CubeSat Deformable Mirror Demonstration (CDMD)

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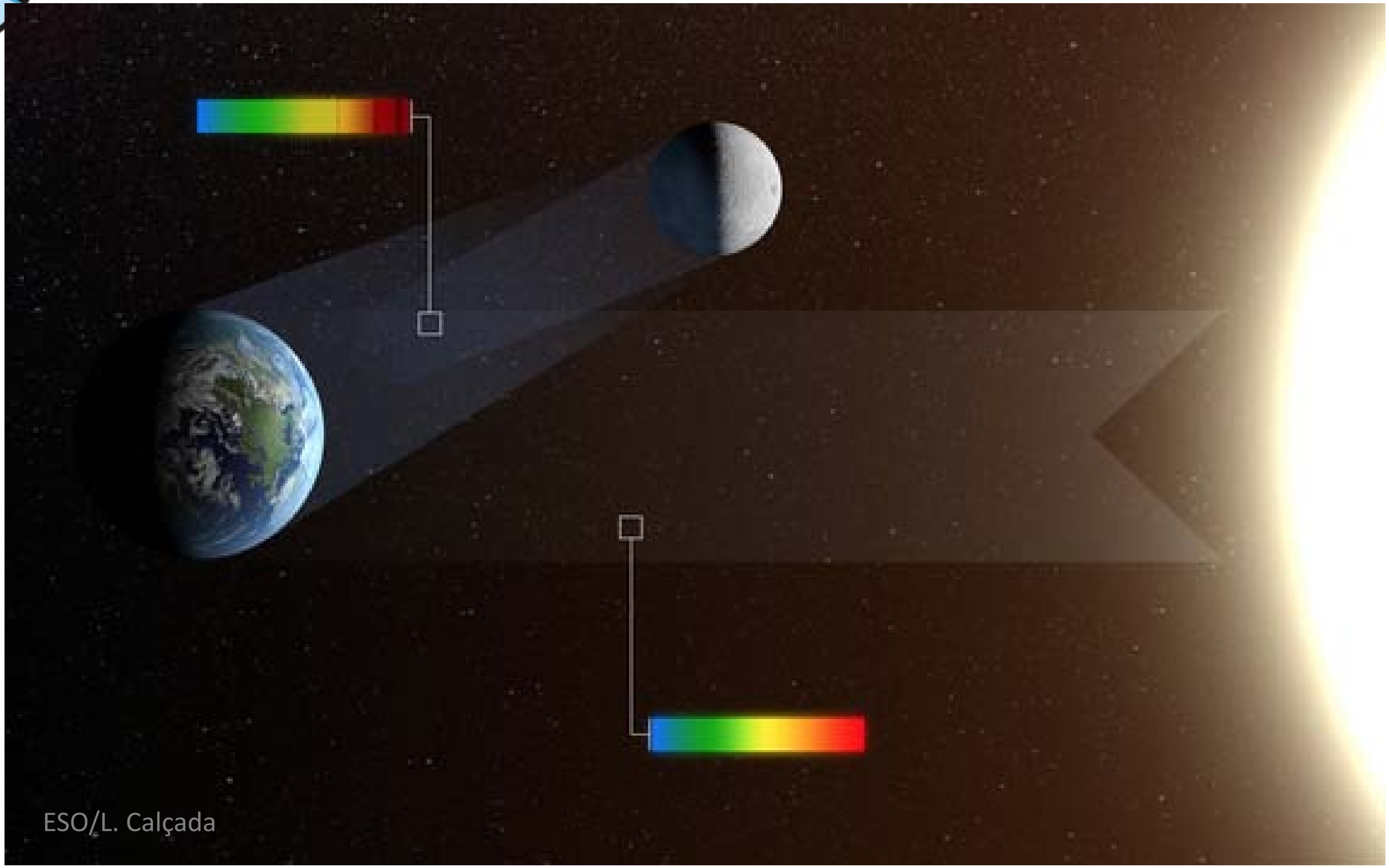
Is there *other* life out there?

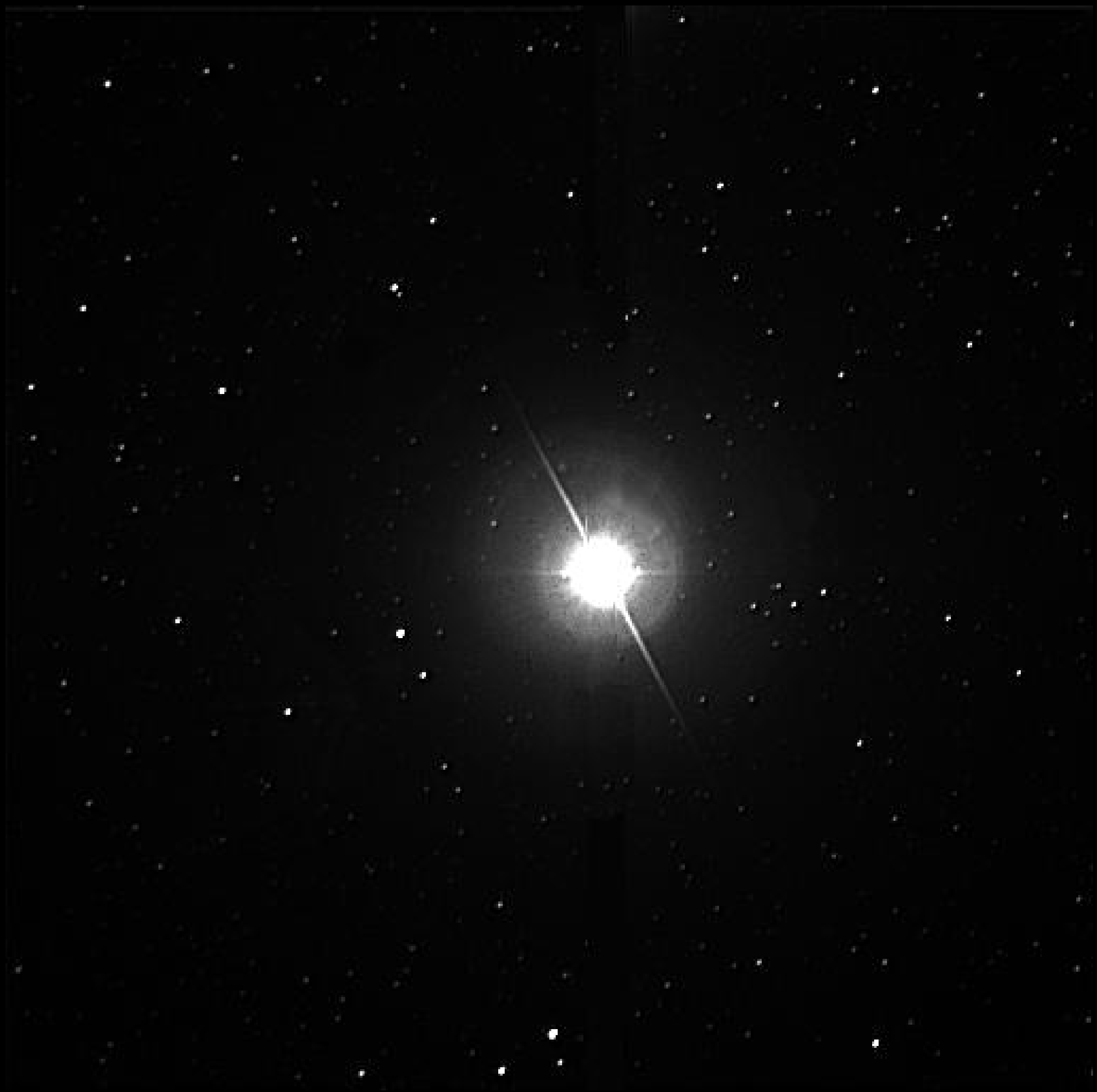
earthobservatory.nasa.gov

Reflected starlight: spectra



- Look at absorption features in spectra: $O2$, $H2O$

But stars are really bright…



http://photojournal.jpl.nasa.gov/catalog/PIA04204

CDMD

Hmm...

