Integration and Testing of the Deformable Mirror (DeMi) CubeSat Payload

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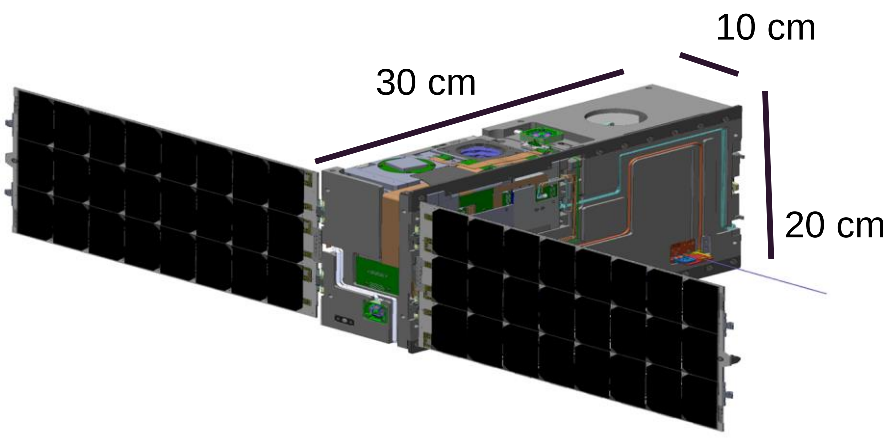
1. Massachusetts Institute of Technology, 2. Wellesley College, 3. Aurora Flight Sciences

Overview

- DeMi payload overview
- Integration progress
- Calibration and testing
- Conclusions



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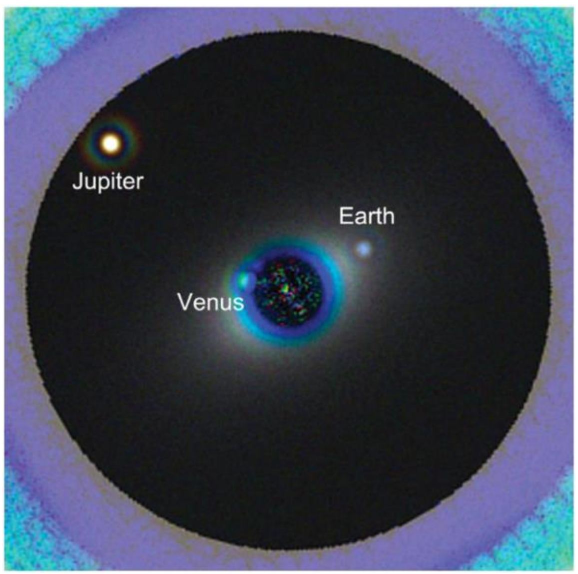
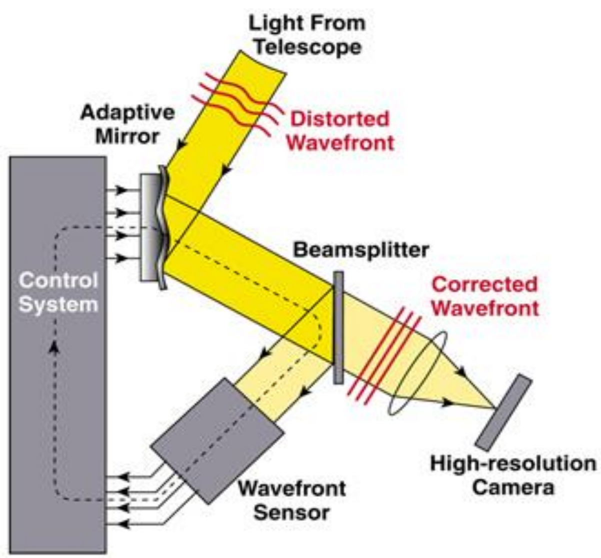
Motivation: Adaptive Optics in Space

- DeMi: Deformable Mirror Demonstration Mission
- Deformable mirrors correct aberrations and speckles due to mechanical, thermal, and optical effects as part of AO system
- Enables high wavefront stability required for exoplanet direct imaging with coronagraphs



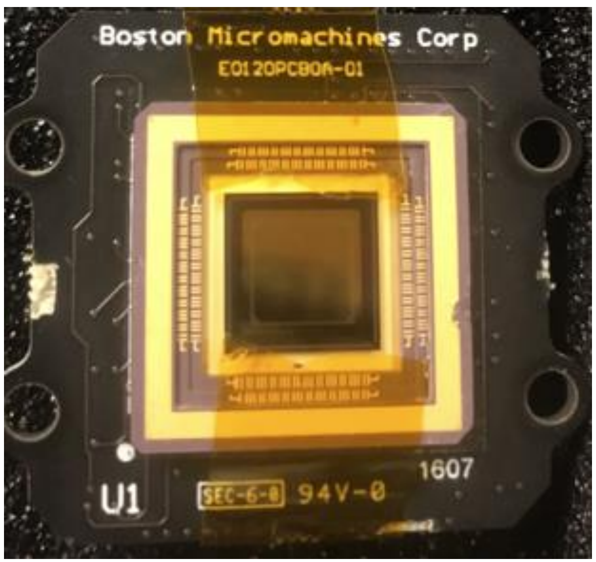
Pueyp and N'Diaye 2015

Simulation of inner solar system imaged through 12m HDST with Apodized Pupil Lyot Coronagraph at 13.5 parsecs (~44 ly)



Claire Max CfAO

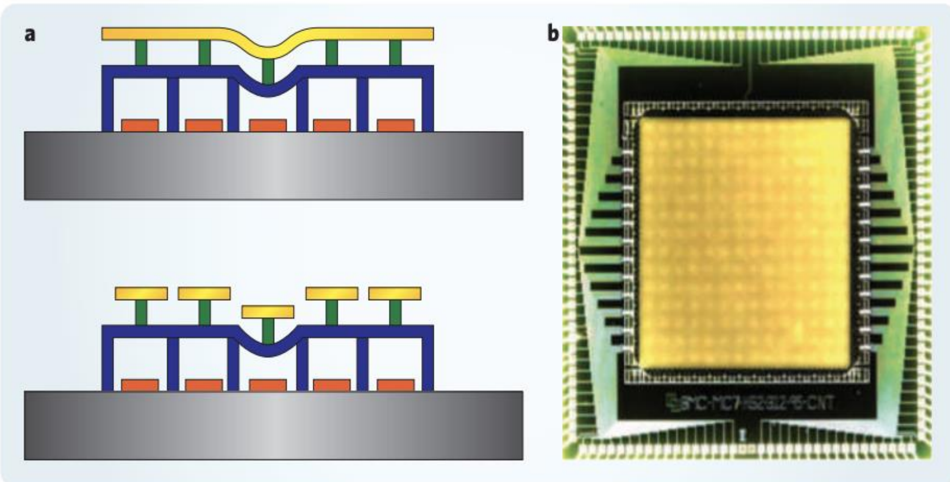
Diagram of typical AO (adaptive optics) system



