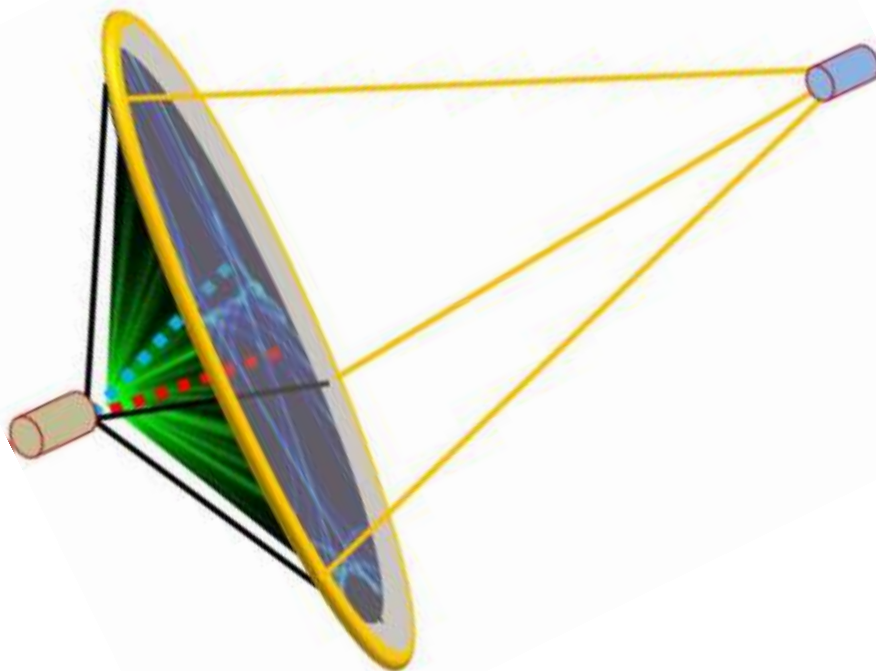


NIAC Phase I Study Final Report on Large Ultra-Lightweight Photonic Muscle Space Structures

Submitted on behalf of our team by
Joe Ritter Ph.D.



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I Introduction:

Optically Controlled and Corrected Active Mirror Technology (OCCAM)

The research goal is to develop new tools support NASA's mission of understanding of the Cosmos by developing cost effective solutions that yield a leap in performance and science data.

'Maikalani' in Hawaiian translates to, "knowledge we gain from the cosmos." Missions like Hubble have fundamentally changed humanity's view of the cosmos. Last year's Nobel prize in physics was a result of astronomical discoveries. \$9B class JWST size (6.5 meter diameter) space telescopes, when launched are anticipated to rewrite our knowledge of physics. Here we report on a neoteric meta-material telescope mirror technology designed to enable a factor of 100 or more reduction in areal density, a factor of 100 reduction in telescope production and launch costs as well as other advantages; a leap to enable missions to image the cosmos in unprecedented detail, with the associated gain in knowledge.

Whether terahertz, visible or X-ray, reflectors used for high quality electromagnetic imaging require shape accuracy (surface figure) to far better than 1 wavelength (λ) of the incident photons, more typically $\lambda/10$ or better. Imaging visible light therefore requires mirror surfaces that approximate a desired curve (e.g. a sphere or paraboloid) with smooth shape deviation of less than approximately $1/1000^{\text{th}}$ the diameter of a human hair. This requires either thick high modulus material like glass or metal, or actuators to control mirror shape.

During Phase I our team studied a novel solution to this systems level design mass/shape tradespace requirement both to advance the innovative space technology concept and also to help NASA and other agencies meet current operational and future mission requirements.

Extreme and revolutionary NASA imaging missions such as Terrestrial Planet Imager (TPI) require lightweight mirrors with minimum diameters of 20 to 40 meters. For reference, NASA's great achievement; the Hubble space telescope, is only 2.4 meters in diameter. What is required is a way to make large inexpensive deployable mirrors where the cost is measured in millions, not billions like current efforts. For example we seek an interim goal within 10 years of a Hubble size (2.4m) primary mirror weighing 1 pound at a cost of 10K in materials.

Described here is a technology using thin ultra lightweight materials where shape can be controlled simply with a beam of light, allowing imaging with incredibly low mass yet precisely shaped mirrors. These "Photonic Muscle" substrates will eventually make precision control of giant space apertures (mirrors) possible.

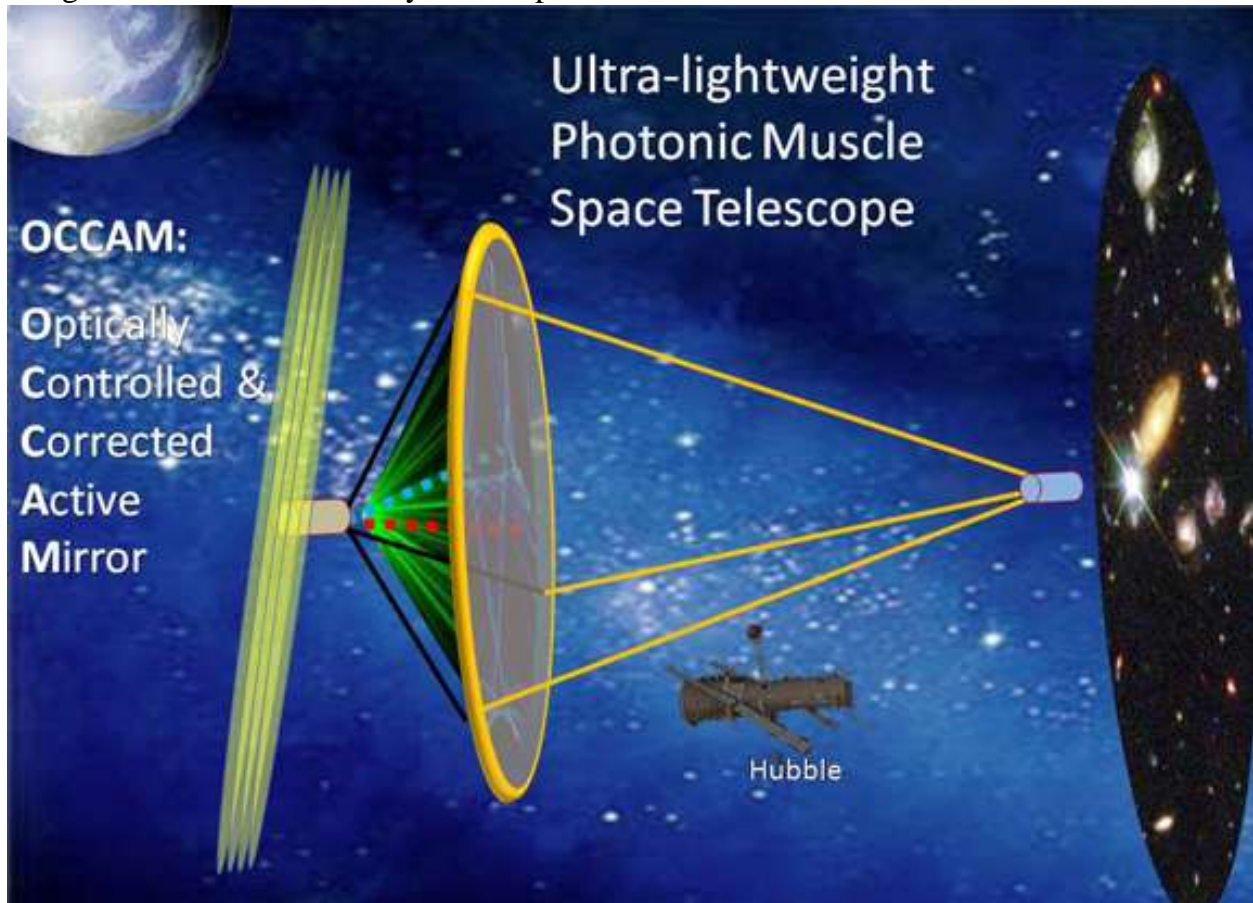
OCCAM substrates make precision control of giant ultra light-weight mirror apertures possible. This technology is posed to create a revolution in remote sensing by making large ultra lightweight space telescopes a fiscal and material reality over the next decade.

II The Innovative Advanced Concept:

Our team worked over the last year to investigate a technology to produce ultra lightweight laser controlled (optically addressed) active space telescope mirrors for future extreme NASA NM imaging missions.

