Improving Nanosatellite Imaging with Adaptive Optics

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ABSTRACT
Active and adaptive wavefront control can be useful on space platforms for a variety of observation applications. For example, to achieve high contrast imaging to a level of 1e-10 with a coronagraph (required to image an Earth-like planet around a Sun-like star), space telescopes require high spatial frequency wavefront control systems. To achieve intersatellite links through the atmosphere, wavefront correction is needed to counter the effects of atmospheric turbulence and scintillation. For deployable apertures, active correction is desired to properly align and calibrate optical systems. Deformable mirrors (DMs) are a key element of a wavefront control system, as they correct for imperfections, thermal distortions, and diffraction that would otherwise corrupt the wavefront and ruin the measurement. High-actuator count mirrors are required to achieve the desired level of correction on space telescopes, but this key technology lacks spaceflight heritage. The goal of the CubeSat Deformable Mirror (DeMi) technology demonstration mission is to characterize a microelectromechanical system (MEMS) deformable mirror and to demonstrate its ability to perform modest wavefront correction on a nanosatellite platform.

DeMi is a 6U CubeSat that houses a 2U optical payload. The payload is a custom optical bench with a Boston Micromachines deformable mirror and custom-modified driver electronics to fit within a CubeSat system. The payload is expected to draw <8 W when enabled. The payload has both an external aperture and internal laser diode as well as a focal plane sensor and Shack-Hartmann wavefront sensor. The remaining volume in the CubeSat is reserved for the supporting bus, which uses a combination of COTS components and custom interface boards to provide power, pointing knowledge and control, position knowledge, thermal stability, command and data interface, and communications.

In this paper, we present the payload design and describe two key applications: (1) as a component technology demonstration of MEMS DMs for next-generation space telescopes, and (2) as a component technology demonstration for small satellite intersatellite optical links (for either communications or atmospheric sounding laser occultation). We also present results from a payload laboratory hardware demonstration and describe progress towards the flight design and build for this CubeSat mission.

INTRODUCTION
Nanosatellites are becoming increasingly important to Earth-based observation and atmospheric characterization. CubeSats in particular are improving in capability, and small-satellite launch capabilities are providing realistic opportunities for constellations of such satellites to be deployed. The 2007 National Academy of Sciences Decadal survey calls out the importance for improved weather monitoring and a need for “increased accuracy, reliability, and duration of forecasts with finer spatial and temporal detail for a wider array of weather variables.” Measurements of interest include all-weather atmospheric sounding with 15 to 30 minute revisits and 25 km ground resolution, radio occultation measurements at 200 m vertical resolution with ~2500 measurements globally per day,
and overall increases of global composition and pollutant measurements. There is both a scientific and commercial interest in remote sensing, and several start-ups have based their operations on generating data for interested end users (agriculture, government, military, scientific) using constellations of micro- and nanosatellites.5

Small satellites and nanosatellites, specifically CubeSats, offer the opportunity to improve global measurements. Constellations of small satellites in low earth orbit (LEO) can enable global coverage and improved temporal resolution and concurrent measurements at geographically diverse locations compared with large monolithic satellites in higher orbits, though typically at the expense of reduced spatial resolution due to their comparatively small apertures, and reduced precision, or accuracy due to the widespread use of COTS components. In this paper we address uses of nanosatellites in the improvement of atmospheric sensing and characterization. We focus on technology demonstration of key components in adaptive optics systems that can be applied to both Earth and exoplanet characterization experiments.

The next section gives an overview of adaptive optics and its usefulness for space applications. We highlight the advantages of microelectromechanical systems (MEMS) deformable mirrors on satellite platforms and the challenges associated with operating and testing MEMS devices in a space environment. We also present two potential uses for adaptive optics: Earth atmospheric characterization through Intersatellite laser occultation, and exoplanet direct imaging. The CubeSat Deformable Mirror Demonstration is a 6U CubeSat flight mission to demonstrate the long-duration on-orbit performance of a MEMS deformable mirror. We present the operation overview, the payload design and laboratory validation, and the supporting bus design considerations.

