JPL Document D- 81373

TECHNOLOGY DEVELOPMENT FOR EXOPLANET MISSONS

Technology Milestone White Paper
MEMS Deformable Mirror Technology

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9 December 2013

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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California Institute of Technology

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Released by

Feb.20, 2014

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Acronyms

BMC:	Boston Micromachines Corporation
CDM:	Continuous Surface Deformable Mirror
DM:	Deformable Mirror
ETIF:	Environmental Test and Integration Facility at Godard Space Flight center
FEA:	Finite Element Analysis
HCIL:	High Contrast Imaging Laboratory
MEMS:	Micro Electro Mechanical Systems
TDEM:	Technology Development for Exoplanet Missions
VSG:	Vacuum Surface Gauge

TDEM Milestone White Paper:
MEMS Deformable Mirror Technology

1. Objective

In support of NASA's Exoplanet Exploration Program and the ROSES Technology Development for Exoplanet Missions (TDEM), this whitepaper explains the purpose of the first TDEM Milestone for **MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection**, specifies the methodology for computing the milestone metrics, and establishes the success criteria against which the milestone will be evaluated.

The objective is to achieve a technology development milestone that demonstrates the capacity of the Micro Electro Mechanical Systems Deformable Mirrors (MEMS DMs) for use in exoplanet detection instrumentation after being exposed to the environmental conditions that would be experienced during launch and operation. Without such technology development, a coronagraph mission using MEMS DMs would not be possible.

2. Introduction

TDEM Technology Milestones are intended to document progress in the development of key technologies for a space-based mission that would detect and characterize exoplanets, thereby gauging the mission concept's readiness to proceed from pre-Phase A to Phase A.

This milestone addresses MEMS deformable mirrors used in high precision wavefront control in high contrast imaging instruments. Completion of this milestone is to be documented in a report by the Principal Investigator and reviewed by the Exoplanet Exploration Program.

This milestone reads as follows:

2.1. Milestone 1 definition:

Demonstrate survivability and functional performance repeatability of the BMC 952-actuator MEMS CDM to within the noise floor of the various test equipment after exposure to dynamic mechanical environments representative of a range expected in coronagraph launch.

- Characterize the degree of degradation in CDM optical and electromechanical performance through functional test and interferometric surface mapping. The level of measurement repeatability in this series of tests will be 5nm using the BMC interferometer and <100pm using the JPL Vacuum Surface Gauge.

- Characterize any changes to CDM performance in an existing coronagraph test bed (Princeton's High Contrast Imaging Laboratory), as measured by the achievable null depth and its stability.

2.2. Relevance for a Future Exoplanet Mission

In the ROSES-NRA the Strategic Astrophysics Technology program calls directly for efforts of this type: "In order to achieve the requisite degree of starlight rejection, the light paths within both coronagraphic and interferometric systems must be controlled to sub-nanometer precision. Advances in control algorithms, sensing technology, and *deformable mirror technology* are central to implementing such instruments on a space-based platform (emphasis added)."

The strategic goal of the work proposed here is to advance MEMS DMs as an enabling technology in NASA's rapidly emerging program for extrasolar planet exploration. That goal is supported by an Astro2010 white paper on *Technologies for Direct Optical Imaging of Exoplanets* [*1*], which concluded that DMs are a critical component for all proposed internal coronagraph instrument concepts. That white paper pointed to great strides made by DM developers in the past decade, and acknowledged the MEMS components made by Boston Micromachines Corporation to be among the "most notable options".

Conventional DMs (e.g. the 48x48 actuator Northrop Xinetics DMs that are used as baseline technology for PECO and in the HCIT at JPL) are currently at a higher level of technology maturity (~TRL 6) than their MEMS-based counterparts. However MEMS components are likely to be of increasing importance in space-based mission concepts because of mass and cost considerations [1].