Membrane mirror shape and dynamics can potentially be precisely controlled with low power light. This work leveraged TRL 1-2 material and control development efforts from earlier efforts by the PI

Our goal is to build this and fly one in space. Hubble is shown for scale:



Innovative Advanced Concept Motivation:

Telescopes require sub-wavelength figure (shape) error in order to achieve acceptable Strehl ratios. Traditional methods of achieving this require rigid and therefore heavy mirrors and reaction structures as well as proportionally heavy and expensive spacecraft busses and launch vehicles. This effectively limits the diameter and therefore the resolution and collecting area of space optics. Large diameter telescopes must either be heavy or actively controlled. Space telescopes of the size proposed for missions such as TPF, TPI etc. will likely

require large active primaries, active structures, as well as corrective optics to implement downstream wavefront control.

Moreover, high resolution space imaging requires the production of lightweight large aperture optics subject to design tradespace constraints based on nanometer physical tolerances, low integrated system aerial density, high control authority, suitable thermal and mechanical properties, deployment capability, launch vehicle volume constraints, as well as production cost and schedule risk mitigation. Deployable segmented large aperture systems impose additional requirements on segment alignment, wavefront phasing, deployment and mass constraints.

Photons weigh nothing. Why must even small space telescopes have high mass? Using our novel optically controlled molecular actuators allows the substitution of optically induced control for rigidity and mass. We have rudimentally demonstrated a completely novel approach to producing and correcting active optical primary mirrors to be used specifically for NASA's future large space telescope missions. Photoactive isomers will be incorporated into space durable membrane optics to construct giant active primary membrane mirrors utilizing over 10^{23} of our nanomachine "laser controlled molecular actuators". This will enable a revolutionary leap in high-resolution imaging capabilities, dramatically enhancing active optic correction capabilities while reducing costs.

The key innovation of our teams approach is using photoactive materials to produce optically addressable **non-contact molecular actuators, actually a part of the mirror itself**. Photo-initiated distortion makes these materials ideally suited for integration into space optics platforms because of the simplicity of a central scanning shape control system, lightweight, no need for wires or actuators, and high control capability.

The ultimate research goal is to produce a mission capable Ultra-light-weight membrane optic for a space telescope whose shape can be remotely controlled using a laser beam.

Early Vision: The hope is to in 2-5 years to be ready (with future funding) to produce a Hubble size membrane, which has an areal density 0.2% as much as the Hubble primary. A 0.5 meter version would be a great success. With funding this definitely is possible. The grand vision is to produce 100 meter diameter space telescopes that weigh no more than the Hubble, and costs (much) less than the JWST. Results thus far lead me to firmly believe this is also possible. This is the vision which NIAC is funding. Thank you for that!

The short term goal is a microsat flight test. The midterm goal is 1-2 meter flight test.

Longterm Vision: The longterm goal is 20 to 100 meter apertures then within another decade arrays of these giant apertures.

This research will enable innovative missions for imaging the cosmos, resolving spectral and spatial details of exosolar planets and searching for life, including evidence of Earth's Origins, while substantially reducing mass, launch and fabrication costs for space telescope. Mirrors will literally have the areal density of a feather. Missions like TPI will become feasible.

III System and Mission Concept and System Level Impacts

As NIAC funding is intended for the concept level, here are described system level impacts:

Photonic Muscle Active correction in OCCAM mirrors will allow increased reliability and decreased vulnerability by; mitigating in space optical system degradation issues e.g. hysteresis from thermal cycling, also allowing in space re-calibration of the optical assembly. Launch and deployment mechanical risks as well as manufacturing tolerance error risks are also negated by allowing in space aberration correction - no unfortunate Hubble like surprises need ever happen again.

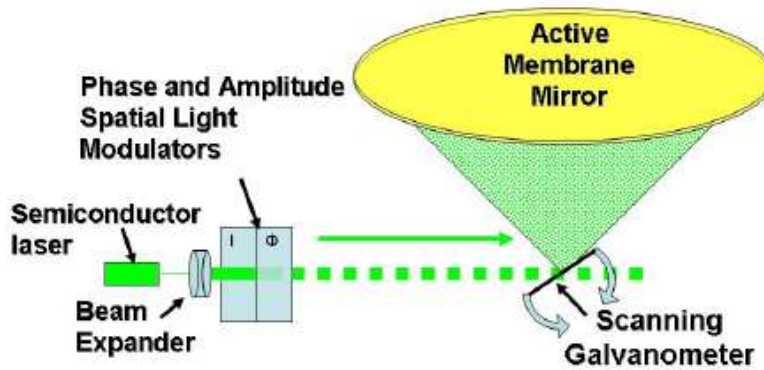
Using low mass high collection area mirrors support a leap in primary mirror diameter and therefore resolution and cosmic physical knowledge. When this technology is deployed, it can have wide application in all high resolution space based optical systems.

How to integrate the new material into a system and operations concept:

Systems and architectures for space based optical telescopes already exist and have been flown. Systems and architectures for deployable lightweight space based radio telescopes already exist and have been flown. We propose to leverage this existing technology base by augmenting it with our new mirrors and control systems. Shown below is the PI with an older technology developed by L'Garde in California. It appears that this existing technology with augmentation by Ritter's mirrors could be synergistically combined with a reasonable amount of effort.



Note the wrinkled face (on the radio dish) is the front of a deflated lenticular membrane, a shape control technique no longer needed with the pursued technology. Although such membranes have been used for radio, and the optical light imaging figure requirements are literally a factor of 10,000 more stringent, this is potentially a good technology teaming match and the pre-existing technology is a good match and will be leveraged.



Baseline minimal system architecture: A system design architecture is one of the foci of phase II effort, but NIAC has requested that here it be qualitatively addressed. The basic OTA (optical telescope assembly) system consists simply of a control computer a correctly modulated light source, a method to deliver this beam to a photonically controlled substrate, and the substrate itself. This system is then integrated with a simple spacecraft buss already having a conventional pre-developed (COTS) command and control system including Power, ADCS/GNC, Comm, Propulsion, CDH, Thermal, Housekeeping, Instrument buss interfacing etc. Using existing solutions mated with this new technology is an inexpensive way to demonstrate this as a game changing technology.

As for instrumentation (such as cameras, spectrometers etc.) astrophysics instrumentation can easily be provided by any vendor specializing in this. For future versions such as 'exoplanet query systems' will necessarily utilize off axis versions and be optimized for spectropolarimetry and spectropolarimetric astrometry.

Detail on future enabled architectures and system impacts

Next Generation system architecture: Ritter's OCCAM concept will support multiple concepts including not just single telescopes, but also interferometric arrays/sparse apertures and even highly filled segmented arrays where each segment is what we would now call a space telescope. In a future report we will provide detailed analysis for a base candidate mission using specifications comparable to JWST but with a smaller aperture as a cost saving effort in transitioning this to a flight test program.

Substantial architecture preparation is needed to formulate an optimal, consistent and realizable set of Science and Mission Objectives for an astronomical investigation and is not the intent herein. Therefore, although the thrust of phase II is *push-tech development*, we shall also in parallel assess the concept in a mission context. Our next study will examine feasibility and comparing properties/performance with those of current missions.

As an example: control authority and bandwidth required for an imaging telescope like JWST requires both 5nm level shape precision as well as large correction for boundary condition imperfections and compensation for failed actuators. Surfaces must have a minimal amount of high frequency noise (micro-roughness), with an ultimate goal of <1nanmeter rms. Systems

must perform at cryogenic temperatures to be used for extreme IR telescopy. Requirements such as these are also being built into current testing procedures for this project.

In Phase II As one data product our delivered analysis will assess the relationship between the concept's complexity cost, and performance and its benefits. Our team will develop a pathway for development of a technology roadmap and identify the key enabling technologies. This will also be delivered to NASA.

Our team will then develop a full mission architecture, capture a mission objective, science goals science requirements and sponsor's mission constraints (e.g., mission cost). This will likely be a ROM cost nano-class satellite, <10kg, which will deploy a thin ultra-lightweight optically controlled and corrected meta-material (OCCAM) photonic muscle mirror telescope. This would likely be a 7U cubesat deploying a near 1meter mirror to achieve a low cost success proof of concept demonstration. Pushing the boundaries of optical resolution with large diameter mirrors will come eventually.

