NASA SBIR Subtopic:

S2.03
Advanced Optical Systems and Fabrication Testing/Control Technologies for EUV/Optical and IR Telescopes

H. Philip Stahl, Ph.D.

Sub-Topic Manager

NASA ‘Optics’ Award Statistics Total

	Phase 1	Phase 2
2005	21% (8/38)	71% (5/7)
2006	28% (8/29)	63% (5/8)
2007	36% (4/11)	50% (2/4)
2008	59% (10/17)	50% (4/8)
2009	56% (9/16)	50% (4/8)
2010	50% (11/22)	11% (1/9)
2011	28% (7/25)	20% (1/5)
2012	28% (8/29)	50% (4/7)
2014	54% (7/13)	33% (2/6)
2015	48% (10/21)	**20% (3/8)**
2016	**29% (7/24)**	
Total	36% (89/245)	44% (31/70)

S2.03 “Advanced Optical Systems for UVO & IR”

	Phase 1	Phase 2
2015	50% (5/10)	20 % (1/5)
2016	42% (3/7)	
Total	47% (8/17)	20% (1/5)

S2.04 “X-Ray Mirrors, Coatings and Free-Form”

	Phase 1	Phase 2
2015	45% (5/11)	66% (2/3)
2016	24% (4/17)	
Total	32% (9/28)	66% (2/3)

2015 SBIR S2.03 'Normal Incidence'

Phase I 10 Submitted 5 Funded

- **Additive Manufactured Very Light Weight Diamond Turned Aspheric Mirror;** Dallas Optical Systems, Inc.
- **High Performance Consumer-Affordable Nanocomposite Mirrors with Supersmooth Surfaces, Precise Figuring, and Innovative 3D Printed Structures;** Lightweight Telescopes, Inc.
- **Additive Manufacturing for Lightweight Reflective Optics;** Optimax Systems, Inc.
- **Ultra-low Cost, Lightweight, Molded, Chalcogenide Glass-Silicon Oxycarbide Composite Mirror Components;** Semplastics EHC, LLC
- **Diffusion Bonded CVC SiC for Large UVOIR Telescope Mirrors and Structures;** Trex Enterprises Corporation

Phase II 5 Submitted 1 Funded

- **Ultra-low Cost, Lightweight, Molded, Chalcogenide Glass-Silicon Oxycarbide Composite Mirror Components;** Semplastics EHC, LLC

NASA SBIR/STTR Technologies

S2.03-9856 - Large-Scale Molded Silicon Oxycarbide Composite Components for Ultra-Low-Cost Lightweight Mirrors

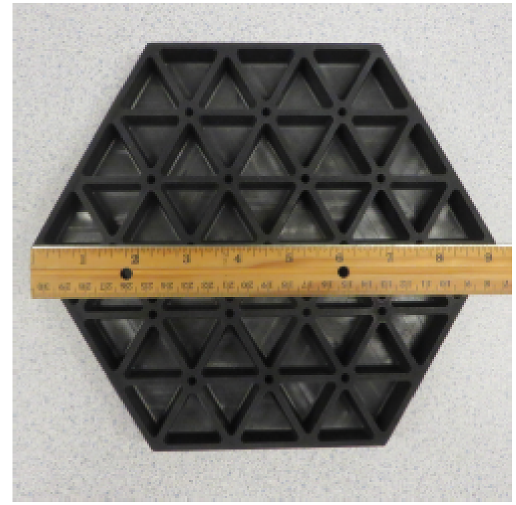
PI: William Easter

Semplastics EHC, LLC - Oviedo, FL

Identification and Significance of Innovation

Next-generation telescopes need mirrors that are extremely stable, lightweight, and affordable. Semplastics has developed a novel, innovative ceramic material which is lightweight, low-cost, and ideal for application as a mirror substrate. High-thickness, high-stiffness objects with excellent dimensional stability, low density, and low coefficient of thermal expansion can be manufactured in one piece through our energy-efficient process. Semplastics is proposing to extend prior research and manufacturing process development to produce larger-scale circular mirrors. This innovation will reduce mirror costs per sq. meter by an order of magnitude over current approaches based on glass or glass-ceramic solutions. Semplastics will deliver four large mirrors (up to 0.6m in diameter), sealed to address the residual surface porosity using one of two different coating systems, with ground and polished surfaces. At the end of Phase II, we will have matured and developed our production processes such that we are ready to establish the capability to produce mirrors of 1 meter diameter or larger.

Estimated TRL at beginning and end of contract: (Begin: 3 End: 5)



Technical Objectives and Work Plan

The Technical Objectives for this work include scaling up our production process to larger-scale mirrors, evaluating and analyzing two different approaches to sealing the mirror blank surface, and producing usable mirrors at greatly reduced cost. To achieve these objectives, we will produce ceramic test coupons for initial research in pyrolyzing, sealing, grinding, and polishing. We will partner with the University of Central Florida to perform testing and analysis of the materials produced. We will use the results of this initial research to reduce risk and provide lessons learned as we then process larger objects to produce the deliverable mirrors. Our innovative manufacturing technology will be refined and improved through this effort, enabling the production of larger ceramic objects at a significantly reduced energy footprint than traditional ceramics manufacturing, with positive results for the environment

NASA Applications

Several NASA activities benefit from improvements in mirror performance as well as a significant reduction in areal costs. Earth-observing and space-observing telescopes that are either balloon-borne or on-orbit have a constant need to reduce the cost and mass of their optical systems. Specific programs with interest in improved mirror technology include the Wide-Field Infrared Survey Telescope (WFIRST) and the Climate Absolute Radiance and Refractory Observatory (CLARREO).

Non-NASA Applications

Our process can be used to manufacture mirrors for professional and amateur telescopes, as well as adaptive mirrors for military, medical, and automotive applications. Beyond optics, our lightweight, high stability materials technology has the potential to supplant older materials technologies in various industries, such as energy, automotive, and aerospace, in addition to military applications.

