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Optical Modeling and Validation for the Deformable Mirror Demonstration Mission

by

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Abstract

Microelectromechanical Systems (MEMS) Deformable Mirrors (DMs) are a promising technology to enable the wavefront control required for high contrast imaging and characterization of exoplanets with coronagraph instruments. MEMS DMs are a key technology option for future exoplanet imaging space telescopes because they can provide precise wavefront control with low size, weight, and power required. The Deformable Mirror Demonstration Mission (DeMi) CubeSat mission will demonstrate MEMS DMs in the space environment for the first time. 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 will be able to measure low order aberrations to λ/10 accuracy and λ/50 precision, and will correct static and dynamic wavefront phase errors to less than 100 nm RMS. The DeMi payload contains both a Shack Hartmann wavefront sensor and an image plane wavefront sensor to monitor the DM behavior on orbit. In this thesis, an optical diffraction model is developed to simulate the signals on both the Shack Hartmann wavefront sensor and the image plane wavefront sensor. The flight payload alignment and integration process is described, and the optical model is validated with relevant data from the flight payload. The DeMi satellite is expected to launch in February 2020.

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This research made use of POPPY, an open-source optical propagation Python package originally developed for the James Webb Space Telescope project [1]. The POPPY simulations were performed on the Engaging cluster at the MGHPCC facility.
(www.mghpcc.org).
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Chapter 1

Introduction

The Deformable Mirror Demonstration Mission (DeMi) CubeSat payload was built at MIT in order to demonstrate a Microelectromechanical Systems (MEMS) Deformable Mirror (DM) in space and provide on-orbit operations data for future space telescope missions for exoplanet high-contrast imaging. This thesis focuses on optical modeling and testing of the DeMi flight payload. Section 1.1 provides motivation for MEMS DMs for astronomy application and summarizes design considerations and previous technology demonstration efforts for MEMS DMs.

1.1 Motivation: MEMS Deformable Mirrors for Exoplanet Direct Imaging in Space

MEMS DMs are a promising technology to enable precise wavefront control for high-contrast imaging applications. MEMS DMs offer high-actuator density, large stroke, and precise control in a small, low-power form factor, which makes them suitable for space-based wavefront control applications, such as space telescope coronagraph instruments for exoplanet direct imaging [3, 4]. For instance, the Boston Micromachines Corporation (BMC) 4K DM has 4092 actuators across a 25 mm × 25 mm aperture with a stroke of 4 μm [5] and is used on the ground for extreme adaptive optics on the Gemini Planet Imager [6].
High-contrast imaging can enable detailed characterization of exoplanets [7] by gathering precise astrometric data [8] and measuring a planet's atmosphere through spectroscopy [9]. This data will be key for constraining the orbits of exoplanets [10] and detecting biosignatures in order to assess their potential habitability [11]. High contrast imaging can also detect and characterize circumstellar debris disk structure to understand solar system formation [12, 13].

Directly imaging Earth-like exoplanets is an immense technical challenge. Resolving an Earth-like planet near a Sun-like star with a telescope requires instruments that are able to image at extremely high contrasts of $10^{-10}$ [14]. Achieving this contrast level with a coronagraph instrument, which blocks out the light of the target star so the dim companion planet is visible, requires an adaptive optics system capable of picometer-level wavefront control [15]. Deformable mirrors can be used in coronagraph systems to control the wavefront in order to prevent speckles and stray light from degrading the contrast [16, 17, 15]. Picometer-level control has been demonstrated at the NASA Jet Propulsion Laboratory (JPL) High Contrast Imaging Testbed [18]. This level of stability refers to the average surface flatness over many spatial modes, not the flatness of individual atoms [7].

1.1.1 Deformable Mirror Technology

An adaptive optics system corrects wavefront errors in a telescope system in order to improve image quality and contrast. It was first proposed in 1953 to correct for errors due to atmospheric turbulence for ground-based observatories [19]. For space telescopes, adaptive optics is proposed to correct wavefront errors due to thermal and mechanical effects in space. In an adaptive optics system, a wavefront sensor is used to detect wavefront errors, which are corrected by controlling an adaptive or deformable mirror to counteract them. A deformable mirror can also be used to inject known perturbations into the system in order to probe the wavefront for common-path wavefront sensing [20].

MEMS DMs are one proposed technology to enable the precise wavefront control required for space-based high contrast imaging. There are several other types
of DMs that have been used for astronomical applications, which are summarized in Madec 2012 [21], a review of deformable mirror technologies for ground-based astronomy applications. Stacked array PMN and PZT, bimorph, and voice coil actuator technologies are summarized here at a high level. Stacked array DMs use ferroelectric actuators made up of stacks of individual disks. Lead zirconate titanate (PZT) actuators are made up of piezoelectric ceramic disks that elongate with a linear response to the applied voltage [21]. These actuators can provide \( \sim 5 \, \mu m \) of stroke, but exhibit hysteresis effects which makes high-speed, precise control of the actuators difficult [22]. Another type of stacked array DM is based on lead magnesium niobate (PMN) piezoelectric ceramics. PMN actuators elongate with a quadratic response to applied voltage, and are sensitive to temperature [23, 21]. Adaptive Optics Associates (AOA) Xinetics PMN DMs are currently baselined for the Wide-Field Infrared Survey Telescope (WFIRST) mission and have been used at the NASA Jet Propulsion Laboratory High Contrast Imaging Testbed [24].

Bimorph DMs use the transverse piezoelectric effect to control the curvature of the DM [21]. These DMs offer high reliability, large stroke, and high accuracy [25], but require high voltages and are limited to actuator counts of \( \sim 200-300 \) [21]. Voice coil actuator DMs use the Lorentz force to control the shape of a thin floating optical shell [21]. Voice coil actuators are typically larger, high power systems to achieve large strokes, and have been used as deformable secondary mirrors for large ground-based telescopes [26].

1.1.2 MEMS Deformable Mirrors

MEMS Deformable Mirrors were first developed in the 1990s [27, 28, 29]. They are manufactured in batches out of layers of conducting and insulating polysilicon films and then selectively etched to form the actuators which are individually addressable through wire channels on a ceramic carrier [30]. The continuous or segmented mirror surface is coated for optical quality. Each actuator is controlled by applying a voltage to the actuator electrodes which electrostatically attracts the electrically grounded actuator membrane. Figure 1-1 shows an example of a MEMS DM from Boston
MEMS DMs are small in size and have low power requirements which makes them promising for aerospace applications [22]. MEMS DMs can enable extremely high actuator densities with actuator pitches of \( \sim 300-400 \mu m \) [31, 32] compared to actuator spacings of \( \sim 5-7 \) mm for PMN DMs [23], which allows for high resolution control with smaller optics throughout the system which can reduce cost [31]. MEMS DMs are manufactured in a bulk machining process at a cost of \( \sim $100 \) per actuator, which is an order of magnitude less than the \( \sim $1000 \) per actuator cost of conventional DMs [33, 21].

MEMS DMs have been shown to be capable of providing subnanometer scale flattening needed for high contrast imaging applications [34, 35]. A stability test showed a median of 0.08 nm actuator motion over 40 minutes of operation, and a repeatability test showed that the displacements were repeatable to less than 1 nm surface precision [3]. Laboratory tests have demonstrated their use for phase correction to 6 nm root-mean-square (RMS) residual errors within the controllable spatial frequencies [36]. DMs can also be used to remove phase differences between the arms of an interferometer for speckle nulling applications [37], and a MEMS DM has been demonstrated to reach path-length difference control down to 2 nm RMS [38]. In addition to astronomy, MEMS DMs are used for applications such as biological imaging [39], laser communications [40], and Earth observation imaging [41].

Other types of optical MEMS devices have flown in/near space before, such as the
single micromirror used on the MEMS Telescope for Extreme Lightning (MTEL) [42] and the microshutter array used in the Far-UV Off Rowland-circle Telescope for Imaging and Spectroscopy (FORTIS) sounding rocket instrument [43, 44]. MEMS Fast Steering Mirrors (FSMs) have been proposed for pointing control in free space laser communications systems [45], and MEMS Digital Micromirror Devices (DMDs) have been tested for space applications to be used as a programmable slit mask for multi-object spectroscopy [46].

1.1.3 Ground-Based Astronomy Applications

MEMS DMs have been used successfully for ground-based astronomy applications. The Gemini Planet Imager uses a $64 \times 64$ actuator BMC MEMS DM [47] and achieved an order-of-magnitude improvement in contrast compared to previous adaptive optics instruments [6]. The GPI mirror underwent extensive qualification and testing before on-sky operations [48].