Boston Micromachines Corporation

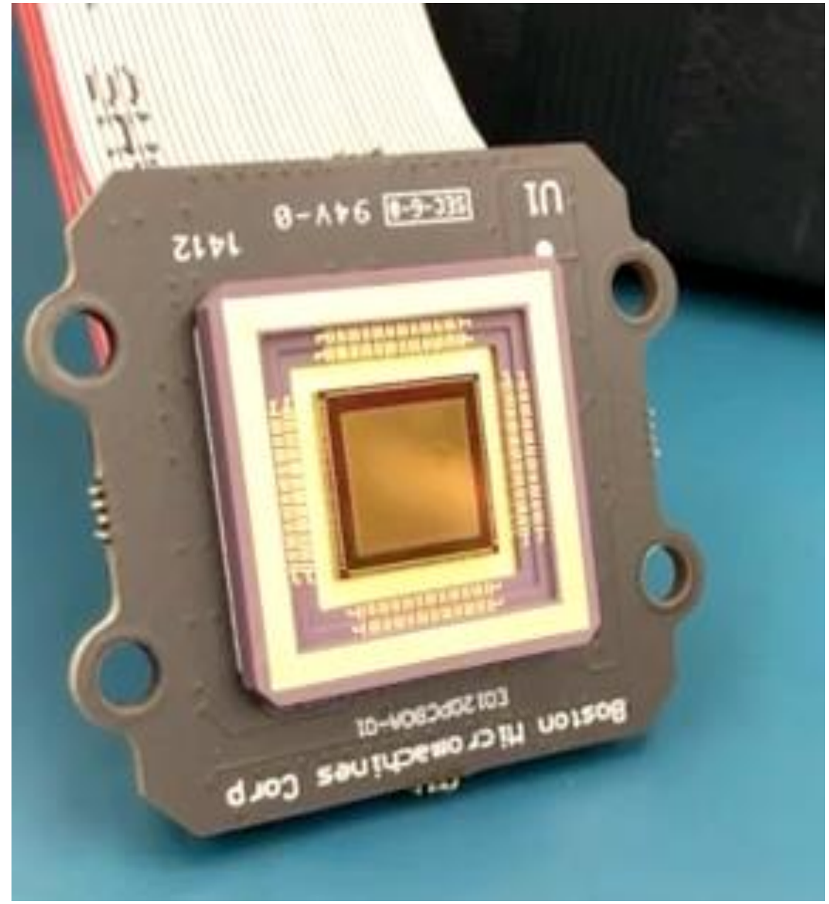
DeMi BMC Kilo 140-actuator DM

Deformable Mirrors Background



BOSTONMICROMACHINES

Credit: Bifano 2011



(Above) MEMS DM Design

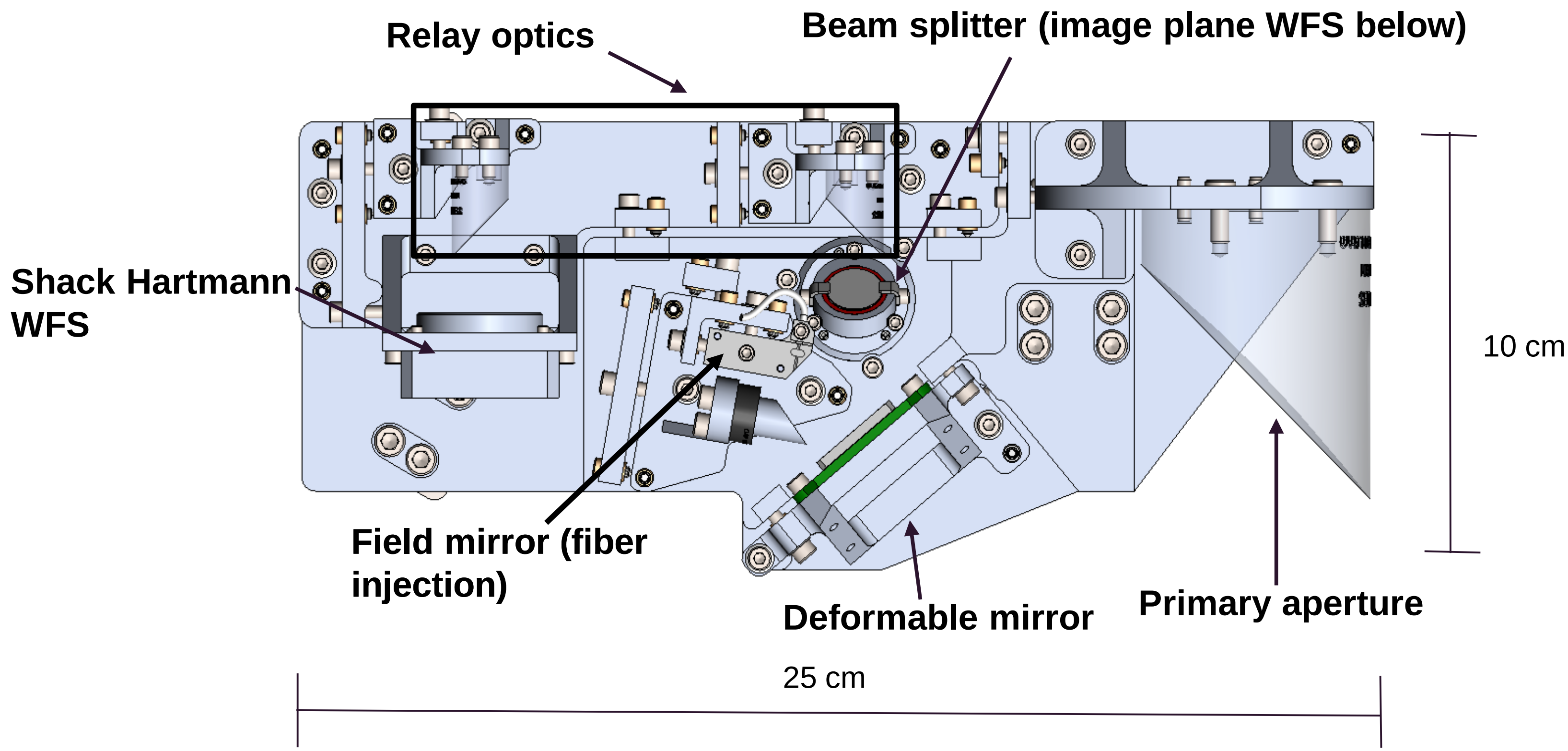
(Right) Video of poke test of DeMi DM

- DeMi space technology demonstration mission will show MEMS DM performance response to **launch vibrations**, **space radiation effects, orbital thermal environment, and long duration space operations**

DeMi Mission Overview

CubeSat mission objectives:

1. On-orbit characterization of 140-actuator BMC MEMS deformable mirror
2. On-orbit demonstration of closed-loop mirror control using both a Shack Hartmann and an image plane wavefront sensor
3. Improve the point spread function (PSF) of an astronomical source