Another Astro2010 white paper entitled *Overview of Technology Development for the Phase-Induced Amplitude Apodization (PIAA) Coronagraph [2]* noted that "the current PECO baseline uses eight Xinetics DMs, which are 48mm in size. With this many relatively large DMs on a relatively small telescope, there is a strong incentive to test smaller DMs, such as the Boston Micromachines MEMS DMs, and this technology is currently being explored at the NASA Ames test bed."

If this project is successful, a critical milestone will be reached for CDM components based on MEMS technology. The potential benefit to NASA will be both timely and important.

3. Deformable Mirror Component Fabrication and Test

3.1. Modeling and design

The MEMS to be tested in this work have been fabricated previously by Boston Micromachines Corporation (BMC), and all masks, layout, and process technology required to produce and package these mirrors exist and have been proven reliable. The specifc proposed DM design and fabrication processes will be based on Boston Micromachines Kilo DM (32x32 actuators) used in adaptive optics instruments and testbeds for ground and space-based astronomical imaging around the world, including the PIAA testbed at the NASA AMES Coronagraph Laboratory[3], the High Contrast Imaging Laboratory at Princeton University[4] and at the Laboratory for Adaptive Optics at University of California, Santa Cruz [5] . This effort will also leverage design and fabrication process enhancements developed in previous NASA funded efforts that will improve overall actuator reliability and yield. The actuator design is the same as the heritage design, and will give the same electromechanical performance. The difference is the arrangement of the actuators. This mirror design consists of 952 actuators arranged in a Cartesian grid with 34 active actuators across a circular aperture. The "corners" of the grid are not active. A schematic of the mirror compared to the heritage 32x32 DM is shown in Figure 1.

Table 1: Characteristics of MEMS Deformable Mirror

Mirror architecture	952 actuator continuous facesheet
Active aperture	9.9 mm Circular, 34 actuators across diameter
Actuator pitch	300µm
Fill Factor	99.6%
Surface figure error	<5nm RMS, λ<400µm
Surface Roughness	<2nm RMS
Mirror segment material	Silicon, 1000 Å gold coating
Actuator stroke	2µm

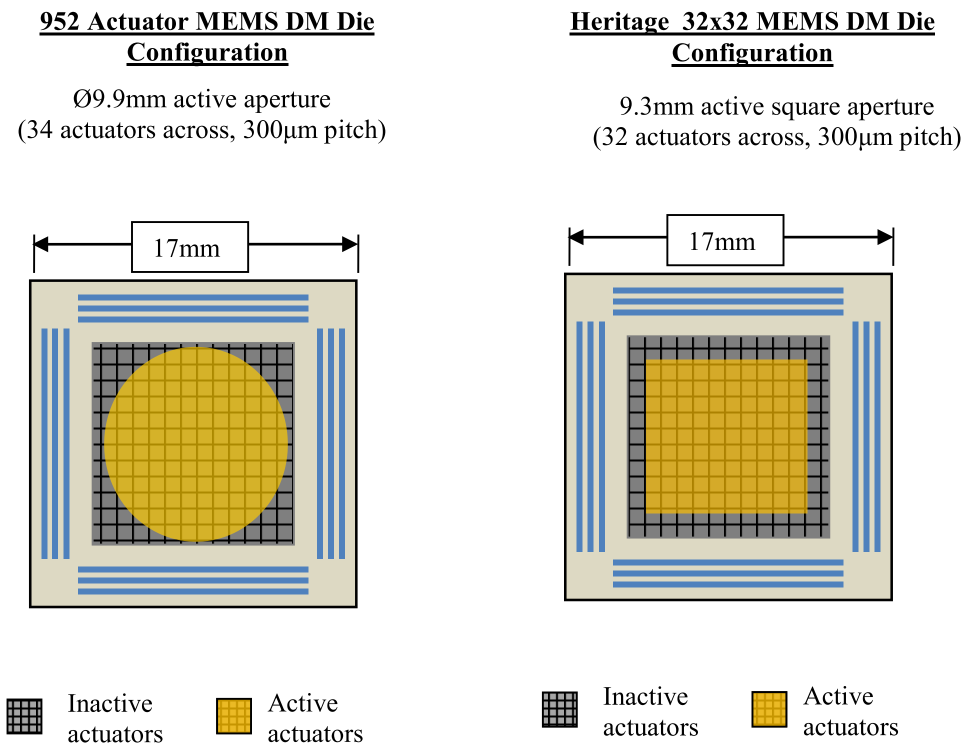

Figure 1. Comparison of the heritage 32x32 "Kilo" and 952 actuator MEMS DM die configuration. The die size and pitch is identical for the two devices.