BMC MEMS DMs have also been deployed in the Robo-AO system at Palomar Observatory (later moved to Kitt Peak) [49], the Shane-AO system at Lick Observatory [50], and the SCExAO system at the Subaru Telescope [51, 52]. The upgraded MagAO-X instrument plans to use a 2040-actuator BMC MEMS DM, and a laboratory DM characterization pipeline has been developed to test these mirrors at the University of Arizona Wavefront Control testbed [53].

Ground-based high contrast imaging instruments are likely limited to contrasts of between $10^{-8}$ and $10^{-9}$ due to the effects of Earth’s atmosphere [54, 55, 56] unless new technology such as bright satellite-based laser guide stars can be used for wavefront sensing [57]. Space-based observatories are the platform of choice to reach the $10^{-10}$ to $10^{-11}$ contrasts required to image Earth-like exoplanets around Sunlike stars [14, 58]. Proposed starshade missions [59] and satellite laser guidestar missions [57] trade significantly relaxed telescope stability requirements for a new set of manufacturing and formation-flying challenges and are likely best-suited to deep characterization of a few high-priority systems because the maneuvering time for the starshade or laser guidestar satellite to traverse between targets leads to a low observational cadence.
1.1.4 Design Considerations

The goal of an adaptive optics system for space telescopes is to counteract optical aberrations due to thermal and mechanical variability in the telescope system. Mitigating the wavefront errors resulting from these dynamic effects in space typically requires control loops at a few Hz [60], much slower than the 2500 Hz required to compensate for atmospheric aberrations in a ground-based astronomical observatory.

A derivation of how deformable mirror parameters affect wavefront correction performance can be found in [7]. This section summarizes the key results from that chapter.

The number of actuators across the DM governs the spatial frequency of errors that can be corrected [7]. Since they are able to fit and subtract higher spatial frequency surface errors, high actuator density DMs can correct contrast over a larger angular area with smaller optics along the optical train, which can reduce overall cost [31]. The actual shape and size of the dark hole, or area of high contrast in the science image, depends on the design of the coronagraph system.

The stroke required for the DM is related to the expected amplitudes of the errors the DM needs to correct in the system [21]. Achieving high strokes on MEMS DMs can be a challenge due to the tight actuator spacing, but this can be resolved by using a high stroke, low actuator count non-MEMS DM to correct larger low frequency errors in addition to the lower stroke, high spatial frequency MEMS DM to correct residual high frequency errors in a “woofer-tweeter” configuration [61, 62].

Speckles due to phase errors alone can be corrected by a single DM across the image, but speckles due to phase and amplitude errors can only be canceled on one side of the star or the other unless a second DM is used [7]. For high contrast space-based applications, the use of two DMs is planned to enable dark holes on both sides of the star [63].

Other important characteristics of DMs are actuator speed, stability, repeatability, hysteresis, and inter-actuator influence. Actuator speed determines how fast the wavefront control loop can respond to disturbances. Testing with a 32 × 32 actuator
BMC continuous facesheet MEMS DM demonstrated fast actuation with a response time of \(<0.35\) ms [37]. The MEMS DM in the Gemini Planet Imager was able to meet the maximum update rate requirement of 2500 Hz to correct for atmospheric turbulence [61, 6].

Actuator stability refers to the ability of the actuators to hold their shape over time, while repeatability refers to the ability of the actuator to return to the same position under the same applied voltage consistently. Laboratory testing with a 1024-actuator continuous facesheet BMC MEMS DM demonstrated flat shape stability to 0.08 nm RMS over 40 minutes of operation [3] and median actuator repeatability to 0.046 nm surface [31]. Stability testing of a sample of IrisAO 37 piston/tip/tilt actuator MEMS DMs showed that the open-loop flattening error increased by 5.68 nm rms over 29 months of testing [64].

Hysteresis occurs when a system’s response to an input control signal is not perfectly repeatable, but depends on the prior states of the system. For MEMS DMs, this means that the mirror elements actuate to a different position depending on whether the voltage was ramping up or down to a given value. This effect has been tested in the lab with a 1024 actuator BMC continuous facesheet MEMS DM and shown to be negligible [31].

The inter-actuator influence refers to the passive motion of nearby actuators due to the deflection of a single actuator. This property was measured with a 140 actuator BMC continuous facesheet MEMS DM to be 13.5% for the first directly adjacent actuators and \(<1\)% for diagonal actuators and second neighboring actuators [65].

A major step in qualifying a DM for high-contrast imaging is assessing how flat it is under closed loop control. Testing with a 1024-actuator continuous facesheet BMC MEMS DM demonstrated flattening in lab to 0.54 nm RMS [3, 66].

### 1.1.5 Previous Deformable Mirror Technology Demonstrations

Applying MEMS technology to space missions introduces several challenges due to the launch and space environment. The launch environment requires spacecraft components to withstand acoustic shocks and vibrational loads during launch. Once the
spacecraft is in space, the components must operate in vacuum over varying thermal conditions while withstanding the effects of ionizing radiation. This section summarizes the progress of technology demonstrations aimed at preparing this technology for future space telescope missions.

**Ground Testing**

A key test for space technology is the ability to operate in vacuum. A $32 \times 32$ actuator BMC MEMS DM was used in vacuum to create a dark hole with $10^{-7}$ contrast with polychromatic light for the EXoplanetary Circumstellar Environments and Disk Explorer (EXCEDE) mission concept study [67, 68]. The Visible Nulling Coronagraph (VNC) testbed used an Iris-AO DM with 169 hexagonal segments to demonstrate a dark hole with $10^{-9}$ contrast in vacuum [69].

A set of IrisAO 37 piston/tip/tilt actuator segmented MEMS DMs underwent thermal testing to assess the mirror response to temperature fluctuations between 21–28 °C. The average change in the surface of the flat DMs due to the temperature change was 0.62–1.42 nm rms/°C [64].

Another consideration for potential infrared imaging applications is the ability to operate at cryogenic temperatures in order to reduce thermal noise, which can dominate infrared observations. A cryogenic MEMS DM design was developed by BMC by mounting the mirror chip on a silicon board to reduce thermal stress and oxidizing the substrate to form an insulating layer [70]. A 32-actuator prototype cryogenic DM demonstrated no significant change in performance at 95 K and at room temperature [70], and a 1020-actuator cryogenic DM demonstrated successful operation during three cooling cycles between 5 K and 295 K [71]. A 37-actuator membrane DM by OKO Technologies was tested at cryogenic temperatures and demonstrated similar influence functions with surface deflection reduced by 20% at 78 K compared to room temperature [72].

Radiation can affect MEMS devices when dielectric insulating materials trap charge, impacting the device response to electrostatic actuation [73, 74]. The deflection of a single actuator of a BMC MEMS DM was measured under total dose
radiation levels of 0–3000 Krad (Si) and demonstrated no significant change during radiation testing [74].

Technology Development For Exoplanet Missions Program

The NASA Exoplanet Exploration Office funds a series of Technology Development for Exoplanet Mission (TDEM) awards to demonstrate technologies for exoplanet missions. BMC has been awarded a TDEM grant in 2010 in order to demonstrate survivability and performance repeatability of the 952-actuator BMC MEMS continuous DM after exposure to launch-like vibration, shock, and acoustic conditions [75]. The testing was conducted on a set of 952 actuator continuous facesheet DMs at NASA Goddard Space Flight Center’s Environmental Test and Integration Facility [75]. The mirrors were split into groups and tested to low, medium, and high vibration, acoustic, and shock levels. The mirrors were be tested before and after testing using a combination of instruments available at BMC, NASA JPL’s Vacuum Surface Gauge instrument, and Princeton High Contrast Imaging Laboratory equipment. A sample result from this testing showed that a DM could be flattened to 5 nm RMS before and after vibration testing, and the residual between the pre- and post-vibration flattened profiles was 4 nm RMS [76]. This testing will assess any changes in performance by measuring influence functions and displacements of each actuator and measuring the achievable dark hole contrast and stability [75].

The PICTURE Missions

The Planet Imaging Concept Testbed Using a Recoverable Experiment (PICTURE) and Planet Imaging Coronagraphic Technology Using a Reconfigurable Experimental Base (PICTURE-B) sounding rockets and the Planetary Imaging Concept Testbed Using a Recoverable Experiment - Coronagraph (PICTURE-C) high-altitude balloon payload are a series of projects with the goal of demonstrating planet imaging technology in a space and near-space environment. The missions are designed to observe the Epsilon Eridani circumstellar disk environment [77]. The science payloads use MEMS DMs to enable wavefront control and high contrast imaging. For a description of the
PICTURE optical payload, see Mendillo et al. 2012 [77]. For a description of path length control in the nulling interferometer with the DM, see Rao et al. 2008 [38]. This section summarizes the design and results of the PICTURE sounding rocket mission (launched October 11), the PICTURE-B sounding rocket mission (launched November 2015), and the PICTURE-C high altitude balloon payloads (launching June 2019 and September 2020).