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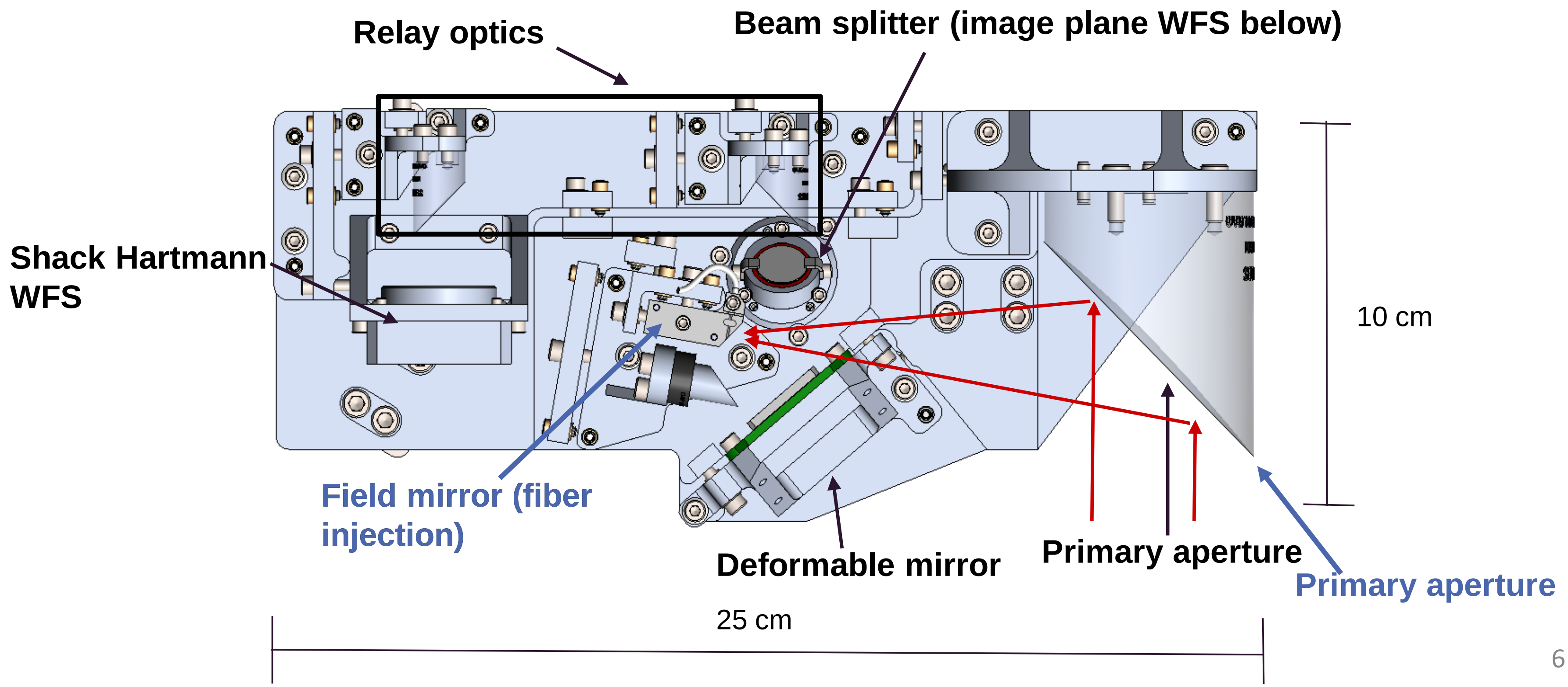

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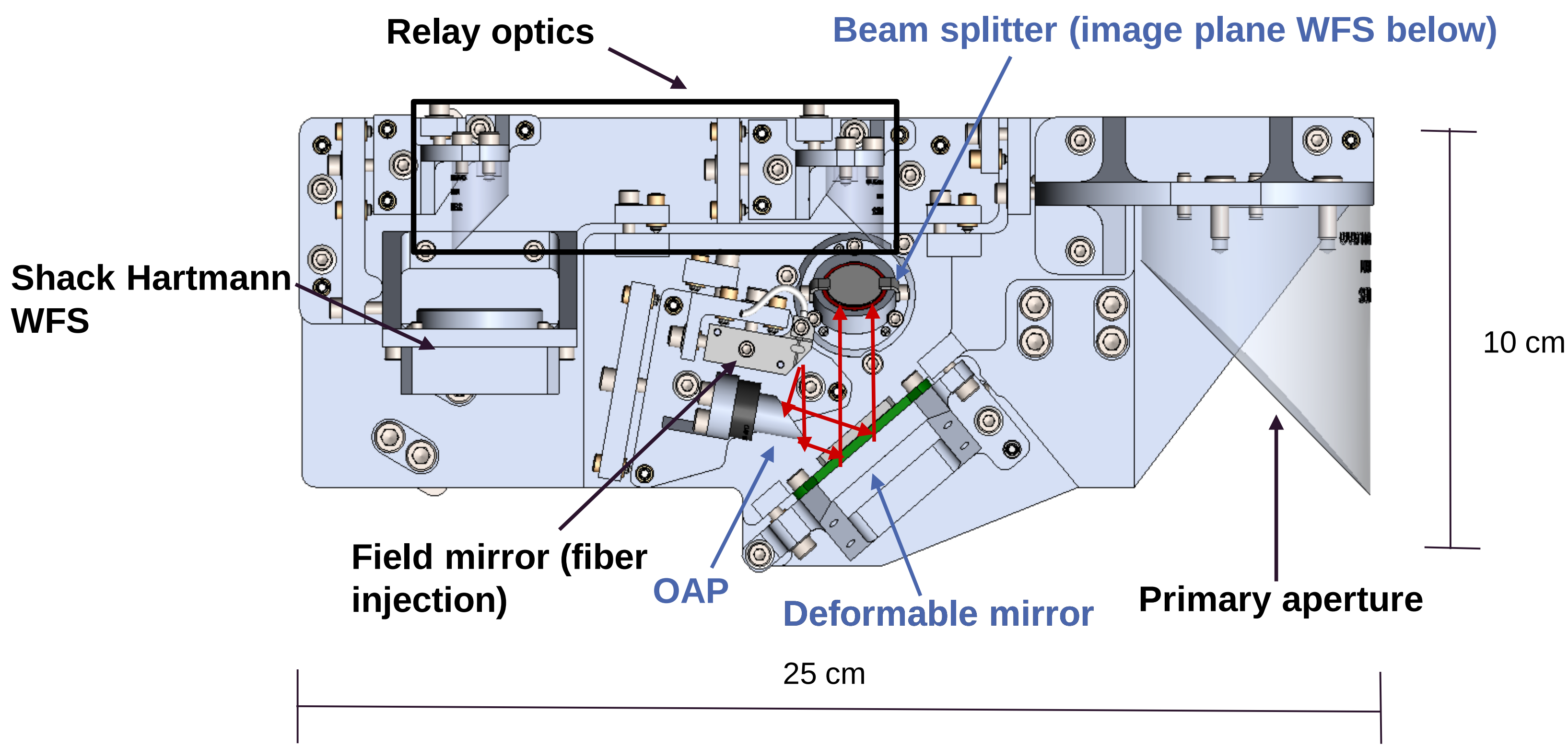

