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Marshall Space Flight Center

RESEARCH AND TECHNOLOGY REPORT 2018

NASA/TM—2018–219998

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Research and Technology Report 2018

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Marshall Space Flight Center, Huntsville, Alabama

ACKNOWLEDGMENTS

The points of contact and coordinator at Marshall Space Flight Center (MSFC) for this Technical Memorandum (TM) are John W. Dankanich (256-544-3441) and Heather Morris. The MSFC Office of Center Chief Technologist recognizes Janice Robinson, NiCarla Friend, and Kathy Jobczynski of the MSFC Scientific and Technical Information Group for assisting in the development of this report. The Center Chief Technologist, John Dankanich, and Technologist Heather Morris provided the support, insights, and decisions required for the compilation of this TM.

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FOREWORD

At Marshall Space Flight Center, we make human deep space exploration possible. We do this by developing and integrating propulsion, transportation, and other space systems to create vehicles and scientific instruments that allow us to explore and discover for the benefit of humankind. The technologies required to make exploration and discovery possible are paramount, and our investments in technology not only support NASA's current missions, but also enable new missions and scientific pursuits.

This year's report features 11 of the Agency's 15 Technology Areas, and I am proud of Marshall's role in creating solutions for so many of these daunting technical challenges. Many of these projects will lead to a sustainable in-space architecture for human space exploration that will allow us to travel to the Moon, on to Mars and beyond. Others are developing new scientific instruments capable of providing an unprecedented glimpse into our universe.

Marshall's work is driven by the Agency's vision to discover and expand knowledge for the benefit of humanity. While each project in this report seeks to advance new technology and challenge conventions, it is important to recognize the diversity of activities and people supporting our mission. This report not only showcases the Center's capabilities, it also highlights the progress our people have achieved in the past year. These scientists, researchers and innovators are why Marshall and NASA will continue to be a leader in innovation, exploration, and discovery for years to come.

I hope you enjoy reviewing this year's report. We have made incredible progress, and I know we will see even more advancements in 2019.

Jody A. Singer

Director
Marshall Space Flight Center

INTRODUCTION

I am honored to deliver the Marshall Space Flight Center Research and Technology report from 2018. MSFC is known for the Space Launch System development and broad categories of technology work including advanced manufacturing, life support, habitat systems, lander systems, science initiatives and propulsion systems. However, the portfolio from MSFC spans vast and diverse technology initiatives to position MSFC and NASA for future.

There are expectations for NASA to remain a leader of innovation. Much like our industry and academic partners, innovation is critical to enable us to meet our core objectives in a constrained resource environment. The following concepts presented address known technology gaps and/or provide disruptive performance advantages over incumbent technologies. They represent investments spanning the full taxonomy of the NASA roadmap, the Technology Readiness Level scale from new ideas to integrated systems, and major customers for Human Exploration, Science and Technology. I am humbled by this portfolio of innovation at MSFC, and the potential to impact the future of a wide range of NASA and partnered aerospace ventures.

John W. Dankanich

Center Chief Technologist
Marshall Space Flight Center

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LAUNCH PROPULSION SYSTEMS

Development of Floating Slosh Dampers for Propellant Tanks

OBJECTIVE: *To characterize and optimize floating dampers consisting of many particles.*

PROJECT DESCRIPTION

Propellant slosh can cause loss of control in launch vehicles. Traditionally, slosh is controlled through slosh baffles distributed throughout propellant tanks. Floating baffles have the potential to reduce weight, cost, and complexity of slosh control devices. It has been shown that floating particles on a fluid's surface dissipate fluid slosh, but optimization is needed if this method of slosh control is to be utilized. This project is an effort to determine how to optimally design a damper consisting of floating particles through analysis of previous data, new slosh testing, and evaluation of potential particle geometries, materials, and configurations.

Floating dampers have been tested at times in the aerospace industry and even utilized in the Redstone rocket, but weight and potential for foreign object debris have seen fixed dampers become the preferred method. Development of nonreactive foam fluorocarbons makes the potential of floating slosh dampers worth revisiting. The use of multiple particles for a floating damper has not been previously employed, but it may prove to have significant benefits. For instance, the particles are individually too small to make a significant impact on tank walls, keeping stress loads on the tank relatively low. Also, design and manufacture of a damper of this sort is trivially simple. This project involves the review of earlier test results, analysis of trends and scaling behavior, evaluation of materials appropriate for the application, and slosh testing to determine the effect of damper weight, density, and particle geometry on damping efficiency.

In this year, the second of the project, a number of slosh tests were conducted in equipment similar to that shown in figures 1 and 2. These tests involved dampers made of particles with differing numbers of layers, different densities, and finally, differing tank size to determine how the damping behavior changed with tank diameter. This data will be used to optimize the design of slosh dampers made of floating particles.

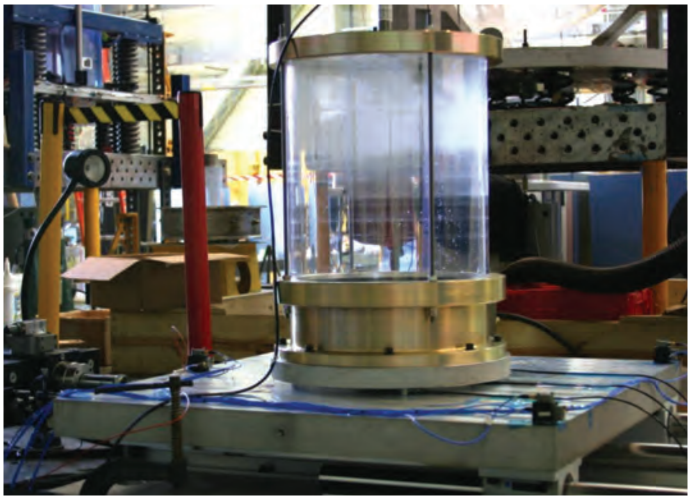


FIGURE 1. The test setup used for some of the data collection. The tank is mounted to a plate instrumented with three accelerometers. The plate rides on three rails allowing accelerations to be applied to the tank.

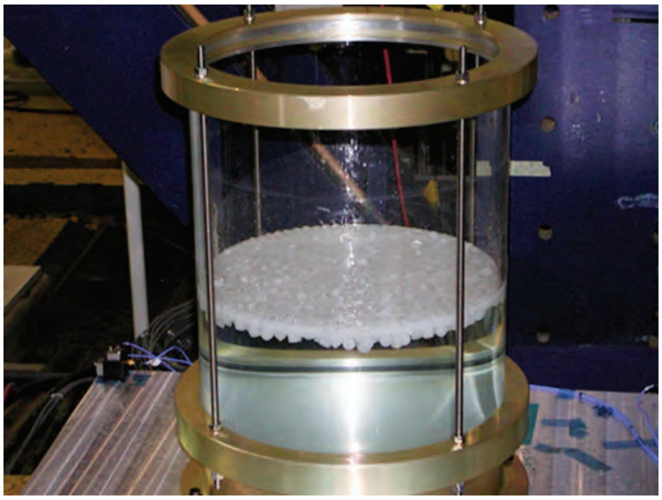


FIGURE 2. The tank in a test configuration of fluid and floating particles.

ACCOMPLISHMENTS

In the previous year's effort, it was determined that polymeric fluorocarbon foams have excellent thermal and chemical compatibility for use in virtually any and perhaps all propellants as a floating damper material. Closed-cell polyvinylidene fluoride (PVDF) was particularly impressive in its ability to go through cryogenic to room temperature and back sudden shock thermal cycles without noticeable change in properties. Based on these findings, this year's effort primarily utilized fluorocarbon foams for damper material.

Slosh tests to obtain damping data were performed for the following cases. All cases used annular particles of approximately 0.5-in diameter and 0.5-in length made of expanded foam polytetrafluoroethlyene unless otherwise noted. Tests involved a cylindrical 18-in-diameter tank filled with water to a height of 14.4 in except as otherwise noted. The test cases were as follows:

1.) low-density particles (0.45 g/cc) two layers thick,
2.) high-density particles (0.8 g/cc) two layers thick,
3.) low-density particles, two layers thick, in 25% by weight salt water,
4.) high-density particles, two layers thick, in 25% by weight salt water,
5.) an even mix of high- and low-density particles one layer thick,
6.) an even mix of high- and low-density particles two layers thick,
7.) an even mix of high- and low-density particles three layers thick,
8.) an even mix of high- and low-density particles four layers thick,
9.) roughly cubic particles of closed-cell foam PVDF of 0.5-in-long sides and two layers thick,
10.) O-rings 0.5-in wide made of polyethylene (to be compared with previous work with polyethylene particles), and
11.) a single layer of mixed high- and low-density particles in a 28-in-diameter tank.

Collectively, these test cases, combined with previously obtained data, will clarify the effect on slosh suppression of the following parameters — the material density of the particles, the individual particle shape/geometry, the number of particle layers, and the scaling of slosh suppression with tank size.

SUMMARY

Our previous year's result shows one or more layers of floating particles provide significant damping, but it is questionable whether the effect scales well to larger tanks. This is a major question that the yet-to-be analyzed data collected this year using a 28-in-diameter tank will help answer. Data taken last year show that particles with larger surface area-to-mass ratios provide better damping. For the same material type/density, particle diameter, and total mass of particles, the data show that spheres, right cylinders, and then annular particles are progressively better at slosh suppression. This implies that the total surface area of the particles has a significant effect on slosh suppression. The test data obtained this year will help to clarify this effect as well. Finally, analysis of the recently obtained data will allow optimization of damper material density relative to the fluid. This is an effect which has not been previously examined.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: James Patton Downey, Russell Parks, Ravi Purandare

FUNDING ORGANIZATION: Center Innovation Fund

Combustion Stability Tool Development Project

OBJECTIVE: *To use Marshall Space Flight Center design development test and evaluation capability to generate multi-element thrust chamber validation data (stable and unstable desired) and to support before, during, and after the test program with performance, combustion stability, and thermal assessments.*

PROJECT DESCRIPTION

The Combustion Stability Tool Development (CSTD) program, funded by the Air Force Space and Missile Systems Center, was tasked to develop a predictive tool for combustion stability of oxidizer-rich staged-combustion (ORSC) engine thrust chambers. As part of this program, NASA Marshall Space Flight Center (MSFC) Engineering was contracted to design, fabricate, assemble, and hot-fire test a multi-element integrated test rig (MITR) demonstrating combustion characteristics of a representative oxygen/hydrocarbon propellant ORSC engine thrust chamber. The primary objective of this hardware and test program was to provide hot-fire combustion dynamic data to validate the combustion stability analytical tool.

The MSFC design, development, test, and evaluation (DDT&E) capability was used to generate multi-element thrust chamber validation data in both stable and unstable combustion conditions. MSFC Engineering supported the project before, during, and after the test program with performance, combustion stability, and thermal assessments. Multiple lessons learned were gained along the way for the MSFC Engineering team, including new analysis processes for structural/fluid/thermal assessments, and the first hot-fire demonstration of an additively printed 3D copper injector faceplate.

FIGURE 1. 3D-printed copper faceplate.

ACCOMPLISHMENTS

The MSFC engineering team, consisting of members from the Propulsion, Materials, Test, and Space Systems Departments, successfully designed a unique combustion test article utilizing a combination of existing and new components. The Propulsion Department led the design effort, which utilized expertise from hardware design, advanced computational analyses, and manufacturing groups to create a first-of-its-kind test article to generate the validation data required by the Air Force Space and Missile Systems

FIGURE 2. Combustion test article hot fire.

Center (AF-SMC). Fabrication of the new test article components was performed in part using the Materials and Space System Departments capabilities, and testing was conducted at the MSFC East Test area by the Test Laboratory. Testing was successfully conducted, producing the first domestic dataset for ORSC combustion data.

SUMMARY

The MSFC Engineering team completed a multiyear effort in the design, fabrication, test, and analysis of a subscale ORSC integrated test article. Multiple injector types and tests were conducted to provide the Air Force with the requested combustion stability dataset sought after. This unique dataset was provided AF-SMC within the project's need dates, and the MSFC team was commended by the Air Force for their expertise and timely delivery.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Robert Jeremy Kenny

PARTNERSHIP: Air Force Space and Missile Systems Center

FUNDING ORGANIZATION: ST23

IN-SPACE PROPULSION SYSTEMS

Production and Hot Hydrogen Testing of Molybdenum Matrix Ceramic Metallic Fuels for Nuclear Thermal Propulsion

OBJECTIVE: *To produce molybdenum matrix ceramic-metallic fuels via spark plasma sintering and test hot hydrogen to assess their feasibility for nuclear thermal propulsion applications.*

PROJECT DESCRIPTION

Through the use of a hydrogen (H2) propellant, nuclear thermal propulsion (NTP) is a nonchemical propulsion technology capable of high specific impulse (850–900 s) and thrust (100–1,100 kN), allowing for reduced trip times for crewed missions to beyond lower Earth orbit. Neutronic analyses, undertaken by NASA partners, have predicted that low enriched uranium-(LEU-) fueled nuclear thermal rockets (NTRs) with <20% uranium-235 (^{235}U) enrichment can be designed to allow for comparable performance to high enriched uranium (HEU) alternatives. LEU engine designs are anticipated to significantly reduce the perceived high maintenance costs and political hurdles traditionally associated with developing HEU NTP systems. The successful development of a LEU engine requires the affordable production and qualification of a fuel form—which allows for operation in excess of 2,500 K—resists interaction with the hydrogen propellant, and exhibits the nuclear properties to enable engine criticality with reduced uranium enrichment. Through this Center Innovation Fund (CIF) project, molybdenum (Mo) matrix ceramic metallics (cermets) were produced via an innovative direct current consolidation technique and hot hydrogen tested using surrogate materials in place of the uranium dioxide (UO_2) particles.

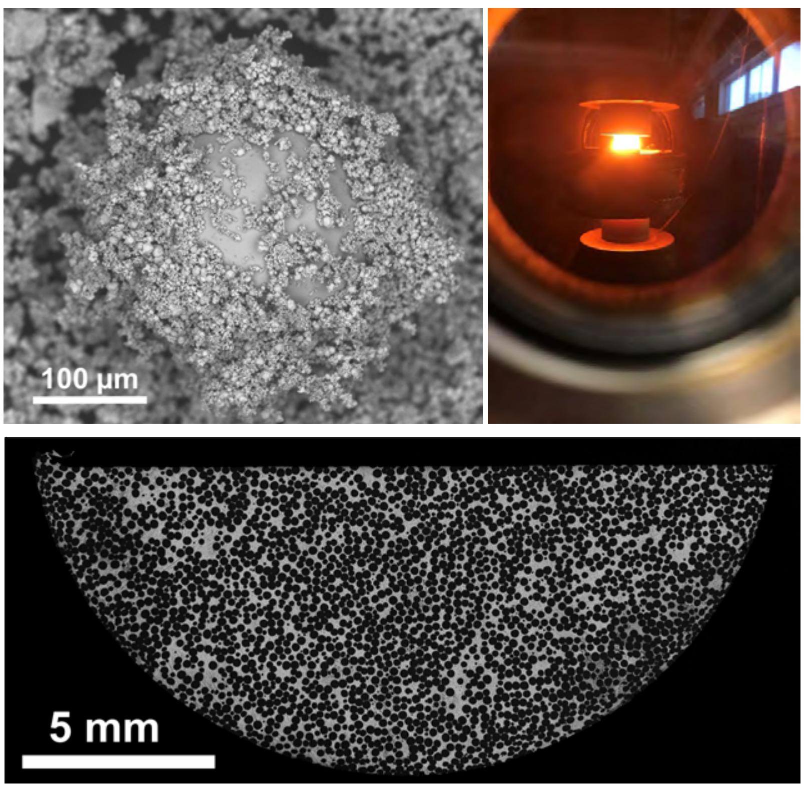


FIGURE 1. Blended Mo-ZrO_2 powders (top left) are consolidated into cermet wafers with desirable microstructures (bottom) for NTP applications using spark plasma sintering (top right).

Key objectives of this work include production, testing, and characterization of Mo-matrix cermets for NTP applications. The innovation in this work was to evaluate Marshall Space Flight Center's (MSFC's) capability to produce cermet wafers using alternative metal matrix materials and innovative, modern consolidation techniques, thereby reducing process times and temperatures. Use of a two-step powder blending, spark plasma sintering (SPS) approach has the potential to attain more desirable cermet microstructures, compared to traditional hot rolling or hot isostatic pressing processes, to enable higher performance NTP systems. Reduction in process time and temperatures can allow for more affordable manufacture of an engine on a production scale as well as more optimal conditions for sintering of the ceramic fuel, which is susceptible to reduction (microstructural degradation) at high temperatures. Other innovations from this work approach include the development of a congruous microstructural characterization-verification test plan to evaluate and qualify cermet microstructural stability in a relevant environment. Although

Schedule of Technical Accomplishments and Milestones	Completion Date
Feedstock Powder Vendor Identification and Procurement	October 2017
Feedstock Powder Characterization	December 2017
Demonstration Cermet Production	December 2017
Hot Hydrogen Test Plan Report	December 2017
Demonstration Thermal Cycle Testing of Cermet Sample	May 2018
Powder Blending Optimization Study Completion	May 2018
Sintering Parameter Optimization Study Completion	July 2018
CIF Short Video Production	July 2018
Hot Hydrogen Testing (2,000 K) Completion	August 2018
Hot Hydrogen Testing (2,250 K) Completion	October 2018
End-of-Year Reporting	October 2018

TABLE 1. Technology development milestone accomplishments and completion dates.

return on investment is not typically reported as a merit for CIF projects, the research conducted through this CIF has allowed for future development investment on the order of $800K. With the successful demonstration and testing of Mo-cermets with desirable microstructures, continued development to investigate net shape manufacture and scalability is being supported as a part of the NTP development project as a Fiscal Year 2019 risk-reduction task.

ACCOMPLISHMENTS

In this project, over 20 cermet samples have been fabricated to explore the effect of SPS parameters (dwell time, sintering temperature, pressure) and test environment on cermet performance and microstructural stability. Sintering and powder-processing parameters were optimized to identify requirements for repeatable production of high-density Mo-cermets with desirable microstructures. Cermets with ceramic fuel particle loadings of 40, 50, 60, and 70 vol% have been demonstrated using a zirconium dioxide (ZrO_2) surrogate for uranium dioxide (UO_2). Tested cermets retained structural integrity with minimal mass loss in both steady state and thermal cycling conditions; anticipated use temperature of Mo-cermet fuels is 2,250 K for a minimum of 80 min operation time. Proposed NTP engine lifetime at maximum temperature may be as low as 30 min based on available trajectories; higher Mo-cermet use temperatures may be feasible for reduced engine lifetimes. Ongoing university efforts include microstructural evaluation to understand evolution in the structural matrix properties and compositional stability of the ceramic fuel surrogate. It is desired to understand if fuel volume loading in the surrogate impacts anticipated service lifetime. Lessons learned from this project include a more nuanced understanding of the powder blending process and post-processing required for synthesizing repeatable, high-quality fuel coupons.

SUMMARY

Molybdenum cermets for NTP applications have been produced via a two-step powder blending SPS process. Produced subscale samples coupons with cermet microstructures containing volume loadings of 40–70% ceramic particles have been demonstrated. Production parameter optimization has been performed and as-produced sample microstructures characterized to enable identification of production parameters, which allow for the most desirable sample microstructures, as produced samples have been tested under steady state and thermal cycling conditions in hot flowing H_2 at relevant timescales (up to 80 minutes) and temperatures (up to 2,250 K) for NTP relevant conditions. Samples retained structural integrity throughout testing with minimal mass loss. Upcoming testing is planned to test cermet fuels under extreme temperatures (2,500, 2,750 K) in NTP relevant environments. Forward work aims to work to transition production processes from the lab scale to the production scale include assessing geometry, scalability effects, and integration of relevant cladding techniques in order to demonstrate full-length fuel elements. Future verification testing should aim to test Mo cermets to failure in order to characterize total temperature dependent lifetime capability, as well as probe the effect of hydrogen pressure and flow rate on cermet fuel failure mechanisms.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Marvin Barnes and Kelsa Benensky.

PARTNERSHIP: Steven Zinkle, The University of Tennessee

FUNDING ORGANIZATION: Center Innovation Fund

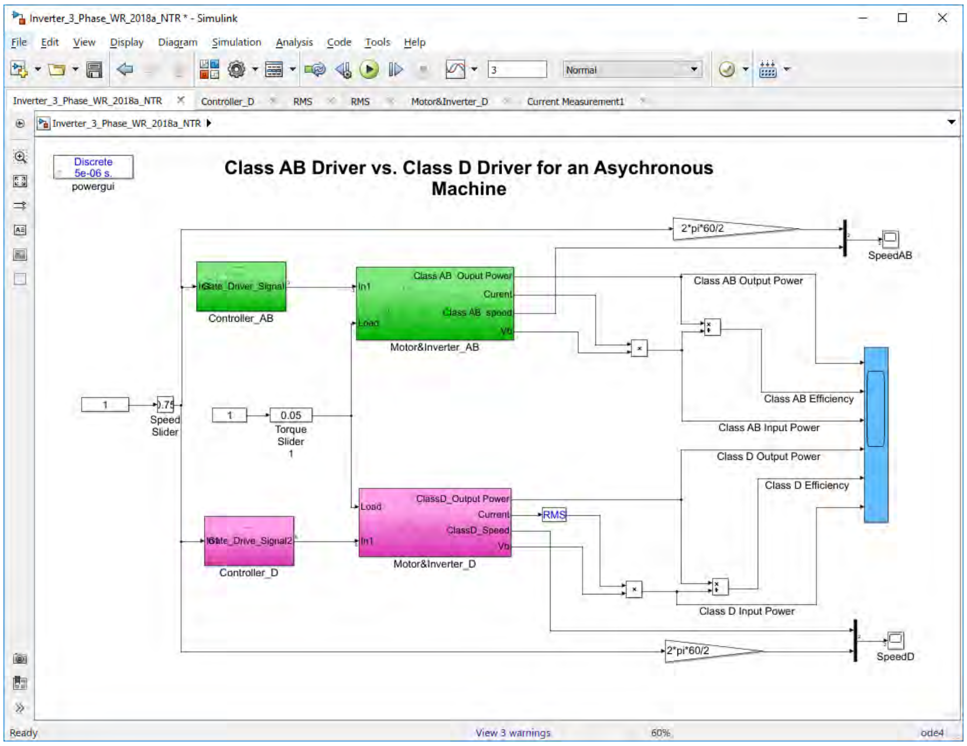
A Novel Hybrid Variable Speed Drive With Improved Efficiency And Reliability

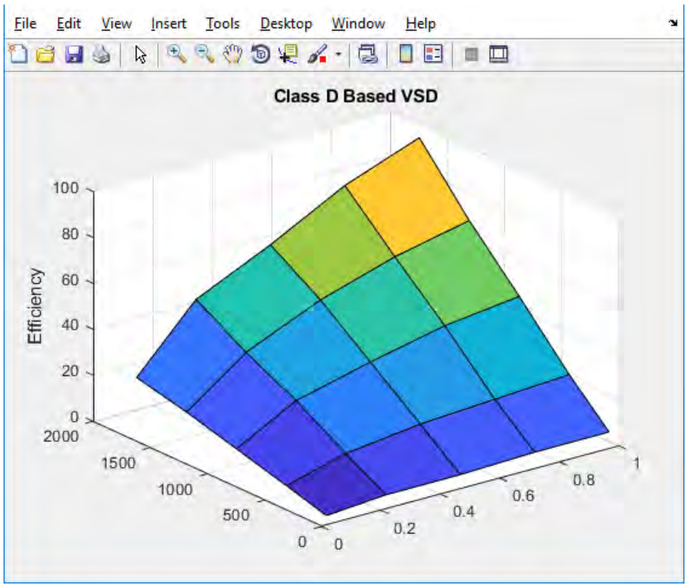
OBJECTIVE: *To increase the efficiency of a variable speed drive (VSD) to reduce the demand on the energy resources. In the case of batteries, doing this will increase the vehicle range. As a beneficial side effect, it also improves the inverter life. It also reduces conducted and radiated electromagnetic interference.*

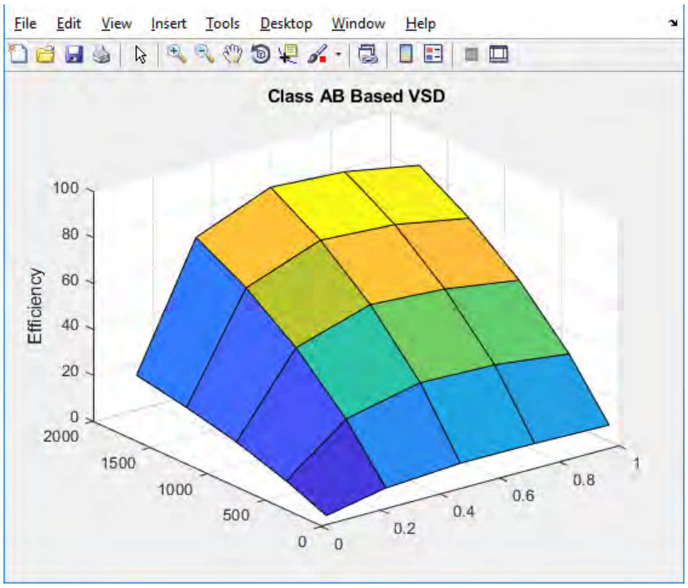
PROJECT DESCRIPTION

Variable speed drives (VSD) have found extensive application in terrestrial and space-based applications. A novel hybrid VSD motor controller is proposed, and improvements in efficiency, extended component life, and reduced emissions of electromagnetic interference (EMI) are expected. The hybrid VSD controller uses an inverter based on both Class AB and Class D amplifier topologies. Under certain operating conditions, inverters based on Class D topologies are most efficient, while under other operating conditions Class-AB-based topologies become more efficient. The hybrid VSD controller automatically chooses the topology optimized to the operating condition.

Because complex electromechanical systems are best studied, and optimized, via mathematical modeling and computer simulations, a hybrid VSD controller model was developed. Subsequent to this effort will be the construction of a 2-kW prototype of the proposed controller. This prototype will verify theoretical results using a dynamometer to evaluate the hybrid VSD controller based on performance and efficiency of the overall system under a wide range of operating condition.







ACCOMPLISHMENTS

In 2018, we have successfully developed the mathematical models and completed initial simulations of the proposed hybrid VSD system. The MATLAB modeling and simulation environment was the main tool used for this activity. The results are very promising. This work has shown that a VSD system based on the Class D topology is most efficient only at maximum speed and maximum torque conditions, whereas a Class AB-based VSD is more efficient at lower speeds and lower torque operating conditions.

SUMMARY

Energy efficiency and system reliability have paramount importance for space vehicles as well as for terrestrial systems. The novel hybrid VSD that we propose should provide higher energy efficiency and increased reliability over a wide range of operating conditions. We wish to construct a prototype to verify these important theoretical results.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Haik Biglari

PARTNERS: David Young, Blake Stuart, Nicholas Mateo

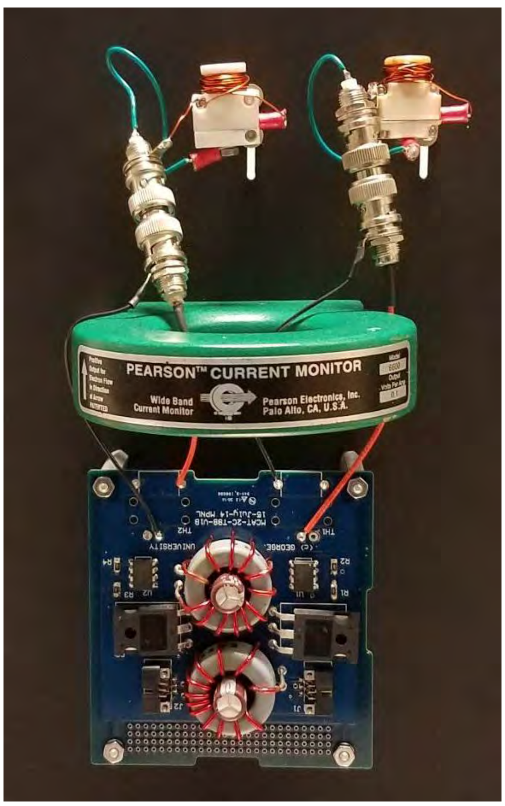
FUNDING ORGANIZATION: Seedling Investment Program

Micro-Cathode Arc Thruster Technology For Attitude Control And Primary Propulsion For Small Spacecraft

OBJECTIVE: *To bring the Micro-Cathode Arc Thruster technology along the path to qualification as a propulsion solution for secondary payloads launched on NASA's Space Launch System (SLS).*

PROJECT DESCRIPTION

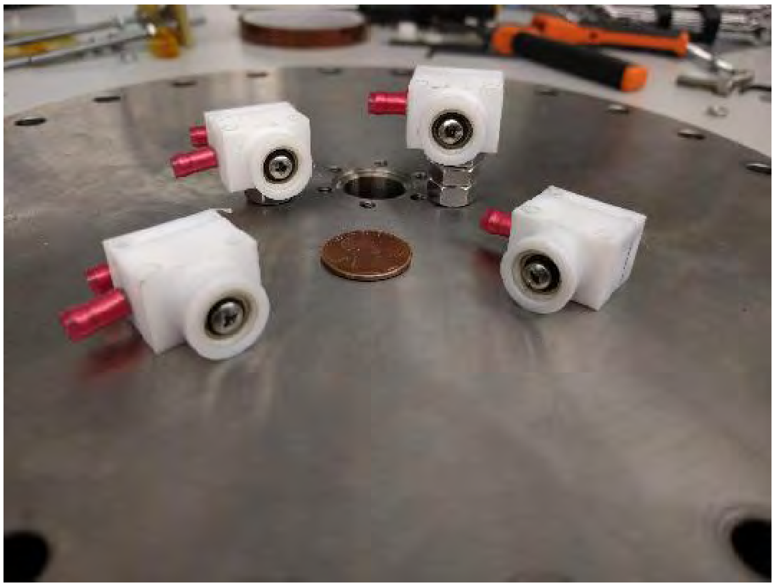
The Micro-Cathode Arc Thruster (µCAT) system has been flown on Ballistic Reinforced Communication Satellite (BRICSat-P), which is a 1.5U CubeSat mission led by the United States Naval Academy (USNA). Preliminary reports show that the propulsion system was capable of detumbling the satellite to a rate of less than 1°/s on all axes within 48 hr of deployment. The system is scheduled to fly on two more missions within the next 12 months. Even though this system has flown before, it is not a matured technology; therefore, steps must be taken to advance this technology to higher test readiness levels (TRLs). It is for this reason that George Washington University (GWU) partnered with NASA Marshall Space Flight Center (MFSC) to improve and mature the technology.



The goal is to bring the µCAT technology along the path to qualification as a propulsion solution for secondary payloads launched on NASA's Space Launch System (SLS). This high goal, if achieved, would mature the µCAT technology to the broadest possible infusion potential. The proposed high-level phased tasks are to evaluate, evolve, and apply the technology to this goal. Task 1 was to perform an extensive evaluation of the µCAT's performance from beginning of life (BOL) to end of life (EOL). Successful completion of this objective will establish a substantive baseline from which engineering decisions can be made regarding how performance can be improved by applying advanced manufacturing techniques, making modifications to operational parameters, or selecting new materials. Task 2 was to apply the engineering improvements formulated in phase 1 for both thruster and controller electronics in order of precedence as assessed considering priority, time, and funding. Areas of known interest are improvement in thrusts, efficiency, life, graceful degradation, reliability, and manufacturing. GWU will lead the overall evolution of the µCAT with MSFC offering consultation and design support. Task 3 will be to advance to a preliminary design phase maturity a new CubeSat propulsion system for a 6U CubeSat that incorporates both a green propellant hot gas thruster(s) used for primary delta-v maneuvers and the µCAT thrusters used for three-axes attitude control or momentum wheel desaturation. MSFC will manage the design of the hybrid propulsion module. GWU will be available to consult on the design. The application phase may be advanced to an integrated hardware demonstration article if schedule and funding permitted.

ACCOMPLISHMENTS

MSFC and GWU have completed task 1. A successful evaluation program was performed at MSFC, including a detailed evaluation of electrical, electronic, and electromechanical components selection, board-level



design, workmanship, and a 'flatsat' test firing campaign at MSFC. MSFC has completed task 2 inputs to GWU, making recommendations on improvements to thrusters, controller electronics, and conops. GWU is currently working on implementing task 2.

SUMMARY

CubeSats represent a strongly growing market in the field of small satellites. Their small size and relatively short development time make them perfect for universities and small companies that wish to test new technologies on orbit. Moreover, CubeSats with propulsion systems are becoming more and more common. As new technologies are developed or existing technologies get smaller and more power-efficient, CubeSats are being used for new and incredible missions in and beyond Earth orbit. Even a modest propulsive capability would help a CubeSat compensate for atmospheric drag and perform station-keeping maneuvers, allowing it to stay in orbit longer, maintain higher pointing accuracy, and conduct better science. When appropriate and complimentary propulsion technologies are paired together, new and innovative hybrid propulsion systems can unlock many new missions. The µCAT developed at GWU caters specifically to the small satellite community. The technology is scalable and could be used for satellites of up to 50 kg in mass, which would roughly represent a 54U CubeSat.

The µCAT is an electric propulsion system that is based on the well-researched ablative vacuum arc or 'cathodic arc' process. Cathodic arcs have been known for several centuries. This physical phenomenon is known to erode the negative electrode (cathode) with every discharge. In this case, this is highly desirable, as the cathode is the thruster's propellant. Therefore, during each discharge, a small amount of metallic propellant is eroded, ionized, and accelerated. The efficiency is enhanced by a magnetic field. The magnetic field is caused by the arc current as it travels through a magnetic coil prior to arcing between the electrodes. Due to the physical nature of the arc discharge, any conductive material can be used as a propellant, as long as it is solid. This allows the thruster to operate with different metals, each with different physical properties, giving the mission designer flexibility when it comes to the mission's design.

PROJECT MANAGERS AND/OR /PRINCIPAL INVESTIGATORS: Daniel Cavender, Marshall Space Flight Center; and Michael Keidar, George Washington University

PARTNERSHIP: George Washington University

FUNDING ORGANIZATION: Cooperative Agreement Notice

Mars Ascent Vehicle

OBJECTIVE: *To thermally and structurally characterize SP7 fuel to be used in the Mars Ascent Vehicle hybrid motor.*

PROJECT DESCRIPTION

The Mars Sample Return mission concept (fig. 1) is being considered for launch as early as 2026, so technology development to enable this potential campaign is currently underway. One of the critical items in the campaign is a Mars Ascent Vehicle (MAV), which is responsible for getting the samples from the surface of Mars to orbit around Mars. This will be the first rocket launched from another planet. A technology development program to determine the feasibility of a hybrid rocket for an MAV is entering its fourth year. Major risk areas have been identified for mitigation over Fiscal Year 2018–2019. At that point, the goal is for the technology to be well enough understood to select it (or not) for the development-and-qualification timeline leading to a potential 2026 launch. NASA Marshall Space Flight Center (MSFC) tasks related to fuel grain manufacturing include SP7 material properties assessment, MAV fuel grain manufacturing for hot-fire testing, coefficient of thermal expansion (CTE) of fuel and liner mismatch investigation, environmental cycling of a loaded motor, and SP7 residual stress analysis.

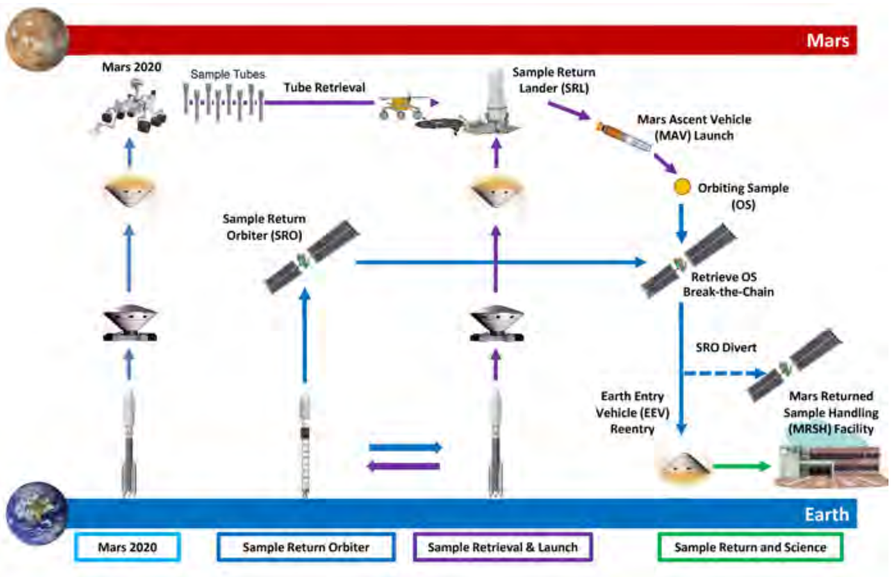


FIGURE 1. Mars sample return overview.

The hybrid fuel chosen for the MAV vehicle is a wax-based material designated SP7. SP7 was developed specifically for this application. It has a higher melt temperature and viscosity than neat paraffin. MSFC has successfully scaled up the grain to the full-scale diameter and has segmented the grain to reach the overall length needed. The grains are poured larger than needed and cooled in a temperature-controlled oven (fig. 2). This process takes approximately 1 wk. After cooling, the grains are machined to the desired inner and outer diameter and face on both sides (fig. 3). Typically, one MAV fuel grain is made up of four segments.

SP7 has interesting phase change properties and a high coefficient of thermal expansion. In transition from the liquid to solid phase, the material shrinks 15–20%. The material cools from the outside inward. A solid crust

FIGURE 2. Oven cooldown of SP7 grains.

FIGURE 3. Three of four segments making up a full-scale fuel grain are shown being packaged for shipment.

forms on the outer sections as they cool first, and the inside cools slowly and retracts as the heat is removed. Therefore, the inside of the grains pull on the outside, leaving residual stresses within the segment.

Modeling efforts to understand the stress state are planned; however, SP7 properties need to be characterized more. Commercially available software is going to be used for this phase change problem, but it needs specific property data. Southern Research, Inc., is doing the material property testing on the SP7 to feed into the model.

Initial investigation into annealing the grains after manufacturing has led to success in removing some of the residual stress. The process is shown to change the SP7 material properties in samples cut from ambient cooled grains but has not been attempted for the oven cooled grains. The oven cooling processes reduces the residual stress, but there is potential that further reduction could still be achieved by subjecting the grains to another heating cycle after they have been processed. Additional testing with the oven cooled samples in currently in process.

ACCOMPLISHMENTS

Two vendors, Space Propulsion Group (SPG) and Whittinghill Aerospace (WASP), have completed hybrid motor testing at near full scale (fig. 4) over the past year and a half. At the end of the testing campaign, the vendors delivered motor designs for the Mars application. Both were heavier than desired for flight. With the benefit of knowledge from both vendors, a new design has been put forth by the NASA team focusing on simplicity to minimize system mass. The two companies have been asked to join forces and work at improving this single motor design going forward.

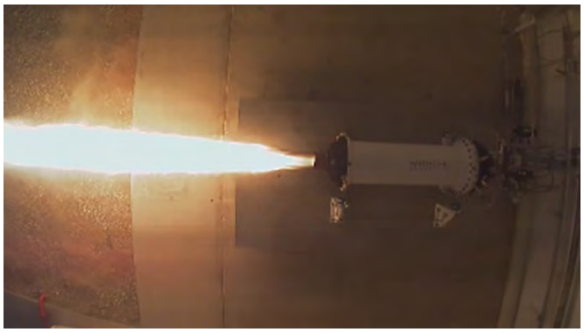


FIGURE 4. WASP motor firing.

SUMMARY

The goal of this technology development program is to have demonstrated the major milestones required for a hybrid MAV design that closes under the current assumptions. A substantial amount of research will be required to ensure the possibility. The highlight of this effort will be testing of a thermal-cycled, full-scale hybrid motor under relevant conditions. To realize that goal, the propellant combination must be fully characterized and hot-fire testing must be completed to confirm the behavior and all potential materials need to be analyzed. Trades will be carried out on many design features, including motor case materials. The potential design is continually updated based on the developments of the development program. The goal is to demonstrate a design that closes by the end of Summer 2019.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Angie Jackman, Jessica Chaffin, George Story

PARTNERS: NASA Jet Propulsion Laboratory and NASA Ames Research Center

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://mars.nasa.gov/

Analytical Mechanics Associates Green Propellant Piston Tank

OBJECTIVE: *To develop a novel propellant tank with an integrated propellant management system for green, economical propulsion systems for small satellites up to 50 kg.*

PROJECT DESCRIPTION

The overall objective of the Analytical Mechanics Associates (AMA) Green Propellant Piston Tank project was to develop a novel tank design that employs an internal piston pressurized with an inert gas to expel propellant to thrusters. This tank offers an integrated propellant management device that has high reliability, large blowdown ratio, low friction, and high expulsion efficiency. Completion of a recent Cooperative Agreement Notice (CAN) activity resulted in the design, fabrication, and testing of a prototype, sized for a 3U CubeSat system. The knowledge gained through this activity gave evidence that the piston tank design may be scalable to meet the requirements and constraints of other small satellite systems.

