SSC20-III-06

Thermomechanical design and testing of the Deformable Mirror Demonstration Mission (DeMi) CubeSat

Paula do Vale Pereira, Bobby Holden, Rachel Morgan, Jennifer Gubner, Thomas J. Murphy, Christian Haughwout, Gregory Allan, Yinzi Xin, William Kammerer, Kerri Cahoy
Massachusetts Institute of Technology
Department of Aeronautics and Astronautics
77 Massachusetts Avenue, Cambridge, MA 02139
paulavp@mit.edu, kcahoy@mit.edu

Ewan Douglas
Department of Astronomy, Steward Observatory
University of Arizona, Tuscon, AZ
douglase@arizona.edu

John Merk
Aurora Flight Sciences, Cambridge, MA
merk.john@aurora.aero

Mark Egan, Gabor Furesz
Department of Physics
Massachusetts Institute of Technology, Cambridge, MA
mdegan@mit.edu

ABSTRACT

The Deformable Mirror Demonstration Mission (DeMi) is a 6U CubeSat that will operate and characterize the on-orbit performance of a Microelectromechanical Systems (MEMS) deformable mirror (DM) with both an image plane and a Shack-Hartmann wavefront sensor (SHWFS). Coronagraphs on future space telescopes will require precise wavefront control to detect and characterize Earth-like exoplanets. High-actuator count MEMS deformable mirrors can provide wavefront control with low size, weight, and power. The DeMi payload will characterize the on-orbit performance of a 140 actuator MEMS DM with 5.5 µm maximum stroke, with a goal of measuring individual actuator wavefront displacement contributions to a precision of 12 nm. The payload is designed to measure low order aberrations to λ/10 accuracy and λ/50 precision, and correct static and dynamic wavefront phase errors to less than 100 nm RMS. The thermal stability of the payload is key to maintaining the errors below that threshold. To decrease mismatches between coefficients of thermal expansion, the payload structure is made out of a single material, aluminum 7075. The gap between the structural components of the payload was filled with a thermal gap filler to increase the temperature homogeneity of the payload. The fixture that holds the payload into the bus is a set of three titanium flexures, which decrease the thermal conductivity between the bus and the payload while providing flexibility for the payload to expand without being deformed. The mounts for the optical components are attached to the main optical bench through kinematic coupling to allow precision assembly and location repeatability. The MEMS DM is controlled by miniaturized high-voltage driver electronics. Two cross-strapped Raspberry Pi 3 payload computers interface with the DM drive electronics. Each Raspberry Pi is paired to read out one of the wavefront sensor cameras. The DeMi payload is ~4.5U in volume, 2.5 kg in mass, and is flying on a 6U spacecraft built by Blue Canyon Technologies. The satellite launch was on February 15, 2020 onboard a Northrop Grumman Antares rocket, lifting off from the NASA Wallops Flight Facility. We present the mechanical design of the payload, the thermal considerations and decisions taken into the design, the manufacturing process of the flight hardware, and the environmental testing results.

INTRODUCTION

The Deformable Mirror Demonstration Mission (DeMi) is a CubeSat technology demonstration mission to provide on-orbit data for a Microelectromechanical Systems (MEMS) Deformable Mirror (DM). MEMS DMs are a promising technology that can support the precise wavefront control required for future exoplanet direct imaging space missions.

Direct imaging can enable detailed characterization of exoplanets by gathering astrometric and spectroscopic data to study exoplanet orbits and atmospheres.[1] Coronagraphic instruments are used to block the light of the star so the dim planet can be resolved. Coronagraphic direct imaging requires precise control of the optical system. For instance, resolving an Earth-like planet orbiting a Sun-like star requires contrasts of 10^{-10}, which translates to picometer-level control of the optical wavefront.[2] Adaptive optics systems can provide this level of control by measuring optical aberrations and precisely controlling a deformable mirror to correct them. Adaptive optics systems are used for ground telescopes to correct for atmospheric turbulence[3] and are proposed for future space telescopes to correct for thermal and mechanical effects on the instruments and spacecraft in the space environment.[4] MEMS DMs are a promising technology for space-based adaptive optics because of their small size, high actuator density, and low power requirements. [5]