A batch fabrication run is required, both to generate twelve candidate components for testing and to implement minor design changes to parts of the component that preliminary analysis has shown to be at risk of failure in the proposed dynamic mechanical testing. These modifications include strengthening the adhesive die attach connections and replacing bare wire with insulated wire for chip-to-package wire bond connections.

Potential failure mechanisms for the die attachments include detachment or plastic deformation, which could lead to anomalous performance of the component. We will model and empirically characterize mechanical properties and yield strength of attachments, and will model forces expected during dynamic mechanical tests using commercially available elastic-plastic FEA software (Abaqus® or Comsol®). We will redesign attachment geometry and material as needed to ensure a factor of safety of at least two with respect to yield under modeled test conditions.

Potential failure mechanisms for wire bonds include detachment from bond pads or electrical shorting between adjacent wires due to wire sway during dynamic loading. Preliminary analysis of shock loading on thin, compliant, closely spaced bond wires indicates relatively high risk of inter-wire shorting, and little risk of bond pad detachment. We anticipate substituting insulated wire for the bare wire currently in use, to mitigate this risk. We will analyze expected wire plastic deformation using elastic-plastic FEA subjected to inertial and vibrational forces expected in EFIT dynamic mechanical tests.

Potential failure mechanisms for thin film mirror and actuator structures are perhaps the most challenging aspect of the modeling and evaluation proposed in this project, since the coronagraph application requires picometer-scale stability and precision, and environmental effects that impact performance at that scale are difficult to model precisely. The primary failure mechanism will be plastic deformation or fracture of the thin-film flexural elements in the device. This failure can manifest itself in different ways. If there is a weakening in the actuator due to fracture, it can show as an increase in the gain (i.e. more voltage is required to actuate the mirror to a given deflection). If there is plastic deformation in the actuator, the mirror element can stand proud of its neighboring actuators in the unpowered state. Our plan for modeling is to employ elastic-plastic FEA and to simulate loading environments expected in ETIF dynamic mechanical tests. There are other failure modes for MEMS devices that are induced by the electrical properties of the system (e.g. electric over stress and electrostatic discharge) that can cause permanent damage and result in mirrors that to do move from either the unpowered position, a "pinned" position at maximum deflection, or somewhere in between. As this project is only studying the dynamic mechanical behavior, we will not be analyzing these failure modes.

3.2. Fabrication

Core MEMS processing to define actuator and mirror structures will be completed at a MEMS surface micromachining foundry (MEMSCAP), using established processing techniques that have been developed over a decade of research and that have included more than twenty batch fabrication runs involving these basic DM architectures. The process begins with a batch of twenty wafers, polished on both sides. Using cycles of thin film deposition by chemical vapor deposition, lithographic patterning with photoresist, and reactive ion or wet etching, the foundry process builds DM device structures. Thin film layers alternate between structural silicon and sacrificial silicon dioxide, and at the conclusion of MEMS processing the oxide layers are dissolved to yield released silicon structures. Roughly thirty die sites are included across each of the twenty wafers in the batch. Following MEMS fabrication, components are processed at BMC. They are inspected, coated with gold, die-attached to ceramic pin grid array chip carriers, wire-bonded, and then tested interferometrically.

3.3. BMC Opto-electro-mechanical Characterization of Components

After fabrication, twelve working devices will be selected for dynamic mechanical tests. In addition, eight blank die (Blank #1-8) will be attached to ceramic chip carriers for destructive tests of die attachment bond strength.