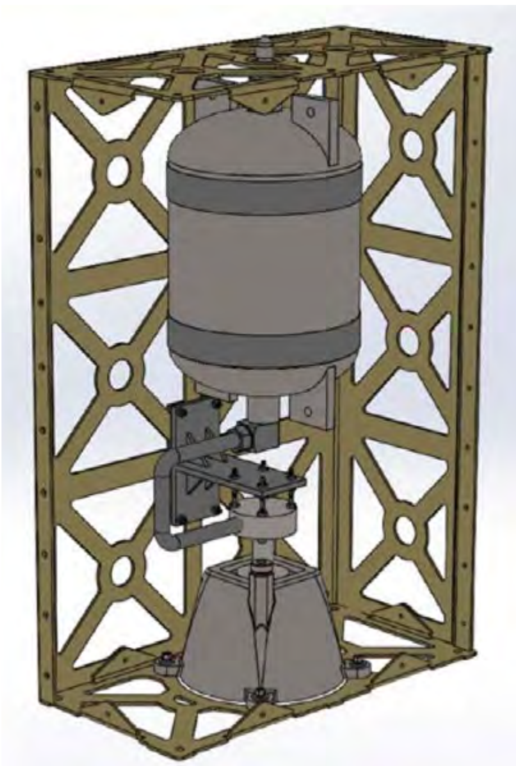


FIGURE 1. GEPS concept.

A key technical challenge of this tank was determining the shape of the piston. During the design phase, different piston shapes were compared. The piston shape chosen offers a high propellant-to-tank mass ratio (i.e., high usable-propellant storage volume). The piston shape also allows for a high blowdown ratio of 4:1.

Another key technical challenge was finalizing the design of the piston seal bearing. Two different bearing designs were tested. This allowed for AMA to down select to a final design. The chosen seal bearing design showed to prevent cocking of the piston, while maintaining low static and dynamic friction. Multiple test trials demonstrated repeatable flow characteristics in both steady state and pulsing modes. The use of multiple surrogate fluids demonstrated usefulness of the tank with both AF-M315E and LMP-130S.

FIGURE 2. Prototype tanks.

This tank design shows potential for use for many SmallSat propulsion system (up to 50 kg). The tank was designed specifically to be compatible for use with green propellants (e.g. AF-M315E and LMP130S).

ACCOMPLISHMENTS

At the end of the CAN activity, the follow tasks were completed: (1) design of tank prototype, (2) structural and thermal analysis, (3) propellant tank prototype manufacturing, and (4) propellant tank blowdown/cold flow testing demonstration. The cold flow tests demonstrated the tank's functionality with both surrogate fluids representing AF-M315E and LMP-103S propellants in both pulsing and steady state modes of operation. The tests also showed consistent, repeatable flow characteristics. By the conclusion of the CAN activity, the test readiness level (TRL) of this technology was raised from TRL 2 to TRL 4.

SUMMARY

AMA has developed a piston propellant tank design tailored for use in Green Propellant SmallSat propulsion system application. AMA, in collaboration with the Marshall Space Flight Center, was able to build and test a prototype over the performance period of a CAN activity. The activity results in maturing the technology from TRL 2 to TRL 4.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: John Abrams

FUNDING ORGANIZATION: Cooperative Agreement Notice

Nuclear Thermal Propulsion

OBJECTIVE: *To develop a low enriched uranium (LEU) nuclear thermal propulsion system that is the most promising advanced in-space propulsion option for crewed missions as well as a safe, affordable game-changing technology for space propulsion that enables faster trip times, safeguards astronaut health, and provides abort scenarios not available from other propulsion architectures.*

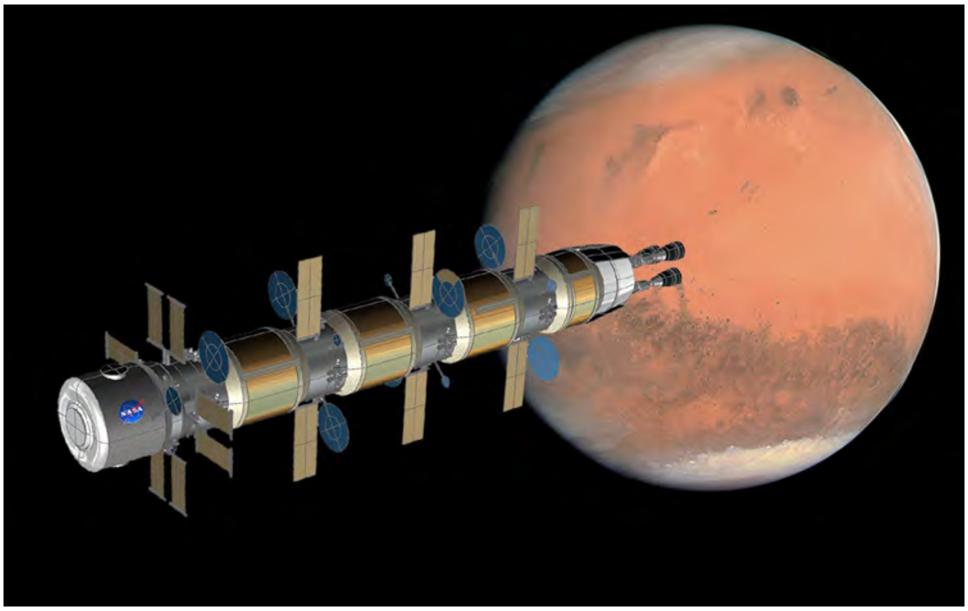
PROJECT DESCRIPTION

NASA's history with nuclear thermal propulsion (NTP) technology began in the earliest days of the Agency in 1958. Since then, consistent recognition exists that an NTP system offers significant advantages for operations for human Mars missions and in cislunar space. NTP could also enable highly advanced science and exploration missions, and power systems derived from NTP could enable a power-rich environment anywhere in the solar system (or beyond). The current NTP Project objective is to determine LEU NTP feasibility and affordability with good cost and schedule confidence. The use of LEU offers potential advantages for a nuclear propulsion program that may include less burdensome security regulations similar to those for a university research reactor. This opens the development effort to partnerships with industry and academia. The project is focused on the establishment of a conceptual design for an NTP LEU engine in the thrust range of interest for a human Mars mission, the development of technologies that enable the robust production of LEU fuel elements and reactor core, and demonstration of the feasibility of exhaust capture methods that can be used to test operations of a subscale nuclear rocket engine.

One of the challenges to NTP development is maturing the technologies for fuel production and fuel element manufacturing that meet the extreme temperature requirements for an NTP engine not required by commercial power reactors. The current project is pursuing a multifaceted approach using an LEU fuel system with a refractory metal-based fuel element. The strategy includes axial zoning for fuel element structures of 'cold-end' cans of molybdenum alloy and 'hot-end' cans with a molybdenum tungsten alloy. Tests of small segments will be performed in the NASA Marshall Space Flight Center Compact Fuel Element Tester (CFEET) in fiscal year (FY) 2018–2019 and larger development articles in the MSFC Nuclear Thermal Rocket Element Environmental Simulator in FY 2019. A more traditional ceramic metallic (cermet) fuel element development approach is also being pursued in conjunction with the Department of Energy, with small segments to be tested in the Idaho National Laboratory Transient Reactor Test facility in FY 2019.

ACCOMPLISHMENTS

The Project demonstrated the feasibility of a stacked and bonded fuel element fabrication approach and successfully tested a fuel element segment in CFEET at elevated temperature in a pure hydrogen environment. Additional updates were completed to the engine performance and feasibility analysis that met NTP driving requirements. A draft NTP Technology Maturation/Ground Demonstration Plan was completed detailing NTP integrated engine development to a technology readiness level (TRL) 6, including engine, fuel, reactor and facilities development. The project assessed multiple reactor concepts and identified fuel and core manufacturing options culminating in a recommended alternate fuel development approach. The project also completed an initial LEU cost analysis report that provided an in-depth preliminary system cost analysis including a cost summary, breakdown, risk analysis and drivers, and opportunities for cost savings.



SUMMARY

NTP is directly relevant to the Agency's vision, mission, and long-term goal of expanding human presence into the solar system and the surface of Mars. As missions aim for targets farther out into the solar system, nuclear propulsion may offer the only viable technological option for extending the reach of exploration, where solar panels can no longer provide sufficient energy, and chemical propulsion would require a prohibitively high mass of propellant and/or prohibitively long trip times. NTP provides the fastest trip time of all currently obtainable advanced propulsion systems. Fast trip times will safeguard astronaut health by reducing exposure to zero gravity and cosmic radiation. Reduced travel time also reduces risks associated with reliability uncertainties inherent in complex systems as well as those associated with life-limited, mission-critical systems. NTP also enables mission abort options not available from other propulsion architectures for human Mars missions.

PROJECT MANAGER: Sonny Mitchell

PRINCIPAL INVESTIGATOR: Michael G. Houts

FUNDING ORGANIZATIONS: Game Changing Development

FOR MORE INFORMATION: http://gameon.nasa.gov/

Near-Earth Asteroid Scout

OBJECTIVE: *To use a solar sail to propel a small spacecraft on a 2.5-yr mission to explore an asteroid.*

PROJECT DESCRIPTION

Before committing a crew to visit a near-Earth asteroid (NEA) or Mars moon, it is important to send precursor robotic reconnaissance mission(s) to assess their suitability for future human exploration. The NEA Scout, scheduled to launch in 2020, will use its solar sail propulsion system to send a small spacecraft to flyby asteroid 1991VG, providing important images and scientific measurements. Solar sails 'sail' by reflecting sunlight from a large, lightweight, reflective material that resembles the sails of 17th- and 18th-century ships and modern sailing ships. Similar to how a ship uses the wind to sail, the solar sail derives thrust by reflecting solar photons. While the force exerted by sunlight is extremely small, it is relatively constant, resulting in a slow-but-constant acceleration that pushes the sail, and the spacecraft attached to it, to higher and higher speeds with minimal use of fuel for reaction control. Elements of NEA Scout are being developed at NASA Marshall Space Flight Center (MSFC), NASA Jet Propulsion Laboratory, and NASA Langley Research Center. MSFC manages the mission and is developing the 86-m^2 solar sail propulsion system onsite.

The NEA Scout spacecraft is housed in a 6U CubeSat form factor. A CubeSat is a very small spacecraft built on a modular design architecture of 10 × 10 × 10-cm cubes. Each cube is called a 'U' and is typically allocated about 2 lb of total mass. A spacecraft can then be built by combining these cubes together.

The innovations are the design, development, and test of a solar sail system that fits within such a small volume and that is capable of providing the propulsion required for the mission and the flight control system that will manage the sail's continuous low thrust throughout the flight. The solar sail is a single sheet deployed on four booms from the center 2U of the 6U spacecraft. The solar sail subsystem consists of a single 86 m^2 colorless polymer (CP1), 2.5-μ-thick aluminized sail that will sit on top of and be deployed by four

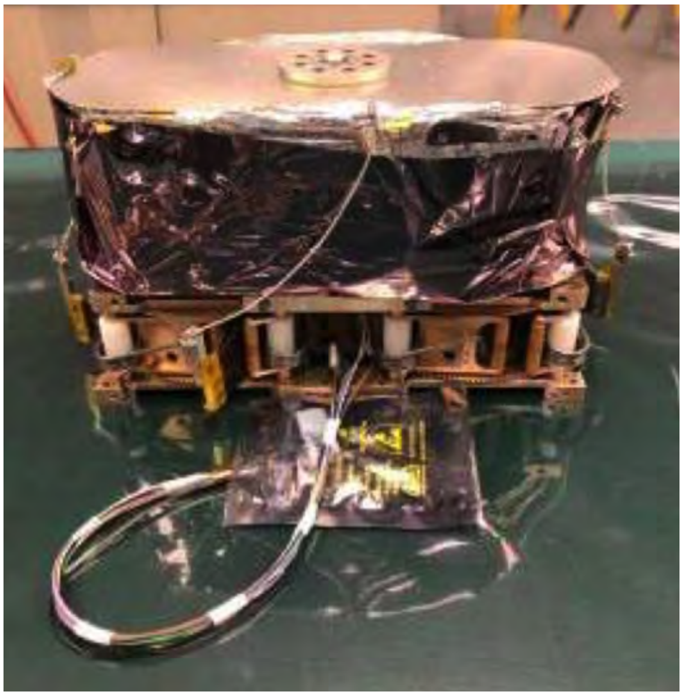


FIGURE 1. The NEA Scout solar sail and booms integrated into the deployment system before deployment.

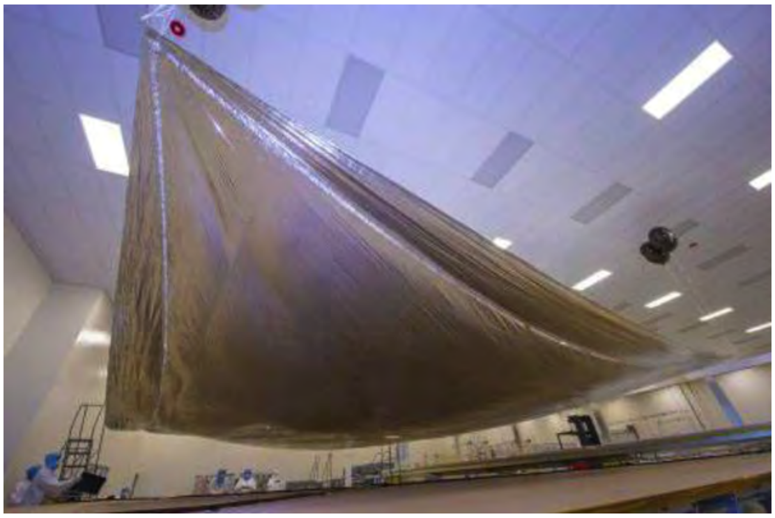


FIGURE 2. The NEA Scout flight sail was lofted for inspection after its successful deployment.

Elgiloy (stainless-steel alloy) booms integrated with an active mass translation (AMT) device to support attitude control of the spacecraft. Key objectives for the year included testing the solar sail and AMT subsystems. These two subsystems will be integrated into the spacecraft and delivered to the launch site next year.

ACCOMPLISHMENTS

The 86-m^2 flight solar sail and 6.8-m Elgiloy TRAC booms were integrated into the deployer and completed a successful full deployment and thermal vacuum tests. The AMT, developed to correct for the offset in the center of mass (CM) and center of pressure (CP) in the solar sail flight system, resides near the geometric center of NEA Scout and adjusts the CM by moving one portion of the flight system relative to the other. The flight AMT is currently in integration and will complete thermal vacuum testing in the first quarter of fiscal year 2019.

SUMMARY

The NEA Scout will demonstrate the feasibility of using a low-cost, solar-sail-propelled CubeSat on an asteroid reconnaissance mission. If successful, it will be the USA's first interplanetary mission propelled by a solar sail and a pathfinder for many potential missions using sail technology in the future.

PROJECT MANAGER: Joe Matus

SOLAR SAIL PRINCIPAL INVESTIGATOR: Les Johnson

SCIENCE PRINCIPAL INVESTIGATOR: Julie-Castillo Rogez

PARTNERS: NASA Jet Propulsion Laboratory and NASA Langley Research Center

FUNDING ORGANIZATION: Advanced Exploration Systems

FOR MORE INFORMATION: https://www.nasa.gov/content/nea-scout

Characterization of a Low-Temperature Co-fired Ceramic-Manufactured Electrostatic Thruster

OBJECTIVE: *To valuate the operation and performance of a prototype electrostatic thruster.*

PROJECT DESCRIPTION

The goal of the project was to evaluate prototypes of an experimental thruster developed by the University of Arkansas. The design under evaluation is a radio frequency (RF) electrostatic thruster that was fabricated using the low-temperature co-fired ceramic (LTCC) materials and fabrication process. This materials system is analogous to printed circuit board technology, with the most significant difference being that the laminate is replaced by a ceramic material, and the metal sheet is replaced by printed sinterable silver paste. LTCC designs are baked after fabrication and assembly to realize an entirely monolithic structure with internal conductors and cavities. This means that the LTCC electrostatic thruster (LTCC-ET) is a monolithic ceramic thruster capable of withstanding temperatures in excess of 500 °C. The CAN between University of Arkansas and NASA Marshall Space Flight Center (MSFC) was established to test prototypes. The LTCC-ET was tested at MSFC in May 2018 over a 1-wk period. There were two goals for the test program. The first goal of testing was to determine the operating parameters required to create plasma ignition in the test articles. This was explored by setting a propellant flow rate and increasing RF power until plasma ignition was observed and conducted with Argon and Krypton gases. The second goal was to investigate the thrust and specific impulse (I_{sp}) performance of the thruster as a function of propellant flowrate and grid voltage. This goal was not met, as there were technical challenges in maintaining stable plasma ignition.

The impetus for the LTCC electrostatic thruster (LTCC-ET) project came from considering what features a propulsion system purpose-built for interplanetary CubeSats would contain. The ever-growing capabilities of and technologies for CubeSats give rise to more and more ambitious mission concepts. This is evidenced by missions such as MarCo, launched on May 5, 2018, and the 13 CubeSats manifested on the SLS Exploration Mission 1 (EM-1) flight, 11 of which include some form of propulsion including: cold gas, water electrolysis, monopropellant, solid rockets, electrospray, and ion engines. All of these propulsion systems are commercial solutions or custom solutions developed for each mission. The goal of the work conducted for this project was to present a generic alternative rather than a custom solution that could address a wide range of interplanetary mission needs.

The design team sees several key performance factors that need to be met to realize a generic solution for interplanetary CubeSats. First, the system would need to have significant delta-v. This led to an RF electrostatic ion propulsion architecture for its high I_{sp}. Second, limited sunlight and solar panel area constraints interplanetary CubeSats will face lead to a system that has low power needs. This led to a compact design using low-loss materials. Third, the system must be compact given the form-factor considerations of CubeSats. Fourth, the limited power and compact size will lead to low thrust. Therefore, this system would need to have a very long burn time in order to achieve significant delta-v. This led to embedding the electrodes in ceramic for maximum durability. Additionally, the durability afforded by the ceramic makes the thruster compatible with corrosive propellants such as solid subliming iodine, which is of significant interest due to its high propellant density. A fifth factor was not a design goal but is a significant benefit is the scalability of system's manufacturing process. This process enables batch fabrication of highly complex structures for relatively low cost. These considerations, in conjunction to the unique fabrication facilities at the University of Arkansas, lead to the adoption of the LTCC materials system and ultimately the LTCC-ET design.

ACCOMPLISHMENTS

The project has resulted in two specific accomplishments. First, the LTCC-ET was successfully ignited with Argon and Krypton plasma. This was the first time the thruster had ever been ignited and served to

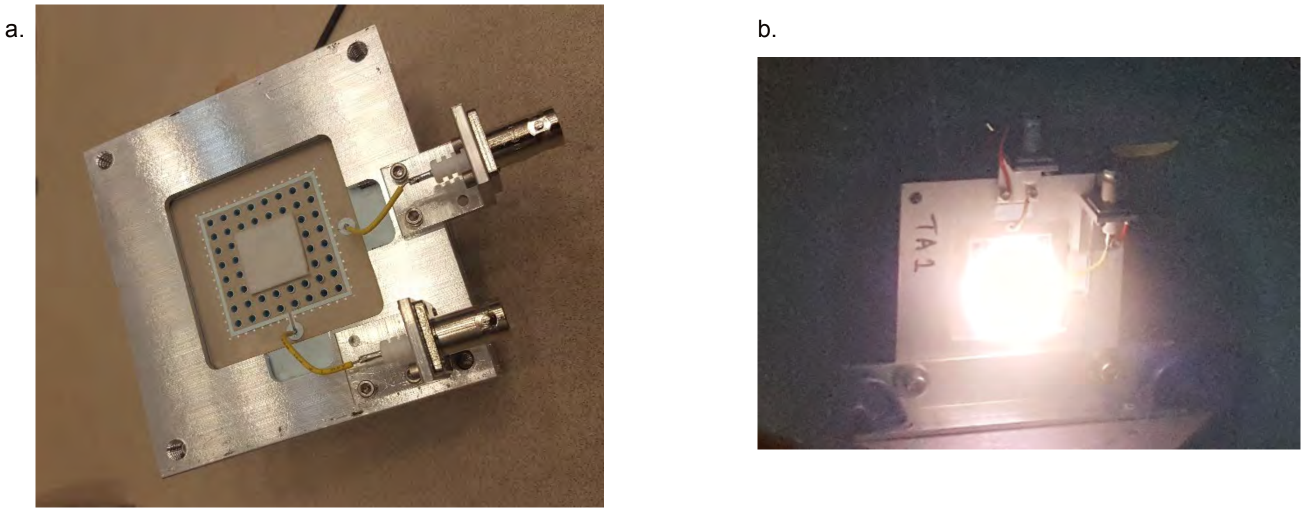


FIGURE 1. Photograph of the LTCC-ET (a) packaged for testing and (b) during a plasma ignition test with Argon gas.

validate the design approach of using the LTCC materials system and an RF parallel-plate ignition technique. This accomplishment gives credence to moving forward with further investigation of the design due to modest success in prototyping and potential value of the technology. The second accomplishment was to determine the ways in which the LTCC-ET prototype is in need of modification. There were technical challenges during the plasma ignition testing that must be addressed. First, the plasma chamber pressure was lower than it should have been, so it took a greater amount of RF power to ignite a plasma that would be seen in an optimized device. This led to heating in RF cables and connectors that caused them to fail and create open circuits. Simple design modifications have been conceived and can now be retrofitted to the existing prototypes to improve their performance by increasing plasma cavity pressure.

SUMMARY

In summary, a prototype thruster design built by the University of Arkansas was tested for the first time ever at MSFC to determine basic performance metrics and functionality. It was determined that the design was not sufficiently optimized for a significant test campaign or characterization program. The propellant outlet orifices must be reduced in size, and RF connectors must be replaced with versions that can handle higher power than what was originally used. However, the LTCC-ET has demonstrated that its design approach is valid and can be improved to realize a working thruster. The design is especially compelling due to its low cost of manufacture and the fact that it is scalable. This means that additional structures can be added to give the design thrust vectoring and exhaust neutralizing functionality.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Adam Huang, John Dankanich, Kurt Polzin, Morgan Roddy

PARTNERSHIP: University of Arkansas

FUNDING ORGANIZATION: Cooperative Agreement Notice

Steerable Tether Deployment CubeSat for In-Space Propulsion and Electric-Sail Deep Space Electrostatic Propellantless Propulsion

OBJECTIVE: *To research and develop electrostatic propulsion CubeSats to deploy 10-km tethers without gravity gradients, small self-contained air-bearing simulators with indoor navigation were assembled to demonstrate the required electrostatic tether deployment, braking, and rotation maneuvers.*

PROJECT DESCRIPTION

To utilize the momentum of the solar wind's protons moving at 400 km/s for propulsion, electrostatic (ES) tethers must deploy in deep space beyond Earth's magnetic shield. But deploying and spinning up one or more tethers that are 10 km long without the help of Earth's gravity has never been done in deep space and has been identified as the highest technical risk for deep-space ES tether propulsion. However, deep-space ES tether deployment can be investigated and has been demonstrated on NASA Marshall Space Flight Center's epoxy 'flat floor' using small, self-contained, steerable CubeSat simulators that incorporate air pump air bearings, rugged paintball air tank propulsion, miniature high-torque reaction wheels, and indoor star tracker emulators for tethered CubeSat vehicle guidance, navigation, and control (GNC). Two tether deployment approaches are being explored, beginning with a cold gas pod to pull out and then rotate the tether around the base/main CubeSat and an alternate method using a triple-boom CubeSat that spins up to stabilize and deploys tethers from the booms using centrifugal force.

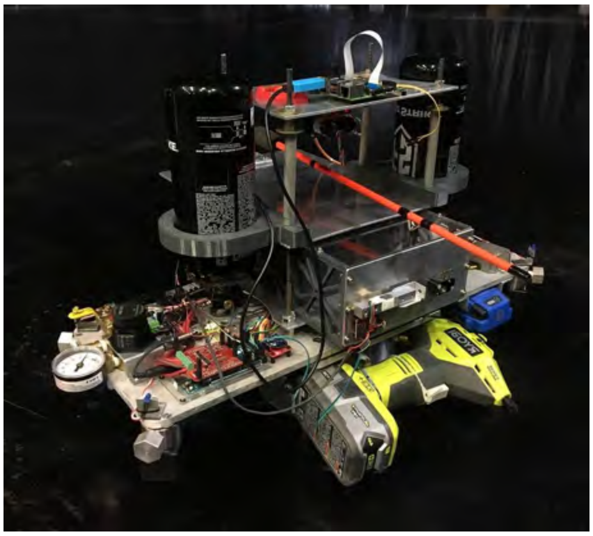


FIGURE 1. Cold jet tether deployer CubeSat with star tracker emulator.

Using iterative design cycles, each phase of development achieved most or all of the planned major technical demonstration goals by using a blend of existing or updated flat floor equipment design and incorporation of current hobbyist electronics, sensors, and software with the different practical experiences of the mentors and the motivated college and graduate school interns, as well as employing six interns who have been accepted into the government's PATHWAYS programs or gone onto graduate degree programs.

The simple fiscal year (FY) 2017 tether deployment CubeSat simulator using a battery-powered Arduino controller firing cold gas thrusters (built with pneumatic solenoid valves with screw-in thruster nozzles) and paintball air tanks was originally developed to incorporate and demonstrate a miniature tether brake mechanism and canister but showed limited test float time and vehicle stability during linear travel. The next design iteration in FY 2018 added battery-powered air pumps to extend the simulator float time to 90 min per charged battery and a 'yaw' stabilizer arm that uses the tether's tension to reduce 80%–90% of the yaw thruster firings during linear tether deployments. Additional air-pump air-bearing platforms are now used by university senior design teams to test their ES tether deployment projects.

The next design iteration needed a star tracker sensor emulator that could look at ceiling-mounted optical patterns to determine the relative x-, y-, and yaw-orientation of each of the individual optical patterns. The emulator would therefore calculate the position and pose of each air-bearing simulator on board using $50 processors, video cameras, and printed 2D barcodes printed on

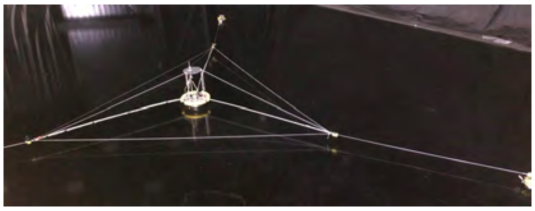


FIGURE 2. Three boom spinning tether deployer CubeSat.

poster boards and cable-tied to the ceiling joints above the epoxy flat floor. This would enable future automated linear tether deployment using emulation of flight-like sensors.

The final design iteration was a departure from the original linear tether deployment, followed by the twin tethered CubeSat simulators rotating the tether by trying to fly around the virtual center of the tether. By putting the tether spools and brakes on small air-pump air-bearings deployed from the tips of three rigid booms of a spun-up CubeSat, the starting rotational speed required to deploy long tethers using only centrifugal force was orders of magnitudes lower that a spacecraft without booms and tether spools mounted on the central vehicle. The simple 'spin up and then release the tethers' sequence has been described as an 'elegant solution' for deploying ES Tethers. This spun-up extendable boom CubeSat concept will be iterated upon by adding a reaction wheel for spin-up, change out to extendable booms, incorporation of real-time position, and pose sensors but will be used as is by university senior design teams to test their electrostatic tether deployment projects.

ACCOMPLISHMENTS

FY 2017's miniature air-pump air bearing CubeSat simulator that uses four corner-mounted thrusters for translation and rotation, was improved with a tether stabilizer boom that reduces thruster firing for attitude control by 80–90%, a lesson learned from the Naval Research Lab's Tether Electrodynamic Propulsion CubeSat Experiment. Another intern team developed an Indoor Star Tracker emulator that provides x-, y-, and yaw-navigation measurements using a new software package (now released by NASA) running on a hobbyist video processor mounted on the CubeSat simulator(s). An alternative ES tether CubeSat configuration that uses extendable boom(s) to generate centrifugal force to deploy tethers from end of the boom(s) after vehicle spin stabilized was analyzed, assembled, and demonstrated to various personnel including the In-Space Propulsion Chief Technologist. Continued flat floor testing will be used to support the analysis and design of a Deep Space Electrostatic Tether Propulsion Technology Demonstration Mission (TDM) to enable a low-cost CubeSat to prove this revolutionary propulsion method.

SUMMARY

Self-contained air-bearing simulators are being assembled in MSFC's flat floor to evaluate various CubeSat configurations used to deploy multi-km-long ES tethers. MSFC flat floor personnel have developed various low-cost simulators and subsystems, including a compact (25 kg) cold-gas steerable CubeSat simulator for thruster deployment of ES tethers and an alternative boom CubeSat simulator that spins up for centrifugal deployment of ES tethers. By using low-cost hobbyist electronics and software that is familiar to motivated college interns, combined with existing and updated flat floor lab equipment and expertise, two different ES-tether deployment CubeSat simulator concepts have been assembled for evaluation of different deep-space ES tether propellantless propulsion CubeSat concepts.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Thomas C. Bryan

FUNDING ORGANIZATION: Technology Investment Program

eCryo – Evolvable Cryogenics Project

OBJECTIVE: *To create and manage a portfolio of efforts that aim to increase the technology of storage and use of cryogenic fluids (mainly propellants) for space exploration. The Evolvable Cryogenic project is a joint effort between Glenn Research Center (GRC), the lead on this project, and Marshall Space Flight Center (MSFC).*

PROJECT DESCRIPTION

The Evolvable Cryogenic (eCryo) project has had a couple projects under its management over fiscal year (FY) 2018: a 4-m cryogenic tank (fig. 1), computer thermal modeling of propellants (fluids), and low-leakage cryogenic valves. These elements comprise the majority of the projects that are shared by NASA Glenn Research Center and NASA Marshall Space Flight Center under the eCryo project aegis. The large cryogenic tank (right) is at MSFC for a spray-on-foam-insulation (SOFI) coating and was delivered to the Plumbrook facility (near GRC) for cryogenic testing of insulation after exposure to acoustic launch environments.

Up to this point, the need to keep cryogenic propellants ‘conditioned’ has only been 8–12 hr from loading to use (in general). This has been sufficient for low earth orbit (ISS and Shuttle) and journeys to the moon (Apollo). As the push to move deeper into space grows ever stronger, the need to keep propellants usable for longer and longer periods becomes more mission critical and more difficult. The eCryo project has created a roadmap of cryogenic technologies that have been deemed essential to improving the capabilities to store and transfer cryogenic propellants. The eventual goal is a state called ‘zero boiloff’. The eCryo project office continues to look for ways to improve the technology readiness level of these nearly 30 different technologies. The project is also looking for ways to engage the aerospace industry in public/private partnerships that will join NASA on the development path for cryogenic storage. The low-leakage valves work was handed over to the Nuclear Thermal Propulsion project to continue the maturation process that eCryo has produced.

ACCOMPLISHMENTS

The 4-m tank pictured in figure 1 is the other significant piece of work that eCryo has achieved over FY 2017. The tank was designed with the assistance of MSFC engineering. The tank was constructed by a contractor and then delivered to MSFC for instrumentation and SOFI application. The tank was white light scanned to assist in the SOFI application and thickness measurement. Figure 2 shows deviation on the real article from the planned CAD model. The red end of the spectrum represents where the real tank exceeds the CAD model in the outward direction. Green represents no deviation and blue is deviation towards the inside of the tank. Figure 3 is the 4-m-tank being loaded onto the truck to deliver to Plumbrook station.

SUMMARY

The eCryo project continues to be a successful and necessary joint effort between GRC and MSFC. The need to keep, maintain, and transfer cryogenic propellants is only going to increase as NASA and NASA partners continue to push the physical boundaries of exploration further out from low earth orbit. Regardless of the type of propulsion system (liquid propulsion), the need to keep cryogenic propellants in liquid form is a mission-critical technology that needs to continue the path to maturity.

GRC PROJECT MANAGER (Lead): Hans Hansen

MSFC MANAGER: Arthur Werkheiser

FUNDING ORGANIZATIONS: Technology Demonstration Missions

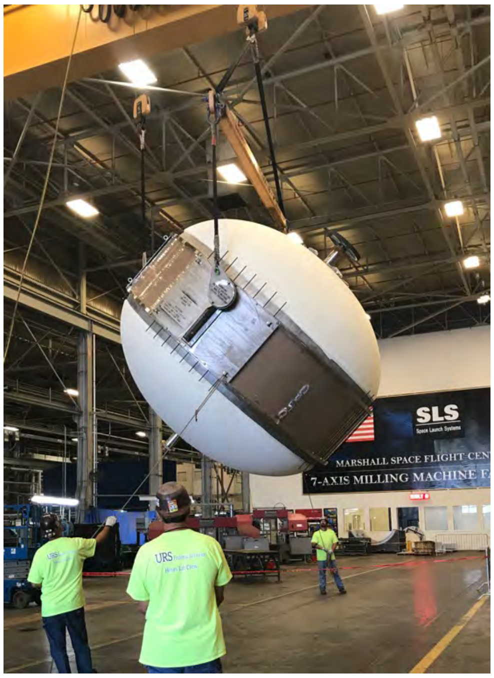


FIGURE 1. The 4-m cryogenics tank.

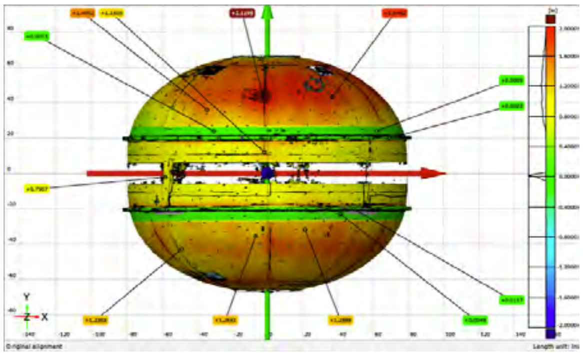


FIGURE 2. White light scan with deviation.

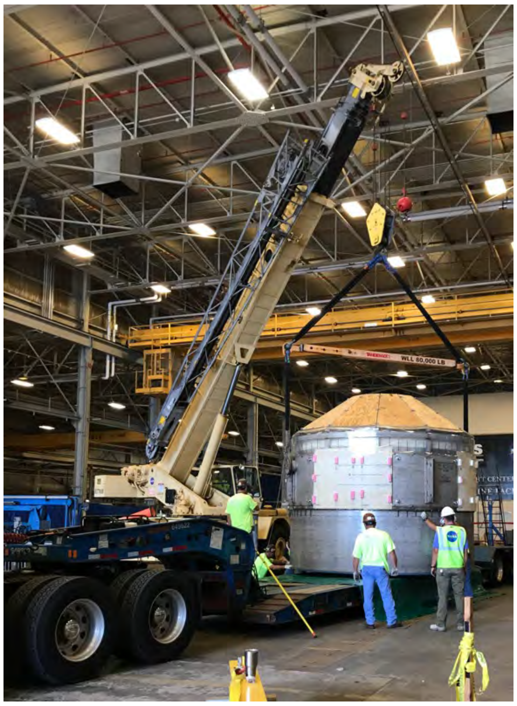


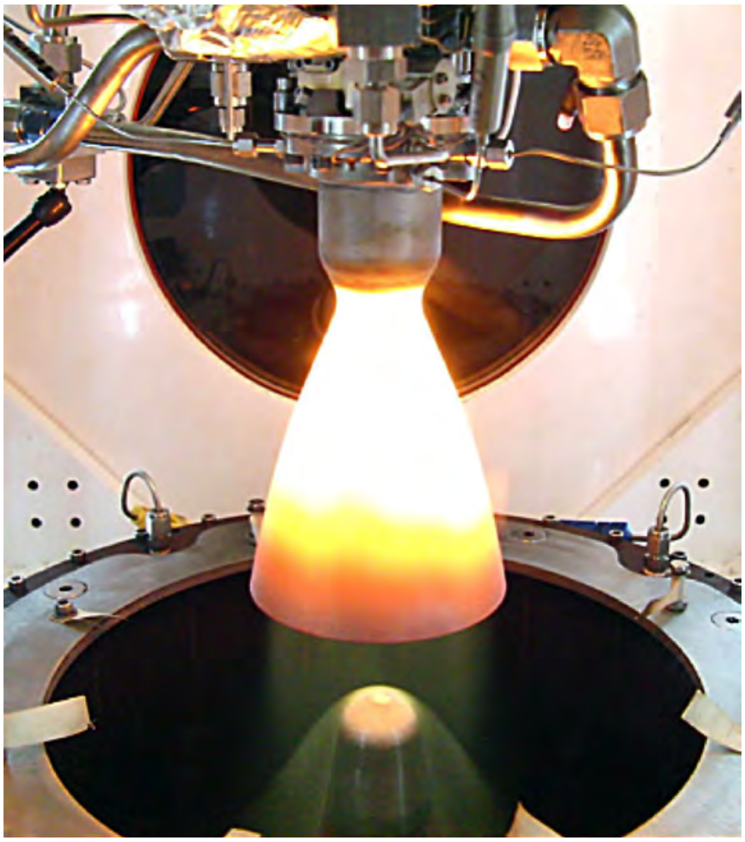
FIGURE 3. The 4-m tank on its to Plumbrook station.

Deep Space Engine

OBJECTIVE: *To qualify a low-cost, lightweight, low-propellant-temperature thruster.*

PROJECT DESCRIPTION

The Deep Space Engine (DSE) is an improved in-space chemical propulsion thruster. It offers multipurpose space mission utilization and economy-of-scale benefits because the engine is adaptable for spacecraft main propulsion, reaction control systems, and lander descent/ascent. Reducing propulsion system weight and volume increases available payload mass and/or acceleration capability, thereby expanding launch vehicle opportunities. Reduced propellant freezing point and thermal management power draw enable long-duration, ultra-cold deep-space missions and reduce spacecraft heater power demand. Additionally, DSE retains fine-grain impulse bit control for more precise control of lander descent/ascent trajectories.



DSE offers enhanced affordability through improved designs, modern materials, and advanced manufacturing processes, which lower thruster unit cost for missions and reduce propulsion system costs. This technology is key to the enhanced affordability of science and exploration missions. The project goal is to qualify DSE thrusters (150 lbf and 10 lbf) to a test readiness level (TRL) 6 level.

The DSE project aims to perform qualification tests that represent the mission duty cycles of both a potential future Technology Demonstration Mission (TDM) on the Astrobotic Peregrine Lunar Lander and the NASA Resource Prospector Lander.

The primary challenge with mixed oxides of nitrogen with 25% nitric oxide (MON-25) is producing a high-performance thruster that does not exhibit combustion instabilities. Current state-of-the-art in-space thrusters use MON-1 or MON-3. Adding more nitric oxide to the mixture reduces the propellant freezing point but consequently raises the vapor pressure. The increased vapor pressure of MON-25 reduces the combustion stability margin of a MON-1 or MON-3 thruster. However, it has been demonstrated that stable operation is achievable with MON-25.

Led out of NASA Marshall Space Flight Center, the DSE will begin with a development effort called work horse testing. The workhorse testing will provide data that will be used to finalize a design for the qualification thruster. DSE will then undergo design verification testing, which will further progress the workhorse design toward a flight weight design. Finally, qualification testing will validate the DSE flight requirements and provide TRL 6 data.

SUMMARY

Advancements in MON-25/MMH hypergolic bipropellant thrusters represent a promising avenue with tremendous mission enhancing benefits. DSE is much lighter and costs less than currently available domestic thrusters in comparable thrust classes. Because MON-25 propellants operate at lower temperatures, less power is needed for propellant conditioning for in-space propulsion applications, especially long duration.

DSE offers enhanced affordability through improved designs, modern materials, and advanced manufacturing processes, which lower thruster unit cost for missions and reduce propulsion system costs. This technology is key to the enhanced affordability of science and exploration missions.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Gregory Barnett

PARTNERSHIP: Frontier Aerospace Corporation

FUNDING ORGANIZATION: Game Changing Development

FOR MORE INFORMATION: https://gameon.nasa.gov/projects/deep-space-engine-dse/

ACCOMPLISHMENTS

The DSE project has already completed an initial workhorse risk-reduction development hot-fire test of the conceptual thruster. The risk-reduction testing demonstrated the high performance and stability characteristics that are expected for the final design. Qualification testing will verify design requirements and robustness and qualify the thrusters to a TRL 6.

