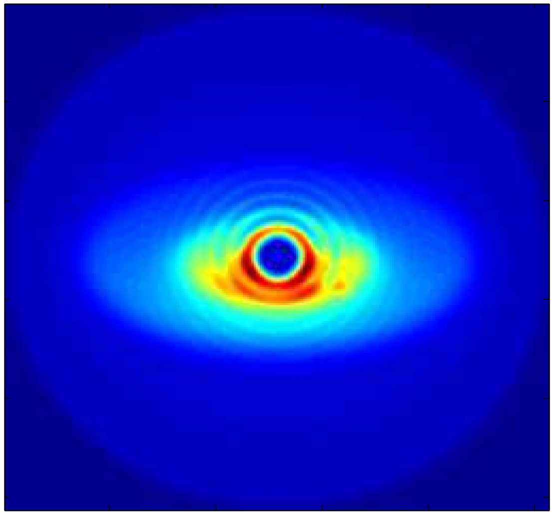
Wavefront Control Systems for Exoplanet Direct Imaging



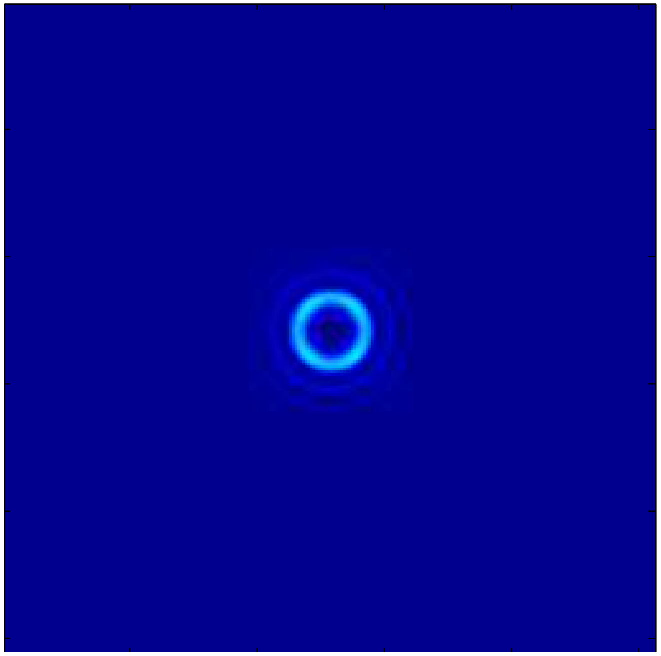
K. Cahoy

MIT

Overview

1) What do Wavefront Control Systems do?
2) Why are they needed to image exoplanets?
3) Which algorithms are used?
4) What are (some) configuration trades?
5) How well will they work in space? Where are they being developed?
6) When will these systems be ready for a dedicated mission?

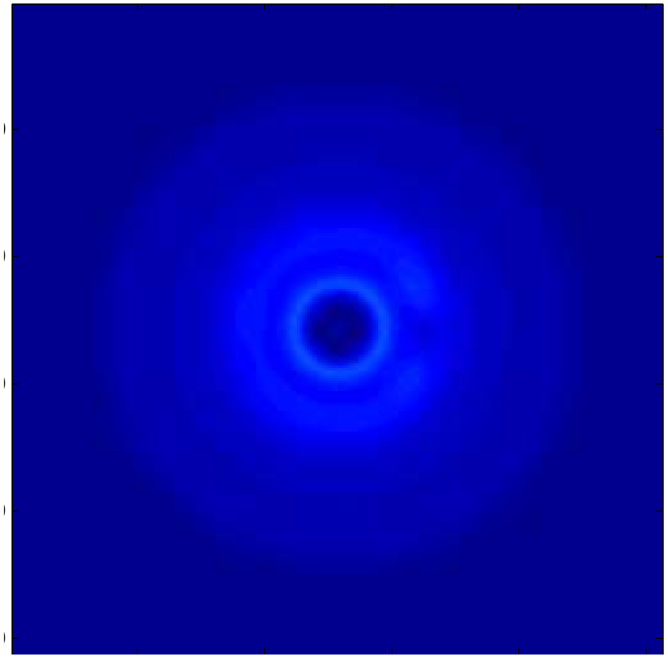
Blocked Star



Cahoy & Stark, 2011

- Sun at 10 pc
- 4 m space telescope, PIAA coronagraph
- 365 nm, 20% bandwidth (73 nm)

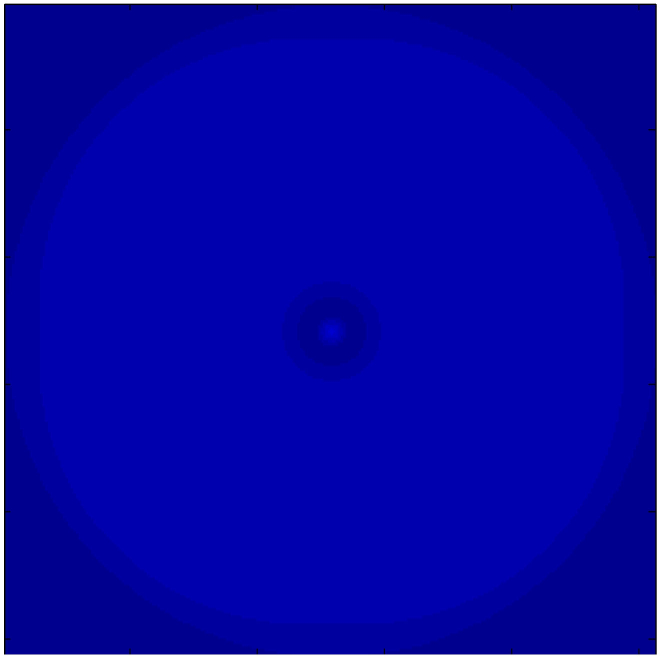
Exozodiacal Light



Cahoy & Stark, 2011

- 1 zodi, C. Stark
- Structure after forming 1 M_{Earth} planet at 1 AU
- Disk parameters: albedo = 0.5, g = 0.5, inclination = 0°