Each component will be characterized in four tests at BMC to evaluate mirror surface topography and electromechanical actuator performance. The first test will be a measurement of topographic surface maps and root mean square (rms) surface deviation from flatness over the entire mirror, using a wide field interferometer (Zygo Verifire ®). This measurement will quantify to ~1nm precision any topography in the mirror shape.

The Zygo Verifire has a listed RMS wavefront repeatability of < 350pm, but the laboratory where the measurements will be made is not temperature controlled or environmentally controlled (i.e. not in vacuum), therefore the precision will be higher than the instrument specification. Mirror non-flatness can be attributed to residual stresses in the thin films or the die, or print-through, so this measurement provides a baseline that is sensitive to changes in stress that might result from planned ETIF testing. (An example measurement, showing 4.7nm rms non-flatness on the full active aperture of a previously tested 1020 actuator CDM is shown in Figure 1 at spatial frequencies outside of the controllable bandwidth. The overall unpowered peak-valley in the active aperture has been measured up to 500nm, allowing for over 1µm of stroke after flattenning). The second test will be a series of measurements of topographic surface maps and rms surface deviation from flatness over 600µm subapertures for each component, using a surface mapping interferometer (Veeco 9100 3D ®). This subaperture spans approximately one-and-a-half times the inter-actuator spacing in a CDM. Subapertures centered on *each actuator* will be measured for CDMs. These measurements will quantify small-scale topography in the component with ~1nm precision, providing a baseline for similar measurements made subsequent to dynamic mechanical testing. The third test will be a quasi-static electromechanical measurement of mirror displacement (measured in surface normal direction directly above each actuator post) in response to a series of applied voltages spanning the operational range of the actuator. Only one actuator will be energized at a time in this test. All others will be held at ground potential. Multi-point displacement curves will be measured multiple times for each actuator in the component to establish an error-bounded electromechanical performance baseline. This data will also confirm the integrity of wire bond attachments on the device. The fourth test will involve imposing known surfaces on the mirror surface at multiple offsets. In this test the mirror will be driven to flat in a closed loop control system with the Zygo

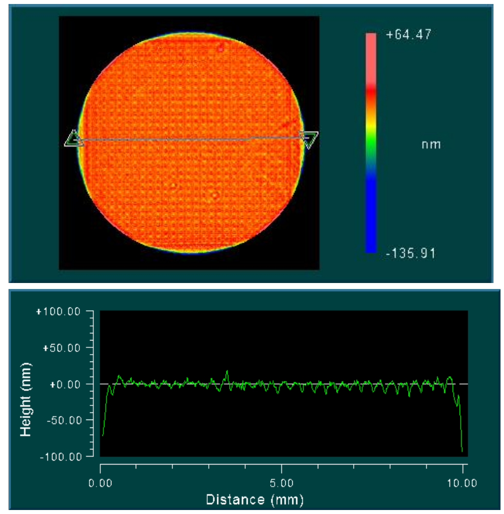

Figure 1: Interferometric surface map of a BMC CDM mirror. Shows surface error of Rq = 4.7nm RMS

Verfire providing surface measurement feedback. This will be performed at offsets of zero, mid stroke, and full stroke. The resulting surface figure will be measured and recorded. Also recorded will be the voltage map that has been applied to the actuators. The mirror surface will also be driven to a series of sinusoidal pattern with the same closed loop control system and the voltage maps recorded. These voltage maps will be compared against a predicted one knowing the unpowered surface figure and the voltage deflection characteristics measured previously. Any anomalous coupling or interaction between actuators will be shown by comparing the two maps and noting any differences outside of the expected variation due to the drive electronics. If any anomalous behavior is noted, it will be investigated as to potential causes and effects on future tests.

Four of the blank die will be used in destructive tests to establish a baseline of die adhesion strength, using a Instron® bond testing apparatus. Nominally, the bond-testing apparatus records normal force required to detach the die from the chip carrier. After ETIF testing, the other four blank die will be destructively tested to evaluate whether bond strength has been compromised.