MEMS DMs are batch manufactured out of layers of conducting and insulating polysilicon films and then selectively etched to form individually addressable actuators. The DeMi mission will fly a Boston Micromachines Corporation (BMC) continuous facesheet MEMS DM with 140 electrostatically controlled actuators. A BMC MEMS DM was at least briefly powered and actuated in near-space on the Planet Imaging Coronagraphic Technology Using a Reconfigurable Experimental Base (PICTURE-B) sounding rocket mission.[6] Other types of optical MEMS devices have flown at high altitudes or in low-Earth orbit, such as a micromirror on the MEMS Telescope for Extreme Lightning (MTEL) satellite[7] and the microshutter array for the Far-UV Off Rowland-circle Telescope for Imaging and Spectroscopy (FORTIS) sounding rocket mission.[8]

The goal of the DeMi mission is to raise the Technology Readiness Level (TRL) of MEMS DMs from 5 to at least 7. The key payload requirements are to measure individual DM actuator wavefront displacement contributions to a precision of 12 nm, measure low order optical aberrations to $\lambda/10$ accuracy and $\lambda/50$ precision, and correct static and dynamic wavefront errors to less than 100 nm root-mean-square (RMS) error.[9] The DeMi mission will demonstrate that MEMS DMs can survive the vibrational, thermal, and radiation effects of launch and long duration operations in space.[10]

DeMi will be deployed from the International Space Station (ISS) via a NanoRacks CubeSat Deployer.[11] The orbit in which DeMi will be inserted is at about 410 km altitude and 51.6° inclination.[11] In this orbit, DeMi will circle around the Earth once every 1.5 hours, being in eclipse for about half that period, and in sunlight for the other half. The cyclic thermal profile creates intense stresses and very limiting boundary conditions for the payload. These considerations have to be taken into account while designing a satellite payload.

The launch of a satellite is another important environmental constraint: during the launch, the spacecraft is subjected to heavy vibration loads both laterally and longitudinally. The loads are dependent on the launch provider and the stowing configuration of the spacecraft into the rocket. These loads have to be taken into account while designing and testing the spacecraft.[12]

PAYLOAD OVERVIEW

The DeMi payload design is described in detail in Allan *et al.* 2018[13] and briefly summarized here. The DeMi optical design is essentially a miniature space telescope with an adaptive optics instrument, but without a coronagraph. The primary mirror is a 50 mm diameter, 100 mm focal length off axis parabola (OAP) that focuses external starlight light onto a field mirror, where an internal calibration laser source is injected. The light from either an external target or the internal laser calibration source is collimated by another OAP and reflects off of the 140-actuator continuous facesheet BMC MEMS DM (note that in the flight configuration, not all actuators are fully illuminated). A non-polarizing 50/50 beamsplitter splits the light. Half of the beam is focused onto an image plane wavefront sensor (WFS), which measures the point-spread function (PSF) to monitor the wavefront correction and measure tip-tilt errors. The rest of the light bounces off of a pair of relay OAPs of 12.7 mm diameter and 15 mm focal length, and is measured by a Shack Hartmann WFS, which uses a lenslet array to focus the light into spots on the detector and measures the spot displacements to calculate the shape of the wavefront. The Shack-Hartmann wavefront sensor uses the Moore-Penrose pseudoinverse approach to perform zonal reconstruction of the wavefront. Figure 1 shows the DeMi optical design with the ray trace overlaid.