Adaptive Optics
Adaptive Optics (AO) is a method for real-time correction of wavefront distortions that may affect the performance of an optical system. For signals that pass through the atmosphere, a typical cause of wavefront aberration is atmospheric turbulence, which encompasses changes in the atmosphere due to temperature, pressure, wind velocities, humidity, and temporal changes. In space, wavefront control systems are needed to correct for the effects of diffraction, manufacturing imperfections, the changes in an optical system after surviving launch and operating in a varying thermal environment (both local to the spacecraft, throughout the orbit, and as a function of pointing), and the structural and mechanical effects of actuators and the spacecraft attitude control system, such as jitter. A traditional adaptive optics system is illustrated in Figure 1.

![Figure 1: There are three main elements to an adaptive optics system: the deformable mirror, the wavefront sensor, and the control system.](image)

Typically an adaptive optics system contains three main elements: a deformable mirror to change the wavefront of light propagating through the system (see Figure 2), a wavefront sensor to measure distortion, and a control system to calculate the mirror deflection required to correct the wavefront.5

![Figure 2: Electrostatic DM actuator architectures: (Top) continuous facesheet and (Bottom) segmented apertures.](image)

Deformable mirrors (DM) are a key part of adaptive optics systems, and existing mirrors have been shown to correct wavefront aberrations to better than nm levels in ground operation. Frequently-used DM options currently include Xinetics piezoelectric and lead-magnesium-niobate (PMN) actuators, technology that is currently at NASA Technology Readiness Level 6.
Microelectromechanical Systems (MEMS) DMs, such as the devices manufactured by Boston Micromachines, are cheaper than piezoelectric devices, have smaller actuators (so more will fit across a given pupil), and do not exhibit hysteresis. The compact size of a MEMS DM of a given actuator count means the other optics in the system can also be smaller and lighter, which is beneficial for space-based systems. Another benefit of MEMS DMs versus conventional macro-scale DMs that use piezo or electro-restrictive actuators is that their capacitance is lower, so for comparable drive voltages they should consume less power. In practice, the amplifiers typically used in driver electronics have high slew rates that drive up the power requirements. For longer timescale applications, alternative drive electronics may be more efficient.

While a nanosatellite platform is perhaps not the best platform with which to achieve high-contrast imaging science of stars in the local solar system neighborhood, CubeSats offer a relatively low-cost, fast opportunity to space-qualify mission critical technologies. Flying adaptive optics systems on nanosatellite platforms paves the way for future flagship class missions or next-generation space telescopes, serving as technology demonstrations for larger platforms characterizing exoplanets with highly precise wavefront control systems.

Implementing active and adaptive optics on a nanosatellite platform is of interest to demonstrate and characterize MEMS deformable mirror in space. Adaptive optics can enable improvements in intersatellite links through the atmosphere, measuring the intensity and bending angle of these links (yielding atmospheric composition and atmospheric thermophysical parameters). Improvements in intersatellite links also can apply to crosslink communication, expanding the effective range for data transfer between satellites and supporting penetration deeper into the atmosphere. Elements of adaptive optics systems are also useful in alignment corrections for deployed or distributed aperture concepts.

**SPACE QUALIFICATION OF MEMS TECHNOLOGY**

To be considered space-qualified, a component must survive both the launch environment and long-term on-orbit operations. There are varying degrees to which NASA considers a technology space-qualified, and for typical missions, all component technology should be at or above Technology Readiness Level (TRL) 6 by the Preliminary Design Review. There are several testing methods and approaches to increasing space technology readiness. High-actuator count MEMS deformable mirrors are currently below TRL 6 for high contrast imaging applications, though there are several technology development efforts through NASA Ames, NASA JPL, and Boston Micromachines Corporation.

