Report on NIAC Phase II Study
OCCAMS: Optically Controlled and Corrected Active Meta-material Space Structures

Prepared for NIAC
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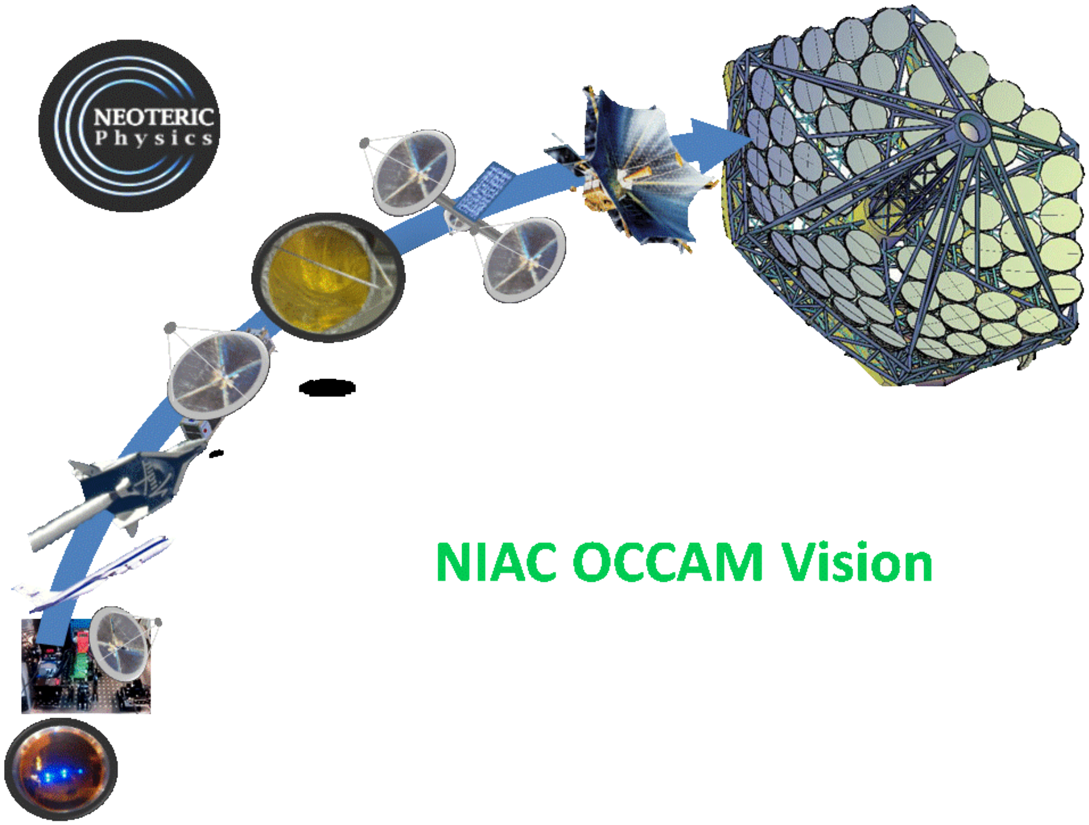

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Grand Challenges Addressed:
Innovative methods for understanding and imaging the cosmos
Novel searches for life—including evidence of Earth's Origins
Lightweight construction and fabrication of space systems

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Executive Summary

This document is summary of progress on the OCCAMS project:

OCCAMS: Optically Controlled & Corrected
Active Meta-material Space Structures
(Ultra-Lightweight Photonic Muscle Space Structures, Phase II)

This Final Technical Report details the concept and what it offers to NASA, the approach used to evaluate the concept, and the findings with regard to the concept's technical feasibility.

Photons weigh nothing. Why must even small space telescopes have high mass? Our team has demonstrated this is not the case using a completely novel approach to producing and correcting active optical primary mirrors to be used specifically for NASA's future large space telescope missions.

Unprecedented advances in nano-engineered meta-materials have produced a laser actuated liquid crystal elastomer (LCE) polymer substrate with controllable reversible bi-directional bending. Using our novel optically controlled molecular actuators allows substitution of optically induced control for rigidity and mass making telescope mirrors the size of the Hubble M1 weighing only 1 pound possible.

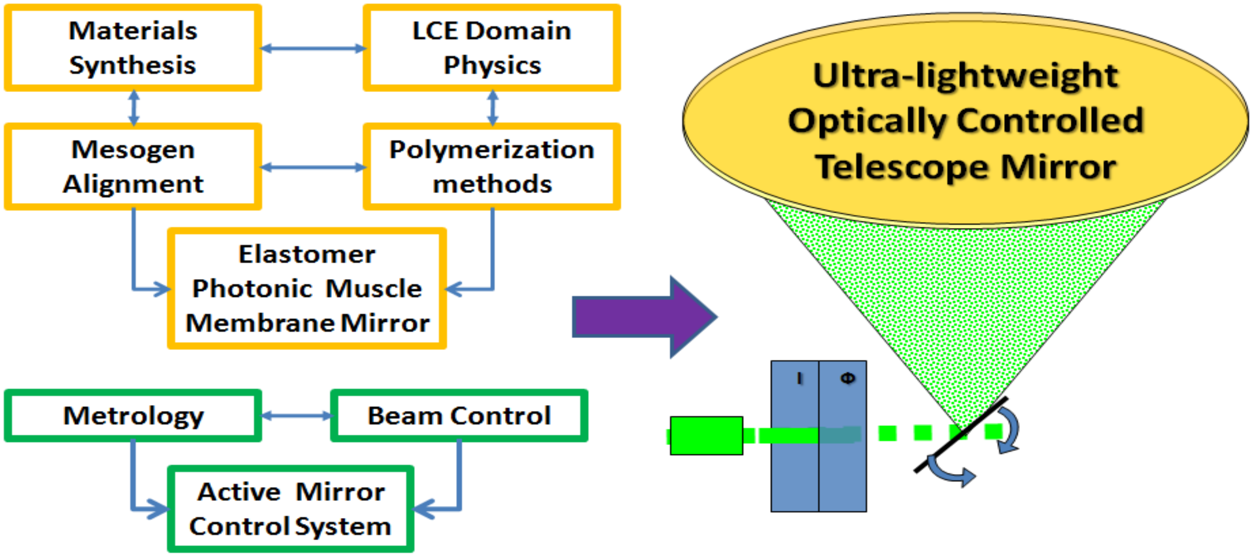


Figure: Phase II efforts involved interacting interdisciplinary efforts to design materials, control systems and optics. Mission architecture was also studied.

Positive Outcomes:

Chief among the positive outcomes of this phase 2 effort are a more exciting science and exploration future and a more robust national capability for aerospace activities enabling new industries and contributing to economic growth. This was pushed forward by development of multiple novel meta-materials and material technology, control system refinement and progress toward a diffraction limited membrane telescope with areal density of <1% of the JWST primary mirror. Our team has not yet reached the diffraction limit however our new materials and systems make this imminent and we will seek to continue this research program. New materials and control system refinements continue.

Our team is pleased to report that under Phase II we have:

- Scaled our original photonic material process
- Learned new fabrication processes
- Made a new telescope material with every virtually property we initially wanted including photonic control of a shape memory polymer. The areal density is approximately 100g/cm^2.
- Developed a reflective coating process
- Developed a photo-polymerization process for photonic muscles to write molecular domains
- Developed a spray on photonic polymer manufacturing process
- Developed new control algorithms and are completing a 3rd generation control system
- Developed a mission Architecture using the Photonic Muscle OCCAM technology.
- Outlined next steps for development of this novel Photonic muscle OCCAM technology

Two of the three NIAC programs that have gone on and been infused into NASA missions have been imaging systems. Here a novel technology for large aperture imaging is presented.

Project Background

Development of optics for space telescopes has traditionally been one of the most risky and costly facets of astronomy missions. The advancement of science is a function of the tools at hand. The level of tools is based on materials available. Nano-engineered meta-materials stand today as semiconductors did 50 years ago ready to transform our knowledge of the cosmos.

Active meta-material *Photonic Muscle* substrates can make precision control of relatively inexpensive giant apertures possible by precisely controlling membrane mirror shape and dynamics with a low power beam of light. The key innovation here is incorporating optically addressed photo-initiated distortion of photoactive meta-materials; optically addressable laser powered non-contact molecular actuators become molecular units of the mirror itself. Such materials are 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. Stable set and forget poly-domain LCE materials minimize power consumption for active figure control. A single low power laser is used for occasional mirror figure refresh even on a giant aperture.

A single low power laser is used for occasional mirror figure refresh of an active primary membrane mirror utilizing 10^{23} nanomachine “laser controlled molecular actuators” eliminating need for conventional figure control actuators providing enormous cost, mass and areal density reduction.

In Hawaiian Maikalani means, “Knowledge we gain from the cosmos.” Missions like Hubble have changed our world view. The 2011 Nobel prize in physics was a result of astronomical discoveries. JWST is posed to rewrite the physics texts. Here we advance our neoteric meta-material technology to enable a factor of 100 reduction in areal density, a factor of 100 reduction in telescope costs, a leap to enable missions to image the cosmos in unprecedented detail, with the associated gain in knowledge. Phase II worked towards a proof of concept. Ritter’s “Photonic Muscle” substrates finally make precision control of giant ultra light-weight mirror apertures possible. This concept was refined and further demonstrated in phase II which leveraged over a decade of research.

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 space telescopy. 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 mandrel would be reusable for mass production, and the control system is on the order of $20K of off the shelf components (for a ground test version). The potential cost savings are revolutionary. Inexpensive 6 meter class telescopes are a near term goal which would revive missions like the Space interferometry mission and save taxpayers $billions while relieving NASA budget issues.

The intrinsic value of this technology, potential scientific impact, vast cost savings and programmatic risk reduction with related program benefits and cost vs. performance value all become apparent now that we have developed our latest generation of technology. This bold novel technology represents a fundamental shift in possibility, and a removal of current barriers to knowledge we can gain from the cosmos.

Innovative Advanced Concept Description

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 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 and structures and corrective optics to implement downstream wavefront control. We propose a novel viable enabling technology.

High resolution space imaging requires the production of lightweight large aperture optics subject to design tradespace constraints based on nanometer physical tolerances, low 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*. Segmented systems impose additional requirements on segment alignment, wavefront phasing, and telescope mass with increased edge diffraction.

Photons weigh nothing. Why must even small space telescopes "weigh" tons? Our team is working to demonstrate that they do not, by leveraging 15 years of effort and a novel advanced consept.

The ultimate research goal is to refine technology to produce a mission capable ultra-lightweight membrane optic whose shape can be remotely controlled using a laser beam. Using our novel optically controlled molecular actuators allows substitution of optically induced control for rigidity and mirror mass. In analogy with noise canceling headphones, this technique also potentially provides a way to excite vibratory modes to couple with and damp out normal modes of oscillation induced by slewing, other motion and thermal changes, thus allowing a robust response to repointing of a large aperture.

How Does It Work?

Everything in the universe is a transducer (converts one form of energy to another). A "Photonic Muscle" is a transducer that can convert photon energy into mechanical motion. Materials we have made which incorporate π-π^* mixed valence organic laminates and various Azo-Benzene related liquid crystal elastomer (LCE) compounds undergo change in dimension with the application of light. Reversible *trans–cis–trans* photoisomerization of aromatic azo groups covalently bonded within polymers can trigger a variety of motions in the polymer materials at nanometer to centimeter levels. When constructing artificial muscles, it is desirable to use soft materials with high mechanical flexibility and durability rather than hard materials like metal. Effective muscle-like actuation works best in materials with stratified lamellar structures and high molecular ordering. LCEs are soft polymer network materials that possess both the domain order of liquid crystals and the elasticity of elastomers. LCEs can convert external energy into macroscopic amounts of mechanical energy resulting in controlled deformation of a surface, in this case a mirror.

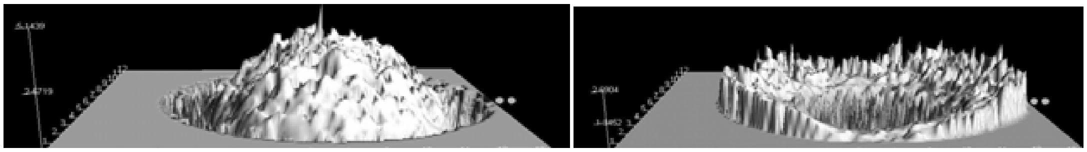
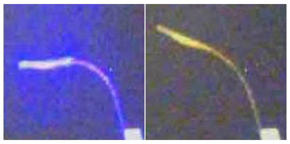


Figure: Membrane mirror shape controlled at micron level

Shown above is micron scale control of a simple photonic muscle mirror measured by the PI using Shack Hartman metrology: Left warped mirror, right after optical correction with polarized beam. Optical figure was reconstructed integrating slope of optical path difference from gradient determined using lenslet array. Vertical axis 5um.

Goal

The research goal is to demonstrate an ultra-light-weight membrane optic (think of a shiny balloon with a controllable shape) whose shape can be controlled using only a laser beam. The goal is to make an **active primary membrane mirror utilizing 10^{23} nanomachine "laser controlled molecular actuators"** eliminating need for conventional figure control actuators providing enormous cost, mass and areal density reduction.



When isomerization occurs in azobenzene, the 4,4′ intramolecular distance is decreased from 9Å to 5Å. This enormous strain and resulting compression of the molecule causes a macroscopic volume contraction. This is exploited to achieve active mirror shape control in engineered azo liquid crystal elastomer substrates.

Neoteric nano-engineering technology:
Technology to produce diffraction limited ultra-low mass space telescope mirrors via photonic elastomer transduction. Mirror shape is controlled by a beam of light from a single small laser!

Key technology to:

- Reduce Telescope mirror costs by 500x
- Enable 10-30x higher resolution systems
- Reduce areal density of mirrors by 250x and spacecraft bus & launch mass by 100x
- Mitigate development and deployment risk

A Hubble size active mirror that weighs 1 pound made out of $10k of chemicals? YES this is possible.

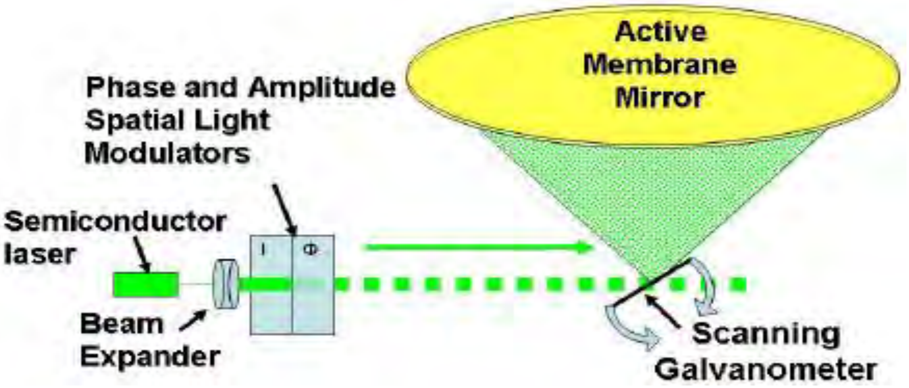


Figure: Notional space telescope control system

Figure: Existing toroidal mirror support JWST size (From Colleagues at UAT Huntsville)

This technology hinges on the now proven advances of

- Optically powered motion
- Optically controllable actuation
- Memory material
- Control mirror with a single polarized beam
- Demonstrated Wavefront Control

Goals that the team is working toward are summarized in the following table:

Spec	JWST	OCCAM	Improvement
Areal Density	25Kg/m^2	0.1Kg/m^2	250x
Mirror Cost/m^2	>$26M	<$0.05M	>500x
Diameter	6.5m	20-40m	3-6x

JWST Primary Mirror Comparison

Originally our team demonstrated optical control and feasibility of this idea thus meriting further investigation. Phase II worked towards a proof of concept using space durable materials and novel processing techniques. This research leverages meta-material development efforts and over a decade of research by the PI and team dating back to 1999.

Phase II Study Overview

Under NIAC our team has successfully advanced technology to produce ultra lightweight laser controlled active space telescope mirrors for extreme NASA imaging missions. Missions such as Terrestrial Planet Imager require lightweight mirrors with minimum diameters of 20 to 40 meters. Inexpensive 6 meter class telescopes are a near term goal which would revive missions like the Space interferometry mission and save taxpayers $billions while relieving NASA budget issues.

Technical Approach Overview

The proposed research was to design, synthesize, fabricate, optimize and test light activated mirror substrates which use photoisomer-chromophore enhancements to harness molecular forces to create a basis for ultra-lightweight laser controlled (optically addressed) active space telescope mirror for extreme NASA imaging missions. Phase II has 2 objectives: **I)** Continued technology development to demonstrate a brass board level prototype demonstrating feasibility of the concept and proving that mirror figure requirements such as bandwidth, stroke and control authority of our proposed laser figure control system when combined with our new materials will result in a diffraction limited optic. **II)**Mission concept development using this novel technology as a baseline for several missions from single large apertures to interferometers to large telescopic arrays.

Our Phase II efforts as per the proposal included interacting team efforts across the US. These efforts focused on

- Multiple Meta-Materials Synthesis Study: Chemical Synthesis for Mirror Fabrication
- Metrology and control systems
- Materials processing
- Technology Development Roadmap and Mission Architecture

The plan involved continuing to develop the concept studied further developing numerous refinements and advances identified and learned by the team in earlier work. Phase II was requested to take the technology to the next level to progress toward a diffraction limited membrane optic telescope. We did not hit the diffraction limit but all of the tools are in place and we continue post proposal development.

The team assessed the concept in a mission context with a main focus of determining feasibility and comparing properties/performance with those of current missions/concepts including detailed analysis for a candidate mission.

The main thrust of this effort was to continue our significant progress showing a clear and viable pathway for development of a technology roadmap and identifying the key enabling technologies required to make this technology not only a reality but also a highly cost effective tool for advancing our understanding of the cosmos.

Materials Development

Our Phase II material efforts as per the proposal focused on a number of items all with success. We put resources toward a scale of up of our the best pre-phase II Azo Liquid Crystal Polymer Elastomer as its components were essential in more advanced materials development. We also heavily invested in 2 parallel meta-materials synthesis studies to make a photoactive radiation resistant POSS based material which is now a reality. Additionally we worked on advanced materials processing including optical polymerization to control domains as well as successfully developing a spray on material for application to precision mandrels (existing glass mirrors) to allow mass production of large space apertures enabling a new class of Astronomy. The potential of combination of these new technologies is exciting to say the least.

A critical part of our technology development roadmap is to make space durable materials for the photonic OCCAM telescope. This project is about novel uses of meta-materials. Meta (from the Greek preposition and prefix meta- (μετά-) meaning after, or more to the point here-beyond- indicate a new property added to a material. Metamaterials are artificial materials engineered to have properties that have not yet been found in nature. We have designed and now made some new telescope meta-materials that have ever existed on Earth. These new materials are a giant step toward active optics with good optical control authority, thermal and UV and radiation resistance, core qualities required for a space mission.

Synthesis of new materials and fabrication of new substrates necessarily proceeded in concert. Designing new materials required an interaction of knowledge of the following disciplines and more.

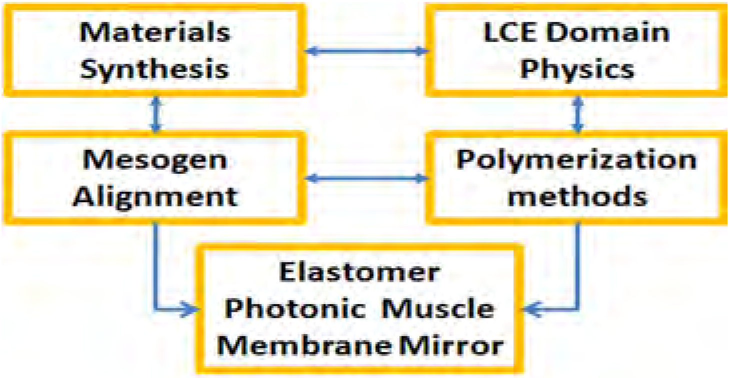


Figure: The interplay of disciplines required to develop OCCAM technology.