- Must block starlight to see planets around star

Coronagraph

- Use a coronagraph to block the star's light

Basic Coronagraph Optics

- If life were perfect…

1. Input Pupil
2. Image Plane
3. Reimaged Pupil
4. Reimaged… Image Plane

Fourier Transform

Inverse Fourier Transform

Fourier Transform

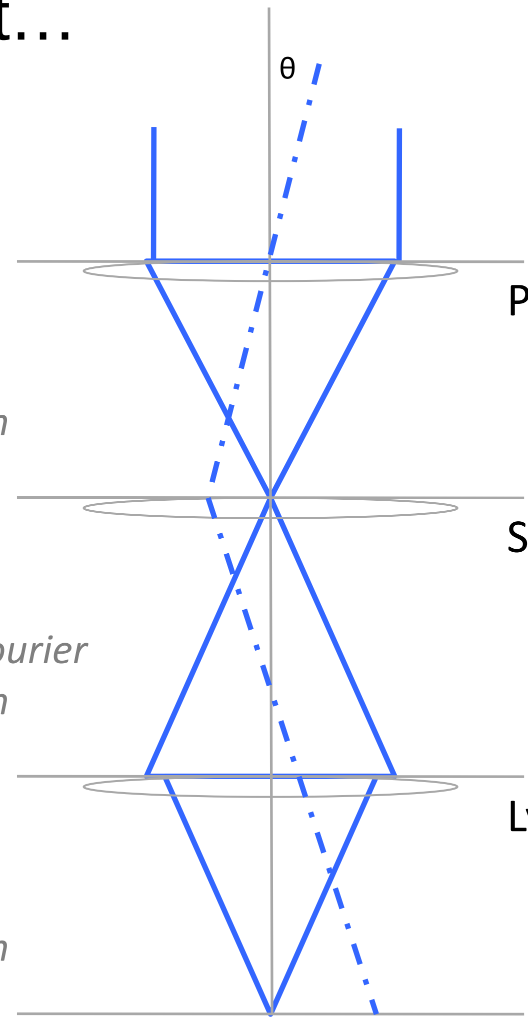
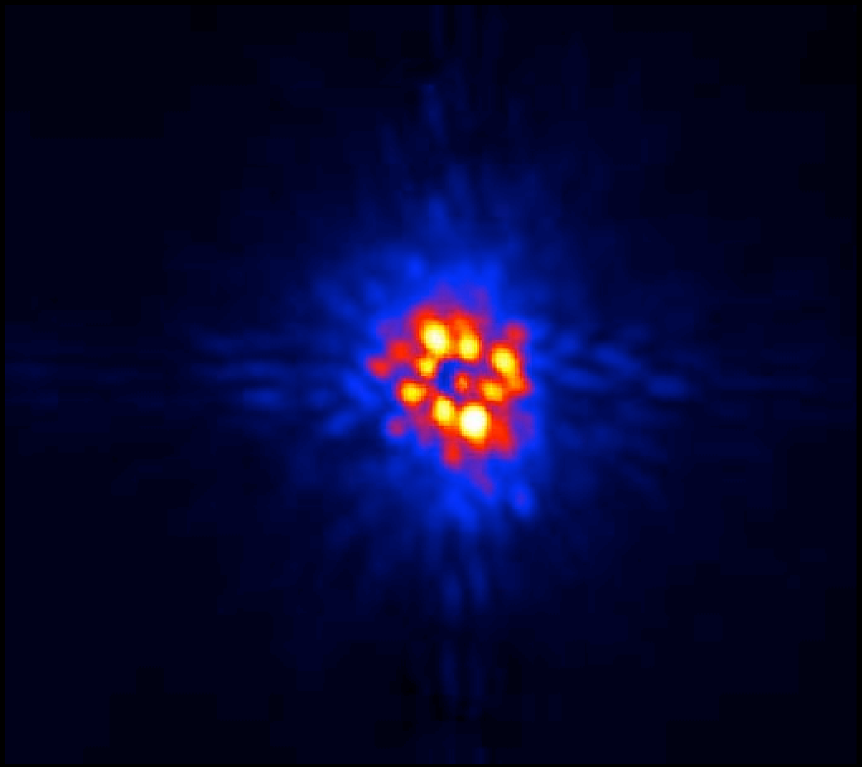


Figure adapted from Traub & Oppenheimer 2010

But life is not perfect: speckles



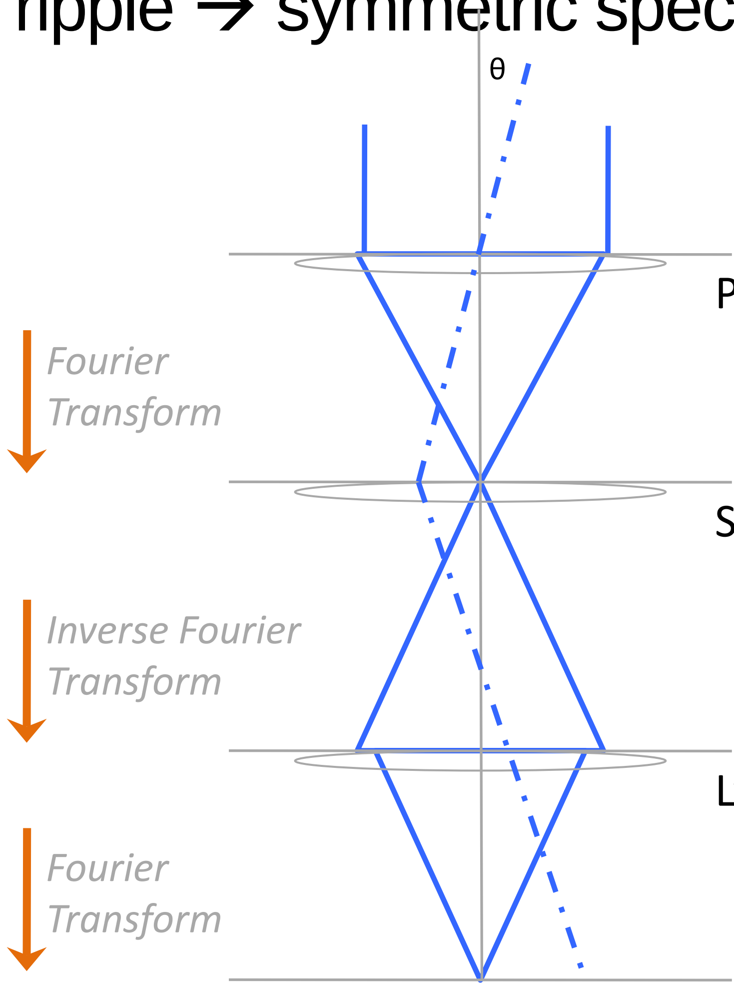
The star 55 Cancri observed with the Lyot Project coronagraph at AEOS in Maui. The symmetric "speckles" arising from atmospheric effects and imperfections in the telescope optics are clear. http://www.lyot.org/results

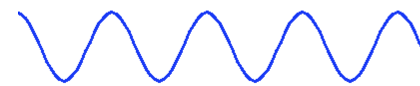
Corrupting an innocent wavefront

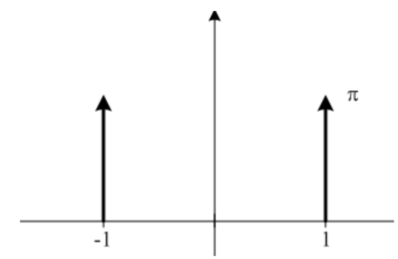
CDMD

- Cosine ripple → symmetric speckles

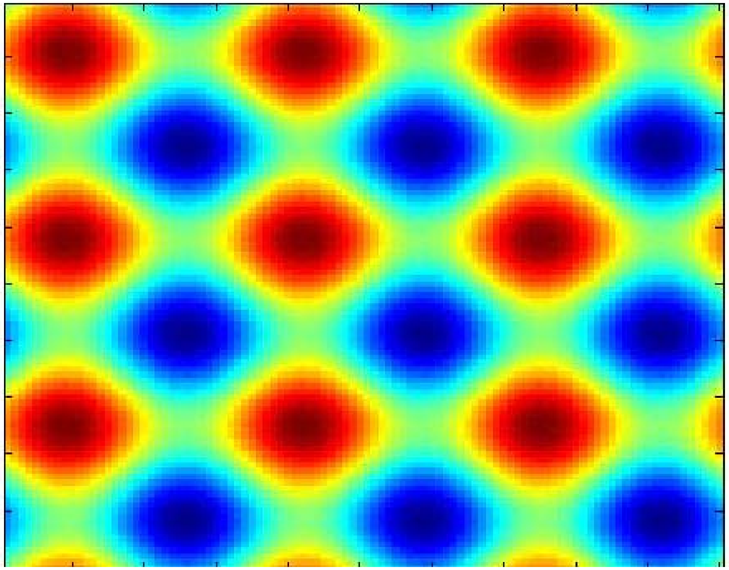
1. Input Pupil
2. Image Plane
3. Reimaged Pupil
4. Reimaged… Image Plane

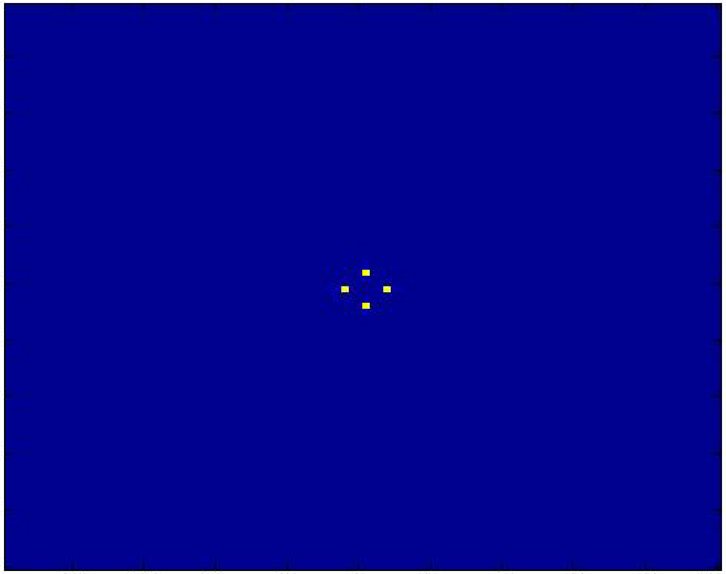






2D Speckles



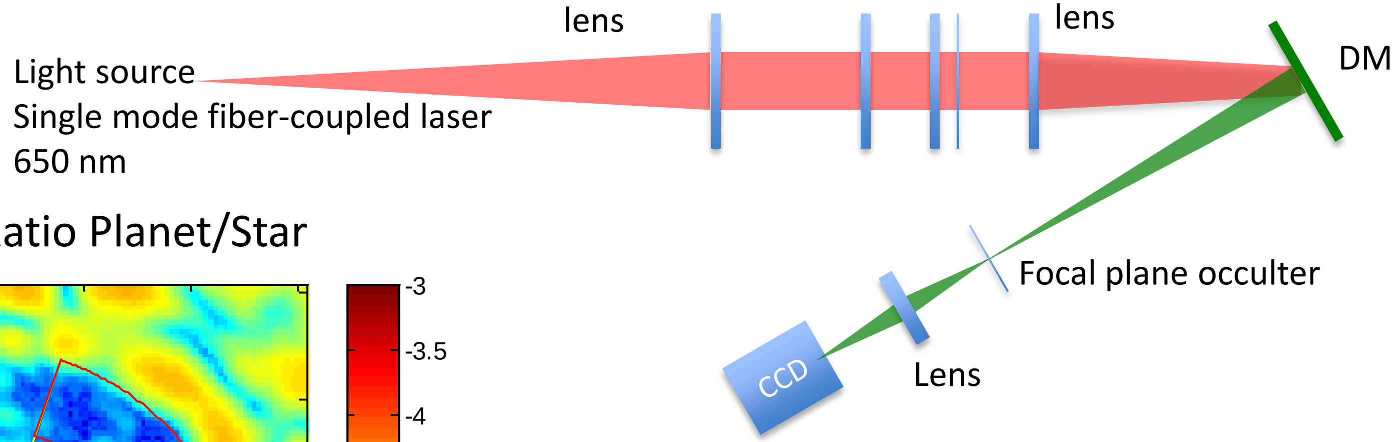


- 2D FFT of X, Y ripple pattern (e.g. surface error, stray light)
- Lower spatial frequencies at center, higher outside
  - Outside is where planets will be, need dark hole → Deformable Mirror
- N actuators per side of a DM, null N/2 waves, θ(dark hole) = ± Nλ / 2D