3.4. Coronagraph Test Bed Component Insertion and Baseline Null Testing

3.4.1 ExEP facilities at JPL

After characterization at BMC, two of the twelve DMs (Serial Numbers 1 & 2) will be sent to the ExEP facilities at JPL, where they will be inserted and tested in the Vacuum Surface Gauge (VSG). The testing will be performed at the VSG to give a higher precision measurement than achievable at Boston Micromachine's facility due to the fact that BMC measurements will be taken in air, whereas the VSG measurements will be taken in vacuum. With this additional benefit of taking the measurements in vacuum, the instrument has recently shown a 70-80pm measurement precision and can potentially achieve 20pm. As mentioned before, the Boston Micromachines interferometer has a measurement precision an order of magnitude greater. The driver electronics that will be used to actuate the mirrors have 16 bit control over 200V, resulting in a ~3mV LSB. The MEMS mirrors have a response of 10nm/V in their linear range giving a 30pm step. It is therefore required to have an instrument with the precision of the VSG to measure the small steps achievable. Earlier work has demonstrated that MEMS mirrors with design and electromechanical performance similar to the mirrors used in this program have a stability on the order of 100pm [6]. Along with each CDM will be a voltage map that will produce a flat mirror surface to the level of measurement capable with BMC's Zygo interferometer. This will allow testing at the VSG from a relatively flat starting point.

With the standard optical setup, the resolution of the system is 1 pixel of the VSG CCD, which corresponds to 100µm on the deformable mirror surface. This has been designed to achieve 100 pixels per actuator for the standard DM. To achieve the same spatial resolution on the MEMS DMs being tested in this program, the f-number going into the VSG CCD will be changed to result in 1 pixel, corresponding to ~33µm on the MEMS DM mirror surface.

To characterize the VSG a series of tests will be performed to quantify the measurement noise of the instrument before the deformable mirrors are characterized and tested. This test will involve inserting a mirror with a known surface topography. The surface of this mirror will be measured multiple times over a period of 48 hours. From this information, the static noise of the instrument will be determined. This result will be the metric on which future testing is based.

The tests performed on the deformable mirror on the VSG will include influence function measurement on the mirror surface at different voltages and biases. This will be a quasi-static electromechanical measurement of mirror displacement (measured in surface normal direction directly above each actuator post) in response to a series of applied voltages spanning the operational range of the actuator. First, the measurement of the surface will be taken when the voltage map proved by BMC resulting in a flat surface is applied. Then a different voltage pattern will be applied to the mirror and a surface measurement taken. The difference between these two measurements will show the displacement and influence function. To expedite the testing procedure, an array of 8x8 actuators, spaced 4 actuators apart will be energized (Figure 2). This will allow for the displacement measurements at 64 locations for a single measurement and reduce the measurement time dramatically. All others actuators will be held at ground potential. Five point displacement curves will be measured.