**Failure Modes**

Potential failure mechanisms for MEMS devices have been studied and presented in detail. For launch and on orbit operations of high actuator count MEMS deformable mirrors, the main concerns are:

- Mechanically-induced failures from launch loads
  - Detachment or plastic deformation of die attachments
  - Wire bond detachment from bond pads
  - Electrical shorting between adjacent wires
  - Plastic deformation or fracture of thin film elements
- Electrically-induced failures from on-orbit environment
  - Actuator stiction
  - Actuator unresponsiveness
  - Actuator drift
  - Variations in actuator gain
- Mechanically-induced failures from on-orbit environment
  - Break of hermetic seal; actuator ringing
  - Thermally-induced surface distortions
  - Jitter-induced surface distortions

**Testing Platforms**

Some of these failure modes can (and should) be addressed through ground tests and modeling, particularly launch-induced failures. The loads and environment for launch vehicles is very well understood, and testing profiles (vibration, acoustic, and shock) are available from launch providers. Any atypical launch configurations (e.g. helium purging) are also known ahead of time and can be successfully mimicked in ground testing. Ground testing is useful to observe mirror response to high radiation environments, and tests performed on similar devices (digital micromirror devices) showed that faults due to proton and heavy ion radiation do occur but are recoverable. Thermal vacuum testing is also useful, and MEMS deformable mirrors have been successfully tested in vacuum environments at NASA Ames.
High-altitude platforms such as balloons, sounding rockets, suborbital flights, and microgravity flights\textsuperscript{22} are useful platforms to test devices in near-space environments. Two sounding rocket experiments have flown MEMS deformable mirrors, and a high altitude balloon flight is planned.\textsuperscript{23,24,25} These tests verified short-term performance of MEMS devices in a low-altitude space environment. The positive results are encouraging for future space qualification, but they are not sufficient to evaluate the success of long-duration operation in a higher orbit. Test facilities on the International Space Station also offer fairly low-cost methods to further space-qualify components in a controlled (and comparatively benign) environment.\textsuperscript{26} A recent ISS test of MEMS micromirrors (different from the deformable mirrors identified in this paper) showed very promising performance during depressurization, heating, electrostatic charging, shock, and vibration tests.\textsuperscript{27}

Ground and sub-orbital tests are useful to identify and substantially mitigate known failure modes in space qualifying components. However, on-orbit qualification of critical components (such as MEMS deformable mirrors for high contrast imaging) is useful for establishing heritage and understanding how the device is expected to perform in its design environment. Ground-based facilities have been used to simulate elements of the space environment for over 40 years, but thermal vacuum chambers offer only approximate on-orbit conditions, and solar and radiation simulators do not provide the vacuum intensity or full energy spectrum of particles present on orbit.\textsuperscript{28} There is also the question of failure modes that occur due to interactions of several facets of the space environment that cannot be predicted or created on the ground.

One of the main challenges associated with on-orbit testing is the cost and complexity typically associated with space missions. Space-based platforms such as nanosatellites have the potential to bridge that gap and provide critical information about a component’s behavior in the space environment on a free-flying platform within an achievable cost and timeline. This approach requires careful consideration and design of the platform itself and the kinds of experiments and data that will provide sufficient information to characterize the component.

**APPLICATIONS FOR AO ON SPACE PLATFORMS**

Adaptive optics improve the quality and capabilities of imaging platforms and have a variety of applications both on the ground and in space. We focus on two applications of adaptive optics: (1) Earth atmospheric characterization through intersatellite optical links, and

(2) exoplanet direct imaging. Atmospheric sounding provides data on atmospheric thermophysics and composition that are used to improve global models of weather and climate patterns. Exoplanet detection and characterization is important for understanding the formation of our solar system and discovering if other habitable planets exist.