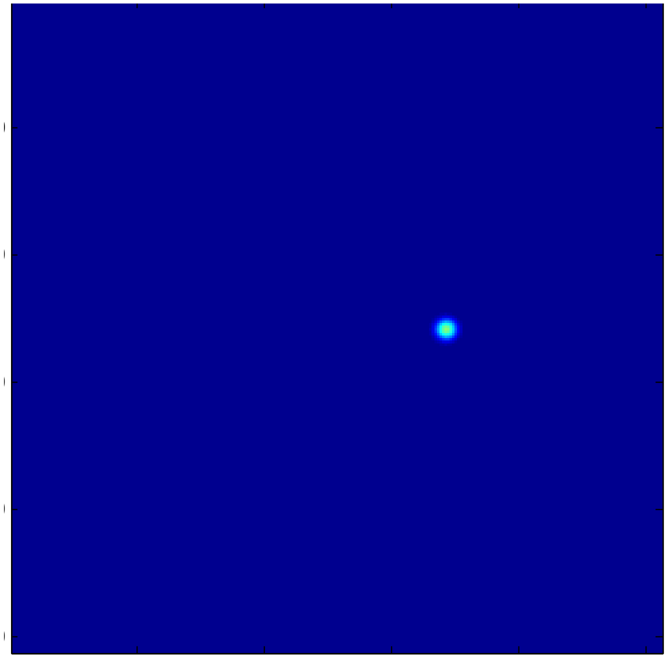
Local Zodi



Cahoy & Stark, 2011

- 1 zodi
- Brightness is function of position of target system on sky

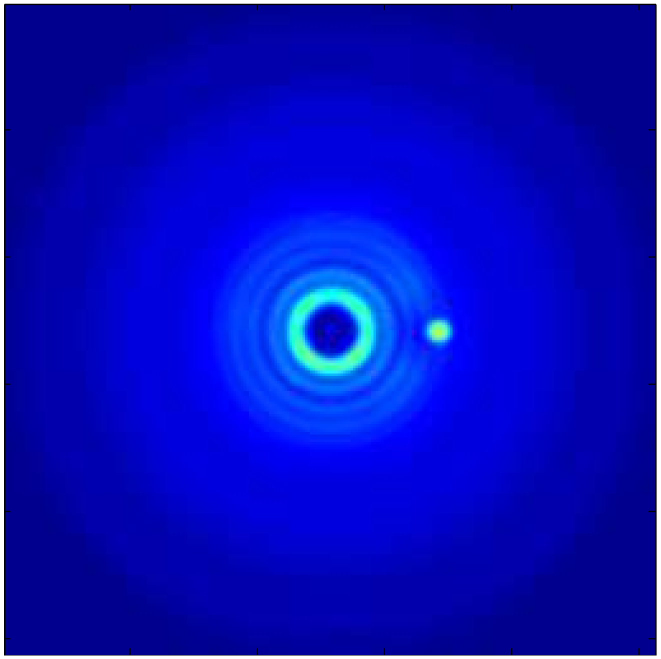
Planet



Cahoy & Stark, 2011

- Earth at 1 AU

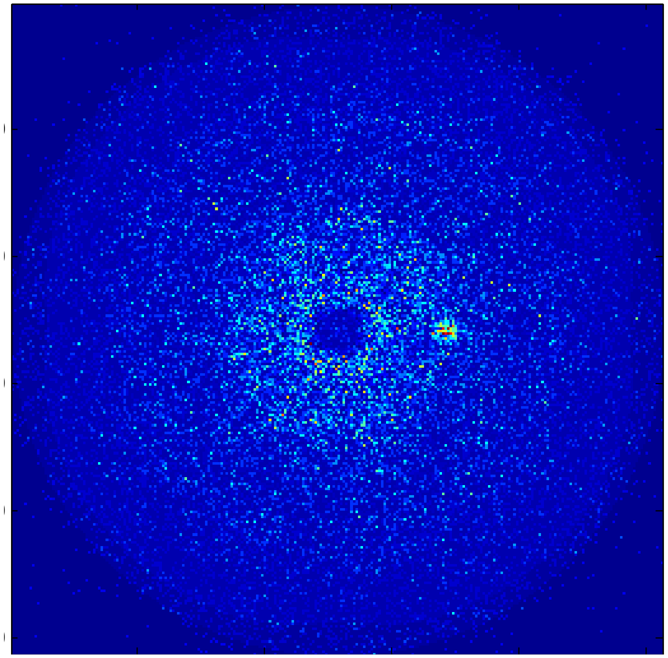
Sum



Cahoy & Stark, 2011

- 10,000 s integration time
- 45% throughput
- Blocked star + exozodi + zodi + planet

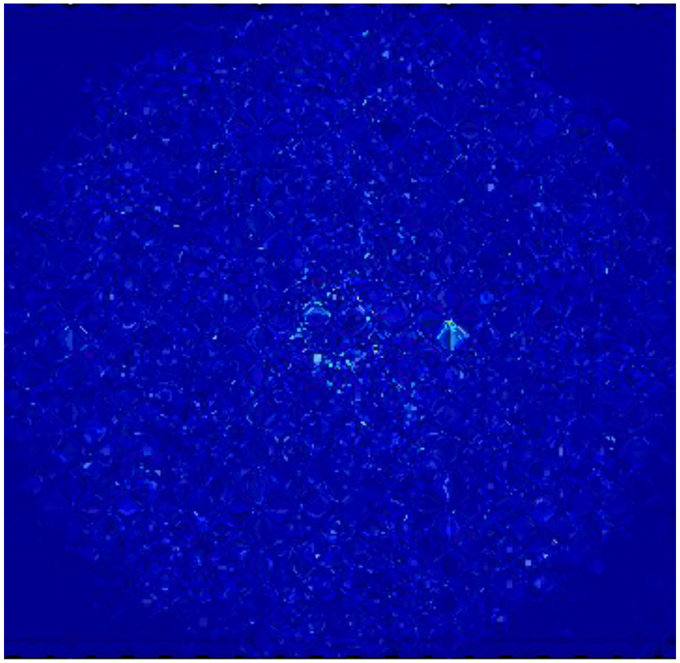
Noise



Cahoy & Stark, 2011

- Sum + Poisson noise

Speckles



Cahoy & Stark, 2011

1) What do wavefront control systems do?

They actively correct *aberrations*

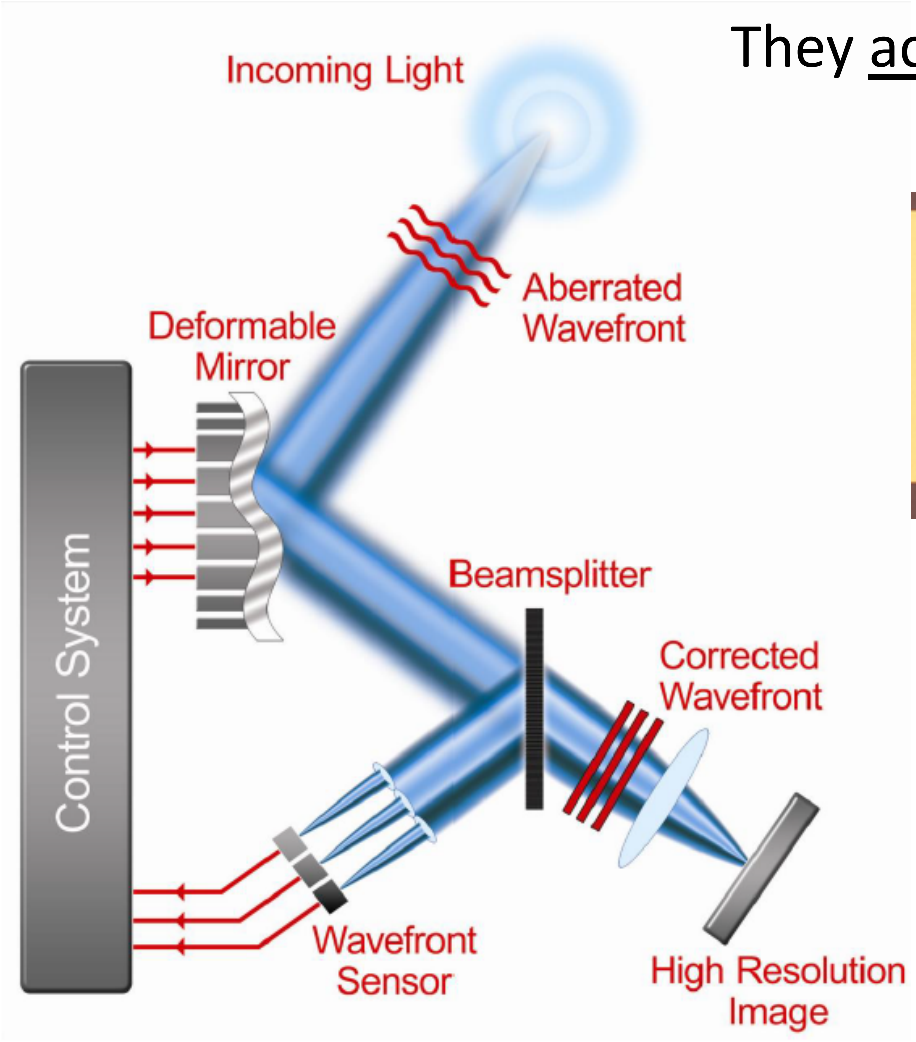
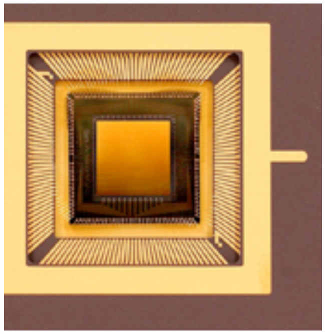
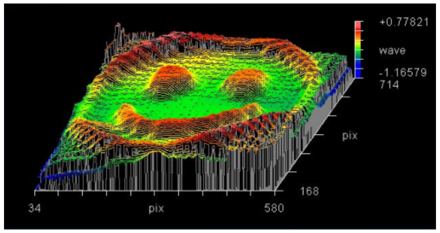