The DSE preliminary design review (PDR) was completed at Frontier Aerospace Corporation's facility in Simi Valley, CA, on June 28, 2018. The PDR was successful and represented an important milestone of the project. Frontier Aerospace Corporation was also awarded a Tipping Point proposal with NASA's Space Technology Mission Directorate (STMD) to produce the first flight set of thrusters.

Carbon-Carbon Nozzle Extension Testing

OBJECTIVE: *To collect data on carbon-carbon nozzle extensions in a liquid oxygen/methane hot-fire test environment.*

PROJECT DESCRIPTION

The carbon-carbon (C-C) nozzle extension testing development efforts assists in the future fabrication and design of C-C nozzle extensions for future NASA or industry applications such as liquid oxygen (LOX)/methane upper stage, in-space, and deep-space missions.

A lot of C-C development work has been done with LOX/hydrogen. However, methane is a different gas species than hydrogen, and there are potential unknowns that will only be uncovered and mitigated through hot-fire testing of C-C nozzles in a LOX/methane environment. The project is working to document the oxidation kinetics and their effect on the C-C nozzle surface in methane versus hydrogen and to define suitable transition and/or regen points for future designs.

Carbon-carbon nozzle extensions are essential for several applications of interest to NASA, including launch vehicle upper stage propulsion, in-space liquid and nuclear thermal propulsion, and lunar/Mars ascent and descent propulsion. Carbon-carbon nozzle extensions offer high area ratios without the often-unacceptable weight disadvantages of a metallic extension. Carbon-carbon nozzle extensions have demonstrated significantly higher thermal margins versus metallic extensions, and groundbreaking C-C materials have the potential to increase upper limit temperatures to 4,000 °F. The state of the art for metallic nozzle extensions is 2,000 °F.

The state of the art in C-C nozzle development has advanced in recent years through Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) projects and in-house NASA Marshall Space Flight Center development tasks primarily driven by the Co-investigators of this proposal along with commercial industry partners. Carbon-carbon nozzle extensions have been tested in LOX/liquid hydrogen environments, but with significant and growing NASA and industry interest in LOX/methane engines, additional testing is needed to leverage the advantages of C-C in these environments.

Leveraging a previous Technology Investment Program (TIP) effort, the C-C nozzle extension development approach is to gain as much test data as possible utilizing multiple nozzle extension providers. Several domestic companies have provided in-kind nozzle hardware in order to evaluate the nuances of varying C-C fabrication processes and validate their high-temperature capability.

Nozzle hot-fire data will be evaluated, and several samples will be cross-sectioned and examined by NASA material experts to determine if any unanticipated phenomenon emerge.

Hot-fire test conditions will simulate the relevant LOX/methane operational environment. The chamber pressure (Pc) and Mixture Ratio (MR) are set to produce a representative thermal environment on the nozzle extension. The target Pc will be 750 psig, and the target MR will be 3.5. The thrust chamber assembly in figure 1 is representative of the hot-fire test setup.

ACCOMPLISHMENTS

In-kind hardware contributions have been made by All-Comp, C-CAT, and Northrup Grumman. Several nozzles are ready to test, and the test facility has completed the setup. A 3D printed, slip jacket bimetallic chamber, and a matching injector have been fabricated. Hot-fire testing took place in October of 2018 and extended about 3 weeks.

SUMMARY

Carbon-carbon nozzle development is needed for LOX/methane applications for lander missions considering methane. Carbon-carbon nozzles provide advantages for upper stage and other in-space engine applications such as potential 50% weight reduction (versus metallic), improved thermal design margins (500–1,500 °F), and simplified designs and manufacturing process controls.

Carbon-carbon nozzle development is currently at test readiness level (TRL) 3 in a LOX/methane environment (TRL 6 for LOX/hydrogen). The development testing will advance TRL from 3 to 5 for C-C nozzle extension applications in LOX/methane.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Greg Barnett, Paul Gradl, and Pete Valentine

FUNDING ORGANIZATION: Technology Investment Program

Lifeline for the ISS and Future Space Tethers

OBJECTIVE: *To reduce the cost of access to medium Earth orbit (MEO), students at The International Space University, in consultation with NASA experts, examined the feasibility of using the International Space Station as the orbital anchor for a 6,500-km tether from high low Earth orbit to MEO.*

PROJECT DESCRIPTION

The reuse of the International Space Station (ISS) as the basis of a large tether system has the potential to serve as the first demonstration of large tethers in space for eventual lower Earth orbit (LEO) to geosynchronous orbit (GEO) transfer. The obstacles presented by deployment of the tether, the need for large end masses to enable the lifting of payloads, and the difficulty of gaining public support for tether projects all find natural solutions through the reuse of ISS.

A variety of payloads could potentially see noticeable delta-v savings by using the tether to travel from LEO to medium Earth orbit (MEO). The study examined the technical, programmatic, cost, and international legal and policy considerations of adapting the ISS for use as a commercial space research and transportation hub.

A concept for a modular tether system developed as a new module for the ISS was developed. The module would be sent to the ISS and attached at the docking port closest to the current center of mass of the station. Once attached, the ISS will use either its own propulsion system or that of a docked spacecraft to transfer from its current orbit to a new circular orbit at an altitude of 7,000 km. The tether will then deploy downwards from the ISS towards Earth. Its full extended length will be 6,500 km, stretching from LEO to MEO, providing an elevator for transferring payloads to MEO with minimum propellant expenditure. The station can then be reoccupied, after a commissioning period for the tether, and used as a commercial research laboratory and space transportation node.

ACCOMPLISHMENTS

The ISU completed the concept study, and their report, "Lifeline for the ISS and Future Tethers," is available from the International Space University here: https://isulibrary.isunet.edu/index.php?lvl=notice_display&id=10466.

FIGURE 1. The ISS would serve as an 'anchor' for a 6,500-km tether extending from MEO to LEO to act as an elevator from one orbit to the other.

SUMMARY

While this concept would face many obstacles to implementation, including the likely decommissioning of the ISS in the 2020s, many are resolvable, and the potential benefits are many. Engaging students in the intellectual exercise of considering not only the technical design, but the economic, political, and policy implications of fielding such a system was the goal and, as the study report indicates, that goal was achieved.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Les Johnson

PARTNERSHIP: The International Space University

FUNDING ORGANIZATION: Center Strategic Development Steering Group

Lunar Flashlight Propulsion System

OBJECTIVE: *To place a 6U spacecraft in lunar orbit to search for and measure quantities of ice water in permanently shadowed south pole craters.*

PROJECT DESCRIPTION

The Lunar Flashlight Propulsion System (LFPS) is a VACCO low-toxicity 'green' monopropellant system. The propellant is an ammonium dinitramide-based propellant named LMP-103S. The propulsion system will be used for lunar orbit insertion, station keeping, and momentum wheel desaturation. NASA Marshall Space Flight Center (MSFC) manages the project. VACCO Industries is the propulsion system prime contractor.

LFPS is an all-welded titanium module with highly integrated manifold. The LFPS has integrated microcontroller and RS-422 interface-enabled high-level commands from the spacecraft. The system holds up to 2 kg of propellant and will have a wet mass of less than 5 kg. The LFPS will have four 100-mN thrusters, built by Bradford ECAPS. The propulsion system is approximately 3 U in volume and uses four Bradford ECAPS 100-mN thrusters to develop 3,000 N•s of total impulse.[1] (See VACCO's LFPS webpage at: https://www.cubesat-propulsion.com/lunar-flashlight-propulsion-system/).

ACCOMPLISHMENTS

VACCO completed a successful Burst Test Unit development and testing series, validating the structural design and manufacturing processes. ECAPS has performed numerous informative development hot-fire test programs leading up to the qualification test program of Fall 2018. A majority of the major fabrication and assembly of the Flight Unit has been completed. Delivery is expected in the second quarter of fiscal year 2019. MSFC has built a propellant loading system for green propellant loading at range locations.

SUMMARY

This year, MSFC has established the capability to produce the wax-based fuel developed by the SPG of California. This fuel production has been demonstrated by manufacturing a monolithic grain. However, due to the large temperature swings on Mars, the flight grain may be multisegmented. The grains from this effort have been fired in all the full-scale testing.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Daniel Cavender

PARTNERS: NASA Jet Propulsion Laboratory, VACCO Industries

FUNDING ORGANIZATION: Advanced Exploration Systems

SPACE POWER AND ENERGY STORAGE

Multimethod Wireless Energy Transfer Sensor Nodes

OBJECTIVE: *To demonstrate a wirelessly powered data sensor system that utilizes multiple methods of wireless power transfer as well as wireless data transfer.'*

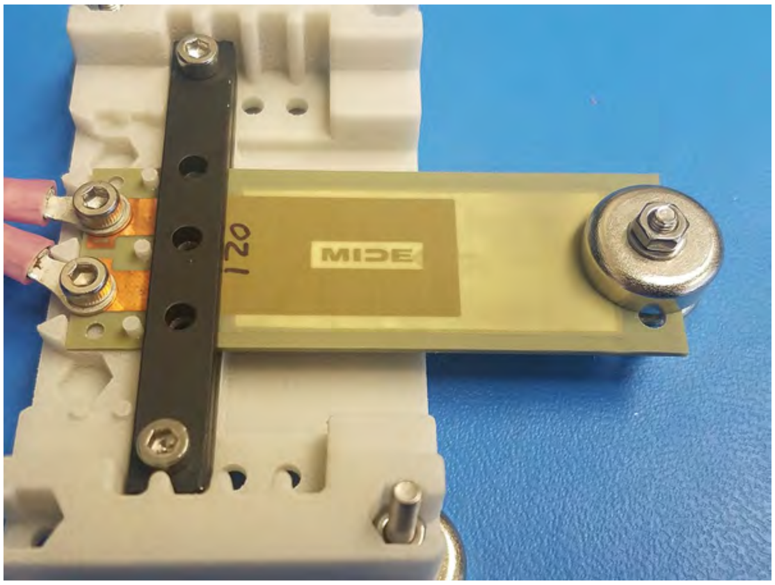
PROJECT DESCRIPTION

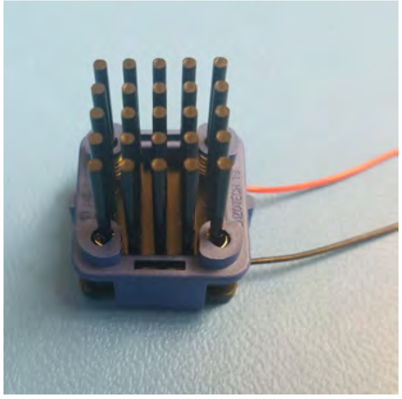
Current sensor systems in space and launch applications rely on extensive cabling for power supply and data capture. Not only does this make them inflexible, but these cables add design effort, mass, space claim, installation effort, failure points, and crosstalk opportunities. Such systems require lengthy custom design work for each application and are a burden to maintain and repair. Wireless data systems are extremely mobile and easy to replace/upgrade. They are well known in terrestrial applications where power sources are easily applied. However, the motivation for such systems in space and ground testing applications has been limited in part due to dependency on power cabling or battery maintenance. Therefore, wireless energy transfer methods are in great demand. Common and upcoming wireless energy transfer methods require specific wireless energy transmission components and may struggle to generate sufficient power collection individually to meet the needs of the sensor and wireless data communication system. Radio frequency (RF) power harvesting, magnetic inductive coupling, thermal energy harvesting, vibration energy collection, photovoltaic cell technology, and acoustic energy collection are being explored in various ways in the current terrestrial market. However, these systems utilize only one of these methods and are therefore limited in power collection and application. To overcome this wireless power supply struggle and maximize flexibility, this project seeks to develop a sensor network that truly 'cuts the cord' by providing sufficient amounts of wireless power through multiple techniques while also communicating data wirelessly. In doing so, these sensor nodes will be capable of harvesting energy from whatever sources are available to them in their specific application or combine multiple techniques for increased power capabilities. These systems are also being developed with an awareness of the unique challenges of future application in space environments.

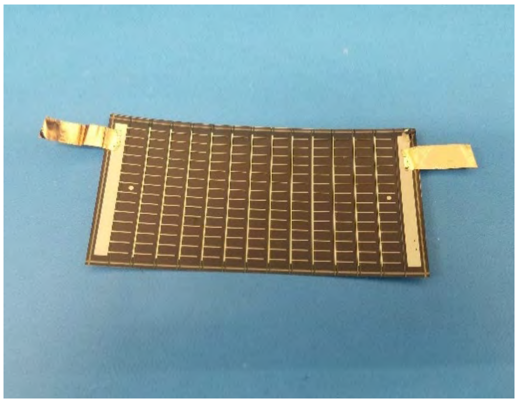
Each sensor node in this system will be designed to utilize multiple wireless energy transfer methods. RF power harvesting, magnetic inductive coupling, thermal energy harvesting, vibration energy collection, photovoltaic cell technology, and acoustic energy collection capabilities are being tested and evaluated. These wireless power collection methods can be used independently or in combination maximizing application flexibility and power capability. This harvested power will be stored without the use of batteries eliminating the challenges that come with them including replacing, recharging, and maintaining. Instead, supercapacitors are currently used with a long-term plan to use a NASA Marshall Space Flight Center (MSFC) ultracapacitor solution. This wireless energy collection will be integrated with example sensor elements and smart wireless data components to maximize energy efficiency. This system of eight multimethod, wirelessly powered data sensor nodes is being developed and will be demonstrated in both a lab environment and in MSFC's human habitat testing facility. In addition, a user-friendly data interface is being developed using a commercial-off-the-shelf single-board computer and a custom-designed power conditioning and wireless data-handling circuit board.

ACCOMPLISHMENTS

Testing and optimizing techniques for magnetic inductive coupling and harvesting RF, vibration, thermal, and photovoltaic energies are still underway. Acoustic energy harvesting will be further explored soon. Sensor node enclosures have been designed and 3D printed. Latest versions of the sensor node circuit boards and data collection/inductive coupling transmitter mobile stations are being produced in the Fall 2018. Software refinements to the system are also being made.







SUMMARY

In order to overcome power transmission challenges and maximize flexibility in data systems including sensors, a system of sensor nodes that is powered wirelessly and harvests energy from the surroundings is being produced. This energy transfer is done using multiple methods including RF power harvesting, magnetic inductive coupling, thermal energy harvesting, vibration energy collection, photovoltaic cell technology, and acoustic energy collection. These sensors will allow for fast and flexible measurements without traditional energy storage and will open the doors for the use of wireless power transfer and environmental energy harvesting in many future applications within NASA's missions.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Darren Boyd

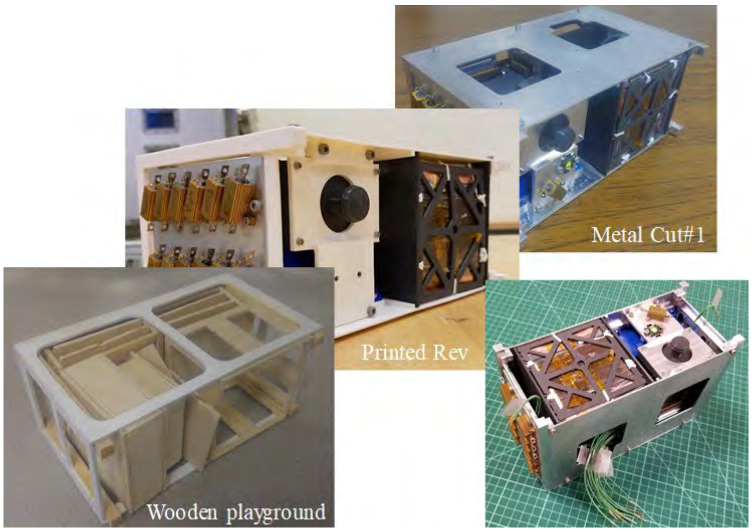
FUNDING ORGANIZATION: Technology Investment Program

LISA-T Early Agile Pathfinder Technology Demo Engineering Model

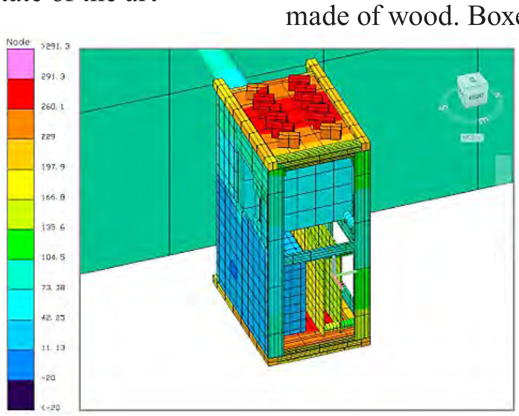
OBJECTIVE: *To develop integration lessons learned for flight unit application and securing additional funds due to showcasing a tangible product, as the LISA-T project team is enabled by the LEAPEM project, as a result of a Pathfinder technology demonstrator engineering model.*

PROJECT DESCRIPTION

The Lightweight Integrated Solar Array and Antenna (LISA-T) solves the small satellite and CubeSat power epidemic. LISA-T leverages thin-film solar cells, lightweight polyimides, and compact deployment mechanisms to create a low mass array which stows into a small launch volume and deploys into a large area on orbit. LISA-T adds the advantage of integrated antennas, reducing bus space claim and mass while creating



opportunities for higher gain designs, omnidirectional communication, and electronically steered arrays. Compared to small satellite arrays state of the art (SOA), LISA-T provides greater than 300% more power (230.9W demonstrated) with greater than 300% improved stowed density (461.8 kW/m3 demonstrated) and approximately 275% improvement to specific power (378.5 W/kg demonstrated). The LISA-T deployable array was integrated with a system for the purposes of on-orbit demonstration. The Pathfinder Technology Demonstrator (PTD) offers payloads (up to 2.4U, 12 × 20 × 10 cm) an opportunity for short duration on-orbit exposure; thus, a cartridge design was selected. The PTD project plans to pay for integration and launch for (originally) five payload providers. The PTD Project office highly rated the LISA-T proposal in the Spring 2017 payloads call and ultimately awarded a sixth opportunity to LISA-T. As of this article, LISA-T PTD has moved up to the fourth opportunity spot.



LEAPEM is an Engineering Model (EM) for the PTD payload opportunity. Agile engineering techniques were used to design and integrate the LISA-T deployable array with a system for the purposes of on-orbit demonstration. A cartridge (modular) design was selected to contain the flight demonstration for ease of integration to the PTD bus. A camera was mounted within the cartridge to capture video and still pictures. An input/output circuit board, combined with instrumentation and a load regulation board, will monitor 'beginning of life' power generation and degradation over the orbit life. An X-Band Software Defined Radio was integrated with the system to telemeter the collected data through the LISA-T embedded helical antenna, which will be compared to the data received through the PTD telemetry.

Agile techniques were evident with the maturation of the cartridge design. The first released cartridge was made of wood. Boxes were made to reserve volumes for internal components. The second released cartridge was made using additive manufacturing (also known as 3D printing) with polymer filaments. The geometries became more representative of the final design since a computer model was used to print components. The third released cartridge was made of metal and real hardware. Each release provided team members physical representative hardware, leading to real hardware, to mature the design and components placement. The third cartridge was used in June 2018 to showcase the LISA-T technology at a Space Mission Directorate 'Lunch-n-Learn'. The Science Mission Directorate (SMD) Chief Technologist was impressed by both the LISA-T technology and the LEAPEM aggressive development. The Small Satellite Technology Program (SSTP) Manager, and the SMD Chief Technologist agreed that this technology needs to be demonstrated. As a result, the SSTP Manager provided additional funding of $369K.

Agile engineering techniques were also evident with the circuit board development. The first several iterations were performed using computer-aided design and reviewed by expert electrical designers. The first board production (also known as spin) incorporated several test subcomponents, which permitted real-time modifications if any issues were discovered. As evident to the first several 'virtual' iterations, no major issues were experienced, and a re-spin was planned to remove the test subcomponents.

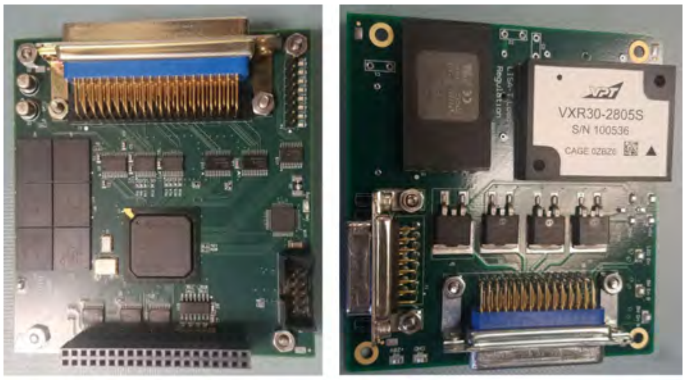
The previously mentioned SSTP funding will be used to procure additional engineering model hardware and will procure a LISA-T flight unit from the industry partner.

ACCOMPLISHMENTS

The LEAPEM project used a KanBan SharePoint site for tracking releases and action progress. The site provided a method for knowledge capturing and knowledge sharing. The site format was designed to look like cards for team members to grab open actions.

The LEAPEM project started from the LISA-T Mission Concept Review (MCR) design. The Concept of Operations was modified based on lessons learned from generating the power estimate list (PEL) and power profile. The cartridge design evolved from the MCR design, which the first release was made of wood. By the second release, the cartridge was fully designed in a computer aided design (CAD) model and components were moved within the cartridge based on the initial thermal analysis. Continued thermal analysis resulted in both design and operational concepts to mitigate the high temperatures caused by large power generation with minimal power consumption.

Several demonstration components were traded and procured. Initially, LEAPEM planned to borrow a camera from another project. LEAPEM had to procure a generic camera due to the other project commitments. Ultimately, LEAPEM was able to procure a better camera option with the added SSTP funding. A light emitting diode (LED) was procured for illuminating the deployment. Illumination testing with this LED drove the current and voltage requirements. As mentioned already, the cartridge chassis evolved from wood to plastic and plastic to metal. The first metal chassis was fabricated for the third design release. A second metal chassis was later procured for a spare, which now will be loaned to NeXolve for their microgravity testing (parabolic flights) planned for 2019. Wire routing and cable harnessing were also completed. Lastly, two of the three circuit boards were electrically integrated



Input/output and Load regulation boards.

with the LEAPEM cartridge. The executing firmware was successfully written, installed, and tested for basic functionality.

SUMMARY

The LISA-T Early Agile PTD Engineering Model (LEAPEM) exceeded the initial project objectives. An engineering model was not only procured and integrated, but the project team modified the design based on additional analyses performed along the way. Lessons learned were captured to better prepare the flight unit for demonstration.

Additionally, showcasing a tangible product to potential stakeholders led to unexpected (but greatly appreciated) funding. SSTP funds allow for continuous engineering development unit (EDU) hardware acquisitions, as well as some flight hardware. This funding will permit LEAPEM team members to continue marching towards the PTD flight.

PRINCIPAL INVESTIGATORS: Eric Eberly and John Carr

PARTNER: NeXolve

FUNDING ORGANIZATION: Technology Investment Program

Spark Plasma Sintered Ultracapacitors For Space Applications

OBJECTIVE: *To determine the dielectric breakdown strength of ALD coated barium titanate.*

PROJECT DESCRIPTION

Several dielectric materials were evaluated for their suitability to replace batteries in space applications. Ultracapacitors are energy storage devices that offer the promise of higher power and greater number of charge/discharge cycles than present rechargeable batteries. In addition, the theoretical energy density when compared to today's electrochemical batteries indicates that a significant weight savings is possible. A special sintering process was employed to produce barium titanate ($BaTiO_3$) nanoparticles. This was further coated by atomic layer deposition with a thin silica coating of a few nanometers and sintered into samples of high density.

Materials were first tested for dielectric constant and electrical breakdown strength. These are the two factors that play an important role in improving energy storage density (ESD), as demonstrated by eq. 1: $ESD=(½v)\epsilon_r.\epsilon_0 E^2_b$, where ϵ_r is the relative permittivity of the material, ϵ_0 is the permittivity of air, E_b is the breakdown field, and v is the sample volume as shown in eq. 2: $\epsilon=\epsilon_r.\epsilon_0$ where ϵ gives the total dielectric constant of the material. The relative permittivity of the evaluated samples of different grain sizes was measured to be in the range of 104 to 106. The breakdown strength of these samples was found to be in the range of 200 to 600 V/mm. These materials with this dielectric breakdown strength are equivalent to nickel/cadmium batteries with respect to energy density. Since these materials are solid state ceramics, there is no electrolyte to worry about if failure occurs.

In order to compensate for the low breakdown strength, it was proposed to disperse this material in polymer films, which have high-voltage withstand abilities of more than 10 kV/mm. In fact, many electronic systems in space applications, such as satellites, employ film capacitors (e.g., in the direct current-to-direct current power converter), and these also need to have high energy density. Here, we used the room-temperature vulcanized (RTV) silicone polymer, which has an additional advantage of higher thermal range and is widely employed in high-voltage insulation. However, like most polymers, its relative permittivity ranges between 2 and 3.

Initial research was carried out to develop thin films of this polymer successfully in our clean room facility. The electric field modeling software COULOMB was employed to model the electric field along the spherical electrodes with the polymer sheet in between them. This showed that the breakdown occurs through the sheet and not on the surface. The breakdown strength was experimentally evaluated to be about 11 kV/mm.

ACCOMPLISHMENTS

The following are the significant accomplishments from this project:

1.) We have modeled the breakdown of polymer films in COMSOL software.

2.). We have obtained the breakdown strength of pure $BaTiO_3$ pellets and estimated their dielectric constant. Their relative permittivity was found to be in the range of 104 to 106.

3.) We have measured the breakdown strength of fabricated pure polymeric and composite film.

4.) The capacitance as well as the dielectric constant of these films were also measured, except in cases where the non-uniformity of the nanoparticle dispersion rendered the polymer film uneven.

5.) We have fabricated the layered structure of the polymer-metal-polymer film and compared its breakdown strength with polymer only-film. Our measurement result shows significant enhancement of the breakdown strength for the layered structure compared to the polymer only film of the same thickness.

6.) Our capacitance measurements confirm that capacitance remains same for both the layered structure and the polymer only layer of same thickness, as predicted by theory.

7.) We theoretically estimate the performance gain that can be achieved with a layered structure of polymer-metal films.

SUMMARY

The purpose of the research was to determine the dielectric breakdown strength of ALD coated barium titanate samples. The breakdown strength varied between 200 and 600 V/m. To enhance this property, polymer films containing the ALD coated barium titanate particles were prepared.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Dennis S. Tucker and Curtis Hill

PARTNERSHIP: University of Alabama in Huntsville

FUNDING ORGANIZATION: Cooperative Agreement Notice

Optimizing Dielectric Properties and Energy Density on SPS-Sintered Supercapacitors

OBJECTIVE: *To optimize coatings and particle sizes of the perovskite ceramic powder in order to increase energy density of the sintered supercapacitor devices.*

PROJECT DESCRIPTION

Optimization of spark-plasma-sintered (SPS) supercapacitor devices is focused on increasing voltage breakdown and permittivity of the dielectric material. Our Cooperative Agreement Notice (CAN) collaborative research with Auburn University Material Science Department is focused on optimizing the particle size of the ceramic powder and improving the quality and consistency of the silica nano-coating of the ceramic particles, in order to achieve extremely high energy storage of the resulting devices.

We have the capability at Marshall Space Flight Center (MSFC) to micromill these ceramic powders to extremely small particle sizes (<100 nM) with very precise control of particle size distribution. We are focusing on the effect that particle size plays on dielectric properties. In addition, we are evaluating alternative processes for the nanocoating of silica that is required. Auburn is preparing powder via different coating methods, and we also have the ability to evaluate other coatings. In addition to the effects upon dielectric properties, we anticipate that these processes and materials will lead to increased voltage breakdown of the material, resulting in extraordinary energy densities.

We are testing, analyzing, and characterizing the ferroelectric-based supercapacitors prepared using the SPS process. We would like to direct this research towards more effective energy-storage devices with a significantly higher energy storage density.

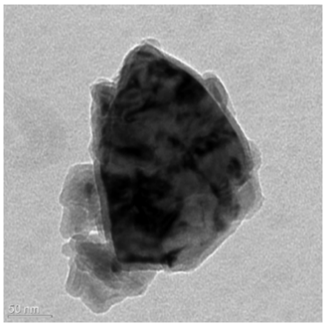


FIGURE 1. SPS-sintered sample 20mm diameter – density >99%.

FIGURE 2. High-resolution TEM image of SiO2 coated BT, coating thickness 5nm.

In this project, we are improving the electrical breakdown strength of ferroelectric-based supercapacitors through optimizing microstructure and optimizing the SPS sintering process with critical design parameters targeted towards maximizing energy storage.

A continuous increase in energy requirements has made the need for alternate and novel means of improving the efficiency of energy storage more critical to our mission in space as well as to our modern power-consumption society. Capacitors are devices that allow electrical energy to be stored and then released as required for shorter time periods under controlled conditions. Other significant advantages of supercapacitors for energy storage include: complete safety from potential overcharging and overheating, virtually unlimited duty cycles, and stability in a wide range of environments. Releasing stored electrical energy over a short time period is critical for various applications ranging from civilian to military including devices/components/systems in NASA's Space Launch System and space vehicles.

ACCOMPLISHMENTS

Our CAN collaboration with Auburn University began in May 2018 as a continuation of earlier research and collaboration between MSFC and Auburn University. We have been able to achieve gigantic dielectric permittivity of $>10^6$ through our previous work, and we continue to optimize the SPS sintering process to further increase the dielectric properties of the material.

This work began with a collaboration between the Department of Energy at Oak Ridge National Laboratories to evaluate the SPS method for fabricating supercapacitors. This research has continued and is more specifically focused on perovskite ceramics as potential supercapacitor materials as MSFC now has its own Direct Current Sintering Furnace for this research.

In addition, our previous research has identified the coating process and particle size of the perovskite ceramic material as potential areas for improvement in energy density/storage, so we are focused in these areas going forward. This technology has significant potential benefit for NASA's missions and is of great interest to commercial companies in evaluating it for commercial battery replacement products.

SUMMARY

The potential benefits of a solid-state energy storage device to replace electrochemical batteries is the area that we are focused on for this research. Our previous research has indicated that these SPS supercapacitors have the potential to provide game-changing energy storage, with remarkable solid state safety and other properties, for NASA's near and long-term missions. We are working with the Material Science Department at Auburn University to test, analyze, and optimize the properties of our supercapacitor devices to provide this benefit to NASA and the rest of the world.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Dennis S. Tucker and Curtis Hill

PARTNERSHIP: Dr. Zhongyang Cheng, Auburn University

FUNDING ORGANIZATION: Cooperative Agreement Notice

FOR MORE INFORMATION: NASA Tech Transfer, Mr. Sammy Nabors

Better, Cheaper Shock and Radiation Protection for CCAs/PCBs

OBJECTIVE: *To employ and evaluate a new a high-yield and low-cost process for protecting CCAs and/or populated printed circuit boards from vibration and cosmic radiation.*

PROJECT DESCRIPTION

The current processes employed to protect circuit card assemblies (CCAs) and/or populated printed circuit boards (PCBs) from shock and vibration are embedding the assemblies in molten material, which reduces the yield of the process (increasing cost) and embedding the assemblies in epoxy-type materials (higher cost and lower protection than cement paste). To protect the same assemblies from cosmic radiation, they are currently shrouded or surrounded by beryllium-aluminum (Be-Al) alloys, which is costly and subject to 'leaks'.

A better and cheaper alternative is needed.

The purpose of this project is to employ and evaluate a new a high-yield and low-cost process for protecting CCAs and/or populated PCBs from vibration and cosmic radiation. This will be accomplished by taking commercial-off-the-shelf (COTS) CCAs, specifically USB drives, and stripping them of their encasing material so that the bare circuit boards are exposed, and then embedding them in Portland cement paste (ASTM Type I).

The embedded CCAs will then be tested/evaluated for the effectiveness of the protection provided by the Portland cement from vibration and cosmic radiation.

The primary hypotheses under examination are:

1.) The cement encasement provides the same or better (statistically significant) protection of the assemblies from vibration and radiation.
2.) The cement encasement provides a significant (greater than 5%) reduction in cost per CCA for equivalent or better protection from vibration and radiation.

The approach to testing the primary hypotheses will be to select a commonly-used COTS USB memory stick, remove its protective housing, and encase it in ASTM Type 1 (Portland) cement.

The memory device will be loaded with an ASCII text file that produces a bit pattern of alternating ones and zeros – ASCII "UUUU…".

Three separate methods will be used to encase three prototypes, for a total of nine prototypes. The three methods of encasement are:

1.) Molding the cement paste in a form around the memory drive.
2.) Dipping the memory drive in a slurry of cement paste.
3.) Depositing a coating of slurry on the memory drive using a sprayer.

These prototypes will be exposed to Environmental Stress Testing to simulate the shock and vibration of launch and flyout, and simulate the exposure to cosmic radiation encountered during flyout and interplanetary travel.

Measurements to be taken on the prototypes (and control devices) are:

1.) The integrity of the function of the drives. This will provide an indication of ability of the encasement to protect the CCA from shock and vibration.
2.) The preservation of the bit pattern on the silicon technology. This will provide an indication of the protection of the memory module / silicon wafer from cosmic radiation (specifically Single Event Upsets (SEUs) caused by high energy particles).
3.) The cost of this manufacture of the prototypes. This will indicate the relative cost in material and staff-hours required to manufacture the prototypes compared to the current cost of protection from vibration and radiation.

KEY INNOVATIONS:

1.) This is an innovative use of the properties of Portland cement that will allow COTS electronics to operate under the extreme environments of launch and spaceflight. Cost reductions are anticipated in the areas of:

(a) CCA design: The cement encasement will allow the use of COTS without redesign for launch and spaceflight.
(b) Vibration: The cement encasement cost is easily an order of magnitude less than the materials now used to protect from vibration, or redesigning CCAs to dampen/eliminate resonance.
(c) Radiation: The cost of cement encasement is easily an order of magnitude less than the materials now used (beryllium alloys) to protect from cosmic radiation or the design of radiation-proof enclosures for CCAs.

2.) The usual purpose of Portland cement is to contain radiant sources such as nuclear piles, not protect electronics from the harsh environments of space travel.
3.) Test results may well demonstrate that the CCAs no longer need to be isolated from the sources of vibration, such as motors.

KEY CHALLENGES:

1.) Obtaining floor/lab space to conduct cement preparation, application, curing, and testing.
2.) Obtaining environmental test chamber timeslots for shock, vibration, and radiation exposure.

If adequate floor or wet-lab space is unavailable from NASA, this researcher will independently seek short-term (1 yr) laboratory floor space from an alternate source.

Similarly, if Vibration and Radiation Environmental Test facilities are unavailable from NASA, this researcher will solicit cooperative agreements from alternate aerospace endeavors to fulfill the test needs of this project.

PLAN FOR PROTOTYPING AND TEST:

1.) Continuing review of literature and research on this topic (avoid ‘re-inventing the wheel’).
2.) Obtain source of unadulterated ASTM Type 1 Portland cement.
3.) Set up lab space for mixing, applying, and curing cement coatings on CCAs.
4.) Prepare prototypes for environmental tests.
5.) Conduct environmental tests.
6.) Quantify results of testing.
7.) Quantify and compare prototype performance results with control CCAs and flight avionics currently in production.

MILESTONES:

A.) Laboratory obtained and equipped.
B.) Prototypes complete and cured.
C.) Shock and vibration test and data collection complete.
D.) Radiation test and data collection complete.
E.) Performance data tabulation and comparison with current flight avionics.
F.) Cost data tabulation and comparison with current flight avionics.
G.) Statistical analysis of comparisons.
H.) Summary report documentation and recommendation(s).

NEXT STEPS:

A.) Determine applicability of process to current and new flight avionics.
B.) Develop methods for lot and mass production.
C.) Investigate the effects of adding iron and beryllium salts to the coating.

ACCOMPLISHMENTS

This researcher has begun delving into the literature and research data to establish the prototyping and test plan. This has resulted in two key findings:

1.) NASA’s Long Duration Exposure Facility (LDEF) failed to include Portland cement or concrete among the materials investigated.
2.) The National Bureau of Standards and the University of Cape Town (South Africa) have done considerable research — available to the public — on the interactions of nuclear radiation (including x-rays) with cement pastes and concrete.

Please note that this research was done independently of the funding grant, and is on-going.

SUMMARY

This project is ready to get underway.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Bruce McConnell

FUNDING ORGANIZATION: Seedling Investment Program

Microcontroller-Based Switched Mode Power Supplies

OBJECTIVE: *To develop an innovative design package for rapid prototyping and development of switch mode power supplies for space applications, with the goals of reducing cost, simplifying implementation, and easiness of adaptability to emergent requirements.*

PROJECT DESCRIPTION

At NASA Marshall Space Flight Center (MSFC), two types of switch mode power supplies (SMPS) that are frequently used for low-to-high levels of power conversion are the flyback and full bridge SMPS. Full-bridge power supplies are utilized when a medium-to-high level of power conversion is needed (i.e., 500 W or greater). An example of applications for a full bridge power supply include the oxygen generation assembly power supply module. The flyback power supply configuration is ideal for any level of power conversion. An example for applications for a flyback power supply is the fast neutron spectrometer, where high levels of voltage and very low currents are needed to provide power to the instrument's photomultiplier tube.

This design activity aims to develop an innovative design package for two frequently used types SMPS at MSFC. The design package will consist of a set of circuit boards developed in-house that can be custom configured for specific power supply applications along with a set of configurable programs for the microcontroller. The microcontroller will implement the major control functions of a power supply including power control, telemetry, monitoring, and commands. The candidate microcontroller chip is from ATMel®, a major microcontroller supplier, which has developed a space-qualified version of one of its most powerful microcontrollers: the ATMegaS128. This microcontroller is capable of implementing virtually any SMPS that might be needed for space use from instrumentation supplies to high-voltage power pulse units (PPUs) for electric propulsion.

Successful completion of this proposed effort will result in significant advancements in the state of the art for space power supply development, increase abilities to meet the cost of schedule of upcoming NASA missions, and strengthen MSFC's current design capabilities. Implementing a microcontroller-based SMSP design will dramatically decrease parts count, lower overall cost, and significantly decrease the design and prototyping periods. This design will incorporate the use of commercial-equivalent parts of flight-grade parts that are either radiation hardened or radiation tolerant. Furthermore, requirements for the design will be derived from previous in-house flight power supply designs in order to replicate a flight-like environment as much as possible.

The current approach of designing an SMPS at MSFC heavily relies on analog circuitry. Although this approach is reliable, it requires extensive design, resources (i.e., personnel time and parts procurement), and testing in order to successfully build prototype unit. Furthermore, the customer trend is leaning over requesting accelerated ways of producing these power supplies to ultimately save project cost and schedule. Compared to an analog-based SMPS design, integrating a microcontroller into the design can drastically simplify the design complexity by taking on the major control functions, including all power control, telemetry, monitoring and commands. This results in lower parts count, a dramatic reduction in SMPS size and overall weight, lower cost, plus a reduction in design and prototyping time of the SMPS. A microcontroller approach in a SMPS will allow for software updates to be uploaded from ground control, drastically reducing the implementation time and providing an easiness to adapt the supply to emergent needs. Furthermore, power supply parameters to be remotely controlled via remote ground control and implement strategically power management schemes to maximize efficiency.

The approach to this research project was to divide design activities by sections amongst several engineers and a student intern. The overall project duration was between 1 and 1.5 yr. The design activities included identifying design requirements; identifying and procuring parts, designing and prototyping the SMPS boards, identifying and designing additional boards (e.g., input/output filter boards); developing of the C++ API Software Library for the SMPS; integrating and testing the microcontroller with the SMPS boards, and documenting the design proces.

ACCOMPLISHMENTS

A total of two main boards were built for rapid prototyping of SMPS. Figure 1 shows the full-bridge power supply, with the integrated microcontroller. The micro-

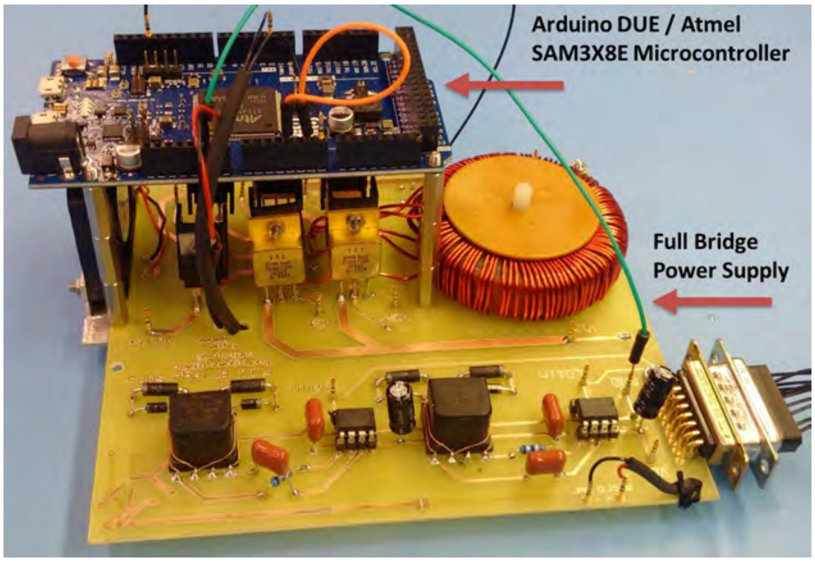


FIGURE 1. Full-Bridge SMPS.