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2015 SBIR S2.04 ‘X-Ray & Freeform’

Phase I 11 Submitted 5 Funded

- **Low Coherence, Spectrally Modulated, Spherical Wavefront Probe for Nanometer Level Free-Form Metrology**; Apre Instruments, LLC
- **Precollimator Manufacturing for X-ray Telescopes**; Mindrum Precision, Inc.
- **Freeform Optics: A Non-Contact "Test Plate" for Manufacturing**; Optimax Systems, Inc.
- **Manufacture of Monolithic Telescope with a Freeform Surface**; Optimax Systems, Inc.
- **InTILF Method for Analysis of Polished Mirror Surfaces**; Second Star Algonumerix

Phase II 3 Submitted 2 Funded

- **Manufacture of Monolithic Telescope with a Freeform Surface**; Optimax Systems, Inc.
- **InTILF Method for Analysis of Polished Mirror Surfaces**; Second Star Algonumerix

NASA SBIR/STTR Technologies

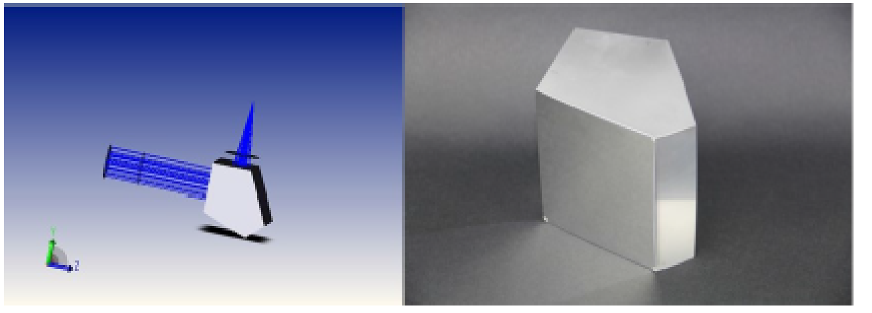
S2.04-9683 - Manufacture of Monolithic Telescope with a Freeform Surface

PI: Todd Blalock
Optimax Systems, Inc. - Ontario, NY

Identification and Significance of Innovation

Optimax Systems, Inc. has developed a unique and robust manufacturing process for the production of individual freeform optical surfaces. Until now the availability for freeform optics is limited due to the lack of design tools, manufacturing quality, and metrology. Optimax has addressed the manufacturing quality issue of the production of freeform optics. Instrument designers often want two apparently mutually-exclusive characteristics from their optical systems: ruggedness (especially in a rocket-launch environment) and minimal size/weight. Our proposal capitalizes on recent advances in monolithic and freeform optics in order to achieve both characteristics.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)



Technical Objectives and Work Plan

Objective 1: Design improved monolithic telescopes
Objective 2: Improve manufacturing processes to manufacture High-resolution(HR) and lightweight (LW) monoliths
Objective 3: Manufacture HR and LW monolith telescopes
Objective 4: Accurately measure freeform surfaces of monoliths
Objective 5: Show system performance improvement by figure correction of one surface on the HR monolith

For the design portion of the project will use standard optical design software, Zemax, for both the HR and LW telescopes. The imaging will be analyzed with sequential ray tracing and stray light analysis will be accomplished using non-sequential ray tracing. A tolerance analysis will be done to understand the mechanical sensitivities to the final performance of the telescope.
The design of the lightweight mirror structure will need more mechanical analysis for the final design. Since the goal of the lightweight monolith is to have as little material as possible, we will optimize its form using finite element analysis (FEA) to design a structure that is rigid, lightweight, and manufacturable. To efficiently manufacture the monoliths we will experiment with different tooling materials and analyze the force feedback data to verify optimal glass removal rates.

NASA Applications

CubeSat telescopes - High resolution and lightweight teelscope that are conducive for cubeSat requirements
Exo-planet imaging systems and Chronographs - Exo-planet imaging systems require minimal scattering due to mid-spatial frequency errors on their primary and secondary mirrors. The specification for the Jovian planet finder optical system was less than 1 nm rms in the 4 – 50 cycles/aperture range.

Non-NASA Applications

Freeform optics - Many optical designers are starting to use freeform optics to achieve optical performance (less aberrations), lighter weight optical systems through a reduced number of components, and an increased ability to go off axis with smaller and tighter packages. Example aplication are beam shaping, corrector plates, conformal windows, and head-up displays .

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NASA SBIR/STTR Technologies

S2.04-9193 - BeatMark Software to Reduce the Cost of X-Ray Mirror Fabrication by Optimization of Polishing and Metrology cycle

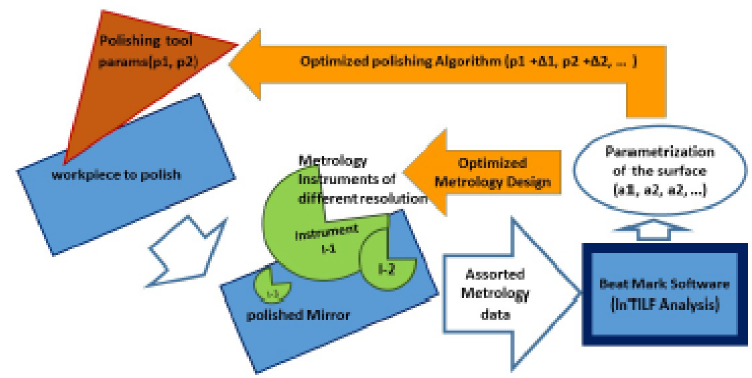
PI: Anastasia Tyurina

Second Star Algonumerix - Needham, MA

Identification and Significance of Innovation

As the cost of X-Ray mirror fabrication continues to grow, the cost threatens the viability of missions such as the X-Ray Surveyor. A quality mirror surface should be homogeneous and devoid of pattern. The BeatMark software detects the patterns indicative of mirror imperfections and generates actionable information for repolishing instructions. The tool can also be used as a compact description of metrology data for generating statistically equivalent synthetic metrology data for system planning and simulations. In Phase I Second Star built a 1D-prototype software implementation of the method and it confirmed our theoretical results by demonstrating the ability to represent important optical properties of the surface and pass them on to generated data. We also developed a 2D algorithm to demonstrate the feasibility of a full software implementation in Phase II. This leads to an optimized polishing-and-metrology cycle which reduces the fabrication cost of the mirrors.