Figure adapted from C. Max, UCSC CfAO



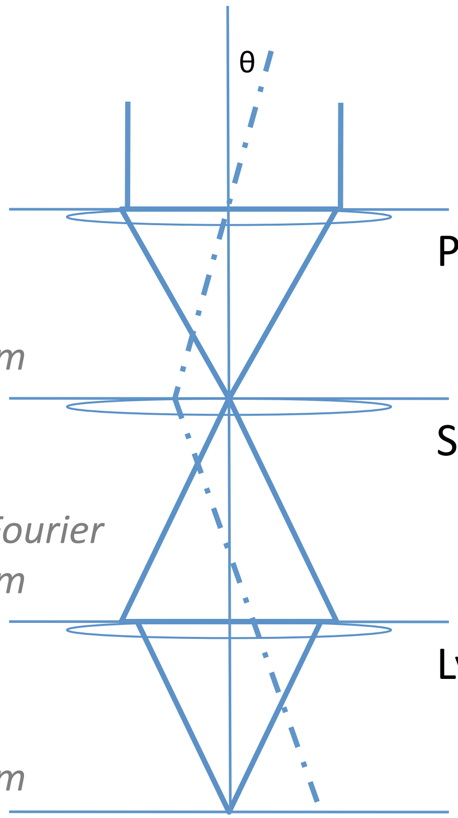
Boston Micromachines MEMS Deformable Mirror (DM)



R. Belikov, 2009

Shack-Hartmann Wavefront sensor (WFS)