The PICTURE (and PICTURE-B) science instrument is a lateral-shearing Mach-Zehnder nulling interferometer, which suppresses the light from the target star through destructive interference while transmitting light through closely spaced bright fringes [38, 78].

The payload employs a $32 \times 32$ actuator BMC MEMS DM for wavefront control in order to minimize the path length difference between the two arms of the interferometer. Thus, the DM does not flatten the overall wavefront or increase the image Strehl, but increases contrast by suppressing transmitted light. The payload also uses a piezoelectric fast-steering mirror for optical stabilization. The wavefront control system measures the wavefront with a calibration interferometer that varies the path length differences between the arms of the interferometer to step through a series of phase offsets and measure the resultant fringes. These fringes are used to build up a phase map of the wavefront in the system, which is used to control the DM to flatten the wavefront and minimize the path difference between the two arms of the interferometer.

**PICTURE Testing and Flight Results**

Prior to launch, the PICTURE payload underwent vibration testing to NASA Vehicle Level 2 levels with the DM in place. The payload was shaken in three axes for 10 seconds per axis according to the spectrum specified in [79]. The DM was tested successfully after the vibration test.

The PICTURE sounding rocket flew on 8 October 2011. Unfortunately, ~70 seconds into flight the primary telemetry transmitter failed. The fine pointing system was demonstrated but none of the other flight demonstration goals can be confirmed.
due to lack of data [77].

The MEMS DM survived the launch and recovery, but was not measured in the near-space environment [77]. The telescope primary mirror shattered and was not recovered intact but the nuller assembly survived landing and recovery [77]. Some DM actuators were not working after recovery, but the cause of failure cannot be confirmed due to lack of flight data. The DM and cables could have been damaged in assembly, landing, recovery, transport, or disassembly. Since the mirror and cables were permanently bonded together, the entire assembly, including the Kilo-DM, breakout board, and flex cables were replaced prior to reflight. The primary mirror was also replaced before reflight as PICTURE-B.

PICTURE-B launched with a new Kilo-DM and a new primary mirror in November 2015 [2]. The PICTURE-B flight experienced a payload anomaly, likely due to shifting of the DM mount during flight. During this flight, the instrument did not advance past the wavefront measurement phase.

The data that was collected demonstrates wavefront sensing and shows that the DM flattened, actuating in the space environment, as shown in Figure 1-2. Since the full payload survived flight and is still assembled, the mirror has not been individually characterized. In qualitative end-to-end payload tests post-recovery, which subject the payload to the expected vibrational and atmospheric disturbances across the 0.5 m telescope, the MEMS DM has been observed to respond as expected.

The PICTURE project is continuing with the Planetary Imaging Concept Testbed Using a Recoverable Experiment—Coronagraph (PICTURE-C) instrument high-altitude balloon payload [80]. This instrument uses a Vector Vortex Coronagraph instead of a nulling interferometer. The project has recently switched away from the baselined DM [81] and has selected a BMC 952 actuator MEMS DM driven by a miniaturized DM controller [62] for high-order wavefront control and a pathfinder flight with the instrument was completed in 2019 (without the DM incorporated into the payload).
Figure 1-2: Flight measurement of MEMS DM actuating in the space environment during the PICTURE-B sounding rocket flight. Figure reproduced from Douglas et al. 2018 [2].
The High-Contrast Imaging Balloon System

The High-Contrast Imaging Balloon System (HiCIBaS) high-altitude balloon payload is designed to test high contrast imaging equipment and algorithms in a near-space environment at a low cost [82]. This technology demonstration payload uses a IrisAO MEMS DM with 37 hexagonal piston-tip-tilt segments for wavefront control with its Coronagraph Wavefront Sensor (CWS) instrument. For a description of the balloon mission objectives and instrument design, refer to Cote et al. 2018 [82]. The full payload flew successfully on 25 August 2018 [83]. During flight, a cabling issue prevented commands from being sent to the DM, so in-flight operation cannot be confirmed. Images taken with a calibration source during flight agreed well with images taken in lab with the DM powered off, which implies that the DM did not move significantly during flight. The DM is still operational, with a single stuck actuator and a small loss of stroke measured post flight. On sky testing of the Low Order Wavefront Sensor (LOWFS) was conducted in 2018 to validate the wavefront sensors and compare the measurements from external starlight and the internal laser source [84]. These tests also compared the signals from the payload Shack-Hartmann wavefront sensor and the pyramid wavefront sensor and showed good agreement between all configurations [84].

1.2 The Deformable Mirror Demonstration Mission

The Deformable Mirror Demonstration Mission (DeMi) CubeSat payload will demonstrate the on-orbit performance of a 140-actuator BMC MEMS DM on a 6U (10 cm × 20 cm × 30 cm) CubeSat [85, 86, 87, 88, 89]. The goal of this mission is to raise the Technology Readiness Level (TRL) of MEMS DM technology from a TRL of 5 to at least a TRL of 7 for future space telescope applications [90]. The key DeMi mission 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 RMS error.
The DeMi optical design contains an off axis parabola-based telescope with a 50 mm primary mirror, a 140-actuator BMC Multi DM, and both an Image Plane wavefront sensor (WFS) and a Shack Hartmann WFS [91]. The Image Plane WFS captures pictures of the system Point-Spread Function (PSF) and serves as a truth sensor for wavefront correction. The Image Plane WFS is also used to detect tip-tilt errors. The Shack Hartmann WFS uses a lenslet array to split the light into sections and focus it into a grid of spots on the detector. The displacement of each spot corresponds to the wavefront slope incident on the corresponding lenslet. This sensor is used to measure wavefront aberrations and monitor the DM health on-orbit. A diagram of the DeMi optical payload is shown in Figure 1-3.

The original driver electronics for the DM were not designed for space operation and were too large to fit onboard the 6U CubeSat, so custom miniaturized drive electronics based on commercial components were developed [22].

![Figure 1-3: Diagram of the optical components for the Deformable Mirror Demonstration Mission (DeMi) CubeSat payload with ray path overlaid.](image)

A summary of the DeMi concept of operations is shown in Figure 1-4. The DeMi payload has both external and internal operational modes. It can observe stellar targets and collect photometric measurements through the primary aperture, or it
can use the internal laser fiber source for calibration measurements. For external observations of stellar targets, the Image Plane WFS will be used for closed-loop control of the DM, and performance will be measured with the Shack Hartmann WFS. For internal calibration, the internal laser source will be turned on and either the Image Plane WFS or the Shack Hartmann WFS will be used for closed-loop control of the DM, with the other sensor measuring performance. The internal laser source will also be used for actuator tests of the DM where each actuator will be poked and the resultant wavefront will be measured on both the Image Plane WFS and the Shack Hartmann WFS. This data will be used to assess the on-orbit performance of the MEMS DM over a year of operation.

![Figure 1-4: Summary of concept of operations for the Deformable Mirror Demonstration Mission. A DM actuator poke test refers to actuating each actuator of the deformable mirror and measuring the deflection with the Shack Hartmann wavefront sensor in order to measure the behavior of the mirror over time. WFC stands for wavefront control using either the Shack Hartmann wavefront sensor or the image plane wavefront sensor.](image)

1.3 Summary of Thesis Contributions

This thesis summarizes the development of an optical model for the DeMi payload, as well as the alignment and integration of the flight payload. In Chapter 2, development and results of an optical diffraction model of the payload are described. Chapter 3
summarizes the alignment and integration of the DeMi flight payload. Chapter 4 presents measurements from the flight payload and compares them to the optical diffraction model. Chapter 5 summarizes the results and contributions of this thesis.
Chapter 2

Optical Diffraction Modeling in
POPPY

In this work, an optical diffraction model has been developed for the DeMi payload in order to predict measurements on both the image plane wavefront sensor and the Shack Hartmann wavefront sensor in response to different shapes applied to the DM. This will give the DeMi team a baseline to compare the payload performance to during ground testing and in-flight operations. The optical diffraction model is also useful to simulate the effect of the DM being inclined 45° relative to the incident beam in the payload on the wavefront sensor measurements for DM shapes. The DeMi design has the DM at a 45° inclination in order to save space in the optical bench to fit within the CubeSat form factor. The optical diffraction model was developed using the open-source Physical Optics Propagation in PYthon (POPPY) software package [1]. POPPY was chosen because it is a fast way to develop an optical model based on diffraction integrals using open-source software that can be easily run on a computing cluster.

