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TECHNOLOGY DEVELOPMENT FOR EXOPLANET MISSONS

Environmental Testing of MEMS Deformable Mirrors for Exoplanet Detection

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Environmental Testing of MEMS Deformable Mirrors for Exoplanet Detection

1. Objective

This whitepaper supports NASA's Exoplanet Exploration Program and the ROSES Technology Development for Exoplanet Missions (TDEM). It explains the purpose of the first TDEM Milestone for ***Environmental Testing of MEMS Deformable Mirrors for Exoplanet Detection***, it specifies the environmental tests and performance characterization metrics, and finally it specifies the success criteria against which the milestone will be evaluated.

This milestone is designed to establish any potential performance shifts in the Iris AO 163-segment MEMS DMs (product name: PTT489) as a result of environmental testing. The tests to be conducted here are the highest-priority launch and operational environments as deemed by the DM testing standards work group and documented in *Environmental Testing Requirements for TDEM Deformable Mirror Technology* (Lawson *et al.* 2013). Subsequent milestones will include additional environmental testing of a flight-like DM system that addresses critical scaling issues and includes mounting hardware and wiring harnesses.

2. Introduction

In general, TDEM milestones are meant to track the progression in development of critical technologies for the direct detection and characterization of exoplanets. A critical component in all of the proposed systems is the deformable mirror (DM). The objective of this TDEM milestone is to test a meaningful sample of Iris AO PTT489 DMs (see Figure 1) under environmental conditions that simulate launch and operational environments. Success is defined by measuring and characterizing any potential performance shifts resulting from the environmental tests.

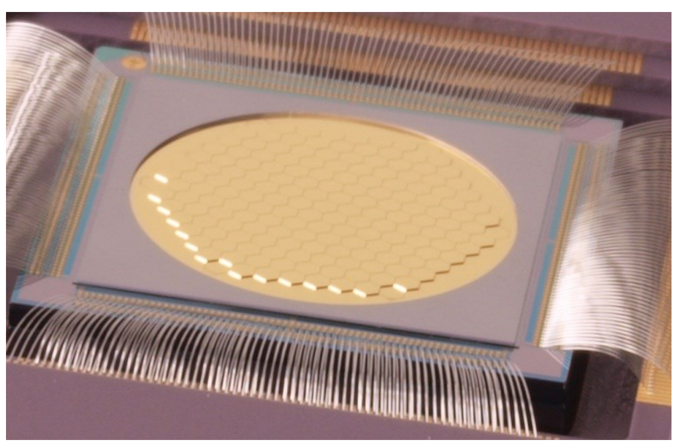

Figure 1: Die photograph of the Iris AO PTT489 DM. This 163-segment DM will undergo rigorous environmental testing and characterization.

Environmental testing of packaged DMs will be conducted both by Iris AO and the Environmental Test and Integration Facility (ETIF) at Goddard Space Flight Center (GSFC). The ETIF has the facilities and technical expertise to conduct vibration tests, acoustic tests, acceleration tests, and shock tests of components, instruments, and spacecraft. Performance characterization will be conducted primarily by Iris AO using established tests and metrology equipment. The final performance characterization will be to demonstrate performance on an actual laboratory coronagraph with the DM operating in vacuum. In this case, the demonstration will be in the Visible Nulling Coronagraph (VNC) under parallel development at GSFC (Clampin *et al.*, JPL Document D-80950, 2013).

Completion of this milestone is to be documented in a report by the Principal Investigator and reviewed by the Exoplanet Exploration Program.

Milestone 1 Definition: Determine the effect of launch environments by environmentally testing 14 separate Iris AO PTT489 DMs and characterizing the degree of performance change (pre- and post-test) to 90% confidence via 5 metrics. The ground test configuration consists of environmental testing (shock, vibe and acoustic) of the DM traceable to 3 flight launch environments.

A. Performance metrics to be measured are: 1) unpowered segment position change; 2) powered segment position change for 5 predefined positions; 3) positioning resolution change of a 1 LSB change in drive voltage; 4) segment figure change, and 5) contrast changes in the VNC at an inner working angle (IWA) of 2λ/D at 633 nm over a narrowband spectral filter of 1.2 nm FWHM bandpass. Where change is the statistical difference between pre- and post-environmental testing.
B. Confidence levels will be estimated for the changes in all 5 performance-metrics measurements based on a Student t-test. Performance changes measured with ≥90% confidence level will be deemed meaningful. Performance metrics 1-4 will be measured with a white-light interferometer at Iris AO. Performance metric 5 will be measured at the GSFC VNC. See Appendix C for examples of measurement capabilities of the white-light interferometer. See Appendix D for a general description of how the 90% confidence level will be determined.

Rationale: The described measurements span the set of key performance metrics relevant to the exoplanet community for high contrast coronagraphic instrument design. Evaluation of this set of metrics will uncover and quantify any pre- and post-test performance changes likely to occur as a result of the stressing range of environmental testing described herein.

In support of this milestone Iris AO, in collaboration with GSFC, will develop a high-fidelity finite element method (FEM) model of the DM segment unit cell and a medium fidelity FEM model of the packaged DM array to further support this milestone. On a best-effort basis, the FEM model of the unit cell and representative test structures will be validated by correlating simulation results with physical measurements of the DM. Model simulation results will be considered suitable if they bound physical measurements of the DM sub-structure. Subject to funding constraints, modeling errors will be reported for the following structures: 1) bimorph cantilever deformation (shape) at 2 temperatures; 2) actuator platform shape at 2 temperatures; 3) mirror segment height at 2 temperatures; 4) mirror-segment bow at 2 temperatures, and 5) correlation of failure locations based on maximum von Mises stresses. The results will be based on using literature reported ranges for thin-film materials properties, measured film stresses, and measured dimensions.