Coronagraph diagram



1. Input Pupil

Pupil stop

2. Image Plane

Fourier Transform

Star blocker

3. Reimaged Pupil

Inverse Fourier Transform

Lyot stop

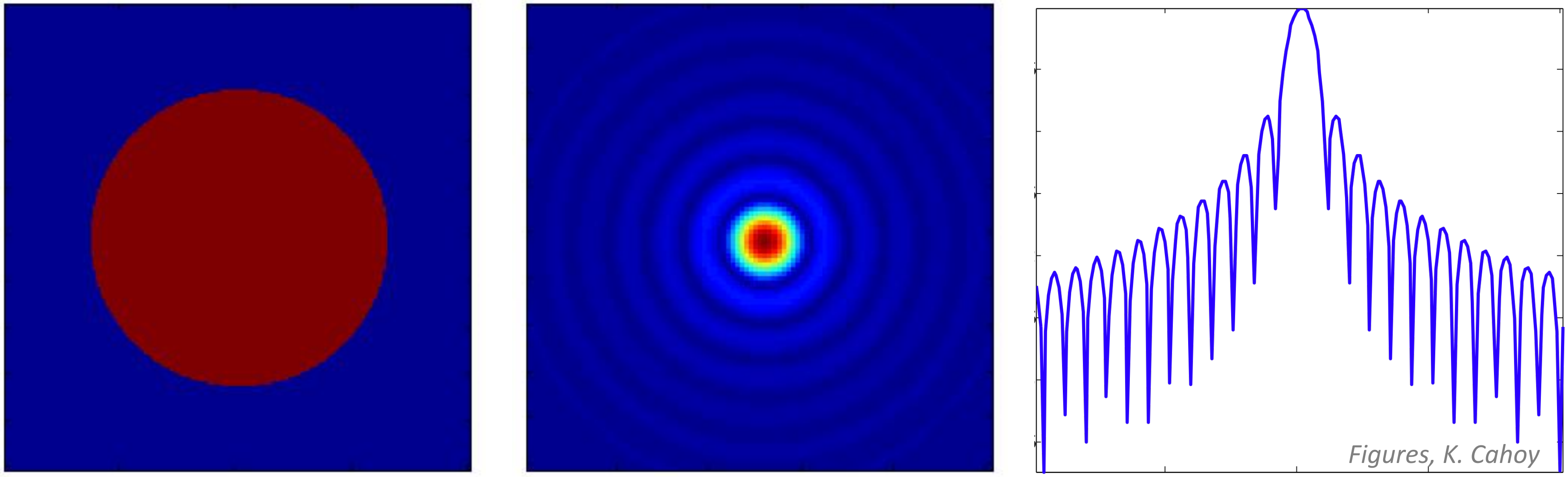
4. Reimaged… Image Plane

Fourier Transform

Detector

Figure adapted from Traub & Oppenheimer 2010

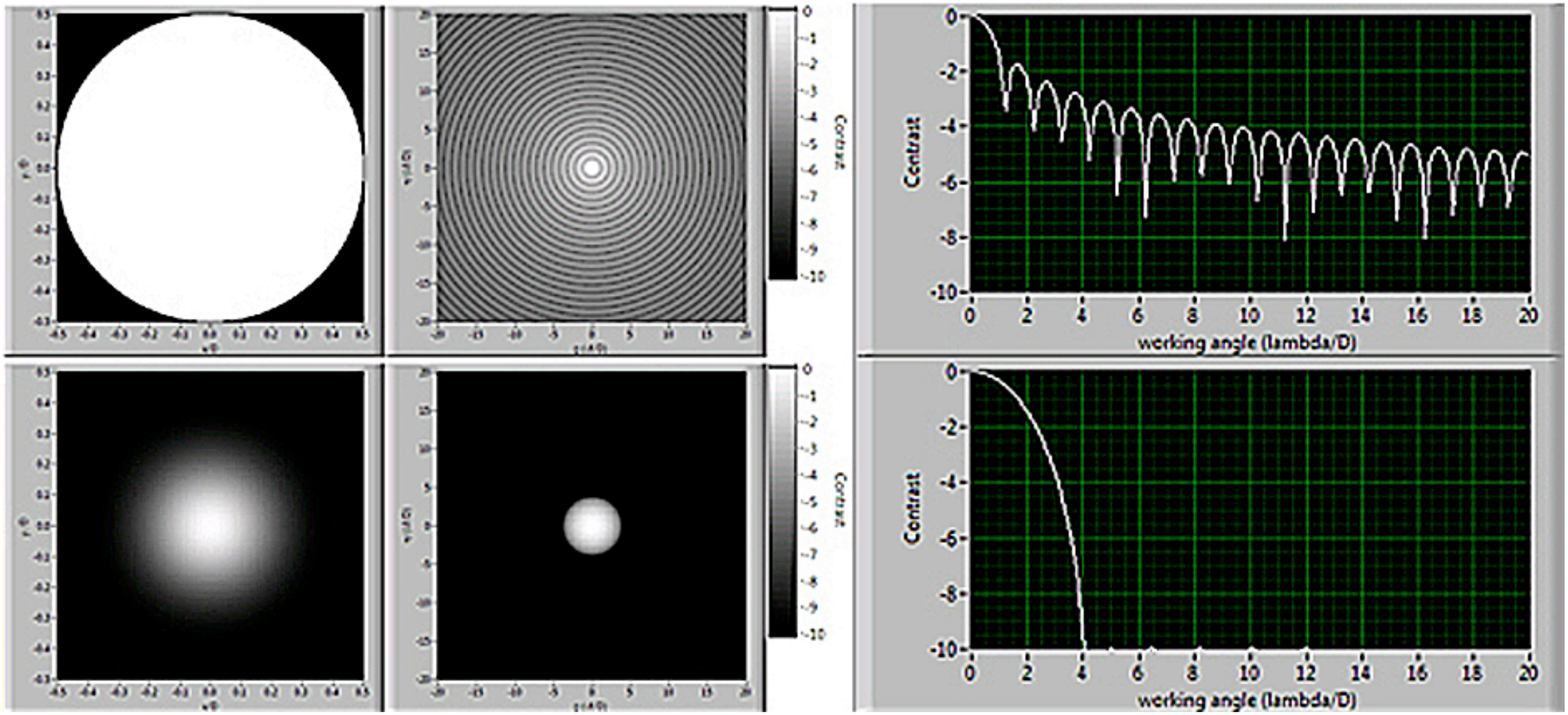
Circular aperture diffraction



Figures, K. Cahoy

- Circular telescope aperture diameter D
  FT → Airy function image
- Airy rings are a problem if trying to achieve high contrast
  - Location depends on telescope D and wavelength λ
- Apodize
  - Phase, amplitude, or both

Pupil remapping reduces aperture diffraction



- The apodized pupil is created by ‘‘concentrating’’ light in the central part of the pupil and ‘‘diluting’’ light in the outer parts of the pupil.
- The phase slope is amplified in the central part while it is decreased toward the edges.

Direct imaging: resolves planet from star

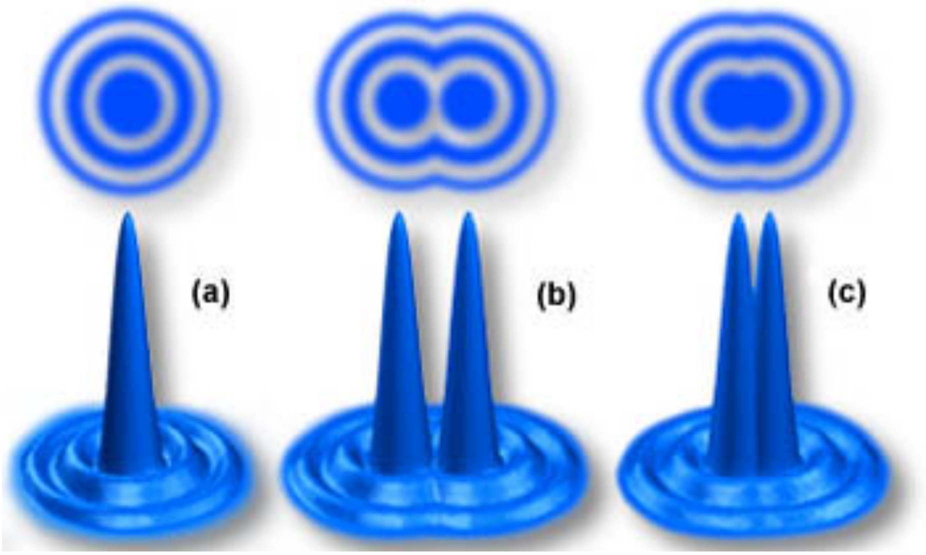
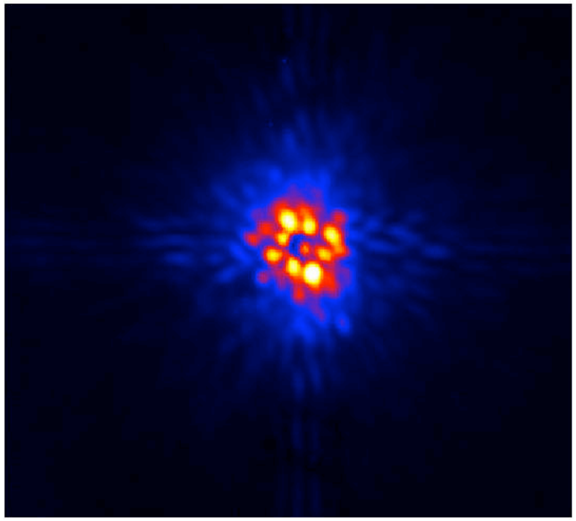


Figure from micro.magnet.fsu.edu

- Rayleigh criterion
  - Can resolve 2 objects separated by 1.22 λ/D
  - Star, planet
- Bigger D → Can resolve closer-together objects
  - But also must launch D!

2. Why are WCS needed to image exoplanets?

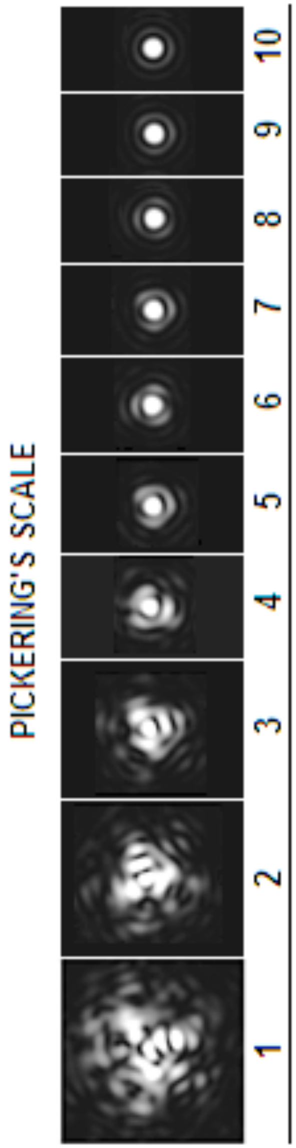
- Wavefront Control Systems *actively* combat “speckles”
  - Speckles could otherwise foil exoplanet direct imaging
  - Need high contrast: 10^{-8} (Jupiters) to 10^{-10} (Earths)
  - There are also other operational + post-processing methods:
    - Angular Differential Imaging (ADI), Simultatenous Spectral Differential Imaging (SSDI), Reference Star Differential Imaging, (RSDI), Locally Optimized Combination of Images (LOCI), Dual-mode polarimetric imaging, Chromatic speckle suppression, etc.
- Speckles can be caused by:
  - Optics + stray light (space + ground)
  - Atmospheric effects (ground)