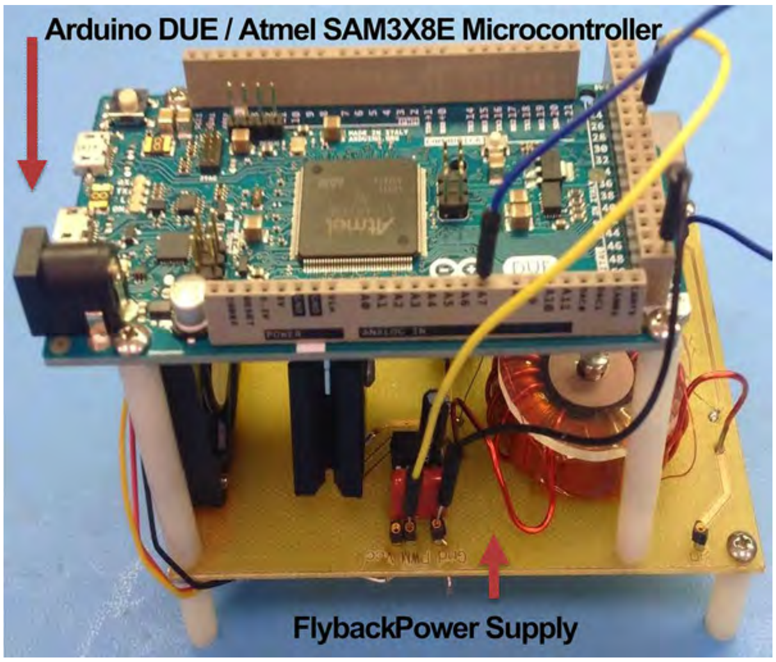


FIGURE 2. Flyback SMPS.

controller chosen to prototype the design was the Arduino DUE/Atmel SAM3X8E due to the availability of the evaluation board.

During the development of the power supplies, it was noted that gate drive circuitry needs to be in place for proper functioning. Whenever possible, parts with high reliability and specific levels of screening were utilized for the prototyping of the power supplies, such as the IRHM7260 Metal Oxide Semiconductor Field Effect Transistors (MOSFETs). A small fan was integrated with to allow for better heat dissipation. The prototype accepts from 10–120 VDC. The output voltage range is from 0–200 VDC, and the power rating is 50 W.

Figure 2 shows the flyback power supply, with the integrated microcontroller. The same microcontroller evaluation board was chosen due to it being easy to prototype. A small fan was also integrated to allow for better heat dissipation. The input voltage range for this prototype is 5–10 VDC. The output voltage range is 0–1,000 VDC, and the power rating is 5 W. A third board, the filter board, was built and prototyped. The input filter designs include common-mode chokes for common-mode and differential-mode noise suppression, plus transient voltage suppressors. The size of the prototypes can be further reduced in the next iteration of the printed circuit boards, where the microcontroller chip can be either integrated with the power supply board, or made as a stand-alone board.

SUMMARY

An innovative design package was designed for the types of SMPS utilized at MSFC. The design package consists of a set of circuit boards developed in-house, that can be custom configured for specific power supply applications along with a set of configurable programs for the microcontroller. The design package includes a microcontroller in order to integrate the main functions of the power supply, which allows it to control the main functions of the power supply. Added benefits to this include reduction in size, reduction of parts count, and added flexibility in changing design parameters. The full-bridge prototype board provides an output of up to 200 VDC and 50 W; the flyback prototype board provides an output of up to 1,000 VDC and 5 W.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Miguel Rodriguez-Otero, Leo Fabisinski

FUNDING ORGANIZATION: Technology Investment Program

COMMUNICATIONS, NAVIGATION, AND ORBITAL DEBRIS TRACKING

SVGS-Based Navigation of RINGS Onboard the International Space Station

OBJECTIVE: *To integrate the Smartphone Video Guidance Sensor with the Resonant Inductive Near-field Generation Systems vehicles in a 3 degree-of-freedom formation flying demo as precursor to deployment onboard the International Space Station (ISS).*

PROJECT DESCRIPTION

The Smartphone Video Guidance Sensor (SVGS) packs all the functionality of the NASA Marshall Space Flight Center (MSFC)-developed Advanced Video Guidance Sensor (AVGS) in the form factor of a smartphone for use as a 6-degree-of-freedom (6DOF) rendezvous and docking sensor. The SVGS utilizes a pre-defined pattern of four retro-reflective targets on a target vehicle. The SVGS sensor resides in a smartphone mounted on the chase vehicle. The smartphone flash illuminates the retro-reflective targets. The smartphone camera then acquires an image of the illuminated targets. A smartphone software app processes the image to estimate the 6DOF state between the chase and target vehicles.

The Florida Institute of Technology's (FIT's) Resonant Inductive Near-Field Generation Systems (RINGS) experiment, mounted on the Massachusetts Institute of Technology's (MIT's) SPHERES vehicles, attempted to demonstrate electromagnetic formation flying inside the ISS. RINGS provides actuation by generating electromagnetic fields which would either attract or repel the two vehicles with respect to each another; however, due to difficulties with its navigation approach, RINGS failed in its primary objective. As the SVGS is a navigation sensor which had yet to be demonstrated in a closed control loop and RINGS needed an optical navigation sensor, this was an excellent synergistic opportunity. The goal of this project was to integrate SVGS with RINGS so that the SVGS would provide adequate optical navigation to accomplish the RINGS objectives. The SVGS/RINGS system would be tested in FIT's flat floor facility to prove 3DOF-formation flying of two RINGS vehicles. Successful ground demonstration would prove feasibility for deployment onboard the ISS.

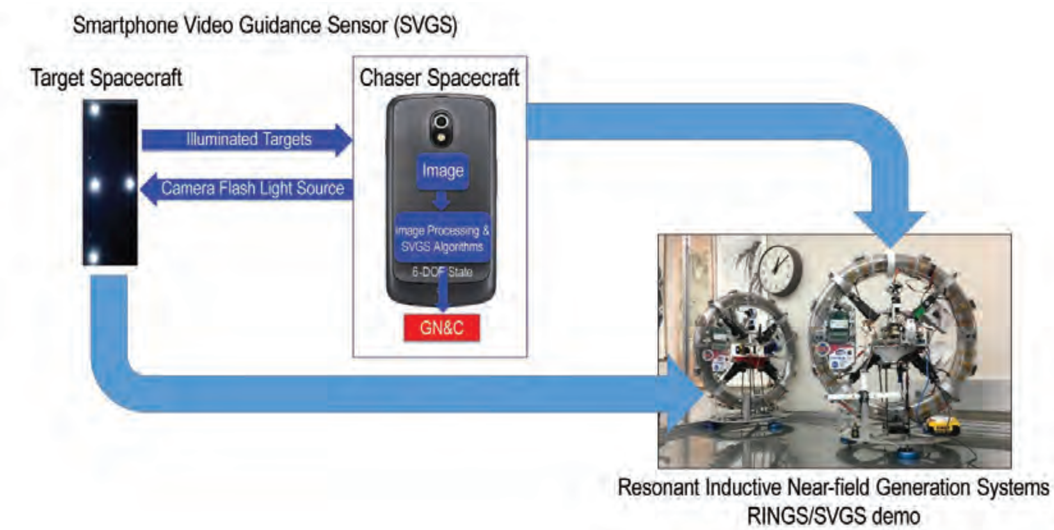


FIGURE 1. SVGS/RINGS integration concepts.

Under the purview of a Cooperative Agreement with FIT, MSFC delivered a version of the SVGS software app to FIT. FIT students implemented the app on a Samsung Galaxy S8 Android smartphone. FIT attached new LED targets to two RINGS air-bearing-mounted vehicles which were actuated in 3DOF via propulsion from ducted fans. The students mounted the smartphones on the RINGS vehicles. The second RINGS vehicle followed the first vehicle around the flat-floor table while students commanded the first vehicle along a prescribed trajectory. Thus, closing the feedback control loop around SVGS and performing proximity operations via SVGS was successfully achieved.

ACCOMPLISHMENTS

In 2018, the team achieved four major accomplishments:

1.) Integrated LED targets into SVGS and performed characterization to show that LED targets provide better accuracy and robustness than retro-reflective targets.

2.) Successfully demonstrated formation flying in 3DOF of two ducted-fan-actuated vehicles.

3.) Successfully maintained the leader-follower formation in following a prescribed path and subject to disturbance perturbations.

4.) Successfully demonstrated formation flying via electromagnetic actuation in 1DOF while controlling the other 2DOF via ducted fans. This is the first known demonstration of formation flying via electromagnetic propulsion.

SUMMARY

This highly successful project proved SVGS's viability for use by small spacecraft for proximity operations. Formation flying FIT's RINGS vehicles proved to be an excellent application of SVGS. FIT's RINGS vehicles now have an adequate navigation system to complete their original mission on ISS with the SPHERES vehicles. As an Android OS application, SVGS also shows promise as the RINGS navigation sensor for future integration on the Astrobee vehicle, the successor to SPHERES onboard ISS. The RINGS objective of using electromagnetic forces to maintain a formation was successfully demonstrated.

PRINCIPAL INVESTIGATORS: John Rakoczy, Ivan Bertaska, Chris Becker, and Ricky Howard

PARTNERSHIP: Hector Gutierrez, Florida Institute of Technology

FUNDING ORGANIZATION: Cooperative Agreement Notice

Mars Ascent Navigation

OBJECTIVE: *To identify technology needs and evaluate performance requirements for a vehicle lifting off from the surface of Mars, with a specific focus on state initialization and inertial navigation.*

PROJECT DESCRIPTION

Much work has been done on the architecture development for a large payload Martian ascent vehicle. These studies have focused on overall mass to orbit, propulsion systems design, and trajectory design for a notional vehicle. There has been only limited analysis of the guidance, navigation, and control (GNC) components required to meet mission requirements. This project addresses that gap and lays the groundwork for further detailed analysis. A Martian craft must be capable of autonomous operations to support initial determination of its launch attitude and location, which are some of the fundamental drivers to insertion accuracy that bound how well the vehicle can attain a desired orbit. The ability to accurately perform this directly correlates to delta-v and propellant requirements. The focus of this work is to apply knowledge in Earth-based launch vehicle GNC to a Martian scenario to provide insight into the capabilities afforded by state-of-the-art systems through detailed Monte Carlo analysis. This helps to identify long lead hardware items and potential risks. The goal of this research is to develop a modeling and simulation environment in order to assess the navigation system. In order to accomplish this, generic inertial navigation unit models are integrated into a simulation framework to assess navigation accuracy over a variety of ascent trajectories. This is intended to capture launch site and sensor sensitivities with a focus on how the navigation accuracy affects vehicle sizing in terms of propellant required for on-orbit trajectory corrections.

To support development of Martian Ascent Vehicles, analysis tools are needed to support the development of GNC requirements. This research presents a focused approach to navigation analysis to capture development of requirements on initial state knowledge and inertial sensor capabilities. A simulation-and-analysis framework was used to assess the capability of a range of sensors operating inertially along a range of launch trajectories. The baseline Martian Ascent Vehicle was used as the input for optimizing a set of trajectories from several launch sites, pulled from the Mars 2020 landing site studies. These trajectories were used to perform Monte Carlo analysis, which dispersed error sensor terms and their effects on integrated vehicle performance. As part of forward work, these analysis tools are being integrated and used to support continued vehicle design studies for both human and sample returns and their interaction with guidance algorithms.

Additionally, this approach provides insight into the use of optical navigation techniques to assess state determination. This provides an initial level of performance assessment of navigation components to support continued requirements development of a Martian Ascent Vehicle with applications to both crew and sample return missions. This technology is called the Stellar Positioning System and allows for high accuracy measurement of landing site location given star tracker and inclinometer measurements. In the current fiscal year, the team is working to develop a Fine Stellar Positioning System version with improved accuracy and ground demonstration in the coming year through further collaboration with Texas A&M University.

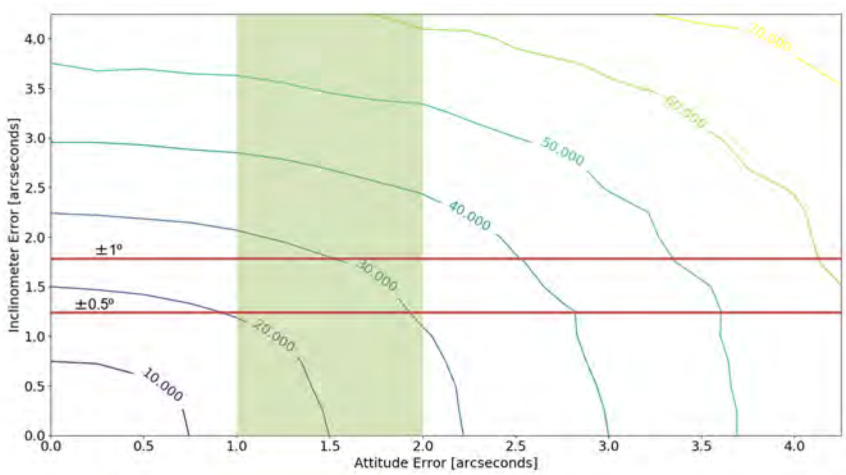


FIGURE 1. Stellar Positioning System Accuracy (m) on contours. Highlighted area shows star tracker attitude estimation capability with the red lines showing inclinometer hardware options.

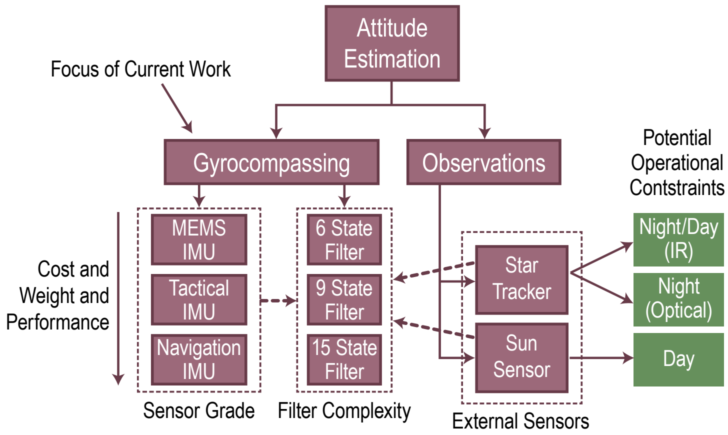


FIGURE 2. Options being assessed for initial attitude determination.

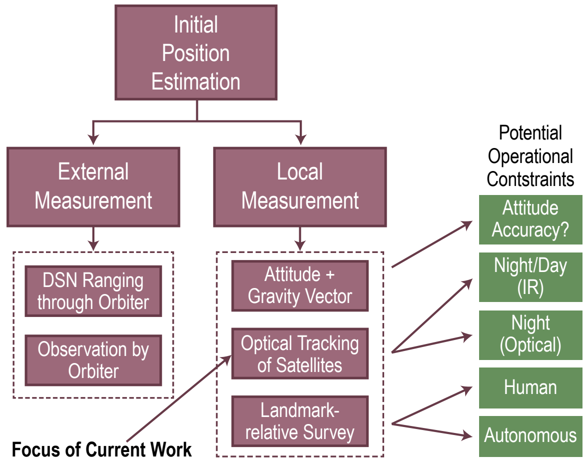


FIGURE 3. Tradespace for Initial position estimation.

ACCOMPLISHMENTS

As part of this research and development effort, a six-degree-of-freedom (6DOF) simulation was used to assess navigation performance for a human Martian Ascent Vehicle. Using the identified potential landing sites and current representative vehicle, the POST tool was used to generate optimized trajectories to maximize mass to orbit. Following this, navigation analysis was performed, assessing inertially measured initial attitude for a range of sensors. Additionally, the inertial navigation capability of each sensor was assessed over the optimized trajectories to determine state errors upon reaching orbit. These uncertainties are used to feed an in-space analysis in the Copernicus tool that is used to reoptimize the trajectory given the initial dispersion. Using this approach, the effect of navigation error can be directly tied to high-level vehicle metrics, i.e., total delta-v required for the mission. This work identified the need for high accuracy navigation sensors in order to determine initial attitude. This analysis assumed a closed-loop guidance scheme in which navigation errors directly correlate to insertion state errors. As the guidance algorithms are advanced, the sensitivity to integrated navigation position may be reduced by flying in an open-loop manner via a predetermined flight profile. Ongoing work is continuing to address this interaction for Sample Return missions.

In addition to purely inertial navigation, this research also addressed the potential to use star trackers to aid in initial state estimation. Several methods were simulated and assessed including use of the Stellar Positioning System and observation of Martian satellites (both natural and man-made). The analysis was able to determine that accurate initial state estimates could be calculated using a star tracker and inclinometers. Observations of satellites produced lower quality results due to the high altitude of the natural satellites and orbit uncertainties in orbits of manmade satellites. Through collaboration with Texas A&M University (developers of the Stellar Positioning System), the team hopes to continue to refine and test these algorithms on flight hardware in the coming year.

SUMMARY

Over the course of this research, the Martian Ascent Navigation team successfully developed a modeling and simulation framework to support navigation analysis of vehicles lifting off from the Martian surface. With this toolset, the team is able to capture end-to-end navigation performance for this mission scenario, from initial position and attitude determination through capability to meet orbit requirements. Continuing work in this area is expanding the analysis to include the implementation of guidance algorithms and robustness to environmental effects (i.e., winds) for human and sample return ascent vehicles. Additionally, the team was able to identify a technology for further development and testing to enable high accuracy position estimation through the use of the Stellar Positioning System. Continuing work in this area will lead to refinement of the algorithms and hardware demonstration.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Evan Anzalone

PARTNERSHIP: Texas A&M University

FUNDING ORGANIZATIONS: Technology Investment Program

Software-Driven Navigation for Station

OBJECTIVE: *To demonstrate two software-driven in-orbit navigation approaches: (1) multi-autonomous positioning system (MAPS) and (2) pseudolites, using the SCaN Testbed onboard the International Space Station.*

PROJECT DESCRIPTION

The Software-driven Navigation for Station (SNS) Experiment's goal is to advance navigation technologies to enable improved capability, expanded operations, and increased autonomy through the use of software algorithms that can both be used in new and existing hardware systems. The first part of the experiment provides an orbital demonstration of the multispacecraft autonomous positioning system (MAPS), which enables interelement ranging through integration of navigation data into the standard digital communication methods. This enables every communication pass between elements (other spacecraft and ground elements) to also provide onboard autonomous navigation measurements. To provide a demonstration of both the technology and the approach to integration with an existing spacecraft, the MAPS algorithms were implemented onboard the space communications and navigation (SCaN) software-defined radio (SDR) testbed onboard the International Space Station (ISS) for transmission to a ground site operated at NASA Glenn Research Center (GRC) by the Testbed Project Office. Additionally, this experiment demonstrated the use of pseudolites for inter-asset navigation. This technology utilizes an algorithm based on the generation of global positioning system (GPS) signals for areas with limited coverage. The SCaN Testbed was used as a pseudolite transmitter with the ground station recording and processing the signal for navigation measurements.

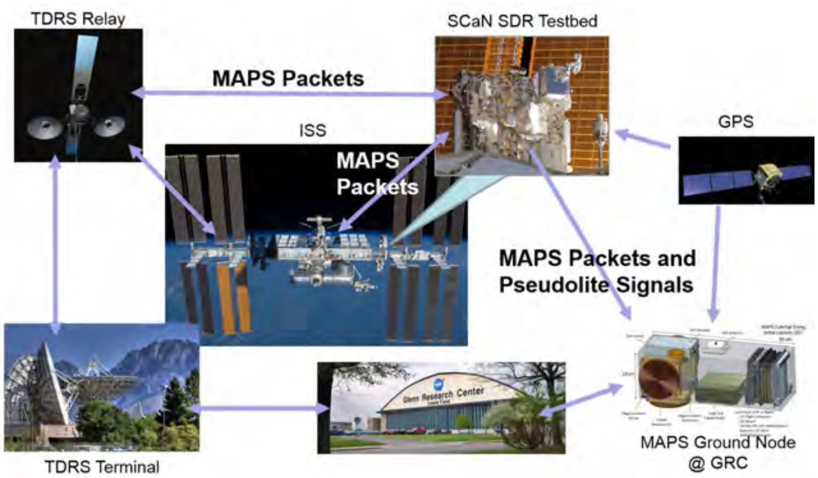


FIGURE 1. Concept of Operations of the Experiment Showing Communication links between SCaN Testbed and the Ground Network.

This experiment was selected in order to push engineering processes and attempt to go from concept to orbital demonstration in a 1-year timeframe. As such, the team implemented a very streamlined approach to systems engineering, software development, and testing to meet NASA standards and ensure successful operations. The key enabler of this experiment was the use of an existing platform (SCaN testbed) with an already-defined experimenter software platform with active operations to allow for independent software development and clear path of testing to certification and flight. Existing MAPS algorithms used in hardware in the loop simulation were ported to utilize the Core Flight Software framework to enable further integration with potential customer payloads and implemented within the SCaN Testbed Avionics processor for flight testing. The utilization of this clear experimenter layer and ability to test on ground hardware allowed for pre-flight characterization and testing of the algorithms. The technologies being testing also provide a unique approach to augmenting existing deep space vehicles with enhanced autonomy in their navigation architectures and reduced reliance on ground networks by moving state estimation procedures onto the spacecraft.

ACCOMPLISHMENTS

As part of this experiment, the MAPS algorithms were ported to and tested in the Core Flight System architecture for ground testing. This software formed the basis of the software ported to operate on VxWorks using the SCaN Testbed Experimenter's Interface onboard the Avionics hardware within the payload. The team conducted ground checkout of the software

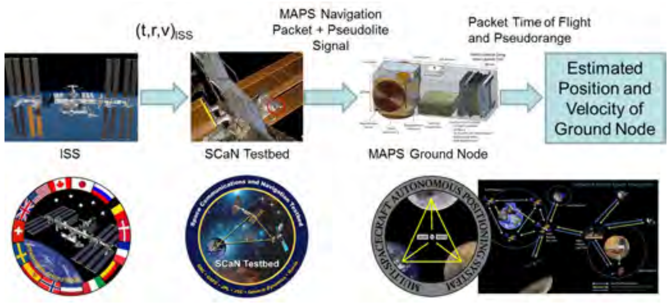


FIGURE 2. High Level Concept of Operations showing key functions and experiment partners.

and operations plan development using the Ground Interface Unit at GRC. This testing demonstrated the operational readiness of the experiment as part of the path to software approval for flight. The software was uploaded to the SCaN Testbed in June of 2018. Following successful checkout, the team performed two sets of orbital demonstrations of the software over the period of June–August of 2018. Over the course of the experiments, the team transmitted MAPS packets over three unique methods with increasing system latency: (1) payload to ground, (2) payload to Tracking and Data Relay Satellite to ground, and (3) payload to ISS telemetry to ground. These varying complexities allow for characterization of the effect of timing synchronization and system latency. These signals were received, recorded, and decoded using a mix of existing hardware and a custom flatsat at GRC, exercising the MAPS and pseudolite algorithms onboard both the flight and ground portions of the network. Altogether, the team collected 12 hr of operational data over the course of 52 ground passes that are currently being post-processed to assess navigation capability within the MAPS framework. Due to the inability to tightly synchronize the internal clocks within the existing hardware framework, the performance results are limited by the small transmission times for low Earth orbit missions that are only an order of magnitude higher than the expected latencies. Thus, the team will need to perform calibration to account for hardware and receive path latencies during each pass for assessing navigation performance. With the final characterized performance of the software algorithms, the team will move towards supporting integration and operations onboard a satellite flying beyond low Earth orbit. Additionally, the results of the pseudolite transmissions are also being processed to show their capability, as the team works to utilize this technology for planetary-wide navigation networks as an alternate approach.

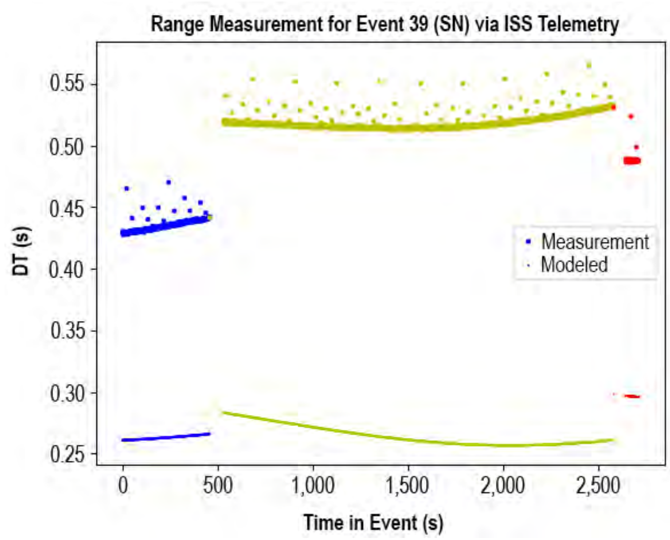


FIGURE 3. Uncalibrated and Modeled Range Measurements between ISS and GRC using the ISS Payload Telemetry Path (SCaN testbed>ISS>TDRS>Payload Operations>GRC).

SUMMARY

This experiment provided an opportunity to gain experience with the integration of two unique software-based approaches to spacecraft navigation in an orbital use-case application. Although the latencies and limited transmission path between the ISS and the ground limit the accuracy of the methods, the software was exercised and experience gained with the integration of these technologies into an existing orbital asset. By considering these timing needs early in a project's lifecycle, it is possible to calibrate the system to high precision. The data collected from the experiment will provide validation of the MAPS algorithms as the team continues to process the flight data. The demonstrated integration and operation of the MAPS algorithms both on the SCaN testbed and at the ground station builds confidence in the software implementation, preparing the technology for infusion into new and existing missions to support autonomous spacecraft navigation.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Evan Anzalone

PARTNERS: SCaN Testbed Office, NASA Glenn Research Center; ISS Payload Office, NASA Marshall Space Center and NASA Johnson Space Center

FUNDING ORGANIZATION: ISS Program and Payloads Office

Wireless Deflection Sensor System for Ground-Based Structural Tests at Marshall Space Flight Center

OBJECTIVE: *To develop a wireless deflection sensor for NASA Marshall Space Flight Center to use in ground-based structural tests, demonstrating the flexibility, versatility, and cost benefits of wireless sensors.*

PROJECT DESCRIPTION

Ground testing of space vehicle components such as fuel tanks often requires structural sensors such as strain gauges, accelerometers, and deflection sensors. Performance tests are conducted in controlled environmental chambers with thermal cycles that mimic space conditions; therefore, all this instrumentation, although used on Earth, needs to be capable of operating in harsh environments. Wiring design and actual cabling and bundling may be cumbersome, costly, or may be infeasible in some cases; therefore, wireless sensing in ground systems can open up a myriad of new opportunities to gather critical data. The focus of the Cooperative Agreement Notice (CAN) proposal was on wireless technology development and demonstration for ground test systems at NASA Marshall Space Flight Center (MSFC) to address an immediate need, while creating a platform for further development in the aforementioned technology areas.

The benefits of using wireless structural sensing are:

- more data acquired for structural analysis not possible using wires,
- cost of tests reduced due to cabling elimination,
- flexibility of test for adding more sensors later without redesigning the wiring plan, and
- versatility in programming testbeds for future tests.

Some of the challenges in developing wireless structural monitoring systems include:

- high-precision requirements in sampling and data transfer,
- interference management among large number of sensors sending data, and
- test setup limitations at specific distances.

The approach included:

- working with engineers within the Structural Test Area at MSFC to develop a set of requirements,
- specifying transmitter/receiver requirements,
- designing and testing the system at the University of Maine (UMaine),
- testing the system at MSFC,
- analyzing performance and incorporate changes into design, and
- completing final design and deliver to MSFC for testing

ACCOMPLISHMENTS

The complete system was design and tested at both facilities and shown to meet the specification having a resolution of at least 0.003 in. The final system is waiting testing at MSFC. Future work will include pairing the sensor with MSFC's wireless energy transfer systems. The graduate student developed a Master's thesis based upon the work and presented at the IEEE WISEE 2017 International Conference.

Testing at MSFC highlighted potential facility factors related to wireless system implementations within Building 4619 that can be utilized during future wireless developments. This led the MSFC Wireless Technology Working Group to consider as a lesson learned that, with wireless, a physical and radio frequency environment assessment needs to be done upfront with any wireless technology development and that there needs to exist a 'clean' environment for testing of wireless systems before being incorporated into the flight systems or test systems.

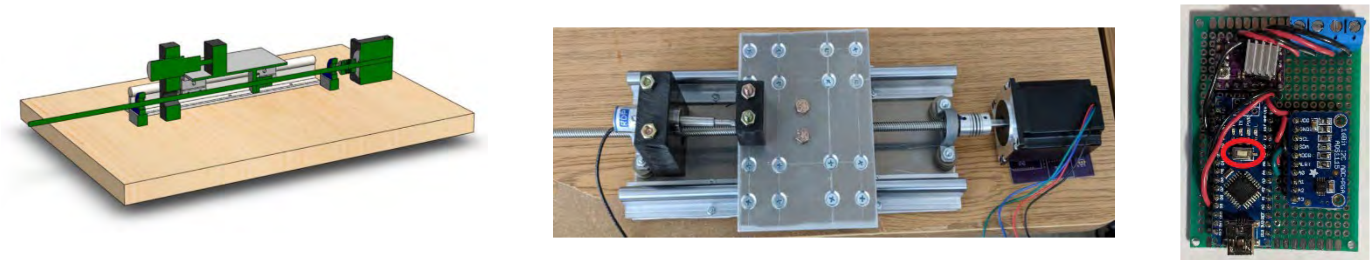


FIGURE 1. UMaine linear testbed design (left) and actual picture (center) and sensor electronics (right).

SUMMARY

In addition to ground structural tests, wireless systems can support NASA MSFC programs such as habitats, manned and unmanned vehicles, and satellites/payloads. The flexibility of the sensors and reduced cabling can lead to reduced cost/schedule/weight during design, production, test, and operation of these types of efforts. As an expert in wireless technology, UMaine helped advance MSFC's wireless test capabilities in a short amount of time. Additionally, MSFC has made numerous contacts in the wireless community through the UMaine professor, who is a leader in the field. For UMaine, the partnership exposed them to MSFC's areas of interest in wireless technology, the challenges of the aerospace environment, additional proposal opportunities for UMaine, and to training a graduate student. The partnership has also led to MSFC supporting an IEEE International Conference for Wireless in Space and Extreme environments in Huntsville in December 2018.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: DeLisa Wilkerson, Marshall Space Flight Center and Ali Abedi, University of Maine

PARTNERSHIP: University of Maine

FUNDING ORGANIZATION: Cooperative Agreement Notice

HUMAN HEALTH, LIFE SUPPORT, AND HABITATION

In-Space Manufacturing of Crew Clothing

OBJECTIVE: *To explore the possibility of manufacturing and recycling crew clothing in space.*

PROJECT DESCRIPTION

On the International Space Station (ISS), clothing is treated as a consumable. Once sufficiently worn by the crew, it is discarded and replaced. For missions beyond low Earth orbit, this approach will prove infeasible due to high logistic and resupply costs. Laundry facilities have been considered and developed to mid-technology readiness levels. However, these facilities invariably require considerable water, add complexity to the Environmental Control and Life Support (ECLS) water recovery system (due to the presence and challenge of handling soaps), and require considerable design complexity for microgravity operation.

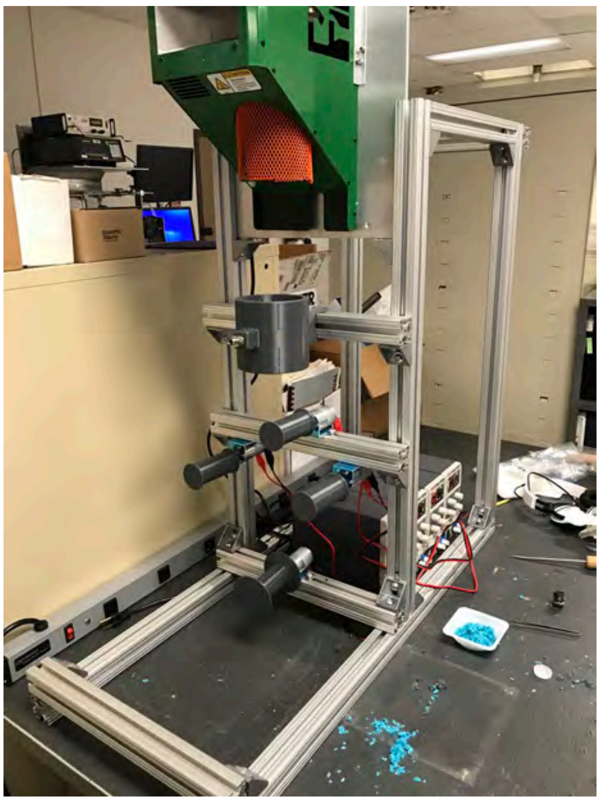


FIGURE 1. Miniaturized PET fabric recycler designed and fabricated in FY 2018.

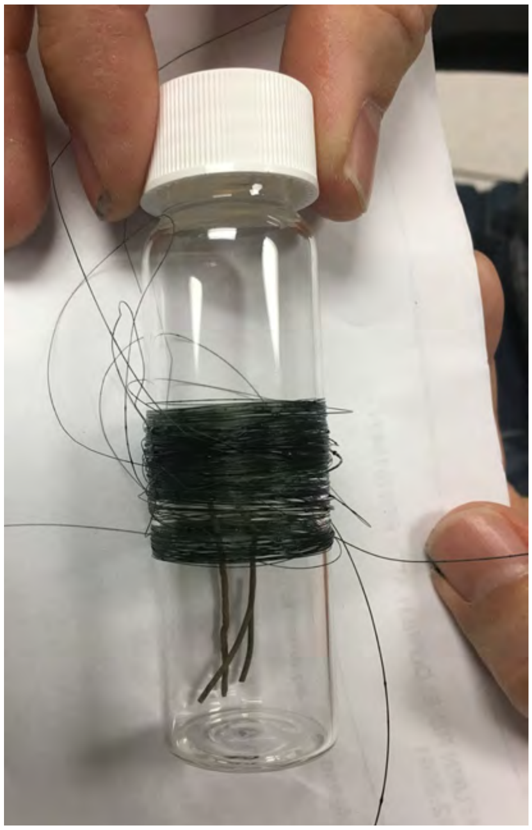


FIGURE 2. Single-stranded recycled PET yarn.

Textiles for clothing have historically been produced from natural sources that result in different textures, thicknesses, and thermal properties (e.g., silk versus cotton versus wool). For clothing, these properties allow for application-specific materials. In the last century, synthetic textiles, such as polyethylene terephthalate (PET), also called polyester, have been developed and demonstrate incredibly versatile properties. For example, PET is used to produce satins, jerseys, flannels, and fleece. The added benefit of PET is that it is a thermoplastic and is 100% recyclable at moderate temperatures. In fact, PET is commonly recycled in industry to produce these various fabrics. This process may be miniaturized and adapted to space flight where complete recycling of materials is necessary to limit resupply and launch mass. The goal of this project was to explore an entirely new approach to providing what the astronauts wear. Rather than cleaning or replacing the clothing, this project explored an in-space manufacturing approach to produce and recycle crew clothes.

This project explored two approaches to using PET as a recyclable material for crew clothing. A key concern with PET is its flammability. Historically, NASA has avoided PET due to concerns with flame retardants damaging the life support systems. For this reason, the first approach involved exploring the production of PET yarns via a miniature extrusion system and identifying flame retardants compatible with existing ECLS systems. In this effort, the goal was to design and build a miniaturized PET extrusion system capable of producing multifilament yarns. Simultaneously, the team leveraged the considerable experience of NASA's trace contaminant and control subject matter expert to help identify a compatible flame retardant. The second approach involved producing PET blends containing the inherently flame-retardant polyimide 84 (P84). In this effort, the goal was to card and spin together various ratios of P84 and PET to produce a flame-retardant yarn that could be recycled using the traditional PET extrusion method.

This innovation, when successful, would eliminate the need for clothing resupply as well as the need for laundry facilities, dramatically reducing the complexity of the missions along with the ECLS systems dedicated to water recycling.

ACCOMPLISHMENTS

In fiscal year (FY) 2018, a miniature PET extrusion system was designed and built, as shown in figure 1, and demonstrated the production of single-strand yarns, as shown in figure 2. This yarn was produced by recycling a commercially available PET fabric purchased at a local fabric store. Based on the demonstrated success of single-strand yarns, a new spinnerette (shown in fig. 3), was designed and manufactured to produce multistranded yarns. The new spinnerette is due to be tested in FY 2019.

FIGURE 3. Multifiber spinnerette for extruding PET yarns.

FIGURE 4. Carded and spun yarns containing 100% PET (left), 90% PET/10% P84 (center), and 80% PET/20% P84 (right).

To evaluate the second approach, yarns containing 100% PET, 90% PET/10% P84, and 80% PET/20% P84 were carded and spun as seen in figure 4. These yarns are due to be tested for flammability at NASA Johnson Space Center (JSC) in FY 2019.

SUMMARY

This project sought to explore the possibility of manufacturing and recycling crew clothing in space. This effort resulted in the design and fabrication of a miniature PET yarn production stand and demonstrated the production of single-strand yarn recycled from PET fabric. Blended yarns containing both PET and P84 were also produced in an effort to address flammability concerns. Materials produced from this effort will be tested at JSC in FY 2019.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Morgan Abney and Bobby Atkins

PARTNER: NASA Johnson Space Center

FUNDING ORGANIZATION: Center Innovation Fund

Brand NEW (Neuropathy Experience Wellness)

OBJECTIVE: *To create an aesthetically appeasing shoe technology beneficial to neuropathic victims that will alleviate neuropathic symptoms, while fortifying the Space Launch System initiative.*

PROJECT DESCRIPTION

More than 20 million people suffer from peripheral neuropathy and are victims of limited mobility, limiting this market's choices and their ability to express themselves outwardly via shoe wear. Brand NEW will leverage the research of NASA Johnson Space Center's (JSC's) X2 Force Shoe technology and utilize in-house motion capture technologies in order to infuse the commercial sector with a fashionable shoe wear that would aid individuals suffering from peripheral neuropathy and limited mobility. Additionally, this project will utilize such technologies in order to fortify the Ground Support Equipment (GSE) platform on the Space Launch System (SLS).

Innovative aspects of this project include the versatility of shoewear that will be developed, and the versatility of individuals that will be impacted as a result of this shoe technology. Neuropathy is a symptom to many underlining causes and diseases specific to individuals. Thus, dancers, athletes, cancer survivors/victims, alcoholics, and diabetics will be the beneficiaries. Currently, market segmentation is ongoing, and neuropathic symptoms amongst the different group classifications are being identified in order to employ the necessary technologies into the shoe design. Additionally, research is ongoing on the SLS GSE platform, and weight requirements sufficient to the project's needs are being identified to advance the SLS initiative. In essence, the objectives of this project include leveraging the research and data regarding Earth applications of JSC's X2 Force Shoes to design a shoe technology that would prove sufficient to bone/joint and muscle health for individuals with neuropathic conditions, assessing and collecting foot load data of individuals of variable sizes in order to discern the correlation of data applicable to SLS structures, and creating a technology infusion roadmap to commercialize such shoes. This project differentiates from other efforts in industry, as aesthetically appeasing shoe technologies aiding neuropathic victims are scarce. As a result of the shoe technology that will be developed, doctor visits and physical therapy treatments will be minimized for such victims.

FIGURE 1. JSC's X2 Force Shoe Technology.

ACCOMPLISHMENTS

Data analysis of preceding research and an assessment of JSC's X2 Force Shoes capabilities have occurred. Additionally, market segmentation has occurred, and variables amongst different groups have been identified for research in answering questions concerning neuropathy and for incorporation into the shoe technology. Furthermore, test subjects have been identified. Lastly, partnerships have been established with academia, and interests from commercial entities have been received.

SUMMARY

This project, if successful, will not only help alleviate pain experienced amongst neuropathic victims, but will also offer a level of social inclusivity in the shoe market, enhancing self-esteem and self-actualization. Currently, shoewear for neuropathic victims are often denoted as orthopedic shoes, lacking style, and are often not included within the name brand shoe sector. This project will improve the quality of life of more than 20 million individuals by minimizing doctor visits and treatments as a result of neuropathy. Additionally, this project will fortify the SLS initiative via enhancement of SLS structures.