Estimated TRL at beginning and end of contract: (Begin: 3 End: 5)



Technical Objectives and Work Plan

The goal of the project is to develop a software tool that will lower the cost of X-Ray mirror fabrication by optimization of polishing-and-metrology cycle. This would allow smaller fabricators to join the precision mirror market and allow automation of fabrication, lowering the final cost for NASA.
We will create the software tool during the Yr 1 and use it to develop an algorithm for polishing optimization. Partnering with OptiPro, we will create an optimization algorithm using BeatMark to optimize OptiPro polishers, lowering metrology costs by 10-15%.

Task List
1 Software design planning & MATLAB prototype; 2 Implement software backbone, 1-D processing demonstration; 3 Implement 2-D Autoregression Filtering; 4 Polishing experiment design & planning; 5 Full-scale 2D processing with command line; 6 UI design; 7 Polishing experiment & data collection; 8 Implement basic UI; 9 Data analysis & preliminary polishing method; 10 2nd data collection; 11 Full-scale 2-D processing UI; 12 Polishing optimization algorithm design; 13 Implement polishing algorithm prototype; 14 Commercialization of BeatMark; 15 Final demonstration and report

NASA Applications

The primary NASA application for the BeatMark software is to reduce the fabrication and testing time and cost for optics to be used in the X-Ray Surveyor Mission. By optimizing the polishing-and-metrology cycle, BeatMark will reduce the cost of manufacturing the mirrors, which will contribute to the approval and success of the mission. Other NASA applications include surface metrology for other X-Ray and ultraviolet optics for astronomy and communication applications.

Non-NASA Applications

Other applications for the software include X-Ray mirror polishing for applications such as medical imaging and teletherapy for cancer treatment, UV mirrors polishing, surface metrology analysis for lithography and other manufacturing processes with tight tolerances for surface finish, imaging texture analysis, and composition analysis.

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2016 SBIR S2.03 'Normal Incidence'

Phase I 7 Submitted 3 Funded

Additive Manufacturing of Telescope Mirrors, Arctic Slope Technical Services

Phase Reconfigurable Nulling Interferometer, Boulder Nonlinear Systems

Ultra-Stable Zero-CTE HoneySiC and H2CMN Mirror Support Structures, Fantom Materials

Phase II TBD Submitted TBD Funded

NASA SBIR/STTR Technologies

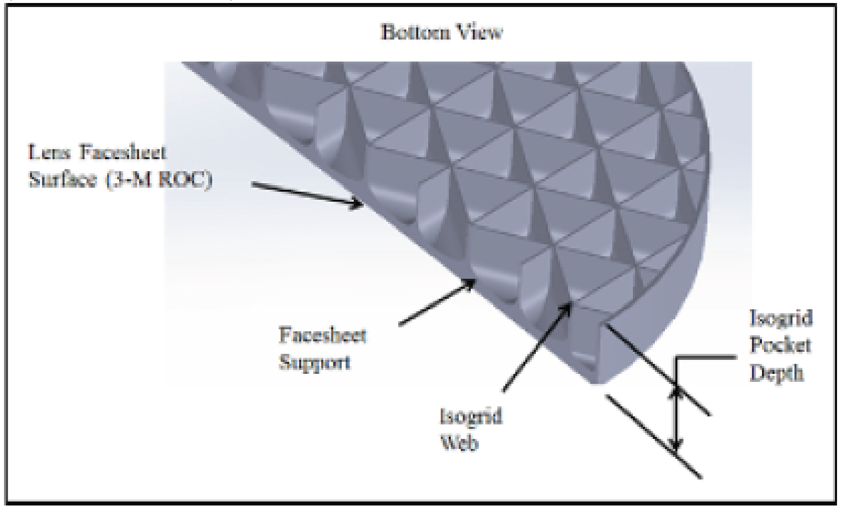
S2.03-8338 - Additive Manufacturing of Telescope Mirrors

PI: Robert Harrison
Arctic Slope Technical Services, Inc. - Huntsville, AL

Identification and Significance of Innovation

This Phase I SBIR is to demonstrate feasibility of using selective laser melting (SLM) to produce a 3-meter symmetrical radius of curvature (ROC) isogrid mirror substrate which will significantly reduce traditional mechanical machining of the mirror surface before and after nickel plating. The technique in accomplishing this is by fabricating the lens facesheet as the top most layers in the melting process. This way, our melting technique in producing the best possible finish on the lens surface SLM can provide. If this is successful, then performing a electro-polishing of the substrate before nickel plating the lens facesheet, single point diamond turning (SPDT) is the only time it is necessary. By developing the SLM techniques having a facesheet ROC with minimum variation, and having an optimized facesheet thickness designed for additive manufacturing, this substrate can be scaled to support flight hardware designs for UVOIR mirrors.

Estimated TRL at beginning and end of contract: (Begin: 1 End: 4)



Technical Objectives and Work Plan

The technical objective of this Phase 1 SBIR is to demonstrate feasibility of using SLM to produce a 3-meter symmetrical ROC isogrid mirror substrate which will significantly reduce traditional mechanical machining of the mirror surface before and after nickel plating. By developing the SLM techniques having a facesheet ROC with minimum variation, and having an optimized facesheet thickness designed for additive manufacturing, this substrate can be scaled to support flight hardware designs for UVOIR mirrors.
Work plan: 1) Isogrid design optimization 2) Manufacturing trials 3) Prototype 250-mm Mirror Fabrication.