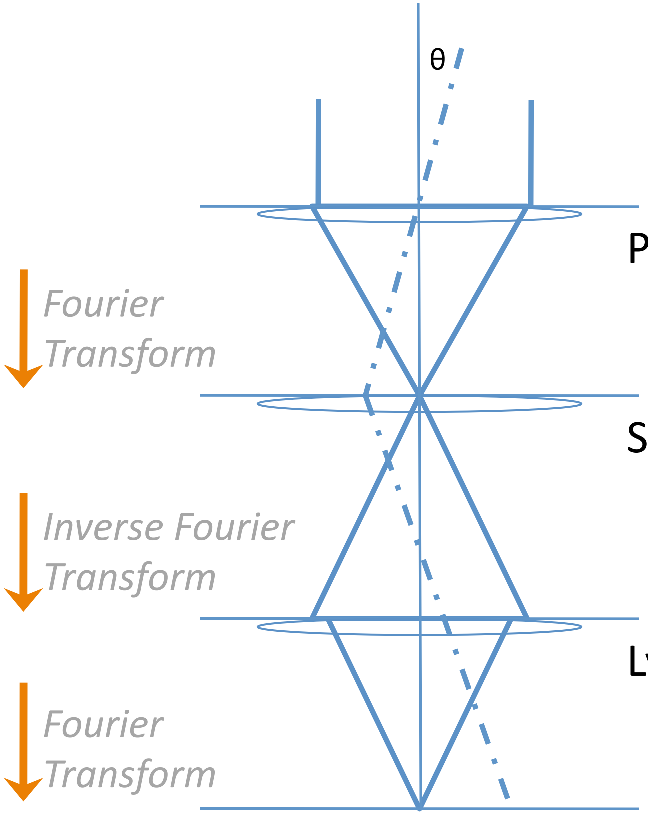
The star 55 Cancri observed with the Lyot Project coronagraph at AEOS in Maui. The symmetric "speckles" arising from atmospheric effects and imperfections in the telescope optics are clear. http://www.lyot.org/results

Speckles

- Caused by changes in amplitude and phase along the photon's path
- Stray light
  - Surfaces of optics
    - Manufacturing tolerances on primary mirrors and optics are not sufficient for the high contrast needed to image Earth-like exoplanets
  - Diffraction from edges of optics
    - Sharp edges (such as the edge of an occulting disk or optical aperture) cause Fresnel diffraction of incoming light around the edge
- Thermal drift
  - For example, thermal expansion affects phase
- Launch misalignments (space only)
- Atmospheric (ground only)
  - r_0 = diameter of spot over which the wavefront has rms variation of 1.015 radians (Kolmogorov)
  - r_0 ~ 10 cm in visible, goes as $\sim\lambda^{6/5}$