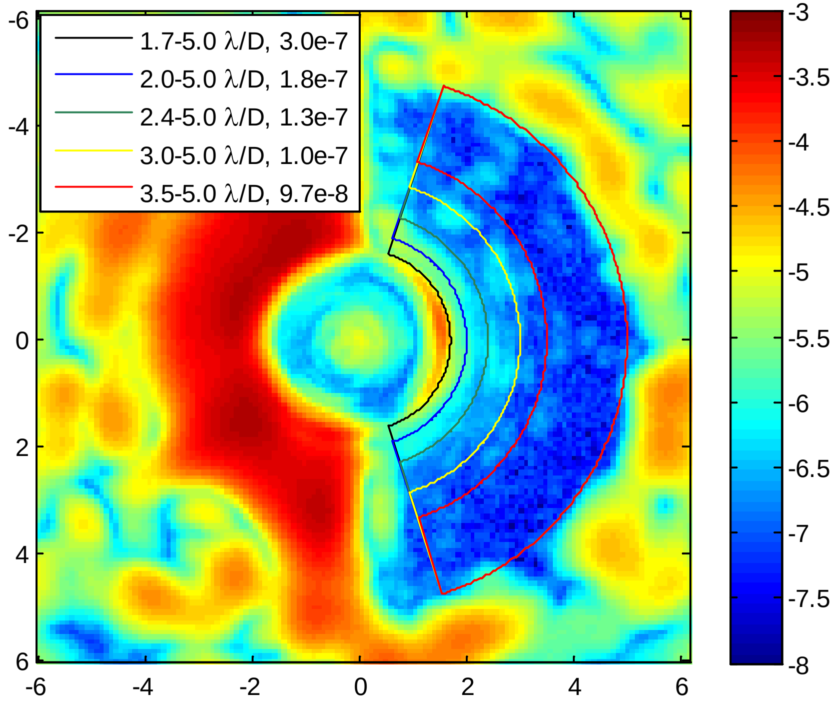
Need deformable mirror with lots of actuators… in space.

The first time to try this is *not* on a $1B space telescope.

Single deformable mirror example



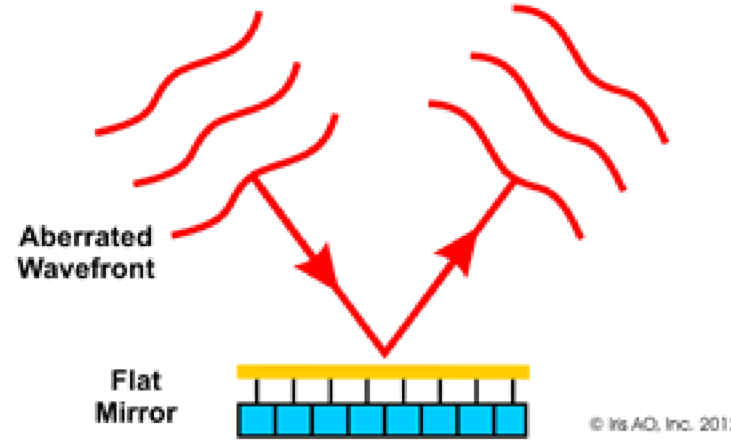
Log10 Contrast Ratio Planet/Star



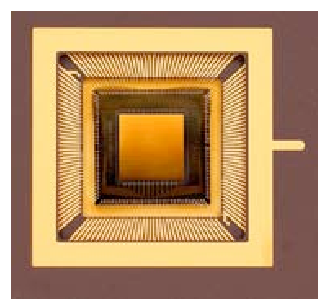
R. Belikov (NASA Ames), results with polarizer, 6/9/09 (in 2011, 5.4 x 10^{-8})

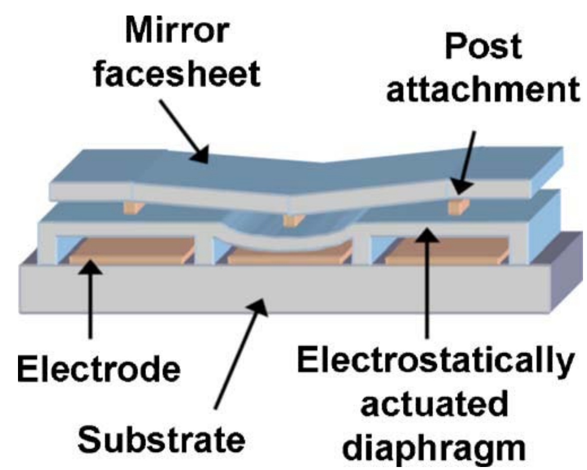
MEMS Deformable Mirrors

- Actuators change the shape of the mirror surface to match the incoming wavefront



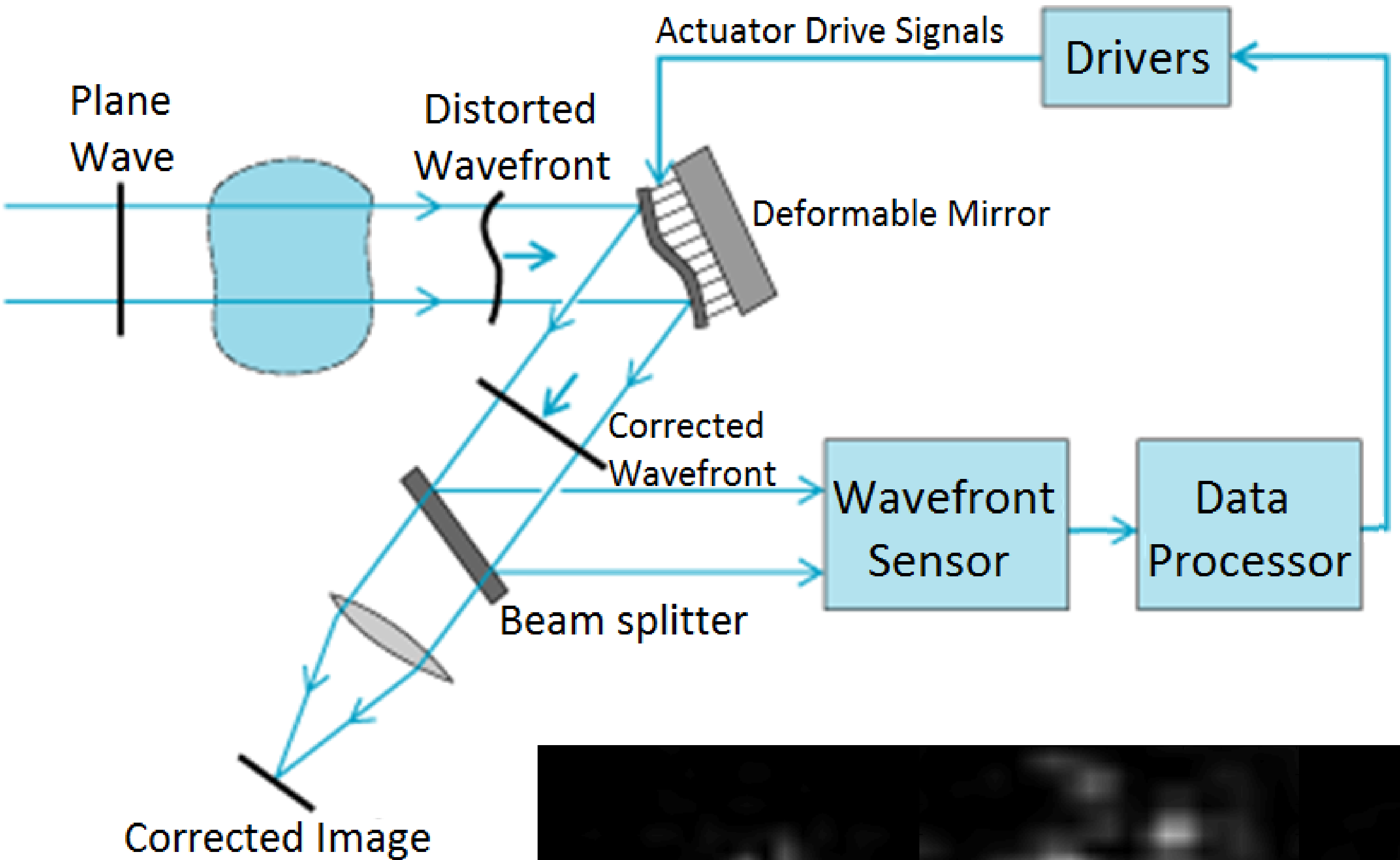
- MEMS devices
  - –Electrostatic actuators
  - –Stroke of ≈ 1—8 µm
  - –Higher voltage, low current
  - –More actuators
  - –Fast response time