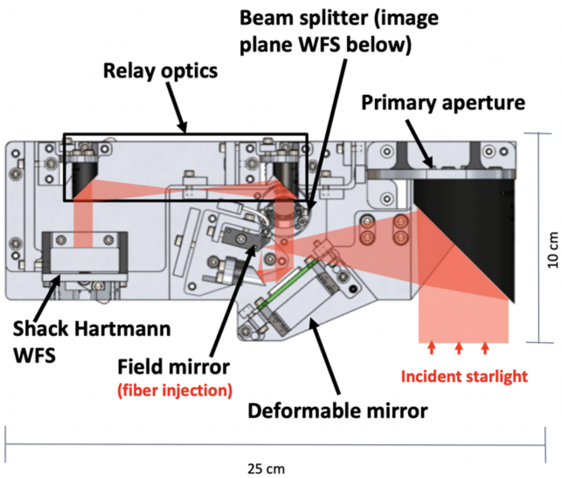


Figure 1: DeMi optical design with ray trace overlaid in red. Figure reproduced from Morgan *et al.* 2019.[4]

The DeMi payload has two operational modes, one that looks at an internal calibration target laser source, and the other that looks at external astronomical sources, e.g., star targets. To observe external star targets, the spacecraft will slew to point at a star and use the image plane WFS for closed-loop control of the DM to correct tip-tilt errors. The PSFs collected by the image plane WFS will be used to collect photometric measurements of stars with V band magnitudes less than 3. The internal laser calibration source will be used to measure the performance of the DM over time by poking each actuator and measuring the resultant wavefront on the Shack Hartmann WFS. The internal laser calibration source will also be used to demonstrate wavefront control using the Shack Hartmann WFS for closed-loop control of the DM while measuring the PSF on the image plane WFS to monitor the results. The DeMi concept of operations is summarized in Figure 2.

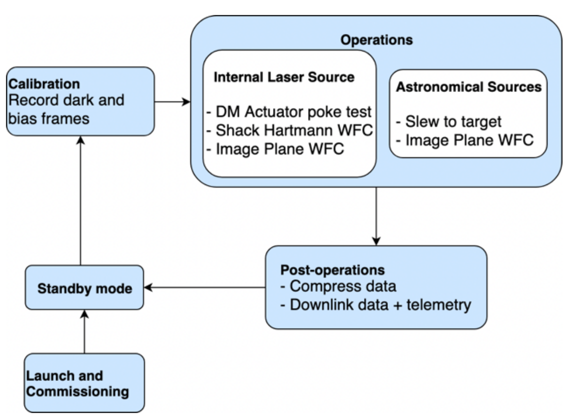


Figure 2: Summary of DeMi payload concept of operations. Reproduced from Holden *et al.* 2019.[14]

The spacecraft communicates with the UHF ground station on the MIT campus in Cambridge, MA, and with the ground station on the NASA Wallops Flight Facility in Virginia. More information on the communication strategy and electronics design, including the payload on-board computer and the DM driver architectures, can be found in Holden *et al.* 2019.[14]

THERMOMECHANICAL DESIGN

The payload mechanical structure and thermal strategy are designed to resist the environmental constraints mentioned in the Introduction, while maintaining the alignment and stability required for the payload's successful operation. This section explains the considerations taken into account during the thermomechanical design of DeMi.

Mechanical Considerations

The foremost and most important requirement for the structure is to provide the optical path necessary to achieve the MEMS DM payload measurement goals. The position and angle of each optical component needs to be aligned to a fraction of a wavelength, as the misalignment wavefront error budget was of a quarter of a wavelength to maximize the stroke available for active control. As it is not possible to achieve such precision levels in usual machining processes, the payload had to be separated into multiple components that could be mounted without full restrictions of all the 6 degrees of freedom. The final position adjustment of the degrees of freedom that impact the system wavefront error would be performed in the assembly stage, using precision optical measurement equipment, such as Zygo Interferometer, and fine-pitch precision screws. Hence, the payload is composed of 5 subassemblies that combine 16 individually machined parts: 3 of which have 3 adjustable degrees of freedom (DoF) and 4 of which have 5 adjustable degrees of freedom. The underlying optical bench is a monolithic piece to increase structural rigidity. Figure 3 shows each machined component of the DeMi structure in a different color to improve understanding.