A Phase II study will focus on initial requirements definition, operations concept development, architecture trade-offs, payload design, bus sizing, subsystem definition, system manufacturing, verification and operations with emphasis on; Risk mitigation, Functional architecture, Physical architecture options, Complexity and cost drivers, Payload design, Derived & allocated requirements, Subsystem Design (Power, ADCS/GNC, Comm, Propulsion, CDH, Thermal, Structures/Configuration) etc.

Enough materials research has been completed to reasonably speculate on future enabled architectures and system impacts. Many systems can be envisioned in the progression of the technology. A reasonable progression roadmap would be:

- Ground demonstration 0.5 meters (Game Changing Technology program)
- Flight Demonstration 0.5 meters (KC-135- Flight opportunities program)
- Flight Demonstration 0.5 meters extended (suborbital- Flight opportunities program)
- Flight Demonstration 0.5 to 1 meter 7U-cubesat based mission (Technology Demonstration Mission/Flight Opportunities)
- Ground demonstration 1.0 -2.0meter (Game Changing Technology program)
- Flight Demonstration 2.4 meter utilizing Ames common spacecraft bus or similar small spacecraft mission (Technology Demonstration Mission)
- Flight Demonstration 8 meters Ames common spacecraft bus (Great Observatories program)
- Ground demonstration 8.0meter
- On orbit assembly QTY 3, 8meter apertures in segmented off axis array (9TDM)
- On orbit assembly QTY 60, 8meter apertures in segmented array (74 meter filled space telescope)-Flagship Mission

These are all feasible within 2 decades. To go to 100 meter telescopes, segments that are larger 10 to 20 or even 100 meters have a number of known difficulties which require a great deal more research. It is important to point out that experts have been considering these ideas for at least 20 years, and a lot is already known. For example shown below is a colleague's effort

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(Bradford-UAT) over a decade ago to make large membranes and support structures. We had teamed together in 2003. With the new photoactive technology suddenly large lightweight telescopes become a reality.

We are ready to accelerate development now

**One Goal: Make a 6 meter diameter *active* mirror that Weighs 6 kilograms not 600 kilos
Costing <1% of current technology**



One may ask: What impact would it have on a JWST-type (or similar) mission in mass, cost, performance?

At the Phase I level this can only be addressed qualitatively or semi-quantitatively. Our team's current estimate is:

Mass: 95% reduction (Spacecraft bus is still considerable even with negligible mirror weight).

Cost: Operations no change, Launch 80% reduction of course this depends on orbit, mirror fabrication 80% reduction for the first copy, 99% reduction for replicas. Science instruments, no change. Overall mission cost approximately 20% of current JWST with similar capabilities.

In the following section goal properties are stretched to develop a full mission concept:

Implications of the concept:

This novel innovative advanced technology will enable innovative missions for imaging the cosmos, resolving spectral and spatial details of exosolar planets and searching for life, including evidence of Earth's origins, while substantially reducing mass, launch and fabrication costs for

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space telescope. We seek an interim goal within 10 years of a Hubble size (2.4m) primary mirror weighing 1 pound at a cost of 10K in materials. The production assembly would be reusable for mass production, and the control system is on the order of \$<100K of off the shelf components (for a ground test version).

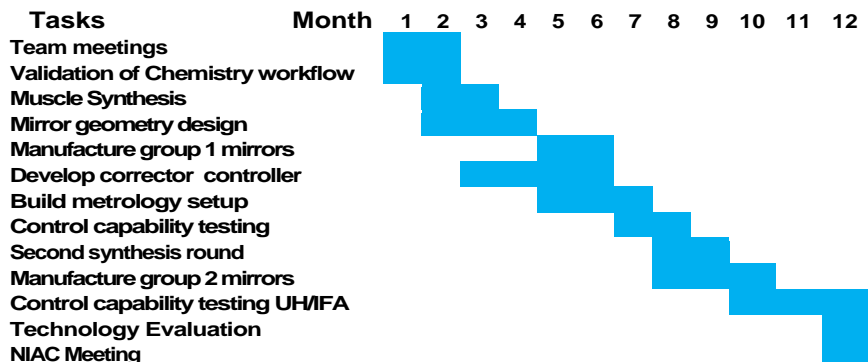
It is not an exaggeration to say that the mass and cost saving implications for NASA space telescopes are staggering, and that this is the future of Astronomy. Further, this technology will allow us to supersede the current spacecraft fairing size limitation enabling giant inexpensive space telescopes. 20-100 meter aperture arrays will become fiscally possible with limited resources.

IV The Technology Details

The Phase I proposal stated:

“After synthesizing appropriate photoactive substances, active mirrors will be produced. An optical metrology test apparatus will be developed to quantify control authority. As the chemistry evolves, a down selection will occur, and improved and larger substrates will be fabricated and tested.” All of this was his was accomplished.

Task Descriptions Phase I Overview: Photoactive optical substrates were developed and tested. The following 13 tasks were to be performed:



Deliverables:

Deliverables by PI are all complete.
 All bimonthly reports have been filed
 Attendance at required meetings has been documented.

Index:

Materials production, Substrate production, and Testing

Two subcontractors were hired to work on Synthesis of the azobased liquid crystal photonic muscles and substrate preparation; Lander University and Beam Company. A number of different materials were made. Below details their efforts and my test of materials from both Lander and BEAMCo.

Work at Lander University on Bulk production:

Beam has experience synthesizing small amount of high purity polymers we need, but they are approximately expensive. We are working to drive the price down with the Lander effort. This is not just to save money, but in actuality to produce bulk quantities needed for a massive Phase II effort. Lander work was initiated in Phase I and will continue in Post Phase I work and is detailed below:

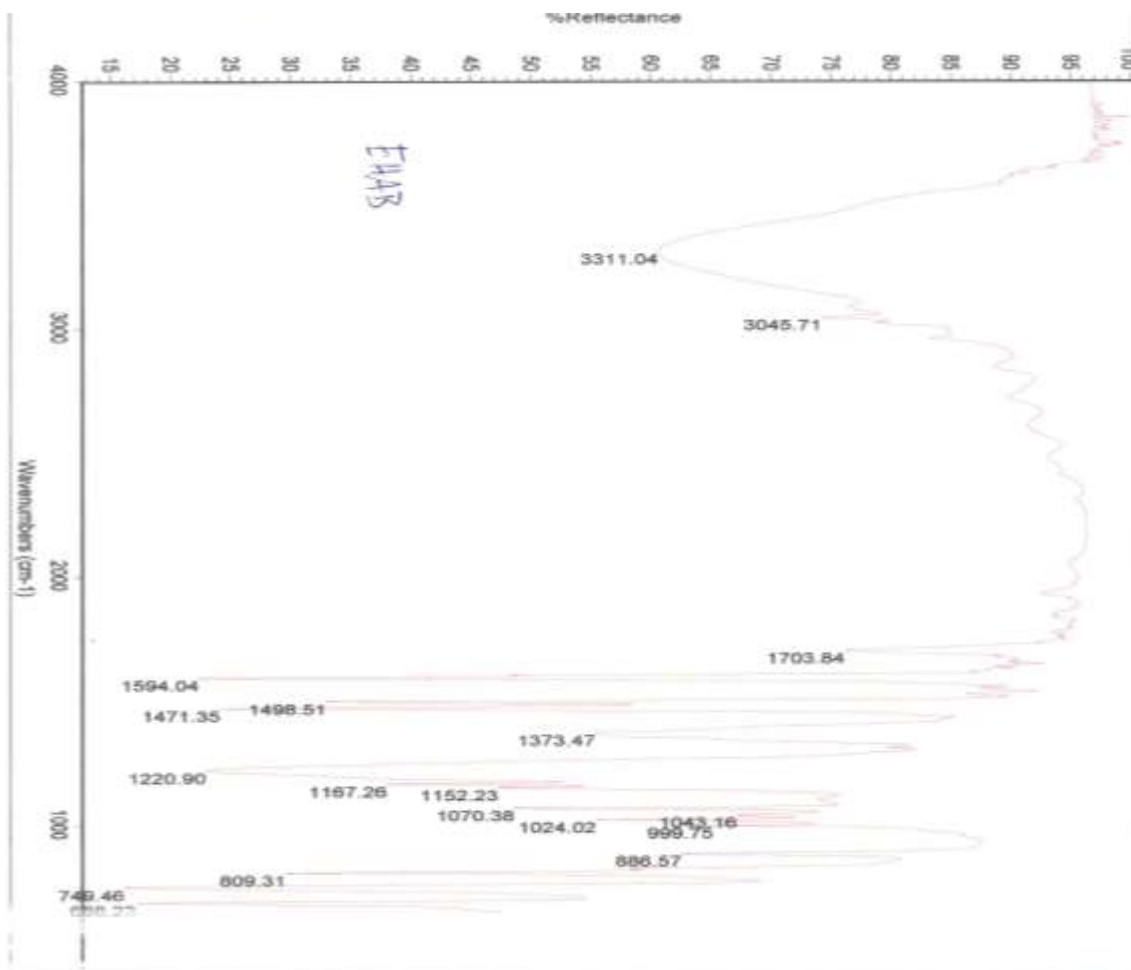
Monomer and Crosslinker Synthesis Summary