2.1 POPPY Model Development

The DeMi POPPY model is based on Fraunhofer diffraction integrals. This approach is based on the assumption that all diffraction effects in the payload are either in
the “far-field” or are placed at principal planes [92]. In the DeMi optical design this assumption is justified because all optical components are at principal planes. These assumptions greatly reduce the complexity of the diffraction integrals, making the optical model less computationally expensive. Fraunhofer diffraction is modeled by computing the two-dimensional Fourier transforms between image and pupil planes according to the formula [92]:

\[ f(x, y) = \frac{1}{(2\pi)^2} \int \int_S F(k_x, k_y) e^{-i(k_x x + k_y y)} \, dk_x \, dk_y \]

POPPY models an optical wavefront as a python object with phase and amplitude stored in arrays. The optical system is modeled as a series of optical elements at principal planes, which are python objects defined by their transmittance and optical path difference (OPD) across the optical element, also stored as arrays. POPPY propagates the optical wavefront between principal planes through a Matrix Fourier Transform to convert between spatial units in pupil planes and angular frequency units in image planes. At each optical element, the wavefront object phase and amplitude arrays are multiplied by the OPD and transmittance arrays of the optical element object. At the image plane detector, the wavefront is propagated to the detector plane and the intensity is computed then sampled to match the specified detector size and pixel pitch. At the Shack Hartmann wavefront sensor, the wavefront is subsampled to simulate the effect of the lenslet array and each subsampled wavefront array is propagated to the detector plane separately then tiled back together to form simulated images of the detector spots [1]. The Shack Hartmann wavefront sensor implementation used for this work was originally written by Ewan Douglas and was developed and validated through this work. This version of POPPY is available on GitHub\(^1\) and will be pushed to the official POPPY source code\(^2\) in the future.

The DeMi optical payload design is shown in Figure 1-3. Following the ray trace in this figure, the design can be represented by a series of optics at principal planes,

\(^1\)https://github.mit.edu/remorgan/poppy/tree/new_lenslet_optic/poppy, contact remorgan@mit.edu for access
\(^2\)https://github.com/mperrin/poppy
shown in Figure 2-1. The primary aperture (OAP1) is at a pupil plane, the field mirror is at an image plane, OAP2 is at a pupil plane, the DM is at a pupil plane, and the image plane focusing lens is at a pupil plane which focuses the light onto the detector in an image plane. Continuing onto the relay optics, OAP3 is at a pupil plane, there is an image plane between OAP3 and OAP4, OAP4 is at a pupil plane, and the Shack Hartmann lenslet array is at a pupil plane. Each lenslet in this array focuses the subsampled wavefront onto the detector in the image plane. The POPPY model uses flight-like parameters to define the optical system, summarized in Table 2.1.

Figure 2-1: Diagram of the optical components for the Deformable Mirror Demonstration Mission (DeMi) CubeSat payload with ray path overlaid and principal planes labeled. PP stands for pupil plane and IP stands for image plane. The POPPY diffraction model propagates incident light to each of these optical planes and simulates the resultant images on the wavefront sensors.

The POPPY model is used to simulate the baseline measurements and effects of individual actuator pokes on the DM as measured on the DeMi wavefront sensors. The POPPY code used to model DeMi is included in Appendix A. The POPPY model results are compared to measurements from ground testing with the DeMi flight unit. A summary of the optical modeling approach for DeMi is shown in Figure 3.3.
<table>
<thead>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Deformable mirror (DM) actuator pitch</td>
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<td>μm</td>
</tr>
<tr>
<td>DM actuators per side</td>
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<td></td>
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<tr>
<td>Internal calibration laser wavelength</td>
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<td>nm</td>
</tr>
<tr>
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<td>μm</td>
</tr>
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</tr>
<tr>
<td>Image plane detector plate scale</td>
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<td>arcsec/pixel</td>
</tr>
<tr>
<td>Shack Hartmann number of lenslets across DM</td>
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<td></td>
</tr>
<tr>
<td>Shack Hartmann detector lenslet pitch</td>
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<td>μm</td>
</tr>
<tr>
<td>Shack Hartmann detector lenslet focal length</td>
<td>3.7</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table 2.1: DeMi optical design parameters relevant to the POPPY optical diffraction model.

2.2 The rest of this chapter describes the results of this POPPY model.

Figure 2-2: Summary of optical modeling approach for DeMi.

2.2 Image Plane Wavefront Sensor Simulations

The POPPY model was used to simulate the Point Spread Function (PSF) on the image plane wavefront sensor. To simulate the image plane wavefront sensor, the wavefront is propagated up to the beam splitter and then reflected and focused by the image plane lens onto the image plane detector. POPPY propagates the wavefront to the detector then samples the resulting PSF to match the DeMi camera settings. The simulation was calculated for the FOV matching the smaller camera axis so the simulation was symmetric in both axes. This simulation was computed for individual actuator pokes and DM shapes. This image plane wavefront sensor simulation is very
quick to run, typically taking 6-7 seconds on a 2017 MacBook Pro as measured by Python’s timeit() function. The image plane POPPY model is included in Appendix A.1.

A simulation of the image plane PSF with a flat DM is shown in Figure 2-3. To determine the size of this PSF, a Gaussian function was fit to the model output as shown in Figure 2-4. The measured size of the PSF Gaussian fit was 3.7 pixels in x and 5.3 pixels in y. A sample result from the POPPY model for a single actuator poke applied to the DM is included in Figure 2-5.

2.3 Shack Hartmann Wavefront Sensor Simulation

The POPPY model was also used to simulate the spots on the Shack Hartmann wavefront sensor. The POPPY model simulates this by propagating the light through the DeMi optical system (transmitting through the beam splitter to reach the Shack
Figure 2-4: Gaussian fit to image plane wavefront sensor PSF simulation with flat DM. (Left) Gaussian fit is shown on left. Measured width of Gaussian was 3.7 pixels in x and 5.3 pixels in y. (Right) Residual between the PSF model and the fit to the model.

Figure 2-5: Image plane wavefront sensor POPPY model with [3,5] actuator poked to 0.27 μm. (Left) POPPY output image zoomed in to see the PSF. (Right) Difference between POPPY output with flat DM and with poked actuator.

Hartmann optics) and then subsampling the wavefront so the light incident upon each lenslet in the lenslet array optic is focused onto the detector individually. Each spot PSF is calculated individually and then tiled together to form the spot field. The large number of lenslets in the DeMi system caused the wavefront object to have very large arrays to keep track of the phase and amplitude along the optical path, which makes the Shack Hartmann simulation computationally intensive. The DeMi POPPY model was run on the MIT Engaging cluster at the MGHPCC facility.
Figure 2-6: POPPY model output for flat DM measured on Shack Hartmann wavefront sensor.

(www.mghpcc.org) and the Shack Hartmann calculations typically took 5 minutes to run. The Shack Hartmann POPPY model is included in Appendix A.2.

The DeMi POPPY model was used to simulate the spot field on the Shack Hartmann wavefront sensor, shown in Figure 2-6. The size of each lenslet spot was determined by fitting a Gaussian function to a single focused lenslet spot, shown in Figure 2-7. The measured spot size was 2.9 pixels in diameter.

The POPPY model was also used to simulate Shack Hartmann wavefront sensor measurements for single actuator pokes. Figure 2-8 shows example output for the [3,5] actuator poked to 0.27 μm.

The Shack Hartmann spot fields were then processed to reconstruct the wavefront. First, the centroids of each spot in the spot field were calculated. Then, centroids from a simulation with a flat DM were subtracted from the centroids with a perturbed DM
Figure 2-7: Single lenslet spot simulation from SHWFS POPPY model. (Left) Single lenslet PSF measurement. (Right) Gaussian fit to single lenslet PSF.