The four OAPs are mounted to the payload through two different features: aligning pins and screws. The two aligning pins ensure that the axis of each OAP is precisely positioned to its mount, and the three screws tightly hold them together. The DM, the WFS, and the Shack Hartmann WFS are attached to their respective mounts through 4 screws. Lastly, the field mirror is secured through 2 screws and adjusted by 4 fine-pitch precision screws.

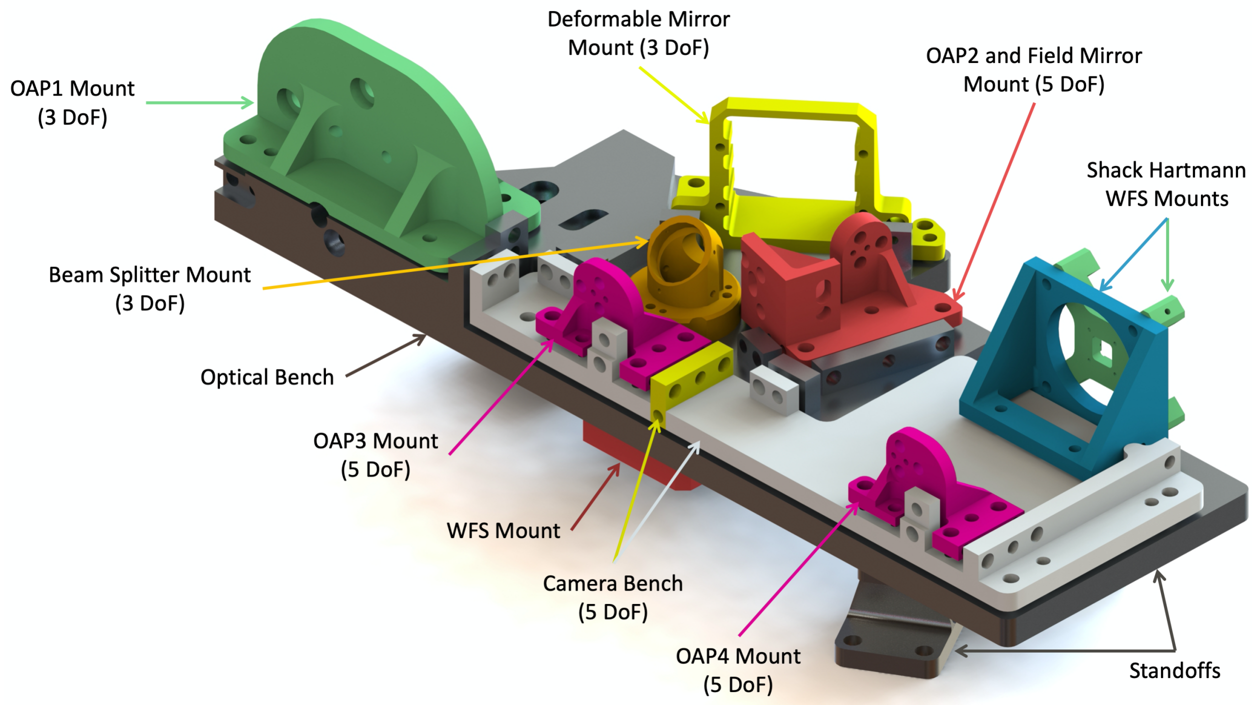


Figure 3: DeMi CAD showing each machined structural component in a different color.

It is important that none of the payload components get overconstrained. To allow for a precise and repeatable assembly without overconstraining, all payload components use kinematic mounting: the contact between each pair of parts are performed by six spheres, which touch the surface at virtually only one point. On the degrees of freedom that need adjustability, the sphere is placed at the end of a Thorlabs M2.5 x 0.20 fine-pitch screw. To pretension the components in place, Belleville washers are used with each screw.

