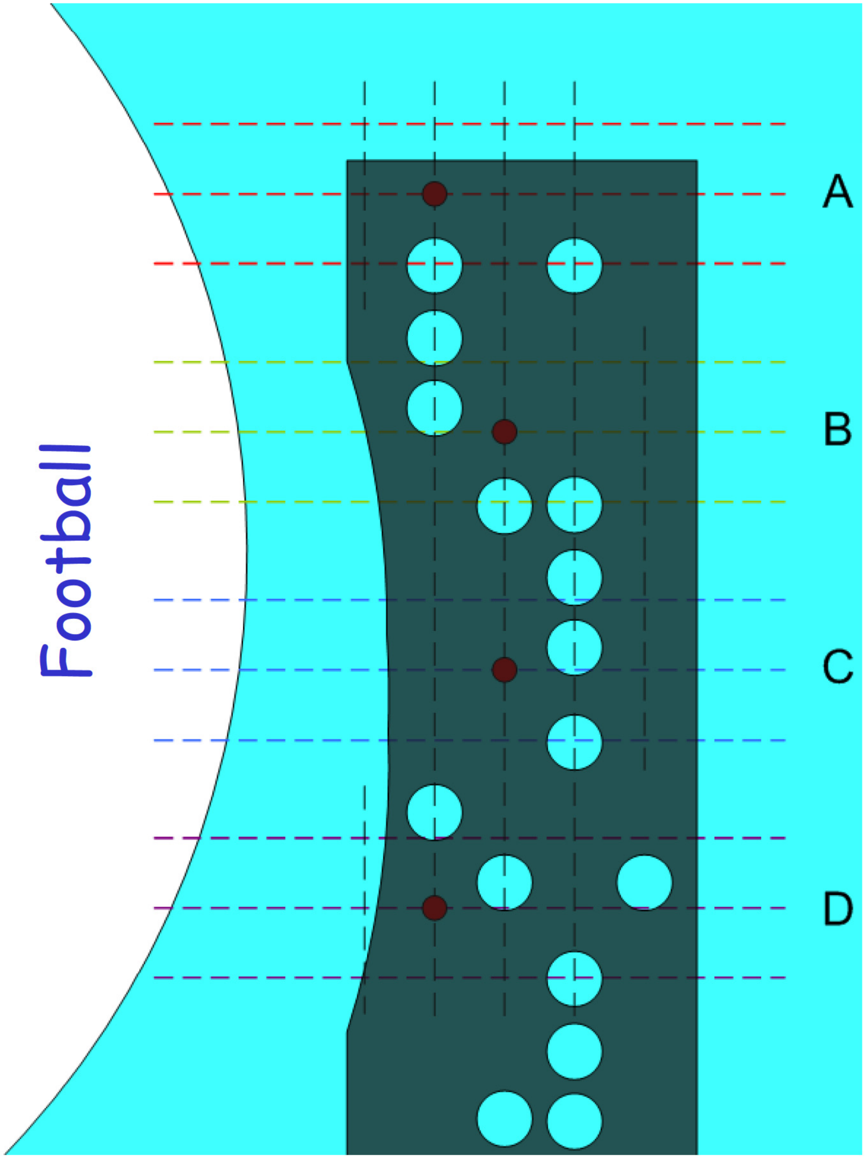
Shutter system to open/close each pinhole

We want to be able to

- "Turn on" each pinhole in turn, or non
- Also combine them in pairs
- 3x4 grid handles 11 states

State	A	B	C	D
1	0	0	1	0
2	1	0	0	0
3	1	1	0	0
4	0	0	0	0
5	1	0	1	0
6	0	1	0	0
7	0	1	1	0
8	0	1	0	1
9	0	0	0	1
10	1	0	0	1
11	0	0	1	1

- Separate shutter blocks the entire "football," where the planet light anc speckles pass through the Lyot stop



Current status

- Hardware installed and tested
- Lyot table just put under vacuum
- Testing procedures defined
- Analysis algorithms developed

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