Figure 2-8: Example output of the Shack Hartmann POPPY model for a DM with the [3,5] actuator poked to 0.27 μm (left). The effects of these pokes is not visible to the eye, but can be seen in the centroid displacements shown on the right. The centroid displacement plot shows the magnitude of the displacement of each lenslet from its nominal position with a flat DM.

to find the difference due to the DM shape. Then, the Moore-Penrose pseudoinverse approach is used for zonal reconstruction of the wavefront according to the Southwell geometry implementation [93] described in Dai 2008 [94]. Then, the gaussfitter python package was used to fit a gaussian to the poke measurement.\(^3\) The height of the gaussian fit was used as the actuator deflection height to compare to physical data. The function used to reconstruct the wavefront from the spot field simulations and

\(^3\)https://github.com/keflavich/gaussfitter
Figure 2-9: Data analysis for POPPY simulation shown in Figure 2-8 for the [3,5] actuator poked to 0.268 um. The reconstructed wavefront is shown on the left, the Gaussian fit to the reconstruction is in the center, and the residual between the data and the measurement (reconstruction subtracted from Gaussian fit in this case) is shown on the right. The actuator deflection measured was 240.7 nm, which is 90% of the input actuator displacement of 268 nm. The residual had a median of 1.2e-4 um and a standard deviation of 2.6e-3 um.

fit Gaussians to the measurements is included in the Appendix A.2.1. Reconstructed wavefronts for the spot fields shown in Figure 2-8 are shown in Figure 2-9. For the 270 nm actuator poke simulation, the actuator deflection measured was 240.7 nm, which is 90% of the input actuator displacement, and the residual had a median of 1.2e-4 um and a standard deviation of 2.6e-3 um. The wavefronts and gaussian fits in Figure 2-9 are reported in units of wavefront error, which are divided by two to convert to physical units to calculate the actuator deflection.

These simulations are compared to testing data from the DeMi flight payload in Chapter 4.
Chapter 3

DeMi Payload Alignment and Integration

3.1 DeMi Flight Payload Assembly and Alignment

The DeMi optical payload flight unit was aligned using a Zygo interferometer. This chapter describes the flight payload alignment procedures as well as the payload integration with the flight bus.

3.2 Payload Alignment

A flight-like engineering model and the flight unit of the DeMi optical payload were both assembled and aligned using a Zygo interferometer. The DeMi payload was aligned to a requirement of 0.25 waves RMS wavefront error. The preliminary alignment procedures are described in detail in [95] and the final flight alignment is summarized here. Jennifer Gubner, Ewan Douglas, Yinzi Xin, and Gabor Furesz contributed significantly to the alignment procedures used for DeMi.

The DeMi payload alignment split the payload into sections of one or more optical elements that were aligned as a section, then aligned within the full optical system. The sections were OAP1 (the primary mirror), field mirror bench (consisting of the field mirror and OAP2), DM (the deformable mirror and its mount), beam splitter
(the beam splitter mount which the image plane lens and camera mount attaches to), relay bench (consisting of OAP3 and OAP4), and the Shack Hartmann wavefront sensor (consisting of the lenslet array mount and the Shack Hartmann camera).

First, all of the optics were mounted or bonded into place and assembled onto their benches. The OAP optics and DMs were mounted to their mounts with screws. A setup DM was used in place of the flight DM during initial alignment to protect the flight DM from damage. The beamsplitter, image plane lens, and Shack Hartmann lenslet array optics were bonded to their mounts with RTV566. The optical fiber for the calibration laser was cleaved and installed into the groove within the field mirror and staked into place using 3M Epoxy Adhesive EC2216. The optical fiber was threaded through a teflon tube which was staked to the fiber output hole in the field mirror mount to protect the fiber during alignment and integration. This optical fiber had an FC/PC connector at the end which allowed us to plug it into a laser to test the optical path of the internal laser source throughout alignment. After alignment, the FC/PC connector end was removed and the flight laser was spliced into place.

Then, the relay bench was aligned by removing OAP4 and installing the relay bench on a tip-tilt and rotation stage in front of the Zygo. OAP3 was aligned to the Zygo using a spherical retroreflector on a translation stage and adjusting tip/tilt/rotation of the relay bench to reduce the RMS wavefront error to less than 0.25 waves. Then, OAP4 was reinstalled and a retroreflector was used to measure the total wavefront error of the full relay. The bushings on the OAP4 mount were adjusted to remove the error caused by misalignment between OAP3 and OAP4 so that the total RMS wavefront error was less than 0.25 waves.

Next, the field mirror assembly was aligned by attaching the optical fiber that was installed into the slot in the field mirror to a laser and using a shear plate interferometer to test the collimation after the light reflected off of OAP2. The bushings between the field mirror and the field mirror mount were adjusted until the shear plate interferometer measurement indicated that the light reflected off of OAP2 was well collimated. A picture of the aligned field mirror assembly with the optical
Figure 3-1: Aligned field mirror/OAP 2 assembly with optical fiber installed and epoxied into place.

The optical fiber installed is shown in Figure 3-1.

At this point, OAP1 was installed into the flight deck and mounted on tip/tilt stages in front of the Zygo interferometer. The OAP was aligned to the interferometer by using a spherical retroreflector to reflect the focused beam off of OAP1 back into the interferometer and adjusting the tip/tilt stage until the errors from misalignment between the OAP1 and interferometer were minimized. The spherical retroreflector was mounted on a linear translation stage along the output optical axis of the OAP to aid in alignment of the spherical retro in the system.

Once OAP1 was aligned to the interferometer, the field mirror assembly was installed. A corner-cube retroreflector was used to reflect the light back into the interferometer, and the bushings controlling the tip, tilt, and rotation of the field mirror assembly were adjusted to minimize the errors caused by misalignment between OAP1 and the field mirror assembly. Figure 3-2 shows the optical payload aligned at this step.

Then, a setup-grade DM was installed into the DM mount and installed into the payload to check the spot location on the mirror. The setup-grade DM is a non-operational Multi DM from BMC with the same form factor as the flight-grade and engineering-grade DMs. For DeMi, the goal was to have the laser spot as centered on the DM as possible. The DM mount had a tendency to cant forward when the screws were torqued, so washers were used as shims to support the DM mount and
prevent this behavior. Figure 3-3 shows the spot location on the setup DM. Once the DM mount was installed into a good location, the setup-grade DM was swapped for the actual flight DM. At this point, the internal laser fiber was connected to a laser, which was powered on to check that the Zygo light spot and the internal laser light spot overlapped. This verified that the optical paths overlapped enough to ensure reasonable alignment of the internal laser optical path. After the DM was installed, the flight DM driver electronics were installed and connected to the DM. Figure 3-4 shows the flight payload at this step of alignment, with the DM driver installed with ribbon cables.

The DM was then powered on to provide zero Volts to each actuator. This served as our flat map, since the provided flat maps from BMC were calibrated with their driver and were no longer flat using the MIT driver. At this point, the beam splitter and image plane camera lens was installed, but not aligned. Then, the relay deck was installed. A corner-cube retroreflector was placed at the Shack Hartmann wavefront sensor location and the relay deck tip/tilt/rotation was adjusted with bushings...
Figure 3-3: DeMi flight payload with setup DM installed. The red laser spot can be seen on the setup DM.

Figure 3-4: Flight DeMi payload with OAP 1, field mirror, OAP 2, and flight DM installed and aligned.
Figure 3-5: Final Zygo measurement of the aligned flight payload. Measurement was taken at the location of the Shack Hartmann wavefront sensor before the lenslet array was installed.

until the total wavefront error throughout the system met the mission requirement of <0.25 lambda RMS wavefront error. The final alignment measurement from the Zygo interferometer is shown in Figure 3-5. The alignment measurement setup with the DM driver for the final alignment and calibration measurements before the lenslet array was installed is shown in Figure 3-6.

After the payload was aligned, the Shack Hartmann and Image Plane wavefront sensor cameras were installed. The image plane camera was installed by inserting its mount into the image plane lens mount and adjusting the height of the camera mount to minimize the PSF size and achieve the best focus. The set screws on the
beam splitter mount were adjusted to steer the image plane PSF into the center of the image plane camera. The Shack Hartmann wavefront sensor camera was installed onto the lenslet array mount and the spot field was checked by plugging in a laser to the internal laser fiber. Figure 3-7 shows the aligned DeMi flight payload with the beam splitter, image plane lens, and Shack Hartmann lenslet array installed.

Once all the optical components were installed and aligned, all screws were torqued (if they hadn’t been torqued during the alignment process) and staked using 3M Epoxy Adhesive EC2216. Thermal gap filler was installed between all the optics component mounts and the optics bench, and the flight space-grade DM ribbon cables
Figure 3-8: Fully assembled and aligned DeMi flight payload with DM ribbon cables and thermal gap filler installed.

were installed into the flight DM. A picture of the full aligned payload is shown in Figure 3-8.

3.3 Flight Payload Integration

After the optical bench was fully aligned, the flight payload electronics, optics bench, and camera boards were installed into the flight bus. The entire DeMi team was instrumental in assembling the flight unit and integrating with the spacecraft bus. This process was done in several stages which are summarized here.

First, the flight electronics (including USB cables mated to the camera boards) were mated to the optics bench and command of the cameras/DM was tested. Figure 3-9 shows the assembled flight electronics stack mated to the optics bench.