A finite element analysis was performed in SolidWorks to demonstrate that all interfaces would survive the vibration loads of the launch environment. The RMS vibration amplitudes were applied as a simulated 100g static load applied along each axis simultaneously. This load was chosen to be more conservative than the requirements of the NASA General Environmental Verification Specification (GEVS),[12] which represents a 3-sigma case of applied acceleration due to launch-induced vibrations. The resulting reaction forces on each of the fasteners were analyzed for failure modes such as bolt shear and tension failure, bolt head pull-through, and bolts near part edges shearing through the sides of their holes. The preload tension required to prevent gapping between parts under these loads (as explained in NASA's Fastener Torque Guidelines[15]) requires fasteners made of stainless steel with more than 100 ksi tensile strength, such as A286. The screws were also all certified according to the National Aerospace Standard (NAS). All failure modes except gapping have margins greater than a factor of 3. As a non-critical failure, a safety factor above 1.8 was deemed to be acceptable for gapping.

The torque applied to preload the screws is also a function of the friction between the screw's thread and the female thread. As the friction increases, the percentage of the applied torque that is being used to keep two components together decreases. The usage of lubricant on the screw thread is critical.

The preparation of the screws started with ultrasonic cleaning for 30 minutes: 10 minutes in soap water, 10 minutes in distilled water, and 10 minutes in isopropyl alcohol. Right before each screw installation, a drop of Braycote 601EF (a high vacuum grease, often used in space applications) was applied to the surface of the male thread. After installation, alignment, and verification, the screw heads were staked with the 3M epoxy 2216 B/A. The staking of the screw heads prevents the screws from coming loose in high vibration level situations.

The optical bench is attached to the bus through three 6Al-4V titanium stand-off flexures, which form an exact constraint and allow the payload to survive launch-induced vibrations.

Both the engineering and the flight models were machined at the Boston University Scientific Instrument Facility. All the structural components were made of aluminum 7075 and anodized to increase the resistance to oxidation in the highly oxidizing space environment. Figure 4 shows the DeMi engineering model and Figure 5 shows the DeMi flight model, already installed into the spacecraft bus.

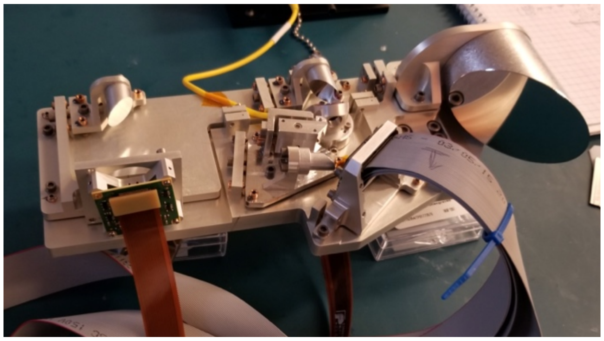


Figure 4: DeMi engineering model.

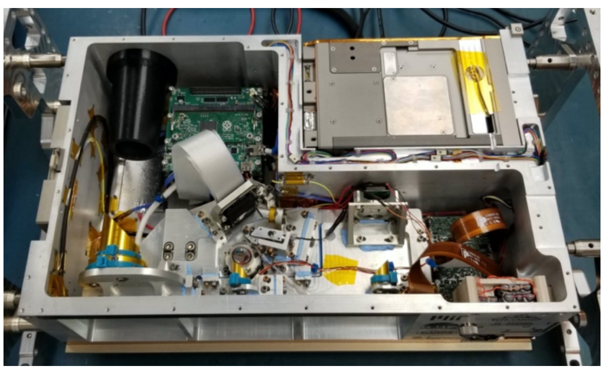


Figure 5: DeMi flight model installed in the spacecraft.

Thermal Considerations

Mismatches on the coefficient of thermal expansion of different components in an assembly can cause significant deformation and degrade the optical quality of the measurements when the temperature of the assembly changes.[16] To make sure the focal lengths and position adjustments of each payload component do not change with temperature variations along the satellite's orbit, the OAP mirrors, the field mirror, and the major structural components are all made of the same material, aluminum.