NASA Applications

Additive manufactured mirrors using the techniques we develop in Phase I can be applied to small aperture mirrors used on sounding rockets, as well as mirror substrates to be used in infrared or ultraviolet or optical applications. A good example is the optical lens associated with missions in the Medium Class Explorers (MIDEX) TESS mission. In addition, continued mirror development and mounting schemes, we can see the development of larger segmented mirror development for launch on the future Space Launch System.

Non-NASA Applications

We envision using Al/Si alloys as a mirror substrate for nickel plating. Application for optical and infrared sensors could be developed as a low cost solution for utilization in unmanned aerial vehicles (UAV) used by DOD, in the agriculture industry, and in the transportation industry.

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NASA SBIR/STTR Technologies

S2.03-7856 - Phase Reconfigurable Nulling Interferometer

PI: Hugh Masterson

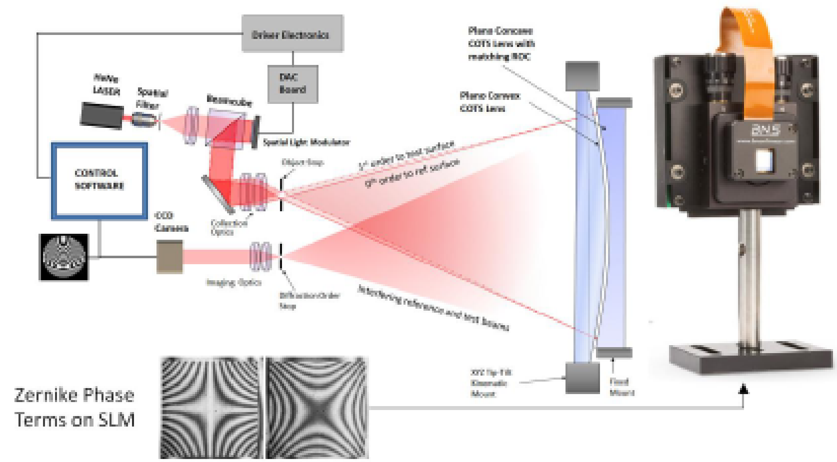
Boulder Nonlinear Systems, Inc. - Lafayette, CO

Identification and Significance of Innovation

A liquid crystal on silicon spatial light modulator (SLM) for interferometric testing of giant telescope mirrors is proposed. A phase programmable component offers significant advantages over astatic computer generated holograms (CGH). In-situ phase nulling means alignment precision is not critical, and multiple optics can be tested without fabricating a new CGH in each case. Vibration free phase shifting interferometry is can be performed by adding piston phase to the SLM for increased precision. Temporal nulling of phase error due to moving air currents is possible, and phase errors due to other components can be compensated. SLMs have 1000th wave phase control or better. The Phase I effort will validate the technology on a benchtop prototype with a 512x512 SLM in a Fizeau Interferometer setup and using commercial off the shelf optical components. In Phase II a full prototype will be constructed with a 1536x1536 SLM, 31mm on the side.

Estimated TRL at beginning and end of contract: (Begin: 1 End: 4)

Fizeau Nulling Interferometer Using SLM



Technical Objectives and Work Plan

The technical objectives are the construction of a breadboard SLM activated Fizeau nulling Interferometer on a floating optical table. The technology will be validated by configuring the SLM to achieve an optical null by extracting the Zernike components of the camera displayed fringe pattern. An iterative procedure using a seek and find algorithm will be used to find the global minimum of the null. Precision and repeatability measurements will be performed and the alignment requirements of the SLM will be examined. Reconfigurability Tests will be performed by repositioning the test plate to generate a fringe pattern and the algorithm will be re-applied to find a new null. Phase shifting interferometry will be included by adding known piston phase changes to the SLM phase hologram to increase the test precision. In Phase II more rigorous examination of the test data and separation of the erroneous phase contributions from sources other than the test-optic, will be performed.

NASA Applications

Optical test metrology for giant telescope mirrors; beam steering for satellite communication links; holographic optical trapping.

Non-NASA Applications

Optical test metrology for giant telescope mirrors; optical test metrology for small scale commercial and custom optics; ground and satellite based beam steering; holographic optical trapping in biotechnology; multi-photon microscopy in biotechnology.

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NASA SBIR/STTR Technologies

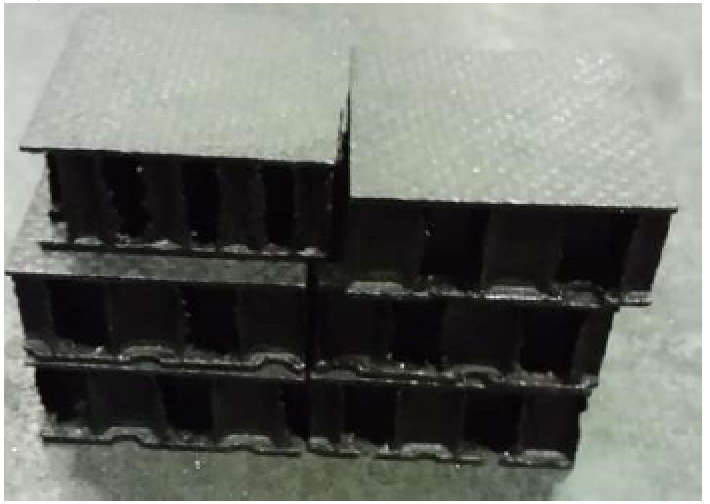
S2.03-8014 - Ultra-Stable Zero-CTE HoneySiC and H2CMN Mirror Support Structures

PI: William Fischer
Fantom Materials Inc - Lihue, HI

Identification and Significance of Innovation

NASA MSFC/GSFC/JPL are interested in Ultra-Stable Mirror Support Structures for Exoplanet Missions. Fantom Materials proposes HoneySiC for ultra-stable mirror support structures traceable to Cosmic Origins for UVOIR/Exo/FIR telescopes, including whiffle plates, delta frames and strongbacks. HoneySiC's inherent features make it an ideal deployment hinge and latching material: 1) It's an additively manufactured Ceramic Matrix Composite (CMC) with no Coefficient of Moisture Expansion. Individually molded parts become a monolithic construct so it's possible to manufacture an entire telescope using HoneySiC, 2) It's extremely light weight; laminate HoneySiC sheets have equal density to beryllium (Be) and HoneySiC panels have ~1/5 density of beryllium, 3) It's extremely dimensionally stable due to a zero-CTE across a temp range of -200 to +25C. The thermal conductivity can be supercharged by adding carbon nanotubes. Project objective: Collaborate with NASA MSFC/GSFC/JPL/NG to demonstrate ultra-stable HoneySiC mirror mounting materials to potentially replace all Be and M55J-954-6 parts.