Then, the laser diode/camera board mount was installed with the laser and attenuator installed as shown in Figure 3-10. Then, the optical fiber between the laser and the attenuator and between the attenuator and the connector was routed and
Figure 3-9: Flight electronics mated to optics bench. The wide shiny white cables between the electronics stack and the optical bench are the space-grade DM teflon ribbon cables while the thinner white cables coming from the electronics stack are connected to the camera driver boards.
Figure 3-10: Camera board, laser diode, and laser attenuator mount installed into DeMi spacecraft bus.

staked into the bus with Arathane 5753 epoxy. The optical fiber that was installed into the field mirror of the payload was spliced to a connector and routed and staked into place on the payload. Figure 3-11 shows the fiber routing on the bus side and Figure 3-12 shows the fiber routing on the payload side.

Next, the electronics were installed, torqued, and staked into the spacecraft bus and mated to the spacecraft avionics. Figure 3-13 shows the electronics installed into the spacecraft bus with the optics bench resting on the spare bench feet to protect the fiber routing on the bottom of the bus. Then, the optics bench was gently lifted up so the spare feet could be removed and the optics bench was lowered into position to fit around the fiber and cable routing between the optics bench feet. Figure 3-14 shows the optics bench being lowered into the flight bus. Once the optics bench was in position, the feet were screwed in, torqued, and staked into place. Figure 3-14 shows the DeMi spacecraft with the electronics and optical payload installed. Then, the camera boards were installed into the camera board mount and the 3d-printed baffle was installed into the spacecraft bus. Figure 3-15 shows the DeMi payload
Figure 3-11: Optical fiber routing for the fiber between the laser diode and attenuator and between the attenuator and fiber connector. The optical fiber is in yellow jacketing. The optical bench is being held above the bus in this picture.

Figure 3-12: Optical fiber routing for the fiber staked into the field mirror and spliced to a fiber connector. The optical fiber is in a white teflon tube or yellow jacketing in this picture.
Figure 3-13: Electronics installed into the DeMi spacecraft bus and mated to spacecraft avionics. The optics bench is resting atop the spare optics bench feet to protect the fiber routing during installation.

fully installed into the spacecraft bus before the spacecraft lid was installed. After integration, the payload was used to take measurements to validate the optical model and calibrate the wavefront sensors.
Figure 3-14: DeMi payload and electronics installed into spacecraft bus.

Figure 3-15: DeMi payload fully installed into spacecraft bus.
Chapter 4

DeMi Payload Data

The aligned and integrated flight DeMi payload was used to gather data to compare to the POPPY model. This chapter describes the data collected from the Image Plane and Shack Hartmann wavefront sensors and compares them to the predictions from the POPPY model.

4.1 Image Plane Wavefront Sensor Data

The PSF on the Image Plane wavefront sensor was captured with the Image Plane camera after DeMi was integrated with the satellite bus. Figure 4-1 shows this PSF measurement. In this measurement, pixels are binned by 2 relative to the POPPY model which assumed no binning. Figure 4-2 shows a zoomed-in view of this measurement, as well as a Gaussian fit to the PSF to measure the size of the spot on the image plane wavefront sensor. The measured spot size was 10.5 pixels by 10.0 pixels.

The actual image plane PSF can be compared to the POPPY simulation shown Figure 2-5 from Chapter 2. The POPPY simulation assumes perfect alignment of all the elements, so the PSF is centered exactly on the sensor. In reality, not all of the optical elements were aligned to be exactly level, so the PSF is not centered on the detector exactly.

The POPPY model predicts that the image plane PSF will be an oval shape. The region illuminated by the primary spot was measured with a Gaussian fit to be 3.7
Figure 4-1: Measurement of Point Spread Function (PSF) on DeMi image plane sensor after integration with satellite. Pixels are binned by 2 in this measurement.

(a) Image plane PSF
(b) Gaussian fit to PSF
(c) Residual (PSF - Gaussian fit)

Figure 4-2: Gaussian fit to measure size of image plane PSF. Measured size of spot on image plane sensor was 10.5 pixels by 10.0 pixels, after accounting for pixel binning by 2.
pixels by 5.3 pixels. The DeMi payload PSF was a more complicated shape, and the spot size was measured to be 10.5 pixels by 10.0 pixels across. The differences between the POPPY model and the physical payload are likely due alignment differences in the real payload. For instance, the vertical placement of the image plane sensor was performed by hand, using the spot size of the PSF to achieve the best focus. This explains why the spot size differs slightly between the POPPY model and the physical payload. The difference in shape is likely due to the small residual errors in the optical path after alignment. These results indicate that the POPPY diffraction model can be used to estimate the image plane signal, but should not be used to predict the exact measurements on the physical payload image plane sensor due to the alignment of the physical payload deviating from the idealized simulation.

4.2 Shack Hartmann Wavefront Sensor Data

The spot field from the internal calibration laser on the Shack Hartmann wavefront sensor was captured after the DeMi payload was integrated with the spacecraft bus and is shown in Figure 4-3. The DeMi payload sensor measurements are binned by two, so the pixel scale is different from the POPPY model outputs.

There are fewer lenslet spots illuminated with the internal calibration laser than there were in the POPPY model. This is because the POPPY model assumes an evenly illuminated plane was incident upon the primary mirror aperture to simulate the satellite observing a point source like a star. In reality, the internal calibration laser outputs a gaussian beam profile which underfills the DM slightly, which leads to this spot pattern with the illumination intensity of spots dropping off towards the edges of the beam.

The size of each lenslet spot was measured by fitting Gaussian functions to the spot measurements and using the width of the Gaussian fit to describe the size. An example spot measurement is shown in Figure 4-4. The average measured spot size was 3.8 pixels with a standard deviation of 0.7 pixels in \( x \) and 3.8 pixels with a standard deviation of 0.6 pixels in \( y \). The POPPY simulation lenslet spots were
Figure 4-3: Measurement of spotfield on DeMi Shack Hartmann wavefront sensor after integration with satellite. Pixels are binned by 2 in this measurement.

measured to be 2.9 pixels by 2.9 pixels. The small difference is probably due to the alignment of the DeMi payload differing slightly from the idealized model.

The Shack Hartmann wavefront sensor was used to measure single actuator pokes of the DM. In these measurements, a single actuator is commanded to move and the centroids of the lenslet spots are recorded before and after the actuator is poked. This displacement is used to reconstruct the incident wavefront to measure the deflection of the actuator.

The x and y spot displacements are analyzed with the same zonal wavefront reconstruction function that was used in Chapter 2 to analyze simulated Shack Hartmann data. The actuator poke is then measured by fitting a Gaussian function to the reconstructed wavefront data using the Gaussfitter package in Python\(^1\). The actuator deflection measured is the height of the Gaussian fit to the reconstructed wavefront data. An example reconstructed wavefront measurement with corresponding Gaussian fit is shown in Figure 4-5. This measurement is similar to the POPPY simulation from Figure 2-9.

The reconstructed wavefronts from both the POPPY simulated Shack Hartmann

\(^1\)https://github.com/keflavich/gaussfitter
Figure 4-4: Gaussian fit to measure size of single lenslet spot PSF on Shack Hartmann wavefront sensor. Measured size of spot shown was 3.8 pixels by 4.2 pixels, after accounting for the pixel binning by 2 in the measurement.
(a) Wavefront reconstruction

(b) Gaussian fit to wavefront reconstruction

(c) Residual (Gauss fit - reconstruction measurement)

Figure 4-5: Example poke measurement data analysis for actuator number 100 poked to 60 V.
measurements and the physical payload Shack Hartmann measurements look very similar and are well described by the Gaussian fits. The Gaussian fit to the simulation from Figure 2-9 had a height of 0.22 μm and a width 1.2 lenslets in x and 1.6 lenslets in y. The Gaussian fit to the flight payload measurement had a height of 0.14 μm and a width of 2.5 lenslets in x and 2.1 lenslets in y. The difference in height measured is due to the fact that the DM is not calibrated to deflect to a specific height, but commanded to a certain voltage, while the POPPY model inputs a deflection height. The simulation shown is comparable but not exactly the same as the deflection from the physical DM in the payload, since the Shack Hartmann wavefront sensor calibration is still ongoing. The small difference in width between the simulation and the DeMi payload data could be due to the actual influence function of the DeMi DM deviating slightly from the model used in the POPPY model, or due to the difference in alignment between the actual DeMi payload and the idealized POPPY model.