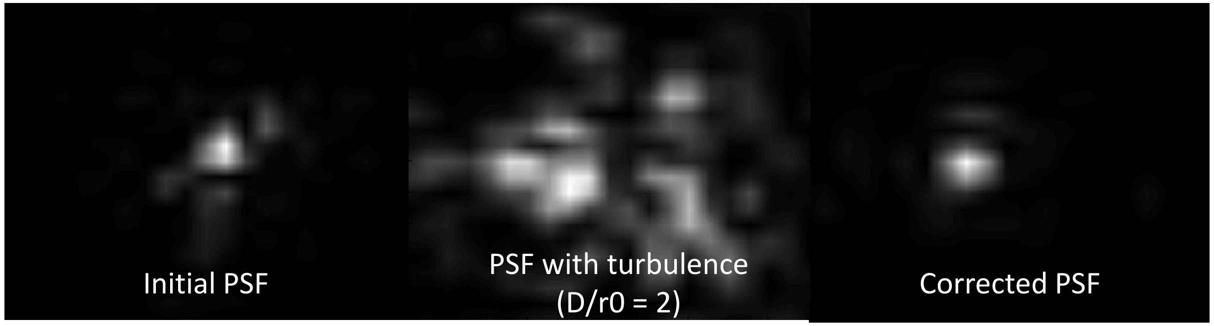




Stewart et al. 2007

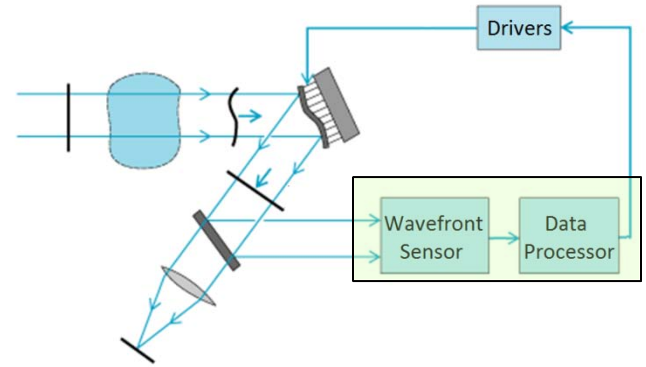
Wavefront Control System

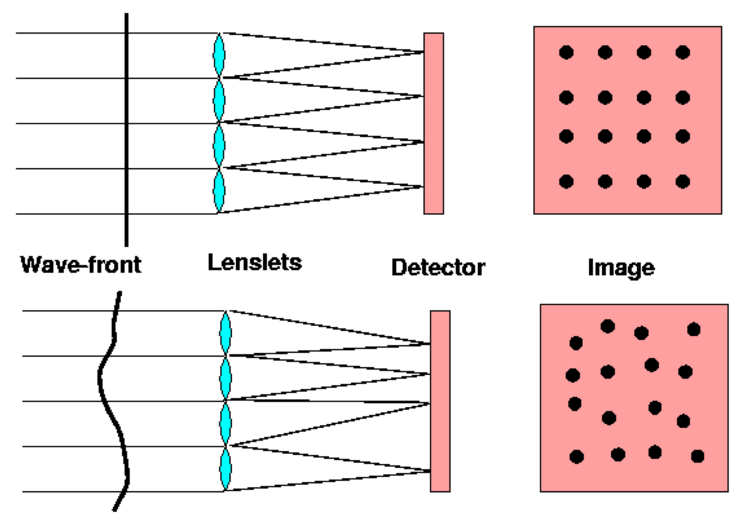




Wavefront Control Sensors

- Measure wavefront and calculate phase error to be corrected
- Sensored
  - Optical element introduced into beam to generate measurement
- Sensorless
  - Intensity-based measurements, computationally intensive





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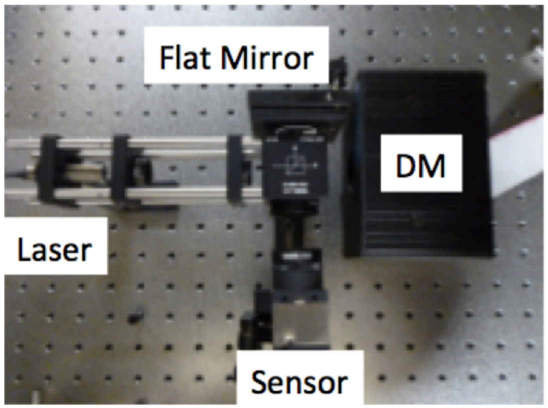
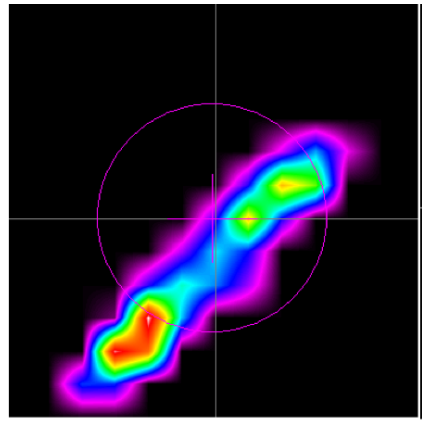
Lab prototype

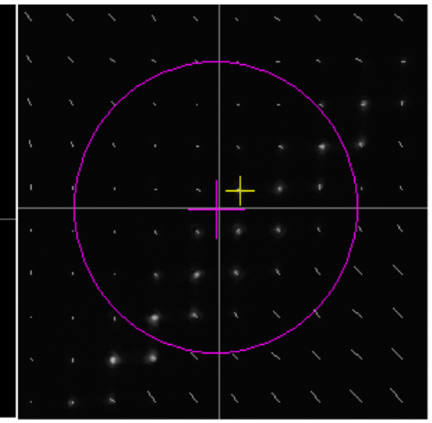
CubeSat-scale setup

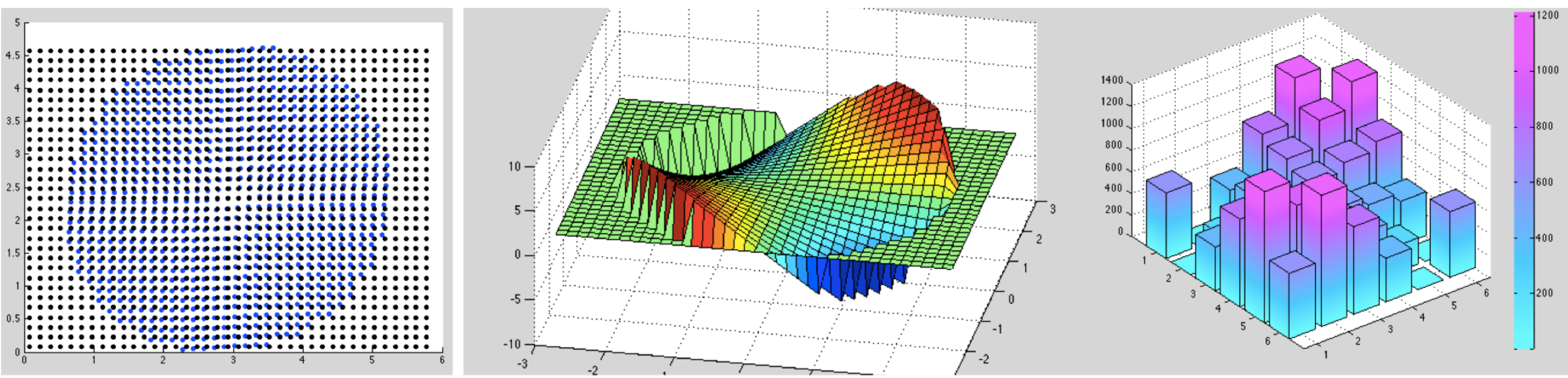


Z(2,-2), 2xy



Shack Hartmann Spots





MATLAB simulation and controller

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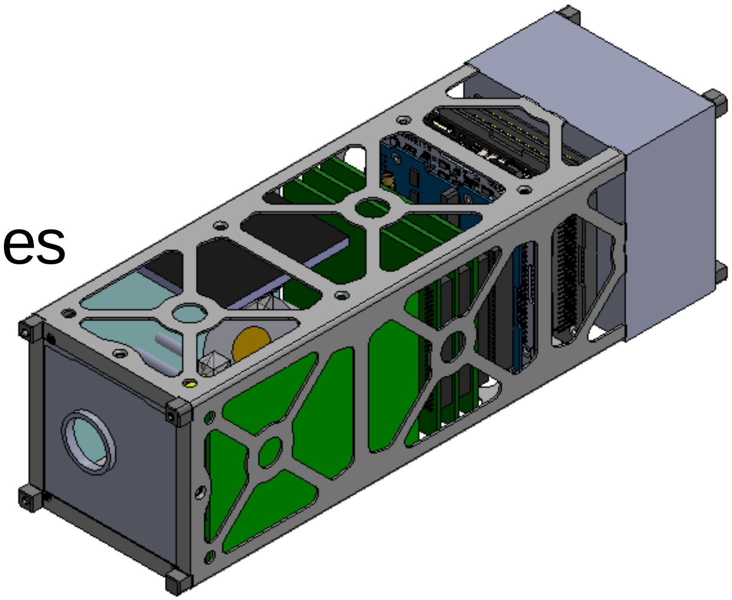
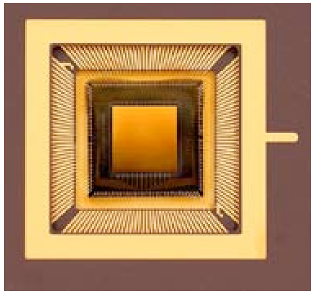
CubeSat Deformable Mirror Demonstration

- On-orbit performance of MEMS DM
- DMs will fit
  - Same actuator technology as big ones
    - BMC Mini MEMS DM, 32 actuators
    - Iris AO PTT111, 37 segment
    - Drive electronics board will also fit
- Laser Diode
  - "Easy" ADCS
  - Aperture can look at stars when laser off
    - But don't really care which star(s)
    - Need only to have slew rate ~ 5 arcmin/s