4-ethoxy-4'-hydroxyazobenzene Synthesis included preparation of diazonium salt, Preparation of phenolate solution and a Coupling Reaction, recrystallization and Analysis for Purity and Composition:

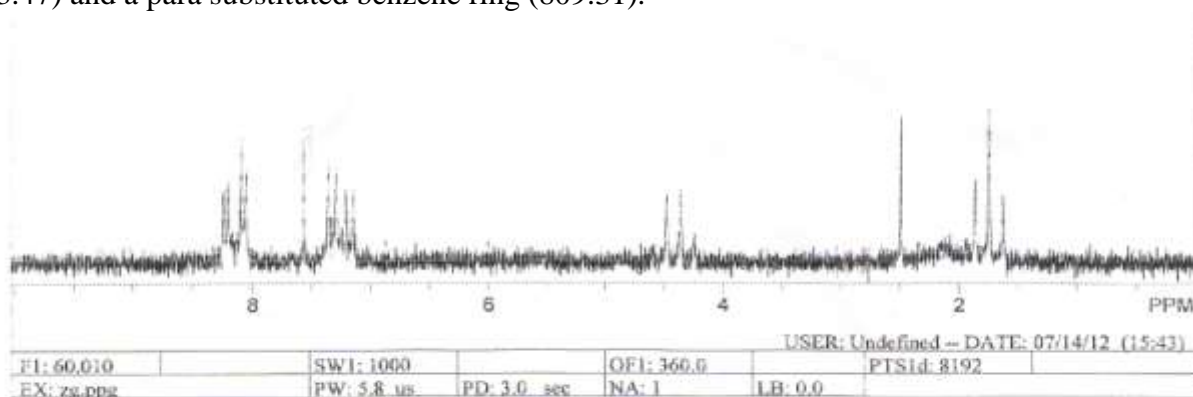


Purified intermediate product EHAB

First melting points are checked to see if they match expected values then IR spectroscopy and NMR analyses are performed. The NMR information is H1 NMR, 60MHz, d-Acetone is the solvent and the FT-IR is an Avatar 360, with a Zn-Se crystal.



An example IR for EHAB: The spectra indicate the presence of an OH group (3011.04); methyl (1373.47) and a para substituted benzene ring (809.31).



NMR for EHAB: 1.9 t CH₂; 2.5 s OH; 4.5 q CH₃; 7-8.5 aromatic peaks (7)

The next step produces EHHAB.



Pure EHHAB

NMR for EHHAB: Despite the noise in the spectra, multiple peaks are present indicating the 6 member carbon chain; aromatic peaks at 7-9.

IR for EHHAB: 3390.70 OH; 1600.02 Aromatic; 1394.14 CH₃; 887.41 para substituted benzene

Additional synthetic steps of this and related azobenzene based compounds are of interest to many researchers, and may be found in the literature cited below.



Pure DHAB crystals.

This took a lot of trial and error. Here are main references for synthetic routines:

1. Zhao, Xiongyan and Wang, Mingzhu. European Polymer Journal. 42, **2006**, 247-253.
2. Angeloni, Caretti, Carlini, Chiellini, Galli, Altomare, and Solaro. Liquid Crystals. 4(5), **1989**, 513-527.
3. Shin and Abbott. Langmuir, **1999**, 15, 4404-4410.

Other references:

1. Richardson, Riegel, and Naemi. Journal of Undergraduate Research in Bioengineering. **2008-2010**. University of Washington.
2. Hu, Zhao, Huat, Gan, and Xia. Journal of Applied Polymer Science. 83, **2002**, 1061-1068.
3. Tsutsumi, Kitsunai, Kanazawa, Shiono and Ikeda. Macromolecules 31, **1998**, 355-359.
4. Tokuhisa, Yokoyama, and Kimura. Bull, Chem. Soc. Jpn. 69, **1996**, 2123-2130.
5. Babu, Kumaresan, Vijayan, Gunasekaran, Gopalakrishnan, Kannan, and Ramasamy. Journal of Crystal Growth. 256, **2003**, 387-392.
6. Li, Lo, Zhu, Li, Liu, and Jiang. Macromol. Rapid Commun. 30, **2009**, 1928-1935.
7. Corvazier and Zhao. Macromolecules. 32, **1999**, 3195-3200.

PI Laboratory work in Florida with Contractor BEAM

The PI Worked with Contractor BEAM on synthesis in Fl. and fabrication techniques. Preliminary analysis of new samples was performed.

BEAM co. a contractor under Phase I delivered a number of azobenzene based membrane materials, 1" sizes

New Group II synthesis and then sample production were completed (as of June 5 the day before the Phase II grant was due. Polymer precursors were synthesized and then polymerized. In cycle2 our team produced 7 new samples ready to coat and test.



One of our key requirements is a set and forget material, i.e. stability once positioned. This eliminates the need for constant laser illumination thus enabling a low power correction update mode of operation. Thus

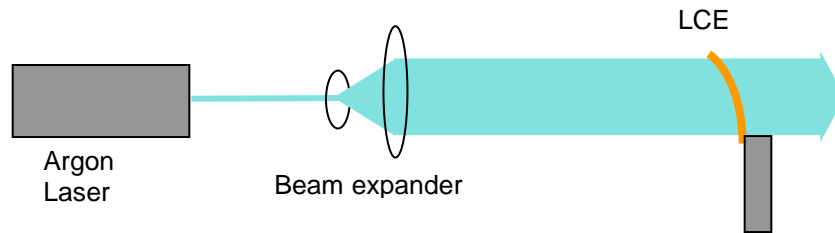


the idea here was to vary process parameters to optimize this requirement. Such experiments yield clues about the fundamental physics at play that we may further optimize a future generation of materials.

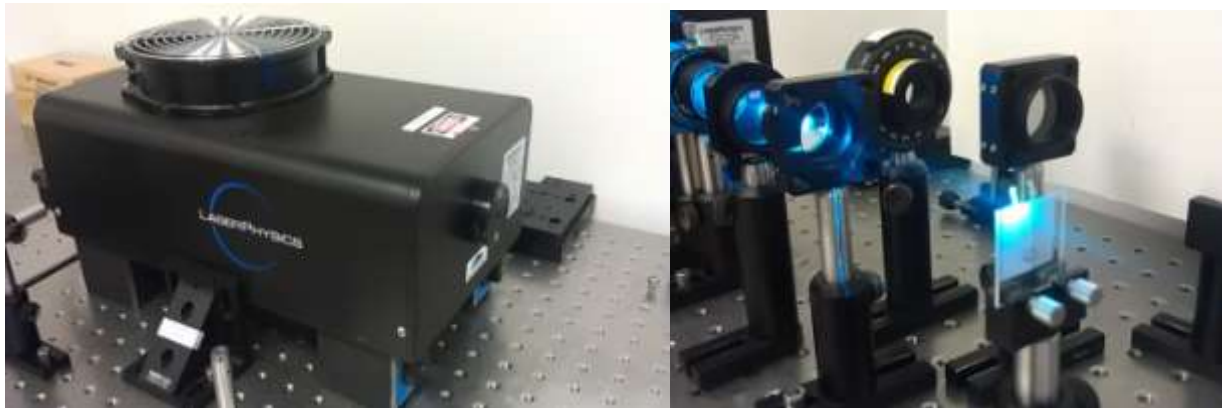
Some molecular structures exhibit better memory (defined here as stability after change, not as return to original state). What parameters are optimum for mechanical and memory properties we require for a photonic muscle telescope have been investigated and will continue to be explored in Phase II

Shown next is a diagram of 4 of the 8 samples made and the memory test (other samples are still to be tested):

Azo polymeric films bending:



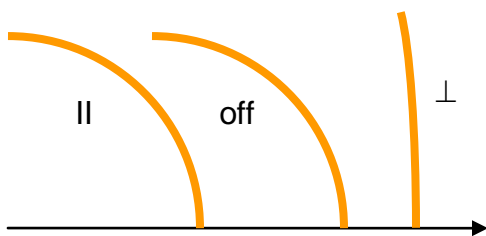
Set-up for bending observation. Argon laser operated in multimode ($\lambda=458, 488$ and 514 nm). Size of azobenzene liquid crystal elastomer (LCE) was $1\text{ mm} \times 6\text{ mm} \times 0.05\text{ mm}$ **thick**. Beam



diameter was 6 mm . Power was 112 mW , intensity was 396 mW/cm^2 .