Aberration example



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Fourier Transform

3. Reimaged Pupil

Inverse Fourier Transform

4. Reimaged…
Image Plane

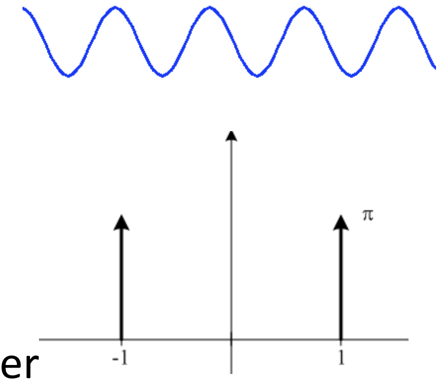
Fourier Transform

Pupil stop

Star blocker

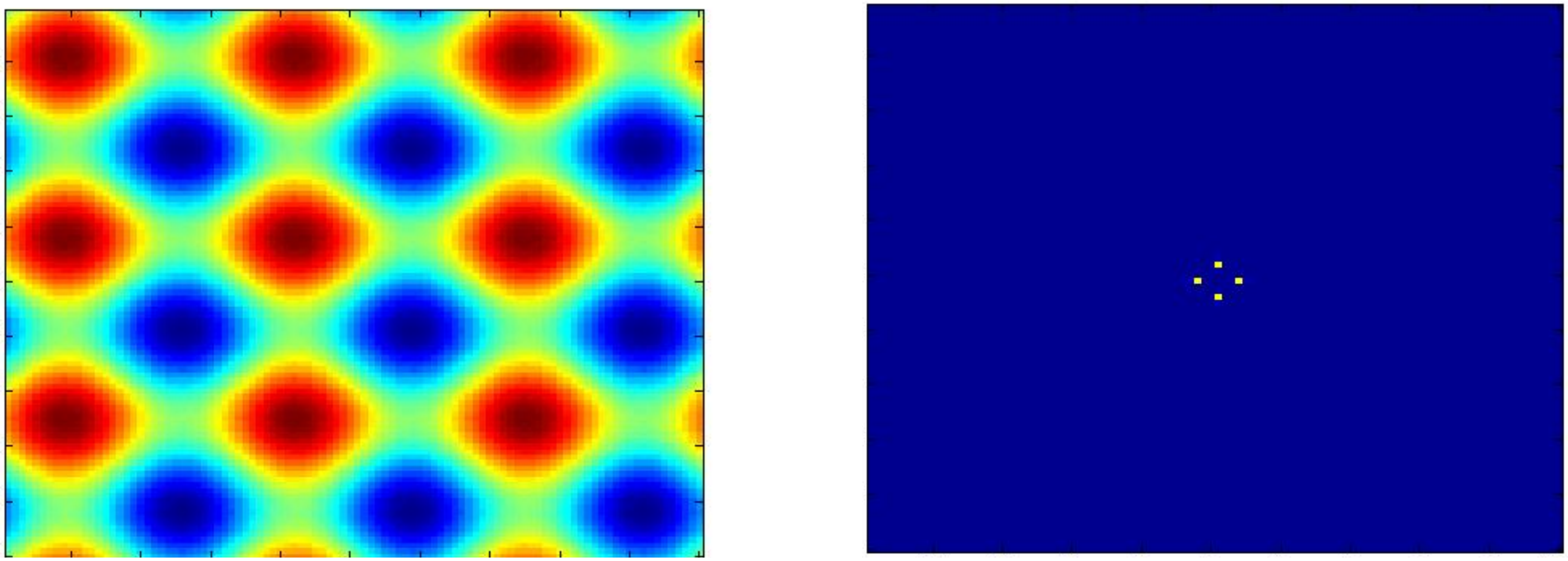
Lyot stop

Detector



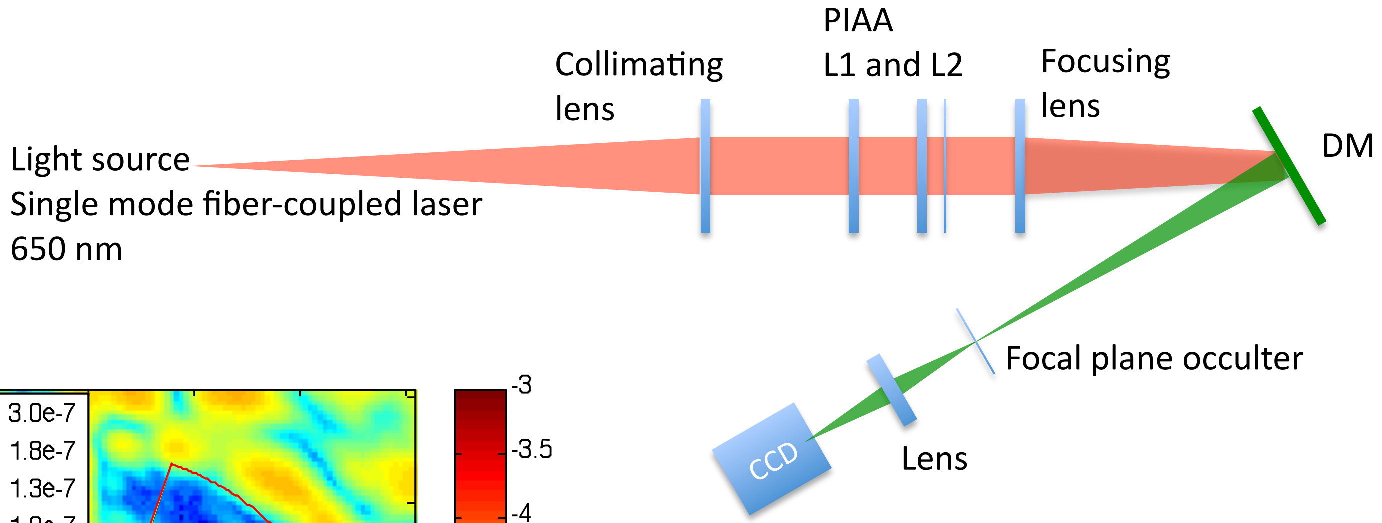
- Cosine ripple → symmetric speckles

2D Speckles



- 2D FFT of X, Y ripple pattern (from a surface, from turbulence)
- Higher frequency, further from center
- Lower frequency, closer to center
- N actuators per side of a DM, null N/2 waves

Single deformable mirror example



Light source
Single mode fiber-coupled laser
650 nm

Collimating
lens

PIAA
L1 and L2

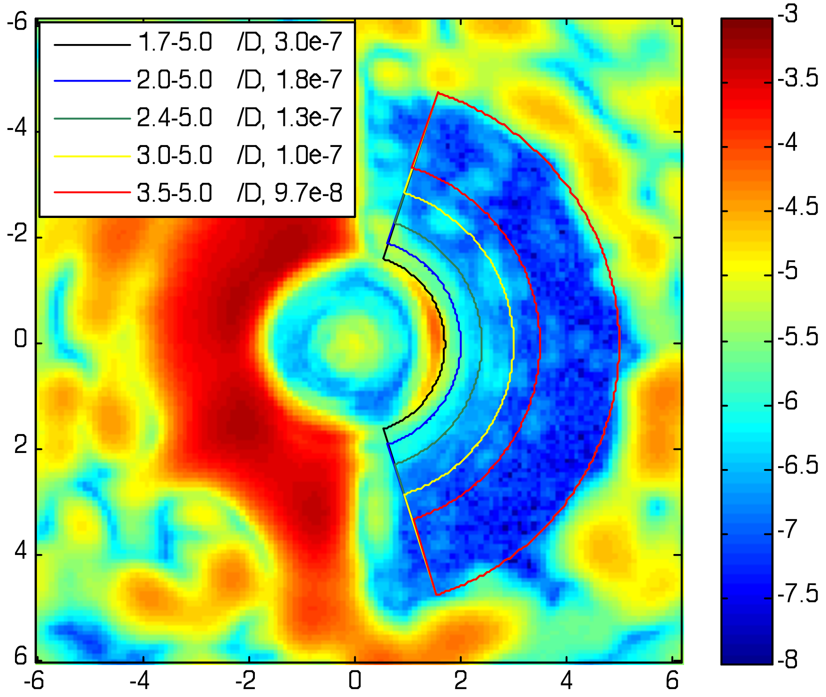
Focusing
lens

DM

Focal plane occulter

Lens

CCD



R. Belikov (NASA Ames), results with polarizer, 6/9/09 (in 2011, 5.4 x 10^{-8})

3. What kinds of algorithms are used?

- Speckle nulling (Trauger et al. 2004)
  - One sided dark hole amplitude + phase: one DM
  - Two sided dark hole amplitude + phase: two DMs
  - Multi-speckle nulling with DM diversity

- Electric field conjugation (Give'on 2006)
- Energy minimization (Borde and Traub 2006)
  - Minimize speckle energy in "dark hole" region

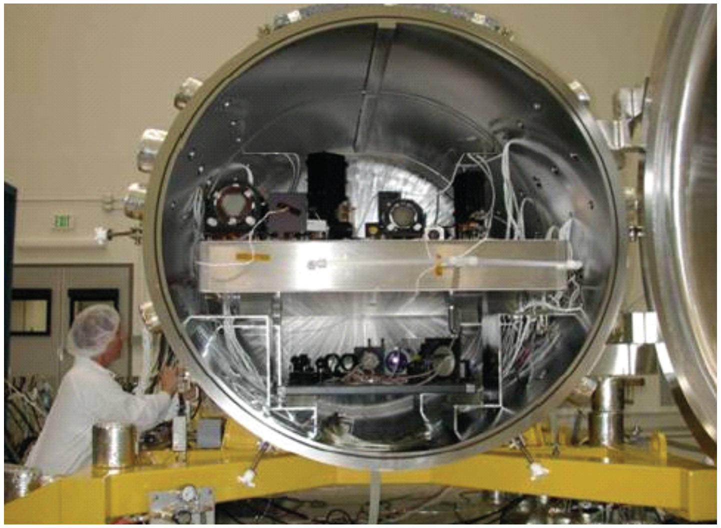
- Gerchberg-Saxton (Gerchberg and Saxton, 1972)

4. What are some configuration trades?

- **Wavefront sensor**
  - Non-Common optical path
    - Beamsplitter + wavefront sensor
  - Common optical path
    - Use rejected starlight as wavefront reference (e.g., DM diffracts starlight to interfere with speckles, Guyon 2005)
  - Chromaticity, aliasing, time delay
- **Deformable mirrors**
  - Number of DMs
  - Number of actuators N per side of DM
    - $\theta(\text{dark hole}) = \pm N\lambda / 2D$
  - Placement
    - E.g. two-sided dark hole, Talbot effect
  - Calibration on-orbit?

5. How well will they work in space?

- We don't know yet, but we're working on it.
- PICTURE (Boston University)
  - Sounding rocket (eps Eri)
  - 32 x 32 BMC MEMS DM
  - Visible nuller (JPL)
- Facilities:
  - NASA JPL HCIT (Trauger)
  - UCSC CfAO (Gavel, Max, others)
  - NASA Ames (Belikov)
  - Princeton (Kasdin)
  - NASA GSFC (Lyon)
  - STScI (Soummer)
  - MIT (Cahoy)

