Strategic Astrophysics Technology
Abstracts of Selected Proposals
(NNH15ZDA001N-SAT)

Below are the abstracts of proposals selected for funding for the SAT program. Principal Investigator (PI) name, institution, and proposal title are also included. Twenty-nine proposals were received in response to this opportunity. On September 16, 2016, seven proposals were selected in full or in part for funding.

James Breckinridge/University Of Arizona
Threshold raw retrieved contrast in coronagraphs is limited by internal polarization

The objective of this work is to provide the exoplanet program with an accurate model of the coronagraph complex point spread function, methods to correct chromatic aberration in the presence of polarization aberrations, device requirements to minimize and compensate for these aberrations at levels needed for exoplanet coronagraphy, and exoplanet retrieval algorithms in the presence of polarizaiton aberrations.

Currently, space based coronagraphs are designed and performance analyzed using scalar wave aberration theory. Breckinridge, Lam & Chipman (2015) PASP 127: 445-468 and Breckinridge & Oppenheimer (2004) ApJ 600: 1091-1098 showed that astronomical telescopes designed for exoplanet and precision astrometric science require polarization or vector-wave analysis. Internal instrument polarization limits both threshold raw contrast and measurements of the vector wave properties of the electromagnetic radiation from stars, exoplanets, gas and dust.

The threshold raw contrast obtained using only scalar wave theory is much more optimistic than that obtained using the more hardware-realistic vector wave theory. Internal polarization reduces system contrast, increases scattered light, alters radiometric measurements, distorts diffraction-limited star images and reduces signal-to-noise ratio. For example, a vector-wave analysis shows that the WFIRST-CGI instrument will have a threshold raw contrast of 10-7 not the 10-8 forecasted using the scalar wave analysis given in the WFIRST-CGI 2015 report. The physical nature of the complex point spread function determines the exoplanet scientific yield of coronagraphs.

We propose to use the Polaris-M polarization aberration ray-tracing software developed at the College of Optical Science of the University of Arizona to ray trace both a “typical” exoplanet coronagraph system as well as the WFIRST-CGI system. Threshold raw contrast and the field across the complex PSF will be calculated as a function of optical device vector E&M requirements on: 1. Lyot coronagraph mask and stop size, configuration, location and composition, 2. Uniformity of the complex reflectance of the highly reflecting metal mirrors with their dielectric overcoats, and 3. Opto-mechanical layout. Once these requirements are developed polarization aberration mitigation studies can begin to identify a practical solution to compensate polarization errors, not unlike the more developed technology of A/O compensates for pointing and manufacturing errors.

Several methods to compensate for chromatic aberration in coronagraphs further compounds the complex PSF errors that require compensation to maximize the best retrieved raw contrast in the presence of exoplanets in the vicinity of stars.

Internal instrument polarization introduces partial coherence into the wavefront to distort the speckle-pattern complex-field in the dark hole. An additional factor that determines retrieved raw contrast is our ability to effectively process the polarization-distorted field within the dark hole.

This study is essential to the correct calculation of exoplanet coronagraph science yield, development of requirements on subsystem devices (mirrors, stops, masks, spectrometers, wavefront error mitigation optics and opto-mechanical layout) and the development of exoplanet retrieval algorithms.

William Klipstein/Jet Propulsion Laboratory
Phase Measurement System for Gravitational Wave Detection

We propose to advance the maturity of the LISA Phasemeter based on our recent experience developing a flight Phasemeter for the Laser Ranging Interferometer (LRI) on NASA's GRACE Follow-On mission. Our three main objectives are to:

1) incorporate the flight GRACE Follow-on LRI phasemeter developments into the TRL4 LISA design used extensively in our interferometer testbed;

2) evaluate the LRI Phasemeter against LISA's more stringent requirements in order to identify required design changes;

3) advance the design maturity of the LISA phasemeter through an architecture study to maintain the viability of the Phasemeter as a contribution to ESA's L3 gravitational wave mission.