Rationale: Validating FEM model simulations of representative test structures and the segment unit cell will give confidence that the model incorporates the critical relations necessary to create a predictive model for any future design modifications.

2.1 Relevance for a Future Exoplanet Mission

Maturation of the Iris AO DM technology will help mature the VNC technology. This has both near and long term impacts on our state of knowledge. In the near term, demonstrating the environmentally tested DM with the VNC is a key milestone to achieving TRL-6 status for the end-to-end performance of the VNC, and would enable consideration of EPIC (Extrasolar Planetary Imaging Coronagraph) as an Exoplanet Probe candidate. This is important for NASA as it provides the flexibility to trade several competing technologies and select the approach that gives the best science return balanced against cost risk. In the longer term, the VNC is a very promising concept for high contrast imaging instruments, particularly on flagship mission architectures that rely upon a large segmented primary mirror. The FEM modeling and validation techniques developed here will help the entire coronagraph community. This work will also establish the ability to develop a predictive FEM model for MEMS deformable mirrors.

2.2 Iris AO DM Background

The Iris AO mirror technology, shown schematically in Figure 2, has been under development for over a decade, with the first reported results in 2001 (Helmbrecht *et al.* 2001). The hybrid architecture was chosen to combine what we believe are the best technologies for actuation (surface-micromachined polysilicon) and building superb quality mirrors (bulk-micromachined single-crystal silicon). The mirror-segment arrays and actuator arrays are fabricated separately. Only in the post-wafer processing phase are chips with mirror segment arrays and actuator arrays bonded together using common thermo-compression bonding techniques.

By separating the process, actuator fabrication can be optimized independently of the mirror-segment fabrication. This dramatically simplifies process development while increasing the process capabilities. The end result is a fabrication process that results in exquisite mirror quality and one that can be rapidly prototyped because the mirror surface figure is independent of the actuator performance.

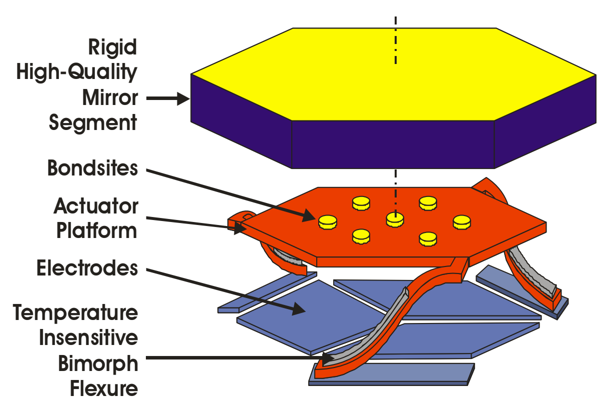

Figure 2: Schematic diagram of a 700 μm diameter (vertex-to-vertex) mirror segment. Scaling is highly exaggerated in the vertical direction.

The actuation mechanism used to

move the mirror segments is electrostatic attraction between the grounded actuator platform and the underlying electrodes in Figure 2. The gap between the electrodes and the platform is created by the platform elevating above the surface of the substrate as a result of engineered residual stresses in the bimorph flexures. Doing so enables both large and low stroke devices using the identical fabrication process. The only difference required is a simple change in the bimorph flexure design. At the early development stages of scaling to larger arrays, DMs typically show large surface figure errors in the unpowered state from global bow and localized non-uniformities. At the outset, these errors must be corrected using valuable mirror stroke. As the fabrication process is refined, the unpowered residual errors are reduced. With the hybrid Iris AO design, DMs have sufficient stroke to compensate for the surface figure errors in addition to correcting for wavefront errors.

Once the fabrication processes have been refined, the Iris AO DM can either be modified to reduce the stroke of the device or simply a smaller portion of stroke can be used. (Iris AO currently has a Phase II SBIR contract with NASA to systematically improve the design and fabrication process used for the PTT489 DM in order to reduce unpowered residual errors. The validated FEM models developed here are fundamental to ensuring that all future modifications are traceable to flight hardware.)

A benefit of the Iris AO design in Figure 2 is that the mechanics and electrostatics are relatively simple. The mirror segments are well modeled with analytical (Euler) beam analysis and simple parallel-plate electrostatics assumptions. Thus, design modifications can be made based on simple analytical expressions. For cases where shock and vibration performance are required, FEM models are used to simulate features where analytic expressions no longer apply.

Modeling of existing Iris AO DMs shows that because the mass of the mirror segments is miniscule, the DM can survive shock and vibration in excess of 150 g. However, stress concentrators at the MEMS scale are not well described with analytical expressions. Thus a large part of this contract is to develop validated FEM models so the flexure designs can be modified in a systematic way to increase robustness to launch environments. Similar techniques have been employed to develop space-qualified mirrors (Yoo *et al.* 2009) and MEMS structures for shock robustness (Cunningham *et al.* 1996).