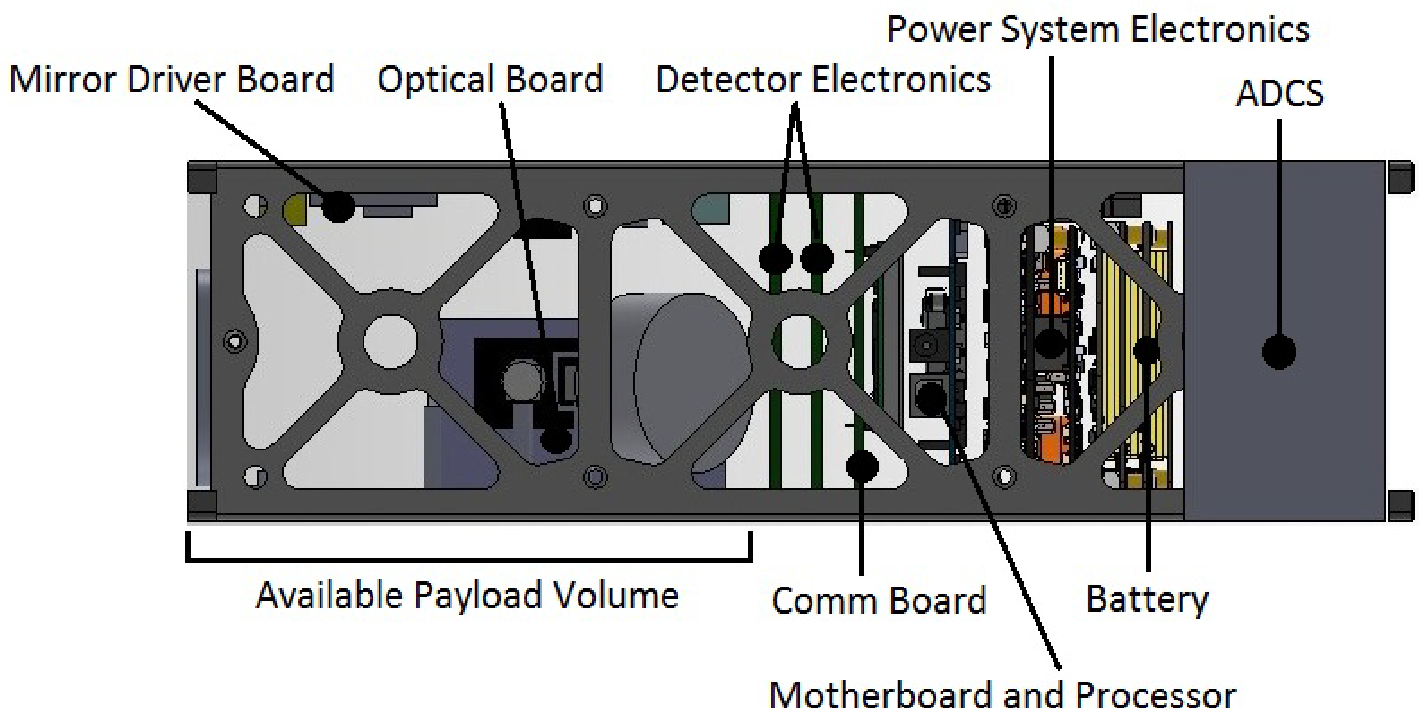




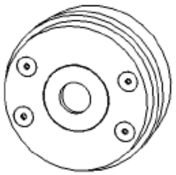
BMC MEMS DM

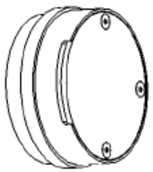
1.5 U Payload, 1.5 U Bus subsystems

- Leveraging experience with MicroMAS, simpler ADCS



Payload Overview





- Boston Micromachines Mini MEMS DM
  - 32 actuators, 5 cm diameter, 2.21 cm tall
  - ~150 g including cables
  - Driver board
    - Existing board nearly CubeSat form factor
    - Straightforward to respin

- Optics
  - DM has >= 1.5 mm aperture
  - UV-grade fused silica
    - Lenses, beamsplitter, ND filters, lenslet array, quarter wave plate
    - Stress-free mounts, lens tubes
- Detector
  - IDS UI-5241LE-M, CMOS (or similar)
  - Closed loop wavefront control; processor

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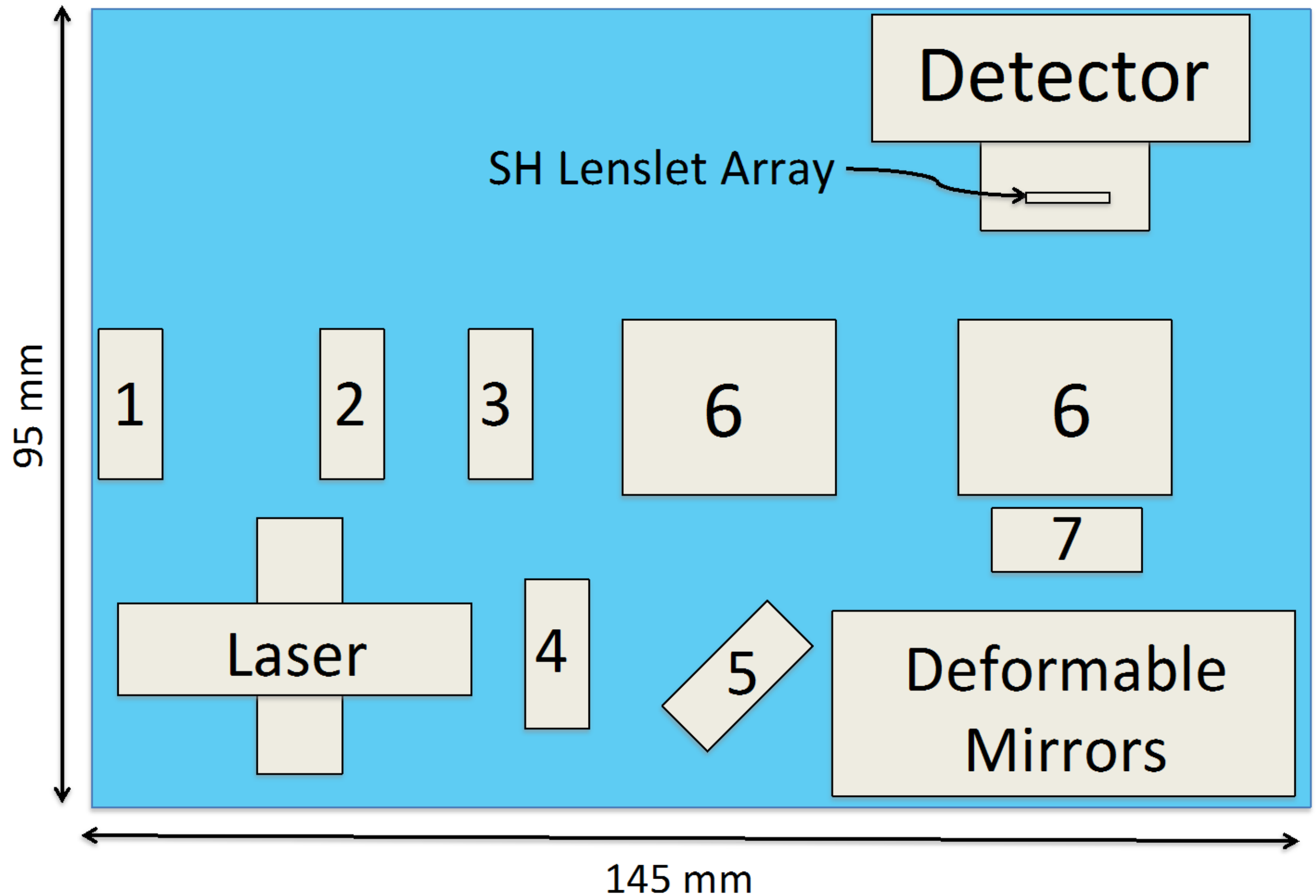
Shack-Hartmann Wavefront Sensing System



1. Aperture Lens
2. Collimating Lens
3. Polarizing Lens
4. Polarizing Lens
5. Flat Mirror
6. Beamsplitters
7. Quarter Waveplate

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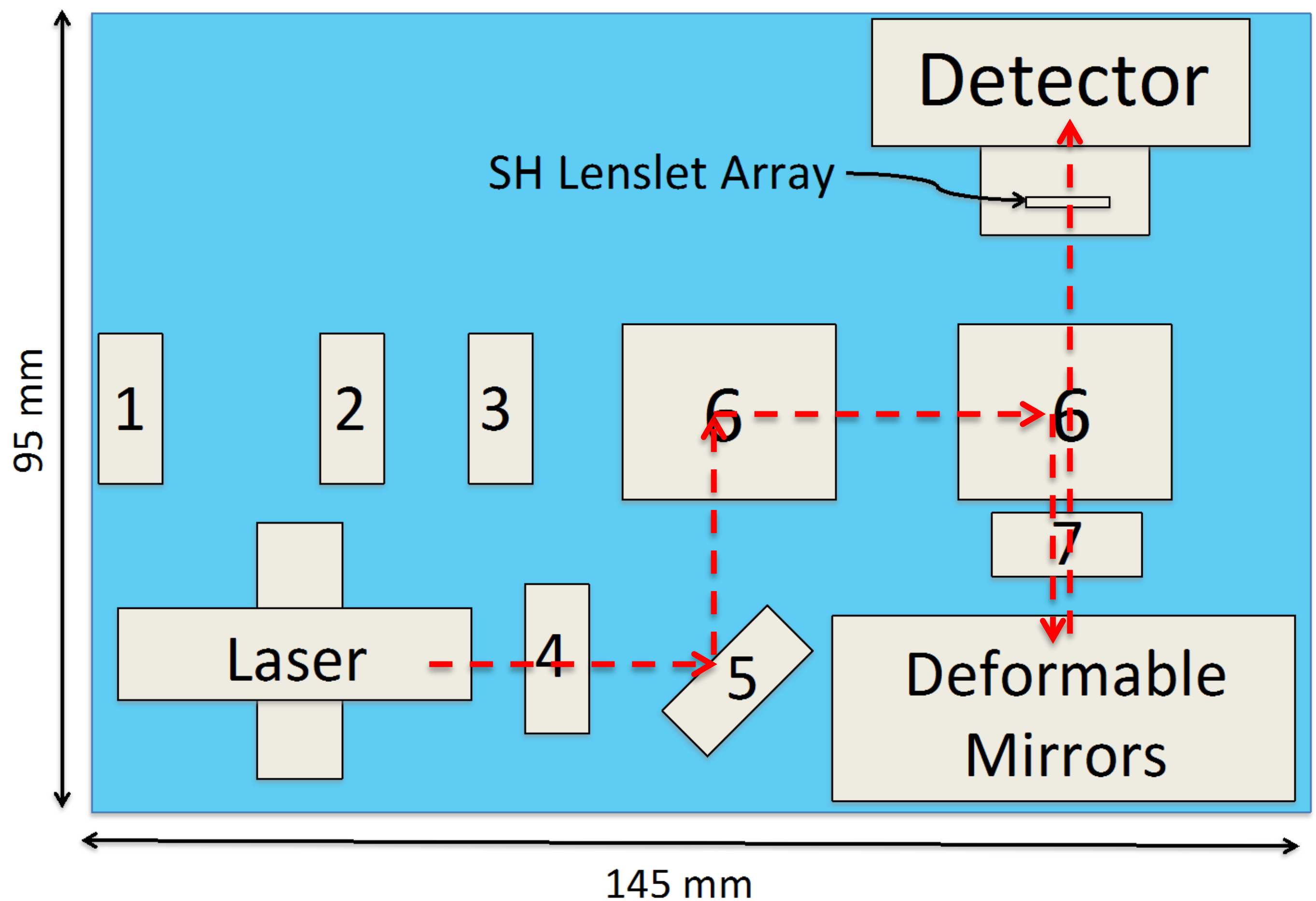
Shack-Hartmann Wavefront Sensing System