Shown are; Laser, Beam expander and half λ plate, quarter λ plate, strip sample.

Many material strips were tested in 1D, here is an example result:



C27-02

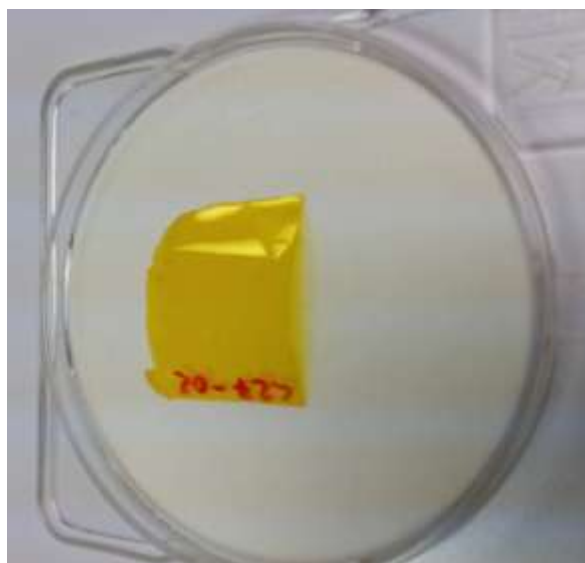
(a) $P \parallel A$

(b) off

(c) $P \perp A$

Round II chemical synthesis and 2d sample fabrication:

The team completed a new round of chemical synthesis and 2 dimensional membrane sample fabrication. Details follow:



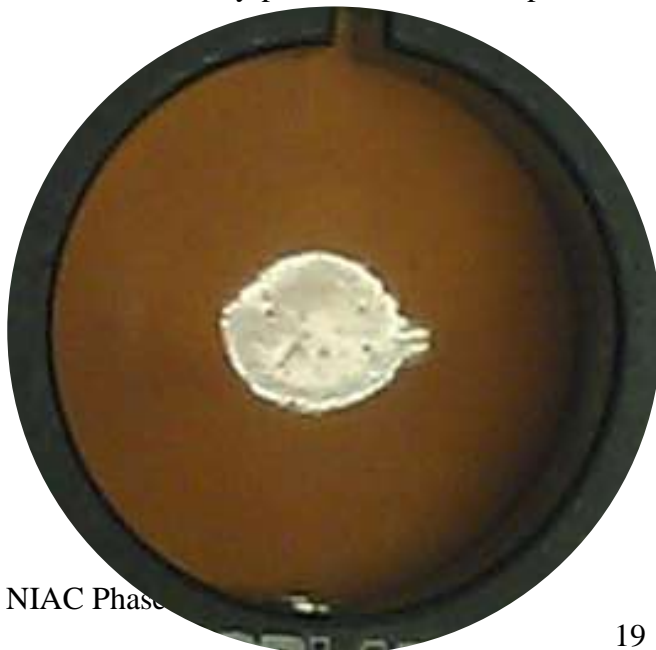
Our team examined multiple processing techniques for producing a curved membrane:

Although the PI made primitive curved mirrors over a decade ago a more advanced new curved mirror was made. It was mounted and tested. This was a non trivial effort.



The mirror substrate is rough on the concave side and perfectly smooth and spherical on the convex side. Under Phase II I shall perform phase shifting micro-interferometry or AFM to determine surface microroughness.

Shown below is a permanent (reversible) deformation made to this powered (curved) optic using a laser. The shiny part is flat the rest spherical. This is significant. This is a perfectly shaped

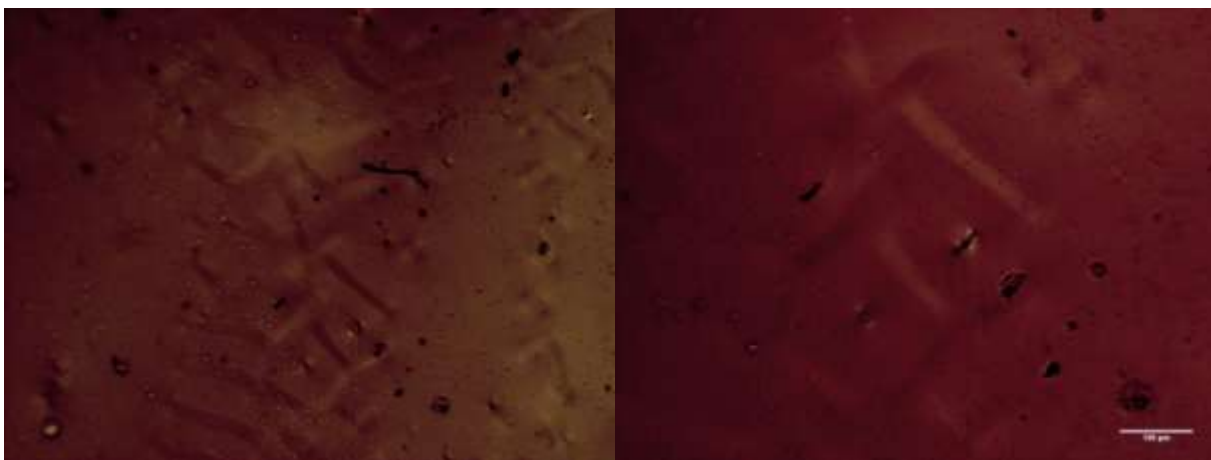


curved photonic muscle mirror with memory. The center was deformed to become a flat instead of a curve demonstrating the large stroke we claimed we could achieve in a membrane. This level of control on a curved surface is a clear indication that the technology performs as claimed.

This picture was taken simply with an overhead fluorescent light illuminating the sample. The camera angle chosen highlights the reflection from the localized flat area. Although the picture does not show it well, the rest of the area is still

round. Further testing with advanced optical metrology tools will be done next in phase II.

On membrane production we have examined multiple techniques for alignment of molecules on our substrates. Samples were examined using polarized transmission microscopy and also using Atomic force Microscopy (AFM). The point is to elucidate microstructure of domains and correlate that with processing parameters that achieve good performance as a telescope optic. Below are cross polarized bright field transmission micrographs used to bring out sample details: Note the orthogonal structures visible only under cross polarized light.