The POPPY diffraction model has been validated for both the image plane and the Shack Hartmann sensor. The model can be used to estimate the signal on either sensor. Since the POPPY model does not account for the actual alignment of the physical payload, the simulation results differ slightly from the actual data from the payload. The model will be useful for predicting the effects of the incline of the DM in the payload on the wavefront sensor measurements.
Chapter 5

Conclusions

In this work, an optical model of the DeMi payload is developed. This model is developed using the open-source software package Physical Optics Propagation in PYthon (POPPY). The Shack Hartmann wavefront sensor model used the subapertures class of POPPY which was originally written by Professor Ewan Douglas and was developed and validated through this work. The signals on both the Shack Hartmann and image plane wavefront sensors are simulated using this model.

The flight payload alignment and integration with the spacecraft are described. The DeMi spacecraft was successfully delivered to the launch provider on December 11, 2019 and is expected to launch in February 2020.

Representative measurements from the flight payload are compared to the POPPY simulation. These measurements validate the POPPY model, which can be used to estimate the DeMi payload measurements. The POPPY model does not account for the actual alignment of the payload, so the results should be interpreted as an estimation of expected results rather than an exact prediction.

In this work, a preliminary software pipeline was developed to analyze data from both wavefront sensors in the DeMi payload. This pipeline will be useful for calibrating the instrument and analyzing flight data. This pipeline will be extended to analyze all types of data from the payload and incorporate calibration information.

Future work for the DeMi project is to calibrate the Shack Hartmann wavefront sensor with ground truth measurements from an interferometer. Payload data taken
during and after spacecraft environmental testing will be analyzed and compared to the interferometer measurements of the DM, using the POPPY model to predict the expected payload measurements for each DM setting.

The DeMi CubeSat is expected to launch in February 2020. Flight data from the DeMi payload can be compared to ground data to assess the on-orbit performance of the MEMS DM in space.
Appendix A

POPPY Optical Diffraction Model

A.1 Image Plane POPPY Model

```python
import matplotlib
matplotlib.use('agg')
# coding: utf-8

import csv
import poppy

from poppy.sub_sampled_optics import subapertures
from poppy.poppy_core import PlaneType
from matplotlib.colors import LogNorm
import poppy.fwcentroid as fwcentroid
from matplotlib import pyplot as plt

import logging
import astropy.units as u
import copy
import numpy as np
import timeit
```

65
act_x = 3
act_y = 5
stroke = 0.268e-6

#define filename to keep track of results
filename = 'act_' + str(act_x) + '_' + str(act_y) + 'poke' + str(stroke*10**6) + '_um'

## define parameters:
wavelength = .635e-6 # red
pixel_pitch = 2.2*u.um # both detectors have same pixel pitch

lenslet_pitch = 150*u.um
dm_size = .0054*u.m # 4.9 aperture size, 5.4 is actuator pitch*n_actuators
n_lenslets = int((dm_size.to(u.m)/lenslet_pitch.to(u.m)).value)
print("n lenslets: ", n_lenslets)

# image plane plate scale
ps_im = (.0059055118*u.rad/u.mm * pixel_pitch /u.pix).to(u.arcsec/u.pix).value
print("image plane plate scale in arcsec per pix: ", ps_im)

### info for image plane detector:
# 0.005905511811023623 rad / mm
# FOV ARCSEC: 3473.0445801479605 arcsec
# pixel scale: 2.6798183488795986 arcsec/pixel

# define optical system for DeMi model
osys = poppy.OpticalSystem(oversample=6) # initialize
osys.add_pupil(poppy.CircularAperture(radius=dm_size.to(u.m).value/2))
# pupil radius in meters, based on dm size:
osys.add_image()  # reflection off field mirror here
osys.add_pupil()  # OAP 2

## keep flat dm version for comparison
osys_flatDM = copy.deepcopy(osys)

## define DM
dm_actuator_pitch = 450*u.um  # from BMC Multi-DM user manual
# max stroke 5.5 um
dm = poppy.dms.ContinuousDeformableMirror(dm_shape=(12,12),
    actuator_spacing=dm_actuator_pitch,
    inclination_x=45)

## add flat dm to model for flat compare
osys_flatDM.add_pupil(dm)  # DM location for flat dm model
osys_flatDM.add_pupil()  # beam splitter location

## plot dm settings
plt.figure()
dm.display(what='both', opd_vmax=1*u.micron);

## compute psf for flat dm model for comparison
osys_flatDM.add_pupil()  # focusing lens
osys_flatDM.add_detector(pixelscale=ps_im, fov_arcsec=3473.04458)
# image plane coordinates in arcseconds or arcsec/pixel
psf_flatDM = osys_flatDM.calc_psf(wavelength)  # wavelength in microns

## plot flat compare psf
plt.figure()
poppy.display_psf(psf_flatDM, imagecrop=50000, title='PSF flat DM')
figname = "implane_psf_flat"+filename+.png
plt.savefig(figname)
plt.close()

# poke dm actuator
dm.set_actuator(act_x, act_y, stroke)

## plot dm settings
plt.figure()
dm.display(what='both', opd_vmax=1*u.micron);

# add poked dm to optical system
osys.add_pupil(dm) # DM location
osys.add_pupil() # beam splitter location

# continue optical path for image plane detector:
osys.add_pupil() # focusing lens

# calculate psf:
# image plane coordinates in arcseconds or arcsec/pixel
osys.add_detector(pixelscale=ps_im, fov_arcsec=3473.04458)

psf_im = osys.calc_psf(wavelength) # wavelength in microns

# plot results:
plt.figure()
plt.imshow(psf_flatDM[0].data[500:800,500:800], cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
```python
plt.savefig('imflat_zoomed_in{}.png'.format(filename))

plt.figure()
plt.imshow(psf_im[0].data[500:800,500:800], cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.savefig('im_psf_zoomed_in{}.png'.format(filename))

plt.figure()
plt.imshow(psf_flatDM[0].data[500:800,500:800]-psf_im[0].data[500:800,500:800], cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.title("PSF difference")
plt.savefig('psfdiff_{}.png'.format(filename))

plt.figure()
plt.imshow(psf_flatDM[0].data[500:800,500:800])
returns = gaussfitter.gaussfit(psf_flatDM[0].data[500:800,500:800], returnfitimage= plt.figure()
plt.imshow(returns[1], cmap = 'gray')
plt.colorbar(label = 'relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.title("gauss width x: {}, y: {}".format(np.round(returns[0][4],4), np.round(returns[0][5],4)))
print("widths: x ",returns[0][4], 'y',returns[0][5])
plt.savefig("gaussfit_im_flat.png")
```
```python
plt.figure()
plt.imshow(returns[1]-psf_flatDM[0].data[500:800,500:800], cmap = 'gray')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.colorbar(label = 'Relative intensity')
plt.savefig('Residual_gaussiflat.png')

# print(psf_flatDM[0].data)
plt.figure()
plt.imshow(psf_flatDM[0].data, cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.title("Flat DM PSF")
plt.savefig('flatDM_im.png')

plt.figure()
plt.imshow(psf_im[0].data, cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.title("DM Actuator Poke PSF")
plt.savefig('im_{}.png'.format(filename))
```
A.2 Shack Hartmann POPPY Model

import matplotlib
matplotlib.use('agg')

import csv
import poppy
print(poppy.__version__)

from poppy.sub_sampled_optics import subapertures
from poppy.poppy_core import PlaneType
from matplotlib.colors import LogNorm
import poppy.fwcentroid as fwcentroid
from matplotlib import pyplot as plt

import logging
import astropy.units as u
import copy
import numpy as np
logging.getLogger('poppy').setLevel(logging.INFO)
# Can be logging.CRITICAL, logging.WARN, logging.INFO, logging.DEBUG for increasingly verbose output

# DeMi: .03 m aperture, relay, DM (colimated space), BS to lens/image plane, else another relay, lenslet array

def run_model(act_x, act_y, stroke):
    filename = 'act_' + str(act_x) + '_' + str(act_y) + 'poke' + str(stroke * 10 ** 6)
    + '_um' + 'inclined_opdfixed'  # define filename to keep track of results
## define parameters:

wavelength = .635e-6 #red
pixel_pitch = 2.2*u.um #both detectors have same pixel pitch
lenslet_pitch = 150*u.um
dm_size = .0054*u.m #4.9 aperture size, 5.4 is actuator pitch*n_actuators
n_lenslets=int((dm_size.to(u.m)/lenslet_pitch.to(u.m)).value)
r_lenslet = lenslet_pitch/2.
lenslet_focal_length = .0037*u.m
pix_per_lenslet = int(lenslet_pitch/pixel_pitch)
plate_scale = 1.0*u.rad/(lenslet_focal_length.to(u.m))
rad_pix = (plate_scale*pixel_pitch.to(u.m))/u.pix #radians per pixel
plate_scale_converted = rad_pix.to(u.arcsec/u.pix).value #arcsec per pixel