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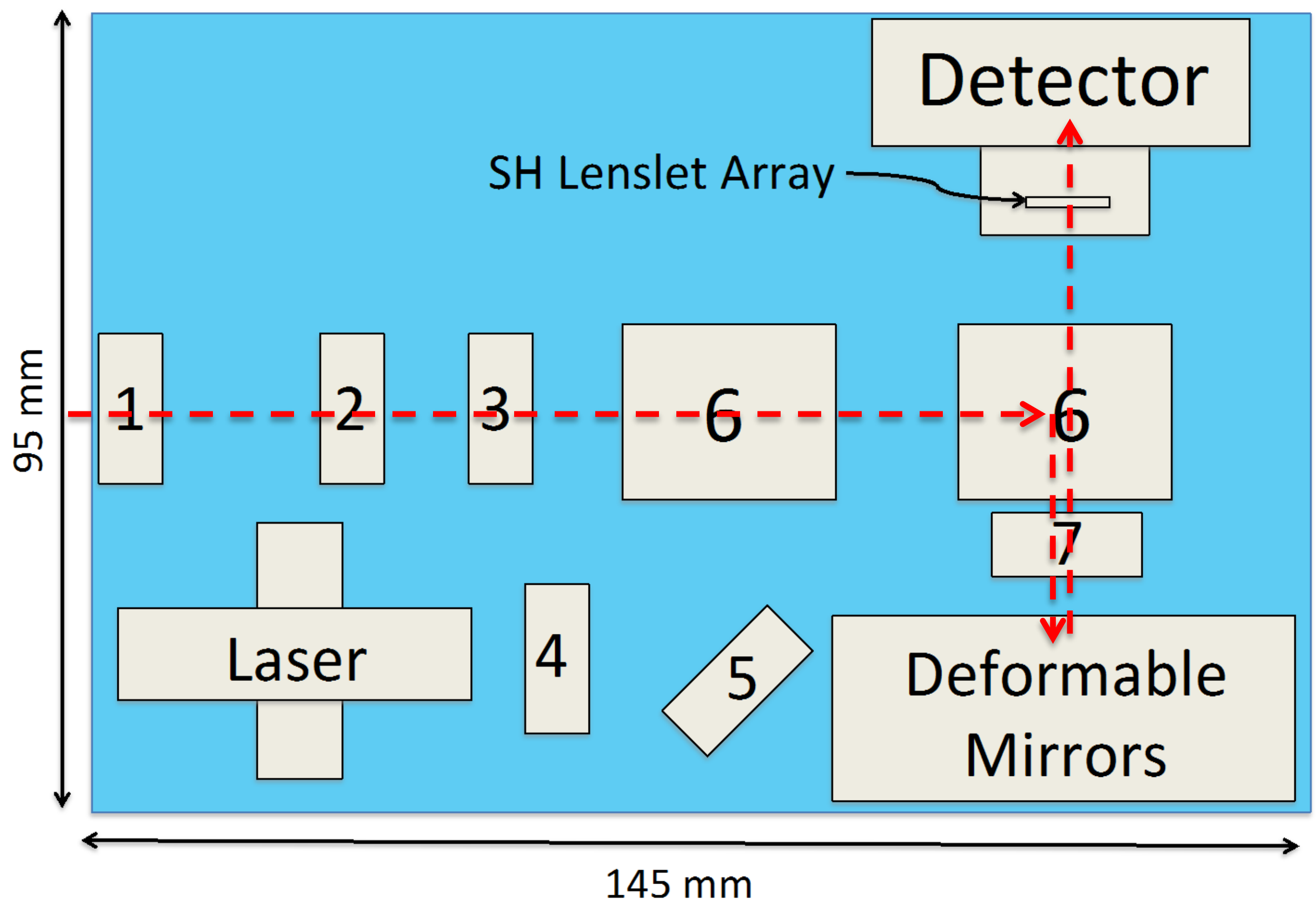
Shack-Hartmann Wavefront Sensing System



1. Aperture Lens
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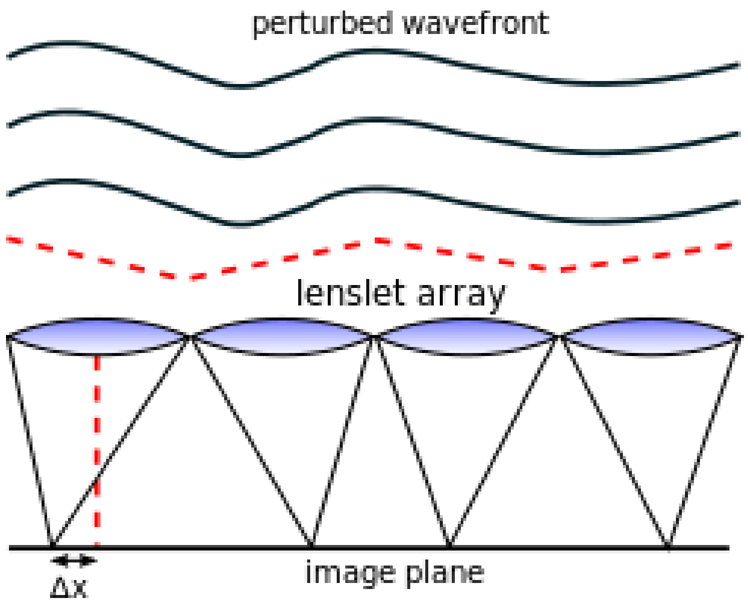
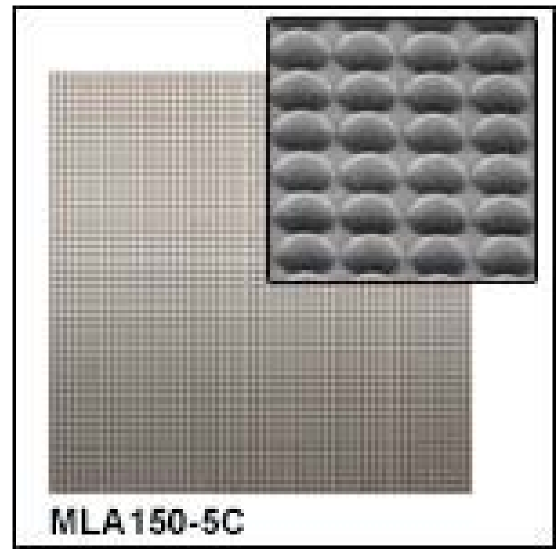
Shack-Hartmann Lenslet Array





- Incoming beam dictated by DM aperture
- Maximize sub-lenses / mm^2
- If lens is 10 mm x 10 mm, with 150 µm pitch = ~67 x 67 spots.
  So, for an incoming beam diameter of 2.25, about 15 x 15 spots.
- Need at least 4 pixels per spot, so for detector,
  need the 2.25mm beam to cover more than 60 x 60 pixels.