Estimated TRL at beginning and end of contract: (Begin: 5 End: 6)



Technical Objectives and Work Plan

Objectives: 1) Collaborate with NASA MSFC/GSFC/JPL/NGAS to design a prototype whiffle plate or delta plate to be made in Phase II using HoneySiC and/or H2CMN to potentially support a mirror for a high-altitude balloon experiment (GHAPS), 2) Evaluate HoneySiC and H2CMN material properties, 3) Prepare a materials properties test matrix to be executed in Phase II.

Task 1: Kick-Off via WebMeeting/Telecon – Discuss project goals and schedule. Participants/Team will include the Fantom Materials PI (Dr. Bill Fischer), Professor Mehrdad Nejhad of UH, the NGAS team, and NASA COTR (TBD). Task 2: Weekly Technical Interchange Meetings (TIMs) – TIMs will establish Action Items, responsible parties, assignments and provide technical progress. Task 3: HoneySiC and H2CMN Coupons– A matrix of test coupons will be defined with Professor Nejhad at U of H. Task 4: Coupon Preparation – UH will prepare coupons. Task 5: Measurements – UH will perform basic mechanical measurements in-house. CTE measurements will be made at Southern Research Institute (SORI) and possibly also at NGAS. Extra coupons will be provided to NASA for independent verification. Task 6: Phase II Plan – Team shall conduct a preliminary design effort for a whiffle plate, delta plate or backplane to be produced in Phase II.

NASA Applications

Present state-of-the-art materials require an 8 order-of-magnitude improvement in stability. This project is the point of departure for ultra-stable mirror support structures made using 1st generation zero CTE HoneySiC (ca. 2014), and 2nd generation H2CMN (ca. 2016). Fantom Materials' promising CMCs will replace beryllium and status quo, moisture-absorbing, organic matrix composites used today. 1st and 2nd gen HoneySiC will provide low areal cost, low areal density, and ultra-stability required for future EUV, UV/O and Far-IR missions.

Non-NASA Applications

Fantom's HoneySiC has use in complex telescopes for Astronomy, Imaging and Remote Sensing applications, including surveillance, mapping and reconnaissance missions for police, paramilitary units and fire fighters, power/pipeline/NOAA monitoring, search and rescue, disaster relief and communications. The dual-use nature of complex telescopes will bring affordability to national defense missions.

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2016 SBIR S2.04 ‘X-Ray & Freeform’

Phase I	17 Submitted	4 Funded

Low Coherence Wavefront Probe for Nanometer Level Free-Form Metrology, Apre Instruments

UltraForm Finisher Optical Mandrel Fabrication, OptiPro Systems

Zero Net-Stress, Non-Distorting Iridium Coatings for Thin-Shell X-ray Telescope Mirrors, Reflective X-ray Optics

Advanced X-ray Telescope Material System, Peregrine Falcon Corp

Phase II	TBD Submitted	TBD Funded

NASA SBIR/STTR Technologies

S2.04-7976 - Low coherence wavefront probe for nanometer level free-form metrology

PI: Artur Olszak

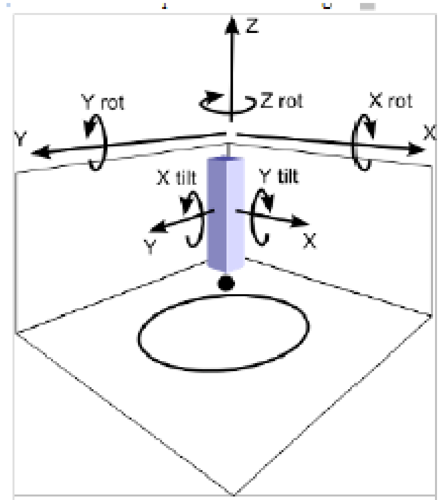
Apre Instruments, LLC - Tucson, AZ

Identification and Significance of Innovation

Apre Instruments proposes (Phase I) a novel low-coherence wavefront PROBE for the measurement of free-form optical surfaces with nanometer level PROBE measurement uncertainty over slopes up to 60 degrees. A simple 3 axis metrology frame architecture can be utilized, enabling nanometer level free-form measurement uncertainty in the Phase II surface profiler.

Future NASA missions benefit from smaller, lighter optical systems with larger fields of view with better resolution and free-form optics promise these advantages. Today's metrology tools, profilers and interferometers lack the accuracy required. This innovation will lead to readily available free-form optics.

Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)



Technical Objectives and Work Plan

Technical Objective:

Verify PROBE feasibility and PROBE + SOURCE performance regarding fringe contrast and location

Work Plan

- Improve SOURCE performance regarding fringe contrast and location.
- Build new PROBE with promised 2 nm RMS measurement uncertainty
- Integrate PROBE + SOURCE and test performance

NASA Applications

"Future NASA missions with alternative low cost science and small sized payloads are constrained by traditional spherical optics. Free-form, non-spherical optics provide better aerodynamics...with light weight components to meet mission requirements." Coronagraphic applications are an example of where field of view can be increased in a practical volume. No process control tools are available today to enable these benefits. The Phase I PROBE enables nanometer RMS free-form optical manufacture.

Non-NASA Applications

Cell phones, tablets, and laptops utilize free-form optics as do other consumer applications. High performance defense, scientific and industrial optics could increase performance with free-form optics. The lack of metrology for manufacturing process control limits the performance or hinders manufacture of free-form optics. This Phase I PROBE enables free-form optical manufacture.