PRINCIPAL INVESTIGATOR: LaBreesha B. Batey

PARTNERS: NASA Marshall Space Flight Center Human Factors Engineering Team, University of Alabama in Huntsville Mechanical Engineering and Biomechanics Department, and NASA Johnson Space Center Robotic Systems Technology Team

FUNDING ORGANIZATION: Seedling Investment Program

Ionic Liquids for Advanced Environmental Control and Life Support System

OBJECTIVE: *To design and fabricate an ionic liquid-based Bosch reactor capable of regenerating a carbon-fouled catalyst from the Bosch process during oxygen recovery from carbon dioxide.*

PROJECT DESCRIPTION

Long-duration manned missions beyond low Earth orbit will require maximum oxygen recovery in order to reduce resupply mass. The current state of art for oxygen recovery only achieves approximately 50% oxygen recovery from metabolic carbon dioxide (CO_2). In order to increase the recovery rate required for exploration, the Bosch process is being investigated. Complete recovery of oxygen can be achieved through the Bosch process; however, the main challenge with this technology is that the solid carbon produced during the process results in undesired catalyst resupply mass. In order to solve this issue, advanced development of a fully regenerable oxygen recovery system is desirable. Regenerable catalysts can be achieved with the aid of liquid organic salts known as ionic liquids (ILs). ILs are of particular interest for space applications due to their characteristics such as low flammability, no vapor pressure, and ability to be modified to be task specific.

Previous studies at NASA Marshall Space Flight Center (MSFC) have used ILs to extract iron (Fe) and nickel (Ni) from a Campo del Cielo meteorite and electroplate the extracted metals onto a carbon substrate. This same approach can be applied to create an IL-based Bosch system which could eliminate the need for resupply for long-duration missions. The goal of this project is to develop a Bosch-based technology that uses ILs to recycle system catalysts. In fiscal year (FY) 2018, the objectives of the effort were to finalize and begin fabrication of an IL-based Bosch reactor.

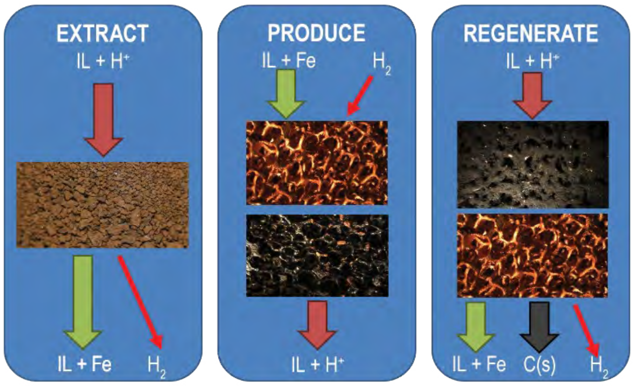


FIGURE 1. A designer IL is used to extract iron from Martian regolith (far left), produce a catalyst for the Bosch process by electroplating Fe onto a copper substrate (center), and regenerate a carbon-fouled catalyst by extracting the iron from the copper substrate and carbon product (right).

The ability to use ILs to extract metals from a meteorite inspired the theory of recycling iron or nickel catalysts that would be discarded as waste once the catalyst is fouled in a traditional Bosch system. An IL-based Bosch system involves the following steps:

1.) Designer IL is used to electroplate iron and/or nickel onto a copper (Cu) substrate to generate an iron/nickel-copper catalyst substrate.

2.) The iron/nickel-copper catalyst substrate prepared in step one is used in the Bosch process for O_2 recovery.

3.) Designer IL is used to regenerate the iron and/or nickel from the carbon-fouled catalyst generated in step two. Upon completion, the iron and/or nickel is suspended in the IL, leaving behind pure carbon. The solution is then ready to be reused in step one, and the carbon is filtered from the solution.

4.) Designer IL is used to extract iron (and/or nickel) from Martian/Lunar regolith to make up for minor handling losses and will be used in step one.

The only consumable in the process is the carbon filter. However, partially regenerable filtration is intended. Although there are various other Bosch-based systems that are currently being researched, no other system proposes zero-catalyst resupply mass with a simplified approach to carbon handling. If successful, this approach represents a complete paradigm shift with respect to closed-loop life support technology.

FIGURE 2. IL-based Bosch reactor.

ACCOMPLISHMENTS

Significant progress was made towards maturing an IL-based Bosch technology in fiscal year FY 2018. Based on the data gathered throughout FY 2017 and early FY 2018, a finalized IL-based Bosch reactor design was completed. The IL-based Bosch reactor design concept incorporates the three main processes into one reactor: (1) electroplating catalyst onto a substrate, (2) carbon formation via the Bosch process, and (3) regeneration of the carbon-coated catalyst substrate. The computer-aided design (CAD) model of the reactor design concept is shown in figure 1. Fabrication of the reactor and test stand is ongoing.

SUMMARY

An IL-based Bosch system approach will provide a fully regenerable technique for recovering oxygen from either metabolic CO_2 or from atmospheric CO_2 by utilizing ILs and in situ resources. Past studies proved the feasibility of such system and provided a first-generation IL-based Bosch system concept. In FY 2017, data was collected in order to scale the technology that is required for an integrated life support system as well as an initial reactor design and concept for an IL-based Bosch system. The initial IL-based Bosch reactor designed in FY 2017 was optimized in FY 2018, and a final reactor design was chosen. The fabrication of the reactor and test stand was initiated; the system will be completed in FY 2019, and initial testing will be conducted.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Brittany Brown and Eric Fox

FUNDING ORGANIZATION: Advanced Exploration Systems

Carbon Dioxide Removal

OBJECTIVE: *The 4BCO2 project seeks to build a full-scale life support subsystem to operate on the International Space Station, on a short schedule, with the goal of demonstrating the technology for deep-space mission success.*

PROJECT DESCRIPTION

The 4BCO2 flight demonstration aims to demonstrate four-bed molecular sieve technology as a robust, autonomous component of the life support systems that can guarantee deep space mission success. The technology is derived from the Carbon Dioxide Removal Assembly (CDRA), a primary carbon dioxide (CO_2) removal system onboard the International Space Station. Although CDRA has a long maintenance history, various improvements have increased its reliability to beyond 2 years and counting. All of these improvements have been implemented in the 4BCO2 demonstration while requiring less mass, power, and volume. The flight demonstration will remove four crew-equivalents of metabolic CO_2 at an average CO_2 concentration of 2 torr and produce high-purity CO_2 for oxygen recovery and loop closure.

The air blower, heat exchanger, sensors, filters, and vacuum pumps will be commercial products from industry state of the art. A prototype four-bed system has been operated at NASA Marshall Space Flight Center (MSFC) to test new design features and the interactions with these new components to ensure effective operation. The new air selector valves are developmental work at MSFC with a particular focus on dust-tolerance, a feature widely recognized as essential for Lunar or Mars surface operations. The heater core was redesigned from scratch to reduce dusting and improve bed performance by incorporating a 3D-printed heater support plate and heat spreaders precision cut via electrical discharge machining (EDM). This heater core will reduce dust generation and improve other reliability aspects.

The fiscal year (FY) 2019 efforts will include complete assembly and qualification of the 4BCO2 flight demonstration. The fully instrumented prototype system will continue to provide data as each flight-like engineering component is integrated. This data also supports a complete system simulation which further advances the state of the art for computer simulations of CO_2 capture and removal systems.

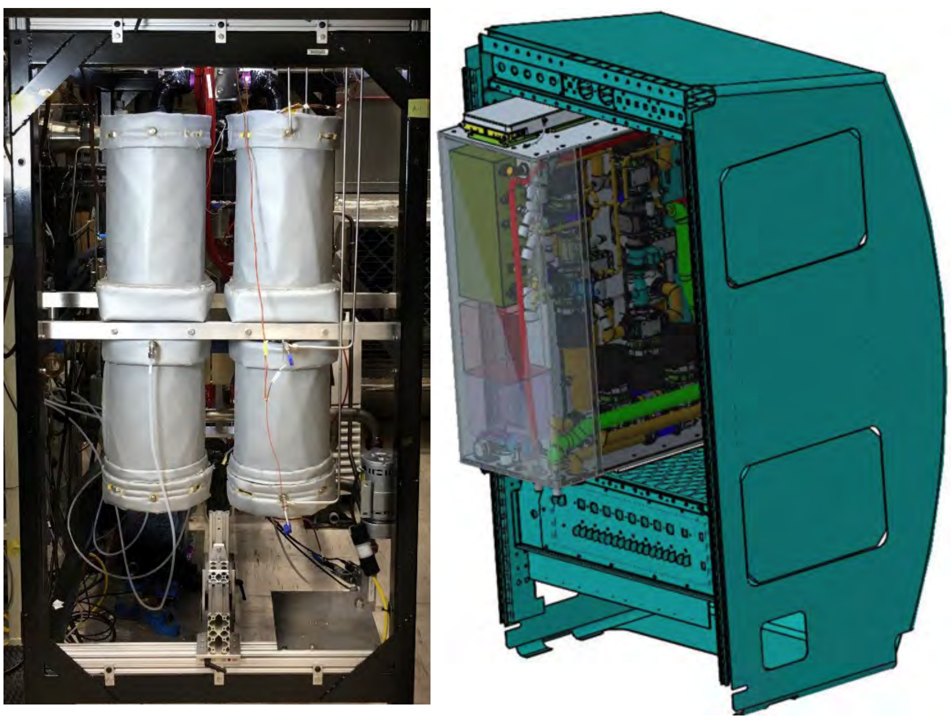


FIGURE 1. Enhanced photo (left) of prototype 4-bed testbed and 3D graphical design (right) of flight system as it would be installed on the ISS.

ACCOMPLISHMENTS

The FY 2017 and FY 2018 efforts focused on selecting the best sorbent material to use in the beds. To replace the obsolete CDRA sorbent, a 13X zeolite was identified out of over a dozen commercially available options as possessing the durability required after extensive testing. Additionally, computer simulations predicted an optimization by

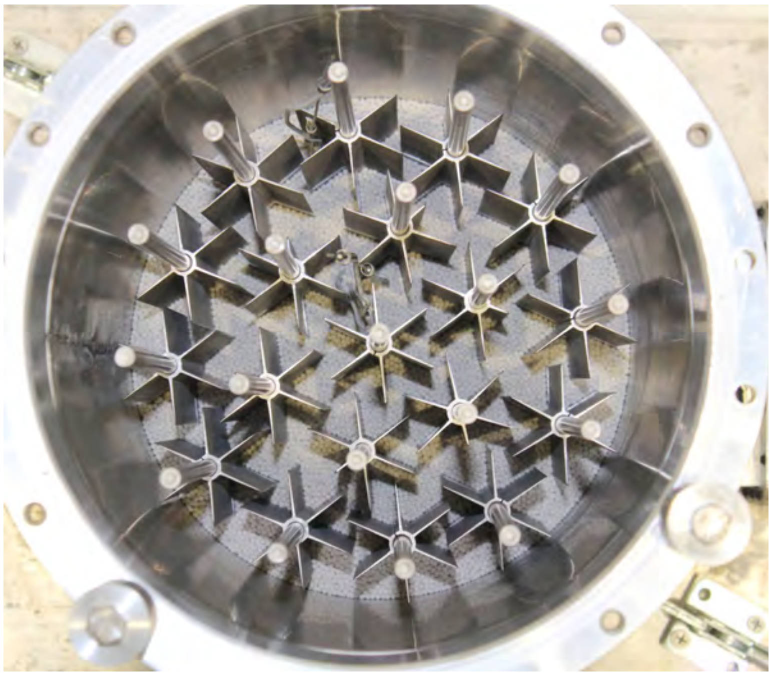


FIGURE 2. Photo of sorbent bed during packing showing new heater core, sorbent, and RTDs.

reducing material loading in the beds and experiments soon confirmed this prediction. The simulation was used to guide the sizing of the 4BCO2 beds. The data collected in the prototype is used to validate the simulation. Improving the model will allow for more precise design of any next-generation CO_2 removal system including a 4BCO2 optimized for surface or deep space missions.

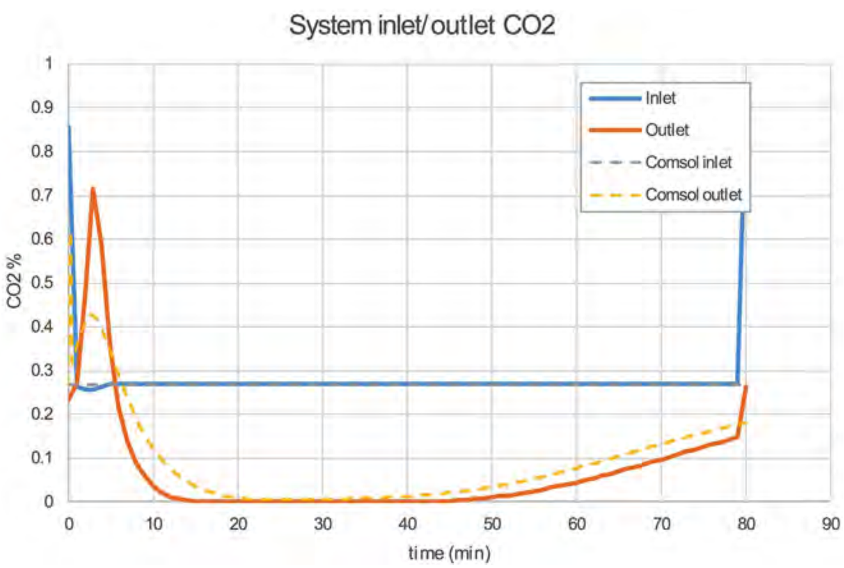


FIGURE 3. Plot of measured testbed CO_2 concentration data versus simulated system input and output.

The prototype system was built as soon as possible to specifically test several new features and enable iteration on the design aspects. To encourage rapid iteration, the design, machining, and testing teams were co-located within the same building at MSFC. This allowed basic concepts to be realized as full-scale components through regular contact and discussions between these experts. Numerous small issues have been identified and rectified early in development due to this arrangement.

The redesigned CO_2 sorbent bed was targeted as a primary need for improving CO_2 capture performance and reducing dust generation. The redesigned heater core incorporates MSFC metal 3D printing technology, precision EDM heat spreaders, and commercial heater elements. The filter element was designed specifically to address several CDRA failures due to dust accumulation. This filter was placed in a slide which can be accessed by crew for rapid maintenance.

SUMMARY

The 4BCO2 project is the culmination of long-term efforts to study and address the causes of CDRA failures. The final product will be a full-scale life support demonstration which will integrate as many commercial-off-the-shelf components as possible. The final product is being assembled and tested at MSFC. This system will be evaluated as a flight demonstration during its first year of operation with the goal of proving the elimination of all the causes of CDRA failures.

PROJECT MANAGER: Donnie McCaghren

PRINCIPAL INVESTIGATOR: Gregory Cmarik

FUNDING ORGANIZATION: ISS Program and Payloads Office

Biochemical Countermeasure to Radiation Exposure

OBJECTIVE: *To test the radio-protective effects of a medical gas treatment for enhancing our natural resistance to radiation induced damage.*

PROJECT DESCRIPTION

Radiation exposure to astronauts is a significant obstacle for long-duration manned space exploration because of current uncertainties regarding the extent of biological effects. Furthermore, concepts for protective shielding also pose a technically challenging issue due to the nature of cosmic radiation and current mass and power constraints with modern exploration technology. The concern regarding exposure to cosmic radiation is the biological damage it induces, which is related to double-strand DNA breaks and oxidative stress. A combination of chemical and biological mitigation techniques, used conjunctively in a 'systems biology' approach is proposed as a countermeasure to mitigate and/or prevent oxidative stress prior to the development of clinical symptoms and disease. New, therapeutic, medical gases as both chemical radioprotectors for radical scavenging and biological signaling molecules for management of the body's response to exposure are proposed. A review of radiochemistry of water, biological effects of CO, H_2, NO, and H_2S gas, and mechanisms of radiation biology, indicates that this approach may have great therapeutic potential for radiation exposure. The goal of this project will be to perform a rudimentary cell survival study using H_2 and H_2S medical gases to examine for radio-protective effects as expected.

The traditional paradigm for radiation protection is to minimize exposure time, maximize distance from radiation sources, and use shielding to attenuate and absorb radiation before it can deposit its energy in humans. In regards to minimizing exposure time, new propulsive technologies could reduce trip times but have yet to be developed and would not address the ability to remain at a location for long durations. It is impractical to maximize distance from cosmic radiation sources. In regards to shielding, aspects of attenuation by mass or deflection by magnetic fields or charge repulsion have been considered. Due to the phenomena of secondary radiation, shielding by other matter may require a significant amount of mass which could be impractical within current mass constraints in space systems. Due to the high energy of the space radiation, magnetic field and charge strengths required may be unreasonable due to current mass and power constraints in space systems along with other system design implications. In short, shielding space radiation is seemingly quite challenging. However, advances in biochemistry may reveal some more tools for radiation protection.

In this research, cells will be cultured and irradiated. Cell survival and other biomarkers of vitality and damage will be measured to examine differences between those that received treatments and those that did not. Forward work could include additional types of cell lines or targets and other types of radiation as well as other medical gases

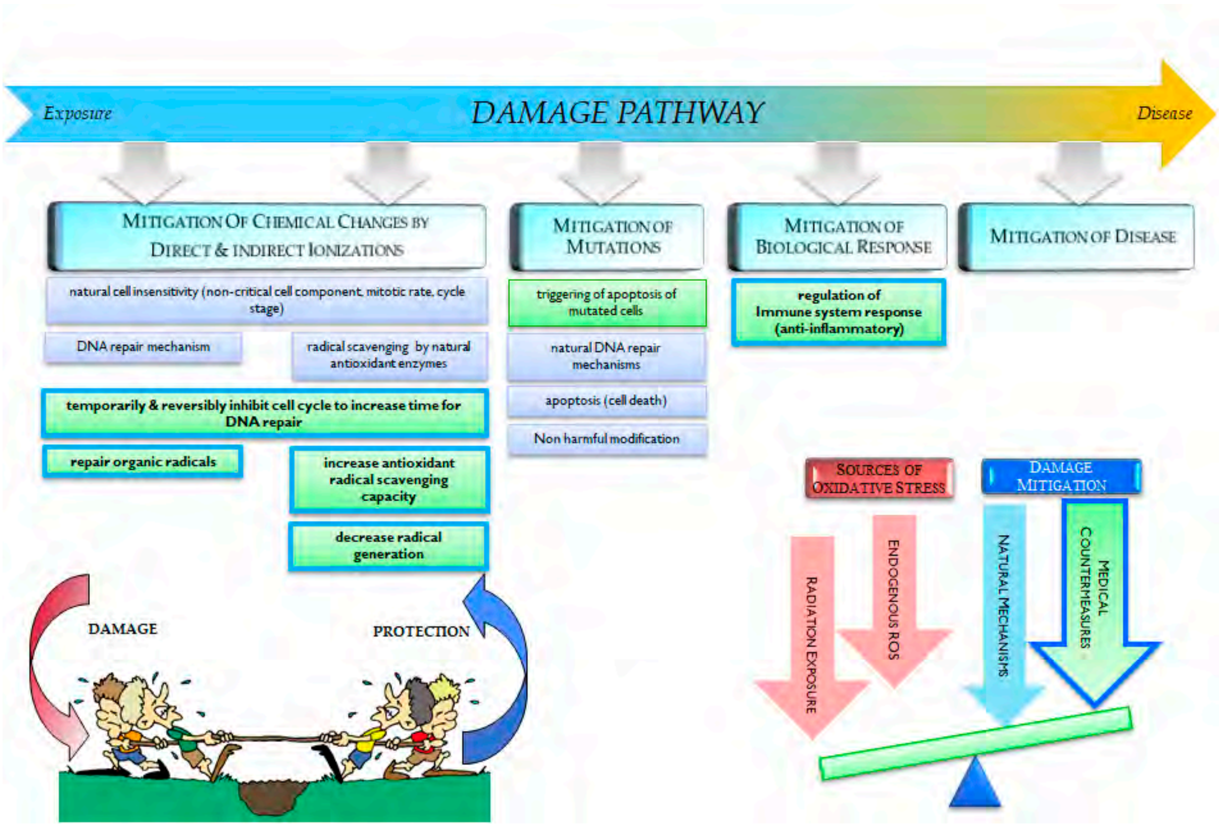
ACCOMPLISHMENTS

Project awarded in late 2018 for 2019 execution.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Michael Schoenfeld

PARTNER: Jacobs Engineering Group, Inc

FUNDING ORGANIZATION: Seedling Investment Program


Exposure
DAMAGE PATHWAY
Disease
Mitigation Of Chemical Changes by Direct & Indirect Ionizations
Mitigation of Mutations
Mitigation of Biological Response
Mitigation of Disease
natural cell insensitivity (non-critical cell component, mitotic rate, cycle stage)
DNA repair mechanism
radical scavenging by natural antioxidant enzymes
temporarily & reversibly inhibit cell cycle to increase time for DNA repair
repair organic radicals
increase antioxidant radical scavenging capacity
decrease radical generation
triggering of apoptosis of mutated cells
natural DNA repair mechanisms
apoptosis (cell death)
Non harmful modification
regulation of Immune system response (anti-inflammatory)
DAMAGE
PROTECTION
Sources of Oxidative Stress
Damage Mitigation
Radiation Exposure
Endogenous ROS
Natural Mechanisms
Medical Countermeasures

Point-to-Point Impedance for Biomedical Diagnostics

OBJECTIVE: *To improve astronaut body imaging through a novel method using bioelectrical impedance and spatial resolution.*

PROJECT DESCRIPTION

Bioelectrical impedance is a method currently used to determine body fat composition in a noninvasive manner. However, the technology currently exists only to perform full-body diagnostics, as the containment of electrical charge has not yet been mastered. I propose the development of novel techniques for achieving point-to-point bioelectrical impedance using oppositely charged electrical stimulation pads with high voltage/low amperage and vector-based mathematics.

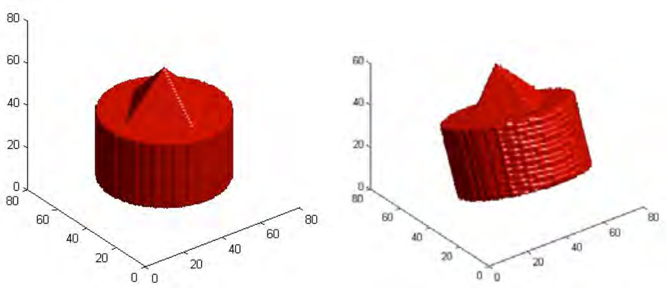
By achieving a vectoral flow of electricity through components with variable density, it is possible to produce a map of these densities that may be useful for various medical diagnostic purposes, including tumor detection. The goal of this research is to achieve the vectoral flow of electricity through the body and map the resulting data using spatial resolution. Astronauts could either wear these pads underneath a spacesuit or use the apparatus on a regular schedule in order to give doctors back on Earth more data to evaluate their health.

A traditional bioelectrical impedance analysis can tell you the body fat composition of the test subject; perhaps many people have received a body fat scan in this way. The point-to-point system proposed would consist of multiple sensors placed in an array across the area of interest. Each sensor acts as both a transmitter and receiver of electrical impulses; using vectoral math and software, it is possible to generate a map of electrical resistance with spatial resolution. No longer is the entire body examined as the resistive element, but just the resistance between each sensor, and as such, more useful information can be extrapolated from the data collected. Scans like this can be taken inexpensively on very frequent intervals.

Following this year's work, the next steps in the completion of this research are to complete the construction of the conceptualized circuit, perform testing, develop a software user interface, and finally gather data for analysis by medical professionals, where ultimately, judgment will be made concerning diagnostic usefulness of the apparatus. In order to ensure that damage could never be done to the test subject, only controlled battery quantities of electricity will be connected to the apparatus, never alternating-current mains.

ACCOMPLISHMENTS

This research is extremely new. As such, much of it remains to be completed. However, in the 2.5 months since Tech Tank, a number of crucial milestones have been reached. On the hardware side, circuit designs have been completed, and a hardware list of items necessary for purchase has been generated. On the software side, much of the MATLAB code necessary to perform 3D spatial resolution from vector inputs has been generated. So much as the apparatus produced is able to generate electrical vectors from point A to point B, a real-time map of internal body composition will result.



SUMMARY

By achieving a vectoral flow of electricity through components with variable density, it is possible to produce a map of these densities that may be useful for various medical diagnostic purposes, including tumor detection. The goal of this research is to achieve the vectoral flow of electricity through the body and map the resulting data using spatial resolution. Astronauts could either wear these pads underneath a spacesuit or use the apparatus on a regular schedule in order to give doctors back on earth more data to evaluate their health.

Much work remains to be done in order to bring this research to a point where it is flight ready. However, the hardware designs computational software are all complete, so in the coming year hopefully, we are able to tie it all together and move closer to a flight-ready system that can help keep our astronauts safe and healthy.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Kyle Costabile

FUNDING ORGANIZATION: Seedling Investment Program

Purge Pump and Separator Assembly

OBJECTIVE: *To combine the urine processor assembly functions of maintaining the vacuum pressure in the distillation assembly, pumping noncondensable gases, and separating liquid distillate from entrained gases for use in exploration life support.*

PROJECT DESCRIPTION

The urine processing assembly (UPA) on the International Space Station (ISS) is used to recover water from the urine produced by the crew. The UPA accomplishes this task by evaporating (distilling) water from urine in a microgravity-compatible distillation assembly (DA). In addition to the DA, the UPA is comprised of five other main sub-assemblies. Among these are the pressure control and pump assembly (PCPA) and the separator plumbing assembly (SPA). The PCPA is used to maintain the vacuum pressure in the DA while also pumping incondensable gases. The liquid/gaseous mixture is pumped to the SPA, where the gas is vented to the cabin, and the liquid is sent further downstream to be combined with the nominal distillate produced by the DA before being pumped downstream to the water processor assembly. The PCPA uses peristaltic technology that has historically experienced failures, primarily due to failure of the tubing used in the pump but is also limited due to the mechanical drive train. On ISS, the PCPA and SPA are each orbital replacement units (ORUs) meaning that when they fail, the entire sub-assembly must be replaced. For future exploration missions, maintainability and repairability of systems will be key to limiting resupply logistics and mass. The Purge Pump and separator assembly (PPSA) (shown in fig. 1) is in development with the goal of demonstrating scroll pump technology within the ISS UPA. The PPSA will substitute the two replaceable sub-assemblies (the PCPA and SPA) with a single sub-assembly that allows the purge pump, and the SPA to be replaced at the component level. A secondary goal of the PPSA's scroll pump is to reduce the mass and volume of UPA components for Exploration missions. The scroll pump is roughly 25% the size of the heritage peristaltic pump, which allows for the combination of the purge pump and SPA functions within one unit.

The existing PCPA uses peristaltic pump technology, which uses a rolling head to move the gas/fluid mixture through plastic tubing. The first component to fail in this type of pump is typically the tubing due to the constant compression and release of the tygon plastic. The PPSA addresses this failure mode by employing a scroll pump. The scroll pump, based on Scroll Labs, Inc., patented floating scroll technology, provides the critical capability of pumping two-phase flow but eliminates the peristaltic tubing, thereby increasing the life of the pump. Due to the decreased size of the scroll pump, the SPA (previously an independent ORU) can now be repackaged into the same sub-assembly as the pump. This eliminates an entire sub-assembly from the UPA rack. Finally, introduction of the new pump provides an opportunity to decrease the overall mass of the manifold for the pump.

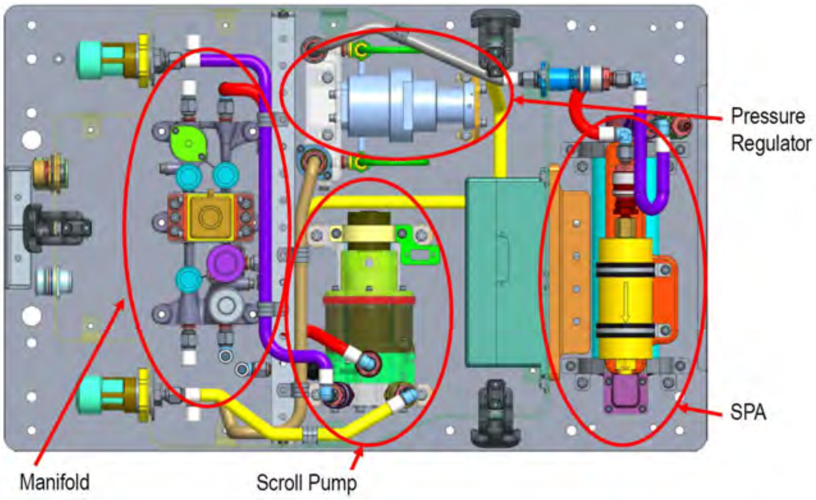


FIGURE 1. PPSA model.

a. b.

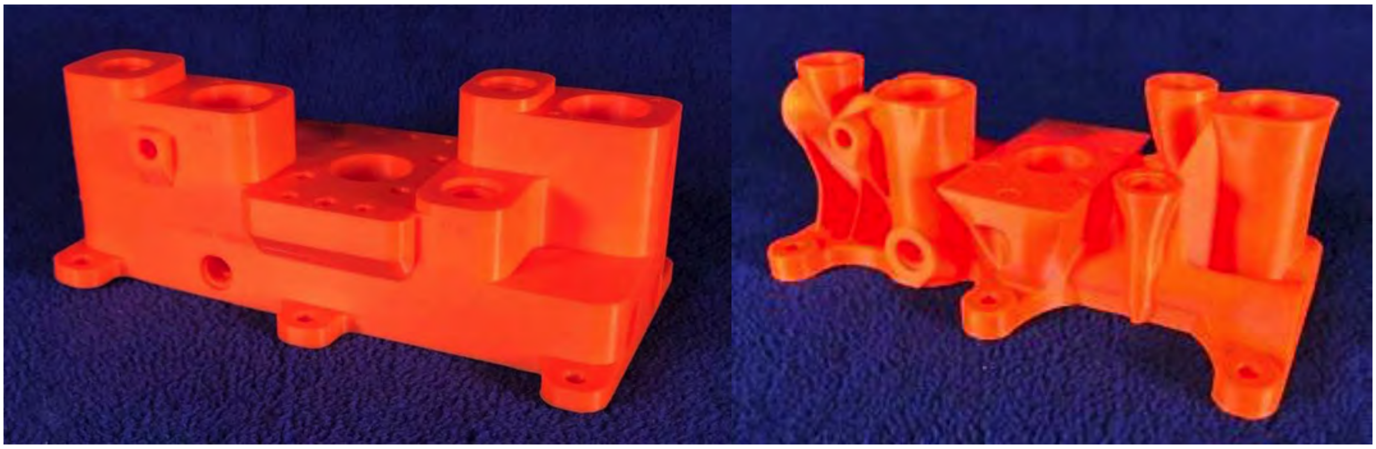


FIGURE 2. PPSA manifold (a) traditionally manufactured and (b) additively manufactured, resulting in ≈40% mass savings.

The PCPA manifold was traditionally machined out of a block of solid titanium. New advanced manufacturing techniques now enable additive manufacturing of the manifold, resulting in a 40% decrease in overall mass, as seen in figure 2.

ACCOMPLISHMENTS

In fiscal year (FY) 2018, the PPSA team completed initial evaluation of two types of scroll pumps: an Air Squared traditional scroll pump and a Scroll Labs floating scroll pump. The Air Squared scroll pump was a stock pump and was not able to meet the target performance. Discussions with Air Squared have resulted in a development effort in which Air Squared is modifying the pump design to meet NASA needs. A commercial-off-the-shelf floating scroll pump from Scroll Labs was also tested and has demonstrated the ability to provide both the upstream suction and the two-phase pumping capability necessary for operation in the UPA system. The UPA testbed at NASA Marshall Space Flight Center (MSFC) has been solely operated using a Scroll Labs scroll pump since December 2017. However, due to material incompatibility between the UPA liquid stream and the internal materials of the pump, the pump has been replaced several times. Efforts are ongoing to fabricate a pump with compatible materials to be tested for flight.

The change from a peristaltic pump, which inherently stops flow when not pumping, to a scroll pump, in which reverse flow may occur, requires the addition of a valve for positive shutoff in the PPSA. Five valves and actuators were tested for 130,000 cycles (≈4× the expected life of 30,000 cycles) in FY 2018. Evaluated valves included an MSFC-designed ball valve (which failed, began leaking at 15,000 cycles), a commercially-designed ball valve (also failed, began leaking at 95,000 cycles), an MSFC-designed linear valve (passed, never leaked), a commercially-designed plug-style valve (failed, began leaking at 110,000 cycles), and a commercially-designed solenoid valve (failed, began leaking at 125,000 cycles). Only the MSFC-designed linear valve was able to meet the required lifetime expectancy and was baselined for the PPSA. Based on previous and ongoing development testing, a finalized design for the sub-assembly was completed in FY 2018, as shown in figure 1. Key subassemblies are indicated.

SUMMARY

The UPA provides the critical function of recovering water from crew urine. Key aspects of the UPA have been identified for improvement based on lessons learned from ISS. The PPSA serves to reduce the number of UPA sub-assemblies while enabling maintenance in preparation for exploration-class missions. On April 9, 2018, the ISS Vehicle Control Board approved a proposal to take the PPSA to flight. In FY 2018, development of the PPSA included testing and down-select of the baseline pump, evaluation and down-select of the shutoff valve, a reduction of ≈40% total mass from the manifold, and baselined design for the flight experiment. The PPSA flight experiment is due to be delivered by March 2, 2020, pending the delivery of development pumps for evaluation.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Davey Jones, Jill Williamson

FUNDING ORGANIZATION: ISS Program and Payloads Office

HUMAN EXPLORATION DESTINATION SYSTEMS

Space Exploration Architecture Studies

OBJECTIVE: *To use methodologies for holistic evaluation of architectures, to be added to low-level considerations, in support of trade-off decisions for cost, risk, and performance, to assess NASA's Deep Space Gateway and Deep Space Transportation architecture.*

PROJECT DESCRIPTION

The objective of this activity is to use techniques developed through a previous Cooperative Agreement Notice (CAN) to perform holistic evaluation of a NASA mission architecture. The techniques include assessments of architecture/system dependencies considering developmental dependencies as well as operational dependencies. Using these dependency networks along with technical and programmatic subject matter expert (SME) input, a quantitative evaluation of criticalities and impact of interactions between systems/capabilities may be obtained. Additionally, one may be able to evaluate risks and robustness of different technological selections. Specifically, this study addresses the Deep Space Gateway, lunar and deep-space transportation architectures, and future habitat systems.

The key innovation is the use of dependency networks to assess the importance of systems/subsystems in given architectures. Systems Operational Dependency Analysis (SODA) is a technique that offers the ability to provide objective and quantitative evaluation of the criticality, impact and propagation of degradation, risk and ultimately goodness of an architecture. Based on the connectivity of elements in an architecture and an assessment of their ability to function within the architecture, one may determine which technologies are of most importance in the overall function of the mission/architecture. Similarly, Systems Developmental Dependency Analysis (SDDA) examines the risks due to technology development selections. Using SDDA, one can model partial parallel developments and provide intelligent scheduling considering delays. Its benefit largely is in the ability to forecast development difficulties and assess those risks.

ACCOMPLISHMENTS

The study kicked off in January of 2018. The goal of the kickoff meeting was to formalize the tasks and develop expectations. After the kickoff, the team developed the elemental networks that would be used to perform the architecture analyses. To develop the detailed information needed for the SDDA and SODA networks and establish a viable set of mission architectures and elements, the analysis team hosted an SME workshop. The goal of the workshop was to familiarize the SMEs with the techniques and obtain expert knowledge required to populate SDDA and SODA. Purdue students used the SME data to develop SDDA and SODA models.

The team presented initial results at a midterm review. First-level architecture element networks were shown with indications of systems dependencies of the current lunar architecture including launch vehicles, transportation stages, and habitat. These were derived from SME inputs and available architecture data. A portfolio optimization analysis was presented which offered suggestions for optimal development approaches considering Agency budget projections, development timelines, and subsystem interactions. Further analyses and SME interactions are planned for the final phase of the study, which will be completed in December of 2018.

SUMMARY

Through a CAN completed in 2017, NASA and Purdue University developed a technique that will enable a top-down analysis for NASA mission and architecture strategies explicitly considering cost, schedule, and risk constraints. With this capability, project managers can evaluate strategies and associated architectures and concepts based on analyses of operational and developmental dependencies between systems. This 2018 effort seeks to expand the CAN-developed capabilities and focus on NASA's shift from a Mars-focused architecture to a Lunar-focused one.

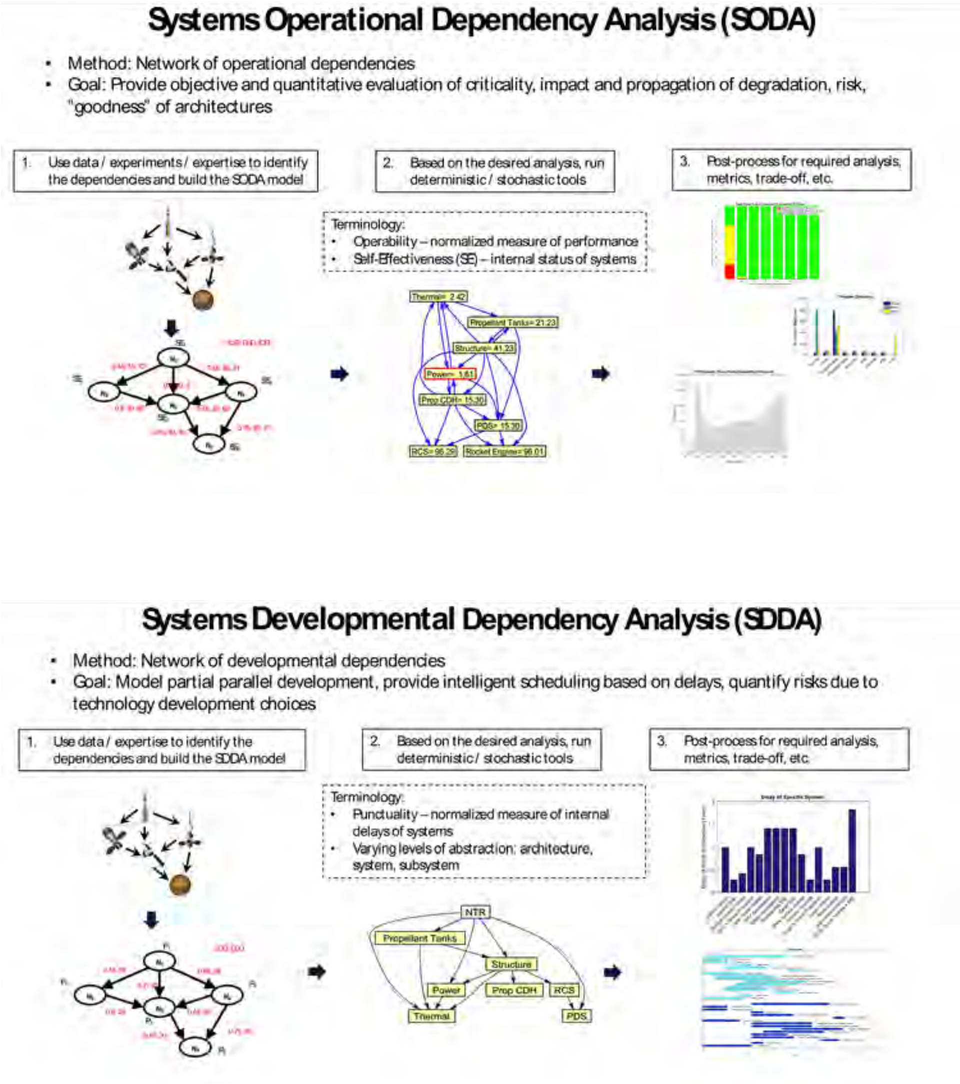


FIGURE 1. Overview of SODA and SDDA techniques/networks.