NASA intends to partner in the European Space Agency's (ESA) Gravitational-Wave detection mission, selected for the L3 mission to launch in 2034. This is expected to be a LISA-like mission with the two enabling LISA technologies:

1. a drag-free system to mitigate or measure non-gravitational forces on the spacecraft,

2. an interferometric measure¬ment system with precision phasemeters to measure picometer variations over the million kilometer separation between the spacecraft.

To validate the key technologies of the drag-free system, the ESA LISA Pathfinder (LPF) mission is currently demonstrating a gravitational reference sensor (GRS) and micro-Newton thrusters in space. While LPF has an on-board interferometer to measure proof-

mass motion with respect to the spacecraft, the LPF interferometer does not test the inter-spacecraft laser interferometry needed for a LISA-like mission.

To validate the key technologies of the LISA interferometric measurement, the JPL LISA Phase Measurement Team has studied and developed a prototype LISA phase measurement system. This phase measurement system has also been adapted for a demonstration mission, albeit in a different arena. GRACE Follow-Ons Laser Ranging Interferometer (LRI), due to launch in late 2017, will make LISA-like inter-spacecraft interferometric measurements across the ~200 km separation between spacecraft. The LRI interferometric measurement system has a LISA-like precision phasemeter as the main science instrument, with similar signal environments but relaxed or reduced requirements.

The proposers first developed the prototype LISA phasemeter that made the LRI possible, and then developed and delivered the flight LRI phasemeter.

Paul Reid/Smithsonian Institution/Smithsonian Astrophysical Observatory
Hybrid lightweight X-ray optics for half arcsecond imaging

This proposal is for the development of grazing incidence optics suitable to meet the 0.5 arcsec imaging and 2.3 square meter effective area requirements of the X-ray Surveyor mission concept, currently under study by NASA. Our approach is to combine two promising technologies, as yet individually unproven at the 0.5 arcsec level, into a hybrid mirror approach. The two technologies are thin piezoelectric film adjustable optics under development at SAO and PSU, and differential deposition under development at NASA MSFC. These technologies are complementary: adjustable optics are best suited to fixing low spatial frequency errors due to piezoelectric cell size limitations, and differential deposition is best suited for fixing mid-spatial frequency errors so as to limit the amount of material that must be deposited. Thus, the combination of the two techniques extends the bandwidth of figure errors that can be corrected beyond what it was for either individual technique. Both technologies will be applied to fabricate Wolter-I mirror segment from single thermally formed glass substrates.

This work is directed at mirror segments only (not full shells), as we believe segments are the most appropriate for developing the ~ 3 m diameter X-ray Surveyor high resolution mirror. In this program we will extend differential deposition to segment surfaces (from line profiles), investigate the most realistic error bandwidths for each technology, and determine the impacts of one technologys processing steps on the other to find if there is an optimal order to combining the technologies. In addition, we will also conduct a conical/cylindrical mirror metrology "round-robin," to cross-calibrate the different cylindrical metrology to one another as a means of minimizing systematic errors. Finally, we will examine the balancing and compensating of mirror stress due to the various thin films employed (piezoelectric layer, differential deposition, X-ray reflecting layer(s)) with an eye to minimizing the net stress post-processing such that the residual stress-induced deformations are well within the correction range of the

adjustable optic technology. As feasible, hybrid Wolter mirrors will be fabricated and measured via optical metrology (post-round-robin).

By looking to develop the combination of these two technologies, while also looking to separately advance each one, this program provides important risk reduction for the key enabling technology of X-ray Surveyor the mirrors.

Mark Schattenburg/Massachusetts Institute of Technology
Development of a Critical Angle Transmission Grating Spectrometer

With APRA and SAT support, MIT has developed a unique blazed soft x-ray diffraction grating called the critical-angle transmission (CAT) grating. This device combines the high diffraction efficiency and resolving power of blazed reflection gratings with the low mass, low power, compact packaging and simple alignment of transmission gratings. We have shown that a spectrometer based on CAT gratings represents a huge leap forward in instrument scientific performance compared to previous missions, leading to much increased collecting area and spectral resolving power, which in turn results in orders-of-magnitude improvement in figures-of-merit for emission and absorption line spectroscopy.