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NASA SBIR/STTR Technologies

S2.04-7686 - UltraForm Finisher Optical Mandrel Fabrication

PI: David Mohring
OptiPro Systems, LLC - Ontario, NY

Identification and Significance of Innovation

Telescope satellites such as Chandra, and XMM-Newton have provided detailed images into the formation of our universe and the study of black holes. New and future missions like the Wide Field X-ray Telescope (WFXT) promise to provide even more detail. These telescopes all require high precision optical surfaces that have tight optical specifications, and slope requirements of less than 1 arc-sec rms. The cost effective manufacture of these precision optics and mirrors requires new tools and processes to meet the stringent grazing incident optical specifications. OptiPro Systems provides innovative manufacturing solutions and proposes to develop a unique rotary axis in combination with the Optipro UltraForm Finishing platform. The work performed in Phase I includes the rotary system to be designed and built to provide test results applicable to mandrel fabrication. OptiPro, as a machine builder, is uniquely positioned to transition this technology to NASA and other optical component manufacturers. This will ultimately lead to a cost-effective solution for NASA programs.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

Technical Objectives and Work Plan

The UFF platform uses sub and mid-aperture tools to polish and figure correct precision optics, mandrels and mirrors. Current X-Ray mandrel designs include cylindrically shaped aluminum workpieces. The axial slope surface form errors are critical to X-Ray grazing incidence mirror fabrication and the surface roughness requirements are determined by the shell electroforming process. Concept designs suggest that the platform requirements for polishing a cylindrical aluminum mandrel involves rotating the mandrel horizontally while traversing the polishing tool across the work piece along the axis of rotation. The design and build of a table mounted precision rotary work axis is the first task in our work plan. The rotary axis will be mounted in 2 distinct orientations on a host UFF platform. The UltraWheel polishing tool provides the belt rotation during the finishing process and various tool orientations will be tested. The polishing and measurement of the mandrel work piece surface will drive the final design requirements for the implementation of the Rotary A-Axis on the existing UFF300 platform. The Phase I process development effort will be focused on implementing the table mounted rotary A-Axis and testing the newly developed toolpaths and axis orientations. The goal of the mandrel polishing is to efficiently figure correct and remove mid spatial slope errors.

NASA Applications

UltraForm Finishing and UltraSmooth Finishing will provide finishing capabilities for the following NASA optical components:
- Forming mandrels used to produce multiple segmented shell mirrors
- X-Ray Mirrors for Hard and Soft X-Ray telescopes for the International X-Ray Observatory (IXO) and (NGXO)
- Aspheric and freeform optical surfaces and CubeSat mirrors
- Fabrication of the segmented optics in telescope systems such as the Advanced Technology Large Aperture Space Telescope (ATLAST).

Non-NASA Applications

- U.S. Military aspheric, freeform and conformal optics
- Polishing of optical injection mold inserts
- Commercial automotive heads-up displays
- Polishing of freeform reflectors for lighting applications
- Solar power intensifiers and mirror guidance optics
- Department of Energy X-Ray Optics

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NASA SBIR/STTR Technologies

S2.04-8306 - Zero Net-Stress, Non-Distorting Iridium Coatings for Thin-Shell X-ray Telescope Mirrors

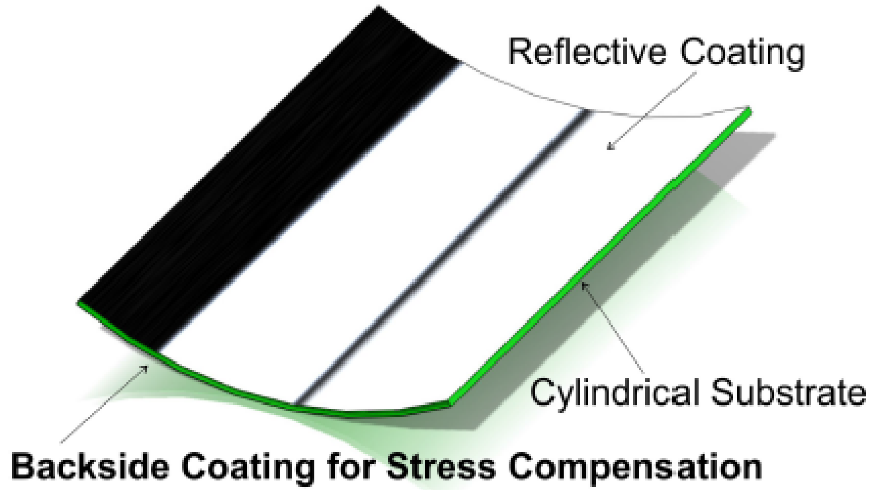
PI: David Windt

Reflective X-ray Optics, LLC - New York, NY

Identification and Significance of Innovation

Future NASA X-ray astronomy missions currently being formulated will require light-weight X-ray mirrors having angular resolution of 1 arc-sec or better. The mirrors comprise a thin-shell substrate and an X-ray reflective iridium coating. Substrate distortions induced by stresses in the reflective iridium coating must be minimized or eliminated so that the angular resolution of the mirror is not degraded. We propose to develop 2D coating uniformity control, and dual-side coating techniques that can be used to balance film stress and thus mitigate film-stress-driven substrate deformation.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 3)



Technical Objectives and Work Plan

1. Zero net-stress Ir-based coatings with two-dimensional uniformity control. We will use recently developed coating technology to control iridium coating thickness uniformity in two dimensions (axial and azimuthal) for films deposited onto cylindrical thin-shell mirror segments. We will determine the level of substrate distortion present when zero net-stress coatings having high uniformity in two dimensions are deposited onto thin-shell mirrors.