The planned activities of this study will consider a large-scale architecture, with in-depth analysis of selected systems. The analyses will focus on habit and transportation systems, with a goal of defining capability and technology gaps. Understanding these gaps may in turn offer suggestions of strategic developments and opportunities for MSFC. The one-year effort kicked off in January 2018 and will be completed in December 2018.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Reginald Alexander

PARTNERS: Dan DeLaurentis and Cesare Guariniello, Purdue University Alkhateb, Department of Civil Engineering

FUNDING ORGANIZATIONS: Center Strategic Development Steering Group

Chaos Baseband Transmitter and Receiver With Software Defined Matched Filter

OBJECTIVE: *To develop, test, and evaluate baseband chaotic communications systems with reconfigurable software defined matched filters.*

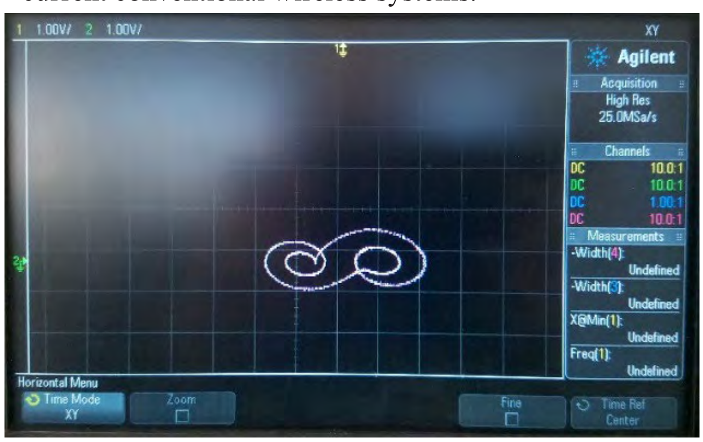
PROJECT DESCRIPTION

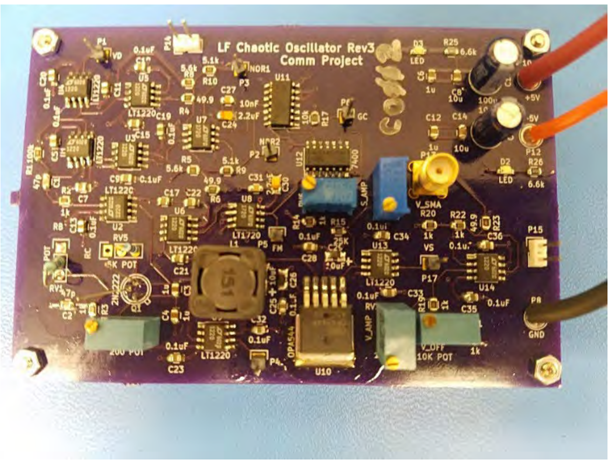
A unique approach to communication is currently being developed and is of great interest for high performance, smaller footprint, and more reliable wireless systems. This novel wireless communications system utilizes exact solvable chaotic oscillator circuits to encode and transmit data. This highly innovative method utilizes control techniques to steer a chaotic oscillator toward distinct trajectories associated with binary values to transmit bits. These bits are then detected at the receiver using a matched filter and threshold comparator. This type of communication system provides several potentially game-changing advantages to current approaches. In this system, optimal efficiency is achieved through the use of a matched filter. There is a low probability of signal detection. There is a theorized immunity to interference to noise, multipath transmission, and other radio frequency transmitters. There is a higher level of performance possible through the relative simplicity of the circuitry, leading to lower power consumption, fewer components, and higher reliability. This approach was originally conceptualized and initially sponsored by the U.S. Army as a spinoff of their work using these chaotic oscillators and matched filters in radar systems. A team at Auburn University, through initial Small Business Innovation Research (SBIR), has taken the technology from concept to laboratory demonstration. We are now working with Auburn and the Army to further test and develop the technology.

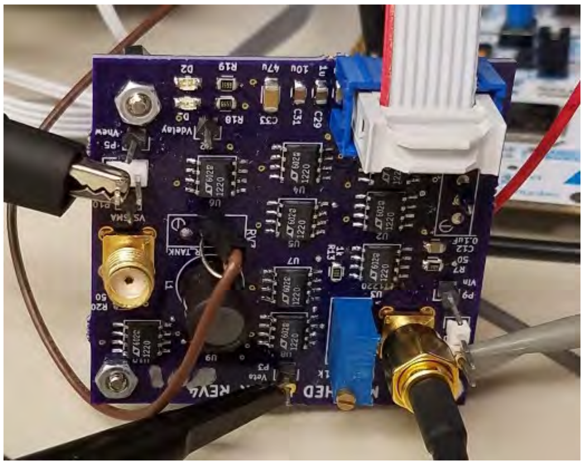
This project included several steps in order to achieve its objective. First was the development of two identical hardware systems, including a baseband transmitter and a receiver with an analog-matched filter and platform for a software-defined matched filter. Next was the initial development of the software portion of the software-defined match filter to operate on this platform. Third was the co-testing of the two identical systems, one at Auburn and one at MSFC, allowing experimental duplication and mitigation of any issues. Lastly were the ongoing software improvements facilitated through co-testing. The major deliverables were two complete software-defined, matched-filter baseband communication systems that were thoroughly tested and updated. This project furthers the development of this novel method of wireless communication and opens the door for future use to solve mission needs.

ACCOMPLISHMENTS

Two complete folded-band chaotic oscillator systems have been developed and tested with hardware and software-defined, matched-filter backends. These tests include the transmission of custom data streams and temperature measurements both at Auburn University and at NASA Marshall Space Flight Center. Bit error rate testing in the laboratory environment and in an enclosed metal habitat will be conducted next. These tests will be done with an emphasis on comparison to current conventional wireless systems.







SUMMARY

Chaotic oscillator systems with simple matched filters provide potential advantages in the areas of performance, circuit footprint, and reliability. In this project, such systems were developed with software-defined matched filters on the receiving end of the data transmission, enabling ongoing improvements and updates without having to rebuild hardware. Initial testing is complete, and more comprehensive ongoing testing and evaluation is underway.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Robert Dean, Auburn University; Darren Boyd

FUNDING ORGANIZATION: Cooperative Agreement Notice

Ionic Liquid Metals and Oxygen Extraction in Microgravity: A Prelude to Asteroid Mining

OBJECTIVE: *To design a hardware prototype for an International Space Station experiment demonstrating electroplating of metals from meteoritic sources.*

PROJECT DESCRIPTION

Exploration within the solar system and beyond will require making use of the resources that are at the destination site, or 'living off the land,' as America's first pioneers did. Task-specific ionic liquids (ILs) can be used in a large variety of ways to enable NASA's exploration missions. One of these uses is for the extraction of metals and oxygen from lunar, planetary, or asteroid soils, using an environmentally safe IL. The metal oxides in the soil reacts with the hydrogen in the IL acid to make water, and the metals are dissolved, forming soluble salts. The water is then electrolyzed to form oxygen and hydrogen. The oxygen can be used for life support or propellant; and in a further step, the hydrogen is used to regenerate the IL to dissolve more soil and to also plate out the metals and use them for manufacture of spare parts. Mining asteroids for their resources will require methods that will work under very low gravity conditions, so it is necessary to test whether it is possible to perform the same methods used on Earth within the low-gravity environment of the International Space Station (ISS). The goal of this project is to develop test hardware for this purpose.

Our team has demonstrated a three-step process using an IL that can extract up to 80% of the metal and oxygen from asteroidal and regolith simulant materials. The acidic IL used in this process is depleted of acid during the plating process. We have developed a method to reprotonate the IL from biproducts of the plating reaction. This method makes the IL almost 100% recoverable. The process can then be repeated to extract and plate further asteroidal materials without resupply from Earth. A rendering of the sequential electroplating system with IL reprotonation is given in figure 1.

The cost to launch all required supplies for life support and further manned travel to worlds beyond Earth's moon and beyond would be prohibitive without using resources available along the way and at the destination. Asteroids, our moon, and other planets and moons can provide a wealth of resources, but we need to learn how to efficiently extract them and process them into necessary materials. Electrochemical extractive processes have a number of advantages. In past projects, we have

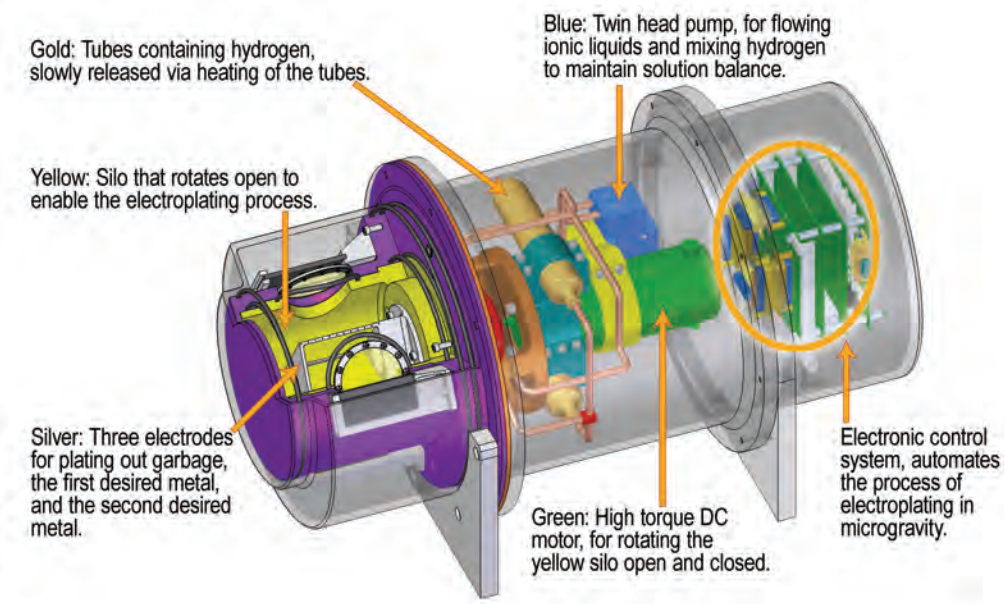


FIGURE 1. Sequential Electroplating System with IL Regeneration.

demonstrated molten oxide electrolysis of lunar simulant as a method of extracting oxygen, iron, and silicon, but this process requires operating temperatures of 1,500–1,700 °C. Using ILs as the electrolyte, we can achieve extraction at 200 °C or less. ILs are a class of organic salts that are liquid at room temperature and can be made task-specific to perform the work that nearly any conventional chemical can but without the vapors and fumes that are often associated with traditional volatile solvent reactions. Because they have no vapor pressure, they work in the high vacuum of space without evaporating, and they also work at much lower temperatures, thus saving energy. Moreover, for this project, the ILs are regenerable and can be reused many times, thus cutting launch costs. The processes used in this project can also be used on Earth, for example, to mine for rare costly metals available in small quantities and for recycling costly metals after use.

ACCOMPLISHMENTS

Last year, we developed the engineering and manufacturing methods that enabled the production of an Engineering Development Unit (EDU), for an ISS apparatus capable of sequential electroplating of several metals on separate cathodes and then regenerating the IL using hydrogen. During laboratory testing of the EDU, we learned that the control system development for the flow of hydrogen from the metal hydride cylinders requires further work to be reliable. We also learned that using O-rings on curved surfaces required supplemental bonding. The electroplating laboratory tests found that there was an activation potential or overvoltage that was necessary to achieve nucleation on the cathode. This made sequential electroplating of metals with similar oxidative potentials difficult and requires a redesign of the cathode material. We believe that the apparatus will prove successful with additional development but determined that to meet our goal of 1-year development to flight, we need to simplify the apparatus.

We utilized the civil service manpower provided by the Technology Investment Plan to design a simplified apparatus that would demonstrate microgravity electroplating but not IL regeneration. A rendering of this unit is given in figure 2. We brought this concept to Microgravity Project Science and obtained some funding to build an EDU for the simplified concept. The microgravity electroplating results will have value for basic materials science experiments on ISS and as a test for applications to advanced life support systems.

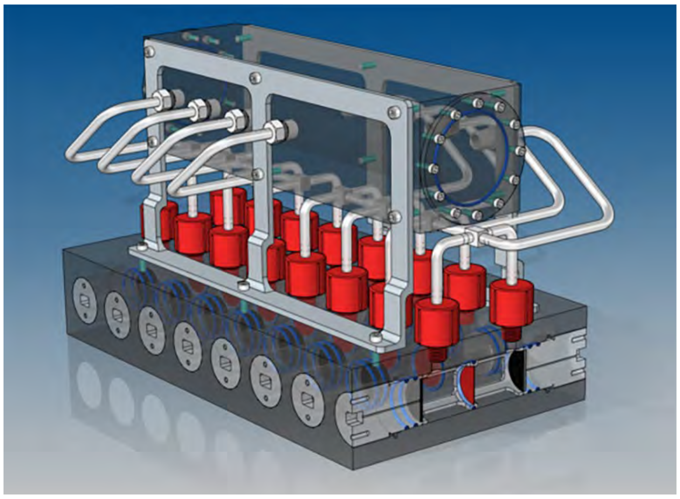


FIGURE 2. Simplified Microgravity 8 Cell Electroplating System (bottom) with fluid transfer device (top).

SUMMARY

There is much excitement about extracting space resources and utilizing them for exploration, commerce, and settlement in space; yet almost no experiments in in situ resource utilization have been accomplished in space. This is because of the expense, complexity, and high-energy requirements of the extractive methods proposed. In this project, we have demonstrated a low-energy, safe, and simple method to test the extraction of resources from asteroid materials in microgravity. IL electrolysis can enable the construction of a small, affordable device to test the extraction of metals and oxygen from asteroid materials in the International Space Station. We have developed EDUs for two apparati suitable for ISS Experiments, one that can accomplish sequential electroplating and IL reprotonization, and a second simpler device that focuses on the electroplating process in microgravity.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Keven Depew, Peter Curreri, and Eric Fox

PARTNERS: Matt Marone, Mercer University Department of Physics; David Donovan and Steven Paley, ESSSA; Gary Thornton and Max Vankeuren, MSFC Engineering; Matthew Regalman, University of Minnesota Department of Electrical Engineering; Levin Mullaney, Montana Tech; Benjamin Plaster, University of Idaho; Morgan Hansen, Boise State University.

FUNDING ORGANIZATION: Technology Investment Program

Purification of Lunar Cold-Trapped Volatiles

OBJECTIVE: *To separate volatiles extracted from the permanently shadowed regions of the Moon for use in propulsion, life support, and other necessary systems for sustainable crewed missions.*

PROJECT DESCRIPTION

The permanently shadowed regions (PSRs) of the Moon contain multiple types of volatiles, including water, carbon monoxide, sulfur dioxide, and ammonia. Any number of technologies can extract these volatiles, but separating the volatiles into their individual species is more of a challenge. This work directly addresses this challenge with ionic liquids (ILs). The process under study involves a cascade of task-specific ILs, which are 'tuned' to sequester specific volatile species. The mixed volatiles will flow through mists of the task-specific ILs. The task-specific ILs will pull a specific volatile species out of the gas flow and isolate it within the IL solution. Later, the specific volatile can be extracted out of the task-specific IL for use in life support systems, fuel formulations, and as material that could be used for 3D printing parts or structures.

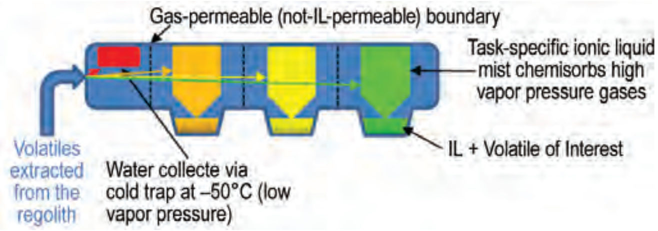


FIGURE 1. Concept of cascade hardware to separate volatiles extracted from lunar PSRs.

Traditional methods of volatile extraction and separation involve cold traps. Given the volatile species present in PSRs, as noted by the Lunar Crater Observation and Sensing Satellite (LCROSS) results and with the exception of water, a series of cold traps will not work due to the overlapping solidification temperature ranges. In addition, some of the volatiles can react with other volatiles (for example, an acid reacting with a base) and form nonvolatile compounds. Thus, additional separation techniques are needed.

The solution investigated here is to have a cascade of task-specific ILs that are designed to extract a specific volatile species from a mixture of volatiles (fig. 1). For example, acidic ILs can extract bases such as ammonia, and alkaline ILs can extract acids such as sulfur dioxide. The process involves cryogenic trapping to remove water prior to purification of the other volatiles using the IL mists. Misting of the ILs in this process provides greater surface area with which the mixed volatiles can interact, increasing the chemisorption of the volatile of interest. The volatiles chosen for this experiment show a range in IL capabilities, as they capture basic ammonia, neutral carbon monoxide, and acidic sulfur dioxide.

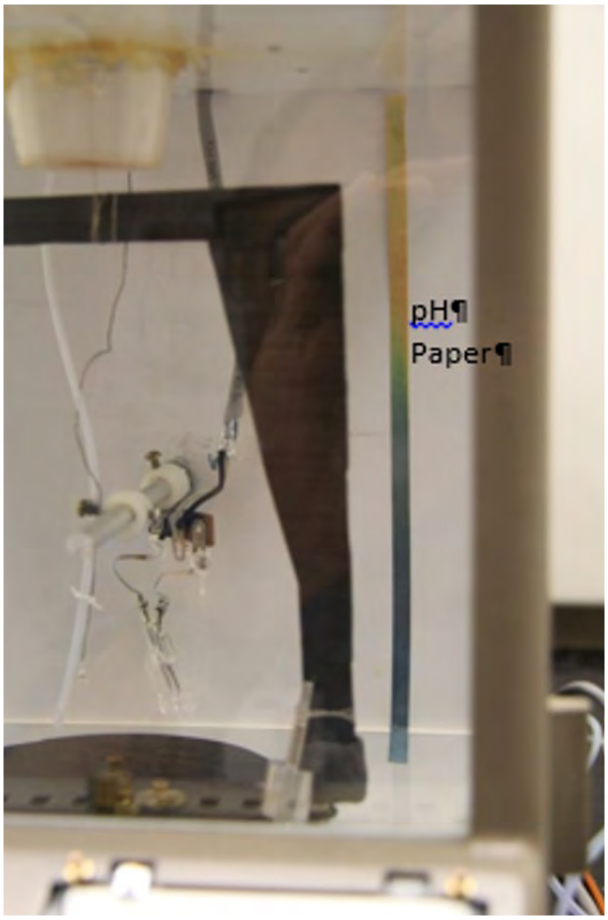


PHOTO COURTESY OF MATTHEW MARONE

FIGURE 2. Photograph of balance during an ammonia test; pH paper shows the ammonia is present in the lower portion of the balance.

EXPERIMENT DATA FROM DR. STEVE PALEY, DR. WILLIAM KAUKLER, AND DR. MATTHEW MARONE

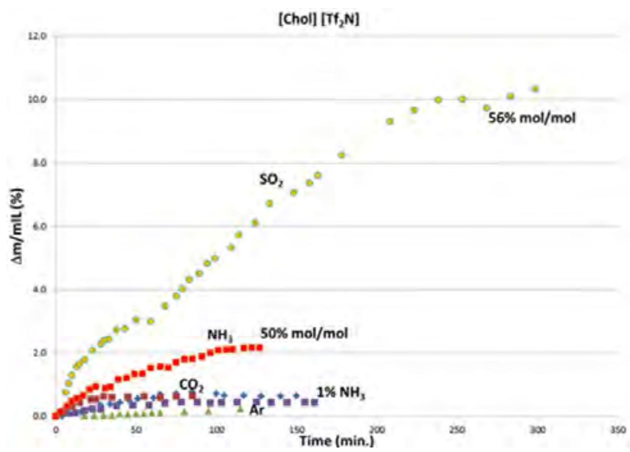


FIGURE 3. Experiments involving the IL [Chol][Tf_2N] and its uptake of various gas species. This work determined the high affinity of the IL for sulfur dioxide (SO_2) compared to ammonia (NH_3) and carbon dioxide (CO_2) which was used as a proxy for carbon monoxide. This indicated a need for an IL that extracted ammonia located in the cascade sequence before sulfur dioxide extraction by this IL.

ACCOMPLISHMENTS

Task-specific ILs were selected, using experience and a literature search, for experimentation in their ability to trap volatiles. A candidate IL was put into a balance modified to allow a volatile to flow into the system. The volatile was allowed to enter the system briefly, then the flow was stopped to allow the balance to remain still during weighing. If the volatile was captured by the IL, the weight of the IL solution on the balance would increase. To show the volatile was present in the system, a litmus paper (pH paper) was attached to the inside of the balance (fig. 2). The uptake of the various species by the IL choline bis(trifluoromethylsofonyl) imide, also known as [Chol][Tf_2N] is shown in figure 3.

Additional experiments with different ILs actually showed a loss in weight of the IL during exposure to the gas, using the same setup as the [Chol][Tf_2N] result. This result is puzzling, and no sufficient explanation has yet been determined.

Despite having relatively low concentrations (less than 1%, similar to the volatile concentrations expected in the PSRs) of ammonia and sulfur dioxide, they reacted at room temperature to form the nonvolatile ammonium sulfite. This result has implications for the ability to test a mixed gas stream.

SUMMARY

Mining and utilizing materials on planetary surfaces reduces the number of launches needed from Earth to sustain a planetary surface colony, thus making the colony self-sufficient and economically feasible. Production of purified volatiles from lunar resources is of significant value to NASA. This work is innovative in that it provides a workable way to separate the PSR volatiles after collection and utilize them to produce propellant, life support consumables, or additive manufacturing and construction materials. Work continues to identify the cause of the weight loss in some of the experiments, as well as continuing the design and build of the cascade hardware.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Kevin DePew, Eric Fox, and Jennifer Edmunson

FUNDING ORGANIZATION: Center Innovation Fund

In Situ Production of Cementitious Material from Martian Resources

OBJECTIVE: *To produce a binding material from regolith and for regolith to maximize the use of in situ resources for additive construction on planetary surfaces.*

PROJECT DESCRIPTION

NASA is investigating a 3D printing process called additive construction for structures, in an effort to make sustainable planetary surface missions economically feasible. Additive construction of infrastructure elements, such as habitats, roads, garages, and berms, will require a lot of material, which would be very expensive to launch from Earth. Ideally, the construction material would be mined from materials indigenous to the planetary surface, which would save the cost of launching them from Earth. This project involves extracting a binder material from available planetary resources that, when combined with regolith, will provide a construction material that is compatible with additive construction technologies. The binder currently under study is sodium silicate, also known as water glass. After combining an aqueous solution of sodium silicate with regolith aggregates, water can be extracted and reused in this process for future building events. This project also employs ionic liquids (ILs) as dissolution media; these catalyst-like ILs can be regenerated for further use to process additional regolith for the sodium silicate binder.

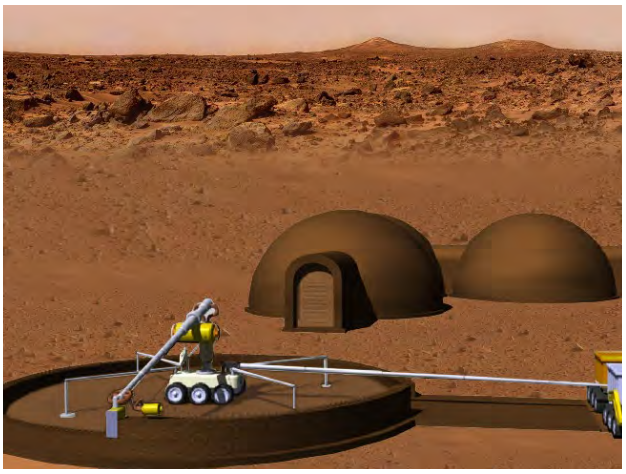


FIGURE 1. Illustration of an additive construction system on Mars.

Sodium silicate can be created by mixing solutions of sodium hydroxide (NaOH) and silica (SiO_2) gel. This mixture will react to form sodium silicate and water. Regolith can then be mixed with the sodium silicate solution, and the water can be removed (and recycled) to form structures. The traditional method of producing sodium silicate involves baking sodium carbonate with silica sand at temperatures between 1,000 °C and 1,400 °C. This process releases carbon dioxide (CO_2). Another method involves producing sodium hydroxide from sodium sulfate, which ultimately produces sulfuric acid. Using ILs not only decreases the amount of heat required (less than 200 °C), it allows sources other than sodium carbonate or sodium sulfate to be used (e.g., the minerals albite, a sodium feldspar; and sodium bentonite, a clay) thus reducing the emission of CO_2 and the production of sulfuric acid during sodium silicate manufacture.

Both albite and sodium bentonite exist on Mars. These two minerals are a source of both the sodium and SiO_2 needed to produce sodium silicate. During dissolution in the IL, the sodium is bonded to the IL, and the undissolved SiO_2 is left behind as an amorphous gel. The IL with the extracted sodium is then placed into a chamber with water in which the sodium is removed from the IL and replaced by a hydrogen atom, thus regenerating the IL for later use; at the same time, the sodium in the chamber is combined with a hydroxyl ion in a process called electrolytic hydrolysis. The SiO_2 is removed from the original solution and combined with the sodium hydroxide to produce sodium silicate. The sodium silicate is then combined with simulated Martian soil and dehydrated to form a building material.

ACCOMPLISHMENTS

Over the course of 2018, the team tested different sodium silicate and binder mixture ratios to determine the optimum ratio for strength as well as three of the factors that are key in additive construction: (1) the pumpability (ability to be moved through the system), (2) printability (the ability to be consistently extruded), and (3) buildability (ability to hold the weight of a superimposed layer without slumping) of the mixture.

FIGURE 3: Sodium silicate and Martian simulant mixture cured in CO_2. Note the formation of a sodium bicarbonate rind.

The three factors assessed are compared in figure 2, where the range of parameters necessary for additive construction is captured within the range of potential printability, below the buildability curve and above the pumpability curve.

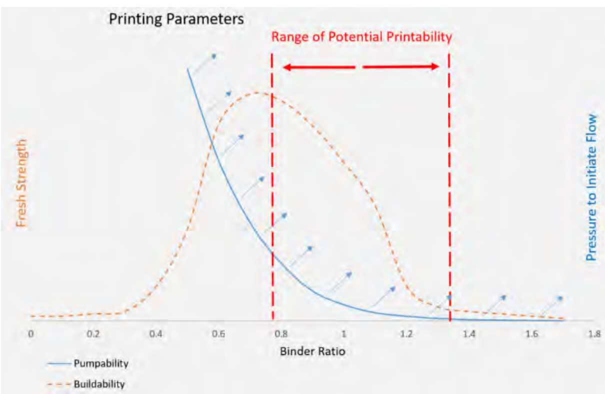


FIGURE 2. Experimentally determined zone acceptable for additive construction for sodium silicate and Mars simulant. The y-axis is relative strength and pressure.

Three different methods of curing the sodium silicate solution and regolith mixture by dehydration were studied: (1) vacuum extraction, (2) microwave extraction, and (3) exposure to CO_2 (which comprises the vast majority of the Martian atmosphere). Vacuum curing forced gases out of the wet mixture, creating a foam-like structure in the solidified material. Microwave extraction removed not only the water in the sodium silicate solution, but it also removed adsorbed humidity and may have extracted other volatiles from the simulated Martian material itself. Curing the sodium silicate and regolith mixture in a CO_2-rich environment created a rind on the material composed of sodium bicarbonate (baking soda).

SUMMARY

Production of construction materials from in situ resources is a gamechanger for NASA. This work provided fundamental research into the production and printing of construction materials on planetary surfaces. Removing the need to launch construction materials from Earth to planetary surfaces by producing them in situ will significantly reduce mission cost and provide the ability to build infrastructure elements on-demand. Additionally, this method of producing sodium silicate using ILs with relatively low energy and no toxic byproducts would be useful to the water glass industry on Earth. Because ILs have a very low vapor pressure and thus low flammability, they are safer and easier to handle than conventional reagents.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: John Fikes, Mallory Johnston, Eric Fox, and Jennifer Edmunson

PARTNERS: Hunain Alkhateb, University of Mississippi Department of Civil Engineering

FUNDING ORGANIZATIONS: Center Innovation Fund

Hardened Extremely Long-Life Information in Optical Storage

OBJECTIVE: *To demonstrate stability of innovative storage media in an actual spaceflight situation.*

PROJECT DESCRIPTION

Can data survive in space over extremely long times and multiple human generations? The possibility of human colonies on other planets may ultimately depend on just such data stability. Hardened Extrmely Long-Life Information in Optical Storage (HELIOS) will demonstrate a century-old, tested, archival media for photography in a completely new way for storing high-density computer data in perpetuity. Inherently secure, low-cost technology that cannot be hacked or altered, HELIOS will test whether the media can survive a hostile space environment during long-term space missions, such as the mission to Mars, and beyond.

The payload consists of borosilicate slides containing raw data which will be exposed to ionizing radiation on the International Space Station (ISS) for no less than 6 months to determine whether the recording medium is impervious to ionizing radiation. If the media is radiation tolerant, it would be a candidate for storage of core flight software and large volumes of critical data subject to long-term radiation for deep-space applications. The media consists of fully processed silver-halide, optically stable photosensitive emulsion, which will be impervious to ionizing radiation, static electricity, and electromagnetic interference.

The experimental material will remain packed inside a HELIOS case during ground processing, launch, onboard, and return. Upon arrival to ISS, crew will stow Helios into a location that will be determined by the Topology Forum with inputs from the payload developer (PD). A radiation monitor will be pre-positioned inside the case prior to flight. At the end of the experiment duration the HELIOS case will be removed and stowed for return. All payload hardware transported to ISS will be returned to the ground upon completion on the earliest return flight after 6 months on orbit. Early hardware return is required.

ACCOMPLISHMENTS

To date, the payload and control hardware supplies are available for preparation for shipping and storing, respectively. Though not yet scheduled, the payload is expected to fly in the near future, with completion and return expected in calendar year 2019.

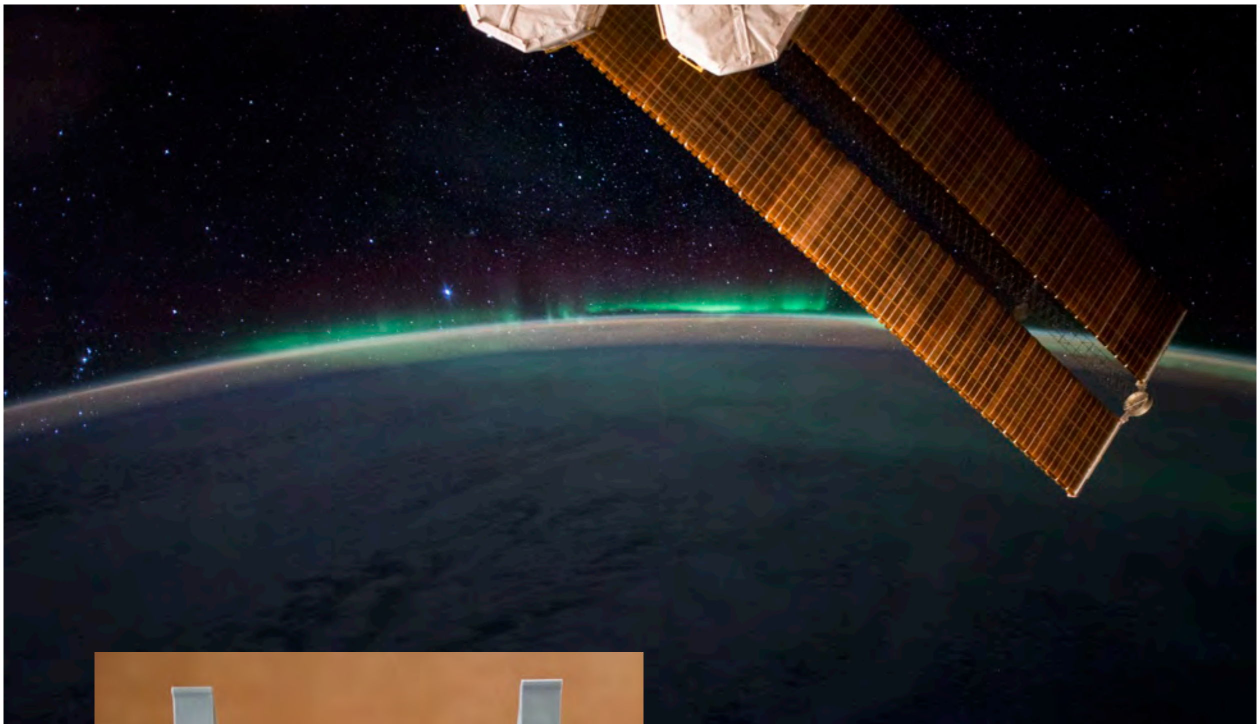
SUMMARY

The payload will consist of up to 50 borosilicate slides (recording media) with prerecorded test data on them identical to data on a control group of 50 borosilicate slides in the PD's lab on the ground. The slides will be stored into two interior microscope slide cases, 25 slides in each case. Both microscope slide cases will be stored into a HELIOS case that will also include one radiation sensor. The HELIOS case will not require any manipulation by the crew other than to place the container in a location for no less than six months. After the 6-month period, the HELIOS case will be returned to the PD for characterization. If the slides prove as impervious to the space environment as the technology has proved on Earth over centuries, the technology may prove to be a secure write-once, read-forever data storage media that can go with mankind to the stars.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Rodney Grubbs

PARTNER: Creative Technology, LLC

FUNDING ORGANIZATION: Advanced Exploration Systems



In-Space Manufacturing Multi-Material Fabrication Laboratory

OBJECTIVE: *To develop and demonstrate a multi-material fabrication laboratory (FabLab) capable of end-to-end manufacturing during space missions. The In-Space Manufacturing FabLab will be demonstrated on the International Space Station and will serve as the first step toward a fully integrated, on-demand manufacturing capability that is able to produce finished, ready-to-use products for exploration missions.*

PROJECT DESCRIPTION

In order to sustainably live off Earth, crews must have the ability to manufacture and repair components and systems on-demand. In providing this capability, the FabLab changes the traditional paradigm of launching all necessary materials and their spares from Earth. NASA's Advanced Exploration Systems (AES) division and Space Technology Mission Directorate (STMD) are investing in this key technology via Next Space Technologies for Exploration Partnership (NextSTEP), a program that provides public-private partnerships to enable commercial development of deep space exploration capabilities to support human spaceflight missions in cislunar space and beyond.

FIGURE 1. ISM mission logo.

The FabLab project builds on the previous success with 3D printing of plastics on the International Space Station (ISS) in 2014 as well as commercial development of several additive manufacturing technologies. This project seeks to expand the Station's on-demand fabrication capability by increasing the number of printable materials (feedstock) available while improving overall manufacturing efficiency. The FabLab payload goal is to demonstrate an end-to-end manufacturing process using multiple materials including metals. This includes the capability to 3D print with metals.

The FabLab capability will be developed in three phases. The objective of phase A is to demonstrate scalable ground-based prototypes designed to be compatible with the ISS Expedite the Processing of Experiments to Space Station (EXPRESS) Rack and capable of remote operation from Earth. The objective of phase B is to further mature the technology towards flight qualification. Phase C will be an ISS technology demonstration to prove the printing method in consistent microgravity, define the parameters necessary for optimized printing in space, fully characterize the printed material, and fabricate usable components for the ISS. Demonstration of the FabLab on the ISS will lead to future manufacturing systems for deep space habitats and transit vehicles.

ACCOMPLISHMENTS

Phase A proposals were solicited under appendix B of the NextSTEP-2 Omnibus Broad Area Announcement.

FIGURE 2. Logo for NextStep. ISM is part of the program.

The solicitation closed in September 2017 with 16 responses. These responses were evaluated for suitability in the following target capabilities:

- The system must provide for on-demand manufacturing of multiple materials in microgravity, including, but not limited to, aerospace-grade metals, polymers, composites, and digital inks for the fabrication of electronic components.

- The design must meet ISS EXPRESS rack operational constraints and maximize build volume (must be greater than a 6-in cube).
- The system must incorporate Earth-based remote commanding and/or autonomous capability for all nominal, maintenance, off-nominal tasks, including part removal and handling.
- The system must incorporate remediation capability for defects identified during an inline quality control process.

Following evaluation of the responses, three US companies were selected for funding: Interlog Corporation of Anaheim, California; Techshot, Inc., of Greeneville, Indiana; and Tethers Unlimited, Inc., (TUI) of Bothell, Washington. Combined funding for the awards is approximately $10.2 million. The companies will have 18 months to deliver the prototype, after which NASA will select partners to further mature the technologies.

Interlog Corporation will develop its microgravity multiple-materials additive manufacturing (M3AM) technology to provide on-demand manufacturing solutions for fabrication, maintenance, and repair on space missions. M3AM is enabled by Interlog's proprietary manufacturing technique that additively constructs a part via a focused bonding-energy mechanism. M3AM is capable of manufacturing aerospace-grade metal alloys (e.g. aluminum, titanium, and nickel) and bonding dissimilar materials (e.g., metals, glass epoxy, flexible ceramics). M3AM seeks to offer multi-material additive manufacturing on a single platform, autonomous operation, autonomous part removal, and multiple-material feeding mechanisms.

FIGURE 3. Techshot FabLab schematic. Image courtesy of Techshot.

Techshot's FabLab effort is focused on producing a ground-based prototype with the ability to mature into a flight demonstration aboard ISS within 3 years. The Techshot FabLab will be compatible with the Station's EXPRESS racks. Remotely controlled operations from Earth will manufacture multi-material components, including metals, ceramics, plastics and electronics.

The TUI Empyrean FabLab increases astronaut efficiency by providing autonomous processing and verification and validation services in a system designed for microgravity operation aboard the ISS. The Empyrean FabLab team, led by TUI with IERUS Technologies, Inc., and BluHaptics, Inc., will develop the Empyrean FabLab to support NASA's long-duration and deep-space manned missions with capabilities for multi-material manufacturing and recycling. The Empyrean team will focus on a suite of support technologies for microgravity-enabled multi-material manufacturing, including robotic handling, quality control, autonomy, and teleoperation capabilities. These capabilities will enable sustainable in-space manufacturing in support of long-duration crewed missions, while minimizing demands upon astronaut time.

FIGURE 4. Empyrean FabLab schematic. Image courtesy of Tethers Unlimited, Inc.

SUMMARY

Sustainable exploration of the Solar System requires the ability to manufacture and repair with readily available materials. In line with the NextSTEP program goals, NASA will utilize a public-private partnership to provide the capability of manufacturing, with metals and other materials, items for use on the ISS in preparation for next-generation systems to be deployed on deep space missions. The FabLab will be the first demonstration of printing with metals in space, and will provide the capability of on-demand, end-to-end manufacturing to design specification. The ability to produce parts and components on-demand during missions will significantly reduce logistics mass in the form of spares, mitigate risk, and enable exploration without dependence on Earth.

PROJECT MANAGER: Niki Werkheiser

PARTNERS: NASA Ames Research Center, NASA Johnson Space Center, University of Alabama in Huntsville

FUNDING ORGANIZATION: Advanced Exploration Systems

FOR MORE INFORMATION: https://www.nasa.gov/press-release/nasa-selects-three-companies-to-develop-fablab-prototypes

In-Space Manufacturing Multi-Material and Digital Fabrication

OBJECTIVE: *To work with industry and academia to develop on-demand manufacturing and repair technologies for in-space applications.*

PROJECT DESCRIPTION

In addition to developing on-demand manufacturing technologies such as the Multi-material Fabrication Laboratory (FabLab), the In-Space Manufacturing (ISM) project is also identifying, designing, and testing the materials and processes needed for on-demand manufacturing of multi-material and digital components. Current focal areas/customers include Life Support Systems (LSS), Habitats, Logistics Reduction, and astronaut Crew Health Monitoring with work underway across multiple NASA Centers, industry (including small businesses), academia, and other government agencies.

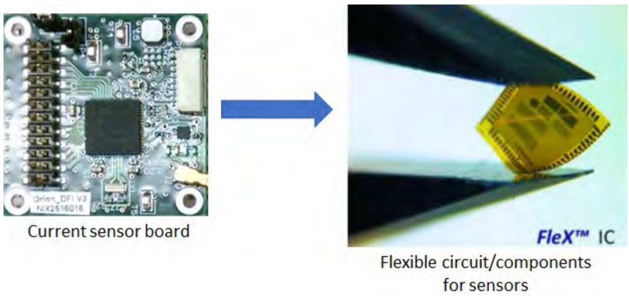


FIGURE 1. Current sensor board, left, and flexible circuit/components for systems, right.

The objective of the multi-material fabrication effort is to develop and characterize stronger types of materials and processes including various metals, plastics, and digital/electronic inks. This enables fabrication of hybrid parts/components, included embedded electronics, which in turn greatly increases the range of applications and uses for on-demand part production during long-duration space missions.

FIGURE 2. AMES supercapacitor pattern, MSFC ink.

The current areas of focus for multi-material fabrication applications includes radio-frequency identification (RFID) sensing, flexible sensing for crew health monitoring, structural health monitoring (SHE), and power generation.

ACCOMPLISHMENTS

The ISM Printable Electronics Workshop was held at Campus 805 in Huntsville, Alabama, on April 3–4, 2018, with more than 60 participants, including representatives from NASA Centers, the Department of Defense, industry, and academia attending. Several breakout sessions were held, and the information gathered on printable electronics equipment, materials, design, and applications will be used to develop the ISM printable electronics (PE) roadmap. The design and prototype of the printed circuitry and enclosure for the ECLSS Pressure Switch is complete, and the NASA Marshall Space Flight Center ISM PE team is working on alternative methods for printing the enclosure on the ISS.