Photomechanical molecular machines were designed and integrated into active optical substrates. This effort involved; new materials processing techniques, advanced synthetic chemistry, spectroscopy, crystal domain design, development of mesogen alignment techniques, and integration of optical metrology with novel control systems development.

The goal is to synthesize materials, refine our physical picture of molecular scale mechanical forces and bulk geometric distortions, optimize systems for active optical elements, and then produce an ultra-light active mirror demonstrator.

After synthesizing appropriate photoactive substances shown below, active mirrors were be produced. In addition we explored functionalizing other polymers such as space durable Tor-NC and POSS (Polyhedral Oligomeric Silsesquioxane) used for the current JWST telescope sun shade. We looked at functionalizing molecular groups to act as reflective coatings.

Scale of up

In pre phase I work azo materials which were not even tailored to our specifications cost over $1000 a gram. In phase II we continued development and processing technique work. The current cost of our base materials is approximately $60/gram.

POSS

POSS (Polyhedral Oligomeric Silsesquioxane) is a cage-like hybrid molecules of silicon and oxygen with similarities to both silica and silicone. Chains act like nanoscale reinforcing fibers, producing extraordinary gains in heat resistance.

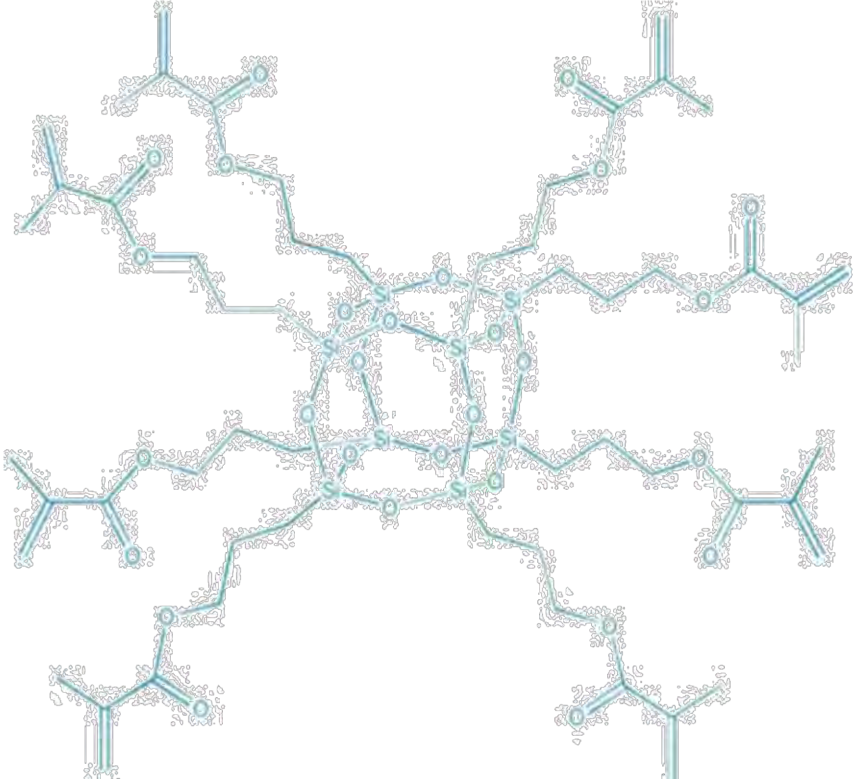


Figure: POSS molecule

What is POSS? POSS is closely related to silicones. POSS chemical technology has unique features: Chemical composition is a hybrid, intermediate ($RSiO_{1.5}$) between that of silica (SiO_2) and silicone (R_2SiO) and it has resistance to heat and radiation.
POSS was chosen for the JWST sunshield for its thermal and space durable properties.

The silsesquioxane cage structure is comprised of 8 silicon atoms bonded to 8 oxygen atoms. At the end of the 8 corners, an organic component can be attached to the silicon atoms. It is possible to attach reactive functionalities to all 8 of these corners as shown in the structure on the left. This polyfunctional cross-linker would result in a higher modulus due to the high crosslink density. Monofunctionality is also possible which allows us to tune the properties of the resulting polymer as shown in the compound on the right. Since there is less cross-linking, the modulus will not be as high, but the benefits of the silicon-oxygen inorganic properties will improve the final polymer.

Azo POSS Development Approach 1-Efforts at WSU

Our team has previously shown optical control of substrates is possible. We have designed a new molecular structure with many hybrid properties. As a new class of smart materials, these photoactive shape memory polymers respond to specific external stimulus and remember the original shape yet can be tailored with optical input.

Azobenzene-POSS Hybrid Polymer I

We have not named the compound yet. It is an OCCAM Star Shaped Azobenzene Polyhedral Oligomeric Silsesquioxane -$(PLA_x)_y$ Macromer. OSSAPOSPM? StazoPos? The synthetic details are included in the appendix to this report.

This novel compound metamaterial has the following traits:

- Photoactively shape controlled via photoisomerization
- It is a photoisomer powered material yet also an inorganic/organic hybrid using POSS which should make it thermally resistant, UV resistant and atomic oxygen resistant.
- Exhibits shape and state reversibility.
- It exhibits crystal state memory which will hold its shape after adjustment (memory zero power mode after laser adjustment).
- It is also a SMP (Shape Memory Polymer)! It can be thermally reset to original shape if desired (for initial mirror deployment which therefore allows exceed fairing diameters without mechanical devices), this is a polymer property directly analogous to shape memory alloys.
- It is redissolvable after initial polymerization using DMF (Dimethyl formamide) (so we can have a fluid form and spray it on a precision mandrel then cure it on that shape). We have made a spray on robot to do that.
- It is a stable thermoset for shape forming processes via thermal polymerization.
- It is flexible and we can tune flexibility by adjusting linker length of arms on polylactide chains on the POSS core.
- We can tune phase transition temperature by adjusting molecular chain length.
- It can be rolled or gently folded (without a crease) to attain high packing ratio for a telescope mirror.

In short we have invented a new telescope material with every virtually property we initially wanted. We have exceeded initial expectations. The areal density is approximately 100g/cm^2.

This is a new material and we have just begun to probe its properties. The extent of the photoreversibility properties is not yet fully known. Work to optimize the processing using what we learned with other materials still needs to be performed. Spectroscopic and detailed synthesis details may be found in the appendix.

The following is excerpted from a video sequence of photo deformation. A laser is scanned vertically.

Figure: Note in the final frame a relaxation resulting in return to near vertical displacement. Also note this is not simply melting as working being performed against gravity by this optical machine.

In a preliminary verification experiment the team has made this material also in a membrane shape as one would require for a space telescope mirror.

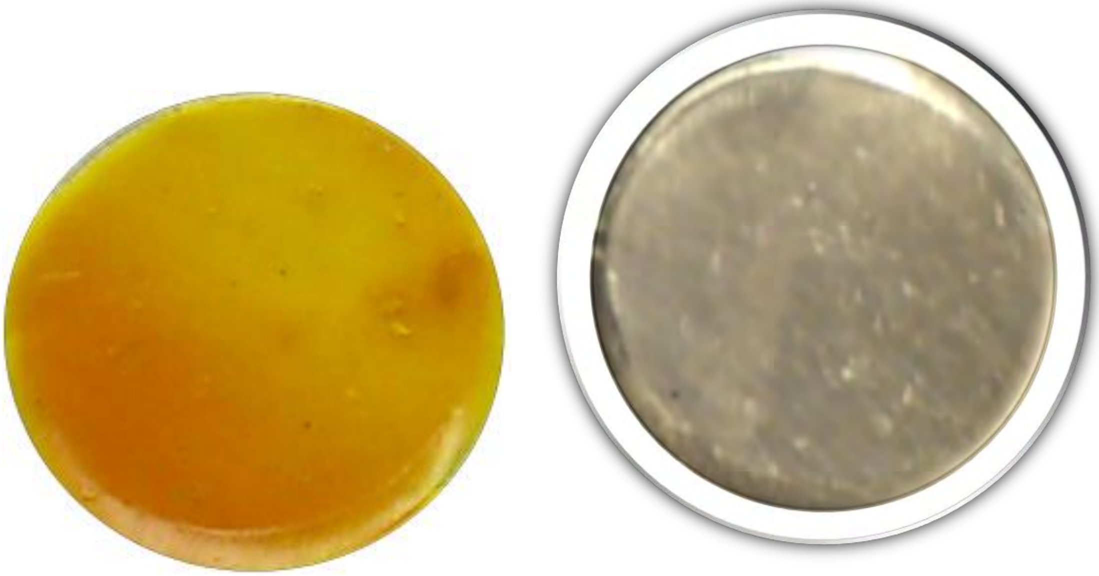


Figure: formed polymerized round OCCAM OSSAPOSPM Star AzoPoss membrane and a crude mold.

Minor imperfections in this shape (left) are not of concern, this was simply an attempt from a crude round aluminum pie mold from which its surface features and imperfections were replicated. No attempt was made to remove evolved N_2 a byproduct of the polymerization agent to optimize microroughness.

As this is a new material, Post Phase II we'll use a precision test plate for replication of a mirror. We have done this before so this is not expected to be difficult

Additionally as we have developed a spray on application we'll spray coat a precision mandrel as well. We also want to thermoform stretch a mirror over a convex mandrel. We will have to attempt this after phase II, but those techniques are at last possible with this materials: The point was to show moldability, flexibility in the AzoPoss material which we have. This is very encouraging. We did it!

The next step is to perform processing experiments to determine optimal macroconfigurations. Probing the relationship between mesogen alignment as well as mesogen conformation and domain size as induced by processing (both alignment and polymerization techniques) and understanding this basic science (fundamental physics) is key to optimizing optical properties of these materials, namely bandwidth, stroke efficiency and power stroke available. One can understand this by imagining randomly oriented muscle fibers versus aligned fibers (or in this case molecular machines) working together. The team will seek modest funding to continue this effort.

Azo POSS Development Approach 2-Efforts at Lander

Our second chemistry team also sought to make a radiation resistant photoactive material but via different methods. We had limited success and made an interesting yet brittle material which will require further refinement to be space ready (for this application). We note the final issues with this second azoposs material are similar to issues solved by team one.

Azobenzene-POSS Hybrid Polymer II

The objective of the research was to make an azobenzene-POSS hybrid polymer for ultra-light weight photonic muscle space telescopes. The starting materials were dihydroxyazobenzene which was synthesized at Lander University and chloropropyl-POSS purchased from Hybrid Plastics. The synthetic details are included in the appendix to this report.

Figures: The reaction setup. A new synthesis path was adopted. Right: Monomer, POSS, and Benzene in Argon atmosphere attached at the end of the condenser and was filled with argon and the polymer was formed.

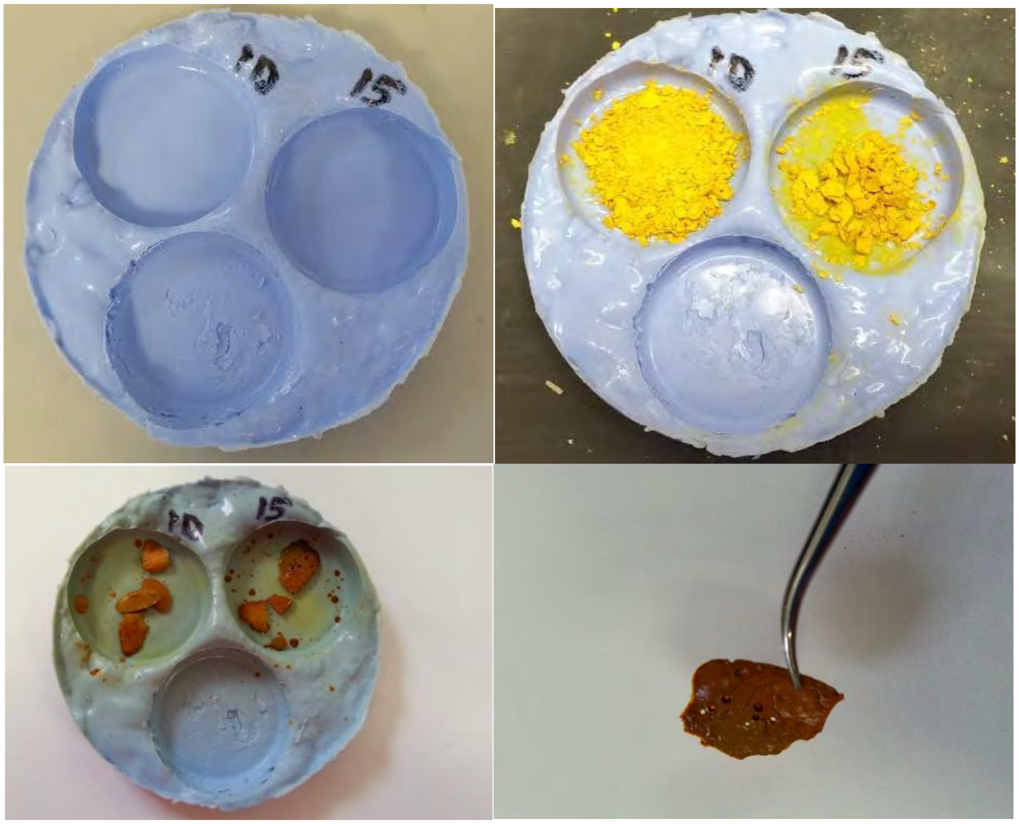
A polymer formed had a smooth surface and could be lifted by tweezers. Unfortunately, the polymer was strong and brittle, so it had to be handled with extreme care

Figures: Crystals obtained from the rotary-evaporator

To increase the size of the polymer a large scale reaction was carried out. It was found out that it was quite difficult to remove the polymer from the dish without breaking it and also it took a long time for the polymer to be released from the dish surface. The researchers look forward to completing a new synthesis and solve the problem of brittleness on the new azobenzene-POSS polymer. They also continue to investigate the effect of the amount of POSS in the polymer.

Figures: Purified monomer prior to polymerization, Right Polymerized product

To increase the size of the polymer a large scale reaction was carried out. A week later, the polymer came off the glass petri dish, however it is very brittle. The image above shows a piece of the polymer next to a quarter.



Figures: silicone rubber mold was made to make it easier to remove the final polymer. There was no problem removing the final polymer from the mold, but again the polymer is very brittle. (bottom right) – The final polymer.

In summary at Lander the team made an interesting material, but it is too brittle to be used for a space telescope membrane. We note however that the WSU team had the same problems and via purification and sublimation were able to generate a usable membrane material. Modest funding over the next year will be sought to correct this.

We find value in listing this null result as we learned and will refine the process. DO not let it overshadow the previously reported excellent result. We did attain our goal, namely a POSS based photoactive polymer, with photonic muscle properties, and shape memory.

Reflective coating via functionalization:

At Lander work was performed on a reflective overcoat with a thiol to protect a spray on silvering. We have attempted to find multiple means of cross-linking self assembling monolayer tail groups. We experimented with a a number of different reaction with varied but promising results.

Figures: Silvered glass slide with a monolayer. The tail end of the monolayer has been cross-linked.

Figure: Glass microscope slides provided an inexpensive and relatively easy substrate for thin-layer silver adhesion.

We are not ready to report on this work publicly yet. Details may be found in the appendix.

In a parallel unrelated effort the PI has possibly invented a low oxidizing method for silver overcoating membranes which should have a very low tarnishing rate. This was outside of the NIAC OCCAM effort but is likely quite useful. This has comparable reflectivity to gold in the IR but is superior to gold in the visible. It has the advantage of not requiring a protective overcoat which alters incoming polarization, and not tarnishing like silver. The method will be described in another paper. We hope to combine these 2 coating methods.

Advanced Materials Processing

- **Polymerization by laser to induce mesogen alignment**
- **Spray on material**

Polymerization by laser to induce mesogen alignment

We attempted domain writing by polarized beam via selective absorption of aligned crosslinkers

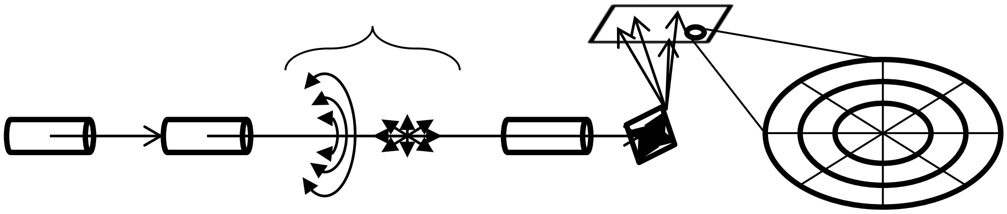


Figure: A polarized beam is presented to a substrate during formation:

We built a setup to do this which used a laser for selective polarization polymerization.

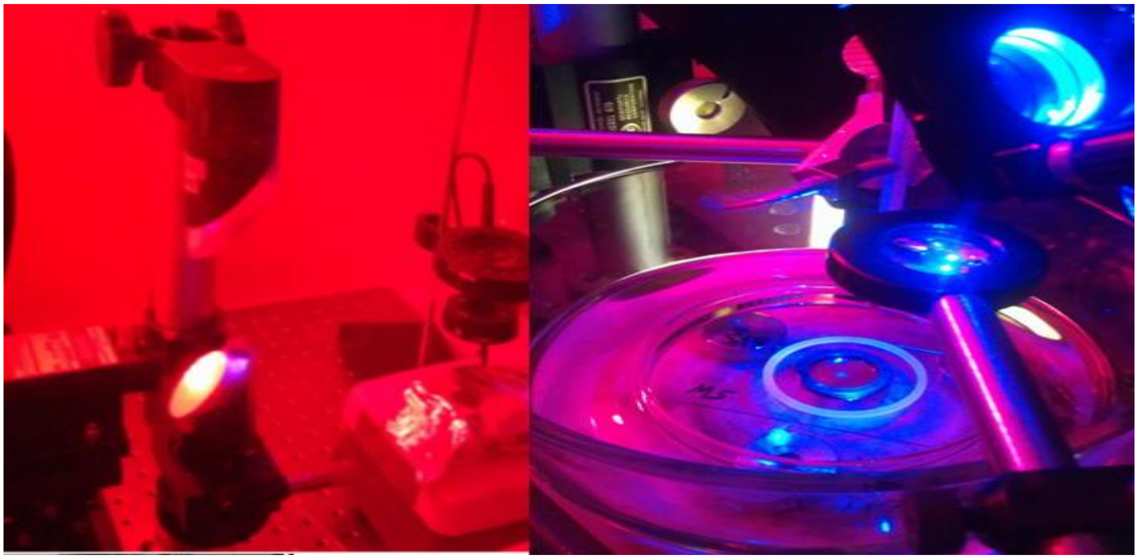


Figure: Optical polymerization initiation

We were able to generate aligned photopolymerization as intended. Testing of samples continues.

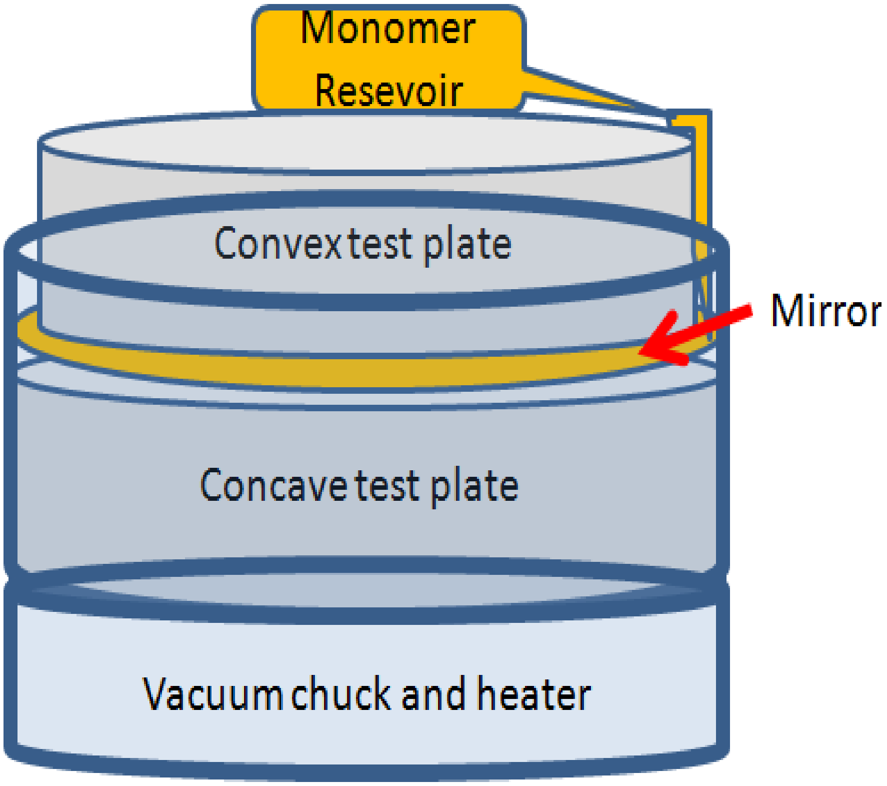
In a related experiment we also used a monochromated UV source for isomerization then polymerization. The intent was to align molecules in the melt. The intent was to use UV exposure of a new mix in the melt to convert to and lock in CIS isomerization while polymerizing with Irgacure photoinitiator. This was also successful; however samples were very fragile. The experiment will take more refinement.