Two important tests have already been conducted on the DMs that are critical for space-based systems. The first was to demonstrate that there are no corona discharges on the mirrors when operating in air or under various levels of vacuum down to 10 mTorr. The second test demonstrated the robustness of Iris AO anti-snap-down (ASD) technology to make snap-down a nearly fail-proof event. The ASD technology is a means to eliminate permanent catastrophic snap-down failures that occur when a structure has been overdriven so that it makes contact with another MEMS surface. Once the two surfaces touch, they can permanently stick together because of stiction forces (a combination of capillary, Van der Waals, and electrostatic forces). The acoustic, shock, and vibration forces that occur during launch can overdrive the MEMS devices as well. Without some means to eliminate this failure mode, there is a credible possibility that a segment will suffer a permanent snap-down and therefore degrade the contrast performance of the optical system. Even a single failure would likely degrade the contrast to a point that the coronagraph could no longer detect exoplanets. Iris AO has developed a technology to turn snap-down from a permanent failure event to a fail-proof event. *Testing has shown that a mirror segment can survive in excess of 100 million snap-in events without failure* (Helmbrecht *et al.* 2010 and 2011).

The Iris AO DM technology has been demonstrated in the VNC testbed at GSFC (Lyon *et al*. 2012). The DM stroke exceeds the 1 µm requirements and is capable of the level of control (~70 pm *rms* for electronics delivered to GSFC) required for the VNC. Mirror segment flatness of DMs delivered to GSFC is approaching that needed for flight to within a factor of 2X.

The main issues that remain with the DM are global bow as described above and building larger 1,000 segment arrays with sufficiently high segment yield. Segment yield will increase as the fabrication process and design is further refined. Ongoing development as well as the work for this TDEM contract will inherently increase mirror yield as a result of building more DMs and modifying the designs to make them robust to shock and vibration.

2.3 TDEM Research Overview

The approach chosen for this TDEM contract is to develop a validated FEM model of the Iris AO PTT489 DM and to environmentally test the DMs for launch and operational environments.

FEM models will be developed by collaboration between Ingenium Scientia Solutions and Iris AO. Eduardo Aguayo will lead the FEM modeling from Ingenium Scientia Solutions. He has had extensive experience with building FEM models of the JWST microshutters and has been running FEM simulations of these models.

The DM models will be validated against actual measurements of Iris AO devices. Modeling the DMs will be critical for interpreting results and for making accurate predictions of performance for eventual flight hardware. The models will also be used to make design modifications to the PTT489 should they be necessary to survive launch environments.

All environmental testing critical for meeting the TDEM milestone will be conducted on packaged PTT489 DMs. A set of fourteen devices will be tested to assess environmental limits. Performance characterization prior to and following environmental testing will be conducted by Iris AO. Performance characterization will also be conducted by GSFC of DMs prior to and following environmental testing. At GSFC DMs will be characterized in the VNC, by using it as an interferometer to characterize performance of the individual segments and as a coronagraph to demonstrate high-contrast nulling.

2.4 Differences Between Flight and Laboratory Demonstrations

The critical differences between the hardware tested here and eventual flight hardware are: 1) tests here are for packaged DMs only, and 2) DMs tested here are 163 segments. Neither wiring harnesses nor mounting hardware will be subjected to environmental testing under this TDEM contract. The DM arrays must also be scaled up. Concept studies for the VNC call for DM arrays with ~1000 segments. If we are successful in meeting the milestone herein, a following TDEM proposal will include the mounting hardware and wiring harnesses used to send command voltages to the mirror actuators. Likewise, testing of larger mirror arrays will be proposed to confirm the technology scales as anticipated through FEM modeling.

As part of an existing NASA Phase II SBIR, Iris AO is developing compact interface boards for the DMs to be mounted onto as well as compact wiring harnesses. The same Phase II SBIR is funding the development of 939-actuator (313 segment) DM arrays as well.

3. FEM Modeling and Validation Procedure

On a best effort basis, Iris AO and GSFC will develop a FEM models to predict performance of the DM array over the operational environment. The models will be validated against physical measurements of static test structures at multiple temperatures and for electrostatic actuation. (Simulations of the FEM model will not be validated with data from dynamic positioning as Iris AO currently does not have the test facilities to conduct these tests in house.) Analytical models will also be compared to FEM simulations for simple test structures where possible.

Because MEMS fabrication techniques have relatively large variations in dimensions and physical properties (e.g. residual stress, Young’s Modulus), detailed FEM models of the segment unit cell will be created to span upper and lower bounds of critical parameters to the simulations. Lower fidelity FEM models of the DM array and packaging will also be developed to assist in interpreting qualification tests. The FEM modeling and simulation will be conducted by Ingenium Scientia Solutions (FEMAP for modeling and NX Nastran for simulations) and Iris AO (COMSOL 4.3 multi-physics package for modeling and simulation).

The underlying philosophy of this study is that space qualification has to be preceded by the development of an FEM model that is validated with high-resolution interferometry and electromechanical testing of the MEMS DMs. An FEM model is critical to interpretation of the subsequent qualification tests. It will also be an invaluable tool for additional development and scaling to flight hardware.

The set of measurements described below will be used to validate the detailed FEM models of the DM unit cell produced for this TDEM research. The ability to model the DM and accurately simulate the performance of the DM within bounds for these tests will validate that the FEM model incorporates the critical relations necessary to create a predictive model for any future design modifications.