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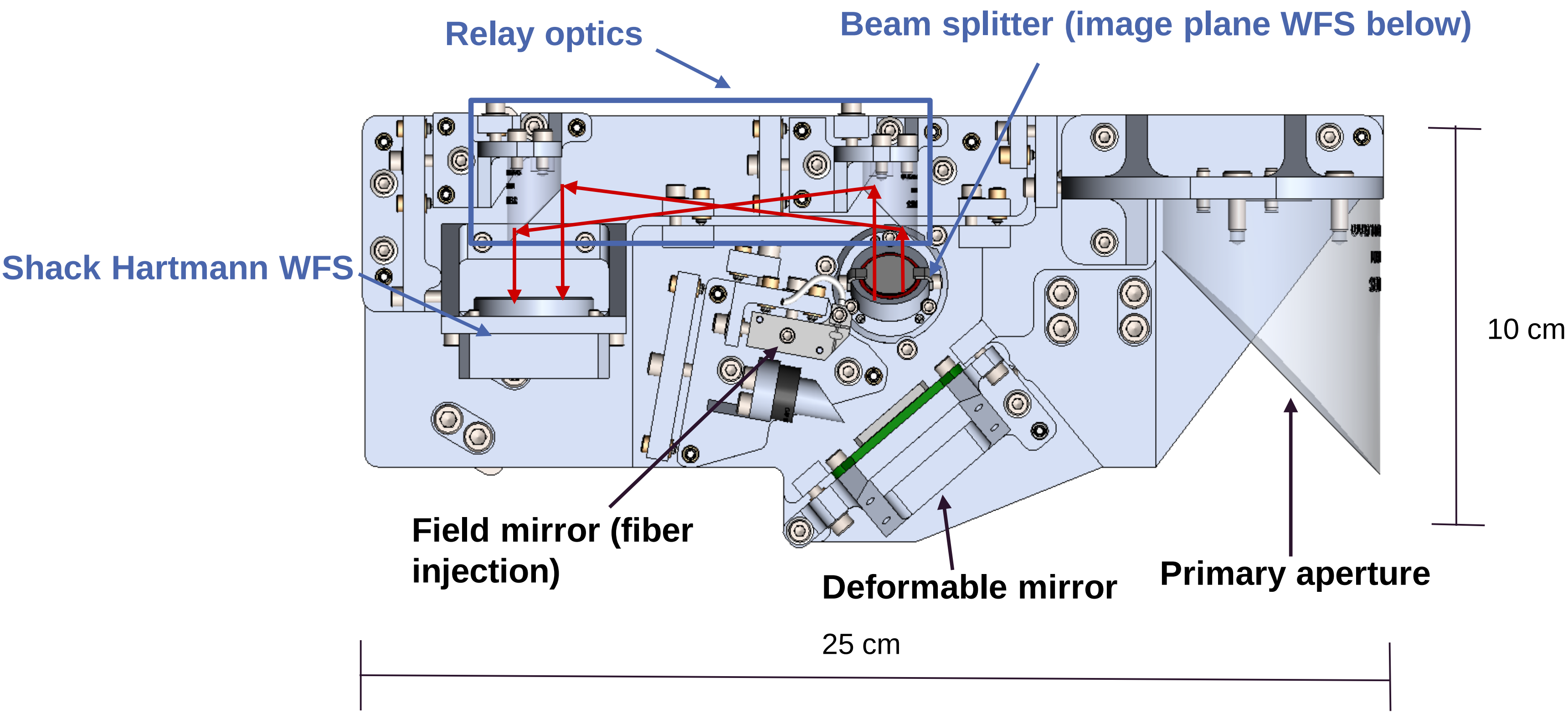
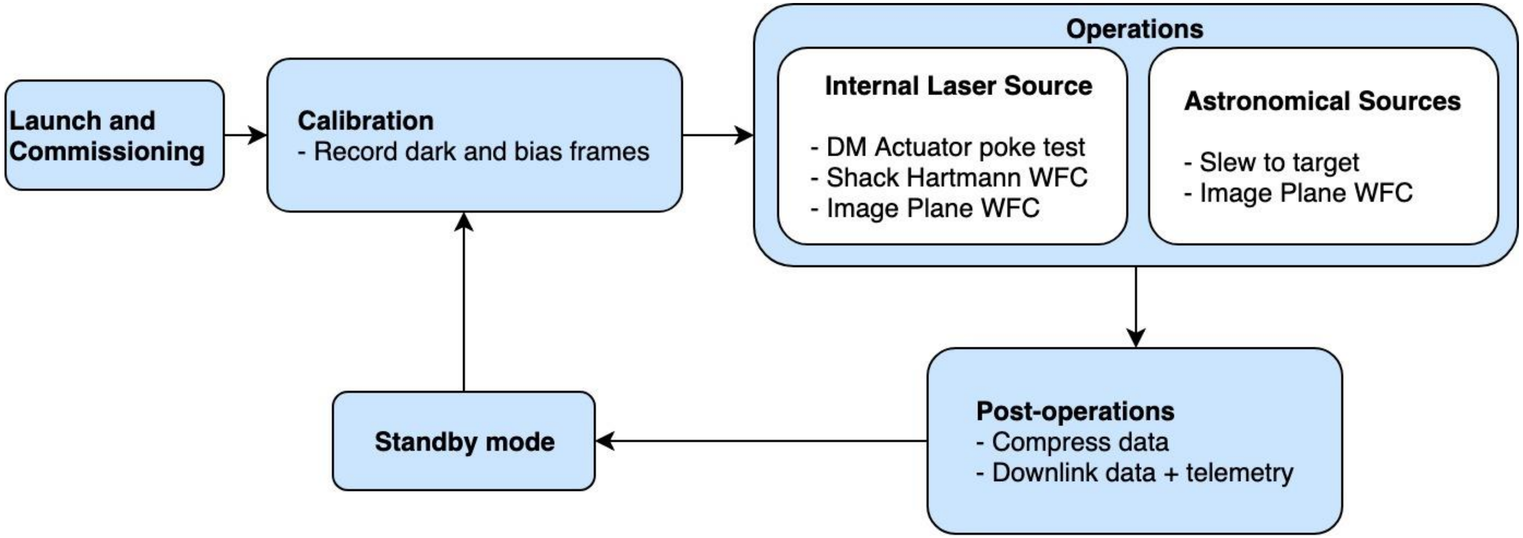
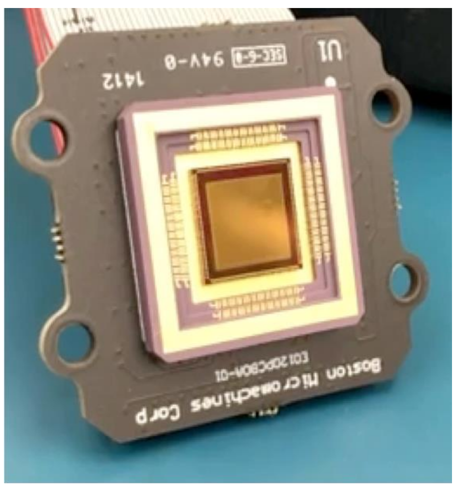


Summary of Science Reqt's

- Key mission requirements:
  - Measure individual actuator contributions to wavefront error **to 12 nm precision**
  - Measure low order wavefront aberrations to **lambda/10 accuracy and lambda/50 precision**
  - Correct static and dynamic wavefront errors with magnitudes below 3.5 microns to **less than 100 nm RMS**
  - **6 months** of on-orbit operations
  - Raise MEMS DM TRL from **5 to at least 7**
  - Monitor the current drawn by each high voltage amplifier

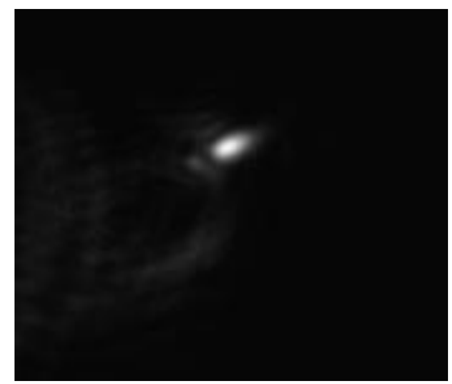
DeMi Concept of Operations





Deformable Mirror with actuator poked

Example spots on Shack Hartmann Wavefront Sensor (spot displacements → wavefront slopes)



Example PSF on Image Plane Wavefront Sensor (measurements with different DM shapes → wavefront shape)

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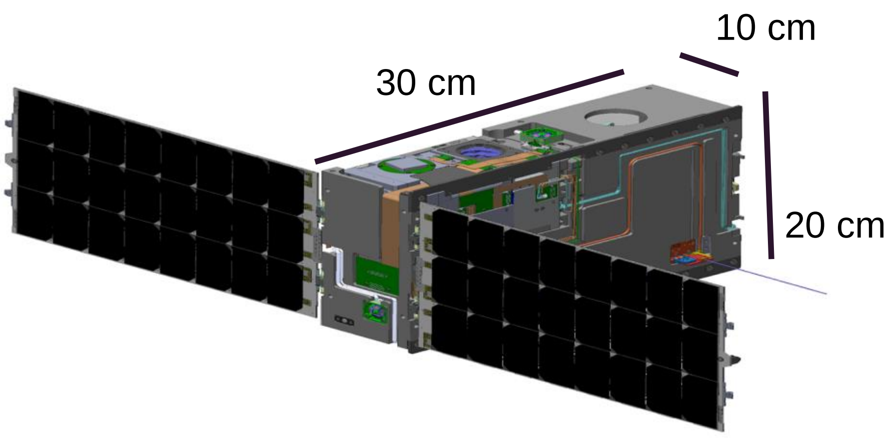