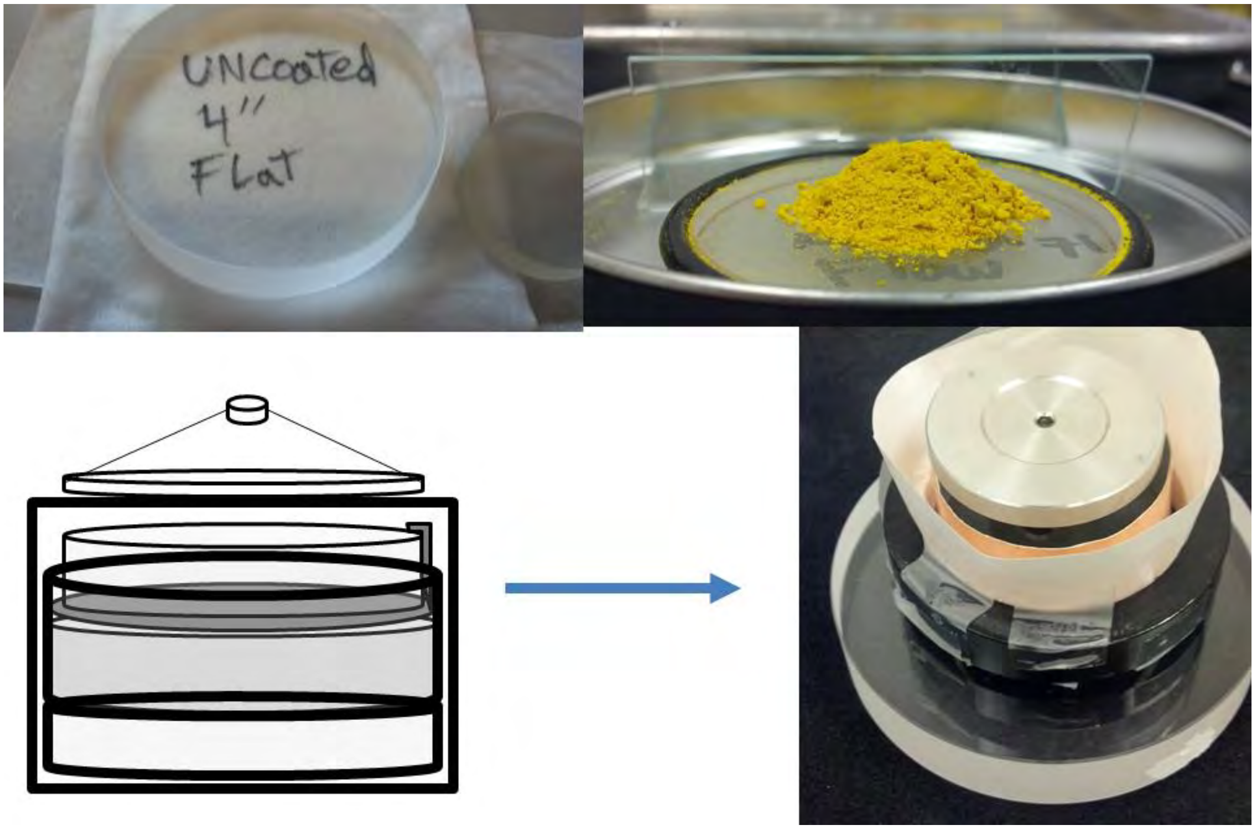
Spray on deposition

We have previously spin coated materials then mounted with low shrinkage epoxy:

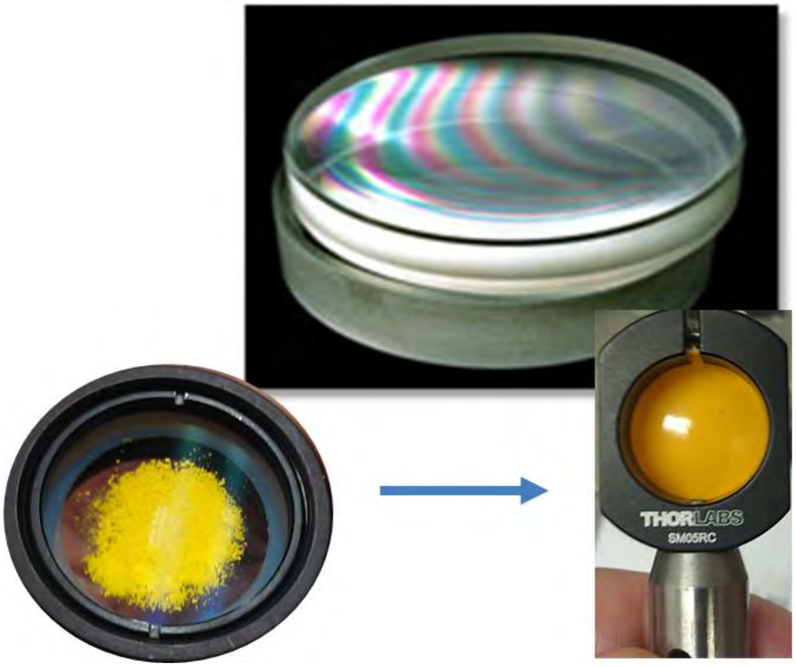
The team has vacuum polymerized curved and flat materials:

We already know we can perform conformal cooking to achieve desired shapes using convex concave test plate pairs:





We have also previously done this for desired curved shapes with our “Conformal Sandwich”:



All of these techniques appear viable for mirror production.

A truly exciting development is a spray on material. What we really want is to use a single mold preferably an 8 meter mirror using the Kuhn slumping method or the UAz Mirrors, as a "mold" to mass produce large apertures. We show examples of each here:

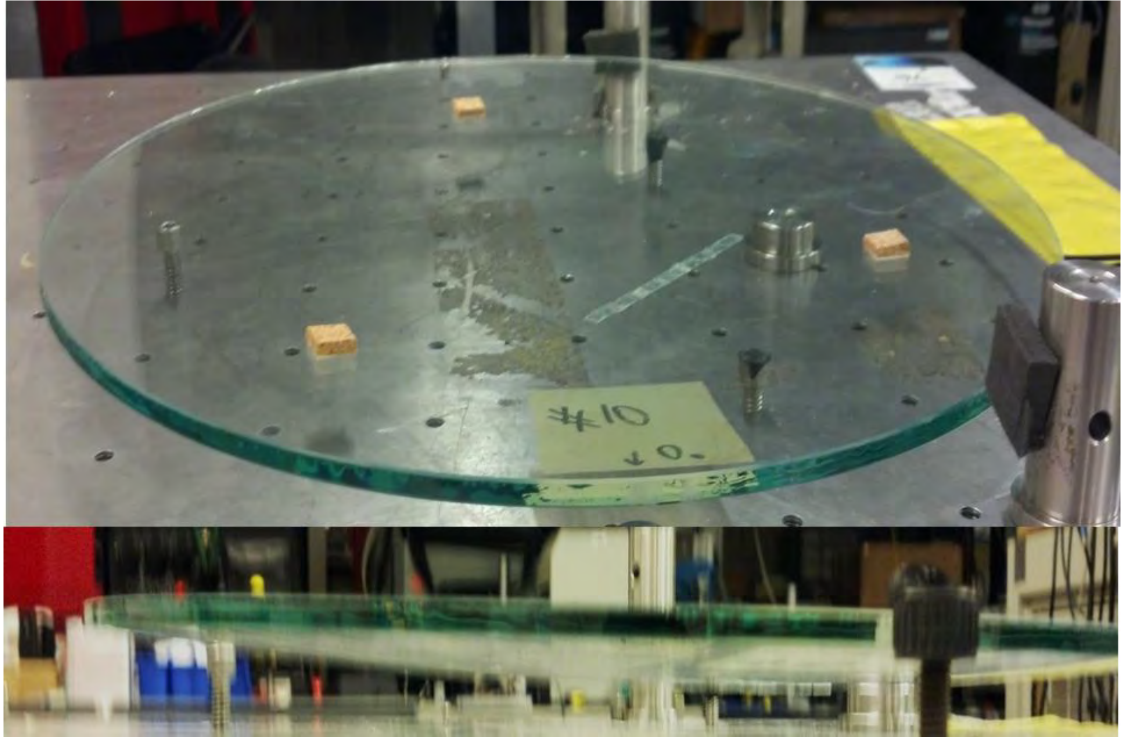


Figure: Paraboloidal mandrel

The preferred glass mandrel is 8.0m, to make Telescope mirrors larger than JWST's M1:

Figure: A University of Arizona 8 meter glass mirror. A spray on mold for OCCAMs?

Our intention was to develop a spray on coating method which would allow rapid and cheap forming of large space mirrors. We have done this!

Using the material we mentioned above, the OCCAM Star Shaped Azobenzene Polyhedral Oligomeric Silsesquioxane -$(PLA_x)_y$ Macromer, (OSSAPOSPM) can be polymerized then macomer units are dissolved in a special solvent. We have built a spray robot for testing. Testing will continue past Phase II and modest funding is sought for that. This device is also ready for mounting of a polarization controlled laser beam for additional photopolymerization experiments. **The combination of the 2 represents a new 3d printing technique.**

Following is a brief summary of this machine for coating and mass producing space mirrors:

3d Polymer Printer Extruder Polymerizer and Cutter:

We took an off the shelf laser cutter kit and highly modified it for both polarization inducing polymerization, laser thermal polymerizaion and for spray on application. It is operational, and an airbrush has been mounted and has computer/pneumatic control.

This unit is designed for 3 uses.

1. Spraying on a liquid polymer.

2. Laser polymerizing samples with photoinitiation
3. Laser polymerizing via thermal initiation polymerization
4. Cutting polymer samples
5. Trimming mirrors

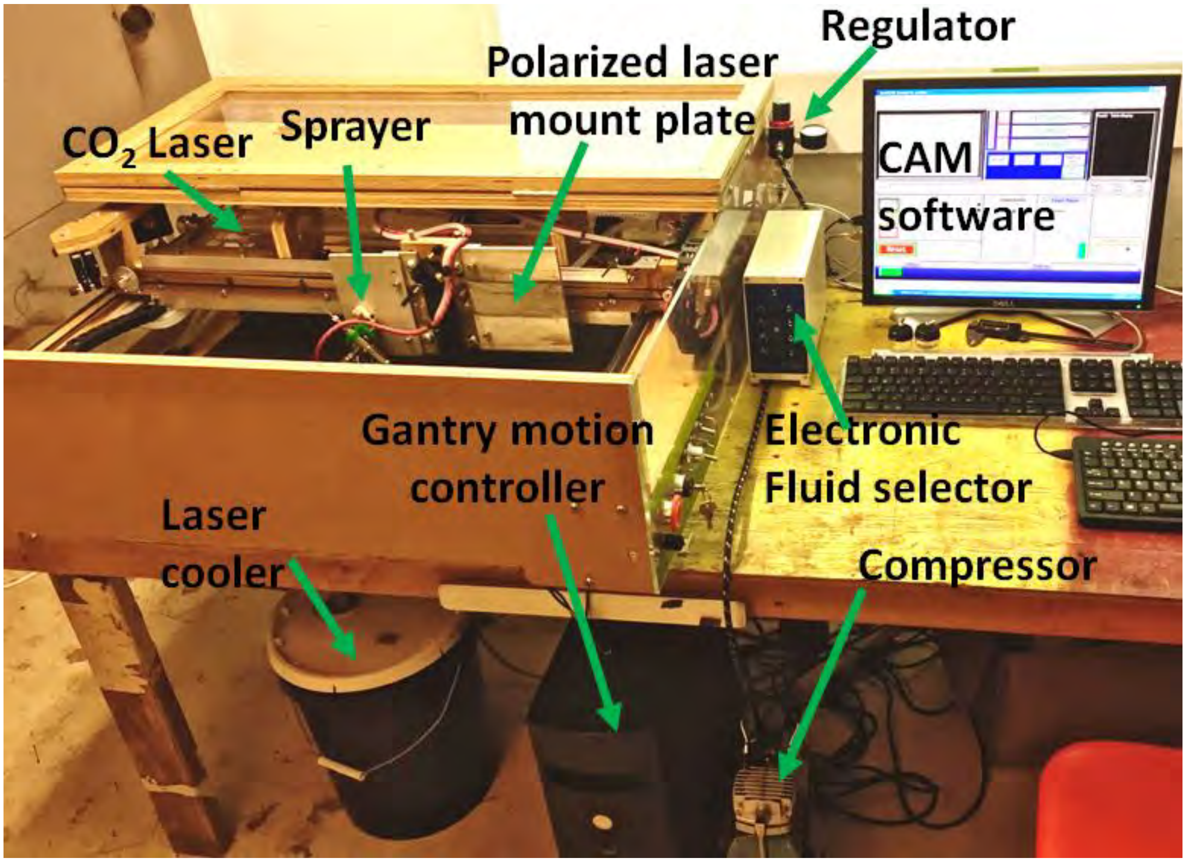


Figure: Polymer sprayer, laser polymerizer, laser cutter.

The liquid polymer dispenser is currently setup with a Paasche airbrush mounted on an adjustable 3d printed mount which can be adjusted for liquid polymer flow rate (axial dial on airbrush), spray pattern (nozzle position or alternate nozzle), air flow rate (pressure regulator and/or thumbscrew adjustment), and angle/nozzle height (angle of the mount).

Figure: Computer controlled polymer spray nozzle mounted on precision computer motion contolled 2 axis gantry

The liquid polymer flow is controlled by switching on a 24V line on the DB9 plug on the pneumatic solenoid controller. Electronic control has been tested, however complete computer control has yet to be tested, but should be simple to implement (and has been tested separately). The current implementation has a narrow air supply line. The hysteresis of the start/stop cycle is roughly equivalent to that of a fused filament 3d printer extruder; as such, it should not be a problem as long as tool paths are arranged to minimize the number of extruder stops and starts.

The current spray pattern is between 0.25” and 0.5”, and is offset from the laser focal point for when laser polymerization is desired. Smaller or larger spray patterns can be achieved by moving the airbrush mount closer or further from the work piece, and adjusting the air and liquid flow rates.

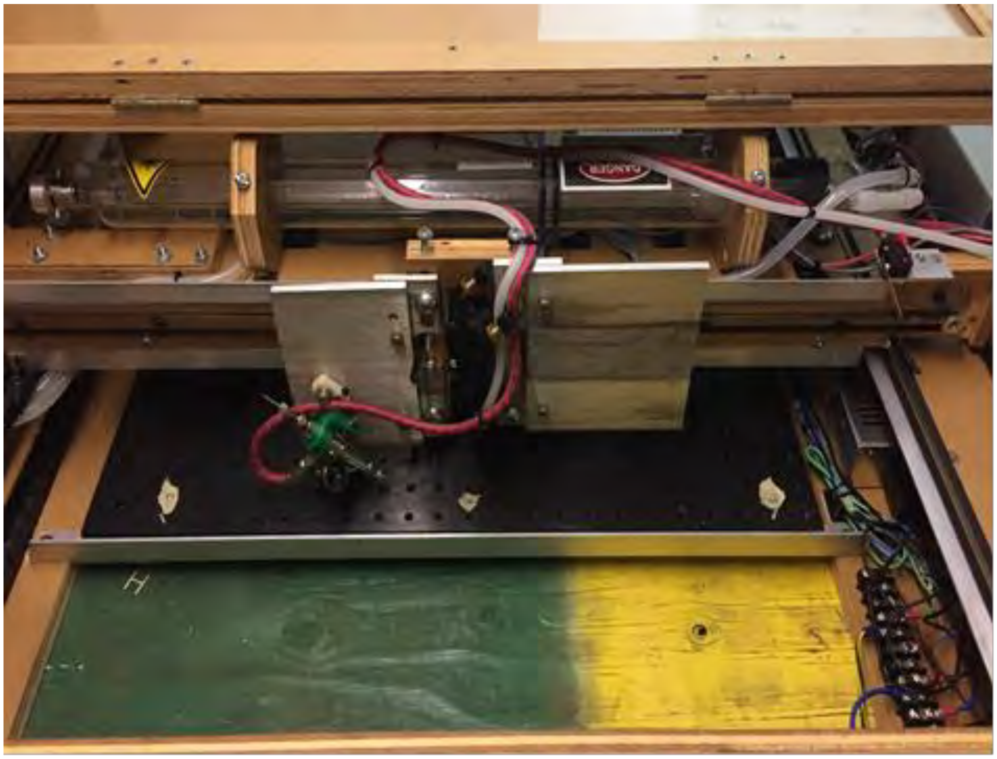


Figure: 2 axis applicatication platform

Optical Mounting Plates

The left plate is being used for the liquid polymer deposition system, and is lowered 0.5” to clear the incoming CO_2 laser beam path. The right aluminum mounting plate is blank, and is reserved for the polarized laser diode apparatus. The polarized diode setup includes 2 LCVR’s to fully control beam polarization during polymerization.

Fluid Supply

The airbrush fluid containers are used. Compressed air is supplied with compressed air from a compressor and tank, regulated to less than 30 PSI: and then fed to the pneumatic controller.

Figure: Spray pressure is regulated and adjustable

Figure: The control panel is shown above.

The CO_2 laser water cooling pump and reservoir consist of a 5 gallon bucket filled with distilled water and 20% antifreeze to prevent bacterial growth:

Figure: Low tech CO_2 laser cooling system

The pump is submersed in the bucket; the thermal capacity of 5 gallons of water is more than sufficient to keep the laser cool under normal operating conditions.

There is an external computer control interface:

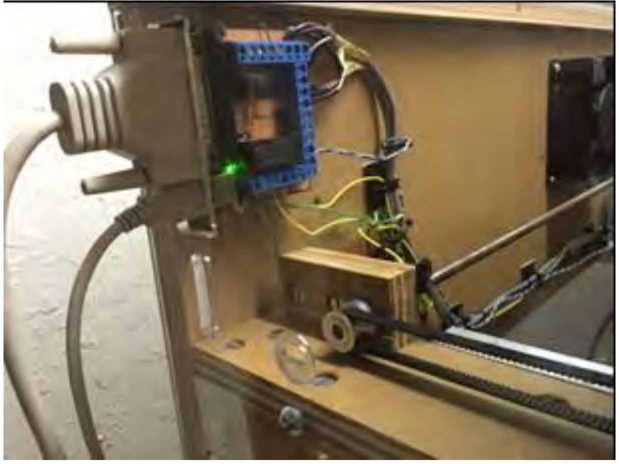


Figure: Control computer B interface

Outstanding to do items:

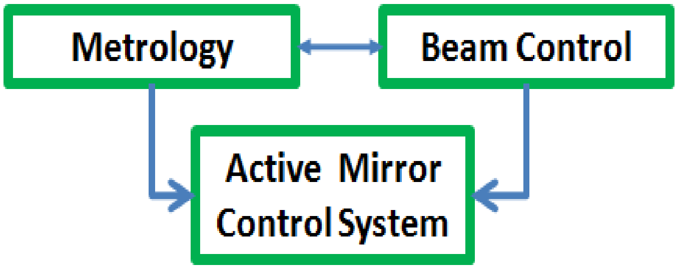
- Finalize software control for pneumatic system (extra spindle control, custom M command?)
- Test and calibrate airbrush liquid dispensing system.
- Add pressurized liquid dispensing system?
- Build and mount polarizing laser diode system.