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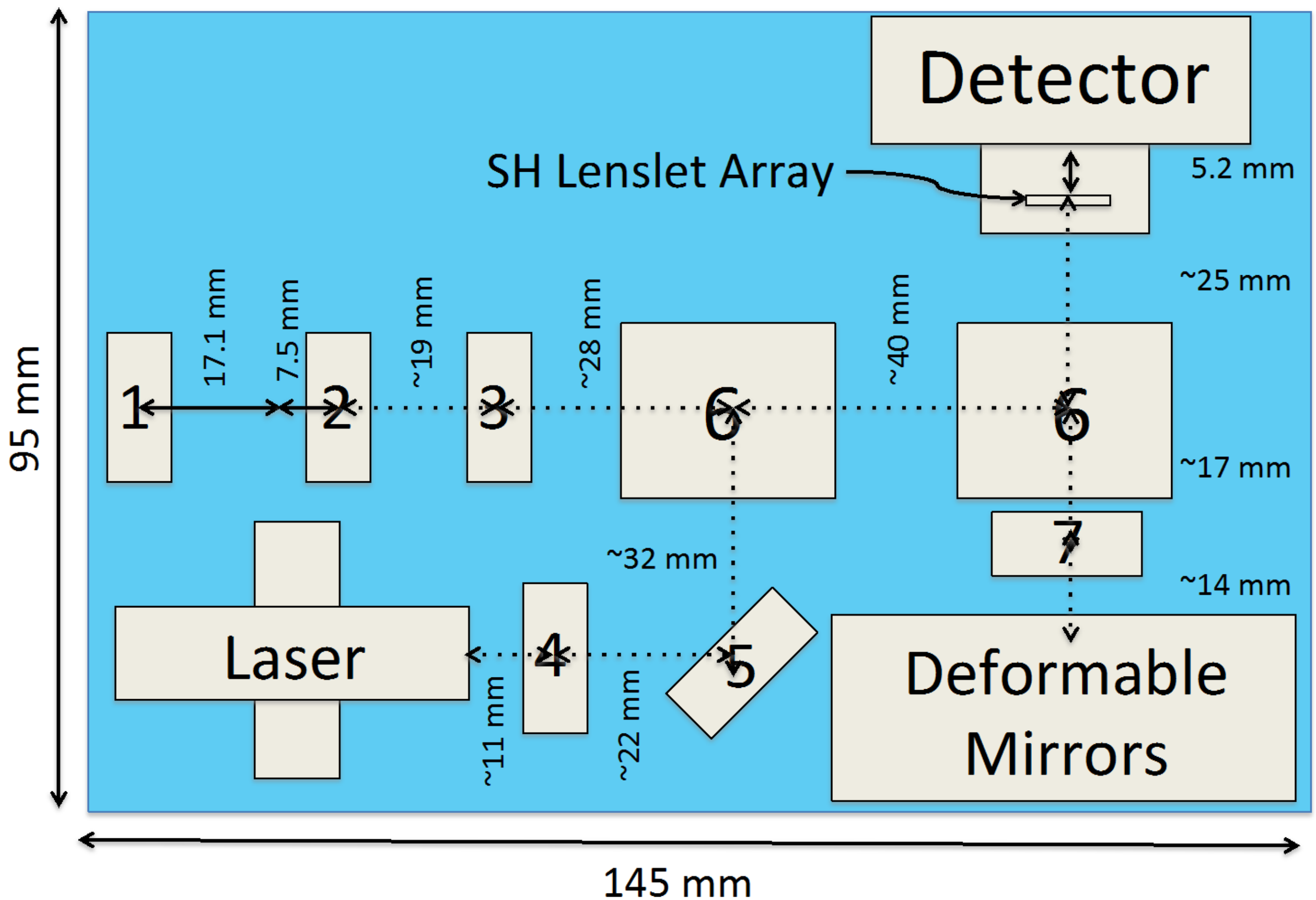
Beam Divergence



$$\theta = 2\arctan\left(\frac{D_f - D_i}{2L}\right)$$

Assumptions:

1. Beam is circular
2. No additional beam divergence through optical components

Avionics

- Avionics Requirements
  - Camera interface / readout
  - Low frame rate image processing
    - Centroid, delta x and delta y, slope reconstruction
    - Linear algebra for mirror controller
- Possible solutions
  - PC104 form factor single board computer
  - Raspberry Pi
    - Also low-speed camera option
    - 5 MO OmniVision 5467 (60 fps at 720p)
  - ODroid-X2
    - ARM, standard peripherals

Raspberry Pi, Wikipedia

Hardkernel.com

Path forward

- Laboratory development
  - Optical tolerancing, payload trades (Zemax)
  - Wavefront sensing, quantify DM reconstruction capability
    - Accuracy as function of # lenslets, alignment, tolerancing
    - Optimize wavefront reconstruction data products
      - Centroids, delta x, delta y, Zernike or Fourier coefficients
  - Update mirror drive electronics
  - Avionics design and testing

- Environmental tests on mirrors, drivers (ref. Shea et al. 2006)
  - Mechanical, electrical, follow up with ground efforts

- Partners, sponsors, launch opportunities, logistics

Conclusion

Design and build cost-effective, small wavefront control CubeSat to characterize high actuator-count **MEMS** deformable mirrors.

Enable implementation of active/adaptive optics with MEMS DMs on future space missions.

High contrast imaging.
Precision pointing.
Modulation.

Thank you!

References

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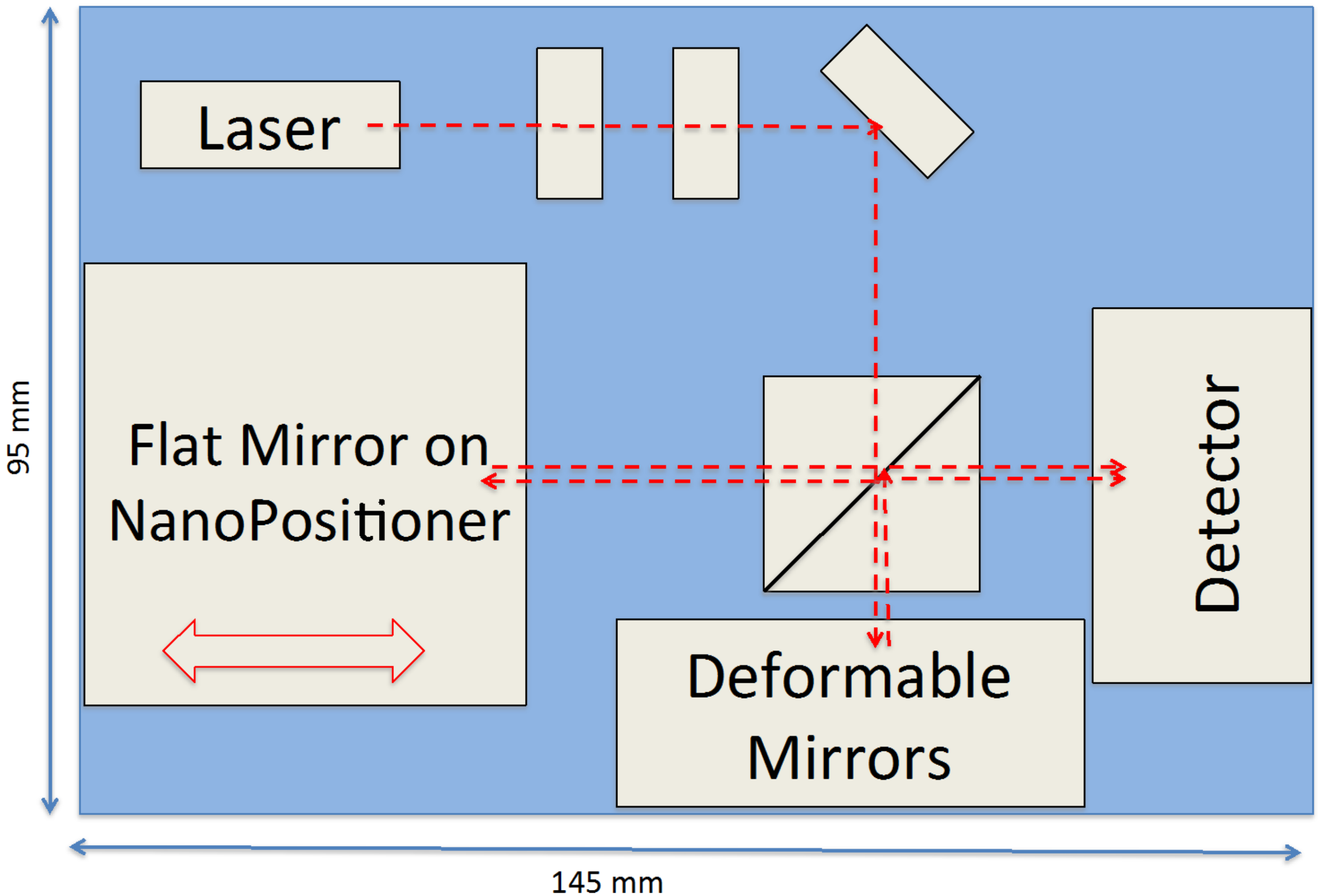
Backup Slides

CDMD

Michelson Interferometer with Flat Mirror on NanoPositioner



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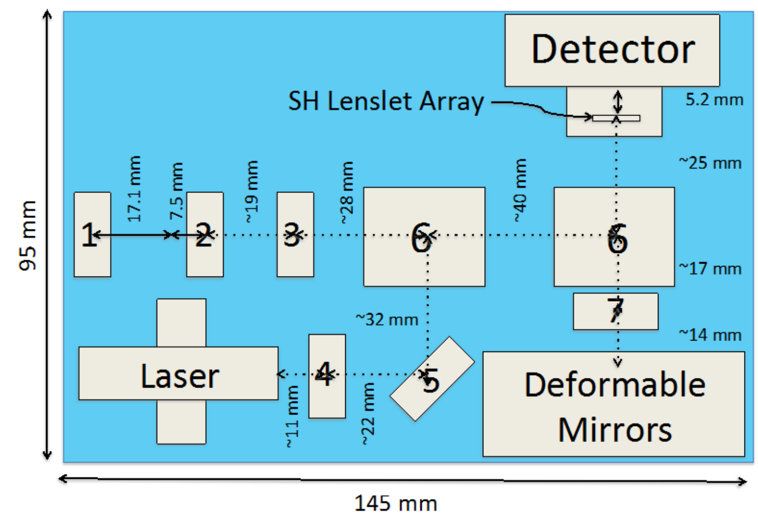
Payload Requirements

ID	Statement	Relevant parts
PLD-1	The payload shall command a MEMS deformable mirror to run a pre-defined test sequence for at least 5 minutes [TBR] each orbit.	All
PLD-1.1	The payload shall have the ability to control any combination of actuators within 0.001 [TBR] seconds of each other, at a minimum rate of 100 Hz [TBR], with a minimum stroke of 1.5 microns, and with a precision of at least 1 nm [TBR].	Deformable Mirror
PLD-2	The payload shall have the ability to measure and reconstruct the optical wavefront at one wavelength for the duration of a 5 minute [TBR] test sequence each orbit.	Avionics Interface
PLD-2.1	The payload shall have the ability to measure the optical wavefront at a minimum rate of 100 Hz [TBR]	Detector, Avionics
PLD-2.2	The payload shall have the ability to reconstruct the optical wavefront with a minimum accuracy of 100 nm rms [TBR].	SH array, Detector

CDMD

Example: Find beam diameter

Beam leaves laser with divergence Θ, and effective diameter D_i, and travels to polarizer, a distance L away. What is the beam diameter D_f entering the polarizer?