To enhance the heat transfer between the structural components of the assembly that are kinematically mounted, thermal gap filler (Bergquist TGF3600) was added between the components to create a thermal interface where not much heat transfer would be possible otherwise. Figure 6 shows how the thermal gap filler was applied.

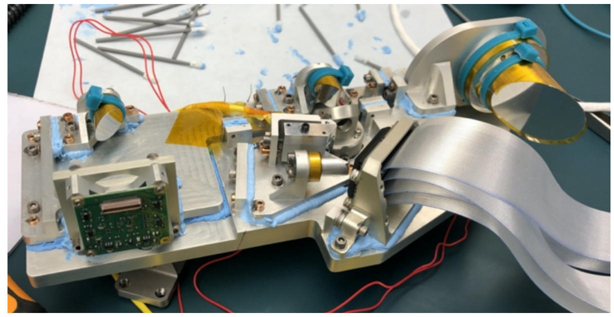


Figure 6: DeMi flight model with thermal gap filler applied between aluminum structural components.

The three 6Al-4V titanium stand-off flexures that mount the payload into the satellite bus also perform two important roles in the thermal design on DeMi:

1. They give the optical bench the flexibility it needs to allow for thermal expansion and contraction during orbit without inducing undesired deformations onto the payload;
2. They allow the payload to be virtually thermally insulated from the bus, as the thermal conductivity of titanium is significantly smaller the that of aluminum, and the cross-sectional area of the standoffs is only of about 10^{-5} m^2.

Thermal analysis was performed for the DeMi payload to assess the temperature ranges that components will experience during all stages of the mission. In order to maintain the thermoelastically induced misalignments as negligible, all optical elements and the bench are required to maintain their absolute temperature to 20°C ± 4°C during operational periods (up to 1000 seconds) and temperature gradients must be less than 2°C between optical components. The DeMi payload must maintain temperatures within the survival ranges of all components at all times. Two 2.5 W heaters were added to the payload to actively maintain the component temperature requirements. The heaters are located on the underside of the optical bench.

Using the bus provider (Blue Canyon Technologies) data, five cases were identified as bounding thermal cases and were modeled in Thermal Desktop: hot operational, hot storage, cold operational, cold storage, and commissioning. More details on the thermal model can be found in Allan *et al.* 2018[13]. It is important to note

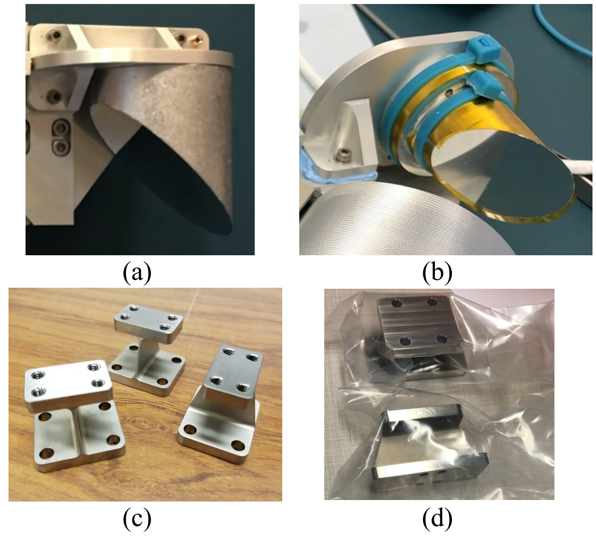
that for all cases examined, the DeMi payload components remained within their required temperature limits and the thermal stability during operational periods was found to be ±1°C across the optical bench and mounted optical components.

THERMOMECHANICAL TESTING

Before manufacturing the flight model, a preliminary vibration test was performed on the engineering model to verify the level of the first natural frequency of the payload. A sine sweep was performed from 30 Hz to up to 2000 Hz, at a 2.5 g average acceleration level. Figure 7 shows the Labworks Inc. shaker, the mounting plate designed and built for this test, and the engineering model of the DeMi payload.