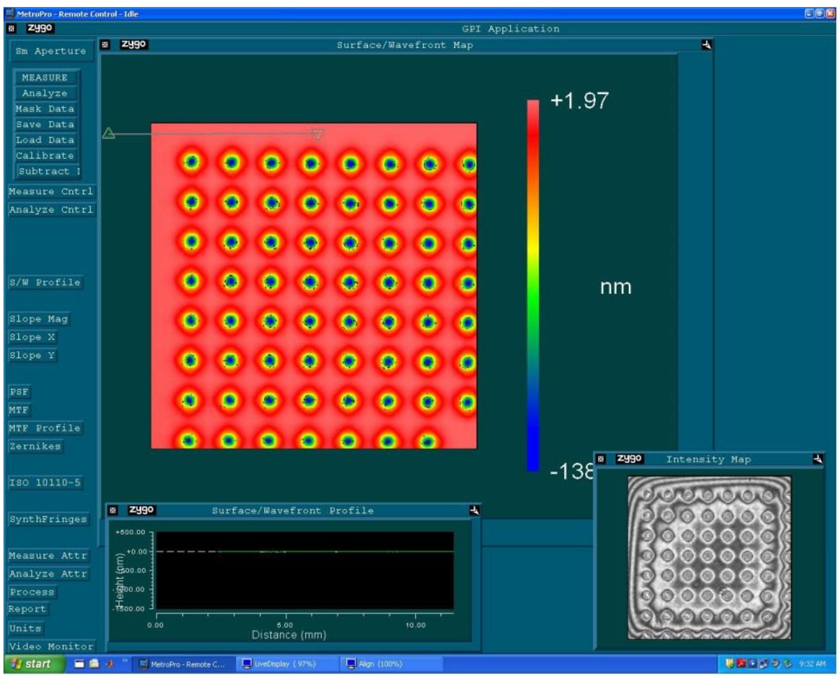

Figure 2: Surface measurement of Kilo-DM with a voltage applied to 64 actuators.

Repeatability of the device and measurements will be made with multiple measurements of a subset of the actuators to establish an error-bounded electromechanical performance baseline. Twelve actuators will be chosen at different locations on the mirror to address any variation due to location. The deflection and influence function of these twelve actuators for an applied voltage will be measured ten times, with the voltage being turned on and off between each measurement. Also tested at the VSG will be position stability. For this test, a voltage pattern will be applied to the actuator array resulting in a predetermined shape on the mirror surface. Measurements of the mirror surface will be taken multiple times over a 48 hour period to show any drift in position over time. Finally, the mirror surface will be driven to a series of sinusoidal pattern from the voltage maps previously recorded from Boston Micromachines' test. The surface measurements will be recorded for comparison to similar measurements that will be taken after the environmental testing.

3.4.2 **Princeton High Contrast Imaging Laboratory**

Princeton will also perform experiments with two of the twelve DMs (Serial Numbers 3 & 4) in the High Contrast Imaging Laboratory (HCIL), a research laboratory at Princeton University led by Professor Jeremy Kasdin and comprising of an interdisciplinary group of faculty, staff, and graduate students from Mechanical & Aerospace Engineering, Astrophysics, the Institute for Advanced Study, Operational Research & Financial Engineering, and other departments. The experiments will be run on the two DMs to be tested as well as a set of identical reference DMs that will remain in Princeton as a point of comparison. The experiments at Princeton will test the performance of two DMs in series with a shaped pupil coronagraph in both monochromatic and broadband (10% and 20%) light to achieve symmetric dark holes in the image plane. A single free standing, shaped-pupil ripple mask will be dedicated to the tests before and after environmental testing. The Stroke Minimization control algorithm and Kalman filter wavefront estimator will be used for these experiments. The specific algorithm will be frozen after the initial tests. The DMs will be taken through a series of tests, specifically by varying the size of the dark hole and its separation from the optical axis from 7 to 10 and -2 to 2 λ/D on each side of the image plane. Varying the size of the dark hole and how close it is to the optical axis will help to decouple model limitations on the contrast performance. For example, a smaller dark hole can reach a deeper null, which tests actuation precision. Varying the dark hole size and location also allows us to provide an image plane analog to a modal decomposition of the DMs, quantifying the controllability of specific subsets of spatial frequencies. For each of these tests the resulting voltage map on the DM will be recorded and used as a base line for any future testing. Such tests will help to determine potential failure modes and performance limitations in the context of speckle suppression for high contrast imaging. From this information, reasonable on-orbit identification and tuning scenarios may be able to be determined, allowing the recovery of the contrast performance if the DM has experienced specific types of performance degradation, such as reduced voltage-to-actuation gain.