All of the measurements described below will be conducted with a Zygo NewView 7300 interferometer. This instrument is a high-resolution white-light interferometer capable of measuring step-heights in excess of 150 µm with nm *rms* level accuracy. Errors are proportional to scan length, so it is possible to measure to <10 pm *rms* over smaller scan lengths if necessary. The interferometer is currently equipped with two objectives (2.5X and 50X) and two field zoom lenses (1X and 0.5X). The spatial sampling with these objectives and field zoom lenses covers the range of 0.22 µm - 8.84 µm. The instrument is also capable of field stitching larger areas.

3.1 Static bimorph cantilever and DM actuator platform heights

The FEM model simulations will be validated using static high-resolution interferometry measurements of released bimorph flexures and actuator platforms. By design, the bimorph flexures deform to elevate the actuator platforms above the substrate once the devices are released (the sacrificial oxide layers have been removed). The final actuator platform and bimorph flexure shape is dependent on the stresses in the materials, material properties, and the physical dimensions. Thus, if the FEM model simulations correlate with measured data, we can be confident that the simulations incorporate the salient effects for the static structure at a single temperature.

FEM simulations will be correlated with the shape of released bimorph-cantilever test structures, actuator-platform shapes (with no segments bonded onto them), and segment heights. The effects of coefficient of thermal expansion (CTE) mismatches from the various MEMS materials will also be studied. The FEM simulations will be correlated with physical measurements at two or more different temperatures. Test structures will include bimorph cantilevers, actuator platforms, mirror segments. Depending on budget constraints, a packaged mirror array will also be modeled, simulated, and correlated with measured data.

3.2 Electromechanical response curves

The Iris AO deformable mirrors are actuated using parallel-plate electrostatic actuators. For this validation test, the COMSOL FEM models will be used to simulate the position-versus-voltage response curves of Iris AO DMs. The FEM simulations will be correlated with measurements of an Iris AO DM. As with the validation in 3.1, the model simulation results should bound the measured response in order to be successful.

3.3 Destructive shock and vibration testing

A final validation test for the FEM models is if they can predict where fractures occur in the actuator platforms (including the bimorph flexures) shown in Figure 2 when the DMs are destructively tested. For these tests, the locations where we expect the actuator platforms to first reach failure criteria (peak von Mises stress) will be determined by FEM simulation for the DM unit cell for each of the most stressing conditions to be tested. At least 10 uncoated DM arrays will be destructively tested and then inspected with an infrared microscope to determine the fracture locations. (An infrared microscope is required to image through the mirror segments down to the underlying bimorph flexures.) This validation will be deemed successful if the actual failure locations and failure modes correlate with the predicted failure locations from FEM simulations.

4. Milestone 1 Demonstration: Environmental Testing

This TDEM is exploratory in nature. It is designed to test beyond the limits the deformable mirrors can handle and provides for rigorous FEM modeling in order to understand failure modes detected during testing. For all of the environmental tests described in the following sections, DMs will be tested at low, medium, and high levels as defined by Lawson *et al*. The low levels are chosen to meet the GEVS "Component Minimum Workmanship" test level. Environmental testing will be conducted by the ETIF at GSFC.

The high levels are chosen to be very aggressive with the anticipation of damaging DMs. Given the exploratory nature of this TDEM, it is possible that damage or performance shifts may occur at medium and potentially low levels. In this case, subsequent tests will be conducted at the level that did not cause damage.

Fourteen Iris AO PTT489 DMs mounted in ceramic pin grid array (PGA) packages will be subjected to environmental tests to simulate operational and launch environments. Performance of the DMs will be characterized by Iris AO before and after environmental tests to assess changes.

At least one (requirement of 1, goal of 5) DM will be characterized in the VNC at GSFC prior to and after environmental testing to determine changes in DM performance and contrast.

The following sections detail the tests to be conducted for the TDEM Milestone. The specifications for each of the tests meet requirements developed by the *Deformable Mirror Testing Standards for Space Maturation* working group described in Lawson *et al*. Appendix A briefly summarizes the tests. Additional tests that Iris AO will conduct but that are not required to meet the TDEM milestone are described in Appendix B.

Definition: *Unpowered* testing means the DM will not be powered or operated during the environmental tests. The unpowered tests simulate launch or storage environments.

Definition: *Powered* testing means the DM will be operated either by holding the DM segments in a fixed position (e.g. to flatten the array) or commanding them to various positions during the environmental tests. The powered tests simulate operational environments.

4.1 Acoustic Testing

Test Type: Unpowered
Acoustic tests will be conducted at low, medium, and high levels as described in Lawson *et al.* Once damage is detected, the remaining DMs will be tested at the highest level that does not result in damage. During these tests, the DM arrays will not be covered with

glass as the glass would act as an attenuator. Performance characterization protocols 5.1.1-5.1.5 described in Section 5.1 will be used to measure potential performance shifts.

4.2 Random Vibration

Test Type: Unpowered

Random vibrations will be tested using the spectra described in Lawson *et al.* Tests will be conducted on packaged DM arrays mounted on a rigid support. The DM arrays will most likely be temporarily covered with protective glass during this test to protect them from dust during the environmental tests. Performance characterization protocols 5.1.1-5.1.5 will be used to measure potential performance shifts.

4.2.1 Necessity for protective glass

In general, there is no good means to clean MEMS DMs once they have been contaminated. For tests conducted in areas where particulate contamination from the test facility is a possibility, the MEMS DMs should be covered in a manner that will not inadvertently affect the outcome of the test. To ease visual inspection, the cover should have a glass window on it.