Figure 7: DeMi engineering model and mounting plate before the preliminary payload vibration test.

The test confirmed what the finite element analysis had predicted: a natural frequency at about 400 Hz, which could be excited during launch and potentially hurt the structural integrity of the payload. To resolve this problem, the diameter of the primary OAP was reduced from 50 mm to 30 mm to decrease the cantilevered mass by 54%. The the standoff under that OAP was also modified: it was enlarged to increase the stiffness of that section of the payload. The calculated natural frequency for the modified assembly raised to approximately 700 Hz and DeMi was successful in its final vibration test. Figure 8 shows the changes performed to the mirror and the standoff.



(a) (b) (c) (d)

Figure 8: Adaptations to increase the first natural frequency of the DeMi payload. (a) original OAP1 mirror; (b) OAP1 mirror with reduced size; (c) original standoffs; (d) enlarged standoffs.

After the final assembly, the DeMi flight model, with the payload integrated into the spacecraft bus, went through environmental testing. The CubeSat successfully passed thermal vacuum after three cycles of hot dwell at 58°C and cold dwell at -18°C. DeMi also passed the 3-axis vibration testing following the NanoRacks soft-stow vibration profile.

MISSION STATUS

The DeMi spacecraft was integrated into the NanoRacks CubeSat Deployer on December 12th, 2019. Figure 9 shows the final visuals on DeMi before it was integrated into the deployer. The assembly was successfully launched on February 15th, 2020 inside the Northrop Grumman NG-13 Cygnus capsule and captured by the ISS on February 18th. The satellite is currently in the ISS and is expected to be deployed into orbit in July 2020.

CONCLUSIONS

The DeMi payload integration and testing was successful, the spacecraft launch was successful, and DeMi is currently in the ISS. The DeMi team is working on preparing the ground station and planning the operations for when DeMi gets deployed and commissioned. The flight results from this mission will provide useful data for future space telescopes that plan to use MEMS deformable mirror technology.

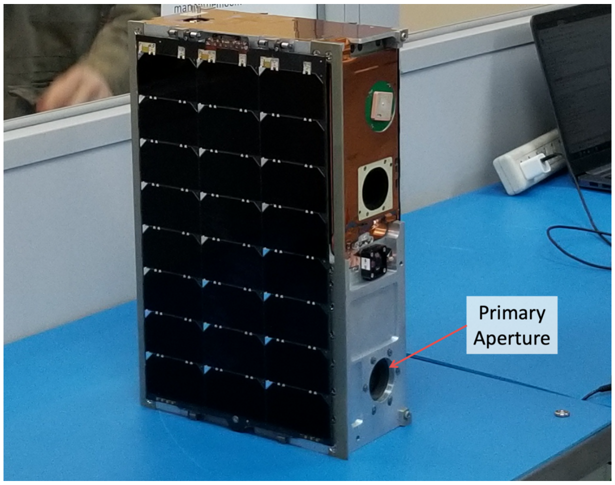


Figure 9: DeMi CubeSat right before being integrated to the NanoRacks deployer.