ISM is delivered of 10 full sets of 3D-printed enclosures for the RFID-Enabled Autonomous Logistics Management (REALM) assembly. This effort involves 3D printing in ULTEM and then adding an electromagnetic interference/protective coating on the housing and SD card assemblies. NASA Johnson Space Center's plan for taking these to flight-readiness is to fabricate and test as class III or uncontrolled parts. When the assembly is complete, they will upgrade to flight Class I-E.

ARC Printable Electronics team developed and printed sensors for the detection of ammonia, carbon monoxide, carbon dioxide, and formaldehyde gas. The team also successfully developed the electronic nose (e-nose) algorithm for separately detecting the various gases and has established a stand-alone system for operating the all-printed gas sensors in ISS temperature and humidity conditions.

FIGURE 3. Composite pressure/temperature sensor for ECLSS materials developed by ISM.

FIGURE 4. 3D-printed ECLSS pressure switch housing in ULTEM.

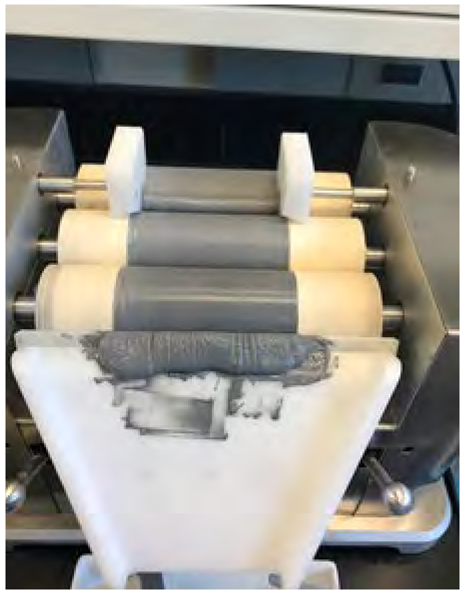


FIGURE 5. Formulation of composite sensor ink.

The Marshall Space Flight Center ISM Materials Engineer developed an aluminum (Al) ink for inkjet rheology for ARC Resistive Random Access Memory and supercapacitor research, and aluminum and aluminum-tin inks for collaborative research with the University of Tennessee and Oak Ridge National Labs for 3D printing aluminum iron (III) oxide (Fe_2O_3) nanothermite-sintered sensors and Al-air batteries.

The effort has resulted in five granted patents with nine additional patents pending, resulting in novel materials for these applications and a robust response from industry and academia through the NASA Technology Transfer Office. The following is a brief summary of the technology transfer activities:

- Ultracapacitor Dielectric Ink: Presented at the TechConnect World Innovation Conference held on May 15–17, 2017, in Washington, DC.; U.S. Patent was granted on August 29, 2017, and an international patent is currently being applied for.
- U.S. patent for solid state ultracapacitor was granted on January 30, 2018.
- Multiple companies have signed commercial evaluation licenses on these and other pending patent technologies.
- Additional patents pending:
  - Spark Plasma Sintered (SPS) supercapacitor, high-performance silver conductor ink,
  - composite polymer-ceramic-carbon nanotube sensor material,
  - pyrometric composite sensor,
  - doped barium titanate ultracapacitor, and
  - atomic layer deposition (ALD)-coated barium titanate ultracapacitor.

SUMMARY

ISM Multi-Material Fabrication is developing the latest leading-edge technologies in on-demand manufacturing, materials development, sensing, and flexible electronics to develop new fabrication materials and processes for long-duration space missions. Many of these new materials and processes are also being integrated into terrestrial-based manufacturing systems to reduce cost and weight, improve functional characteristics of materials, and allow new application spaces to be developed. The coming years for Multi-Material Fabrication will institutionalize these next-generation materials and technology advances to further improve our capability to manufacture the critical items needed for sustainable exploration mission.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Niki Werkheiser, Libby Creel, Curtis Hill, and Furman Thompson

PARTNERS: NASA Ames Research Center, NASA Johnson Space Center, University of Alabama in Huntsville

FUNDING ORGANIZATION: Advanced Exploration Systems

SCIENCE INSTRUMENTS, OBSERVATIONS, AND SENSORS

A BalloonSat Service Bus for Flight Testing Systems for Small Spacecraft

OBJECTIVE: *To develop a service bus capable of supporting balloon flight testing of new science instruments, payloads, and other new technologies developed for small spacecraft applications.*

PROJECT DESCRIPTION

The primary goal of this project is to increase the testing opportunities during development of small spacecraft technologies by providing a new platform to test science payloads, spacecraft subsystems, sensors, and other new spacecraft hardware in space-like environments. The project is developing a high-altitude balloon-borne platform (a BalloonSat) to carry new technologies under development. Primary development for the project is being done by Mississippi State University (MSU). Depending on the size and type of balloon, altitudes in excess of 30 km and flight durations on the order of hours are possible, providing the opportunity to test equipment for extended periods of time in an environment that provides more realistic space-like conditions. The balloon environment offers many advantages over other testing platforms such as sounding rockets or laboratory testing. For example, when testing imaging systems, the terrain and surface conditions that can be observed in a single flight vary greatly, from dense forests to large metropolitan areas, providing a broad range of observation opportunities to test out imager properties. During the flight, the technology under test will experience significant gradients in atmospheric properties (temperature, density, moisture, particulates) that will influence how the system operates. A BalloonSat test flight will thoroughly exercise a new technology, providing its developers with important information on the unit's capabilities and shortcomings. The net result will be an increase in the test article's technology readiness level (TRL), bringing it closer to being an operational system.

The BalloonSat service bus being developed will provide an internal storage bay with a volume sufficient to house a full 6U CubeSat payload or subsystem under test. The service bus will provide the utilities necessary to operate the test platform including communication and tracking of the BalloonSat. The technology under test can then conduct relevant testing and experiments to evaluate its operational capabilities in the relevant space-like environments without having to be concerned with maintaining the stability or conditions of that environment.

The BalloonSat design is based on a system that MSU developed to photograph the August 21, 2017, total solar eclipse. A prototype of the eclipse-viewing system has been design, built and flown. We describe this prototype here to illustrate possible design features of the proposed bus. MSU is leading design, development, construction, and flight testing of the BalloonSat service bus with NASA Marshall Space Flight Center providing requirements and providing technical guidance and input on flight test plans. At the completion of the project, MSU will deliver the operational BalloonSat service bus capable of testing small spacecraft technologies. The service bus can then be used by NASA and other interested customers to accelerate the development of other technology products.

ACCOMPLISHMENTS

The entire contiguous United States experienced a solar eclipse on August 21, 2017, which passed from the Pacific to the Atlantic Coasts. The path of totality crossed 14 states while other states had partial eclipse. When MSU was selected for their Cooperative Agreement Notice award for the BalloonSat service bus project, MSU took advantage of this unique event to develop and test the basic technologies to be used by the BalloonSat bus, using this eclipse imaging system as a development unit.

The eclipse imaging system was designed in order to meet the standards of a 2U CubeSat. One key aspect of the payload is that it was entirely made from 3D printed parts with over 100 prototype parts made over the two year development period. The eclipse system included a custom computer processor board developed by MSU providing flexibility to specialize it for the desired

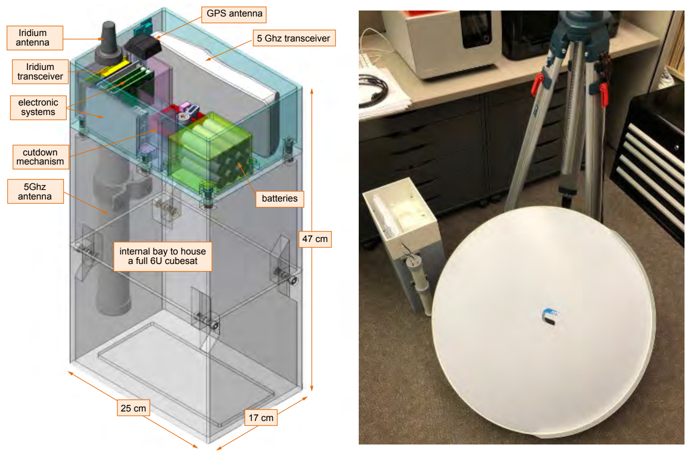


FIGURE 1. BalloonSat bus layout and flight and ground hardware.

computational needs. The eclipse system also included a turret that housed two cameras and could rotate 360°, allowing it to counteract the rotations of the payload in order to obtain a stabilized image. The payload was launched in Kentucky. The flight was successful and the payload was recovered undamaged.

More recently, the BalloonSat service bus hardware has begun to take shape. The BalloonSat bus has been assembled and the ground tracking system is now being developed. The first test flight will include an MSU-built 6U CubeSat with visible and infrared cameras. This CubeSat is being developed with potential wildfire detection applications in mind, with the infrared camera providing resolution of approximately 30 m. First flight test opportunities currently being explored include flights in western Mississippi or flights over the western U.S., such as Colorado. Western US flights are particularly appealing because of the vast wide open territory, which helps in balloon recovery operations, as well as the potential for observing active wildfires.

SUMMARY

The BalloonSat service bus will provide an innovative solution for advancing the development of new small spacecraft payloads and other technologies. The BalloonSat service development efforts by MSU are ongoing with the first test flight expected this fall. This project will support NASA's missions by helping to support other research and technology development efforts by giving them an opportunity to fly in relevant environments for an extended period of time.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Keith Koenig, Professor, Mississippi State University Department of Aerospace Engineering

PARTNER: Mississippi State University

FUNDING ORGANIZATION: Cooperative Agreement Notice

SERVIR

OBJECTIVE: *To connect space to village by helping developing countries use satellite data to address critical challenges in agriculture and food security, land use and ecosystems, weather and climate, and water and water-related disasters.*

PROJECT DESCRIPTION

A joint initiative of NASA and the U.S. Agency for International Development (USAID), SERVIR works in partnership with organizations around the world to help developing countries use Earth-observing (EO) satellites and geospatial technologies. SERVIR empowers decision-makers with the tools, training, and services to act locally on issues such as disasters, agriculture, water, ecosystem health, and land use change. SERVIR is increasing access to information and supporting analyses in over 45 countries through a network of hubs in Africa, Hindu Kush-Himalaya, Lower Mekong, and Amazonia in 2019.

SERVIR's approach to designing geospatial information services is embodied in the SERVIR Service Planning Toolkit. Emphasizing a user-focused perspective, the toolkit engages a broad range of stakeholders and includes guidance to identify development problems, analyze opportunities to link decision-making to satellite data, and deliver custom decision support services. SERVIR continues to invest in collaborative and results-oriented processes, enabling researchers to create solutions integrated with decision making and contribute to positive development outcomes. In the next year, SERVIR plans to iterate on the toolkit, refining it with hands-on experience gained.

ACCOMPLISHMENTS

Over the past year, SERVIR implemented its service planning approach across the global network of SERVIR hubs. The Mekong regional hub collaborated with the Mekong River Commission (MRC) to enhance their current water quality monitoring program. Dam construction and changes in land cover and land use have significantly impacted sediment loads and water quality throughout the Lower Mekong basin. An operational model was implemented in Google Earth Engine, allowing users with limited knowledge of remote sensing to freely access and interpret sediment data.

This tool provides a foundation for subsequent user needs and consultations and allows decision makers to make use of sediment concentrations and land use conversion information to improve regional water, energy production and land use policies.

The Greater Horn of Africa is prone to extreme agricultural shocks, including droughts and floods, leaving countries in the region struggling to systematically monitor crop conditions with limited in situ observations. In response, SERVIR's Eastern and Southern Africa (E&SA) regional hub and Applied Sciences Team collaborated with the Kenya Ministry of Agriculture to produce a satellite-derived national crop conditions monthly bulletin.

The new bulletin enables Kenya to better predict and prepare for fluctuations in agricultural production and mitigate loss and potential damage. Added granularity provided by Earth observations, coupled with economic and market conditions, provides comprehensive and actionable information for agricultural extension agents, farmers, and the broader agricultural sector.

Glacial melt is one of the primary inputs into Afghanistan's Indus River Basin, especially during the dry season. However, few of these glaciers are actively monitored, making it difficult to manage water resources downstream. To address this challenge, the SERVIR regional hub in Hindu Kush Himalaya collaborated with Afghanistan's Ministry of Energy and Water (MEW) to develop the country's first dynamic glacier and glacial lakes monitoring system. SERVIR HKH also conducted multiple trainings to build capacity of MEW staff to map and monitor glacial extent using GIS and remote sensing techniques. This new system enables MEW to better manage water resources and reduce the risk of water-related disasters, such as glacial lake outburst floods (GLOFs).

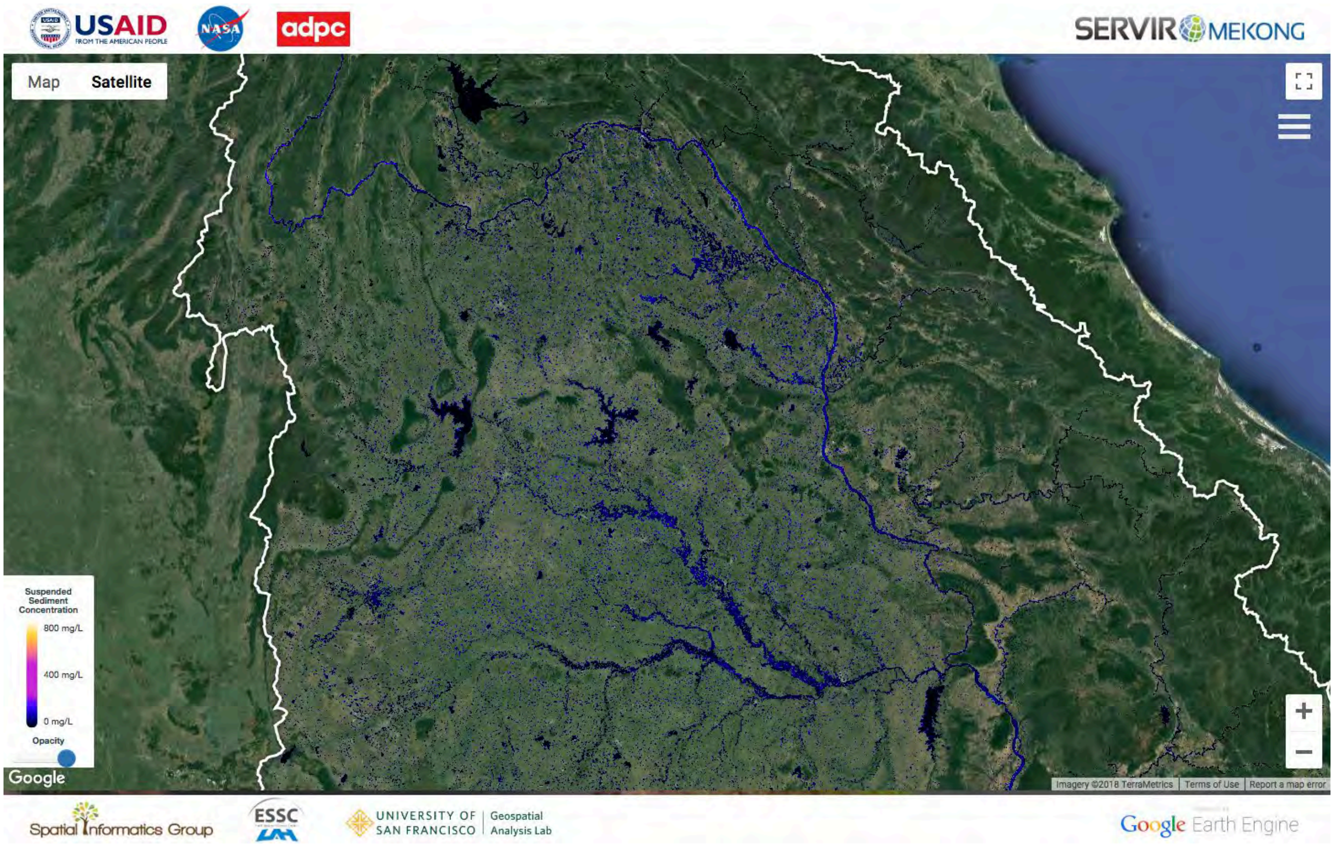


FIGURE 1. A Google Earth Engine application window showing surface sediment concentrations derived from Landsat observations in the Mekong region. This case study was recently featured on the cover of Remote Sensing (vol. 10, issue 6, fig. 2), highlighting the partnership between SERVIR Science Coordination Office, MRC, SERVIR-Mekong, Google, and the University of San Francisco. The web application can be accessed at www.mekong-ssc.appspot.com.

SUMMARY

As global awareness of the value of space-based Earth observations grows, SERVIR will continue to build capacity in partner organizations and countries to use EO data to better inform decisions, policies, and actions. Through the combined efforts of SERVIR regional hubs and technical support from USAID, NASA and U.S.-based collaborators, SERVIR is at the forefront of leveraging Earth observations and geospatial data, products and tools to advance international development through science and technology.

FIGURE 2. Cover of Remote Sensing highlighting research conducted by the SERVIR SCO and Mekong hub in collaboration with MRC, Google, and the University of San Francisco.

PROJECT MANAGER: Raymond French

PRINCIPAL INVESTIGATOR: Daniel Irwin

PARTNER: U.S. Agency for International Development

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: www.servirglobal.net

Lynx X-Ray Observatory Concept Study

OBJECTIVE: *To conduct a concept study for consideration as NASA's next flagship astrophysics mission following the James Webb Space Telescope and the Wide Field Infrared Survey Telescope (WFIRST).*

PROJECT DESCRIPTION

The Lynx X-ray Observatory is a large mission concept under study to aid the 2020 Astrophysics Decadal Survey Committee in formulating their recommendations for future NASA strategic astrophysics missions (for launch in the 2030s). The study goal is to deliver to the Decadal Survey Committee a mission concept that is scientifically compelling and feasible with respect to technical, cost, and risk factors. The study will provide the science objectives, the mission and observatory performance requirements needed to realize these objectives, a design reference mission, an assessment of the current technology, and a roadmap for technology maturation (and the resources needed), a cost assessment, major risk mitigation plans, and a top-level schedule for major development phases. The study will culminate in a final report for submission to the Decadal Committee in 2019.

IMAGE CREDIT: NASA

FIGURE 1. NASA Astrophysics Decadal Survey missions that includes the Great Observatories: Hubble, Chandra X-ray Observatory, and Spitzer (Compton Gamma-Ray Observatory is not shown). The Lynx X-ray Observatory mission concept is being defined for input into the 2020 Decadal Survey.

ACCOMPLISHMENTS

The Lynx study is being performed under the leadership of a Science and Technology Definition Team (STDT) selected from the astrophysics community, by a joint NASA Marshall Space Flight Center (MSFC)-Smithsonian Astrophysical Observatory (SAO) Study Office and with participation of over 300 scientists and technologists worldwide who are dedicated to the success of Lynx. The MSFC Advanced Concepts Office is leading the mission design and is collaborating with the NASA Goddard Space Flight Center (GSFC) Instrument Design Lab and Mission Design Lab for in-depth studies of the science instruments and mission formulation and implementation. The Lynx Study Office has established multiple partnerships with Industry via Cooperative Agreement Notice contracts to perform assessments and provide inputs in areas of technology maturation, design, analysis, and manufacturing. The Study Office has also partnered with the School of Industrial and Systems Engineering at the University of Alabama in Huntsville to assist with Systems Modeling of the Lynx observatory focused on development of concept of operations-type content and identify cost, schedule, and requirements drivers of the system. These mission design and engineering studies are necessary to show a feasible mission path.

The Lynx team has worked to build an exciting science case worthy of a flagship mission. This science case is enabled by an advanced assembly of lightweight x-ray optics coupled to a highly capable suite of science instruments. The science instruments include a low-noise megapixel imaging array called the high-definition x-ray imager (HDXI), a large-format, high-spectral-resolution, small-pixel array also known as the Lynx x-ray microcalorimeter (LXM), and a high-efficiency, high-spectral-resolution, dispersive spectrometer dubbed the x-ray grating spectrometer (XGS). The spacecraft is of standard design with minimum deployments (outer sunshade-contamination door, inner contamination door, solar panels) required. Extensive trade studies

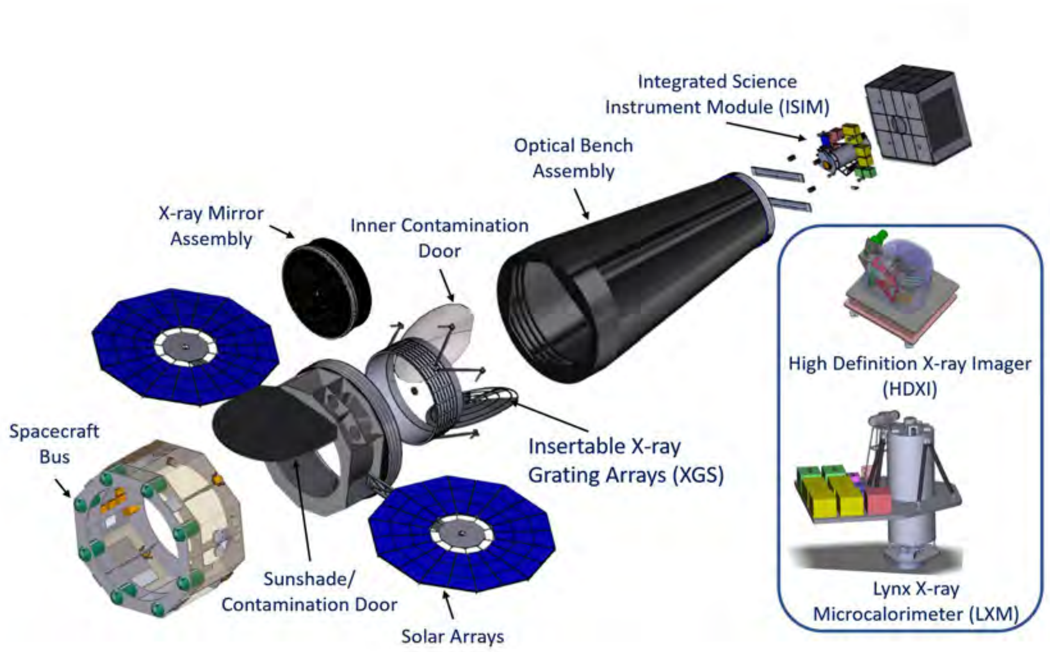


IMAGE CREDIT: NASA

FIGURE 2. Lynx has a 10-m focal length and consists of a high-resolution, 3-meter diameter, large area X -ray mirror assembly with pre- and post- collimators (XMA) surrounded by the spacecraft bus and complemented by an instrument suite that includes a low-noise megapixel imaging array (HDXI); a large-format, high-spectral-resolution, small-pixel array (LXM), and high-efficiency, high-spectral-resolution, dispersive spectrometer (XGS). Detectors for all three instruments are mounted onto the ISIM.

and technology assessments on the payload and spacecraft have been carried out by the Lynx team to define the design reference mission elements and to assess the feasibility of additional developing technologies.

The mission is Risk Class A, as is required for this type of observatory, and Lynx will launch on a heavy-class launch vehicle that uses a standard 5-m fairing and will achieve a Halo orbit around Sun-Earth (SE)-L2. The Space Launch System (SLS) comanifested payload is also being considered, but would require the use of an extendable bench. A trade study is underway to assess the feasibility of this option. Once at SE-L2, Lynx is designed to have a baseline lifetime of 5 years, and extendable to 20 years. Communications with Lynx will be through the Deep Space Network and mission operations will be similar to those of the Chandra X-ray Observatory, leveraging nearly 20 years of experience in this area.

The STDT has established key science themes that will be addressed by Lynx: the dawn of black holes; the invisible drivers of galaxy formation and evolution; and expanding our view and understanding of stars, planets, and collapsed objects.

- ***The Dawn of Black Holes.*** Massive black holes start to form as early as their host galaxies. Lynx will find the first supermassive black holes lighting up in the universe, trace their growth from the seed phase, and shed light on how these dark giants co-evolve with their hosts. Black holes at the seed stage or soon after are best observed in the x-ray band. Reaching into the seed regime in the early universe requires sensitivities that only Lynx can achieve.

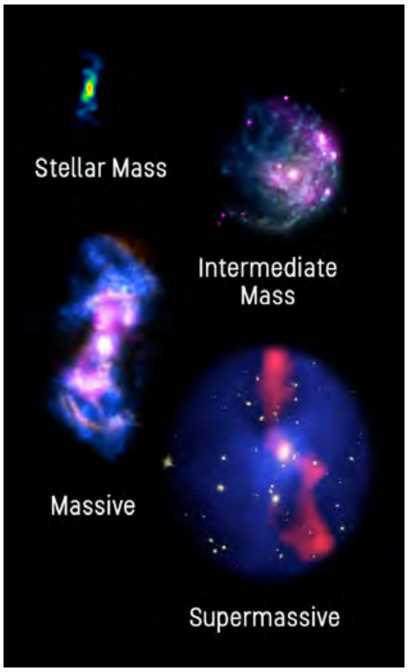


IMAGE CREDIT: NASA/CXC/SAO

FIGURE 3. Massive black holes start to form as early as their host galaxies. The most distant black holes are found when the universe was only a few hundred million years old, and weigh up to a billion solar masses. We simply do not understand how they could have grown so massive in such a short amount of time. Lynx will directly observe their birth and early growth.

- ***The Invisible Drivers of Galaxy Formation and Evolution.*** The assembly, growth, and state of visible matter in cosmic structures are largely driven by violent processes that produce and disperse large amounts of energy and metals into the surrounding medium. In galaxies at least as massive as the Milky Way, the relevant baryonic component is heated and ionized to x-ray temperatures. Only Lynx will be capable of mapping this hot gas around galaxies and in the Cosmic Web, while characterizing in detail all significant modes of energy feedback. Essential observations will rely on high-resolution spectroscopy, the ability to detect low surface brightness continuum emission, and moderate resolution spectroscopy of extended sources on arcsecond scales—all unique to Lynx.
- ***Expanding our View and Understanding of Stars, Planets, and Collapsed Objects.*** Lynx will probe a wide range of high-energy processes that provide a unique perspective on stellar birth and death, star-planet interactions, origin of elements, and energy feedback from star formation on the smallest scales. It will also detect x-ray emission from young stars in active star forming regions, study stellar coronae in detail, and provide essential insight into the impact of stellar x-ray/ultraviolet flux and winds on habitability of their planets. Lynx will observe supernova remnants outside the Milky Way in detail and provide the first chance to study the effects of different metallicities on the physics of stellar explosions and their aftermaths. It will also expand our knowledge of collapsed objects by extending sensitive studies of x-ray binaries from the Milky Way and M31 to galaxies as distant as 10 Mpc and is poised to greatly extend our x-ray grasp throughout the Milky Way and nearby galaxies as it will combine, for the first time, the required sensitivity, spectral resolution, and sharp vision to see in crowded fields.

FIGURE 4. Lynx Interim Report is available for download on the Lynx website: https://wwwastro.msfc.nasa.gov/lynx/ .

The Lynx study team has submitted and published an interim report available on the Lynx website (https://wwwastro.msfc.nasa.gov/lynx/) that describes, in detail, the science goals and credible hardware configurations that will achieve the Lynx science goals. This report also presents a discussion on a design reference mission; schedule, risk, and related programmatic considerations; and a technology development roadmap.

The Lynx X-ray Observatory design work and analyses will be completed by the end of 2018. Following this work, the Lynx Team will prepare and submit a Final Report to NASA HQ that will include all science, technical, and programmatic (estimated cost and schedule) elements. NASA HQ will then submit the Lynx Final Report, along with three other large mission concepts that NASA is studying, to the Astrophysics Decadal Survey Committee in the late summer/early-fall of 2019.

SUMMARY

Only a unique x-ray observatory such as Lynx will give us the capacity to answer fundamental questions regarding the first black holes, galaxy formation and evolution and a range of high-energy processes needed to understand stellar life and death, star-planet interactions, origin of elements, energy feedback from star formation on a range of spatial scales, and protoplanetary disk formation. With its high angular resolution, large effective area and spectroscopic capability, Lynx will be uniquely positioned to provide synergistic observations with both ground-based and space-based observatories, including gravitational wave detectors, through the 2030s and beyond.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Lynx Science and Technology Definition Team and MSFC Study Office

AUTHORS: Jessica A. Gaskin, Karen E. Gelmis, Douglas A. Swartz

PARTNERSHIP: Smithsonian Astrophysical Observatory (SAO)

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://www.astro.msfc.nasa.gov/lynx/ and https://www.lynxobservatory.com/

Complementary Metal-Oxide Semiconductive (CMOS) Camera with Onboard Processing

OBJECTIVE: *To design and build a prototype low-noise complementary metal-oxide semiconductor camera with onboard processing capabilities, one that would only need minor modification to fly on a scientific sounding rocket flight.*

PROJECT DESCRIPTION

NASA Marshall Space Flight Center (MSFC) has successfully designed, tested, and flown low-noise CCD (charge-coupled device) cameras in solar heliophysics Sounding Rocket missions (CLASP, Hi-C 2.1). Complementary metal-oxide semiconductor (CMOS) active-pixel sensors have replaced CCDs in most industrial and commercial imaging applications due to significantly faster readout speed, lower power usage, and shutterless image acquisition. With this Technology Investment Plan (TIP), our objective is to build a prototype camera for testing and evaluating CMOS sensors, one that would only need minimal modification to fly on a sounding rocket experiment. Adding a CMOS camera to our capabilities as a sounding-rocket group will open up possibilities not only for new Low-Cost Access to Space (LCAS) proposals, but allow us to continue to be successful and competitive in space-based solar imaging hardware.

The work covered under this TIP included the acquisition of a next-generation low-noise, space-capable CMOS sensor; design and acquisition of the rest of the camera electronics; part custom and part of commercial-off-the-shelf (COTS); and testing of the camera in a vacuum environment.

The challenge of this project was to create a camera which could easily be flown on a sounding rocket with little to no modifications and with as many COTS components as possible. While similar performance cameras may exist on the market, their price point puts them out of reach for MSFC LCAS research efforts. Having both a CCD and a CMOS camera available in-house for such experiments increases the scientific return on the projects as more funding can be directed at other technological challenges. It also makes MSFC an attractive partner to other institutional and academic teams using LCAS proposals as a means to test new space-born technologies, especially telescopes.

ACCOMPLISHMENTS

This project has not been realized as proposed, and the accomplishments are in the form of lessons learned. Shortly after the proposal was funded at the beginning of fiscal year (FY) 2017, the team identified a new CMOS sensor in late design phase with a vendor that we have had good prior collaboration with Teledyne e2v. This sensor met all of our current requirements and most if not all of the likely requirements for a camera on a future mission. At that time, an early version of the sensor was foreseen to be available to us by approximately May 2017. Based on this information, we requested and received an extension of the FY 2017 TIP into FY 2018. In the intervening months, the vendor has delayed the release of the sensor multiple times, and changed the interface design. As of FY 2019, the sensor has still not been released.

The team completed the procurement of the other COTS components, and the project has been on hold since Spring 2017. As of end of FY 2018, we decided not to pursue an extension of the project, and instead to revisit other options for sensor vendors and project goals.

The team took a calculated risk in going with a sensor which was not yet ready for distribution based on prior performance of the vendor. Unfortunately, that risk was realized and resulted in the noncompletion of the project. In the future, the project will identify sensors which are already in the distribution phase.

SUMMARY

While we have not realized the prototype camera, the ultimate goal of designing and creating a low-noise, science-quality CMOS camera has not changed, and the justification for doing so is still as valid and compelling as when the project began. In fact, our existing collaborators at the Smithsonian Astrophysical Institute in Boston have expressed interest in this camera for future projects.

We will continue to work on this project as available, but will not be re-apply for funding until a suitable ready-to-purchase sensor is found.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Laurel Rachmeler

FUNDING ORGANIZATION: Technology Investment Program

Preparing for MEME-X

OBJECTIVE: *To prepare the calibration facility for MEME-X Phase A.*

PROJECT DESCRIPTION

A team of NASA Goddard Space Flight Center scientists, along with other partners, have proposed to use Earth as a laboratory to understand how planets lose their atmospheres. Called Mechanisms of Energetic Mass Ejection Explorer (MEME-X), this proposal was one of five selected to continue development for further consideration for a NASA Small Explorer. This time period, called Phase A, is a short period of development for the team to provide further detail for their mission concept. Of the five that recently reported their Phase A concept reports, NASA is expected to select one or two mission concepts in the spring of 2019 to continue development through launch.

This MEME-X investigation proposes to map the universal physical processes of the lower geospace system that controls the mass flux through the upper atmosphere to space. It has the potential to help us understand the processes that control our Earth's atmospheric upflow and outflow into space. It will also advance our knowledge of the universal processes of our Sun's solar wind effect on planetary atmospheric control or erosion. If this MEME-X mission is selected to continue through development and launch, NASA Marshall Space Flight Center (MSFC) is tasked to characterize the performance, or to calibrate, some of the team's instruments prior to integration onto the two spacecraft.

This calibration task will be conducted in the Low Energy Electron and Ion Facility (LEEIF) at MSFC. It is a heritage laboratory system designed for the development, testing, and calibration of charged-particle detectors over their complete range of particle energy, mass, flux, and angular acceptance. The calibration of similar types of instruments have been conducted within the LEEIF for the space missions of Dynamics Explorer, Polar, sounding rockets, and most recently the 16 Dual Ion Spectrometers (DIS) for the Magnetospheric Multiscale Mission (MMS) launched in 2015. These DIS units were built for GSFC by Meisei Electric and the Japan Aerospace Exploration Agency (JAXA). Figure 1 is of a photo with a DIS unit in the LEEIF's vacuum chamber prior to its calibration procedures.

During this Phase A development, MSFC focused on studies and improvements desired for the facility's particle source that will be used for the calibration of the instruments. This task to characterize these types of instruments is complicated by exterior or interior electric and magnetic fields acting on the particle beam within the chamber. This includes the effects of the Earth's magnetic field. Improvements to the particle source by continually monitoring and mitigating these fields are needed so that we can accurately calibrate the performance of the delivered MEME-X instruments prior to integration.

ACCOMPLISHMENTS

During the MEME-X Phase A timeframe, MSFC took the opportunity to make improvements and conduct studies within the LEEIF to improve its calibration capabilities. The targeted study and improvements are in particular for an enhanced performance of the calibration source utilized for the task. These efforts include: 1.) further study of the spatial uniformity of the particle beam, 2.) mitigation of the Earth's magnetic field through a Helmholtz Coil system, and 3.) minimizing the energy spread, or temperature, of the ion source's particle beam. These enhancement efforts are still continuing and will be used to accurately determine the performance of the MEME-X particle instruments that arrive for testing and calibration.

SUMMARY

In hopes that the MEME-X investigation is selected for a NASA Small Explorer mission, MSFC is preparing its heritage LEEIF facility to receive some of the team's space flight instruments to further their characterization and performance. After each instrument's characterization at MSFC, they will then be integrated onto one of the two spacecraft. After launch, the information gained from the characterization conducted on the ground is combined with the flight measurements to help the scientists understand the physical information and processes of the space environment. This data

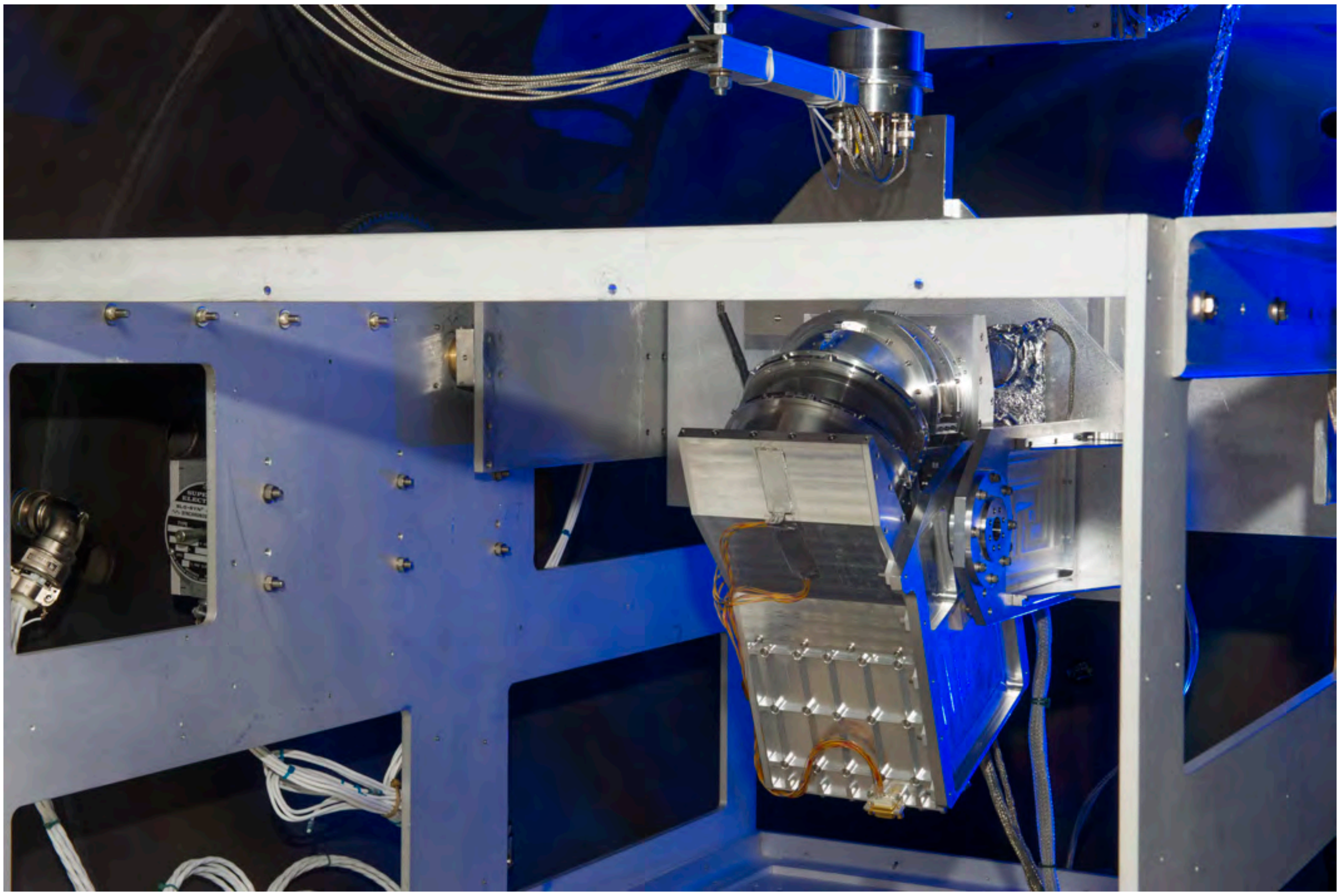


FIGURE 1. A DIS flight unit in the LEEIF vacuum chamber ready for calibration.

along with the other instrument measurements on the two spacecraft will be used to reveal how our Sun's solar wind interacts with our atmosphere and how atmospheric upflow effects our near-Earth space. These answers obtained in our Earth's space environment will lead to important answers regarding the evolution of our planetary atmospheres.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Victoria Coffey

PARTNERS: GSFC, Colorado State University, University of Alabama in Huntsville

FUNDING ORGANIZATION: Center Strategic Development Steering Group

Short-Term Prediction Research and Transition (SPoRT)

OBJECTIVE: *To transition unique satellite observations and research capabilities to the operational weather community to improve short-term, regional forecasts.*

PROJECT DESCRIPTION

Short-term Prediction Research and Transition (SPoRT) is an end-to-end research-to-operations/operations-to-research (R2O/O2R) activity focused on accelerating the use of satellites, nowcasting tools, and advanced modeling and data assimilation techniques to improve short-term weather forecasts. SPoRT partners with universities and other government agencies to obtain near real-time data, develop new products, and obtain operational perspective to increase the likelihood of adoption by the operational weather community.

SPoRT incorporates the end user throughout an iterative R2O/O2R feedback process (fig. 1) by identifying a forecast challenge, incorporating a potential solution into the user's decision support system (DSS), providing training on use of the product, and assessing the product's impact on their decision-making process.