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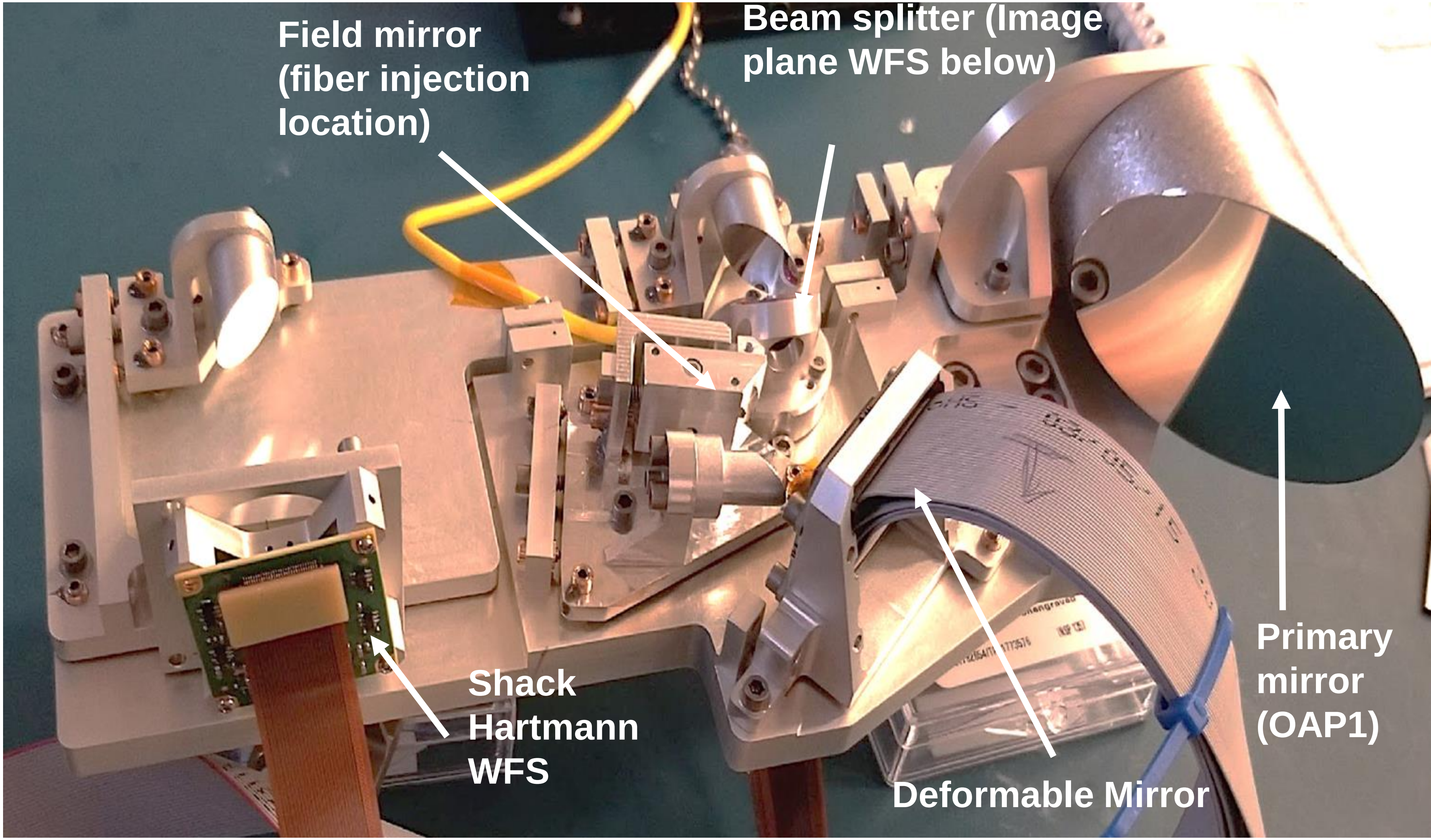
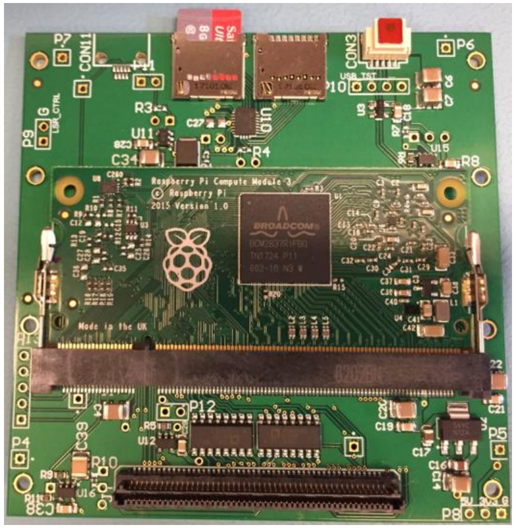
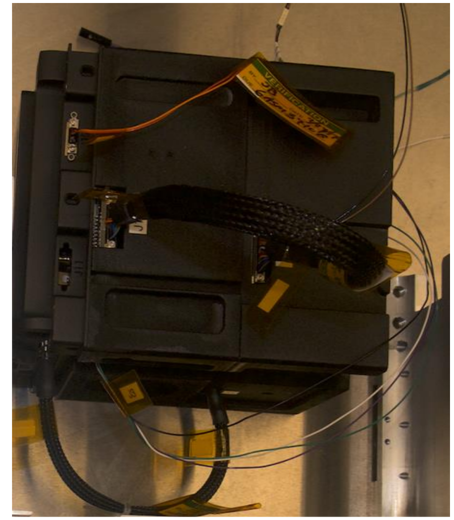
Integration Progress - EM