3.5. Dynamic Mechanical Testing at ETIF

The twelve packaged and wire-bonded DMS that were tested at BMC (including the 2 that were tested at Princeton and 2 that were tested at JPL will be delivered to ETIF, where they will be subjected to random vibration, acoustic vibration, and mechanical shock. ETIF is the Environmental Test and Integration Facility as NASA Goddard. This group has the facilities and technical expertise to conduct vibration tests, acoustic tests, acceleration tests, static loading tests, and mass properties tests of spacecraft, scientific instruments, or their components. As it is yet to be determined what the environmental levels representative of a launch for a coronagraph mission would be, three levels will be tested for each of the environmental test: low, medium and high. The DM components will be tested in each of the environments according to the following table. This distribution of DMs and testing was determined by allowing a number of devices (1-4) to only experience low levels of environmental exposures. This conservative approach will give the best chance of a device being characterized at the test beds before and after environmental testing surviving and providing useful information for the project. Fewer devices will be tested at the high levels, as it is anticipated that these will be "test-to-failure" levels. For medium levels, the distribution was set to expose some to only lower levels on certain tests to bound the potential failure levels. Also, included are two devices that will be exposed to all levels of all testing.

Table 2: Dynamic mechanical tests to be conducted at ETIF

	Environmental Test			
Level		**Vibration**	**Acoustic**	**Shock**
	Low	1,2,3,4,5,6	1,2,3,4,5,6,7	1,2,3,4,5,6 8,9
	Medium	5,6,7,8,9,10	5,6,8,9,11	5,6,7,11
	High	5,6,11,12	5,6,10,12	5,6,10,12

Mirror number and test to which it will be exposed

The specific levels of testing and the rationale behind choosing these levels for each of the three environments are discussed in the *Environmental Testing Requirements for TDEM Deformable Mirror Technology* Document [7].

3.6. Post-Exposure Component Opto-electro-mechanical Evaluation at BMC

After EFIT testing, all devices will be fully characterized at BMC using the protocols established in ***Section 3.3*** to assess any changes to baseline surface quality and actuator function.

3.7. Post-Exposure Coronagraph Test Bed Component Insertion and Null Testing

After BMC post-exposure evaluation, the same devices as previously tested (Serial number 1 & 2 at JPL and 3 & 4 at Princeton) will be retested at the sites described in ***Section 3.4*** to replicate baseline null tests.

4. Success Criteria

The following are the required elements of the milestone demonstration.

4.1 The opto-electro-mechanical performance of the DMs will be measured at BMC before and after environmental testing. This will include testing of no less than 12 DMs as shown in Table 1 and the testing will include all the testing described in Section 3.3.

4.2 The surface quality and operation of at least two DMs will be characterized using the Surface Gauge Instrument at JPL before and after environmental testing to determine any differences in performance.

4.3 Testing of two DMs will be performed at Princeton's HCIL before and after environmental testing to determine any differences in performance.

4.4 No fewer than 12 DMs will undergo the series of environmental testing described in Section 3.5.

5. Certification

The PI will assemble a milestone certification data package for review by the ExEPTAC and the ExEP program. In the event of a consensus determination that the success criteria have been met, the project will submit the findings of the review board, together with the certification data package, to NASA HQ for official certification of milestone compliance. In the event of a disagreement between the ExEP project and the ExEPTAC, NASA HQ will determine whether to accept the data package and certify compliance or request additional work.

5.1. Milestone Certification Data Package

The milestone certification data package will contain the following explanations, charts, and data products.

5.1.1 A narrative report, including a discussion of how each element of the milestone was met, and a narrative summary of the overall milestone achievement.

5.1.2 A description of the MEMS manufacturing procedure including certification that all parts tested were manufactured in a consistent repeatable manner.

5.1.3 A description of the test procedure performed at BMC and the results of same including optical and electromechanical performance, both before and after the environmental testing.

5.1.4 Results of surface measurements made in the JPL Surface Gauge instrument on a representative MEMS mirror both before and after the environmental testing

5.1.5 Results of the testing performed at Princeton's HCIL both before and after the environmental testing.

5.1.6 A report on the environmental tests performed on the MEMS mirrors including levels and durations.

6. References

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