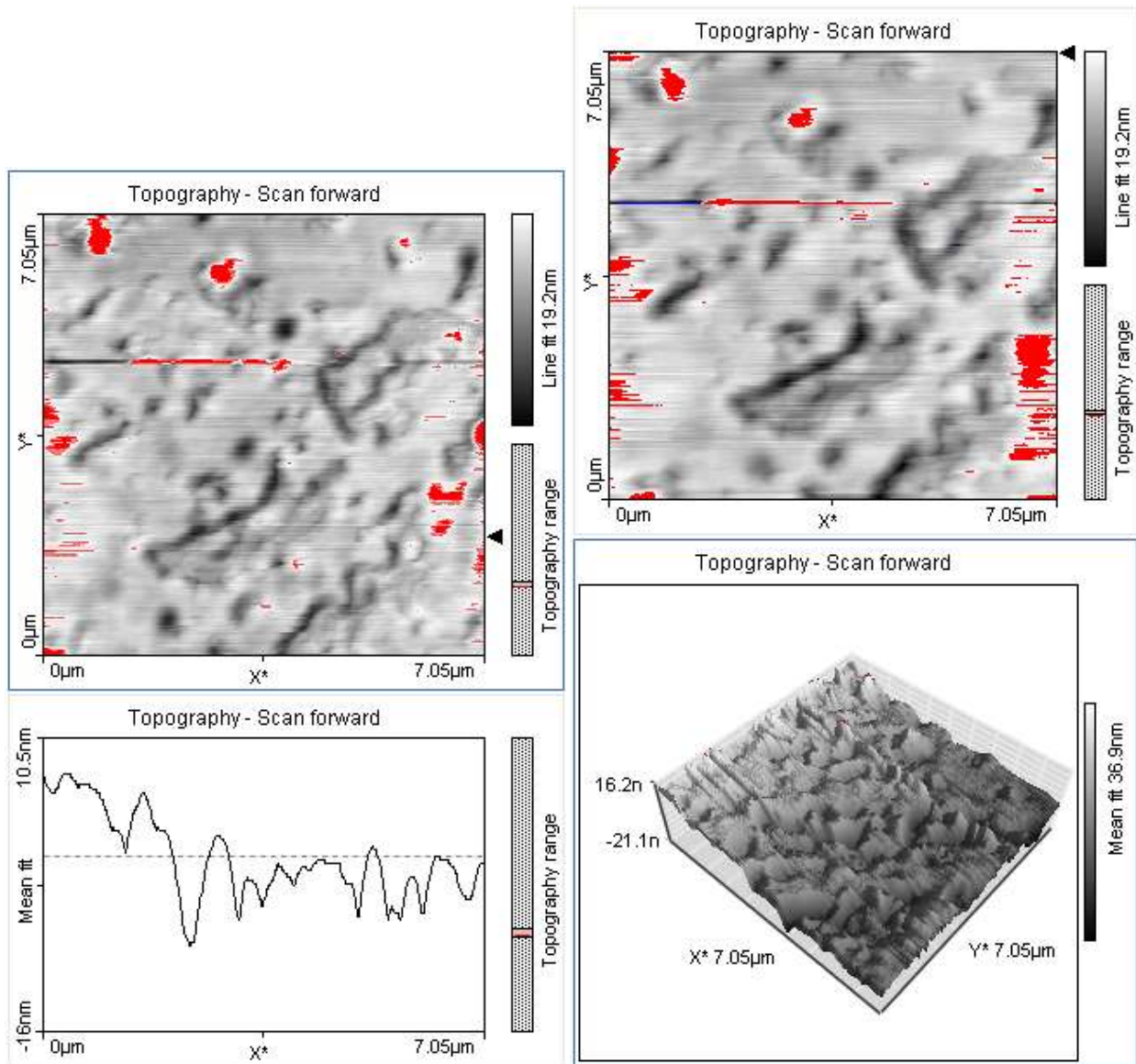


The scale bar in the right image is 100 microns.

Next we did an initial run of AFM (Atomic force microscopy) to learn more about the structures. Shown first is simple the AFM scan head for the reader:



Shown below is a preliminary AFM Scan. This work will continue in Phase II and be reported.



We hope that further analysis of images on a submicron scale will yield domain information specifically size, interstitial component size and orientation. . More on this in phase 2 as data comes in and gets analyzed.

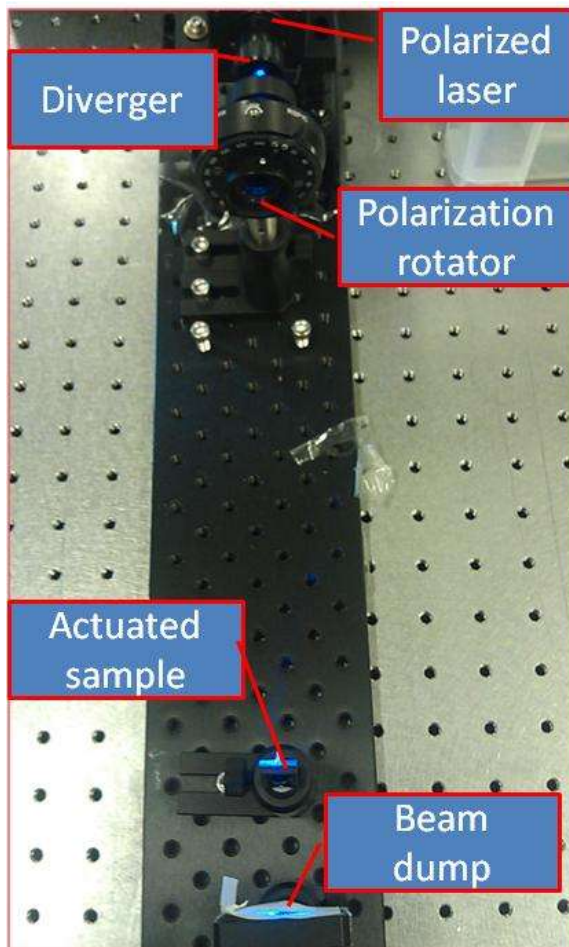
Would a micrometeorite end a mission?

This is analogous to a curvature AO mirror that has lost an actuator. Curvature type adaptive mirrors exhibit a global influence function, i.e., changing the curvature at one point has a global effect on the mirror figure (shape). Fortunately this technology and control algorithms are mature. It is well understood how to correct the shape globally with loss of a single actuator. This adds confidence to the idea that damage to a curved PM membrane on orbit by hypervelocity impact will not end a mission. This is in sharp contrast to a conventional glass mirror where a crack will propagate especially with repeated orbital thermal cycling. The answer to this frequently asked question is no, a micrometeorite would not end a mission.

Testbed hardware

The first testbed/demo

This was based on a test setup the PI had previously tested. Prior to the NIAC trip a desk top portable *demonstration model* of the photonic muscle membrane control technology was developed by the team.



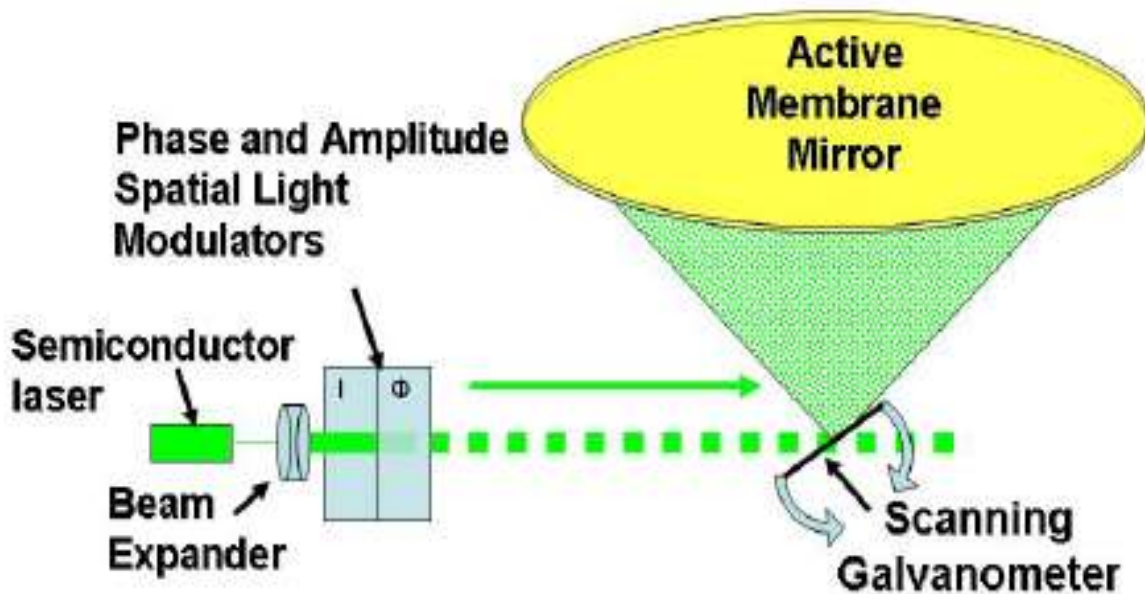
Shown in this picture the model consists of a polarized monochromatic illuminator, a diverger to alter radiance distribution, a half wave plate to rotate linear polarization, a sample photonic muscle, and a beam dump for safety purposes.