References

1. Wesley A Traub, Ben R Oppenheimer, and Sara (Ed.) Seager. Direct Imaging of Exoplanets. In *Exoplanets*, pages 111–156. 2010.
2. Bijan Nemati, Mark T. Stahl, H. Philip Stahl, and Stuart B. Shaklan. Effects of space telescope primary mirror segment errors on coronagraph instrument performance. In *Proceedings of SPIE 10398 UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts* VIII, 2017.
3. H. W. Babcock. The Possibility of Compensating Astronomical Seeing. *Publications of the Astronomical Society of the Pacific*, 65(386):229–236, 1953
4. Rachel E. Morgan, Ewan S. Douglas, Gregory W. Allan, Paul Bierden, Supriya Chakrabarti, Timothy Cook, Mark Egan, Gabor Furesz, Jennifer N. Gubner, Tyler D. Groff, Christian A. Haughwout, Bobby G. Holden, Christopher B. Mendillo, Mireille Ouellet, Paula do Vale Pereira, Abigail J. Stein, Simon Thibault, Xingtao Wu, Yeyuan Xin, and Kerri L. Cahoy. Mems deformable mirrors for space-based high-contrast imaging. *Micromachines*, 10(6), 2019.
5. Christian Haughout. Electronics Development for the Deformable Mirror Demonstration Mission (DeMi). Master's Thesis, Massachusetts Institute of Technology, 2018.
6. Ewan S. Douglas, Christopher B. Mendillo, Timothy A. Cook, Kerri L. Cahoy, and Supriya Chakrabarti. Wavefront Sensing in Space: Flight Demonstration II of the PICTURE Sounding Rocket Payload. 4(1), 2018.
7. S. Nam, S. Artikova, T. Chung, G. Garipov, J. A. Jeon, S. Jeong, J. Y. Jin, B. A. Khrenov, J. E. Kim, M. Kim, Y. K. Kim, P. Klimov, J. Lee, H. Y. Lee, G. W. Na, S. J. Oh, M. Panasyuk, I. H. Park, J. H. Park, Y. S. Park, B. W. Yoo, and H. J. Yoo. A telescope for observation from space of extreme lightnings in the upper atmosphere. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 588(1-2):197–200, 2018.
8. Brian T. Fleming, Stephan R. McCandliss, Keith Redwine Martin, Mary Elizabeth Kaiser Adrian, Jeffery Kruk, Paul D. Feldman, Alexander S. Kutyrev, Mary J. Li, S. H. Moseley, Oswald Siegmun, and John Vallerga. Calibration and flight qualification of FORTIS. In *Proceedings of SPIE 8859: UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy* XVIII, 2013.
9. Gregory W Allan. Simulation and Testing of Wavefront Reconstruction Algorithms for the Deformable Mirror (DeMi) Cubesat. Master's Thesis, Massachusetts Institute of Technology, 2018.
10. Kerri L. Cahoy, Anne D. Marinan, Benjamin Novak, Caitlin Kerr, Tam Nguyen, Matthew Webber, Grant Falkenburg, and Andrew Barg. Wavefront control in space with MEMS deformable mirrors for exoplanet direct imaging. *Journal of Micro/Nanolithography, MEMS, and MOEMS*, 13(1), 2013
11. NanoRacks. ISS CubeSat Deployment. Available online at: https://nanoracks.com/products/iss-cubesat-deployment/. Accessed on May 30, 2020.
12. Milne, J. S. and Kaufman, D. S. General Environmental Verification Specification. Available at: https://ntrs.nasa.gov/search.jsp?R=20030106019 (Jan. 2003).
13. Gregory Allan, Ewan S. Douglas, Derek Barnes, Mark Egan, Gabor Furesz, Warren Grunwald, Jennifer Gubner, Bobby G. Holden, Christian Haughwout, Paula do Vale Pereira, Abigail J. Stein, and Kerri L. Cahoy. The Deformable Mirror Demonstration Mission (DeMi) CubeSat: Optomechanical Design, Validation, and Laboratory Calibration. 1069857(August 2018):180, 2018.

14. Bobby Holden, Rachel Morgan, Gregory Allan, Paula do Vale Pereira, Warren Grunwald, Jennifer Gubner, Christian Haughwout, Abigail J. Stein, Yinzi Xin, and Kerri Cahoy. Calibration and Testing of the Deformable Mirror Demonstration Mission (DeMi) CubeSat Payload. *SmallSat Conference*, 2019.

15. NASA. Mechanical Fastener Torque Guidelines, directive number 540-PG-8072.1.2-A, 2011.

16. Paula do Vale Pereira, Matthew T. Hunwardsen, Kerri Cahoy. Characterization of laser thermal loading on microelectricalmechanical systems-based fast steering mirror in vacuum. *Optical Engineering* 59(5), 2020.