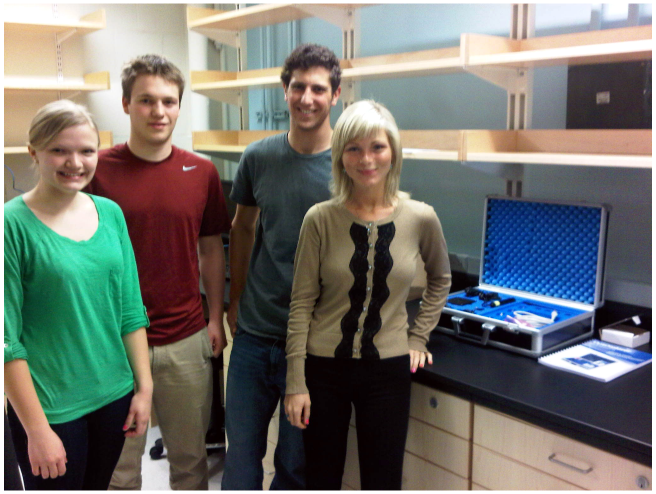


NASA JPL, HCIT facility

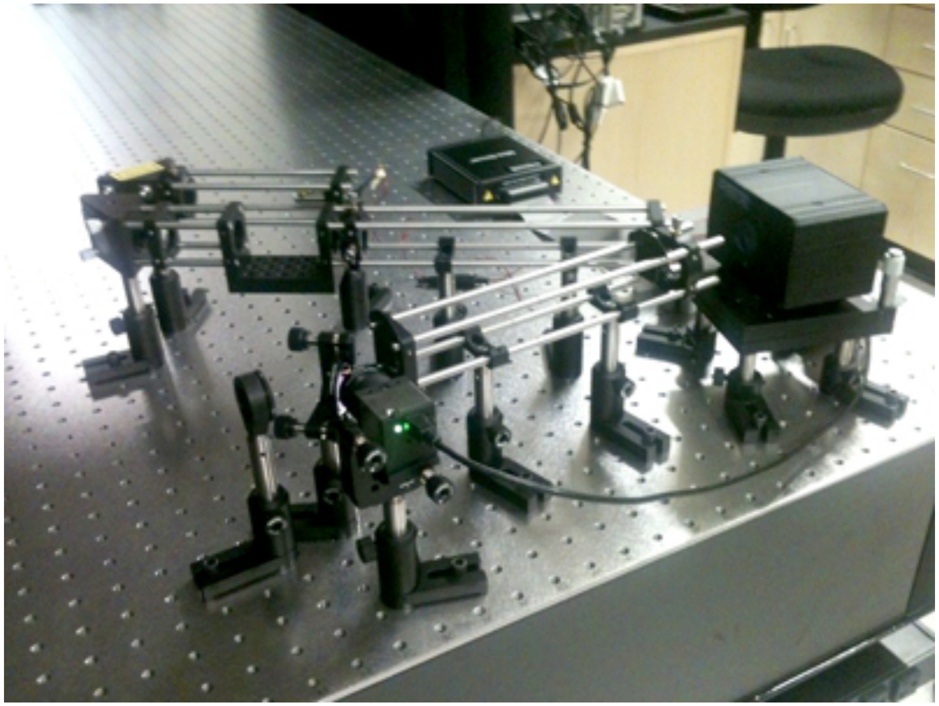
Tim Cook and Andrew Mandigo with PICTURE

MIT Wavefront Control Lab

- Applications:
  - Exoplanet direct imaging
    - Technology development
    - Optimize DM control and placement
    - Prepare avionics, drivers, ADCS for spaceflight
  - Laser communication, surveillance, astronomical imaging
  - web.mit.edu/cahoylab



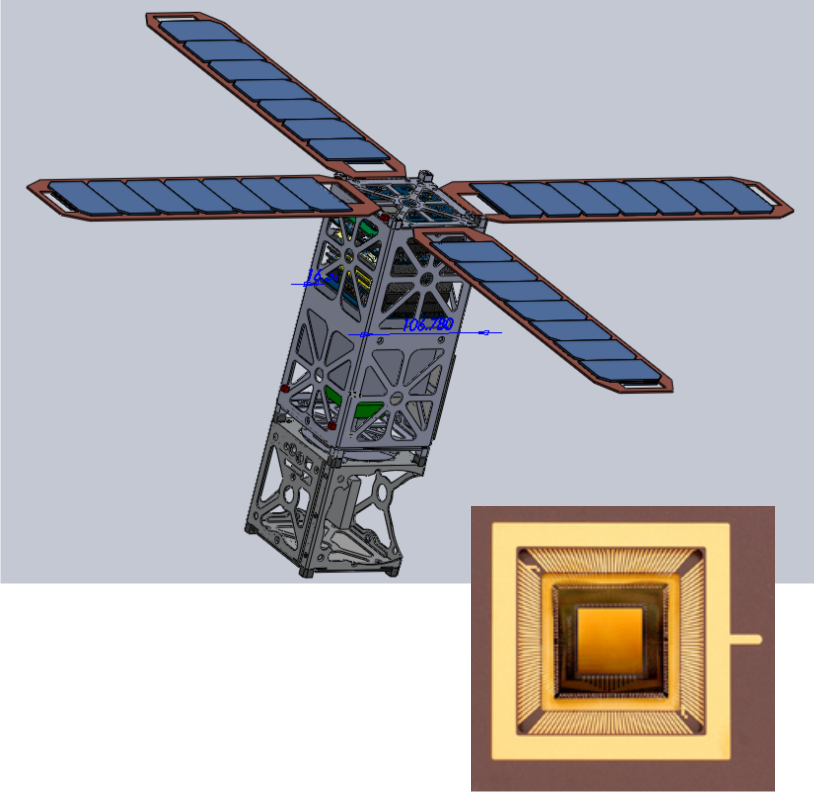
Wavefront Control Lab



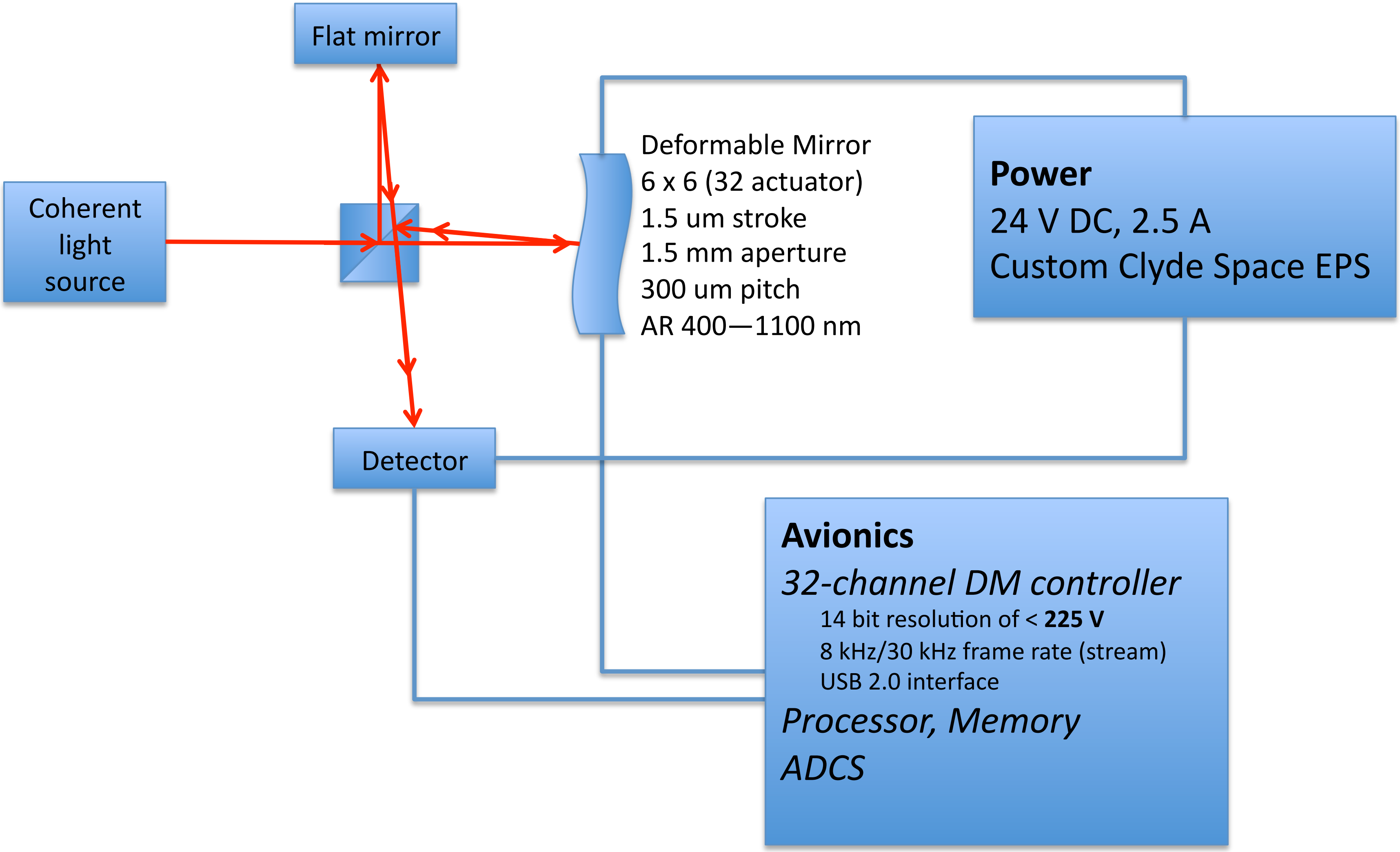
- Photos courtesy Caitlin Kerr ’15
- Experiment setup: Caitlin Kerr ‘15, Nick Roberts ‘15, Isaac Margulies ‘15, Billy Thalheimer ‘14
- 2 x 32-actuator MEMS DMs
- 1 x 140-actuator MEMS DM
- Shack-Hartmann wavefront sensors
- Turbulence simulator