**Intersatellite Links**

Optical signals (visible to infrared) transmitted through the atmosphere experience “bending,” just as radio signals do, so in theory, optical occultations can provide the same atmospheric thermophysical parameters as radio occultations. In practice, however, measuring bending angles at optical and infrared wavelengths has not yet been done.\textsuperscript{29} The expected bending through the atmosphere for an IR signal at the surface is 0.1 to 1 degrees, and it decreases exponentially as a function of height. The required pointing knowledge on both spacecraft would need to be at the mrad level with position knowledge better than 2 km.\textsuperscript{11} For an IR signal, that bending angle would be measured directly on the detector. Implementing optical bending angle measurements from an intersatellite crosslink requires the development of a transmitter and receiver with accurate orbit determination, accurate attitude determination and fine control, and feedback between the two satellites. Research is ongoing to enable high-accuracy pointing requirements for laser communications applications using a dual-stage pointing architecture.\textsuperscript{30} The fine pointing stage in the dual-stage system\textsuperscript{30} uses a fast steering mirror. The mirror is also a MEMS device, though unlike a deformable mirror it features tip/tilt actuation of the entire mirror.

The main challenges in obtaining cross-linked optical occultation measurements on a nanosatellite platform are:

- Accounting for scintillation, beam spread, and pointing offsets caused by atmospheric turbulence
- Resilience to clouds in the crosslink path
- For intersatellite links, maintaining pointing and orbit position to the precision required
- For intersatellite links on a nanosatellite, supplying a transmitted signal bright enough to be received at the longest expected range

These effects are most prominent in the lower atmosphere where water vapor content is most substantial. One way to combat the challenges of sounding deep into the atmosphere is to use adaptive optics to measure turbulence-induced errors and minimize their impact on the measurements.
While there have not yet been nanosatellite missions specifically dedicated to atmospheric characterization through laser occultation, optical beacons have been flown on orbit and are an active area of research.\textsuperscript{31} Beacons have primarily been used for space-to-ground communications, but intersatellite links have also been studied.\textsuperscript{32,33} Satellite crosslinks are useful in formation flying missions and enabling network communication, and this technology can be applied to laser occultation. The use of dual-stage pointing systems (coarse body pointing and fine control with a fast steering mirror—which can be a MEMS mirror)\textsuperscript{30} enables smaller beam sizes, which would make a cross-link system more power efficient but would require improved pointing knowledge and stability.

**Exoplanet Direct Imaging**

In order to image an Earth-like planet, an exoplanet direct imaging system needs to achieve a contrast ratio of $1e^{-10}$ at small inner working angles. A high-performance coronagraph can be designed to meet this requirement. A coronagraph, originally developed to study the solar corona, uses an optical element to achieve the “blocking” of the parent star’s light well enough that reflected light from an orbiting exoplanet can be detected. The coronagraph optical element can be as simple as an amplitude mask,\textsuperscript{34,35} or it can be more complex and use both amplitude and phase to remove or relocate parent star’s light.\textsuperscript{36,37} The coronagraph design must also consider the effect of the point spread function of each point source and the way that diffraction redistributes the light from the parent star across the image.

Even with adaptive optics on a large ground-based telescope, it is currently not possible to overcome the effects from atmospheric turbulence to achieve the high contrast needed to obtain high resolution spectra of an Earth-like exoplanet.\textsuperscript{38,39,40} While a space telescope does not have to overcome the effects of atmospheric turbulence, it is usually at the expense of smaller aperture size (e.g., due to launch cost and launch vehicle limitations), and the performance of a space telescope will still suffer from optical imperfections, thermal distortions, and diffraction that will corrupt the wavefront, create speckles, and ruin the contrast.\textsuperscript{51,42} Active optical control is still needed to achieve the desired contrast on a space telescope.

**CUBESAT DEFORMABLE MIRROR DEMONSTRATION**

The CubeSat Deformable Mirror Demonstration (DeMi)\textsuperscript{43} is a 6U CubeSat mission with the objective to characterize and demonstrate a MEMS deformable mirror for extended operation on orbit. The mission was selected for flight by DARPA and is undergoing contract negotiations for development starting in Fall 2016.