## define DM

dm_actuator_pitch = 450*u.um #from BMC Multi-DM user manual
#max stroke 5.5 um
dm = poppy.dms.ContinuousDeformableMirror(dm_shape=(12,12),
actuator_spacing=dmiactuator_pitch, radius=6*dm_actuator_pitch,
iclination_x =45)

#poke dm actuator
dm.set_actuator(act_x, act_y, stroke)

# set dm surface shape (demo)
#
#    surface = poppy.zernike.zernike(2,0,npix=dm.dm_shape[0],
#           noll_normalize=True, outside = 0)*wavelength*np.sqrt(5)
#    dm.set_surface(surface)

## plot dm settings
## Define Shack Hartmann Lenslet Array

## Create a 2x2 Array of Apertures

```python
optic_array = np.array([[poppy.CircularAperture(radius=r_lenslet, planetype=PlaneType.pupil),
                        poppy.CircularAperture(radius=r_lenslet, planetype=PlaneType.pupil)],
                       [poppy.CircularAperture(radius=r_lenslet, planetype=PlaneType.pupil),
                        poppy.CircularAperture(radius=r_lenslet, planetype=PlaneType.pupil)])
```

# n_lenslets = 32 # number per side

```python
big_optic_array = optic_array.repeat(n_lenslets/2,axis=0).repeat(n_lenslets/2,axis=1)
```

# Define Wavefront Directly to Control Oversampling Factor and Avoid Undersampling Effects

```python
wf2 = poppy.Wavefront(diam=dmsize, wavelength=wavelength, npix=68*n_lenslets*2)
wf2 *= poppy.CircularAperture(radius = dmsize/2)
wf2 *= dm
```

```python
sub = subapertures(optic_array = big_optic_array, display_intermediates=False, detector = poppy.Detector(plate_scaleConverted,
                                      fov_pixels = pix_per_lenslet))
```

# Note: `fov_pixels` refers to pixels per lenslet PSF

# Sample the Input Wavefront
sub.sample_wf(wf2)

#propogate each of the sub PSFs
sub.get_psfs()

#display single psf:
plt.figure()
plt.imshow(sub.wf_array[15,15].intensity, cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.title("Single lenslet PSF")
plt.savefig('single psf_full oversample {}.png'.format(oversample, filename))
plt.close()

# fit gaussian to measure psf size
returns = gaussfitter.gaussfit(sub.wf_array[15,15].intensity,
                                returnfitimage=True)
plt.figure()
plt.imshow(returns[1], cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.title("Single lenslet gaussfit width x: {}, y: {}".format(
        np.round(returns[0][4],4), np.round(returns[0][5],4)))
print("widths: x ",returns[0][4], 'y',returns[0][5])
plt.savefig("single psf gaussfit {}.png".format(filename))
plt.close()

np.savetxt('{}_wf_array.csv'.format(filename), wf_array.intensity, delimiter = ',')
#display spotfield:
plt.figure()
plt.imshow(wf_array.intensity, cmap = 'gray')
plt.colorbar(label = 'Relative intensity')
plt.xlabel('pixels')
plt.ylabel('pixels')
plt.title("SHWFS Spotfield Simulation")
plt.savefig('wf_array_linear_{}.png'.format(filename))
plt.close()
print('sub wf array shape',sub.wf_array[0,0].shape)

#calc centroids and output:
x,y=sub.get_centroids()
filename_x = 'cent_x_{'+filename+'}.csv'
filename_y = 'cent_y_{'+filename+'}.csv'
with open(filename_x, 'w') as myfile:
    wr = csv.writer(myfile)
    for row in x:
        wr.writerow(row)
with open(filename_y, 'w') as myfile:
    wr = csv.writer(myfile)
    for row in y:
        wr.writerow(row)
return

#set filename and poke info to save output for run:
strokes =[0.268e-6,0.07e-6] #can input whatever here, in units of m
act_x = 3
act_y = 5
for stroke in strokes:
    run_model(act_x, act_y, stroke)

A.2.1 Shack Hartmann POPPY data analysis code

## helper function copied from:
#https://github.com/douglase/libtim-py/blob/master/libtim/shwfs.py#L230

def zonalReconstruction(x,y,ds):
    """
    Simple zonal reconstructor based on Matlab example in
    Wavefront Optics for Vision Correction.
    Society of Photo-Optical Instrumentation Engineers.
    Modified to work with rectangular spotfields.
    """
    #flatten operates in row-major order
    g=np.concatenate(np.nantonum([x.flatten().to(u.radian),
                                  y.flatten().to(u.radian)]))
    m=x.shape[0]
    n=x.shape[1]
    S=g

    print("m:",m,"n:",n)
    E = getE(m,n)
    C = getC(m,n)

    C=np.matrix(C)
    S=np.matrix(S)
Epinv = np.linalg.pinv(E)
p=Epinv*C*S.T
return np.multiply(p.reshape(m,n),ds)

def getC(m,n):
    C = np.matrix(np.zeros([(m-1)*n+(n-1)*m, 2*n*m]))
    for i in range(m):
        for j in range(n-1):
            C[i*(n-1)+j, i*n+j]=0.5
            C[i*(n-1)+j, i*n+j+1]=0.5
    for i in range(n):
        for j in range(m-1):
            C[m*(n-1)+i*(m-1)+j, n*(m+j)+i]=0.5
            C[m*(n-1)+i*(m-1)+j, n*(m+j+1)+i]=0.5
    return C

def getE(m,n):
    E=np.matrix(np.zeros([(m-1)*n+(n-1)*m, n*m]))
    for i in range(m):
        for j in range(n-1):
            E[i*(n-1)+j, i*n+j] = -1
            E[i*(n-1)+j, i*n+j+1] = 1
    for i in range(n):
        for j in range(m-1):
            E[m*(n-1)+i*(m-1)+j, i+j*n] = -1
            E[m*(n-1)+i*(m-1)+j, i+(j+1)*n] = 1
    return E
# load data and reconstruct wavefront:
poke_val = "0.07"
xact = "3"
yact = "5"
folder = "engaging run outputs/"
inc = "uminclined_opdfixed"
nlenslets = ""
filename_xflat = folder+"cent_x_act_7_7poke0.0_uminclined_dmred36lenslets_testnooversample.csv"
filename_yflat = folder+"cent_y_act_7_7poke0.0_uminclined_dmred36lenslets_testnooversample.csv"
filename_xpoke = folder+"cent_x_act_"+xact+"_"+yact+"poke"+poke_val+inc+nlenslets+".csv"
filename_ypoke = folder+"cent_x_act_"+xact+"_"+yact+"poke"+poke_val+inc+nlenslets+".csv"
x_flat = read_csv(filename_xflat)
y_flat = read_csv(filename_yflat)
x_poke = read_csv(filename_xpoke)
y_poke = read_csv(filename_ypoke)

# calc offsets for zonal reconstruction:
x_off = np.subtract(x_poke, x_flat)*scale*u.rad*1/10 #times 1/10 to correct # for detector oversample
y_off = np.subtract(y_poke, y_flat)*scale*u.rad*1/10

# run WF reconstruction:
wf_reconstruction = zonalReconstruction(x_off, y_off, lenslet_pitch)
# fit gaussian:
returns = gaussfitter.gaussfit(wf_reconstruction.value, returnfitimage=True)

defl = returns[0][1]
print("measured actuator deflection: ", defl/2)

print("residual median: ", np.median(-wf_reconstruction.value + returns[1]),
"std: ", np.std(-wf_reconstruction.value + returns[1]))

# plot results:
fignamestart = folder + 'x'+xact+'y'+yact+'poke' +poke_val
plt.figure()
plt.imshow(returns[1])
plt.gca().invert_yaxis()
plt.xlabel('lenslets')
plt.ylabel('lenslets')
plt.colorbar(label = 'um')
plt.savefig(fignamestart + '_gauss.jpg')
plt.close()

plt.figure()
plt.imshow(wf_reconstruction.value)
plt.gca().invert_yaxis()
plt.xlabel('lenslets')
plt.ylabel('lenslets')
plt.colorbar(label = 'um')
plt.savefig(fignamestart + '_wfreconstruction.jpg')
plt.close()
plt.imshow(-wf_reconstruction.value + returns[1])
plt.gca().invert_yaxis()
plt.xlabel('lenslets')
plt.ylabel('lenslets')
plt.colorbar(label = 'um')
plt.savefig(fignamestart + '_residual.jpg')
plt.close()
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