The concept is to machine covers that have a thick (2-3 mm) glass window glued into recessed cavity in the cover that provides a large standoff (~1 mm) between the glass and the DM surface. The covers will be clamped down onto the top surface of the MEMS package. (e.g. The cover itself will make contact with the top surface of the package.) The package will in turn sit on an underlying fixture that bolts onto the vibration exciter table. To measure the vibration and shock spectrum, an accelerometer will be attached to the back of the DM package where there is a clearing in the pins.

4.3 Shock Testing

Test Type: Unpowered

Levels for shock testing (low, medium, and high) described in Lawson *et al.* 2013 will be used. Shock tests will be conducted over successively greater magnitude spectra until damage, if any, is detected. The DM arrays will most likely be covered with protective glass during this test to protect them from dust. Performance characterization protocols 5.1.1-5.1.5 will be used to measure potential performance shifts.

5. Milestone 1 Demonstration: Performance Characterization

5.1 Performance Characterization Protocol

Performance characterization testing will be conducted before and after individual environmental tests or series of environmental tests to determine if any shifts in performance have occurred. Performance characterization tests will be conducted on all of the DMs that undergo environmental testing.

Testing will include electrical, optical, and electromechanical characterization. The following tests describe the performance characterization.

5.1.1 Leakage-current testing

Electrical characterization will consist of measuring leakage currents for each electrode to ground and to other electrodes using Iris AO's electrical-testing system. The test system sets a user-defined voltage (e.g. 50V) on an electrode and measures leakage currents to ground and to other electrodes. The test system tests all of the 489 electrodes of the 163-segment PTT489 DMs and archives these on the Iris AO file server.

Any currents larger than acceptable leakage levels (100 nA) but less than a short circuit (1 μA) will be noted as a performance shift. Short circuits (>1 μA) will be deemed as a failure.

Rationale: Testing leakage currents will determine if the underlying electrical interconnect has been damaged, if a conductive particle has moved to an area where it short circuits an electrode to ground or to another electrode, or if the wirebonds at the chip periphery have short circuited. This test is part of Iris AO's DM calibration protocol.

5.1.2 Open-circuit testing

Detecting open circuits is achieved by setting a voltage on the electrodes and verifying the mirror segment has responded to the input. Measuring segment positions is achieved by using the Zygo NewView 7300 interferometer described previously and Iris AO's piston/tip/tilt (PTT) position extraction routines. This test sets a pass/fail criterion on the individual segments. These measurements will be archived on the Zygo system and backed up on Iris AO's file server.

Rationale: As with leakage-current testing, this test will verify that the electrical interconnect is intact after environmental testing. It tests whether the environmental testing has broken any of the underlying interconnect or wirebonds at the chip periphery. This test is part of Iris AO's DM calibration protocol.

5.1.3 Mechanical-bridge testing

Mechanical-bridge testing determines if neighboring segments impinge on each other because of some unwanted mechanical linkage. The test is related to the open-circuit testing in that it uses the Zygo interferometer to measure the response of the mirror segments when they are actuated. In this case, it determines if actuating a segment (~1.5 μm) moves a neighboring segment. If a neighboring segment does move more than a threshold value (e.g. >80 nm in piston and > 80 μrad in tip or tilt), the system flags this as a mechanical-bridge failure. This test sets a pass/fail criterion on the individual segments. These measurements will be archived on the Zygo system and backed up on Iris AO's file server.

Rationale: Environmental testing, specifically random vibration, shock, and acoustic tests could loosen a particle to allow it to wedge between two mirror segments. This test will detect this failure mode. This test is part of Iris AO's DM calibration protocol.

5.1.4 Unpowered segment PTT position and figure testing

For this performance characterization test, the Zygo NewView7300 interferometer will be used to measure the rigid-body segment positions and the surface figure of the individual segments for unpowered arrays. The segment positions and segment surface figures will be extracted using existing PTT extraction routines. The surface figures will be fit with Zernike modes up to 5th order. The residual errors after fitting will also be recorded for each segment. These values will be archived on the Zygo system and backed up on Iris AO's file server.

These measurements will use the surrounding substrate as a fixed reference to determine the PTT positions for the segments. Doing so requires a large interferometer scan to measure the step. Thus, we anticipate a noise floor of 3-5 nm rms. A lower scan range will be used to measure the mirror surfaces to sub-nm *rms* levels. Limits are described in Appendix C.

Rationale: Static testing of the DM arrays will determine if any permanent changes have occurred to the DM segments and package. Because the Iris AO segments are bonded to pre-stressed actuator platforms (see Figure 2), small changes in film stresses or potentially subtle damage from environmental tests will show up as a change in segment position. Thus, high resolution measurements using the Zygo can replace vibrometer measurements often used to elucidate subtle performance changes in mechanical systems. Measuring the mirror segment figures will determine if stresses in the coating have changed or whether the underlying bondsites have come loose for some reason.

5.1.5 Electromechanical response testing

The electromechanical response will also be tested pre and post environmental testing. For these tests, segment PTT positions will be measured for an unpowered array as well as for a set of at least 10 commanded positions on the array. These tests will also be referenced to the surrounding substrate and thus requires a large scan with 3-5 nm *rms* errors.

Segment displacements for a least significant bit (LSB) change in the drive signal will be measured for each segment as well. As described in Appendix C, segment positioning will be determined for segments relative to each other in order to reduce the measurement noise floor.