2. Minimize low-frequency substrate distortions with double-side coatings. We will first use flat wafers to better understand the feasibility and limitations of the proposed double-side coating technique, and will use these flat wafers to demonstrate a proof-of-concept. We will also make preliminary investigations of the ability to control substrate deformation on cylindrical shells using the double-side coating technique, but with uniform coatings on both sides only, simply to establish a starting point for the Phase II program. The Phase II program will then focus on the development of 2D coating uniformity control for both front- and back-side coatings on cylindrical shells.

NASA Applications

Non-distorting iridium coatings are required for future NASA X-ray astronomy missions having 1 arc-second angular resolution or better that are now being formulated.

Non-NASA Applications

Thin-film deformation control techniques developed may be applicable to Si microelectronics and flat panel display industries.

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NASA SBIR/STTR Technologies

S2.04-7737 - Advanced X-ray Telescope Material System

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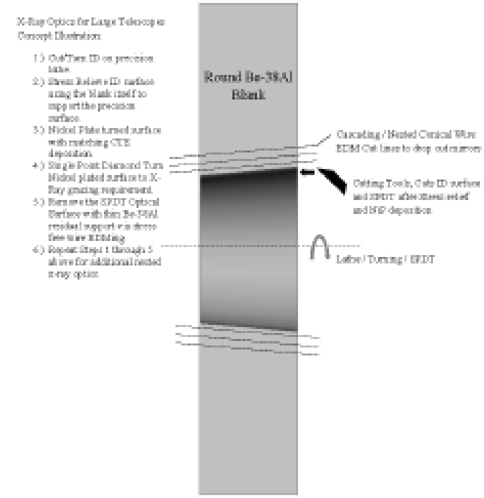
Identification and Significance of Innovation

Peregrine proposes the combination and use of of Be-38Al, electroless nickel plating, and single point diamond turning to create precision x-ray grazing optical surfaces. Large x-ray telescopes will demand large, high stiffness, and lightweight substrates to provide rigidity to support the production of nested optical surfaces while requiring accurate alignment through the use of stable support structures. Ideally, these nested x-ray mirrors would be of heavy metal, microns in thickness and be self-supporting through launch, this is currently impractical. However, near ideal x-ray optics can be produced with the low density material of Be-38Al backing a thin layer of electroless nickel with precision single point diamond turned surfaces. The use of Be-38Al can yield lightweight, precise, and stable substrates. Coefficient of thermal expansion matching electroless nickel can be deposited thinly on top of the Be-38Al substrates, and then single point diamond turned to optical finishes. Be-38Al can be used to produce entire precision athermal telescopes.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 3)



Technical Objectives and Work Plan

Objectives: 1.) Low cost, ultra-stable and lightweight grazing mirrors for x-ray telescopes, 2.) Provide effective stray light suppression, 3.) Capable of producing x-ray/incident grazing telescopes up to 5 m2 in area, and 4.) Allows for the use of Be-38Al to create stable and precision support structures to maintain mirrors in alignment.

Work Plan: 1.) Task 1: Kickoff Meeting and Definitization, 2.) Task 2: Design and Fabricate a Grazing Mirror Element, 3.) Task 3: Testing, 4.) Task 4: Detailed Plan for Follow-on Effort, and 5.) Final Report

NASA Applications

The development and verification of the Be-38Al/NiP/SPDT system to yield x-ray optics will enable future NASA large telescopes to be built and launched. Where there may be commercial opportunities, the key focus of this post SBIR activity will be on large next generation NASA x-ray telescopes.

Non-NASA Applications

Where this technology is focused on x-ray optics and telescopes, it can be beneficial in regards to commercial scanners and x-ray inspection devices. This proposed material system and processing technology can provide the accuracy needed to improve most scanners and optical x-ray systems used for non-destructive examination. This will be of particular interest in the NDE of semiconductors.

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Any Questions?

NASA 2017 SBIR Subtopic:

S2.03 “**Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope**”

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Sub-Topic Manager

New for 2017

- Additive manufacturing technology
- Lightweight low-cost mirror substrates for Far-IR with < 100 nm rms cryo-deformation at 10K.
- Ultra-stable structures for potential telescope assemblies:
    - 0.5 meter LISA,
    - 4-m monolithic HabEx, or
    - 12-m segmented LUVOIR.
- 1.5-meter class Balloon Experiment Telescopes (not in ‘call’).

Generic Instructions to Proposer

Define a customer or mission or application and demonstrate that you understand how your technology meets their science needs.

Propose a solution based on clear criteria and metrics

Articulate a feasible plan to:

- fully develop your technology,
- scale it to a full size mission, and
- infuse it into a NASA program

Deliver Demonstration Hardware not just a Paper Study, including :

- documentation (material behavior, process control, optical performance)
- mounting/deploying hardware

S2.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope

Subtopic solicits solutions in the following areas:

- **Components and Systems for potential EUV, UV/O or Far-IR missions**
- **Technology to fabricate, test and control potential UUV, UV/O or Far-IR telescopes**
- **Telescopes that enable sub-orbital rocket or balloon missions.**

Subtopic's emphasis is to mature technologies needed to affordably manufacture, test or operate complete mirror systems or telescope assemblies.

Ideal Phase 1 deliverable would be a precision optical system of at least 0.25 meters, or a relevant sub-component of a system, or a prototype demonstration of a fabrication, test or control technology. Phase 1 mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials.

Successful proposals will demonstrate an ability to manufacture, test and control ultra-low-cost optical systems that can meet flight requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.

Metrics

The most important metric (after performance) is affordability. Current normal incidence space mirrors cost \$4 million to \$6 million per square meter. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than \$1M to \$100K/m2.