In summary we have developed a spray on technique and have a crude but functional spray robot. Modest funding will be sought to continue this work. Additionally retarders will be added with a secondary laser to do domain writing alignment. We note assistance in this project via the DARPA Space Gambit project.

Control System

Metrology and control systems were also part of our Phase II effort and we made significant progress in algorithm design and actual code generation. Actual computer code (hundreds of pages) is included in the added project appendix.

An optical control system and a metrology test apparatus was iteratively developed to quantify control authority. We have gone through 3 generations of control systems and continue towards developing a next generation system. This is a feedback system where a mirror low and mid spatial frequency figure (shape) is measured and this is used as input for scanning beam control system. Together this constitutes an active mirror control system.

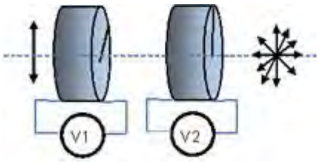


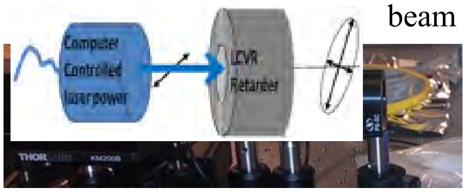
Early Model Summary

Early software and hardware was developed as follows:
An optical metrology and actuation test apparatus was designed to quantify control authority. The system employs liquid crystal modulation to control polarization and power, and a 2 axis orthogonal scanning galvanometer to direct laser control beam position is shown (see again top of this page).

Shown left is the laser scanning drive electronics which we modified to add adequate thermal sinking for long term operation, with a tuned Cambridge PID controlled 2 axis scanning galvanometer for beam direction. The 2 mirrors are simultaneously computer rotated to redirect a laser beam on 2 axes for mirror scanning (part of the control system).

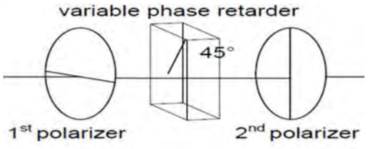
Ferroelectric liquid crystal variable retarder control:
We have interfaced a ferroelectric liquid crystal (FLC) to a high voltage driver, and controlled this with a computer to control polarization state of a control beam incident on a membrane. A sequence of polarizations of various orientation can be obtained from a linearly polarized laser beam by sequentially adjusting V1 and V2 which AC square waves of varying amplitude at a frequency sufficient to influence but not rotate



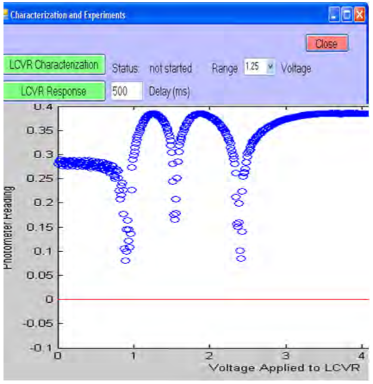


the liquid crystals (approximately 12 KHz). The resultant beam then modulates local curvature in the membrane (mirror). Due to LCVR settling time issues (fully expected) we redesigned this to use a modulated laser driver and <u>a single ferroelectric LCVR</u> shown left:

The FLC Variable Retarder (LCVR) was setup with its axis 45 degrees to a half wave plate (1/2 wave is used to manually rotate electric field angle- linear to linear). This LCVR was then used to electronically control polarization. This new single LCVR configuration is not only easier to control, more robust, and more reliable (I always have a future spacecraft in mind) but also it has double the response time of the initial design.



Such nonlinear systems require calibration. The entire calibration is now automated: Software was designed and implemented to both control electric field rotation (Polarization) when beaming any to any point on a membrane, and special software was written to calibrate the system for retardance vs. peak to peak crystal driving voltage. Shown right is typical nonlinear data obtained for calibration with the beam feeding to a photometer then digitized by computer.


Characterization and Experiments

Status: not started

Range 1.25 Voltage

500 Delay (ms)

As other polarization states may be useful, a separate calibration determines actual retardance vs. drive voltage by simply configuring as above but with polarizers at 45 degrees to each other. Then by measuring the transmission **T**, the retardance **δ** is simply given by : **$T(\delta)=Tmax*(1-\cos(\delta))/2$.** We do have a dual setup as well as a theta cell so any polarization state including elliptical and area distributions such as axial and radial can be generated. See Phase II section on axial radial lamellar domains and the exciting “pie” mirror experiment.

We designed a control program. This loop predictably modulated local curvature in the membrane with no human intervention. This was a success (and very cool) as the membrane tested could be commanded by computer alone to bend with high precision and stability.

<u>Current Model</u>

Two 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 scan galvo 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. The testbed also has computer directed beam target array a polarization indicator, a photodiode calibrated to perform accurate photometry (power measurements), a membrane mirror target (uncoated), 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 which are detailed below.

Hardware

Testbed 1 from phase I is shown below:

It allowed computer control of

- **beam polarization**
- **beam power**
- **beam pointing (2 axis scan galvo)**
- **new custom software for controlling the above simultaneously**
- **low level and high level interfacing routines**
- **special software to generate calibration tables to control these parameters precisely**

Testbed 2 is shown below:

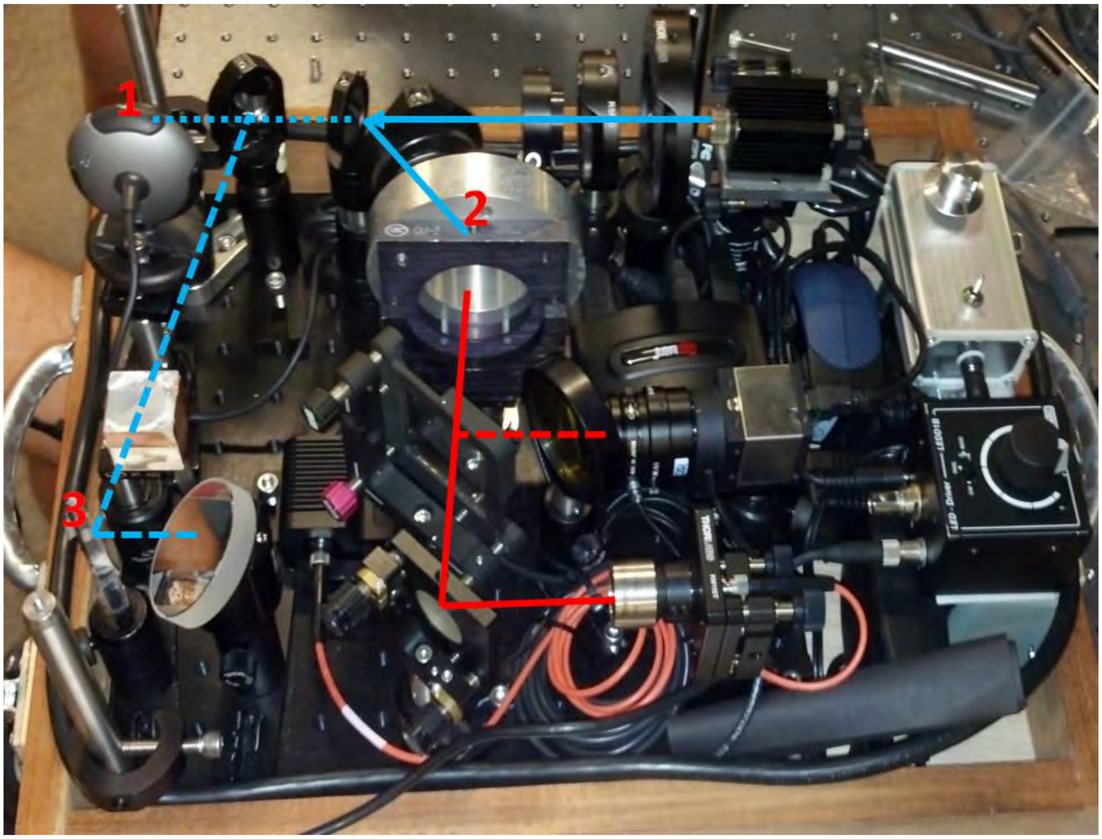


Figure: Testbed 2 Brassboard

This was a version 2 brassboard demonstration including laser control of a membrane along with active shape measurement. A preliminary version of this was presented at the OCCAM midterm review. Functions included:

1. Polarization Modulation Cantilever for sample testing
2. Azo DM w/Shack Hartman for membrane mirror testing
3. Rad Hard Membrane Intensity Modulation demonstration

The only modification required for full system is the addition of a new scanning galvanometer. We note this entire test system in this state conforms with carry on size requirements. It is a prototypefr a space telescope mirror control system. It is supposed to be small.

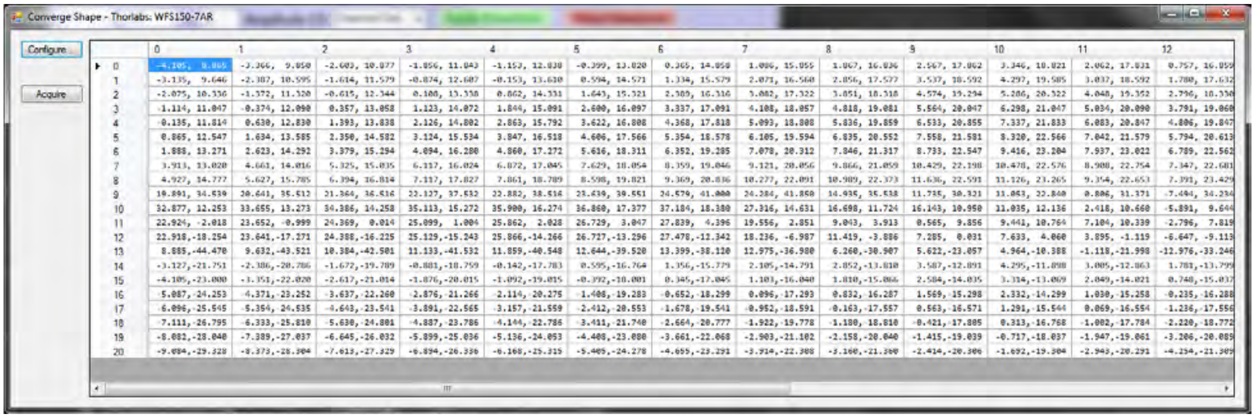
The next generation mirror we will make from the new Azo Poss will require rebuilding this for testing due to the 30 inch focal length of the curved membrane mirror. We will request modest funding to continue that effort.

Software

New software was developed. We decided to switch sensors and a modern Thorlabs Shack-Hartmann sensor was integrated into Photonic Muscle Dish software. This was a decision based on a conscious effort not to use any software not purchased by Neoteric Physics.

Low level and test routines have been previously documented. We have developed a “Converge Shape” window routine that:

- Initializes the SH sensor
- Calibrates optimal SH exposure time
- Acquires initial data for lenslet spot intensity
- Computes centroid to determine spot deviation then slope deviation
- Fills a grid in the window with x,y slope deviation data
- This prepares for iteration of adjustments to reshape a membrane mirror and is a first pass to calibrate and setup the OCCAM active mirror system



	0	1	2	3	4	5	6	7	8	9	10	11	12
0	-4.105, 8.865	-3.366, 9.850	-2.603, 10.877	-1.856, 11.843	-1.153, 12.838	-0.399, 13.820	0.365, 14.858	1.086, 15.855	1.867, 16.836	2.567, 17.862	3.346, 18.821	2.062, 17.831	0.757, 16.859
1	-3.135, 9.646	-2.387, 10.595	-1.614, 11.579	-0.874, 12.607	-0.153, 13.610	0.594, 14.571	1.334, 15.579	2.071, 16.560	2.856, 17.577	3.537, 18.592	4.297, 19.585	3.037, 18.592	1.780, 17.632
2	-2.075, 10.336	-1.372, 11.320	-0.615, 12.344	0.100, 13.338	0.862, 14.331	1.643, 15.321	2.389, 16.316	3.082, 17.322	3.851, 18.318	4.574, 19.294	5.286, 20.322	4.048, 19.352	2.796, 18.330
3	-1.114, 11.047	-0.374, 12.090	0.357, 13.058	1.123, 14.072	1.844, 15.091	2.600, 16.097	3.337, 17.091	4.108, 18.057	4.818, 19.081	5.564, 20.047	6.298, 21.047	5.034, 20.090	3.791, 19.060
4	-0.135, 11.814	0.630, 12.830	1.393, 13.838	2.126, 14.802	2.863, 15.792	3.622, 16.808	4.368, 17.818	5.093, 18.808	5.836, 19.859	6.533, 20.855	7.337, 21.833	6.083, 20.847	4.806, 19.847
5	0.865, 12.547	1.634, 13.585	2.350, 14.582	3.124, 15.534	3.847, 16.518	4.606, 17.566	5.354, 18.578	6.105, 19.594	6.835, 20.552	7.558, 21.581	8.320, 22.566	7.042, 21.579	5.794, 20.613
6	1.888, 13.271	2.623, 14.292	3.379, 15.294	4.094, 16.280	4.860, 17.272	5.616, 18.311	6.352, 19.285	7.078, 20.312	7.846, 21.317	8.733, 22.547	9.416, 23.204	7.937, 23.022	6.789, 22.562
7	3.913, 13.020	4.661, 14.016	5.325, 15.035	6.117, 16.024	6.872, 17.045	7.629, 18.054	8.359, 19.046	9.121, 20.056	9.866, 21.059	10.429, 22.198	10.478, 22.576	8.908, 22.754	7.347, 22.681
8	4.927, 14.777	5.627, 15.785	6.394, 16.814	7.117, 17.827	7.861, 18.789	8.598, 19.821	9.369, 20.836	10.277, 22.091	10.909, 22.373	11.636, 22.591	11.126, 23.265	9.354, 22.653	7.391, 23.429
9	19.891, 34.539	20.641, 35.512	21.364, 36.516	22.127, 37.532	22.882, 38.516	23.639, 39.551	24.579, 41.000	24.284, 41.850	14.935, 35.538	11.735, 30.321	11.053, 22.840	0.806, 31.371	-7.494, 34.234
10	32.877, 12.253	33.655, 13.273	34.386, 14.258	35.113, 15.272	35.900, 16.274	36.860, 17.377	37.184, 18.380	27.316, 14.631	16.698, 11.724	16.143, 10.950	11.035, 12.136	2.418, 10.660	-5.891, 9.644
11	22.924, -2.018	23.652, -0.999	24.369, 0.014	25.099, 1.004	25.862, 2.028	26.729, 3.047	27.839, 4.396	19.556, 2.851	9.043, 3.913	0.565, 9.856	9.441, 10.764	7.104, 10.339	-2.796, 7.819
12	22.918,-18.254	23.641,-17.271	24.388,-16.225	25.129,-15.243	25.866,-14.266	26.727,-13.296	27.478,-12.342	18.236, -6.987	11.419, -3.886	7.285, 0.031	7.633, 4.060	3.895, -1.119	-6.647, -9.113
13	8.885,-44.470	9.632,-43.521	10.384,-42.501	11.133,-41.532	11.859,-40.548	12.644,-39.520	13.399,-38.110	12.975,-36.980	6.260,-30.907	5.622,-23.057	4.964,-10.388	-1.118,-21.998	-12.976,-33.246
14	-3.127,-21.751	-2.386,-20.786	-1.672,-19.789	-0.881,-18.759	-0.142,-17.783	0.595,-16.764	1.356,-15.779	2.105,-14.791	2.852,-13.810	3.587,-12.891	4.295,-11.898	3.005,-12.863	1.781,-13.799
15	-4.105,-23.000	-3.351,-22.020	-2.617,-21.014	-1.876,-20.015	-1.092,-19.015	-0.392,-18.001	0.345,-17.045	1.103,-16.040	1.810,-15.066	2.584,-14.035	3.314,-13.069	2.049,-14.021	0.740,-15.037
16	-5.087,-24.253	-4.371,-23.252	-3.637,-22.260	-2.876,-21.266	-2.114,-20.275	-1.408,-19.283	-0.652,-18.299	0.096,-17.293	0.832,-16.287	1.569,-15.298	2.332,-14.299	1.030,-15.258	-0.235,-16.288
17	-6.096,-25.545	-5.354,-24.535	-4.643,-23.541	-3.891,-22.565	-3.157,-21.559	-2.412,-20.553	-1.678,-19.541	-0.952,-18.591	-0.163,-17.557	0.563,-16.571	1.291,-15.544	0.069,-16.554	-1.236,-17.556
18	-7.111,-26.795	-6.333,-25.810	-5.630,-24.801	-4.887,-23.786	-4.144,-22.786	-3.411,-21.740	-2.664,-20.777	-1.922,-19.778	-1.180,-18.810	-0.421,-17.805	0.313,-16.768	-1.002,-17.784	-2.220,-18.772
19	-8.082,-28.040	-7.389,-27.037	-6.645,-26.032	-5.899,-25.036	-5.136,-24.053	-4.408,-23.080	-3.661,-22.068	-2.903,-21.102	-2.158,-20.040	-1.415,-19.039	-0.717,-18.037	-1.947,-19.061	-3.206,-20.085
20	-9.084,-29.328	-8.373,-28.304	-7.613,-27.329	-6.894,-26.336	-6.168,-25.315	-5.405,-24.278	-4.655,-23.291	-3.914,-22.308	-3.160,-21.360	-2.414,-20.306	-1.692,-19.304	-2.943,-20.291	-4.254,-21.305

Figure: Slope metrology and diagnostic with “Converge Shape” GUI

Clicking on the “Acquire” button then begins a shape convergence loop as follows:

- Acquires data for lenslet spot intensity and slope deviation
- Fills the grid in the window with x,y slope deviation data
- For each grid entry
- Applies voltage to x,y settings to scanning galvo mirror controller to position laser control beam to corresponding spot on Mirror control surface
- Applies a voltage to LCVR based on slope information to set correct influence polarization direction.
- Applies voltage to beam power based on spot intensity to set correct influence power
- Waits 2 seconds and the repeats until all lenslet array items have been processed.

The details of this deceptively simple algorithm are found in the appendix of this report.

We have a new data configuration window that allows us to setup for new test geometries. The interface looks like a previous interface but is used to control for new test setups.

Clicking on the “Configure” button renders the “Configure” window similar in image and use but not functionality to the beam control window described in Phase I. This enables manual calibration for new test setups by entering bias values for x, y beam position, LCVR base voltage and beam power. In this way as new geometry mirrors are produced we can adapt the setup.

Code:

The following is a code snippet of the main part of the software that calculates the re-shaping influence and sets the correction on each part of the sample. It is a simple serial process contained in a nested for loop that iterates over the two-dimensional lenslet array cells and uses the x,y spot deviations to determine voltages to send to the appropriate devices. The bulk of the rest of the code handles device control and the GUI.

Important files (all in Microsoft C# language) can be found in the appendix. This simple high level routine is listed here to illustrate system function. The other 50 pages are left to the appendix.