MIT proposes to bring CAT x-ray grating spectrometer (CATXGS) technology to a higher Technology Readiness Level (TRL). We will increase fabrication yield and grating performance, and develop bonding techniques for grating membranes and alignment techniques for grating arrays. We will build and test robust grating arrays for space deployment, and perform thorough environmental testing. We are very close to achieving TRL4 and ready to move on to TRL5, which we can achieve within the period covered by this proposal. Our rapid progress over the last year was made possible by significant prior investments in our infrastructure, but further progress will require further investments.

Since 2007 we have - with NASA support - demonstrated the CAT grating principle, and prototypes of increasing quality and size have verified theoretical predictions, putting the technology at a solid TRL3. Recent NASA and MIT investments in fabrication and metrology infrastructure has been justified by our rapid progress during the last year: the fabrication of practically defect-free CAT gratings with record diffraction efficiency, the demonstration of extended bandpass CAT gratings using conformal deposition of thin metal films via atomic layer deposition (ALD), and the demonstration of record-setting resolving power for an XGS on the order of R = 10,000, which exceeds the requirements for all currently proposed mission concepts.

Grating fabrication still consumes the lion's share of our efforts and time. In order to maintain momentum and continue progress towards TRL5 in an efficient manner we need to improve our fabrication infrastructure further to accelerate grating fabrication and increase yield, so we can devote more resources to the new work required for reaching TRL5.

H. Stahl/NASA Marshall Space Flight Center
Predictive Thermal Control Technology for Stable Telescope

Predictive Thermal Control (PTC) project is a multiyear effort to develop, demonstrate, mature towards TRL6, and assess the utility of model based Predictive Thermal Control technology to enable a thermally stable telescope. PTC demonstrates technology maturation by model validation and characterization testing of traceable components in a relevant environment. PTC's efforts are conducted in consultation with the Cosmic Origins Office and NASA Program Analysis Groups.

To mature Thermally Stable Telescope technology, PTC has three objectives:

- Validate models that predict thermal optical performance of real mirrors and structure based on their designs and constituent material properties, i.e. coefficient of thermal expansion (CTE) distribution, thermal conductivity, thermal mass, etc.
- Derive thermal system stability specifications from wavefront stability requirements.
- Demonstrate utility of Predictive Thermal Control for achieving thermal stability.

To achieve these objectives, PTC has five quantifiable milestones:

1. Develop a high-fidelity model of the AMTD-2 1.5 meter ULE® mirror, including 3D CTE distribution and reflective optical coating, that predicts its optical performance response to steady-state and dynamic thermal gradients under bang/bang and proportional thermal control.
2. Derive specifications for thermal control system as a function of wavefront stability.
3. Design and build a predictive Thermal Control System for a 1.5 meter ULE® mirror using new and existing commercial-off-the-shelf components that sense temperature changes at the ~1mK level and actively controls the mirrors thermal environment at the ~20mK level.
4. Validate the model by testing a 1.5-m class ULE® mirror in a relevant thermal vacuum environment in the MSFC X-ray and Cryogenic Facility (XRCF) test facility.
5. Use validated model to perform trade studies to optimize thermo-optical performance as a function of mirror design, material selection, mass, etc.

PTC advances the SOA by developing a predictive control method that uses a thermal 'model in the loop' to control the thermal system. Our goal is to demonstrate a 'system technology solution that enables a thermally stable telescope that keeps the telescope at a constant temperature independent of where it looks on the sky.

James Tuttle/NASA Goddard Space Flight Center
High-Efficiency Continuous Cooling for Cryogenic Instruments and sub-Kelvin Detectors

Although large, diffraction-limited telescopes are approaching a size limited by available launch vehicles, there is still an enormous discovery spaceopen to astrophysics through the use of advanced low temperature instruments and deep sub-Kelvin detectors. These

devices offer the potential for orders of magnitude improvement in sensitivity and spectral resolution. In the past, cryogenic instruments have been large, expensive, and power hungry, consisting of complex cooling chains with multiple coolers using different technologies. High cost and complexity have been the major impediment to the selection of missions using these advanced capabilities. We propose to develop a compact cooling system that will span more than a factor of 200 in temperature, lifting heat continuously at temperature below 50 mK and rejecting it at over 10 K, simplifying the overall cryogenic system. The device, based on Adiabatic Demagnetization Refrigerators (ADRs), will have high thermodynamic efficiency. The prototype system will exceed the requirements of all currently conceived cryogenic detector arrays, including those for flagship missions such as the Far-IR Surveyor, Inflation Probe, X-ray Surveyor, and possibly HabEx and LUVOIR. In particular, it will have more than 5 times the cooling power at 50 mK than previous sub-Kelvin coolers, greatly relaxing the requirements on the heat generation in large detector arrays, and simplifying the thermal design of the focal plane assemblies.