Technology Metrics:

Aperture for all wavelengths

- Monolithic: 1 to 8 meters
- Segmented: > 12 meters

For UV/Optical

- Areal Cost < \$500k/m2
- Wavefront Figure < 5 nm rms
- Thermally Stable < 10 pm/10 min (for Coronagraphy)
- Dynamic Stability < 10 pm (for Coronagraphy)
- Actuator Resolution < 1 nm rms (for UV/Optical)

For Far-IR

- Areal Cost < \$100k/m2
- Cryo-deformation < 100 nm rms

For EUV

- Slope < 0.1 micro-radian

Optical Components/Systems for potential UV/O missions

Potential UV/Optical missions require 4 to 16 meter monolithic or segmented primary mirrors with < 5 nm RMS surface figures. Active or passive alignment and control is required to achieve system level diffraction limited performance at wavelengths less than 500 nm (< 40 nm RMS wavefront error, WFE). Additionally, potential Exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pico-meters RMS per 10 minutes. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4 meter and larger telescope. To meet this requirement requires active thermal control systems, ultra-stable mirror support structures, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e. 15 kg/m2 for a 5 m fairing EELV vs. 150 kg/m2 for a 10 m fairing SLS). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m class mirror (with 50 m2 of collecting area) should have an areal cost of less than $2M/m2. And, a 16-m class mirror (with 200 m2 of collecting area) should have an areal cost of less than $0.5M/m2.

Optical Components/Systems for potential UV/O missions

Key technologies to enable such a mirror include new and improved:

- **Mirror substrate materials and/or architectural designs**
- **Processes to rapidly fabricate and test UVO quality mirrors**
- **Mirror support structures that are ultra-stable at the desired scale**
- **Mirror support structures with low-mass that can survive launch at the desired scale**
- **Mechanisms and sensors to align segmented mirrors to < 1 nm RMS precisions**
- **Thermal control (< 1 mK) to reduce wavefront stability to < 10 pm RMS per 10 min**
- **Dynamic isolation (> 140 dB) to reduce wavefront stability to < 10 pm RMS per 10 min**

Also needed is ability to fully characterize surface errors and predict optical performance via integrated opto-mechanical modeling.

Optical Components/Systems for potential UV/O missions

Potential solutions for substrate material/architecture include, but are not limited to: ultra-uniform low CTE glasses, silicon carbide, nanolaminates or carbon-fiber reinforced polymer.

Potential solutions for mirror support structure material/architecture include, but are not limited to: additive manufacturing, nature inspired architectures, nano-particle composites, carbon fiber, graphite composite, ceramic or SiC materials, etc.

Potential solutions for new fabrication processes include, but are not limited to: additive manufacture, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping or replication technologies to manufacture 1 to 2 meter (or larger) precision quality components.

Potential solutions for achieving the 10 pico-meter wavefront stability include, but are not limited to: metrology, passive, and active control for optical alignment and mirror phasing; active vibration isolation; metrology, passive, and active thermal control;

Ultra-Stable UVOIR Telescopes

eLISA

Space-based gravitational wave observatories (eLISA) need a 0.5 meter class ultra-stable telescope with an optical path length stability of a picometer over periods of roughly one hour at temperatures near 230K in the presence of large applied thermal gradients. The telescope will be operated in simultaneous transmit and receive mode, so an unobstructed design is required to achieve extremely low backscatter light performance.

Ultra-Stable UVOIR Telescopes

Balloon Missions

1-m telescopes have flown on balloons, however, their cost can exceed $6M, and their weight limits the duration of the balloon mission.

A 4X reduction in cost and mass is desired.

1.5 meter (and larger) UVOIR balloon telescopes are desired.

Exoplanet Balloon Mission

Desires 1-m class telescope with diffraction-limited performance in the visible and a field of view > 0.5 degree. Telescope operates from +10 to -70 C at an altitude of 35 km and must survive to -80 C during ascent. The telescope should weigh less than 250 kg and is required to maintain diffraction-limited performance over: a) the entire temperature range, b) pitch range from 25 to 55 degrees elevation, c) azimuth range of 0 to 360 degrees, and d) roll range of –10 to +10 degrees. The telescope will be used in conjunction with an existing high-performance pointing stabilization system.

Ultra-Stable UVOIR Telescopes

Planetary Balloon Mission

Optical Requirements:

- ≥ 1-meter clear aperture
- Diffraction-limited performance at wavelengths ≥ 0.5 μm over entire FOV
- System focal length: 14.052-meters
- Wavelength range: 0.3 – 1.0 μm and 2.5 – 5.0 μm
- Field of view: 60 arc-sec in 0.3 – 1.0 μm band, 180 arc-sec in 2.5 – 5.0 μm band
- Straylight rejection ratio ≥ 1e-9

Mechanical/Operational Requirements:

- Overall length: ≤ 2.75 meters
- Overall diameter: ≤ 1.25 meters
- Mass: ≤ 250 kg
- Temperature: -80 to +50 C
- Humidity: ≤ 95% RH (non-condensing)
- Pressure: sea level to 1 micron Hg
- Shock: 10G without damage
- Elevation angle range: 0° to 70° operating, -90° to + 90° non-operating

Other Requirements:

- Must allow field disassembly with standard hand tools
- Maximum mass of any sub-assembly < 90 kg
- Largest sub-assembly must pass through rectangular opening 56 by 50 inches (1.42 by 1.27 meters).

Optical Components/Systems for potential IR/Far-IR missions

Potential Infrared and Far-IR missions require 8 to 24 meter class monolithic or segmented primary mirrors with ~ 1 μm rms surface figures which operate at < 10 K.

There are three primary challenges for such a mirror system:

- **Areal Cost of < $100K per m2.**
- **Areal Mass of < 15 kg per m2 substrate (< 30 kg per m2 assembly)**
- **Cryogenic Figure Distortion < 100 nm rms**

Infrared Interferometry Mission Telescope

A balloon-borne interferometry mission requires 0.5 meter class telescopes with siderostat steering flat mirror. There are several technologies which can be used for production of mirrors for balloon projects (aluminum, carbon fiber, glass, etc.), but they are high mass and high cost.

Fabricate, Test & Control Advanced Optical Systems

In addition to the ability to develop technology to enable potential future UVO and IR missions, it is important to note that this capability is made possible by the technology to fabricate, test and control optical systems. Therefore, this sub-topic also encourages proposals to develop such technology which will make a significant advance of a measurable metric.

Any Questions?