//EXAMPLE of ACTIVE CONTROL NASA OCCAM PROJECT ITERATIVE SERIAL CONVERGENCE ROUTINE:

frmMain.cs – the main GUI window
frmShowSlopes.cs – the “Converge Shape” GUI window discussed above
Three_P_Method.cs – the “Configure” GUI window discussed above

```
    void FillLensletGrid(Single[,] XSlopes, Single[,] YSlopes, bool blnConverge = false )
    {
      string strXdir, strYdir;

      for (int row = 0; row < sensorGeometry.Y; row++)
      {
        for (int col = 0; col < sensorGeometry.X; col++)
        {
          strXdir = String.Format("{0,7:F3}", XSlopes[row,col]);
          strYdir = String.Format("{0,7:F3}", YSlopes[row,col]);
          dgvSlopes.Rows[row].Cells[col].Value = strXdir + "," + strYdir;
                // NOW IF NOT CONVERGED SET POS, POL, POWER
          if (blnConverge) frm4.positionPolarityPower(strXdir, strYdir, 0, Math.Sqrt(Math.Pow(XSlopes[row,col],2) +
Math.Pow(YSlopes[row,col],2)).ToString(), 0);
        }
      }
    }

    private void bwAcquire_DoWork(object sender, DoWorkEventArgs e)
    {
      while (true)
      {
        if (bwAcquire.CancellationPending)
        {
          e.Cancel = true;
          return;
        }
        else
        {
          // use the autoexposure feature to find the optimal exposure time and gain
          AdjustImageBrightness();

          // the camera image can be retrieved for later display
          GetSpotfieldImage();

          // calculate the centroid positions of the spots
          CalcSpotCentroids(out fCentroidsX, out fCentroidsY);

          // calculate the beam parameters, derived from the centroid intensities
          CalcBeamCentroid();

          // calculate spot deviations to internal reference positions
          CalcSpotDeviations(out fDeviationsX, out fDeviationsY);

          // calculate the wavefront
          CalcWavefront();

          // calculate a pre-defined number of Zernike results
          CalcZernikes();

          FillLensletGrid(fDeviationsX, fDeviationsY, true);

          Thread.Sleep(2000);
        }
      }
    }
```

This code runs to provide iterative control and mirror correction. We are in the process of refining the code and will quantify results and report that separately. The next steps are:

- Add test setup offset scaling
- Set new convergence limits appropriate to diffraction limits
- Modify polarization calibration to correspond to gradient calibration
- Introduce live sample and test
- Refine calibration techniques and algorithms
- Refine influence functions
- We are also working toward a parallel matrix inversion method related to AO inversions which will generate voltages to undo computed zernikes.
- We'll tie the voltage with our gradient mapping computation for controlling polarization direction. This will give us tilt as well as piston at each location.
- Evaluate iterative algorithm and proceed to global algorithm.

We are in the process of creating a new AzoPOSS mirror and will use this in our final testing to demonstrate active optic. That will be the real test of this technology. We will seek modest additional funding to quantify these results.

Technology Development Roadmap and Mission Architecture

We have actively advanced the project through team development, hardware and software development as well as materials development. The following details are included in this report.

In addition to developing a technology roadmap we examined possible classes of missions, a progression of candidate missions, and selected one candidate mission architecture for further development. In this section we report first on a sequence of missions to develop and scale the novel OCCAM technology for NASA, then we report in greater detrail on a single mission utilizing this novel technology and others to find life.

OCCAM Mission Development Roadmap

Technology Development Roadmap- Multiple Missions Overview The team looked at mission tradespaces. This included:

- Mission goals division: Tech demo or Science goals
- Required instrumentation for remote sensing
- Initial requirements definition
- operations concept development
- architecture trade-offs
- payload design
- bus sizing
- Orbits available / desired given a bus mass related to science requirements
- Subsystem definition
- System manufacturing concepts or off the shelf alternatives
- 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.)
    - Operations concept development
    - Robotic operations complexity.

From this we considered a number of intermediate missions to advance, scale and demonstrate the technology.

We came up with what at the time seemed like an optimal progressions looking at technknology development cost vs risk. The missions were:

- Step 1A: KC-135 Technology Demonstrator
- Step 1B: FOP Suborbital Flight
- Step 2: ISS JOTI Technology Demonstrator
- Step 3: Cubesat Space Telescope

- Step 4: Off axis Hubble size Exo-Spectropolarimetry
- Step 5: Ultra-resolution Intensity Interferometry
- Step 6: Aperture beam combining Amplitude interferometry
- Step 7: 8m Flagship Science mission
- Step 8: 80 meter array 20 metric ton

Missions are a function of technology status. We would like to see a payoff to NASA and the taxpayers as the technology progresses, yet have some immediate payoff. To that end we looked at mission difficulty. Visible optical shape figure is hard. We want a payout along the development path.

Ignoring instrumentation, missions for diffraction limited performance at shorter wavelengths are hardest when it comes to optical figure:

100μ FIR	**10μ IR**	**0.5 μ (visible)**
• Cosmic Infrared Background – High Z	• Intensity interferometry – Ultra-resolution • IR Telescopes – Galaxy formation	• Visible and longer • Exoplanets • IR SETI • Similar goals as Hubble and JWST
Easiest	Harder	Challenging

We looked at a technology roadmap first with Earth based platforms:

- Prototyping brassboard
- Lab tests of payloads
- Control and Flight Hardware Development
- KC-135

Step 1: KC-135 Technology Demonstrator

- Payload (50kg)
- Purpose:
  - Demonstrate Membrane figure control in Zero-G

Figure: Brassboard transition to Zero-G testing. PI Ritter shown on right.

We then considered a mission roadmap that was spaced based as follows:
- JOTI/JEM airlock test on ISS
- Freeflyer released from ISS
- Cubesat Tech demo
- Secondary payload
- Minisat
- Serious Science
- Ultra-science

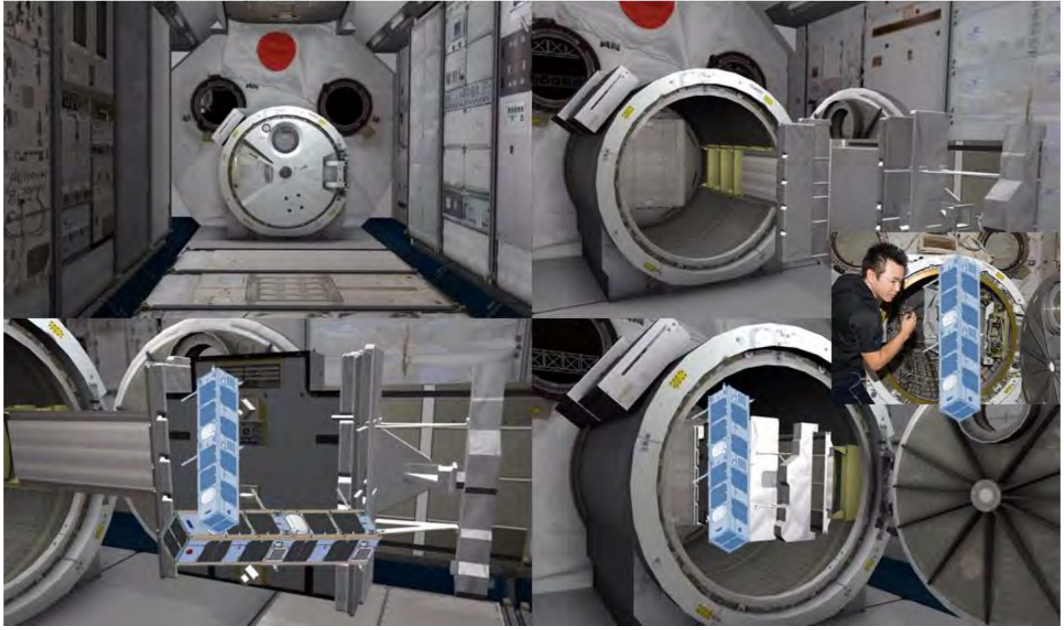
We gratefully acknowledge conversations with Dr. Sonny White at NASA JSC

Following are some viewgraphs detailing some mission ideas:

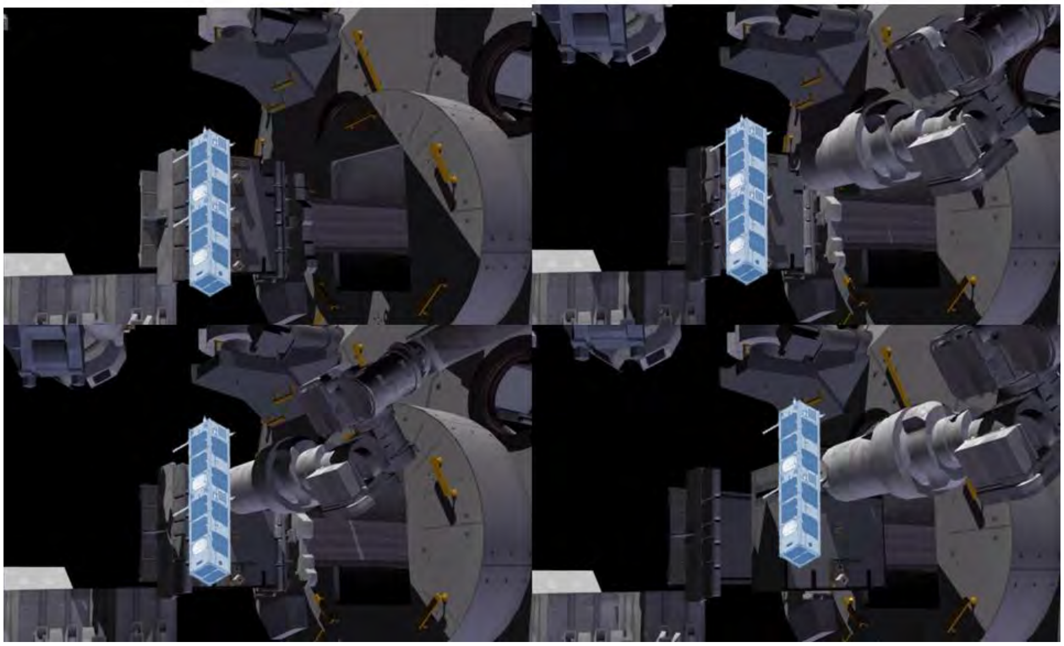
Step 2 would be a low cost ISS JOTI Technology Demonstrator
- Purpose:
  - a tech demo mission to get to TRL7 science- (Space demonstration)
- Payload (50kg) would ride up on Dragon (SPACEx) or Cygnus (Orbital Sciences)
- Could pull power and data from SPDM but this is expensive- Use Batteries: Lithium Iron NOT LiBcx
- No moving parts, power on board.
- Spam Grobs- Control through window in JEM on ISS with a laptop

JEM Airlock JOTI IVA Operations

Internal Vehicle Activity



JEM Airlock JOTI EVR Operations



Figures: Deployment of ISS JOTI Technology Demonstrator

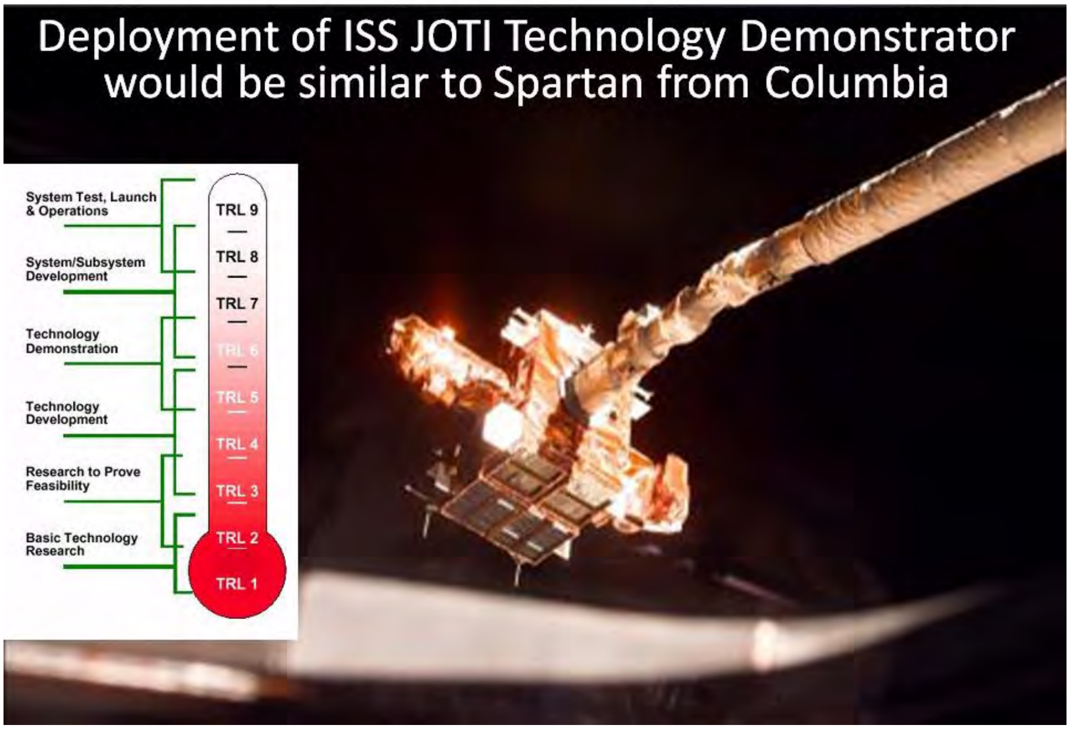


Figure: Deployment of ISS JOTI Technology Demonstrator would be similar to Spartan from Columbia. Image credit NASA.

Step 3 would be a cubesat telescope:

- Purpose:
- 7U cubesat <20kg 400mm aperture imager.
  Parasitic (secondary) payload on a vehicle to LEO
- Limited pointing
- Multi cubesats: ESA Special orbits for Intensity interferometry-Later in mission briefing
  - tech demo mission to get to **TRL 9** science- (Space demonstration)

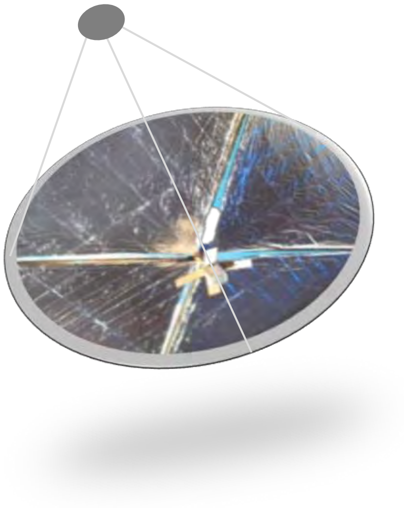


Figure: 7U cubesat pathfinder 40 cm aperture

This could be deployed from JEMRMS if modified for 7U or it could be deployed from a different vehicle.

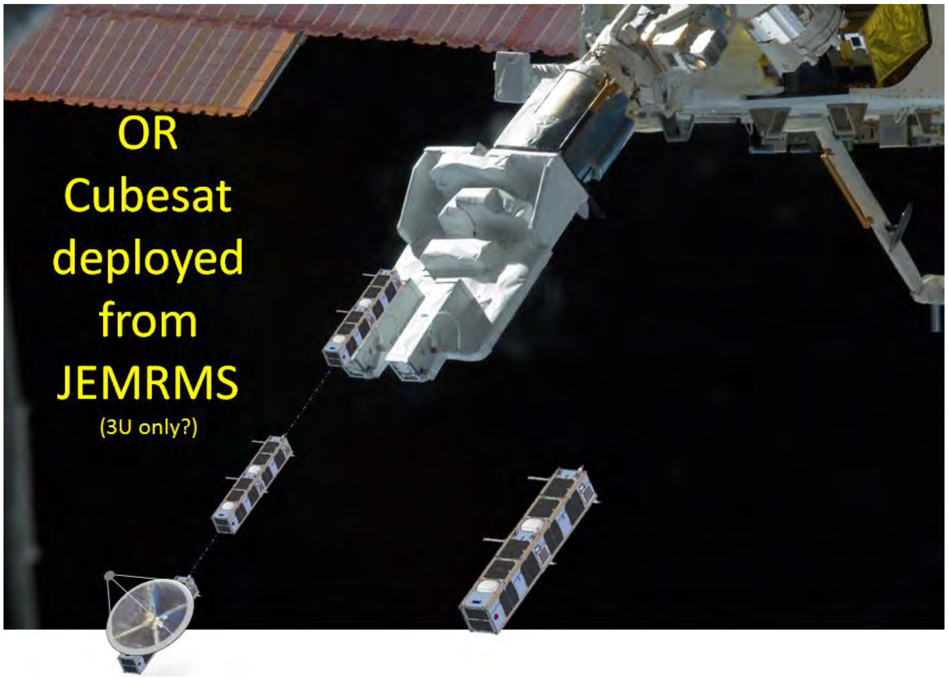


Figure: Deployment of a 3U to 7U cubesat

Once the technology was demonstrated in space we would scale up to a Hubble size telescope mirror (2.4 meter diameter) . This would be an off axis mini-Hubble with a simple imager as a proof of concept.

- Purpose:
  - Spectropolarimetry Science mission
  - Exoplanet atmospheres
  - New Horizons?
- A Hubble size aperture (2.4m) science mission
- 1 metric ton or less to LEO

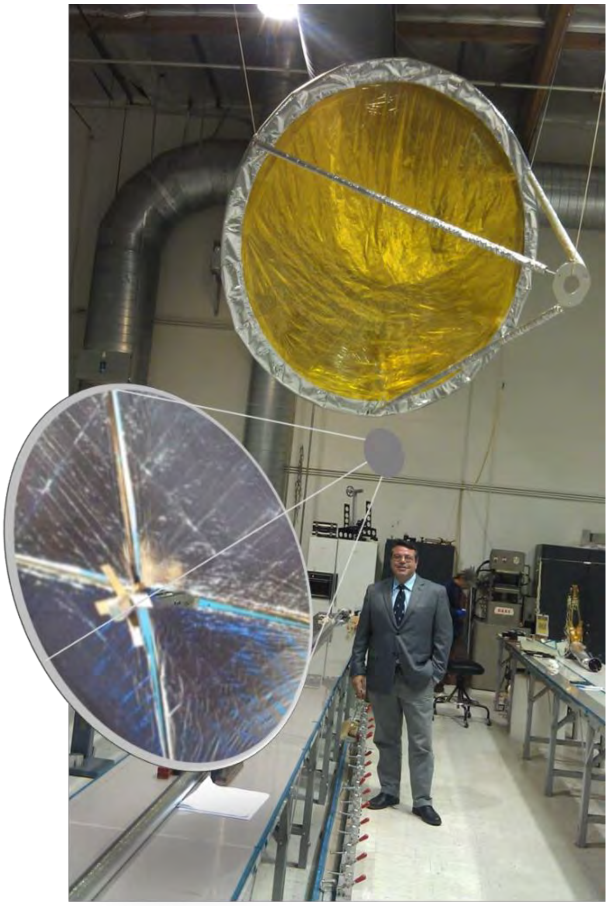


Figure: Left: OCCAM notional telescope, Right:Inflatable Radio technology this size exists.

A combination of the OCCAMS technology with existing technology would make this technology demonstration mission affordable and low risk. Here the PI is seen under an inflatable radio telescope (Courtesy LaGarde).

This would of course be off axis as this is no more difficult for the OCCAM technology, and lower diffraction is preferred. This mission we call Exosat-H1

- **2.4m dedicated telescope**

for dynamic range: polarimetric/coronographic , heterodyne studies

- **Optical design:** off-axis, cassegrain focus instruments
- **Instruments**
  - **Spectrograph/Imager:**

Solar system planets

  - **Spectropolarimeter:** exoplanets, stellar magnetic fields
  - **Heterodyne Spectrometer** R=$10^{6,}$ exoplanet atmospheres

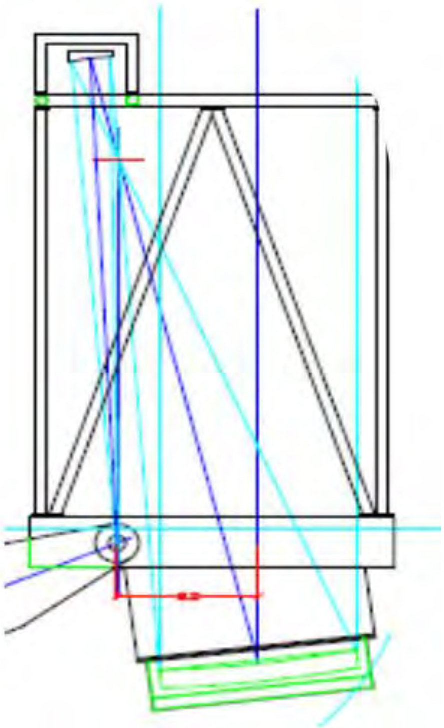


Figure: this first concept is borrowed from Kuhn et al and modeled on the SOLARC off axis telescope and image.

What would the best launch vehicle be? Alsthough the membrane mirror would weigh no more than a pound, we estimate 1 Metric ton to protect a 200Kg Satellite. We would hope to hitch a ride where this is not critical path for main mission (e.g. LCROSS on LRO).

The big brother to this mission, the 20 meter ExoSat-A is developed in some detail the next section as our notional NIAC mission architecture required and planned under Phase II.