A successful flight of the CubeSat Deformable Mirror Demonstration would raise the technology readiness level (TRL) of a BMC Mini (32-actuator) Deformable Mirror to TRL 7 (analog mission flown in a relevant space environment). As a technology demonstration, this mission will not perform any high-contrast imaging from the nanosatellite platform. Rather the goals of DeMi are to:

- Characterize and calibrate the performance of a MEMS deformable mirror over a long-duration on-orbit mission
  - Measure mirror surface to <100 nm
- Demonstrate the use of these mirrors as intended for high contrast imaging
  - Correct in situ aberrations to < 100 nm rms

The mirror performance will be assessed based on the observed mirror response to commands (time and deflection). Successful demonstration will be determined based on the ability of the mirror to correct an image or a signal using closed-loop control. The degree to which the mirror is expected to correct will be determined through hardware experimentation as well as optical modeling. The optical modeling will incorporate expected operational conditions as well as satellite platform stability, a subject for future work.

The mirror chosen for demonstration is the Boston Micromachines Mini DM (32 actuators). A 64 x 64 array with the same technology from this manufacturer is currently used on the Gemini Planet Imager (GPI)\textsuperscript{42} and the PICTURE missions\textsuperscript{25} have flown kilo Boston Micromachines deformable mirrors.

**DeMi Mission Operation**

DeMi will be launched into a low-earth orbit as an auxiliary payload. The baseline orbit design for this mission is 415 km altitude, 52-degree inclination based on International Space Station CubeSat deployments (exact orbit still not determined). From this orbit the satellite will have an expected operational lifetime of approximately 4 months.

There are two modes of operation for the satellite experiments: mirror characterization with an internal source, and observation and image correction of a bright star through an external aperture. While the mirror characterization goals can be achieved with an internal source, the ultimate goal of using this technology on space telescopes motivates the use of an
external aperture in demonstration. The observation environment in space is harsher than on Earth, and effects from energetic particles and extreme UV radiation that could enter the system interact with the mirror can be better characterized with the addition of an external aperture. The inclusion of an external aperture also drives the CubeSat system design in a way that would bring value to future wavefront sensing space telescope missions, such as developing the ADCS algorithms that include both pointing and closed-loop wavefront control.

For the first part of the mission, an internal laser illuminates the mirror to characterize the performance of the deformable mirror through open-loop actuator deflection measurement and closed-loop correction with a Shack-Hartmann wavefront sensor. Once the mirror has been characterized, the telescope will target bright stars and use the deformable mirror for closed-loop image correction based on the quality of the focal plane image. The intended targets for star imaging are very bright objects such as Vega, Alpha Centauri, Arcturus, Sirius, and Canopus, but the feasible targets for this mission depend on the final design. The external observation requires finer pointing and stability control than the internal laser experiment.

The intended experiments are defined based on the source and detector used, as summarized in Table 1. Each of the experiments is designed to measure an aspect of mirror functionality necessary to characterize its on-orbit performance. The desired outcome of these experiments inform more specific subsystem and component requirements for the DeMi CubeSat optical payload.

Table 1: DeMi Optical Payload Experiment Summary

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Source</th>
<th>Sensor</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Internal Laser</td>
<td>Wavefront Sensor</td>
<td>Open and closed-loop mirror characterization</td>
</tr>
<tr>
<td>1</td>
<td>Internal Laser</td>
<td>Focal Plane</td>
<td>Closed-loop wavefront sensing and correction demonstration</td>
</tr>
<tr>
<td>2</td>
<td>External Object</td>
<td>Focal Plane</td>
<td>Closed-loop imaging, wavefront sensing and correction demonstration</td>
</tr>
</tbody>
</table>

The metrics measured are based on characterization of deformable mirrors on ground-based adaptive optics systems [44]. The metrics of interest for mirror characterization are corrected and uncorrected mirror surface figure, actuator stroke, and actuator influence function (how each actuator affects the behavior of the surrounding membrane). The control-loop performance requirements are driven by the expected system disturbances (magnitude and frequency).