Rationale: Actuating the DMs will elucidate any as yet undetected changes in performance. For any changes in performance, these tests can be used to assess changes in the usable stroke of the devices as well as any potential changes in actuator resolution as a result of the performance shift.

5.2 DM characterization in the VNC

Characterization in the VNC will consist of contrast measurements prior to and post environmental testing at an inner working angle (IWA) of 2λ/D, averaged over a region of 1 λ/D in diameter, at 633 nm over a narrowband spectral filter of 1.2 nm FWHM bandpass. Characterization of the DMs in the VNC will follow the protocol described by

Clampin *et al.* 2013. One data collection event will be conducted prior to and post environmental testing for at least one DM (requirement of 1, goal of 5).

6. Success Criteria

The following are the required elements of the milestone demonstration. The elements incorporate all of the environmental tests performed at GSFC and performance characterizations by Iris AO. The final criterion is to demonstrate an environmentally tested Iris AO in the VNC at GSFC.

6.1 Complete all environmental tests described in Section 4

Rationale: The environmental tests described in section 4 and detailed in Appendix A satisfy all of the requirements deemed to be critical by the DM working group for environmental testing of MEMS based DMs. Table 1 shows the anticipated levels for environmental testing under this TDEM contract. At least 14 DMs (seven groups of two DMs) will be tested per requirements documented in Lawson *et al.*

Environmental Test Table – Requirement

Environmental Test	DM ID													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Acoustic	Low	Low	Medium	Medium	Low	Low	Low	Low	High	High	Low	Low	Low	Low
Vibration	Low	Low	Low	Low	Medium	Medium	Low	Low	Low	Low	High	High	Low	Low
Shock	Low	Low	Low	Low	Low	Low	Medium	Medium	Low	Low	Low	Low	High	High

Test Level Key	Low	Medium	High

Table 1: Table of environmental tests to meet minimum success requirements. DMs marked for Medium test levels will be tested at Low and Medium levels subsequently. DMs marked for High test levels will be tested at Low, Medium, and High test levels subsequently.

Should preliminary testing show that the DMs handle higher testing levels, at least 14 DMs will be tested at the goal levels shown in Table 2 or some combination thereof that will result in at least 2 DMs surviving environmental testing. If DMs fail at medium levels, testing will proceed at the low level.

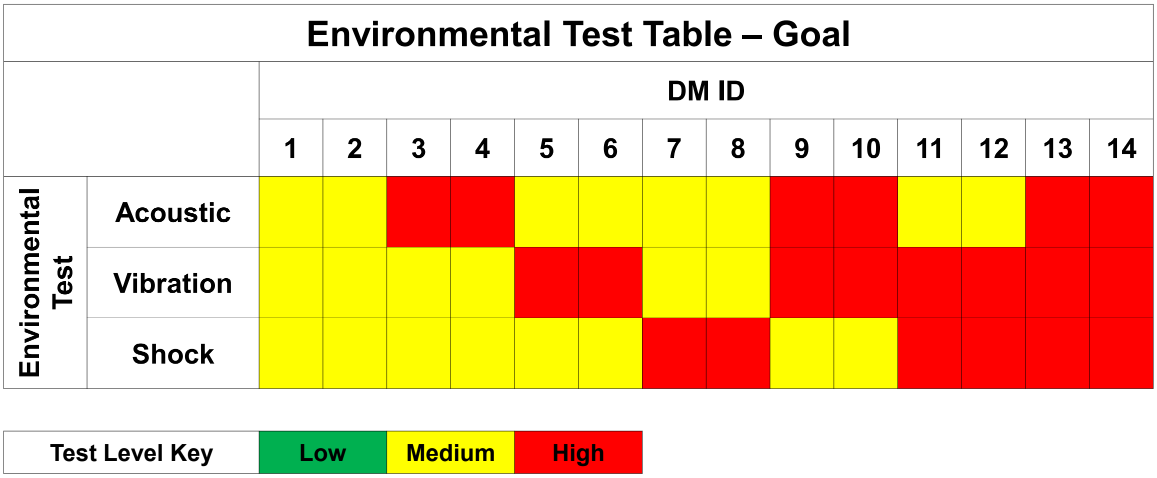

Table 2: Example of environmental tests that exceed minimum testing levels. DMs marked for Medium test levels will be tested at Low and Medium levels subsequently. DMs marked for High test levels will be tested at Low, Medium, and High test levels subsequently.

6.2 Document performance shifts resulting from survivability and operational environmental testing

Rationale: Any performance shifts as well as variability must be well documented to assess their impact on future exoplanet missions.

6.3 Assess effects on VNC performance

Rationale: Describing the effects on VNC performance in advance of actual testing will demonstrate that the impacts are well understood prior to testing. Updating the error budgets after environmental testing will demonstrate that modeling, error budgeting, and testing agree.

6.4 Characterize DM performance shifts in the VNC and assess performance success

Rationale: The impact of potential performance shifts may not be understood or even tested with the protocols defined herein. The best, and possibly only, definitive proof will be to determine the impact on VNC performance with actual hardware testing.

The environmentally tested DM will be considered a success if the mean wavefront errors pre- and post- environmental testing agree to within 64 pm *rms* with a 90% confidence. The wavefront errors will be assessed over the spatial frequency band of 1-4 cycles per aperture.

7. 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.