Shown above is the PI Ritter performing final assembly and a hotel field calibration and alignment of 1d demo unit prior to demonstration at the NIAC meeting in November 2011.

New Testbed:

As promised in the proposal, an optical metrology test apparatus is in development to quantify control authority. Our team has in house several of the components control system. The system is shown in the following cartoon:



The device employs liquid crystal modulation to control polarization and power, and a 2 axis orthogonal scanning galvanometer to direct laser control beam position.

A new test setup based on this design has been fabricated:

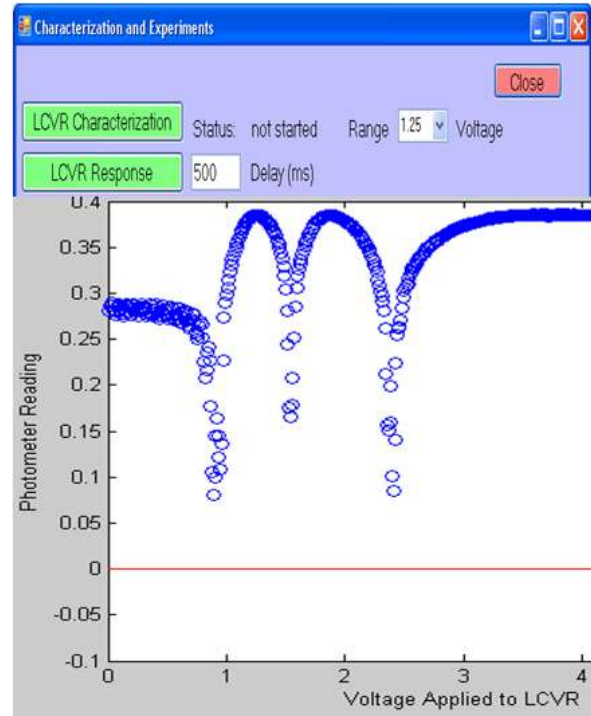
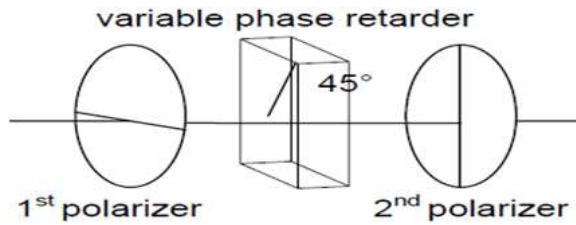


This versatile test bed includes full computer control of actuation laser beam polarization, beam power modulation (new laser with both digital and analog modulation), 2 axis scanning galvanometer, beam pointing control, new custom software for controlling the above parameters simultaneously, low level and high level interfacing routines, as well as special software needed to generate calibration tables to control these parameters precisely for closing the control loop. This will be rebuilt for phase II



The setup also has computer directed beam target array. The targets include (left to right) an O-tools polarization indicator, a photodiode calibrated to perform accurate photometry (power measurements), a membrane mirror target (unsilvered), and a laser beam dump for safe driver electronics stabilization period (warmup).

The test bed utilizes custom software (developed in house) for calibrating beam parameters for all subsystems.



Using this setup we performed extensive calibrations. An early polarization modulation dataset is shown here. As other polarization states may be useful, future phase 2 work will determine retardance vs. drive voltage by simply configuring as above but with polarizers at 45 degrees to each other. Then by measuring the transmission, the retardance δ is simply given by:

$$T(\delta) = T_{\max} * (1 - \cos(\delta)) / 2$$

Testbed Software

We performed a software development platform study:

The software development goals in addition to running calibrations and developing hardware designs is meant to culminate in the following objective: The software should interface with hardware that measures a mirror shape, can control a mirror shape, with modules that pass information to close the control loop culminating in an optical figure suitable for telescoping. Our successful effort over the last few months was to develop the hardware control system. The functions therefore include placing a laser beam with known variable intensity, with arbitrary polarization, on an arbitrary surface

After analysis of requirements, we chose c# for Phase I. This may change in a phase II redesign.

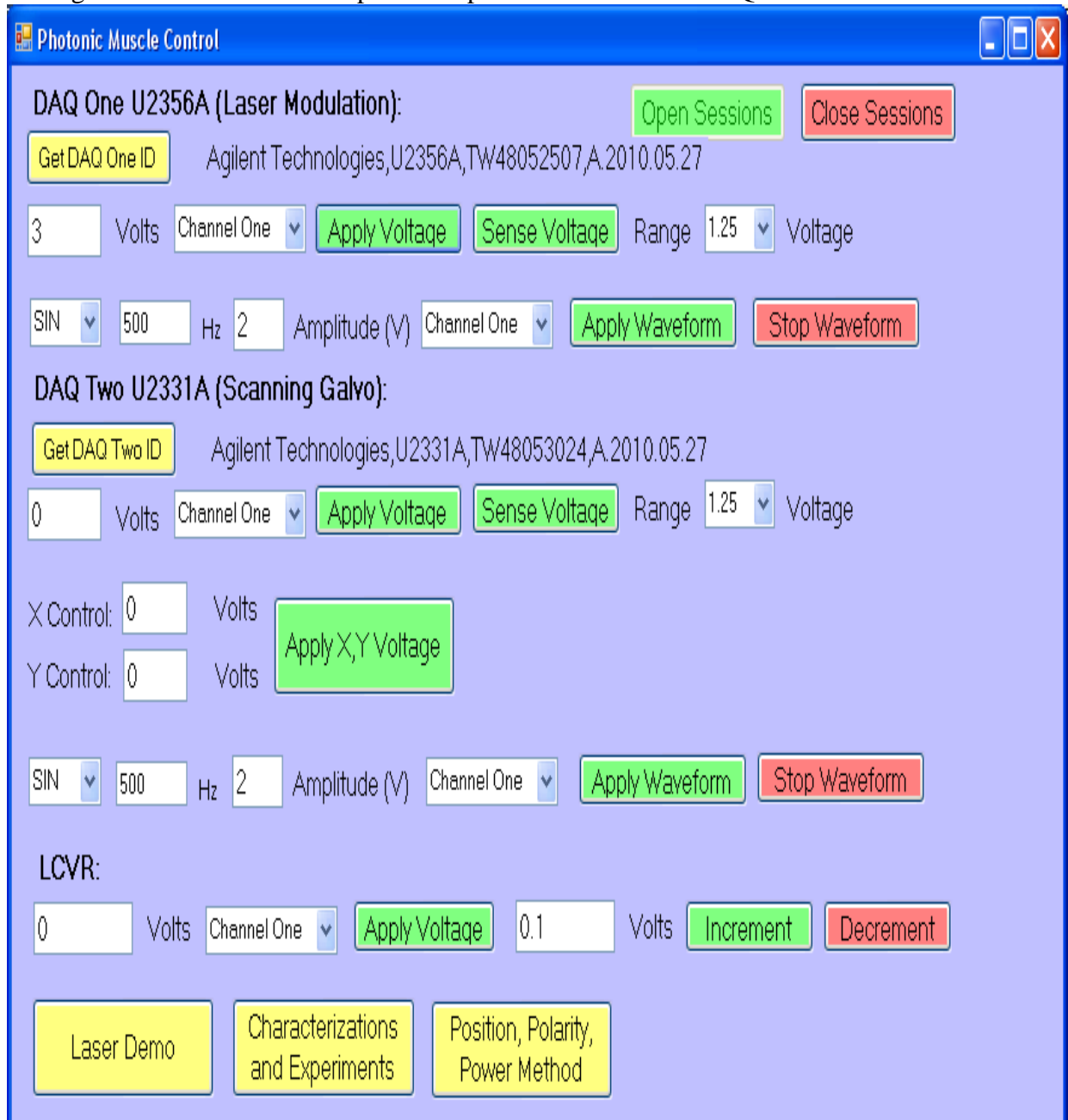
Software development:

The software development goals in addition to running calibrations and developing hardware designs is meant to culminate in the following objective: The software requirements were to interface with hardware that measures a mirror shape, control a mirror shape with modules that pass information to close the control loop, with the plan designed to culminate in an optical figure suitable for telescoping which we will perform under phase II. Our successful effort was to develop the hardware control system. The functions therefore include placing a laser beam with known variable intensity, with arbitrary polarization, on an arbitrary surface.