**Payload Design**

Due to the need to accommodate a deformable mirror and reduce complexity, it is not practical to try to design the CubeSat as a reflecting telescope using mirrors. While it may be possible to integrate a larger standard lens in the aperture (current design is 100 mm), the corresponding longer focal length is not an option due to the limited space available for all components, and resizing the beam would be difficult. A smaller aperture and lens will limit the angular resolution (1.22 Λ/D) and sensitivity as well as increase the size of the PSF (which must also be Nyquist sampled by the pixels on the detector), but tight angular resolution is not a requirement for this technology demonstration. For a 1-inch (25.4 mm) or 0.5-inch lens (12.7 mm) diameter lens, which have minimum focal lengths on the order of their diameter, the angular resolution (width of the center of the point spread function) at 500 nm would be 1.2 arcseconds (1-inch) and 2.4 arcseconds (0.5-inch).

The optical layout shown in Figure 3 was designed to accommodate both an internal and external source as well as a wavefront sensor and focal plane detector within a 2U volume. The aperture is an inch in diameter, and all other optics are 1/2-inch diameter elements. Where possible, f-numbers larger than 2 are used to avoid distortion from edges of refractive optics. Light from either an internal laser diode or an external object (imaged through a 1-inch aperture) is routed to bounce off the Deformable Mirror, after which it is split to send some of the light to a wavefront sensor while the rest is focused to an image plane.

![Figure 3: Design of the DeMi Payload with both a focal plane sensor (green) and a wavefront sensor (blue)]
The baselined detectors are Aptina 2.2 µm pixel monochromatic CMOS arrays. A lower-powered fiber coupled laser serves as the known monochromatic light source for mirror characterization. All of the optical elements are COTS components available from vendors such as Thorlabs, Newark, and Edmund Optics. The refractive optics will be made out of a radiation hard material for the flight version and may require some custom manufacturing.

A wavefront sensor or surface metrology sensor is required to provide high spatial frequency information on the mirror surface. It has a secondary use as the source of wavefront error measurement in a closed-loop operation. There are several options for wavefront sensing in adaptive optics systems: Shack-Hartmann, pyramid, and curvature sensors are commonly implemented on existing systems, while there are several methods such as Zernike phase dimples and sensorless reconstruction algorithms that are under development. There are also methods to obtain high accuracy measurements on surface metrology, such as the Phased Aperture Wavefront (PAW) or interferometry. For the DeMi payload, the Shack Hartmann sensor was selected because of its extensive use history and ease of application for both mirror and wavefront measurements. It also doesn't involve moving parts, and is fairly robust to misalignments. Performance-wise, there some of the other mentioned potential alternatives could offer better measurements, but would add risk and complexity to the system.

**Payload Validation**

The hardware setup is shown in Figure 4. The layout is based on the design presented in the previous section with some modifications including re-imaging of the lenslet spots due to plastic packaging around the mirror and detector. There is also no external science source in this setup; instead, all measurements are taken with a fiber-coupled 635 nm laser.

The fiber-coupled laser is attached to a collimator and iris that can be re-sized to match the diameter of the mirror. A beamsplitter splits the beam into the science and wavefront sensing arms of the payload. The science arm is focused onto a webcam detector. The wavefront sensor is set up such that the mirror is conjugate to the lenslet array, and there is a factor of 2 magnification between the mirror and lenslet array to allow four-lenslet sampling per actuator. The focal plane of the wavefront sensor is re-imaged onto a Thorlabs CMOS detector and read in for each iteration of the control algorithm.

All optomechanical components were procured from Thorlabs. The mirror is a Boston Micromachines continuous facesheet mini deformable mirror (32 actuators, 300 µm actuator pitch, 1.5 µm stroke). The Shack Hartmann detector is an off-the-shelf Thorlabs camera that includes an Aptina detector (monochrome CMOS, 5.2 µm pixels – larger than the intended flight pixel pitch, but easily available from commercial suppliers). The focal plane detector is from a Microsoft WebCam device (front optics removed). A clear plastic element is the source of aberrations corrected for in the closed-loop demonstration.