Step 6 Sparse Aperture beam combining Amplitude interferometry demo:

- Purpose:
  - Phased interferometer
  - Diffraction limited at 0.5μ
- 2x2m aperture interferometric imager- Like DARWIN TPS less expensive

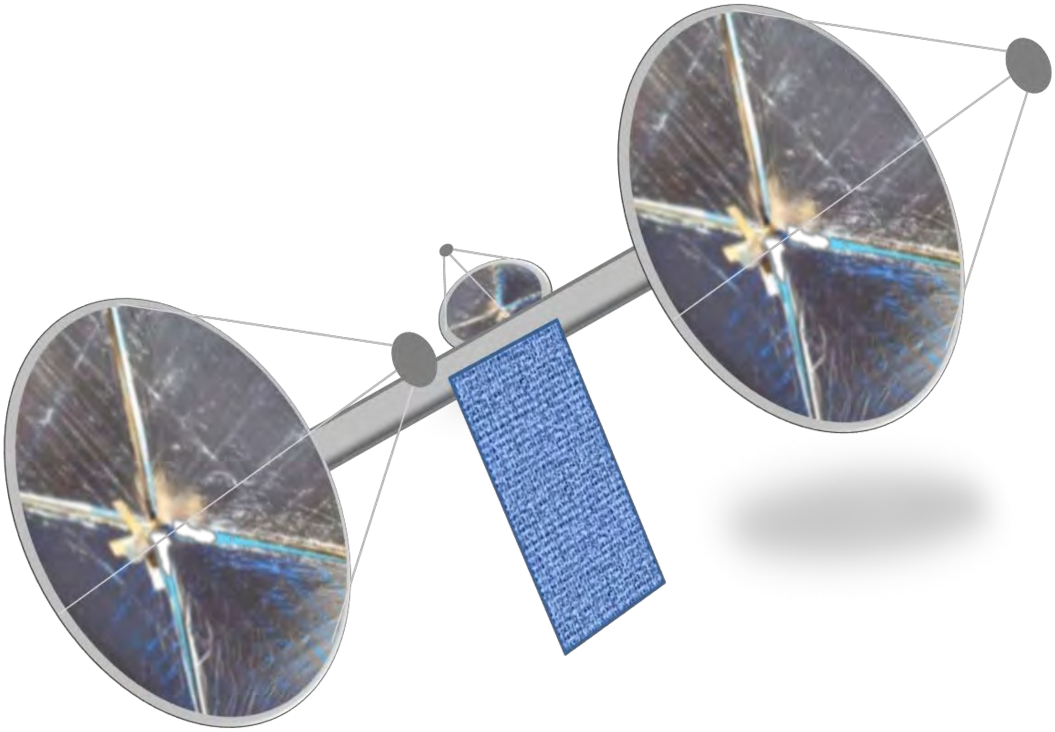


Figure: Mission 6 OCCAM Space Interferometry 2x2

When the OCCAM technology has progressed to this point, the 20 meter off axis EXOSAT-A Lifefinder mission discussed in greater detail at the end of this report would be desirable.

We have discussed a notional mission with NIAC for an 80 meter space telescope. For now it will suffice to transition to actual baseline mission planning. The goal is to make space telescopes with no more mass than the Hubble, with 10000x the collecting area.

The goal here is to change the possible, the NIAC Mantra.

Mission Architecture Concept Document *Exosat-A* Life Finder

Mission Architecture Summary

At least 1/3 stars have terrestrial planets. Solar system analogues of all planets down to Mercury can be resolved as far from the Earth as 25 light years with a 20 meter telescope. OCCAM EXOSAT-A is a science mission. It is intended to answer the question; ***"Does life exist within 25 light years from Earth?"***

HST has been NASA's most amazing astrophysics mission. However, it was ill equipped to find life. This is not a criticism, it simply does not have the capabilities described here.

The proposed mission makes use of OCCAM technology to make EXOSAT-A's unique capabilities of light weight large off axis apertures to answer questions about atmospheric composition. This will dramatically improve our knowledge on exoplanetary atmospheres, of which we know now no more than a dozen.

OCCAM EXOSAT-A is a 20 meter class infrared (IR) telescope designed to find exosolar life by spectroscopically determining exoplanet atmosphere composition. The mission promises to reveal much details of stellar and planetary atmospheres, circumstellar environments, and other non-solar system atmospheres.

The OCCAM EXOSAT-A observatory will be an infrared space observatory optimized for detection of exosolar life signatures located at the second Sun-Earth Lagrange Point (L2). Capturing the full cost, mass and instrument requirements is beyond the scope of this document nevertheless the system, mission and principles will be described as promised in the NIAC contract.

SCIENCE MISSION GOALS

Very simply the mission goal is to characterize exoplanet atmospheres to search for life signatures. Targets will be from the Kepler list and new targets where we avoid high zodiacal light regions. Only OCCAM EXOSAT-A via off axis optics, vector coronagraphy and high resolution spectropolarimetry can reject enough unpolarized signal to answer this fundamental question. Let us keep in mind, the key to this mission is the light large OCCAM mirror.

The primary users of OCCAM EXOSAT-A will be scientists, and their interactions with OCCAM EXOSAT-A operations will follow other space-based, facility-class astronomy missions, such as HST, and JWST.

A Mission:
To focus on delivering optical **performance** while balancing novel design attributes with probability of success using reasonable resources, a firm target time to completion, and an overall cost far lower than previously imagined.

Performance:
Performance will be defined by the compelling big question: Is there life out there?

OCCAM EXOSAT-A will be

- The highest resolution IR imaging telescope ever
- The highest resolution, most sensitive imaging, spectro-polarimetric telescope for bright star circumstellar neighborhoods

Design features include

- Extrasolar Planets Spectroscopic measuring tool
- Thermodynamic Optical SETI device
- Highest imaging angular resolution noninterferometric telescope ever made
- Lowest possible scattered light for coronagraphy and polarimetry
- Relatively bright central objects are OK
- Small field-of-view- this is not a survey telescope, it is a life finder.

The observatory is a 20 meter class infrared (IR) telescope designed to find exosolar life by spectroscopically determining exoplanet atmosphere composition. A scientific successor to the JWST, OCCAM EXOSAT-A will be used by international teams of astronomers to conduct a high resolution survey of exo-atmospheres in the wavelength range 5-25 μm. Potential life signatures such as atmospheric biosignature gases. Examples could be some metabolic byproducts that can dissipate in the atmosphere and accumulate locally to allow detection, bacteria products like carbon dioxide and methane, variable methane combined with oxygen, plant products like ozone and oxygen simultaneous detection of O_3 and H_2O in the outer part of the habitable zone of a star, and many other proposed signatures could be examined.

Though of great interest, detection signatures are not the point of discussion here, they are however the idea behind the mission. In order to measure these signatures this mission will exploit natural phenomena that polarize photons that interact with exoplanets. High dynamic range ultra resolution spectropolarimetry with a large off axis photon collector will increase signal to noise to the point where we will be able to determine exoplanet atmosphere chemical composition.

The 20 meter diameter 310 m^2 OCCAM EXOSAT-A primary mirror will deliver near diffraction limited images (0.1″ at 3 to 25 μm) to 2 instruments capable of wide-field imaging in IR and high resolution ($R>10^6$) Heterodyne spectroscopy in narrow bands coupled with coronagraphic spectro polarimetry over the wavelength range 5-25 μm. A superresolution spectropolariastrometric capability this mission will be discussed in future documents.

This document is an exercise in mission planning not in any way a full mission plan and describes one possible life finding operations concept for the OCCAM EXOSAT-A mission.
The mission concept is tailored to the primary science mission of finding life.

The uses of OCCAM EXOSAT-A are expected to extend well beyond this mission.
OCCAM EXOSAT-A will be instrumented with:

- Wide field Infrared Camera (WFIRCam) - Providing wide-field medium band imaging from 2-5 μm.

- Mid-Infrared Coronagraphic Heterodyne Spectropolarimeter (MICHS) - a combination coronagraphic heterodyne spectrometer and full stokes polarimeter R=1 million spectrograph for select narrow molecular bands of interest in the wavelength range 5-25 µm.
- Membrane Control System Imager and Commander (MCSIC) – a device located at the primary center of curvature for primary mirror shape control.
- Pushing the envelope polarimetry, coronagraphy and off axis low diffraction high dynamic range performance.

This suite promises to reveal much more about stellar and planetary atmospheres, circumstellar environments, and other non-solar system atmospheres.

Overview OF THE OCCAM EXOSAT-A SPACE TELESCOPE

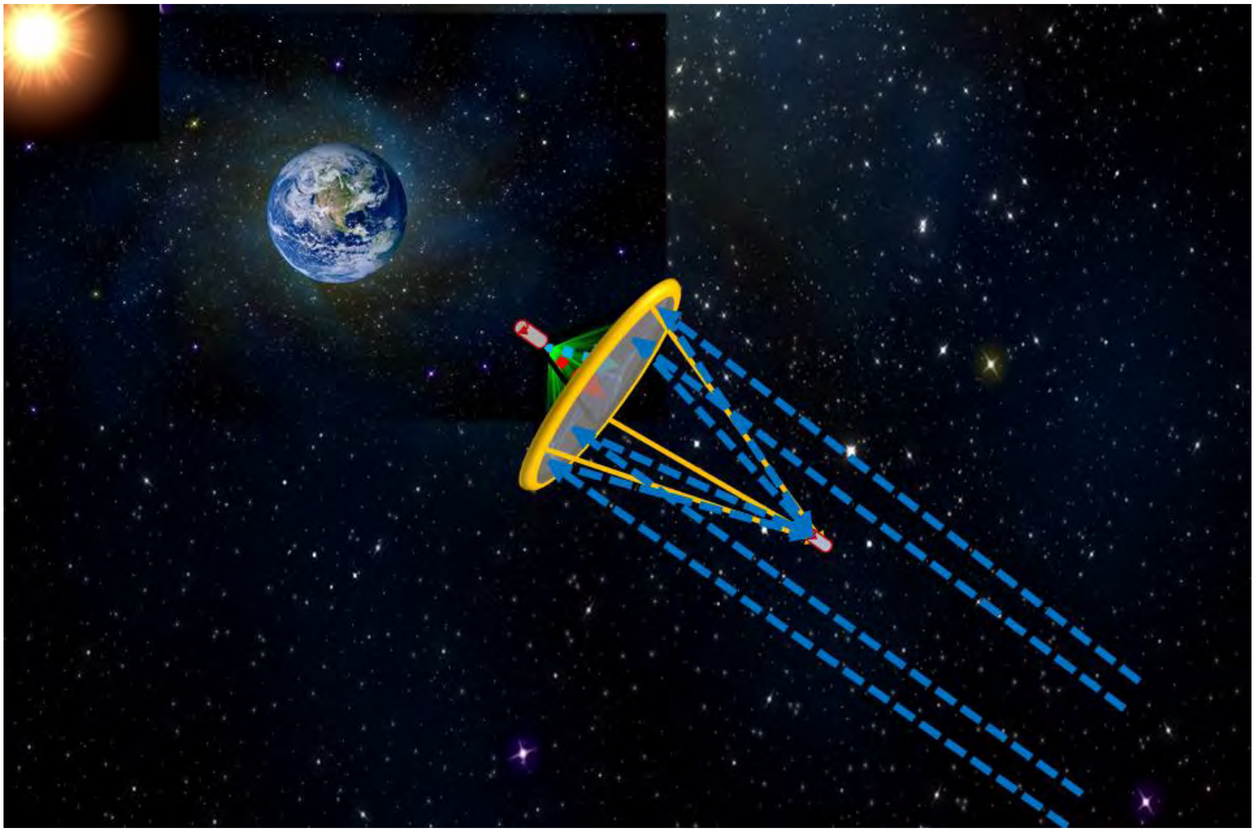


Figure: Exosat-A at Earth Sun L2

This mission is about finding life on exoplanets. Depending on star size and type, planet type and size, planet orbit, and wavelength of interest, parent stars can be 10^6 to 10^{10} brighter than exoplanet targets. At a 20 meter size even the closest stars still will not be resolved and many planets will be in the same pixel as a star. What is needed is a way to look at light from these planets without a small signal being swamped out by the stellar signal. This suggests we should use an off axis primary which has no secondary mirror support spider diffracting light in the entrance aperture. This is dramatically shown below.

Figure: A spider support holding a secondary mirror and the resulting spider diffraction.

What is required to extract a tiny life signal from the enormous fusion peak signal in our neighborhood is a high dynamic range high resolution spectropolarimetry system with exquisite noise rejection.

Polarization

There are many natural phenomena that polarize photons that interact with exoplanets. Atmospheric emission can contain polarization signals: optical pumping, near 90 degree scattering, polarized scattering both from atmospheres and surfaces all can polarize light whereas most star light will be randomly polarized with the exception of some magnetic features and limb polarization effects. Methods of polarization include Rayleigh and Thompson scattering as well as grazing incidence reflections. Kuhn et al have discussed how optical pumping can pump electrons bound within an atom or molecule to a well-defined quantum state. For the simplest case of coherent two-level optical pumping of an atomic species containing a single outer-shell electron the electron is coherently pumped to a single hyperfine sublevel which is defined by the polarization of the pump photons and the quantum selection rules. There are natural phenomena that do this. This mission will exploit natural phenomena that polarize photons that interact with exoplanets.

As it is known that there are many polarizing phenomena we shall exploit them. We therefore borrow a technique related to differential polarimetry well known to chemists as polarization modulation infrared reflection absorption spectroscopy (PMIRAAS). This technique allows small amounts of organic matter to be analyzed by exploiting grazing incidence polarization effects that arise due to electromagnetic boundary conditions in grazing configuration. Similarly the EXOSAT-A will use orthogonal subtraction of differential polarimetry signals to remove randomly polarized light and present a spectrometer with polarized light. One difference here is that the enhanced polarization signal direction is not known *a priori* so a full stokes polarimetry set must be taken. In this way we can drastically increase S/N ratio (essentially planet light/(diffracted + sunlight + instrument scatter etc.) at the expense of utilizing polarimetry at the 10^{-6} level which is now possible. Heterodyne spectroscopy is known and recent advances in cascade laser power and cavity stability control have also increased S/N ratio with such devices. The merger of such techniques will soon be realized by the next generation of interdisciplinary

Physicists. The merger of these techniques will allow exoplanet atmosphere determination even from the surface of the Earth and will be a subject of a future NIAC proposal.

Coronagraphy

Stellar coronagraphy (via a vector vortex coronagraph) will further suppress stellar signals by approximately 10^6. Because of extreme distance, a spatially coherent plane wave is presented from stars on axis. A vectorial vortex is implemented here by using a steering mirror coupled to a rotationally symmetric half wave plate providing a geometrical phase shift that applies opposite phase screws to the two orthogonal circular polarization states. After propagation from a focal plane to pupil plane, the Fourier transform of the product of the PSF by an azimuthal phase ramp sends the light outside the original pupil area. In this way the star can be occulted, improving S/N of off axis objects (planets). Details such as LCVRs for polarization conversion for wave plate processing and static wave plates with analyzers and for polarimetry are implicit.

Once data has been selected as stellar occulted and polarized in nature and therefore likely a state produced by a physical source such as pumping or scattering, these photons will be combined with a cascade laser beam to perform ultra resolution heterodyne demodulation spectroscopy. The resultant spectra from the exoplanet (or other target) will be used to look for life signatures.
Clearly other data products are possible for example, determination of ocean size or planet spin rate by temporal modulation of the polarization signal.

In 2010 JPL demonstrated that a vector vortex coronagraph could enable telescopes to image exoplanets, so the vector coronagraph is integral to both MICHS and to WFIRCam. The LCVR's can be configured to turn of the coronagraphic mode.

A telescope with a shaded monolithic 20 m off axis primary mirror will deliver IR light to the three main scientific instruments of the Observatory detailed in the SIM section.

In addition, a High Resolution Guidance Sensor System (HRGSS) used to provide fine pointing updates to the Observatory, will use narrow band imaging in the NIR for star tracking and attitude determination. HRGSS, will be instrumented with a large format IR array detector and MICHS will use a small format 16x16 IR avalanche photodiode array with variable band sensitivity as a function of array position. Detectors will be kept cold to minimize internal dark current. A sun shield will be deployed to keep the spacecraft from direct solar illumination.

Elements of the Spacecraft include:

- A deployable membrane primary optical telescope, including a membrane control system, secondary mirror and fine steering mirror
- A Science Instrument Module (SIM) housing the imaging and Spectropolarimetry science instruments and the HRGSS tracker
- A spacecraft which provides data relay/telemetry power and telescope services
- A sunshield to shade the observatory, optical telescope assembly and spacecraft bus

Mechanical features include:

- Mirrors
  - OCCAM Photonic mirror hybrid active control primary and tertiary mirrors
  - Elimination of mirror grinding polishing and classic actuation
  - Low mass mirror module
- Mechanical
  - Hybrid (low mass) active optical mirror support structure
  - Low mass mirror and cell Low mass and effective wind screen enclosure
- COTS Spacecraft bus and launch vehicle.
- COTS CD&H, ACS and RCS

Mission Architecture Operation Phases

The OCCAM EXOSAT-A Mission will be divided into 6 operational phases: Pre-launch, Launch, Deployment and Trajectory Correction, Cruise and Commissioning, and Normal Operations.

1. The “Pre-launch” phase will require integration of the EXOSAT payload with the launch vehicle, functional testing and checkout of the spacecraft bus at the launch site, and ends with the launch OCCAM EXOSAT-A.

2. The “Launch” phase includes liftoff, stabilization using thrusters and rough course correction to a trajectory to L2.

3. The “Trajectory Correction” phase will use thrusters for 3 axis attitude stabilization the payload fairing will be jettisoned; communications will be established, and the OCCAM EXOSAT-A propulsion system will be activated. Fairing will be jettisoned and final maneuvering thrusts will occur to place spacecraft in desired orbit.

4. Deployment phase will include sunshield deployment, and mirror then deployment of the solar arrays, the high gain antenna for Ka band, and any required trajectory correction maneuvers. Full communications will be established and the bus will be 3 axis stabilized prior to reaction wheel spin up. Reaction attitude control will be established using the High Resolution Guidance Sensor System (HRGSS) used to provide fine pointing updates to the bus, the loop will be closed and Observatory Reaction Control System (RCS) will be verified.

5. Mirror deployment and correction phase initiate. Prior to mirror shape control initiation the observatory will be placed in an antisun look direction. The shape membrane mirror will be heated and deployed to its nominal uncorrected near paraboloid shape. At this point the Membrane Control System Imager and Commander (MCSIC) will initiate imaging and the control system will close the loop.