Electronics Integration



2 redundant cross-strapped Raspberry Pi 3s used for payload computers



BCT payload bus simulator for electronics end-to-end testing

23 cm x 18 cm x 6 cm

Miniaturized driver electronics to run DM

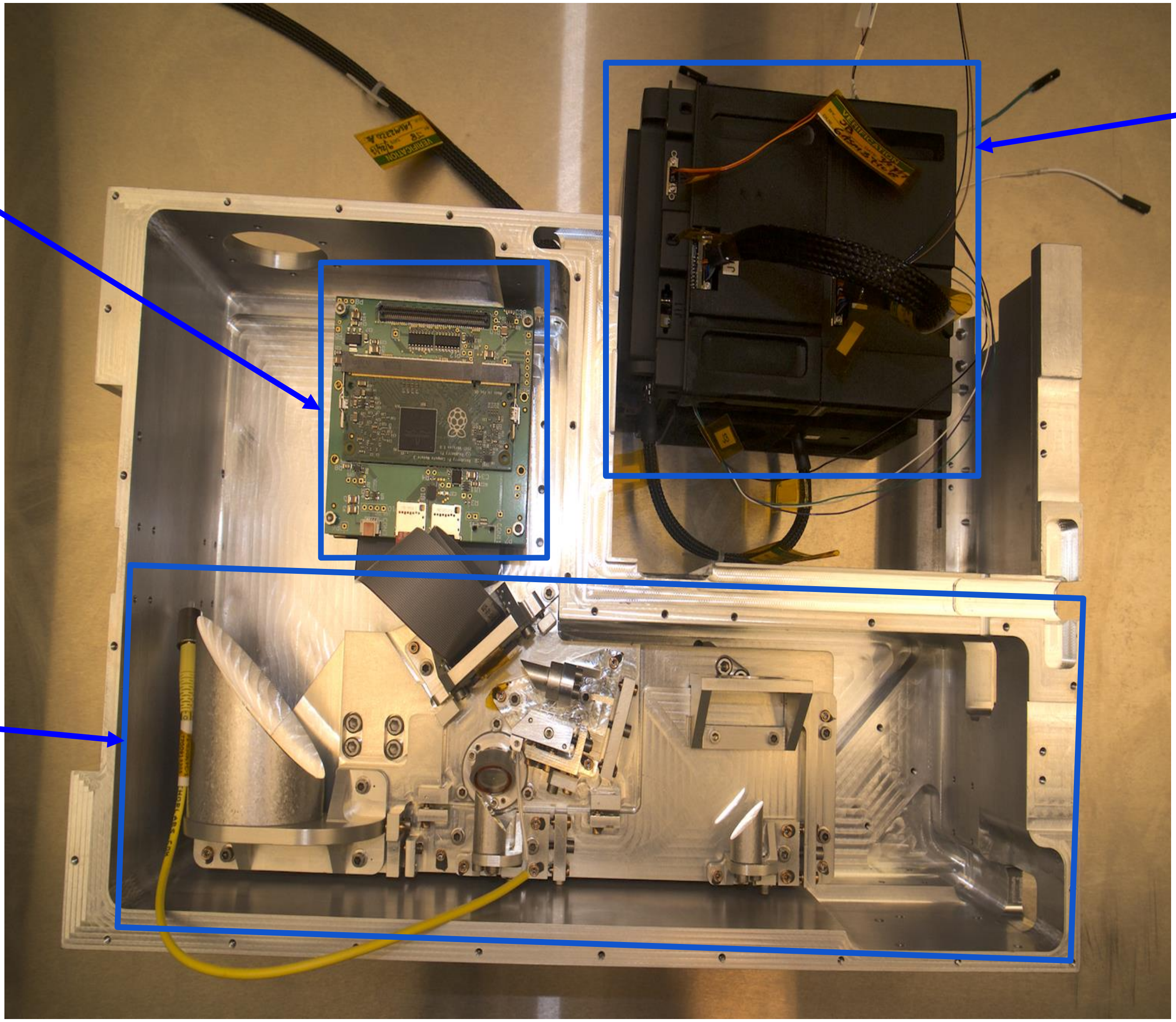
8 cm x 7 cm x 1 cm

Bus Integration

Payload electronics

BCT bus simulator

DeMi payload



Dimensions: 3U x 6U
Total mass: 12 kg
Payload mass: 2.5 kg

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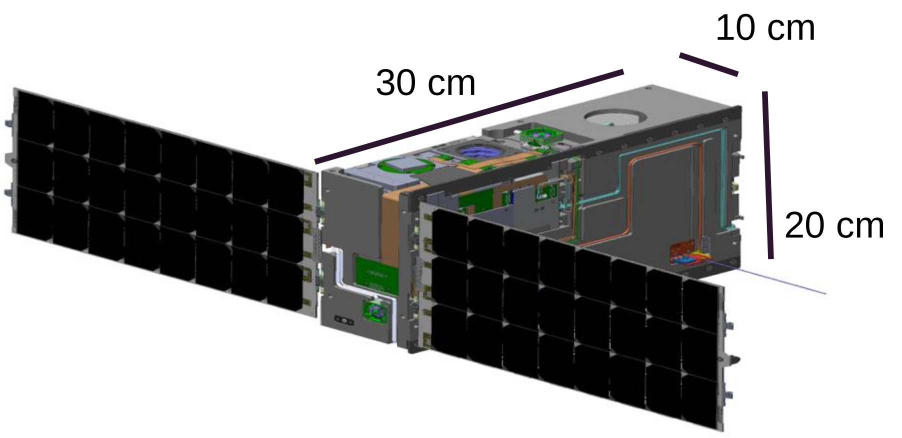

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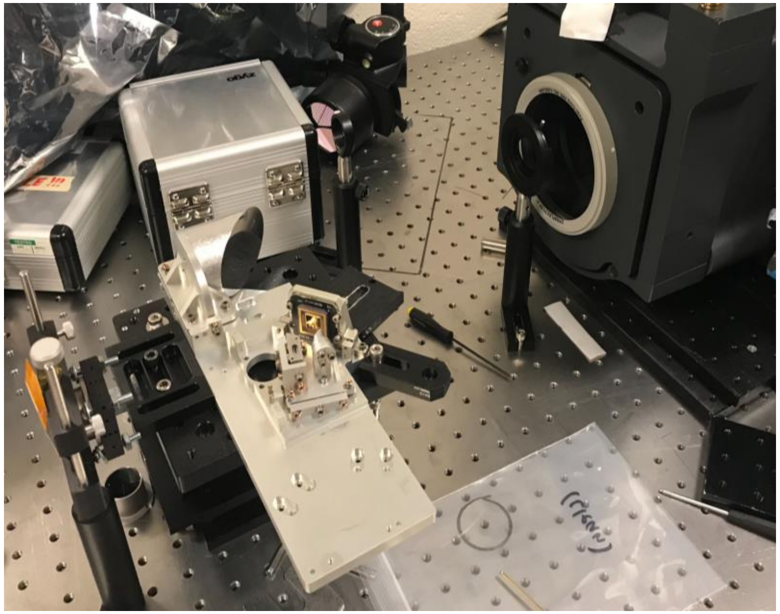
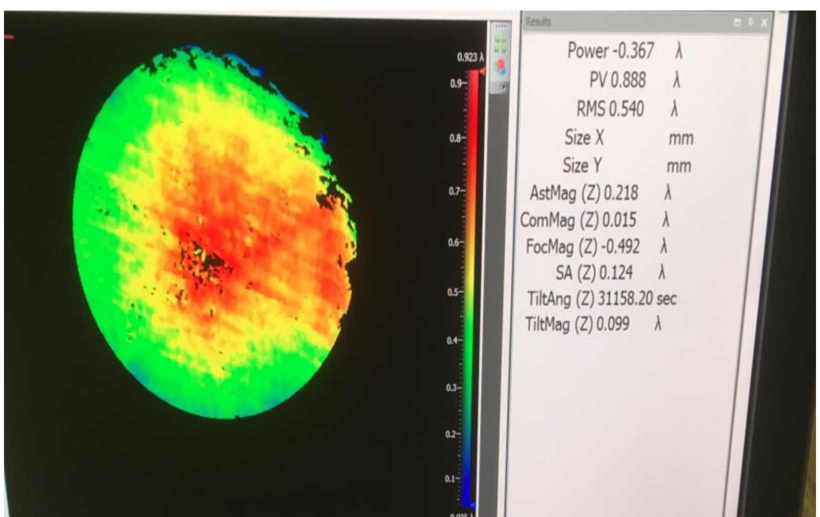
Payload Alignment





- Payload aligned with Zygo interferometer
- Started from primary OAP and iterated through system
- Made some mechanical modifications along the way to incorporate into the final flight design

(Top) alignment test setup with Zygo interferometer
(Bottom) example alignment measurement

Operational Testing

- Validating wavefront sensing and control with both wavefront sensors using internal laser source
- Results of DM poke tests:

Shack Hartmann WFS

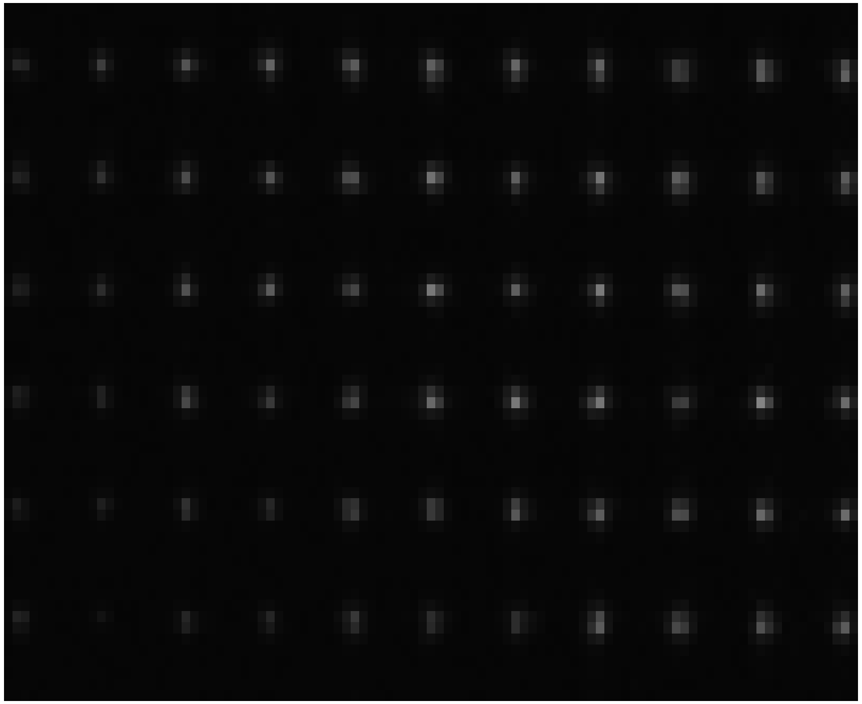
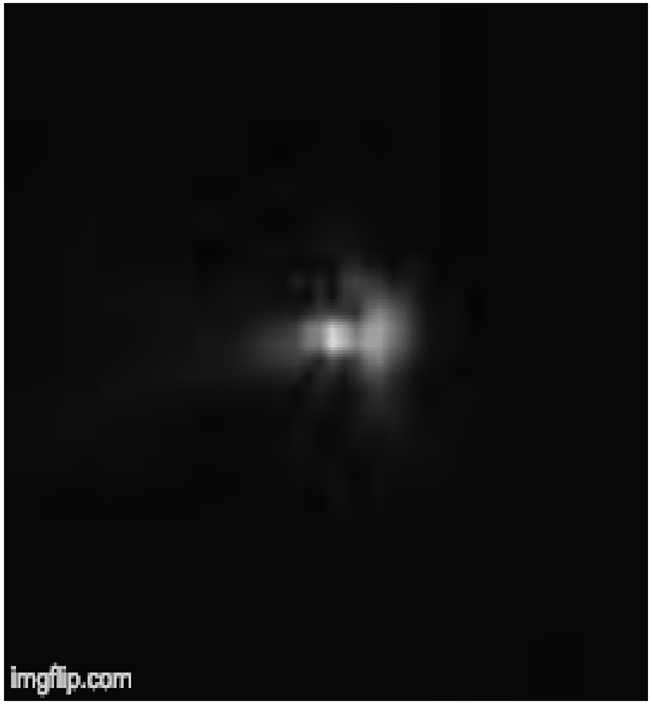


Image Plane WFS



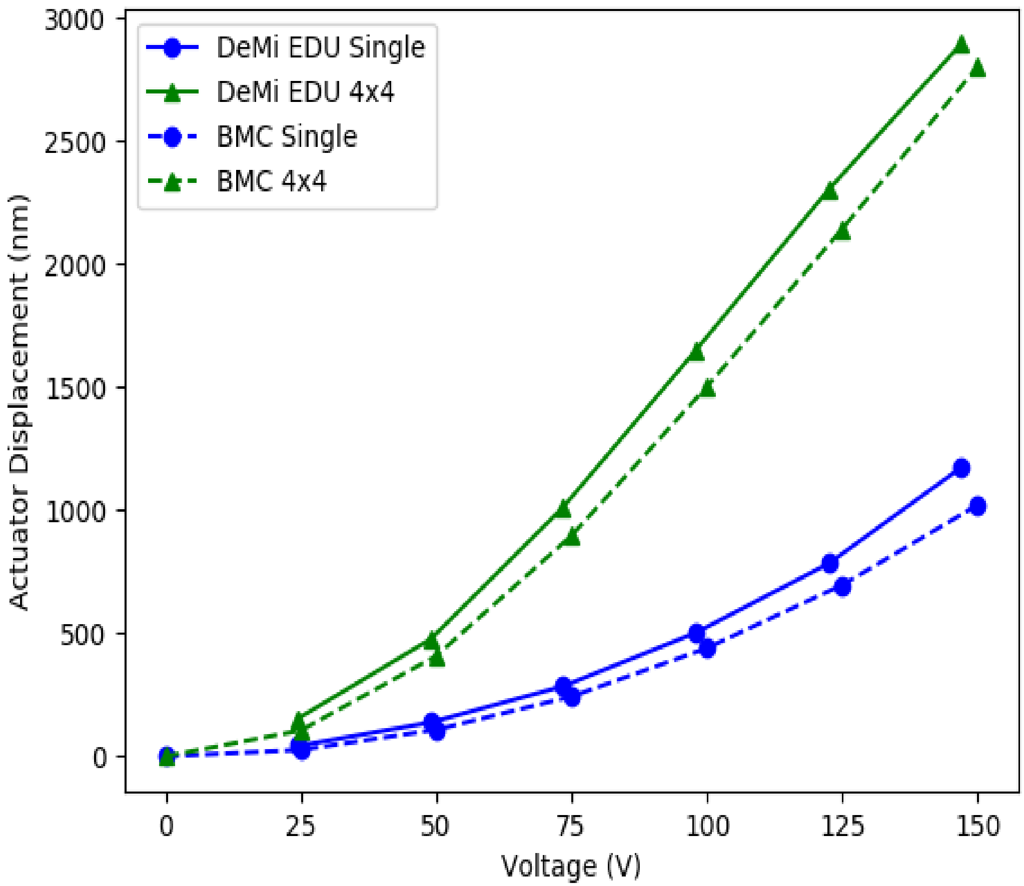
Tip/Tilt control of the DM

Tip/tilt control of the DM measured on the image plane wavefront sensor

Wavefront Sensor Calibration

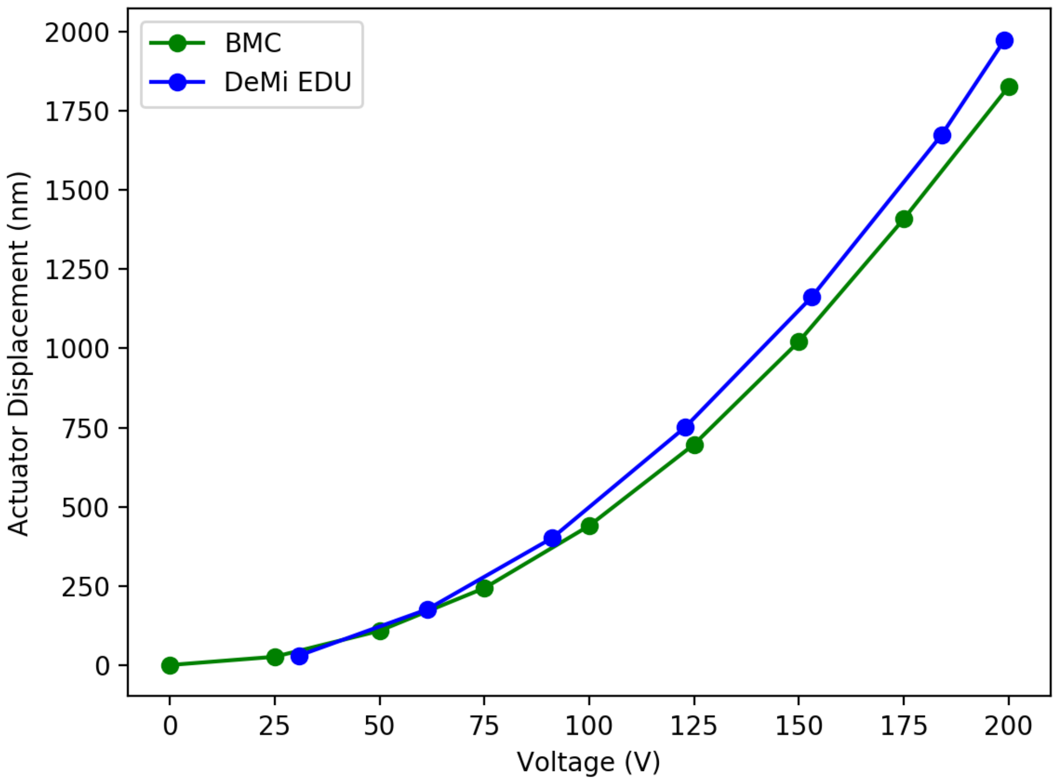
Testing procedures:

1. Displace single actuator (or 4x4 region) on DM
2. Collect frames on SHWFS
3. Measure spot displacements (average 10 frames, darks subtracted)
4. Plot actuator displacement vs applied voltage, compare to reported values from BMC



Mean differences:
Single actuator – 80.6 nm
4x4 region – 145.1 nm

DM Driver testing



- Actuator vs displacement curve for single actuator driven by DeMi miniaturized DM driver board
- Compared to BMC reported values
- Mean difference: 67 nm

Conclusions

- CubeSat payloads are an excellent platform to test new technologies in space
- DeMi can observe stars through a mini space telescope with AO
- Next steps:
  - More testing of wavefront sensors and DM control
  - Finish flight integration and environmental testing
  - Launch 2019 and on-orbit operations!

DeMi is sponsored by DARPA and managed by Aurora Flight Sciences (a Boeing Company)

References

- Bifano, Thomas. “MEMS Deformable Mirrors.” Nature Photonics Vol 5(1) 2011.

DeMi Payload Science Requirements

Requirement	Description
L2-SCI-01	The payload shall measure individual deformable mirror actuator wavefront displacement contributions to a precision of 12 nm.
L2-SCI-02	The payload shall measure low order aberrations to lambda/10 accuracy and lambda/50 precision.
L2-SCI-03	The payload shall demonstrate Deformable Mirror operation for longer than 6 months.
L2-SCI-04	The payload shall correct static wavefront phase errors up to the DM Nyquist spatial frequency with magnitudes below 3.5 microns to less than 100 nm RMS.
L2-SCI-05	The payload shall correct dynamic wavefront errors up to the DM Nyquist spatial frequency with magnitudes up to 3.5 um to less than 100 nm RMS.

DeMi Payload Science Requirements Con't

Requirement	Description
L2-SCI-06	The payload shall measure the PSF of stars brighter than Vmag =3 in the image plane with SNR of TBD sufficient to assess the RMS surface error to within 50 nm at spatial scales between 0-12 Lambda/D.
L2-SCI-07	The payload shall be capable of photometric precision of one part in ten thousand on stars brighter than 3rd magnitude during one orbit.
L2-SCI-08	The payload shall include both image plane and pupil plane sensors to measure the deformable mirror operation in space.
L2-SCI-09	The payload shall be capable of monitoring the current drawn by each high voltage amplifier.

BACKUP – DeMi parameters

Parameter	Value
BCT XB6 pointing stability	Sub-10 arcsec 1 sigma pitch and yaw
Deformable Mirror	BMC Multi 140-actuator continuous phase sheet, gold coated
DM stroke	1.5-5.5 um surface displacement
Primary aperture size	30 mm
Telescope magnification	7
Lenslet pitch (SHWFS)	150 um
Effective lenslet focal length (SHWFS)	3.7 um
Mirrors/optical bench material	Aluminum

BACKUP – Wavefront Sensing

- SHWFS wavefront reconstruction Zonal fit with Southwell geometry
- Singular-value decomposition Moore-Penrose pseudoinverse solution
- See Gregory Allan thesis: "Simulation and Testing of Wavefront Reconstruction Algorithms for the Deformable Mirror (DeMi) Cubesat," MIT 2018

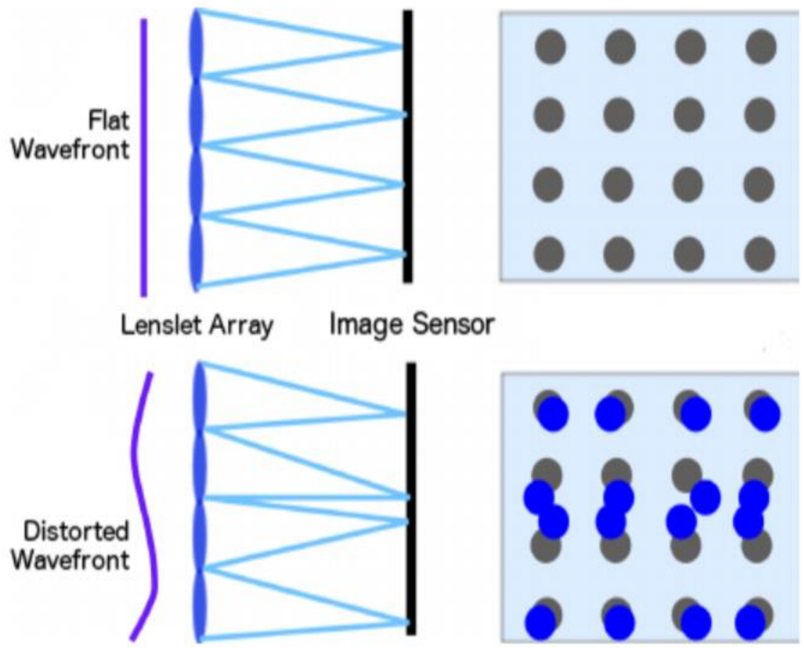


Image Plane wavefront sensing

- Differential Optical Transfer Function
- See Gregory Allan thesis: “Simulation and Testing of Wavefront Reconstruction Algorithms for the Deformable Mirror (DeMi) Cubesat,” MIT 2018

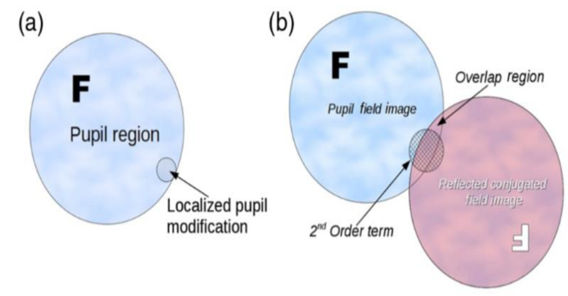


Figure 4-2: Illustration of the spatial distribution of the three terms of the dOTF. [3]

$$
\begin{aligned}
\delta\mathcal{O}(\xi) &= \mathcal{O}_{\psi+\delta\psi}(\xi) - \mathcal{O}_{\psi}(\xi) \\
&= (\psi + \delta\psi) * (\psi + \delta\psi)^* - \psi * \psi^* \\
&= \psi * \delta\psi^* + \delta\psi * \psi^* + \delta\psi * \delta\psi^*
\end{aligned}
$$

$$\delta\mathcal{O}(\xi) = \delta\mathcal{O}_L(\xi) + \delta\mathcal{O}_L^*(-\xi) + \delta\mathcal{O}_{\delta\delta}(\xi)$$

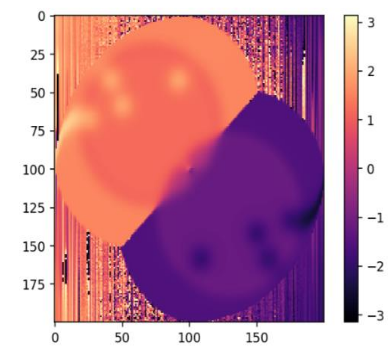


Figure 4-4: Unprocessed, simulated dOTF result, showing the two linear terms of the dOTF are spatially distinct except for overlap at the point of the pupil perturbation. Four actuators are displaced by $\lambda/4$, plus an additional actuator as the dOTF phase perturbation. The expected pupil phase is visible in each term. The spatial axes are given in pixels and the color scale is in radians of wavefront phase.