**Figure 4: In-laboratory adaptive optics payload setup**

The overall effectiveness of the open-loop wavefront reconstructor is evaluated based on measurement repeatability and accuracy. The measurement repeatability is calculated from a series of 10 measurements for each commanded mirror deformation. The measurement accuracy is determined by comparing the results of the CubeSat wavefront sensor reconstruction to the measurements obtained from the Zygo interferometer. It is characterized by error in overall stroke measurement as well as variation in influence function for each actuator.

Figure 5 shows the results from both of these approaches. The figure shows surface maps (color scale on the right in µm) of the entire mirror for each individual actuator poke. The location of the surface maps on the grid corresponds to the location of the actuator on the mirror. The measurements obtained from the nanosatellite-scale wavefront sensor are encouraging in terms of capability (mirror movement at less than 100 nm is detectable by the sensor).
The metrics with which the on-orbit payload experiment will determine how well the closed-loop algorithm worked are time to correction and percent Strehl improvement. Control bandwidth is also important if the intended application is atmospheric characterization, as the on-orbit wavefront measurement and control must keep up with atmospheric distortions that can change over a period of milliseconds (see Chapter 4). For thermomechanical misalignments, the required correction timescale is much longer, so bandwidths of a Hz or longer are acceptable.

The laboratory validation procedure was not optimized for bandwidth, and the purpose of the experiment is to demonstrate a working closed-loop controller that can apply reasonable correction within the operational limits of the mirror (only six actuators across). Strehl ratio is the focal plane measurement metric in the on-orbit experiment architecture. In the laboratory, the focal plane detector was a web camera with limited exposure control, and even with ND filters in place, the sensor was saturated. We instead used encircled energy as the metric for the correction, using a radius of about two times the Airy radius on the detector.

Figure 6 shows an example of the wavefront correction exhibited by the laboratory system, and Figure 7 shows how the mirror correction performed (in terms of Encircled Energy - the ratio of energy within a certain radius of the beam focus to the energy collecting over the whole detector) over time. A piece of plastic was used to induce aberrations. The mirror was able to perform modest correction, but higher-order aberrations beyond the control authority of the mirror, and this prevented the system from reaching pre-distortion encircled energy levels. The control loop is also not optimized for fast performance. For speckle nulling and long time-scale corrections (thermo-mechanical distortions) the demonstrated timescale of the performance is acceptable, though higher spatial frequency correction is needed for speckle nulling and turbulence correction on future scientific imaging platforms. For correcting distortions due to atmospheric variations, the control algorithm bandwidth must be better than 1 kHz. For static measurements and mirror characterization, the current design is sufficient.

There are several mechanical, electro-optical, and software changes that must be made between this laboratory hardware verification and the flight version of the payload. As selected, the DeMi mission chosen to fly is a 6U CubeSat (versus the 3U volume assumed here), so the payload may expand into a larger volume. This could enable a larger aperture and a deformable mirror with more actuators to be flown, which would enhance the overall science and technology demonstrated by this mission. More actuators enable the correction of higher-order modes and better off-axis wavefront correction, while a larger aperture allows dimmer sources to be detected, which relaxes some of the operational constraints.
Bus Requirements

The attitude sensing accuracy is mainly driven by the payload requirements. To validate the deformable mirror the system needs to point at an observation target, driving the attitude control requirement. To maintain a star within the 1-degree field of view during operations, the accuracy of the determination system needs to be a fraction of this quantity (0.1 degrees). Additionally, to avoid blurring the image over an exposure, spacecraft vibrations and jitter must be limited such that the motion over 1 ms is below 20 arcsec. This leads to a 5 degrees per second angular velocity control requirement, and therefore the gyros need to be sensitive to a fraction of that quantity.

The attitude control actuation requirements are driven by the required speed of slew maneuvers, the differential drag, and gravity gradient disturbance and the requirements in maximum jitter. The calculated magnitude of the torque and the angular momentum in a worst-case scenario for such forces is shown in Table 2.