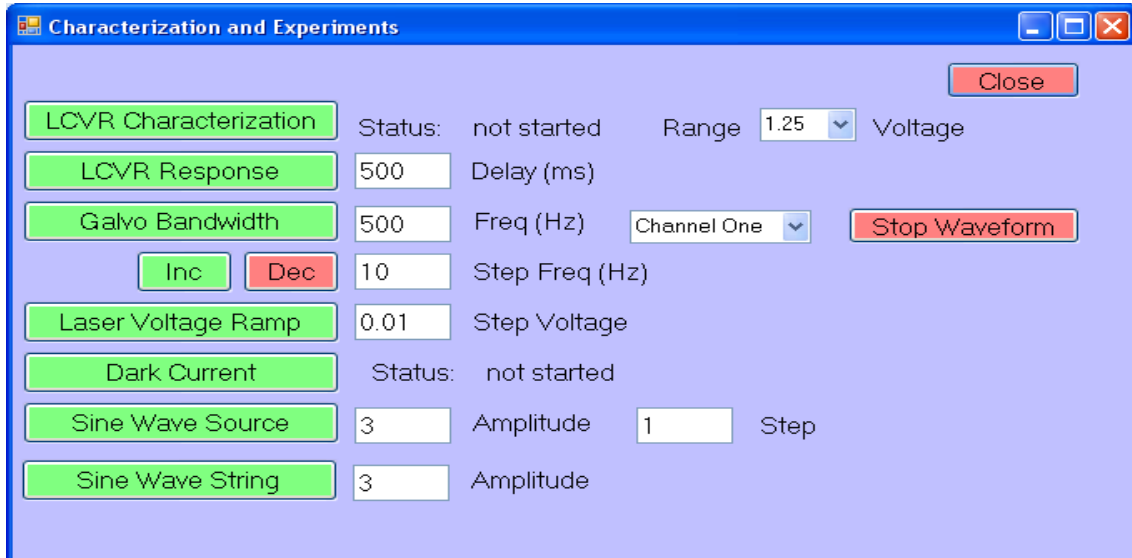
We utilize a small laptop and Agilent USB DAQs with Digital to analog and analog to digital channels. D/A is used for controlling devices like scanners, LCVRs and Lasers, while input is used to measure beam flux and for calibrations. The software is growing and evolving. In Phase II we will need significant additional software development.

A number of software routines have been written.

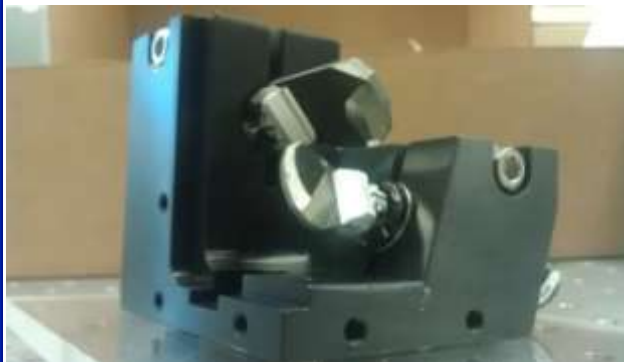
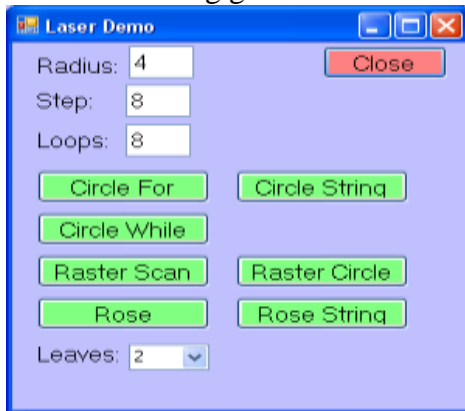
Shown below are screen captures of our control software: The below module has low level and higher level routines for output and input from the control DAQs:



The following module performs tests to determine LCVR retardation, Scan galvo bandwidth, and basic galvo scans



The following module implements various beam positioning strategy tests by directly controlling a 2 axis scanning galvanometer

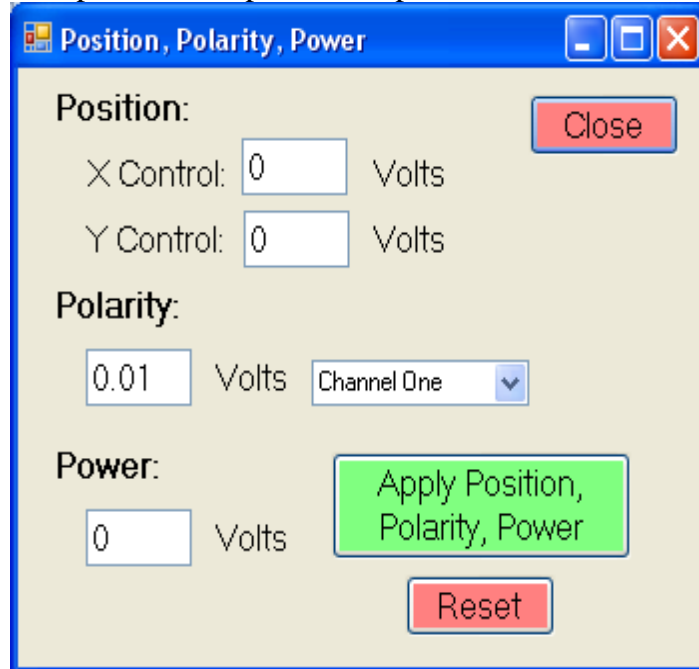


Scan galvo



Laser scanning on membrane is fully programmable now.

The below module though simple in appearance is a test interface for the master control routine, providing control of beam polarization, power, and position:



This deceptively simple GUI is a high level routine using all other control and calibration code developed and is the core of the control output routines; effectively the knobs we can turn to control the shape of a membrane.

The next step will be to implement a new 3d shape input routine. Then additional work will be performed on closing the control loop. This will be done in Phase II.

Although we accomplished and demonstrated manual control, **the next step for automatic control**, will require a major software development effort in Phase II.

Conferences Presentations and Travel:

- **NIAC 2011 Symposium ANSER, VA (D.C. area) November 2011.**
- **Meeting: Meter Class Astronomy Lightweight Optics**
- **NIAC 2012 March Symposium Pasadena**
- **Discussions for Proof of concept- Space Launch Possibilities in Houston**
- **PI Laboratory work in Florida**
- **PI laboratory work in Ohio**
- **Meeting at NASA Ames**

Grant submission:

A substantial amount of time was spent planning future work. Our team submitted a Phase II grant request on June 6th, 2012.

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V Summary of results:

Phase I Overall Status:

Deliverables are complete.

Written status reports to the NIAC Director by the 15th day of the third months following the beginning of the contract all sent. In addition, all requested web presentations, 2 detailed posters as well as email updates were transmitted.

The NIAC Fellow (PI Ritter) was in attendance at both NIAC meetings (D.C. and Pasadena) as required, including presentation at both meetings, delivery of viewgraphs and poster. This final report fully fulfills all PI contractual obligations. The University of Hawaii is required to submit any other required reports e.g. financial.

Deliverables Pending:

None.

In summary

- All tasks promised were performed
- A Testbed was built.
- Materials were fabricated and tested.
- Testbed software was proven.
- Most importantly our concept was demonstrated and we achieved more than promised.

Our team has learned what not to do and what we must do. We have learned how to scale our process. We have developed new tools for metrology and control like our Phase I PMTVDT (Photonic Mirror Versatile Development Testbed) .

Our plan to move forward in Phase II is both ambitious and practical. Our team will continue to overdeliver on developing previously unknown cutting edge technology. We have accomplished far more than expected in this phase I, and the novel technology is well within Mankind's grasp.

VI Acknowledgements:

The PI gratefully acknowledges the support and assistance of NASA including NASA Headquarters, the NASA Space Technology Program, the NASA Office of the Chief Technologist, the NIAC Office and staff, including but not limited to Dr. Jay Falker, Jason Derleth, Dr. Ron Turner, Kathy Reilly and Bob Cassanova, the NIAC advisory council, the work of team members who contributed to this research and last but not least funding through NASA from the taxpayers of the United States of America.

I am personally grateful for both the existence and support of NIAC/NASA OCT. I thank the organization for its support of this exciting project.

This concludes my final Phase I report.

Joe Ritter

Joe Ritter Ph.D.,
Physicist