7.1 Milestone Certification Package

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

7.1.1 Narrative report

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

7.1.2 MEMS DM technology description

A description of the MEMS manufacturing process and certification that all DMs tested were manufactured in a consistent repeatable manner.

7.1.3 Environmental test description

A detailed description of the environmental tests conducted and the DM serial numbers used for testing at specific levels.

7.1.4 Tabulation of significant performance shifts and survivability limits

A narrative will describe any significant performance shifts, the impacts these have on VNC performance, and will describe the development required to make the DM more robust to the particular environmental test if deemed necessary.

7.1.5 VNC performance characterization

A narrative description of the performance characterization tests conducted in the VNC.

Appendix A. Acronyms

AO	Adaptive Optics
CPA	Cycles Per Aperture
CTE	Coefficient of Thermal Expansion
DM	Deformable Mirror
DOF	Degree Of Freedom
ETIF	Environmental Test and Integration Facilities
EPIC	Extrasolar Planetary Imaging Coronagraph
FEM	Finite Element Method
GSFC	Goddard Space Flight Center
IWA	Inner working angle
JWST	James Webb Space Telescope
LSB	Least Significant Bit
MEMS	MicroElectroMechanical System
PGA	Pin Grid Array
PMI	Phase-Modulated Interferometry
PTT	Piston, Tip, Tilt
TDEM	Technology Development for Exoplanet Missions
VNC	Visible Nulling Coronagraph, a TDEM funded coronagraph under development at GSFC: Goddard Space Flight Center

Appendix B. Additional Testing Not Required to Meet Success

In addition to the environmental tests on which success is based, Iris AO will conduct additional testing to better define the capabilities of the PTT489 DM. The following sections describe these additional tests that will be a goal to complete for this TDEM contract.

B.1. Electrostatic Charging

Test Type: Powered

Dielectric materials used to electrically isolate wires and electrodes can charge up during operation. If ground planes are not carefully designed, charging can in turn modify the electromechanical response of the DM. This test will determine the extent to which electrostatic charging occurs with Iris AO DMs. For this test, five DM arrays will be operated for successively longer periods of time (e.g. 1 hour, 5 hours, and 20 hours) and then measured according to performance characterization protocol 5.1.5 to determine how much drift has occurred as a result of electrostatic charging. Tests will be conducted for both randomly positioning the DMs (> 100 Hz update rates) and holding the DM segments at a constant position.

In the VNC, a slow drift can be compensated for. The goal of this test is to assess the extent and rate of change to which charging, if at all measurable, occurs.

B.2. Thermal Testing

B.2.1. Operational Environment

Test Type: Powered

Thermal testing will be conducted over the anticipated operating environment (within existing Iris AO facility testing capabilities*) for coronagraphs as determined by the DM working group. Because of CTE mismatches in the bimorph flexures and the optical coating on the segments, the segments will respond with a shift in bias position (~15 nm/°C) and segment bow (~0.5 nm/°C). Tests will verify these performance parameters with the Iris AO PTT489 DMs over the operating temperatures set forth by the DM working group. Performance characterization protocols 5.1.4 and 5.1.5 will be used to determine the effects of operating the DM over the anticipated temperature range.

*Iris AO facilities are limited to operational testing over the range of 23 – 30°C.

B.2.2. Survivability

Test Type: Unpowered

In addition, Iris AO will test DMs to temperature extremes in order to determine where permanent shifts in performance occur. We anticipate these to come in the form of changes in chip bow and segment bow at higher temperatures (>80°C). Optical quality changes because of plastic deformation in the die attach materials (the low-outgassing epoxy that attaches the DM array to the PGA package) and plastic deformation in the optical coatings respectively. Permanent global changes are manageable as long as DM stroke is sufficient. Changes in the segment bow are uncorrectable by the DM actuators and result in diminished optical performance.

Deformable mirror arrays will be subjected to successively higher (and lower) temperatures for a period of at least 60 minutes until a permanent change in performance has been detected (within existing Iris AO capabilities**). Performance shifts will be assessed with static segment position and segment figure error measurements per performance characterization protocol 5.1.4. The electromechanical response will also be assessed per 5.1.5. Once these threshold temperatures have been detected, the DMs will be tested per the remaining performance characterization protocols 5.1.1-5.1.3.

**For unpowered testing, Iris AO facilities are limited to -10 – 1,200°C in a lab air environment.

Appendix C. Iris AO Metrology for Measuring DM Segment Position Commensurate with 10^9 Contrast

A Zygo NewView 7300 interferometer will be used for absolute and relative segment position measurements. As the following paragraphs describe, absolute segment position measurements have a relatively large noise floor of a few nm *rms*. Relative position measurements of areas closely spaced in the aperture have been demonstrated to be as low as 6 pm *rms*. Thus, Iris AO has the ability to determine segment positioning accuracy of neighboring segments to 10^9 contrast levels. Assuming that all of the segments can be positioned to the required accuracies, it follows that a high-contrast coronagraph capable of measuring to 10^9 contrast levels would be able to position the segments to those levels.

C.1. Absolute Position Measurement

For absolute segment position measurements, a fixed region around the mirror array is used as reference surface as seen in Figure 3. Because of the large scan lengths required to measure the DM segments relative to the reference region, the noise floor is in the 3-5 nm *rms* range for positions across the entire aperture.