For the CPS186 laser:

- $\Theta \leq 1.8$ mrad
- $D_i = 1.2309$ mm

$$\Theta = 2\arctan\left(\frac{D_f - D_i}{2L}\right)$$

$$(1.8 mrad) = 2\arctan\left(\frac{D_f - 1.2309mm}{2(11mm)}\right)$$

$$\therefore D_f = 2(11mm)\times\tan\left(\frac{1.8mrad}{2}\right) + 1.2309mm = 1.2507mm$$

At the detector:
$D_f \approx 1.5859$ mm

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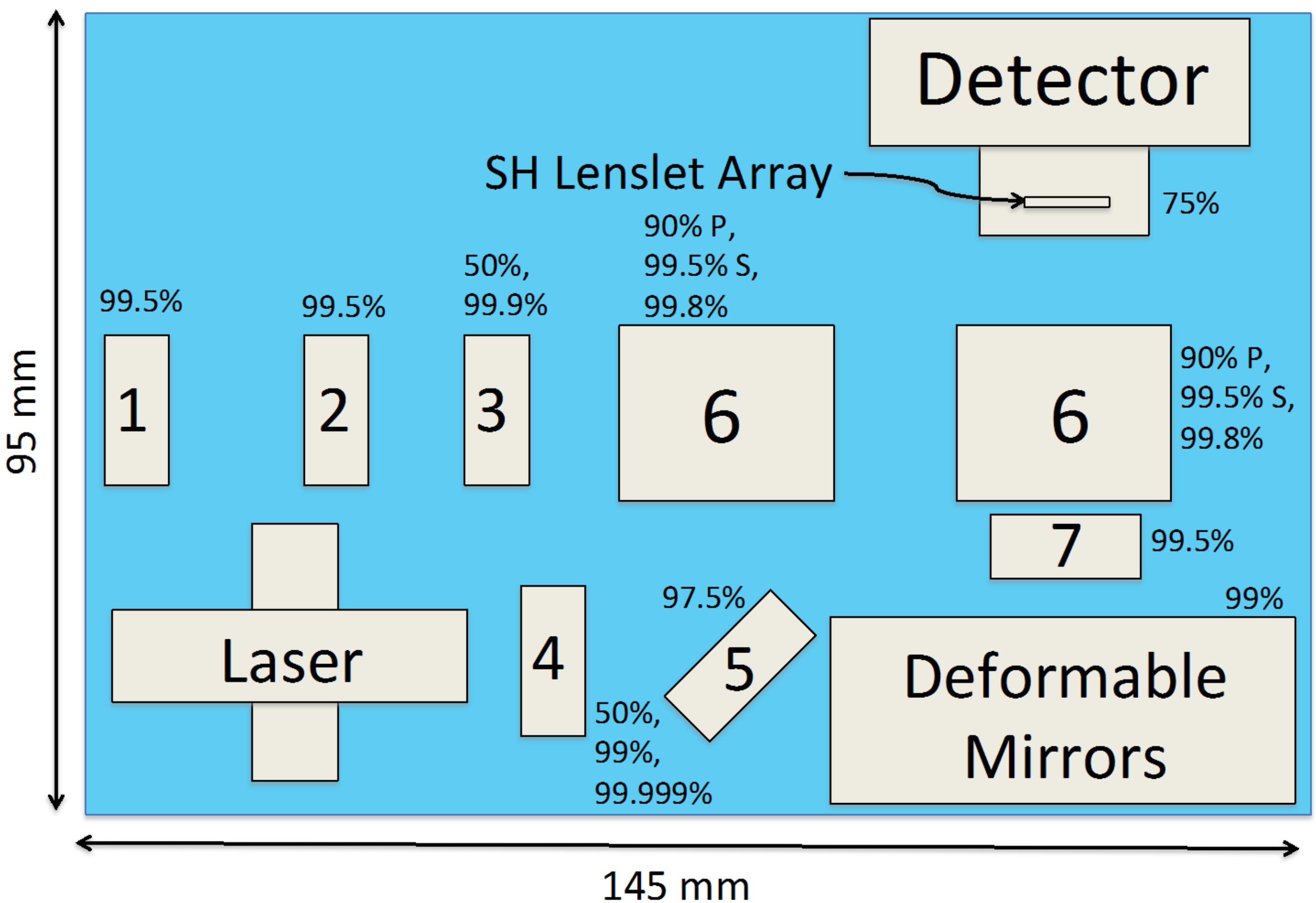
Absorption, Reflectivity, and Polarization



$$P = \int I \bullet dA$$

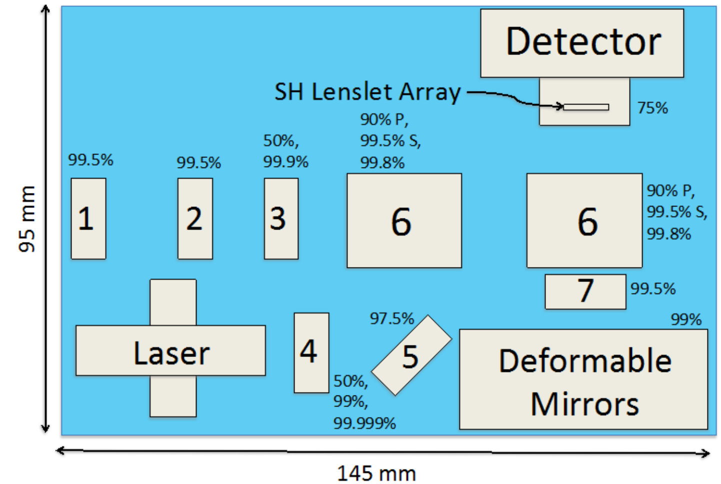
Assumptions:

1. Beam is circular
2. No power/intensity lost between components (small distances)

CDMD

Example: Find beam intensity

Beam leaves laser with power P, and effective diameter D_i, and travels to polarizer. What is the beam intensity after going through the polarizer?



For the CPS186 laser:

- $P = 4.70$ mW
- $D_i = 1.2309$ mm

$$P_i = \int I_i \bullet dA$$

$$P_i \approx I_i\left(\pi r_i^2\right)$$

$$\therefore I_i \approx \frac{P_i}{\pi\left(\frac{D_i}{2}\right)^2} = \frac{4.7mW}{\pi\left(\frac{1.2309mm}{2}\right)^2} = 3.9497 mW / mm^2$$

At the detector:
$I_f \approx 1.2411$ mW/mm^2
$P \approx 2.4514$ mW

Analysis & Design

Actuator:

3- orthogonal torque coils

- Light weight, low power actuator
- Provide actuation for active magnetic control

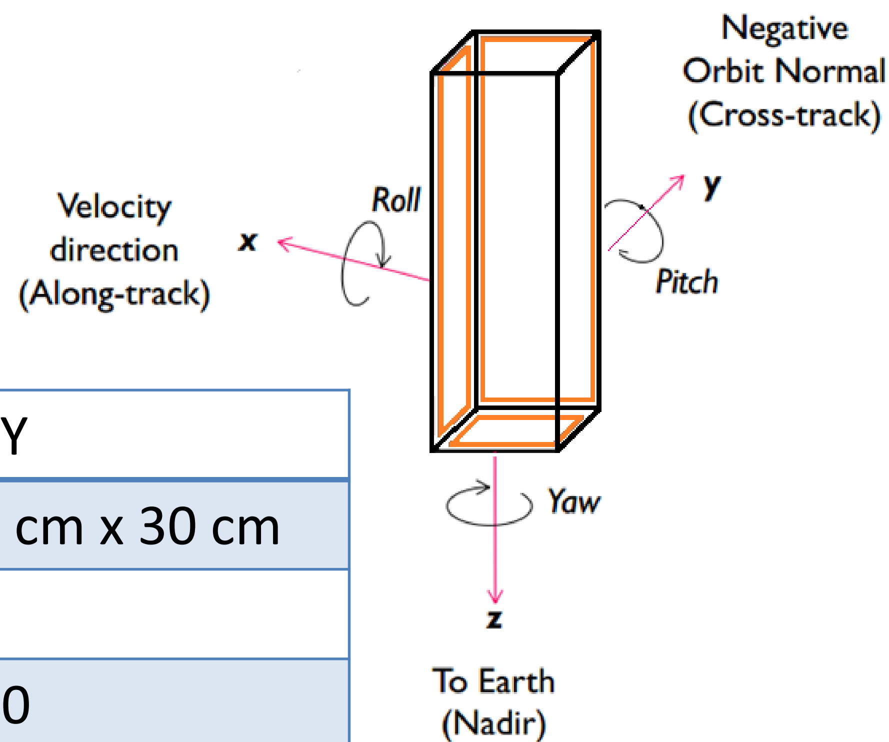
Sensors

- **Magnetometer**
  - Provide reading of local magnetic field for magnetic control
  - Provide attitude knowledge in eclipse
- **Sun Sensors**
  - Provide attitude knowledge in daytime
- **IMU**
  - Provide angular rate knowledge for vibration damping

ADCS

Torque Coil Design

Total Mass	520 g
Max Total Power	1.35 W



Direction	Z	X, Y
Size	10 cm × 10 cm	10 cm x 30 cm
Quantity	1	2
Turns	500	400
Current	0.12 A	0.04 A
Wire Gauge	28 AWG	28 AWG
Magnetic moment	0.60 A*m^2	0.60 A*m^2