CubeSat Deformable Mirror Demonstration

- Characterize on-orbit performance of DM
- 3U CubeSat platform
  - Easy access to space
  - MIT SSL expertise
  - $300-400k
- Small, less expensive 6 x 6 BMC MEMS DM
- Onboard source (e.g., laser diode)
- Detector with beamsplitter (Michelson interferometer) to evaluate performance



Deformable Mirror Demonstration



Flat mirror

Coherent light source

Detector

Deformable Mirror
6 x 6 (32 actuator)
1.5 um stroke
1.5 mm aperture
300 um pitch
AR 400—1100 nm

Power
24 V DC, 2.5 A
Custom Clyde Space EPS

Avionics

32-channel DM controller

- 14 bit resolution of < **225 V**
- 8 kHz/30 kHz frame rate (stream)
- USB 2.0 interface

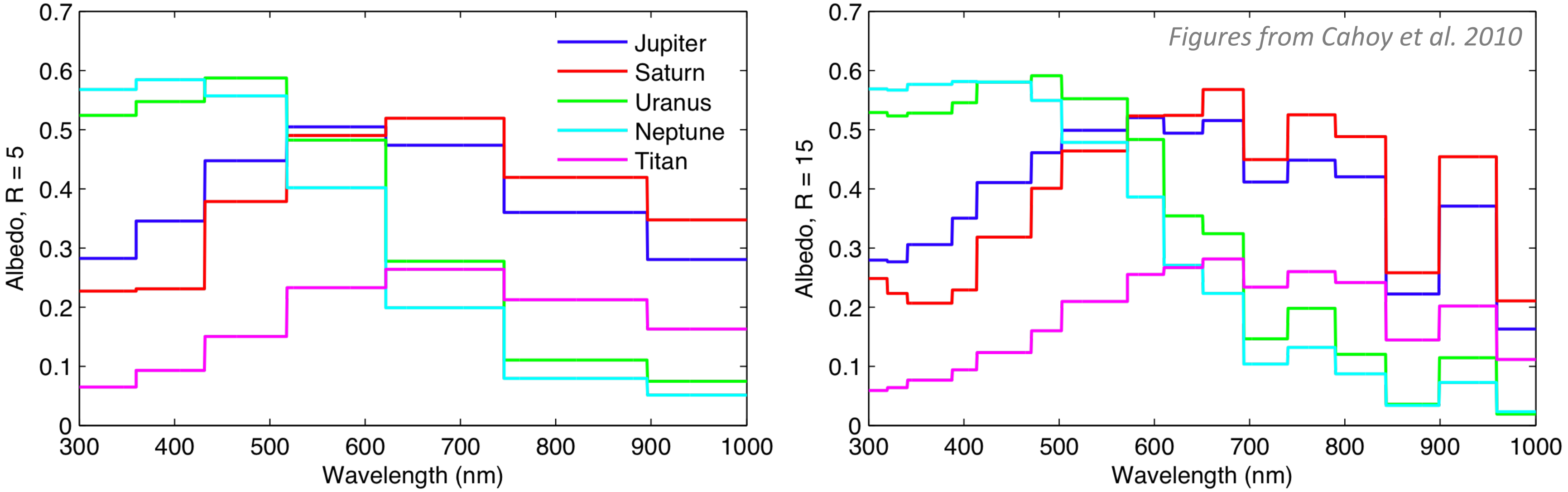
Processor, Memory

ADCS

6. Conclusion:
When will we be ready for a dedicated mi$$ion?

- Build it for space: smaller drive electronics, package
  - E.g., DM wire harness
- Launch environment testing
  - Mechanical, DM and WFS calibration
- Radiation environment testing
- Incorporation of Wavefront Control into spacecraft attitude determination and control system
  - Contribution to spacecraft (telescope) pointing
- Characterization of a Wavefront Control system on-orbit
  - Long duration operation in space environment, software and microcontroller, operations, data management

Direct imaging → Spectra of a ***resolved*** planet



Figures from Cahoy et al. 2010

- Geometric Albedo for Solar System bodies
- R = 5 (left)
  - – Colors, Rayleigh slopes (or haze)
- R = 15 (right)
  - – Start to see prominent spectral features (methane)

Wavefront Control Systems for Exoplanet Direct Imaging

- Direct imaging of exoplanets using telescopes equipped with coronagraphs will require wavefront control systems, whether the instruments are located on the ground, on airborne platforms, or in space. This is due to the high contrast requirement (e.g., 10^-10 to image an Earth-like planet around a Sun-like star at visible wavelengths). In addition to compensating for limitations on manufacturing and integration of optical elements and systems, space-based systems must compensate for the effects of launch and deployment on the instrumentation, as well as contributions from the spacecraft thermal environment, its pointing control, and jitter. Ground and airborne platforms must also compensate for the faster distortions introduced by atmospheric dynamics during an observation. Wavefront control systems consisting of wavefront sensors and deformable mirrors are used to detect the amount of distortion and apply a correction before the wavefront reaches the detector. There are several different approaches and trades to consider for the placement and number of deformable mirrors in the optical system (such as the effect of mirror placement on the coronagraph outer working angle, or the utility multi-conjugate adaptive optics for ground-based observations). There are also trades to consider for the wavefront sensors, for example, whether to include a separate element for the wavefront sensor and introduce non-common path optical errors, or to try to use the science detector for wavefront sensing. For airborne or spaceborne platforms, it is important to couple the wavefront control system to the platform's attitude determination and control system (ADCS), as well as minimize the mass, power, and volume of the wavefront control systems. It is also desirable to minimize cost. The goal of our lab experiments are to study the potential of using multiple microelectromechanical systems (MEMs) deformable mirrors for representative ground and space-based exoplanet observation configurations. The space-based experiments also focus on ways to test and package MEMs deformable mirrors for flight, as well as couple their drivers and control loops in to spacecraft ADCS.