ADRs by themselves have no moving parts and produce no measurable vibration, however upper-stage mechanical coolers have been linear piston devices that export significant vibration. Ameliorating the problems due to upper-stage cooler vibrations has contributed to increased costs on recent astrophysics missions such as JWST and Astro-H. By raising the heat reject temperature to 10 K, the proposed sub-Kelvin cooler becomes compatible with recently-demonstrated extremely low vibration mechanical coolers, eliminating this problem for future missions. Furthermore, a complete cooling chain with extremely low vibration will enable the use of advanced sub-Kelvin detectors on missions with tight pointing requirements.

Multi-stage ADRs offer great flexibility. In addition to continuous cooling at the lowest temperatures, the prototype will have a stage that provides enough power at 4 K to cool a modest sized telescope. This stage could be scaled up to cool a large (multi-meter) telescope. Continuous stages could be added at other temperatures to provide cooling to, for example, Superconducting Quantum Interference Device (SQUID) arrays for Transition Edge Sensors (TES) or High Electron Mobility Transistors (HEMT) for Microwave Kinetic Inductance Detectors (MKID).

Now is the time to pursue this effort. Our team recently completed the end-to-end design, build, and on-orbit qualification of the ASTRO-H ADR. Launched successfully in February 2016, the ADR now provides a stable 50 mK on-orbit detector array temperature. In September 2015, our team demonstrated a laboratory ADR that provided cooling at 4 K and rejected heat to 10 K. We are presently building continuous ADRs with heat rejection at 4.5 K that have much higher cooling power per unit mass than the traditional, ASTRO-H style ‘single-shot’ ADRs. In short, the team is now ready to make this technology mission-selectable by 2020.

At the conclusion of this work, NASA will have a TRL-6 magnetic cooling system ready for missions in the coming decades.

William Zhang/NASA Goddard Space Flight Center
High-Resolution and Lightweight X-ray Optics for the X-Ray Surveyor

Envisioned in “Enduring Quest, Daring Visions” and under study by NASA as a potential major mission for the 2020s, the X-ray Surveyor mission will likely impose three requirements on its optics: (1) high angular resolution: ~0.5 PSF, (2) large effective area: e10,000 cm2 or more, and (3) affordable production cost: ~$500M. We propose a technology that can meet these requirements by 2020. It will help the X-ray Surveyor secure the endorsement of the coming decadal survey and enable its implementation following WFIRST.

The technology comprises four elements: (1) fabrication of lightweight single crystal silicon mirrors, (2) coating these mirrors with iridium to maximize effective area without figure degradation, (3) alignment and bonding of these mirrors to form meta-shells that will be integrated to make a mirror assembly, and (4) systems engineering to ensure that the mirror assembly meet all science performance and spaceflight environmental requirements.

This approach grows out of our existing approach based on glass slumping. Using glass slumping technology, we have been able to routinely build and test mirror modules of ~10half-power diameter (HPD). While comparable in HPD to XMM-Newtons electroformed nickel mirrors, these mirror modules are 10 times lighter. Likewise, while comparable in weight to Suzakus epoxy-replicated aluminum foil mirrors, these modules have 10 times better HPD. These modules represent the current state of the art of lightweight X-ray optics. Although both successful and mature, the glass slumping technology has reached its limit and cannot achieve sub-arc second HPD. Therefore, we are pursuing the new approach based on polishing single crystal silicon. The new approach will enable the building and testing of mirror modules, called meta-shells, capable of 3HPD by 2018 and 1HPD by 2020, and has the potential to reach diffraction limits (~0.1) in the 2020s.