C.2. Relative Position Measurement

In order to attain noise levels below the 64 pm *rms* wavefront control accuracy (32 pm *rms* segment positioning accuracy) required for 10^9 contrast in the VNC, much smaller scans must be used. In this case, segment positions can only be measured relative to other segment positions. Testing with a silicon carbide reference flat showed that for a 5 µm scan, the noise floor across the aperture is 61 pm *rms* for a series of single measurements per sample. When averaging multiple measurements per sample, the noise floor drops to 43 pm *rms* and 33 pm *rms* for four and eight measurements per sample respectively.

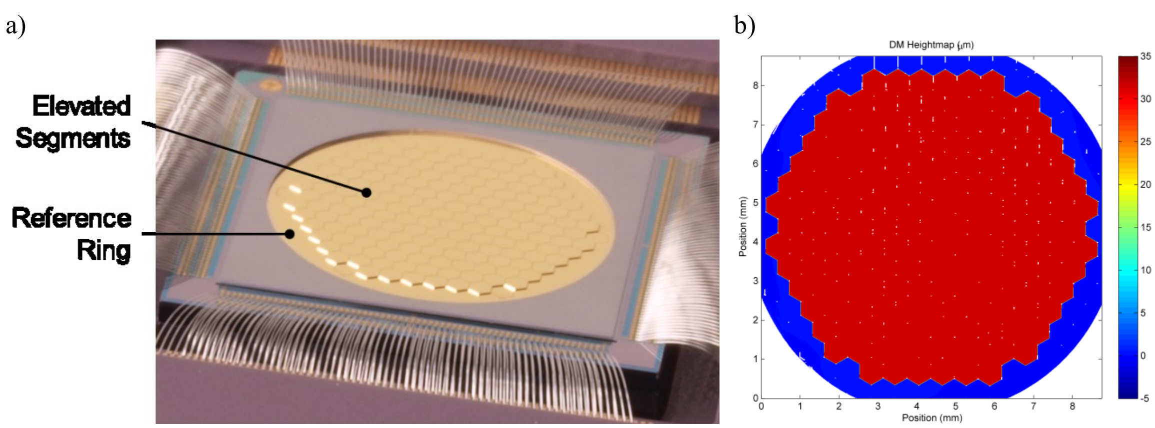

Figure 3: a) Die photo of a PTT489 DM array. The "Reference Ring" region around the periphery of the mirror array is used as the reference surface for absolute position measurements. b) The segments are elevated in excess of 35 µm above the reference ring as shown in this false-color plot of surface height. Because absolute measurements require long interferometer scans, the measurement noise may be as large as 3-5 nm *rms* for a single measurement of points across the entire aperture.

The noise floor drops even further when comparing positions close to one another. For the case of looking at a segment position relative to its neighbors, the noise floor for eight measurements per sample is as low as 6 pm *rms*.

There is the possibility that the reference regions may move because the reference regions are the very DM segments we are attempting to measure. Correlated motions of all segments will not be detectable in this case. This is typically not a concern for coronagraphs. Uncorrelated motions will be a concern as motions of the reference regions will appear as motion in the measured regions. To reduce these errors, multiple reference regions will be used independently to determine the positioning accuracy of a segment. Measured position variations across the baselines will be attributed to motions in the reference regions.

Appendix D. Experiment Design for Pre- and Post-environmental testing of DM

The following is a description of how the 90% confidence interval will be estimated to assess pre- and post-environmental testing performance changes. We employ a form of Student's t-test with unequal variances and/or sample sizes known as a Welch t-test (http://en.wikipedia.org/wiki/Student%27s_t-test). Conceptually the Welch's t-test is evaluated by:

1. Collect NA pre-environmental test realizations (each realization is a single measurement) for each of the 5 DM performance metrics (e.g. segment position, segment figure, contrast,…) denoted as $\left\{W_{A:1}, W_{A:2}, \ldots, W_{A:j}, \ldots, W_{A:N_A}\right\}$.
2. Collect NB realizations of the same 5 DM performance metric post-environmental test and denote as $\left\{W_{B:1}, W_{B:2}, \ldots, W_{B:j}, \ldots, W_{B:N_A}\right\}$ where A and B refer to pre- and post-environmental.
3. Calculate separate means and standard deviations $\left\{\langle W_A\rangle, \langle W_B\rangle, \sigma_A, \sigma_B\right\}$ for each of the 5 pre- and post-test metrics.

The measurement hypothesis is that the mean performance metrics have not changed at a level that is statistically significant between pre- and post-environmental testing. The statistical test determines whether the difference in the two population means, one per set, are the same or significantly different within the range defined by their respective standard errors. The statistic that estimates this is $t = \frac{\langle W_A\rangle - \langle W_B\rangle}{\sqrt{\frac{\sigma_A^2}{N_A} + \frac{\sigma_B^2}{N_B}}}$ where t is an estimator of how many standard errors the pre- and post-environmental test performance metrics differ. The value of t versus confidence limit is a tabulated function (see e.g. http://en.wikipedia.org/wiki/Student's_t-distribution). For example, with 20 degrees of freedom (21 measurements in [1 and 2] above) it is 1.725 for a two-sided 90% confidence limit. Thus if $|t| < 1.725$ for the change in one of the 5 metrics there is no statistical difference, to 90% confidence, between the pre- and post- DM performance for that metric. Thus the metric will be deemed to have passed the environmental test. Tests that fail are valuable in that it shows where to concentrate future DM development efforts, and cross-validation with the model begins the process of identifying why the test failed.

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