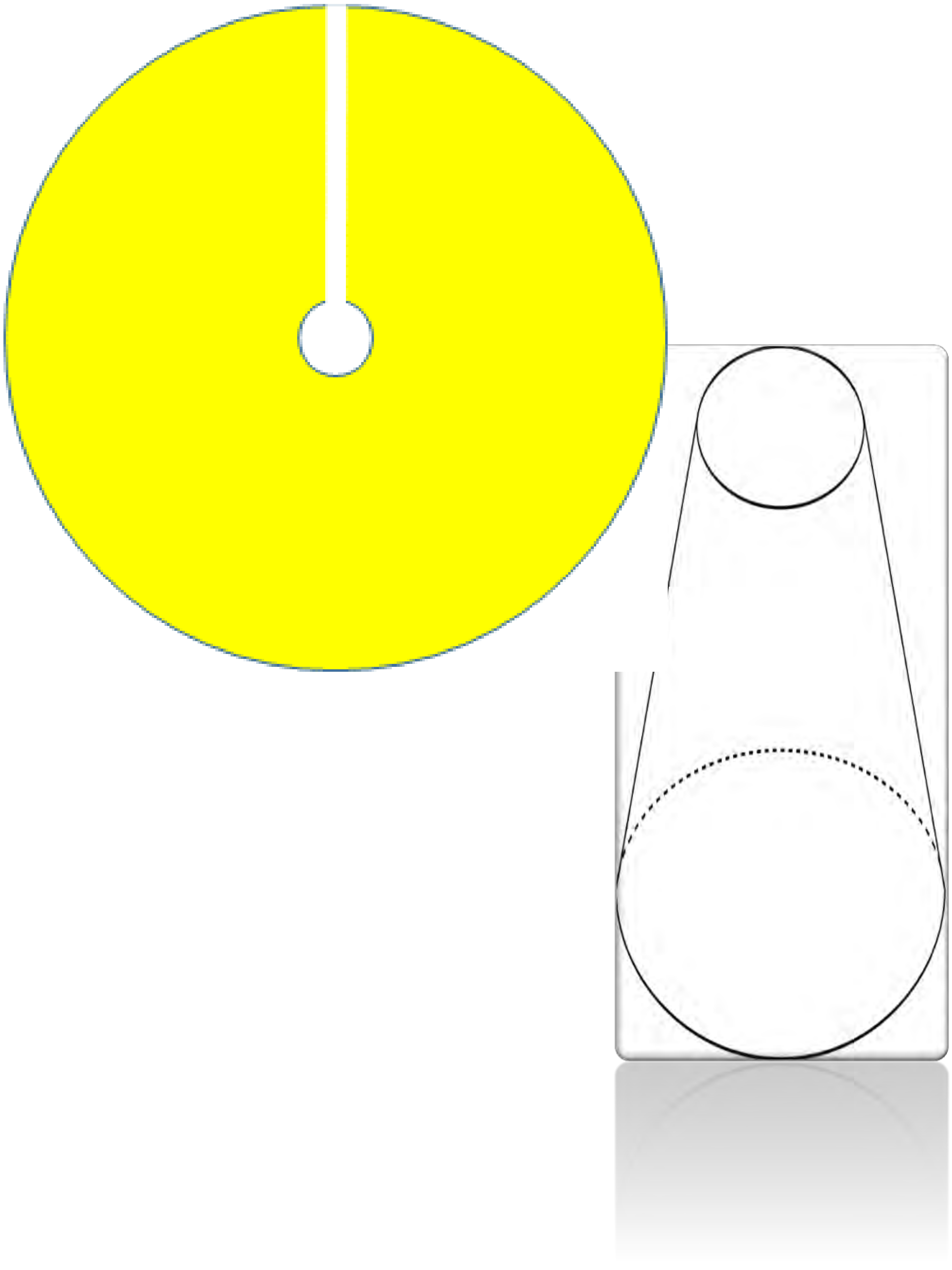
6. The data acquisition and relay part of the mission will then commence.

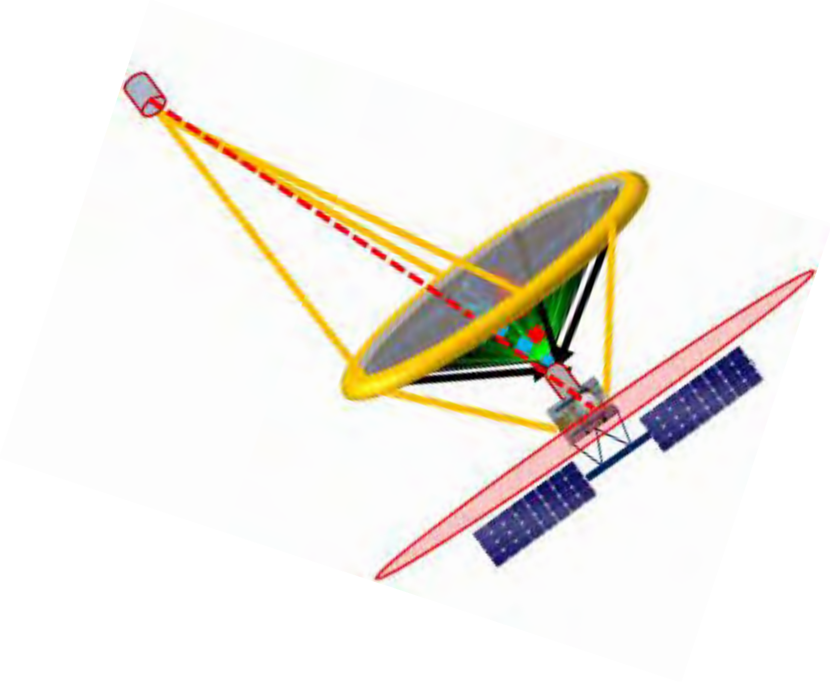
The Telescope And Spacecraft

The Observatory is defined to be the components of OCCAM EXOSAT-A which will reside at L2 during normal operations. The OCCAM EXOSAT-A Observatory consists of three elements, the Optical Telescope Element (OTE), the Spacecraft Element the spacecraft bus includes power and com antennae and sunshield, and the Science Instrument Module (SIM) Element, which includes the instruments and associated electronics.

Conceptual Design of Deployment and Beam Path:

M1is a paraboloid with a hole cut in the middle and rolled up into a frustum:





Figures: M1 slit, rolled and fully deployed

M1 is also a shape memory polymer and as such is simply deployed to a near net shape paraboloid by heating. M1 is off axis and the beam propagates from M2 (secondary) through the hole in the middle of M1to a steering mirror on the science instrument module (SIM). The sun shield is shown in red.

The Science Instrument Module

Science Instrument Module (SIM) has a data and power bus and structure that contain the imaging and Spectropolarimetry science instruments and the HRGSS tracker and provides command and data handling for the science instruments and the HRGSS.

The SIM contains the science instruments, the High Resolution Guidance Sensor Systems, their supporting structure and thermal support systems, their control electronics, and the SIM command and data handling system (IC&DH). SIM Structure is reinforced carbon carbon (RCC) for high specific stiffness with low thermal expansion coefficient. It is essentially rayon cloth graphitized and impregnated with a phenolic resin. It forms a stiff structure with modal design of no modes lower than 100 Hz to assure launch survival.

Pushing the envelope polarimetry, coronagraphy and off axis low diffraction high dynamic range performance OCCAM EXOSAT-A will be instrumented with:

Membrane Control System Imager and Commander (MCSIC)
This is an imaging device located at the primary center of curvature for primary mirror shape control. Currently a 16k lenslet hexagonal array Shack Hartman sensor is planned. The Commander part of the system consists of a polarization and power modulated laser beam with a scanning control system. This is the photonic muscle active mirror control system.

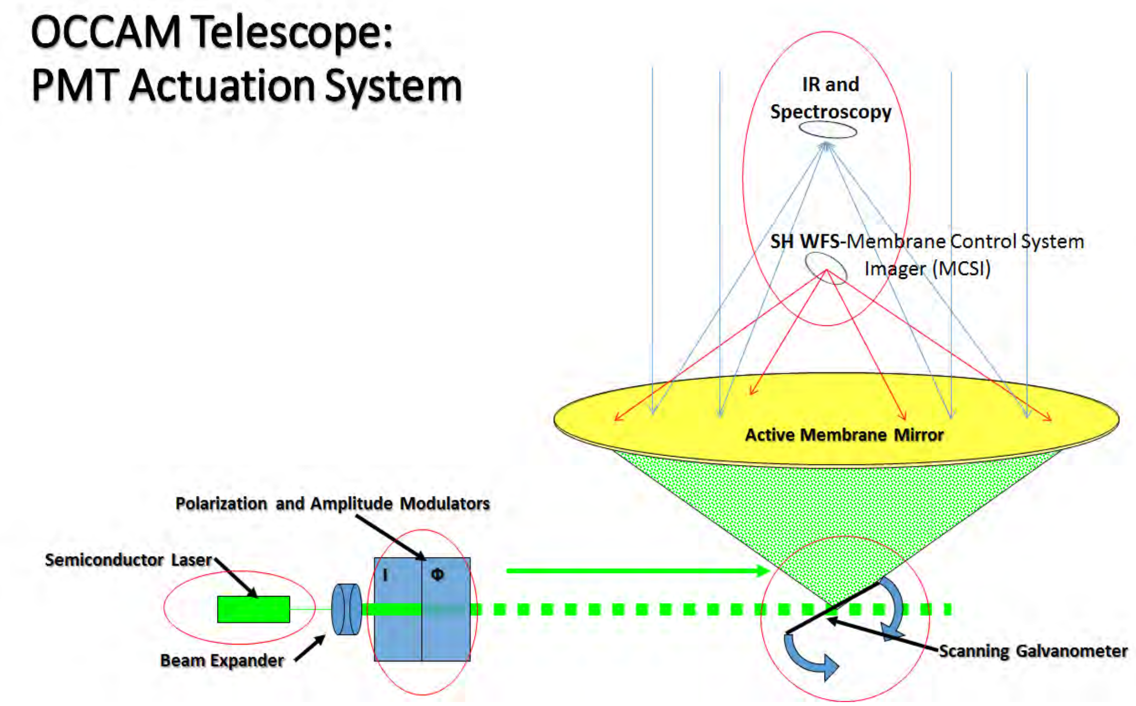


Figure: This illustrates the geometry of MCSIC. The above diagram is generic and the actual spacecraft OTA will have an off axis paraboloid primary mirror.

Mid-Infrared Coronagraphic Heterodyne Spectropolarimeter (MICHS)

This is a combination coronagraphic heterodyne spectrometer and full stokes polarimeter R=1 million spectrograph for select narrow molecular bands of interest in the wavelength range 5-25 μm. This instrument is tunable due to advances in cascade laser tuning. R=1 million spectrograph for selected bands in the wavelength range 5-25 μm.

The Mid-Infrared Coronagraphic Heterodyne Spectrometer (MICHS) on OCCAM EXOSAT-A provides imaging and spectroscopic measurements over the wavelength range 5-25 μm. R= 10^6. MICHS is passively cooled. Heterodyning is accomplished with quantum cascade lasers. The detector array is a 4x4 Mer cad tel optimized for the 5-25 micron wavelength band. Demodulation occurs using a 1MHz 10 GHz bandwidth spectrum analyzer for the demodulated RF signal.

MICHS will contain an internal calibration blackbody illuminating an integrating sphere then illuminating the pupil plane of the spectrograph with appropriate f/# matching. Sub-pixel dithering by the steering mirror will provide a higher resolution, enabling post-observation processing to obtain higher angular resolution.

Wide **F**ield Infra**R**red Camera (WFIRCam)

Providing wide-field medium band imaging from 2-5 μm. The reason for these choices are as follows: WFIR will allow imaging through intergalactic dust of interest to a majority of the astronomical community. MICHS will allow differential polarimetry to reject sunlight and allow spectroscopy of exoplanet atmospheres (to find life or ascertain lack thereof). MCSIC is simply a shape control instrument for the active primary.

Reasons for devices like WFIR are clear from many other missions and will not be detailed here. MICHS on the other hand is unique, and no such instrument exists on Earth even (yet) although all of the individual components are under development. A detailed S/N tradeoff could be performed but will not be attempted here. Future detector selection would require that trade.

High radiation environment will require multiple exposures with pointing dithering to remove both random and systematic signals in imaging detectors. The spectropolarimetric array will have fewer pixels, and will be used in a differential mode to remove background.

The High Resolution Guidance Sensor System (HRGSS)
HGRSS subsystem is essentially a small field of view star tracker used to adjust the fine guiding mirror to compensate for spacecraft motion during long exposures or image stacking. Necessarily the optical axis is nearly parallel with the Observatory primary mirror axis.

No attempt is made here to define the Science & Operations Center or any Flight Software with the exception of the section shape convergence for the OCCAM primary.

Science Electronics

Science Command and Data Handling (ICDH) will provide the basic command and telemetry routing and processing functions for the science instruments. It will have computer 1 for scheduling preprogrammed event processing for target queues which will always be uploaded, never computed on board.

Computer 2 on the same bus will command instruments and manage scripts. It will communicate with the pointing system and request slews. It will read science data, perform compression and pass data to the solid state recorder and the Ka band transmitter. It will also speak to individual instrument control computers and housekeeping sensors. Interconnects have not been determined and are beyond the scope of this exercise.

SIM Thermal Architecture

The SIM has a hierarchy of components. The Sun shield can reach over 500C the OCCAM primary and bus itself will be kept under -100C the cold portion of the SIM containing MICHS is passively cooled cryogenic (70 K) structure.

The Secondary Thermal Control Subsystem (STCS), will be a passive radiation system designed to maintain <100K spacecraft thermal requirements at L2. The spacecraft bus will be continuously illuminated by the Sun but the OTA will be shielded. A cryocooler inside the spacecraft provides cooling for MICHS.

Vehicle and Bus

An Atlas 5 – 551 can deliver 6 Metric tons to ES L2. A cost effective approach will be to decompose a Boeing 702 satellite onto a payload adapter fitting. This will use the Boeing LMK (launch mission kit) – 702 bus (GEONSYNCH SAT LINE) open box and put pieces on Payload adapter fitting for Atlas 5 (Cylindrical truss – semi conical). Similarly the propellant avionics etc. all around PAF decomposed and put on an Atlas 5

We take this example as possible as for ISS Node 1 NASA used 702 bus and G&C RCS and power came from that existing bus.

The spacecraft bus provides power, propulsion for orbit insertion and maintenance and momentum unloading, attitude control, command and data handling (C&DH), and communications services.

The Atlas 5- 551 will provide OCCAM EXOSAT-A a direct transfer to the L2 orbit.

Figure: Atlas 551-5 image from United Launch Alliance

Observatory Stowed in PLF Fairing

The rolled geometry of M1 requires that for a 20 meter diameter mirror we need a 10 meter tall payload launch fairing. Thus the 551-L fairing is selected:

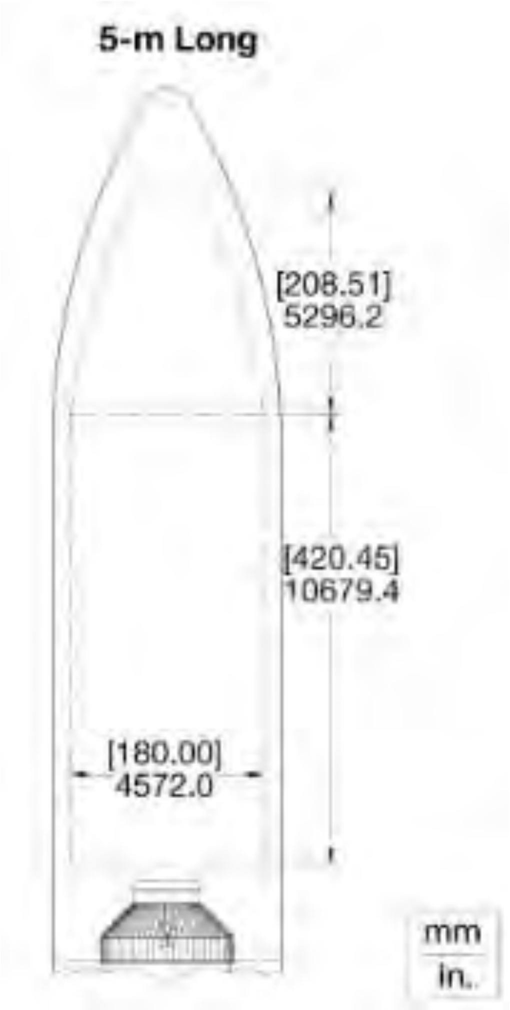


Figure: 551-5 long fairing from United Launch Alliance

The following diagram shows how we would stow the ExoSat-A:

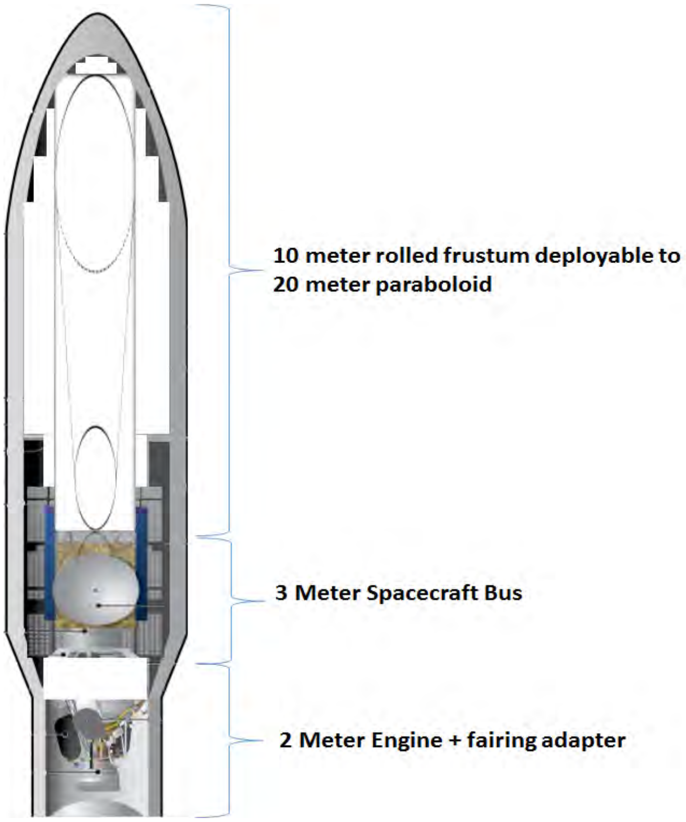


Figure: ExoSat-A in launch configuration

The novel OCCAM photonic muscle shape memory polymer allows deployment with no moving parts. The fabrication and deployment sequence are depicted below:

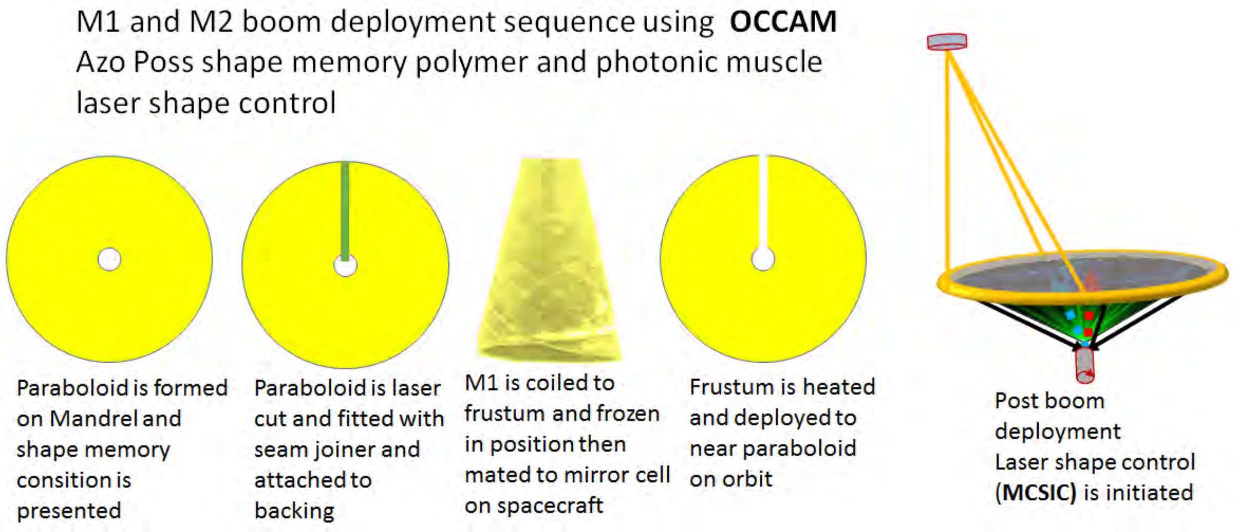


Figure: Shape Memory polymer is used to deploy a 20 meter telescope from a 5.4 meter diameter fairing. M1 is coiled like an ice cream cone, care is taken not to exceed micro strain of material when rolling.