Table 2. Attitude actuation budget

<table>
<thead>
<tr>
<th>Source</th>
<th>Requirement</th>
</tr>
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<tbody>
<tr>
<td>Slew maneuver major MoI axis</td>
<td>$T_{\text{max}} = 0.15 \text{ Nm}$</td>
</tr>
<tr>
<td>(180 degrees in 90 seconds)</td>
<td>$h_{\text{max}} = 12 \text{ mNms}$</td>
</tr>
<tr>
<td>Differential drag torque</td>
<td>$T_{\text{max}} = 0.07 \text{ mNm}$</td>
</tr>
<tr>
<td>(Desaturate duty cycle 1/20)</td>
<td></td>
</tr>
<tr>
<td>Gravity gradient</td>
<td>$T_{\text{max}} = 0.006 \text{ mNm}$</td>
</tr>
<tr>
<td>(Desaturate duty cycle 1/20)</td>
<td></td>
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</tbody>
</table>

The ground link requirement is driven by the payload data. The deformable mirror payload can require up to 15 kB of data per test for the mirror characterization experiment, and up to 2.6 MB of data for the image correction experiment. With at most one test per orbit, the required downlink rate is around 3 MB including state of health information. A downlink bandwidth of 50 kbps will be enough for nominal operations, allowing full test data downlink in 10 to 15 minutes over one or multiple ground passes. Data will be buffered as needed to mitigate against lost passes.

Bus Design

The proposed bus configuration for the system is a combination of commercial off the shelf (COTS) and custom components.

Aurora Flight Sciences has developed a common avionics box for nanosatellites that is baselined for DeMi. Its architecture features a dual-heterogeneous processor design. A PIC microprocessor provides housekeeping processing, while a secondary ARM based processor provides service based processing including floating point operations. This avionics design has been developed to provide excellent processing to power consumption ratio. The design provides a simple structure with a clear separation of functionality: in nominal operations, the primary processor handles high priority tasks at a very high rate with very low power consumption, while the secondary processor provides on-demand processing, including attending attitude sensors. The avionics box integrates an Analog Devices ADIS16488B IMU and a Novatel OEM615/L1L2 GPS with orbital corrections. The GPS can provide an orbit determination accuracy of < +/-1.5 m rms.

For radio communications, several options exist to meet the requirements. The baseline radio is the L-3 Communications Cadet CubeSat radio for UHF communications. The bandwidth does not seem to be a limitation in the operations of the demonstration system and the specific radio implementation will be defined during the design verification process and based on more detailed trade analyses and consideration of the ground segment and frequency band allocation.

The proposed bus configuration for the 6U system has approximately 3U providing bus services and 3U available for payloads. Figure 8 shows an initial conceptual configuration.

Figure 8: Proposed 6U Configuration

A star camera/reaction wheel combination can provide the required attitude determination and control. The proposed ADCS is the integrated Blue Canyon Technologies XACT system. The system includes a star tracker and reaction wheels.

Clyde Space, Inc is the supplier for the power subsystem. For the 6U system, both body panels and deployed solar panels will be utilized (see Figure 8)
though the final configuration will determine on the orbit and power budgeting. Clyde Space’s 28.3% cell panels have flown on more than a dozen successful nanosatellite missions. A Clyde Space 60 W-hr battery will be integrated as a power storage unit, and the Clyde Space Electrical Power System will provide power conditioning and control.

SUMMARY
Adaptive optics systems are useful for several in-space imaging applications, including exoplanet direct imaging and Earth atmospheric characterization. MEMS deformable mirrors offer a low size, weight, power, and cost alternative to traditional adaptive optics approaches, but their operation in space for high-precision applications is currently unknown.

The CubeSat Deformable Mirror Demonstration is a 6U CubeSat designed to demonstrate and characterize the behavior of a MEMS deformable mirror over long-duration on-orbit operations. The payload has been designed to fit in a 2U volume and through laboratory validation we have shown that the payload as designed is capable of characterizing the surface of a deformable mirror to <100 nm precision. DeMi is currently under contract negotiations for flight mission development to start in late 2016.

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REFERENCES