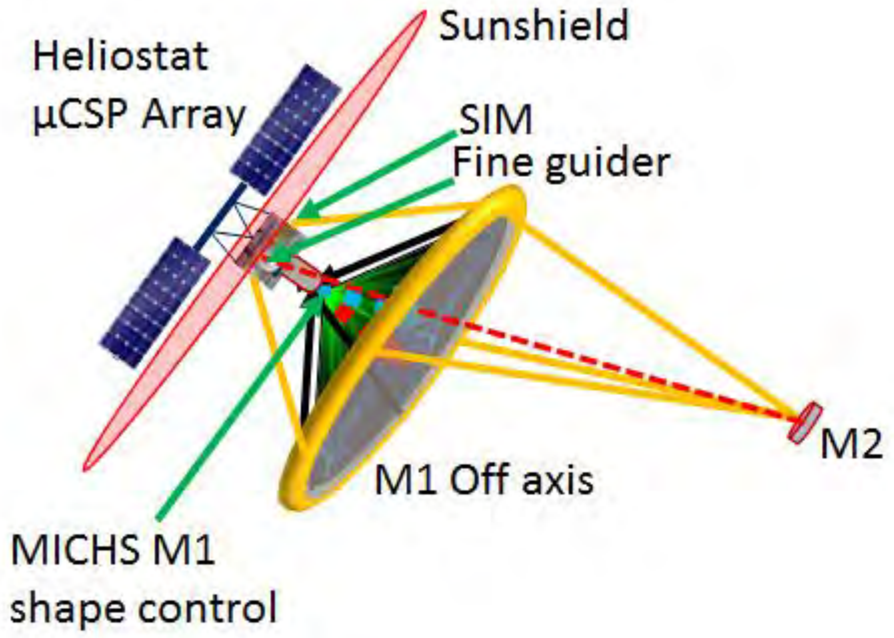


Figure: Notional Exosat-A with off axis paraboloid M1 sunshield and heliostat array deployed

A plasma ram effect may require an ion or electron emission system to maintain spacecraft neutrality. A further detailed study of the orbit and expected energy and number distributions will be required prior to a full shielding design. That is not the point of this mission design exercise and these parameters are known. See section on L2 Hazard environment for more on radiation and ambient plasma.

Optical Telescope Element (OTE)

The OTE will be a deployable off axis primary three-mirror anastigmat + fold and steering mirror with a 20 meter aperture that collects light equivalent to a 300 m^2 (due to the hole cutout at the center). The OTE will provide diffraction-limited performance at 2 µm and a mechanical and optical interface to the SIM. The mass is 30Kg for the polymer membrane and the mirror cell is 55Kg. The mirror shape control system is 5Kg. **The net areal density for M1 here is 0.3Kg/m^2.**

The OTE will consist of a Primary Mirror, Secondary Mirror, Tertiary Mirror and Fine Steering Mirror. The Primary Mirror (M1) has a single membrane mounted on an unrolling which has an alignment servo to be adjusted to achieve optical performance by the mirror control system.

The Secondary Mirror (M2) will be mounted off axis with a hexapod for tip tilt and piston optical alignment. This will be most helpful for on orbit realignment due to the nature of off axis aberrations. The tertiary mirror (M3) will be OCCAM technology to perform a woofer tweeter wavefront correction which in the event of the failure of either OCCAM system the other can take over to provide a level of wavefront correction.

M4 is a fine guiding mirror interface to the HRGSS for steering images for long exposures.

Optical performance

FOV: 5 arc sec
Incoherent photometric observing depth: K' < 24 mag
Diffraction limit resolution =.007 milliarcsec
Polarimetric rejection 10^5
Coronagraphic rejection 10^6

Sunshield (SS)

The sunshield is similar to the JWST sunshield with some enhancements.

At the IR wavelengths relevant to OCCAM EXOSAT-A spectroscopic vibration bands, the primary sources of background are zodiacal light and thermal radiation from the spacecraft itself. The effects of thermal radiation must be smaller than the effects of zodiacal light so the telescope must stay cool (<100 K). This requirement is another reason for not choosing an Earth orbit for OCCAM EXOSAT-A, since radiation from the Earth itself would warm the spacecraft.

The sunshield will be a stacked high emissivity chromium POSS hybrid. The sunshield will provide a 50% celestial field that will allow scheduling flexibility with minimal orbit station keeping. It will utilize shape memory polymer actuators for deployment.

The sunshield size determines look direction which determines slewing and target availability. The region of sky that EXOSAT-A may look within is fixed with respect to the Sun telescope line and will keep the OCCAM primary mirror shaded at all times. This is required both to prevent thermal optical aberrations as well as to prevent unintended optical muscle action from direct sunlight.

The OCCAM EXOSAT-A spacecraft bus is off the shelf COTS. It will use a preexisting Boeing LMK (launch mission kit) – 702 bus (GEONSYNCH SAT LINE) Open box and put pieces on Payload adapter fitting for Atlas 5 (Cylindrical truss – semi conical) G&C RCS and power will all come from the 702. There is no need to redesign the wheel.

A monopropellant hydrazine propulsion subsystem pressurized with helium and mounted to the spacecraft bus will be used. It will consist of three 5 pound opposing dual thruster modules on orthogonal axes 3axis control. Its purpose will be to correct launch vehicle orbit insertion errors, to keep OCCAM EXOSAT-A at L2, and to unload reaction wheel momentum. The Propulsion Subsystem will be a simple blowdown monopropellant system. Location will be opposite the primary mirror to reduce contamination. Nominal burns are orthogonal to the sun line to save fuel.

Attitude Control System (ACS)

ACS includes reaction wheels for and gyros for coarse attitude control, and the HRGSS for imaging of guide stars to provide course correction. This error can also drive a steering mirror which in a woofer tweeter setup can dump accumulated error by offloading to reaction wheels. The resulting jitter must be less than half of the spatial resolution of the WFIRCAM.

The attitude control system (ACS) is linked to the high resolution fine guidance imager and will provide attitude determination and control and interfaces with the High Resolution Guidance Sensor System (HRGSS). This is all located in the SIM and the Fine Steering Mirror (FSM) is linked to the HRGSS for fine pointing control during long integration or stacked image observations.

The Attitude Control Subsystem (ACS) will use the HRGSS sensor to perform pointing, attitude determination and control and as feedback for slewing. The system will have reaction and interfaces to the High Resolution Guidance Sensor System and Fine Steering Mirror. There will be **12 reaction wheels arranged** in a dual pyramidal configuration. The reason for this is the number of failures seen in the last decade and mission terminations due to RCS failures. This is a small investment to make to ensure long life.

ACS will control bus slews in response to commands from the object queuing software or to repoint high gain antenna if ever required. Rates of 1 radian per hour will be the maximum slew.

A full star tracker design will not be analyzed here.

Planned momentum dumps will occur at the optimal attitude as calculated on the ground. Unplanned momentum dumps will occur at saturation.

The Electrical Power Subsystem (EPS) includes the Electrical Power management Unit (EPU), a solar array and a NiH_2 battery. The solar array will use micro concentrators and the latest quadruple junction arrays (>45% efficiency). The system will use a helium tube coupled to a paraffin wax radiator to cool the junctions. Arrays will be motorized on one axis to optimize available power

Communications

The communication subsystem architecture will provide two-way communications through all operational phases using S-band for command uplink and low-rate telemetry downlink, and Ka-band for high rate telemetry downlink. There will also be an Sband omnidirectional link with low bandwidth (<500bps) for new instruction upload in case satellite orientation is lost.

Science and engineering data are compressed, stored on a shielded solid-state recorder and transmitted via S & Ka-band communication links through the Deep Space Network (DSN). As this is not a real mission yet and detectors advance rapidly, data requirements will be determined by final science instrument configuration.

Spacecraft Command and Data Handling (C&DH)

C&DH subsystem consists of three main components: A Command and Telemetry Processor (CTP), the main computer on the spacecraft bus, and a solid state recorder. The data bus provide connectivity to all subsystems of the observatory.

The command and data handling subsystem is essentially a parallel bus will support command processing for the spacecraft bus, command routing to the science instruments, and telemetry routing to the communications system. This will be linked to all three bus computers.

A solid-state recorder will provide 0.1Terabits of engineering telemetry and 1Terabit of science telemetry imaging. The communications subsystem can support communications during observations and slews.

Observatory Orbit

The observatory will be located in an orbit near the second Lagrange Point, L2, approximately 1.5 million km from Earth. The telescope and instruments will be cold (~70K) allowing Stirling cooler usage rather than cryo expendables. A large sunshield made of POSS will be used

A quasi-periodic Lissajous orbit is selected for several reasons. Though not perfectly stable as a saddle point, minimal station keeping can allow a spacecraft to stay in a desired Lissajous orbit. L2 is selected allowing for an orbit where solar panels can be nearly continuously illuminated.

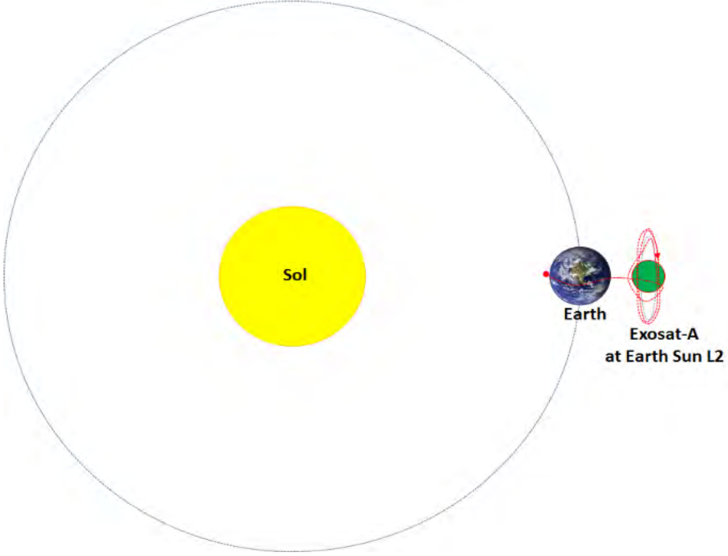


Figure: ExoSat-A location for Observatory operations

The system will be delivered to Earth Sun L2 orbit, delivered by an Atlas 5 – 551 (EELV) which can deliver 6.5 Metric tons to ES L2. This is a delivery system with a Payload Fairing diameter: 5.4m Diameter, 5 Solid Rocket Boosters and one RL-10A Engines on Centaur stage. It will carry a 5.5 metric ton payload for the spacecraft.

The primary mirror is a 20 meter Shape memory monolithic membrane rolled and stowed within the fairing of the Atlas rocket on which OCCAM EXOSAT-A will be launched and deployed on the way to L2.

Target selection will be determined by comparative assessment by Astrobiologists with emphasis on previously determined habitable zone candidates.

OCCAM EXOSAT-A will have three independent computers; one for operations, queuing, command and telemetry processing one for Science data preprocessing and compression prior to transmission and one for mirror shape subsystem control. A reconfigurable "plastic" data bus will connect to the com links. This plastic bus will allow a reallocation of computing resources should a computer failure occur, essentially a non-optimum but functional limp mode. Reprogramming 1 processor with another processors functions is akin to neural plasticity in human brains. This will allow a robust response to control system failures.

The Observatory will execute a preloaded queuing observation plan daily. Observations do not require a real time link. This will be a robot that dumps data periodically. Communication antenna pointing will not be addressed here but is anticipated during slews. Some optimization will be required and communications with the DSN will occur at regular preprogrammed times.

Orbit Determination and Control

Orbit determination tracking and ranging will be required to verify operation of on-board navigation systems, for planning maneuvers required to maintain orbit.

A combination of radar, corner cubes and Doppler information will assist in tracking.

L2 Environment

OCCAM EXOSAT-A will conduct normal operations after being placed in an orbit about the Sun-Earth L2 Lagrange point. The Sun-Earth L2 Lagrange point is located about 1.5 million km from Earth and OCCAM EXOSAT-A will orbit about this point at a distance between about 250,000 km and 800,000 km with a period of about 6 months. Although deployment is quite different, due to the similar orbit choice the launch trajectory and final orbit for OCCAM EXOSAT-A in this scenario are the same as JWST.

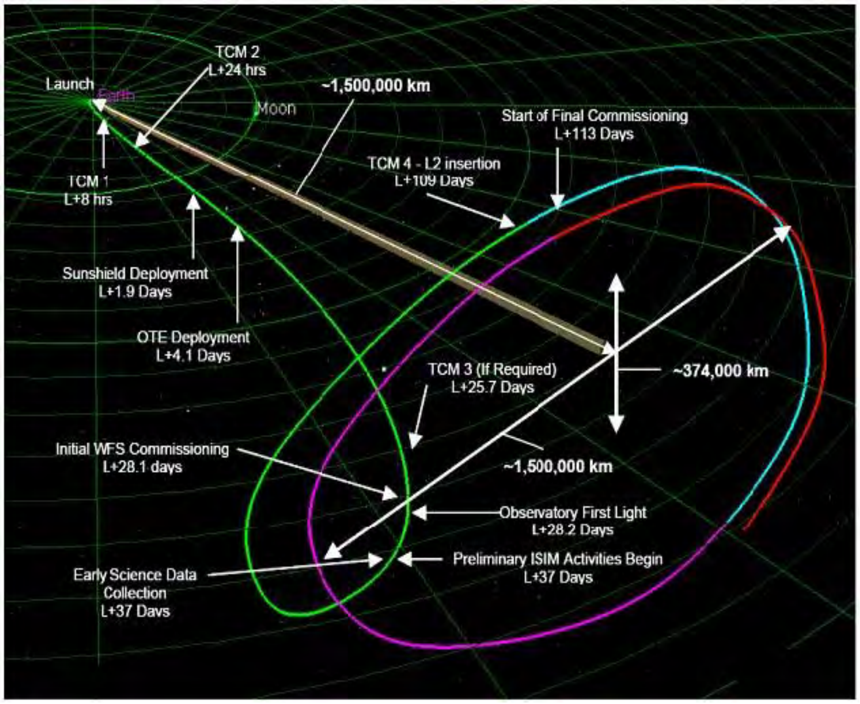


Figure: Launch Trajectory and Final Orbit for JWST at Sun-Earth Lagrange (L2) Orbit. From Sabelhaus, P.A., Decker, J., "An Overview of the James Webb Space Telescope (JWST) Project," SPIE, Vol. 5487, 2004.

There may be some trajectory differences due to the fact that ExoSat-A has lower mass and a different launch vehicle. The orbit and insertion scenarios for ES L2 are well known. The main disadvantage of this orbit is that L2 is at a saddle point in the gravitational potential. It is not a stable orbit and requires orbit maintenance, in the form of regular firings of on-board thrusters to maintain the Observatory at L2. Furthermore, to determine the proper thruster firings accurate knowledge of the orbit via ranging is required. A larger orbit minimizes the Delta-V requirements for orbit insertion and maintenance

One price for choosing L2 is that fuel is required for orbit maintenance at the potential well saddle. L2 is also useful for long integrations, especially at the ecliptic pole, communications are line of sight with Earth and DSN, there is continuous sunlight for solar power, and although a Jupiter radius orbit would reduce zodiacal light, L2 is cheaper (requires less delta-V) especially for a large orbit around L2. Lissajous orbits require less station keeping to maintain a stable libration point so we choose this to minimize station keeping fuel burns.

L2 Hazard Environment

Among the hazards to an OCCAM based mirror and spacecraft are solar radiation specifically UV breaking polymer bonds. This is a primary reason for our team's work developing a POSS based Azobenzene material. For other missions e.g. low Earth orbit, atomic oxygen is also a factor. Micro-meteoroids can also impact the mirror and spacecraft.

Galactic cosmic ray particles will affect imaging arrays as well as potentially risking logic upsets. An exposure strategy of short stacked exposures utilizing low read noise arrays combined with dithering will somewhat mitigate this effect. Not all energetic events can be mitigated so easily. There will be imaging system and communication system outages.

Figure: Earth Sun libration point 2

L2 includes the gravitational fields from the sun, Earth, Earth-moon and planets. It is well known that a spacecraft in an L2 orbit will be subject to the ambient plasma and ionizing radiation environments from the solar wind and the geomagnetic tail. Plasma, magnetic fields, energetic charged particles from the sun and magnetosphere, galactic cosmic rays, solar flares and coronal mass ejections are all threats. Energetic particle fluxes will determine electronic shielding requirements. Solar radiation will also dominate a net energy flux determining thermal shielding requirements. EXOSAT-A will be designed to operate within this energetic environment.

Rotational effects of radiation pressure on the sunshield will require periodic thruster firings to offload momentum from reaction wheels. Pressure on the sunshield will also require reaction wheel compensation and offloading with thrusters. Again, this is one of the trades for picking L2. Contamination of optics will require a further analysis to optimize burns. That is to say burns in the anti-look direction are preferred to keep the optics free of propellant exhaust.

Meteoroid flux may produce risk of damage to the primary mirror due to penetration. A common criticism of membrane mirrors is that a micrometeoroid can punch a hole in a mirror. This is clearly better than a micrometeoroid forming a crack in glass which when thermally cycled will propagate leading to mission failure. The nature of the OCCAM technology is that it is a curvature type mirror thus has a non-local influence function. The analogy would be with small curvature deformable mirrors used in astronomy where loss of an actuator can be compensated with adjacent control areas due to influence function non-locality. A hole in the membrane mirror is ok!

Meteoroid impact damage for the rest of the telescope and spacecraft must be considered. At minimum there should be one “enhanced durability” configuration for predictable periodic events to reduce the probability of damage. There will always be some risk. Heavier spacecraft which are better shielded against hypervelocity impact cost more to launch yet this high mass is what we want to avoid with OCCAM technology. Again a full tradespace analysis is not performed here.

The estimated impact of cosmic rays is detector and shielding independent therefore will not be realistically calculated here. Random sections of imaging arrays will constantly be affected. Previously we suggested observing strategies can be used to mitigate this problem. Communications can similarly be disrupted with bit upsets and error correction codes will be employed. A study of readout time for arrays vs. ion impact rates will yield an optimal solution. As the arrays have not been baselined that is left for future designers.

Last, in the event of high radiation events that are known, the spacecraft can be virtually shut down as the Hubble is with SAA anomaly intercepts.

There will be times on OCCAM EXOSAT-A when the solar radiation background is so high that observations will be lost due to solar radiation. There are no plans to measure the cosmic ray rate and autonomously respond storms. If images are bad they can be requested again in a queue.

Summary

Operational parameters and schemes for array readout, failure handling, ground ops and organizations, observatory maintenance and visits, fine guiding scenarios, full instrument designs etc. are well beyond the NIAC request for a baseline mission plan and are not evaluated here. A true mission architecture would require a 1000 pages.

The ExoSat-A mission has been presented here as a merger of near term possibilities that are cost effective and feasible. The existence of OCCAM EXOSAT-A and any other OCCAM based technologies ultimately depends on future NASA funding to complete the OCCAM telescope and test the concept then to scale it.

The goal of the NIAC study was to show that items like a 1 pound Hubble size mirror are possible and in fact within our reach. The notional mission above is but one example of many possible missions using OCCAM technology.

Next Steps:

Require further study of

- **Control authority**
- **Control system loop**
- **O_1 and UV resistance**
- **Scaling**
- **Complex powered optics**

- **Design trade-space of actual design-Off axis?**
- **Packing ratio**
- **0.5, 1, 2 4, 8 meters**
- **Funding venues**
- **Launch**

Additional Knowledge

In an appendix we additionally submit details of chemical synthesis and software development, algorithms and computer code.

Conclusion

We now have multiple parallel paths making far more advanced hybrid molecules we think should end up being suitable both from a space environment perspective and also from a space telescope control authority perspective. We are evaluating our new polymers. We are about to make a new group of mirror substrates for testing. We continue our software control system development.

A number of new compounds which have never existed on Earth have been made. We cannot over rate the importance of developing these materials, literally the core of this new NIAC technology. We are excited about the potential for these new meta-materials in other fields as well although our prime focus is making space telescopes for NASA.

In addition to new materials and substrates (mirrors) we have new hardware being developed, and software development continues.

We are working hard and making progress. There is still more to do. Progress is encouraging.

The proposed technology is all based on currently emerging technology. Funding and continued development of this technology will enable future NASA missions using low mass high collection area mirrors, and a leap in primary mirror diameter and therefore resolution and cosmic physical knowledge. When this technology is fully developed, it will have wide application in all high resolution space based optical systems.

Support of this technology and our proposal will significantly contribute to the NASA Science mission, as well as all future space imaging. This is our team's lofty yet achievable vision.

We have more to do to get this to TRL9 but in NIAC terms, we have with no doubt shown that we can "change the possible."

Thank you to the taxpayers of the USA and to NASA for the support through NIAC/NASA OCT of our exciting project. I welcome any discussion and am here glad to keep you informed of our progress.

Since 1998 Many people have helped with this work. I wish to acknowledge Team Leaders Professors Brozik and Brodhacker and their Staff and students Dr. Barden and Ms. Kapingidza and Ms. Tabatabaei for their outstanding contributions to this work during Phase II. Many others will be acknowledged as authors and contributors in future publications.

This concludes this report.

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Appendix