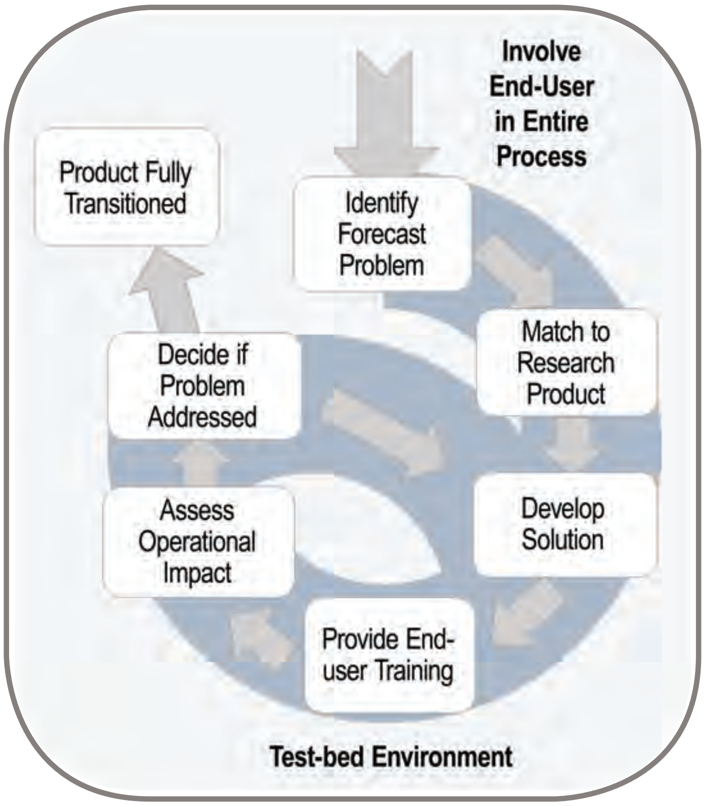


FIGURE 1. Graphical representation of the SPoRT unique R2O/O2R paradigm.

Product iterations continue until a solution is used in regular forecast operations. Collaborative relationships between SPoRT enable honest feedback on product and training value resulting in lasting operational impact of new data products. Often, this feedback includes suggested product changes that lead to significant improvements, increased use of the product, and additional opportunities for research and development. Assessment reports are published for the broader community communicate successful product transitions. These activities are collaborative and complementary to work done by testbeds at the National Oceanic and Atmospheric Administration (NOAA) and National Weather Service (NWS) National Centers and Cooperative Institutes.

ACCOMPLISHMENTS

SPoRT provided one of several numerical weather prediction modeling solutions to South Korea during February and March for the International Collaborative Experiments for PyeongChang 2018 Olympic and Paralympic Winter Games. The ICE-POP field campaign combined a suite of radar, satellite and in situ observations, with numerical modeling assets and data assimilation experiments over the complex terrain of the Korean Peninsula. The SPoRT experimental configuration of the NASA Unified-Weather Research and Forecasting (NU-WRF) model was run in real time during the Olympic and Paralympic Games, and serves as a benchmark for future research to improve our understanding of snowfall in complex terrain, our ability to estimate snow-using satellites, and prediction models that parameterize these intricate processes.

SPoRT has invested in developing applications for new NASA missions. IceSat-2 (Ice, Cloud, and Land, Elevation Satellite-2) is an upcoming mission of interest, launched earlier this fall. The instrument onboard is a photon-counting laser altimeter capable of measuring the elevation of ice sheets, glaciers, sea ice, vegetation, and land. As an Early Adopter, SPoRT will have access to early release mission data to explore use of the data for forecasting challenges related to sea ice thickness

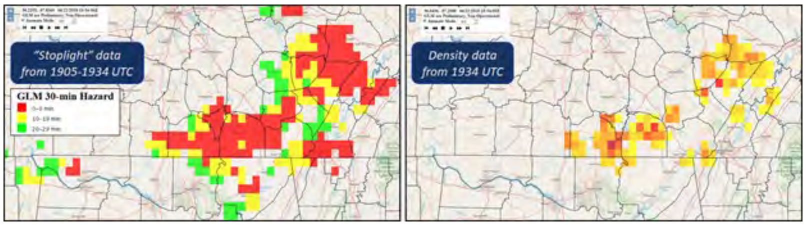


FIGURE 2. An example of the GLM 30 minute hazard, or stoplight, product (left) covering observations from 1905-1934 UTC versus the 1 minute GLM group density (right) for 1934 UTC.

and melt of relevance to NWS Alaska Region partners. In addition, SPoRT has Early Adopter activities related to the TEMPO (Tropospheric Emissions Monitoring of Pollution) mission and has begun developing proxy products, while engaging with end users about applications of the data. TEMPO will launch in the early 2020s and the instrument will provide the first geostationary observations of major air pollutants. SPoRT also have a focus on two missions related to tropical cyclone forecasting and analysis, TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) and CYGNSS (Cyclone Global Navigation Satellite System).

SPoRT has been collaborating with local emergency managers on lightning safety for several years and has created a new visualization of the Geostationary Lightning Mapper (GLM) onboard the GOES-R Series satellites. The GLM 30-min hazard, or 'stoplight', product highlighting hazards with the three-color (red, yellow, and green) scheme was developed to show the spatial extent of lightning and is color-coded based on the age of the lightning observation. The original design is coded such that red is 0–9 min, yellow is 10–19 min, and green is 20–29 min. The image (fig. 2) shows an example of the GLM stoplight product in conjunction with the more traditional 1-min density observations.

SUMMARY

SPoRT is a highly successful project that conducts world-class research and transition activities, with a model that is both sustainable and able to grow with new opportunities. Through collaboration with university and government partners, SPoRT has successfully transitioned value-added observations and capabilities from recently-launched satellites to weather forecasters. These accomplishments further SPoRT's vision to be a 'go-to' project in the applied research community to accelerate the use of next-generation satellite datasets into the operational weather community.

PRINCIPAL INVESTIGATOR: Christopher Hain

PARTNERSHIPS: National Oceanic and Atmospheric Administration, National Weather Service

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://weather.msfc.nasa.gov/sport/ and https://nasasport.wordpress.com/

MoonBEAM

OBJECTIVE: *To use CubeSats to detect, study, and localize gamma-ray bursts.*

PROJECT DESCRIPTION

Moon Burst Energetics All-sky Monitor (MoonBEAM) is a CubeSat concept for deploying gamma-ray detectors in cislunar space to increase gamma-ray burst (GRB) detections and improve localization precision using the timing triangulation technique. The goal is to facilitate multimessenger time-domain astronomy by providing prompt alerts and well-defined locations of compact object mergers.

The first compact binary merger (GW170817) detected by gravitational wave detectors is associated with a short GRB detected across the entire electromagnetic spectrum. The joint detection on August 17, 2017, has provided incontrovertible evidence of the long-suspected connection between the short GRBs and neutron star binary coalescence events and has become one of the most significant scientific discoveries of this decade. The *Fermi* GRB Monitor observations of GW170817 constrained the event's total electromagnetic energetics, allowed for the tightest constraints on the speed of gravity, and provided insight into the neutron star equation of state. Despite these groundbreaking discoveries, a wide range of questions regarding the nature of these sources remain, including the population characteristics as a function of redshift and the contribution of neutron star, black hole mergers to the observed GRB population. Future joint Laser Interferometer Gravitational-Wave Observatory (LIGO)/Virgo and gamma-ray observations, as well as longer wavelength observations of their associated afterglows and kilonovae facilitated by joint gravitational wave/electromagnetic localizations, will allow us to further probe the connection between compact binary mergers and short GRBs, address potential EM emission from black hole mergers, and better constrain the end point of stellar evolution.

Current all-sky monitoring gamma-ray instruments can provide localization precision no better than a few degrees radius depending on the brightness of the GRB. Facilities in other wavelengths typically are required to do tiling observations across the localization area as it is too large for their fields of view, which is a time-consuming technique and risk missing the afterglow. The Interplanetary Gamma-Ray Burst Timing Network has demonstrated the timing triangulation technique to improve localization precision by using instruments near Earth's orbit and other planetary orbits. However, delay in data downlinks for instruments outside the Tracking and Data Relay Satellite network prevents rapid follow-up observations, and the number of gamma-ray detectors in more distant orbits have been dwindling.

CubeSats can be built and launched quickly, providing a viable alternative as current instruments age and decommission. MoonBEAM is a 12U concept with gamma-ray detectors sensitive to detect GRBs near the same significance as current instruments but more compact in size and deployable to a cislunar orbit with its own propulsion. In cislunar orbits, the sky coverage and expected number of GRB detections is increased when compared to low Earth orbit (LEO) due to the lack of blockage by the Earth and no need to turn off during the South Atlantic Anomaly passage. Also, the maximum time difference between two instruments in LEO is <0.1 s, which would only improve localization

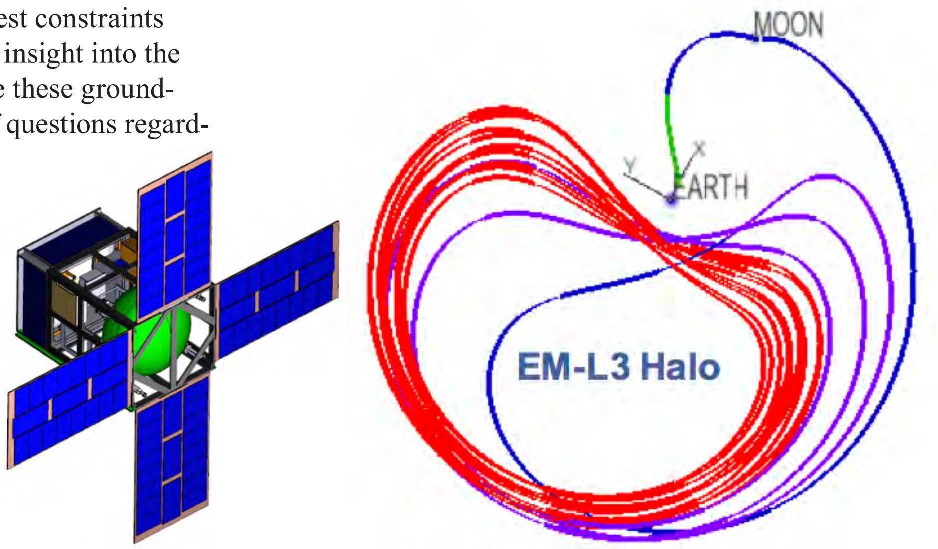


FIGURE 1. Preliminary MoonBEAM 12U design and the Earth-Moon L3 orbit.

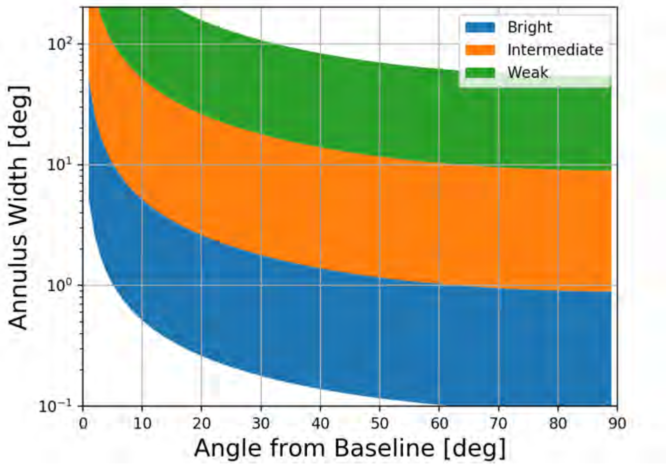


FIGURE 2. Assuming an average baseline, the 1-sigma annulus width for short GRBs with three different intensities: bright, intermediate, and weak. Most bright GRBs will be localized to an annulus with subdegree width.

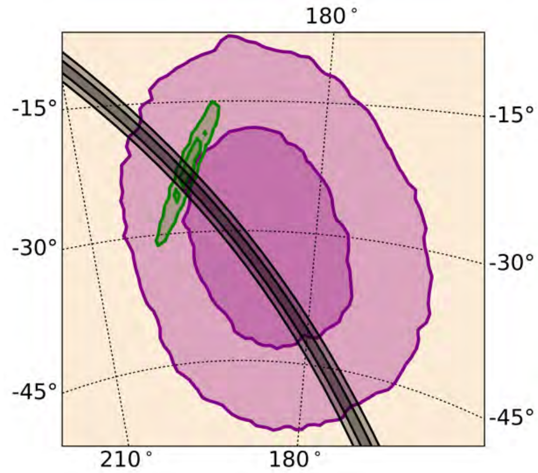


FIGURE 3. An example annulus (black) for an intermediate bright burst detected by MoonBEAM and any instrument in LEO, at a 45° angle to the baseline. For comparison, the final gravitational wave localization for GW170817 is shown in green and the Fermi-GBM localization for GRB170817A in purple. The regions for each localization represent the 50% and 90% confidence regions.

of the top 5% brightest short GRBs. With an instrument in cislunar space partnering with an Earth-orbit instrument, localization improvement is achievable for 20+ short GRBs per year.

ACCOMPLISHMENTS

We have completed a preliminary design study with the NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office in 2017. The Earth-Moon L3 orbit has been identified as feasible with a 12U design, assuming deployment and trajectory from the Space Launch System Exploration Mission 1 (EM-1) rideshare data. This design consists of high TRL components ready for a launch in the 2020s. Using conventional scintillation crystals paired with silicon photomultipliers, MoonBEAM is expected to detect ≈37 short GRBs/year independently. The Earth-Moon L3 orbit will provide a timing baseline of 0.3–2.1 s when paired with an instrument in LEO. Figure 2 shows the localization improvement assuming a baseline of average distance from Earth.

SUMMARY

MoonBEAM is a 12U CubeSat concept of deploying gamma-ray detectors in cislunar space to increase GRB detections and improve localization precision with the timing triangulation technique. Such an instrument would probe the extreme processes in cosmic collision of compact objects and facilitate multimessenger, time-domain astronomy to explore the end of stellar life cycles and blackhole formations. We have identified a feasible orbit to achieve MoonBEAM scientific goals and finished the concept study with a preliminary design of the spacecraft. We will move forward with instrument definition study and concept refinement, with the intent of proposing the MoonBEAM mission in the next Astrophysics Mission of Opportunity solicitation.

PRINCIPAL INVESTIGATOR: C. Michelle Hui

PARTNERS: University of Alabama in Huntsville, United Space Research Association

FUNDING ORGANIZATION: Science Mission Directorate

Wireless, Multicoil Readers for Structural Health Monitoring

OBJECTIVE: *This work is focused on the engineering science to understand how to use multiple detectors/coils housed in a reader to provide accurate measurements of wireless, battery-less sensors embedded or mounted on structures or components.*

PROJECT DESCRIPTION

Characterization of structural health with wired, surface-mounted strain sensors is expensive and time-consuming. To reduce costs and enable rapid characterization of mechanical strain of composites with additive manufacturing-based, polymeric components for space systems, we proposed the design and fabrication of a novel class of wireless strain sensors. The target outcome is a multicoil reader for detecting and locating our embeddable strain-sensing technology for structural health monitoring. The proposed work focused on the engineering science to understand how to use multiple detectors/coils housed in a reader to provide accurate measurements of wireless, battery-less sensors embedded or mounted on structures or components. The use of multiple coils with appropriate kinematics will permit 'triangulation' of the targeted sensor to calibrate the readings of the embedded sensor, as depicted in figure 1. The technical objectives of the multicoil reader are the following:

1.) kinematically analyze to triangulate the position of a single embedded sensor coil given the electrical characteristics of each coil housed in a multicoil reader,

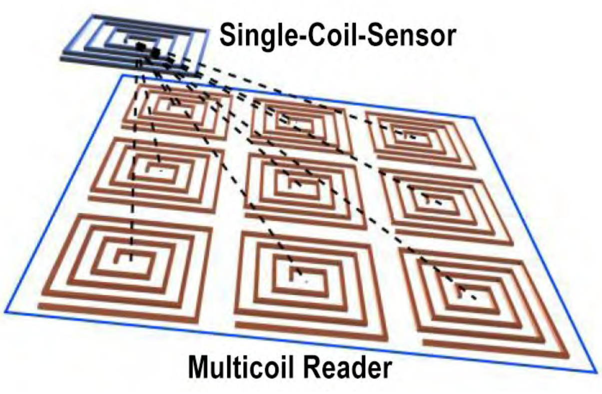


FIGURE 1. Multicoil reader concept. By understanding the coupling between each reader coil and the sensor coil, we can triangulate the position of the embedded sensor coil.

2.) simulate, with COMSOL Multiphysics, the magnetic inductive coupling between two rectangular planar coils as a function of relative position to determine mutual inductance and electrical impedance at each location,

3.) build libraries, with computer simulations, of the mutual inductance and electrical impedance for each known relative position,

4.) 'solve' the backward problem to determine the relative position of an embedded sensor-coil from the electrical measurements of the multicoil reader, and

5.) utilize MATLAB scripts for active interpolation of assembled libraries to quickly determine relative position given electrical measurements.

The deliverables for this project will include MATLAB scripts outlining the kinematic analysis that allows the user to define the makeup of the multicoil reader, computer simulations that emulate the magnetic inductive coupling between two coils, libraries of mutual inductance as a function of relative position, and MATLAB scripts for active interpolation of the libraries to determine relative position from a electrical measurement.

Our concept for determining the position of an embedded sensor coil consists of a multicoil reader used to triangulate the location of an embedded coil. Most of our work, thus far, has focused on characterizing the magnetic coupling between two coils due to relative position both experimentally and in simulated space. From the characterization, we can calculate the expected change in electrical impedance of each coil due to an offset in relative position. The experimental characterization consisted of two coils, one fixed in space, and the other was capable of displacement in the, x, y, and z directions. We have yet to characterize pitch, roll, and yaw.

Due to the complexity of the experiment and simulation, we performed a limited analytical calculation

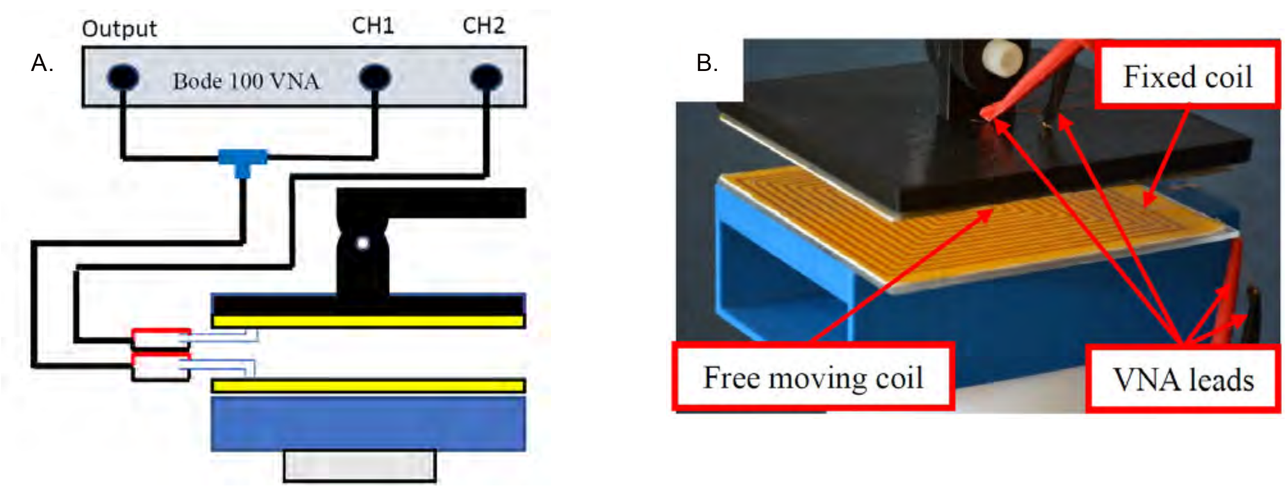


FIGURE 2. A) Experimental setup to find mutual inductance between two planar rectangular coils using the Bode 100 Vector Network Analyzer. B) Fixed coil mounted to black fixture and free moving coil mounted to blue fixture.

based on coil geometry and vertical separation, but the calculation did not account for the frequency of excitation. We obtained the analytical results for the mutual inductance between two rectangular planar coils by writing and implementing a MATLAB script. The analytical calculation defined the diameter of the first single turn rectangular coil as the overall diameter of the coil, and each successive concentric single-turn coil was equal to the following equation for a total of n coils: $dn = doverall - (w+s) * (n-1)$.

From this simplification, we were able to calculate the effect of the magnetic flux from the primary coil onto the secondary coil. We performed the analytical calculation for the same z-displacements as performed in the experiment.

ACCOMPLISHMENTS

We are grateful for the support that allowed us to leverage resources to accomplish the following tasks in Year 1:

1.) Simulated, with COMSOL, magnetic inductive coupling between two coils as a function of relative position to determine mutual inductance and electrical impedance.

2.) Designed and fabricated experimental process to measure mutual inductance as a function of known relative positions to validate computer simulation.

3.) Performed analytical calculation of mutual inductance as a function of vertical position and geometry to reaffirm the results of the experiment and computer simulations.

4.) Built libraries of mutual inductance as a function of relative position from simulated data.

As an overall assessment, we simulated the coupling between two coils, and we validated the simulation by building and testing an experimental setup to confirm our results.

SUMMARY

Confident in our experiment and simulation, we progressed to running experiments and simulations in all three offset directions. We developed a grid of offset displacements at which we ran our experiments and simulations. Due to the symmetry of the rectangular coils, we were able to interpolate the data from the $(+x) - (+y)$ to $(-x) - (-y)$, $(-x) - (+y)$, and $(+x) - (-y)$. From the completed experimental results and computer simulations for a vertical offset of 5 mm, we can compare the complete grid of mutual inductance values at that height. We completed computer simulations for every z-displacement for the x-y grid plane. We also performed experimental spot checking in the x-y grid planes for the remaining z-direction offsets to compare them to the simulation libraries and found the mutual inductance agreed within an acceptable error. This work is ongoing and has extended for another project year.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Patrick V. Hull

PARTNER: Rutgers University

FUNDING ORGANIZATION: Cooperative Agreement Notice

Advanced Microwave Precipitation Radiometer (AMPR)

OBJECTIVE: *To provide calibrated measurements of the Earth's atmospheric and surface characteristics from an airborne platform.*

PROJECT DESCRIPTION

The Advanced Microwave Precipitation Radiometer (AMPR) is an airborne, polarimetric, passive microwave radiometer producing brightness temperatures (T_B) at 10.7, 19.35, 37.1, and 85.5 GHz. These frequencies are sensitive to the emission and scattering of precipitation-size ice, liquid water, and water vapor. AMPR is thus able to provide information on surface and atmospheric parameters, including precipitation over ocean and land surfaces, cloud liquid water, and atmospheric water vapor over the ocean, ocean surface temperature, and near-surface wind speed, soil moisture, and sea ice. AMPR is a cross-track scanning radiometer, and its polarization basis varies as a function of scan angle. In order to retrieve geophysical information, the calibrated horizontally (H) and vertically (V) polarized microwave T_B values need to be determined. This is accomplished by deconvolution of polarization-variable measurements from two orthogonal channels per frequency.

During 2018, the instrument was prepped for a field campaign called Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP^{2}Ex). This work involved, among other things, the procurement of new multifrequency radomes to facilitate integration of the instrument on the NASA P-3, as well as completion of a new data system called Marshall Space Flight Center Instrument Data Architecture for Science–AMPR (MIDAS-AMPR). CAMP^{2}Ex was ultimately delayed to 2019 due to aircraft availability, but the AMPR radome and data system have been delivered and are undergoing continued testing and evaluation.

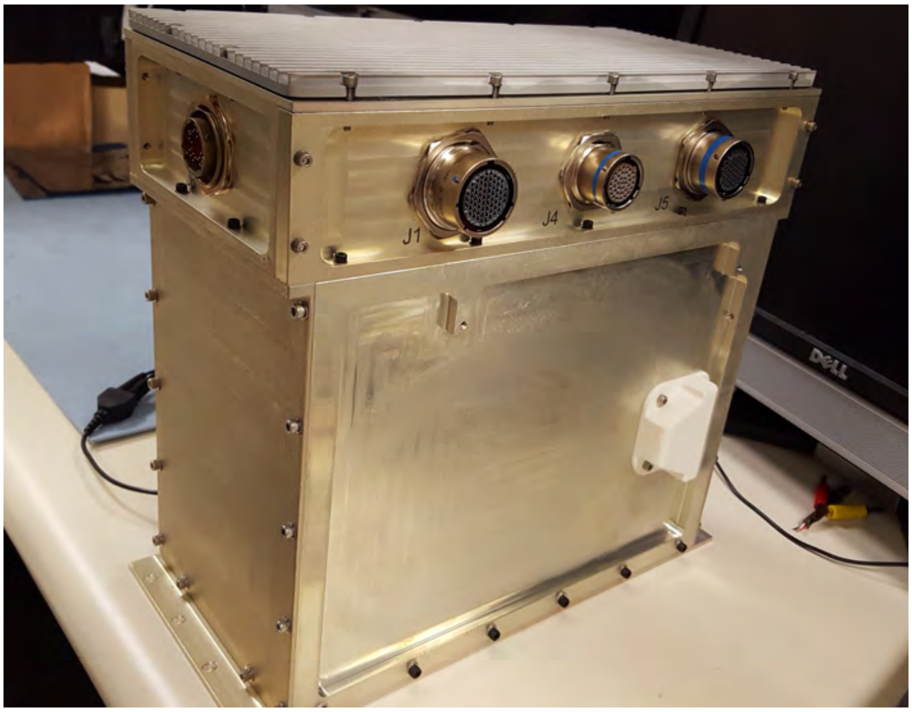


IMAGE CREDIT: TIMOTHY LANG, NASA MSFC.

FIGURE 1. MIDAS-AMPR data system on the lab bench. MIDAS-AMPR is designed to be nearly identical in size and receptacles to the old data system, allowing efficient swapping in the lab or field.

ACCOMPLISHMENTS

The purpose of the MIDAS-AMPR data system (fig. 1) is to reduce the obsolescence risk of the old data system, which consisted of components that were no longer available from the original manufacturers. This caused the old data system to be a potential single point of catastrophic failure while in the field. MIDAS-AMPR was built to be modular and to use modern components, enabling efficient swapping either in the lab or field in case of failures. While reproducing the basic functionality of the old data system, MIDAS-AMPR also provides useful new features that will benefit AMPR deployments. One of the most notable of these new features is a modern Field Programmable Gate Array (FPGA) board that accepts scriptable instrument scanning changes, rather than requiring complicated manual on-board reprogramming to change antenna motor commands. This will enable the use of different scanning

IMAGE CREDIT: COREY AMIOT, UNIVERSITY OF ALABAMA IN HUNTSVILLE.

FIGURE 2. AMPR sky test using the new radome. The instrument is rotated 180° to point skyward, and the wood mounting holds the radome above it at a distance equal to that experienced in the NASA P-3 bomb bay mounting. Sky tests enable calculation of the transmission coefficients for each channel/frequency.

approaches in the field, such as a nadir-only stare mode rather than cross-track scanning. Such scanning flexibility will benefit intercomparison with active microwave sensors such as radars, and allow for novel active-passive retrievals of cloud properties, a key science priority for CAMP^{2}Ex in 2019.

During 2018, ProSensing constructed two new multi-frequency composite radomes for AMPR. A radome is required for integration on the NASA P-3, and the previous radome that supported AMPR's flights during ORACLES (observations of aerosols above clouds and their interactions) in 2016 was borrowed from another technology project, thus not optimized for AMPR's frequencies. One of the new radomes is flat, while the other features a modest curvature that in theory will better match AMPR's cross-track scanning beam as it is rotated by the instrument's splash plate. Both radomes account for the lateral displacement of AMPR's 10.7-GHz feedhorn from the separate feedhorn serving the higher-frequency channels.

The new radomes are built from Rexolite, which was demonstrated in the vendor's lab to optimize signal transmission at all four of AMPR's microwave frequencies. The vendor also performed successful pressure-load tests of the new radomes under direction from the P-3 flight safety engineering team. Supplementary load analysis was performed by MSFC.

The final step is to perform sky tests of the instrument with the new radomes (fig. 2). These sky tests will allow the determination of physical transmission coefficients for developing radome-corrected science data. Initial tests were completed in Summer 2018, with additional tests planned for fall. The new radomes and MIDAS-AMPR will be available for use during CAMP^{2}Ex in 2019.

SUMMARY

In 2018, the AMPR data system was upgraded and a new radome was procured. These improvements will benefit future deployments of the instrument, reducing risk and improving data quality. This will greatly improve AMPR's science impact in current and future field campaigns.

PRINCIPAL INVESTIGATOR: Timothy J. Lang

PARTNERS: University of Alabama in Huntsville, Universities Space Research Association, Aerospace Corporation, ProSensing

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://weather.msfc.nasa.gov/ampr/

Cloud Migration of Global Hydrology Resource Center

OBJECTIVE: *To leverage and utilize commercial cloud infrastructure for the Earth Science Data and Information System by moving existing data, systems, and operations to new infrastructure without disrupting existing day-to-day operations.*

PROJECT DESCRIPTION

Sensors on today's Earth-observing satellites, aircraft, and ground-based platforms produce enormous amount of data. Archiving, processing, and distributing the data from networks of these sensors is a huge challenge. To meet this challenge, NASA established several Distributed Active Archive Centers (DAACs) that provide data services for heterogeneous Earth science data to scientists and other users worldwide. The Global Hydrology Resource Center (GHRC) is one of 12 such DAACs. GHRC's mission is to provide a comprehensive active archive of both data and knowledge augmentation services with a focus on hazardous weather, its governing dynamical and physical processes, and associated applications. GHRC, which is managed by the NASA's Marshall Space Flight Center, is a member of national and international data organizations including NASA's Earth Science Data and Information System (ESDIS), the Federation of Earth Science Information Partners (ESIP), and the International Council for Science (ICSU) World Data System (WDS).

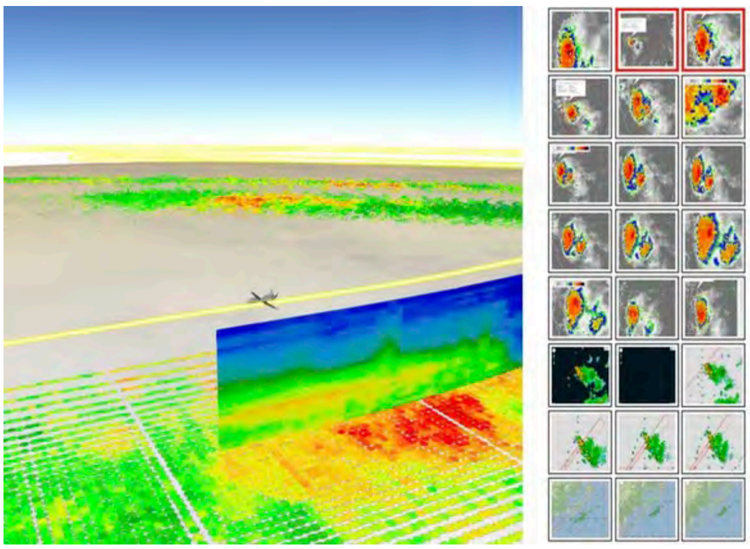


FIGURE 1. Field Campaign Explorer, an example knowledge augmentation tool, that helps user navigate field campaign datasets at GHRC.

One of the key strategic goals of ESDIS is to leverage and utilize commercial cloud infrastructure for the Earth Science Data and Information System. This entails moving existing DAACs with their data, systems, and operations to new infrastructure without disrupting their existing day-to-day operations. Migrating to the cloud will collocate computations and data to enable new science and application of large-scale analytics. Collocation of computations with data will also create opportunities for innovation around the new services DAACs will be able to provide. In addition, the use of a common infrastructure with vendor-provided services will reduce redundant tools/services, enable sharing, and enforce the use of community standards as well as uniform policies and processes. Migration of DAACs to the cloud will bring to bear economies of scale that will improve efficiencies and enable consistent performance for services. The current ESDIS architecture will not be cost effective as the annual ingest rate increases from 4 to 50 PB/year due to upcoming large missions. It will become increasingly difficult and expensive to maintain and improve our current system as data volumes and research demands continue to increase exponentially. Thus, ESDIS is developing Cumulus, a reusable open-source cloud native framework, for data ingest, archive, and processing (fig. 2). GHRC plays a major role in Cumulus effort by providing DAAC requirements, building prototypes, integrating on premise tools, and serving as the first DAAC to deploy the framework and migrate existing and future operations to the commercial cloud.

ACCOMPLISHMENTS

This year, GHRC successfully deployed its own instance of Cumulus framework in the NASA-approved Amazon Web Services (AWS) resources. The deployment allowed GHRC to use the Cumulus framework to publish several datasets to the cloud including the data observed from Lightning Imaging Sensor (LIS) onboard International

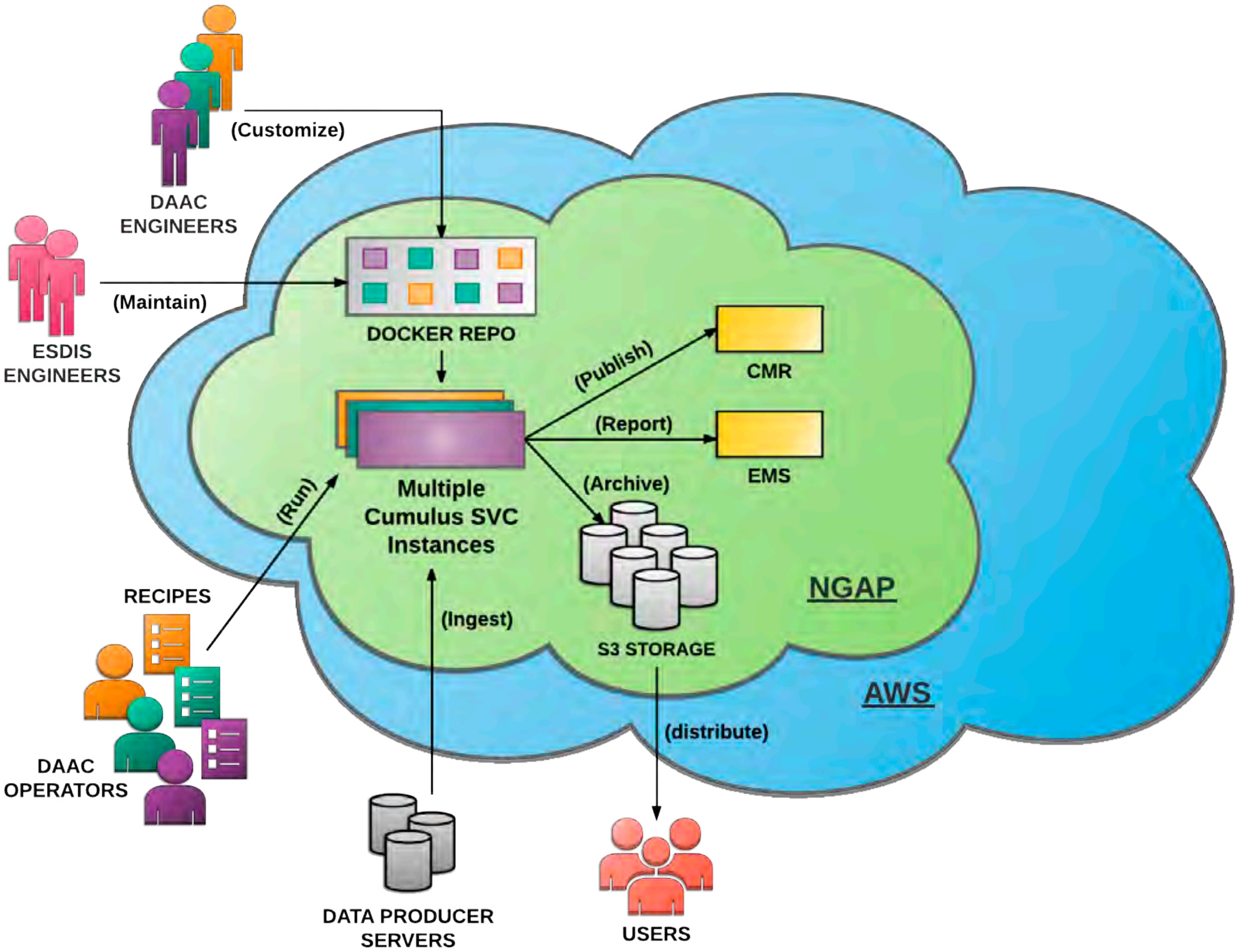


FIGURE 2. Cumulus: Cloud-based data ingest, archive, distribution and management system.

Space Station. GHRC also started integrating several on premise data publication tools with Cumulus to streamline the publication process. In the meantime, the GHRC researchers have explored reusing Cumulus for other knowledge augmenting services for GHRC datasets.

SUMMARY

Cloud offers benefits like the ability to analyze data at scale, analyze multiple datasets together easily and avoid expensive data movement allowing scientists to focus on science. In a cloud-based system, researchers have the ability to work with data directly in the cloud and only have to download the finished, derived product. The GHRC cloud migration demonstrates a first successful transition of an operational DAAC to the cloud to showcase improvements in GHRC's overall efficiency and productivity as a result of the migration.

PROJECT MANAGER: Manil Maskey

FUNDING ORGANIZATION: Science Mission Directorate

Deep Learning-Based Tropical Cyclone Intensity Estimation Portal

OBJECTIVE: *To build a real-time interactive production portal for objective estimation of tropical cyclone intensity using deep learning.*

PROJECT DESCRIPTION

Severe impacts of tropical cyclones are well documented. The main factor that contributes to the resulting death toll or damage amount is associated with the wind speed. Damage models also approximate the threat using a power of wind speed. Thus, accurately estimating a tropical cyclone's intensity (defined as the maximum sustained surface wind speed) is essential for disaster preparedness and response.

Most researchers and forecasters currently rely on the satellite image-based technique developed in the 1970s for estimating tropical cyclone intensity. These techniques utilize infrared temperatures from satellite and employ human visual inspection of image features such as the curvature of the cloud field. There are known limitations to Dvorak-based techniques—namely, the subjectivity of humans in identifying the features. Two well-trained analysts using this technique can derive different intensity estimates.

There is clearly a vital need to develop automated, objective, accurate tropical cyclone intensity estimation tool from satellite data. We use 'deep learning' to address this need by developing an automated and objective tropical cyclone intensity estimation model. Deep learning, the current state of the art in machine learning and pattern recognition, is a multilayer neural network consisting of several layers of simple computational units. It learns discriminative features without relying on a human expert to identify which features are important. We deployed the model in production to automate the intensity estimation in an event of storm. The estimations are displayed with proper context in a map-based interface. We have requested experts to evaluate the portal and the estimation during the 2018 hurricane season. At the end of the season, we will address experts' feedback and improve the system.

ACCOMPLISHMENTS

We have developed a system that, in real time, monitors tropical storm watches, triggers collection of relevant satellite images, estimates storm intensity, and displays the results in a map interface. We worked closely with the NASA Marshall Space Flight Center

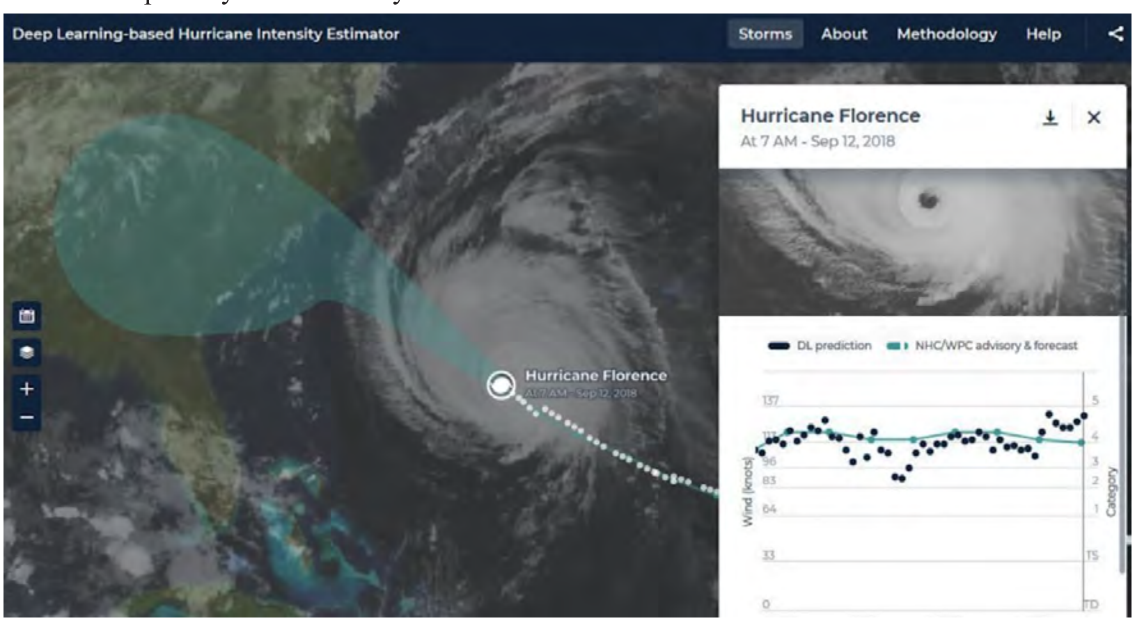


FIGURE 1. Deep learning-based tropical cyclone intensity estimation portal interface. The example shows real-time estimation for hurricane Florence (in the information card) along with advisory from National Hurricane Center.

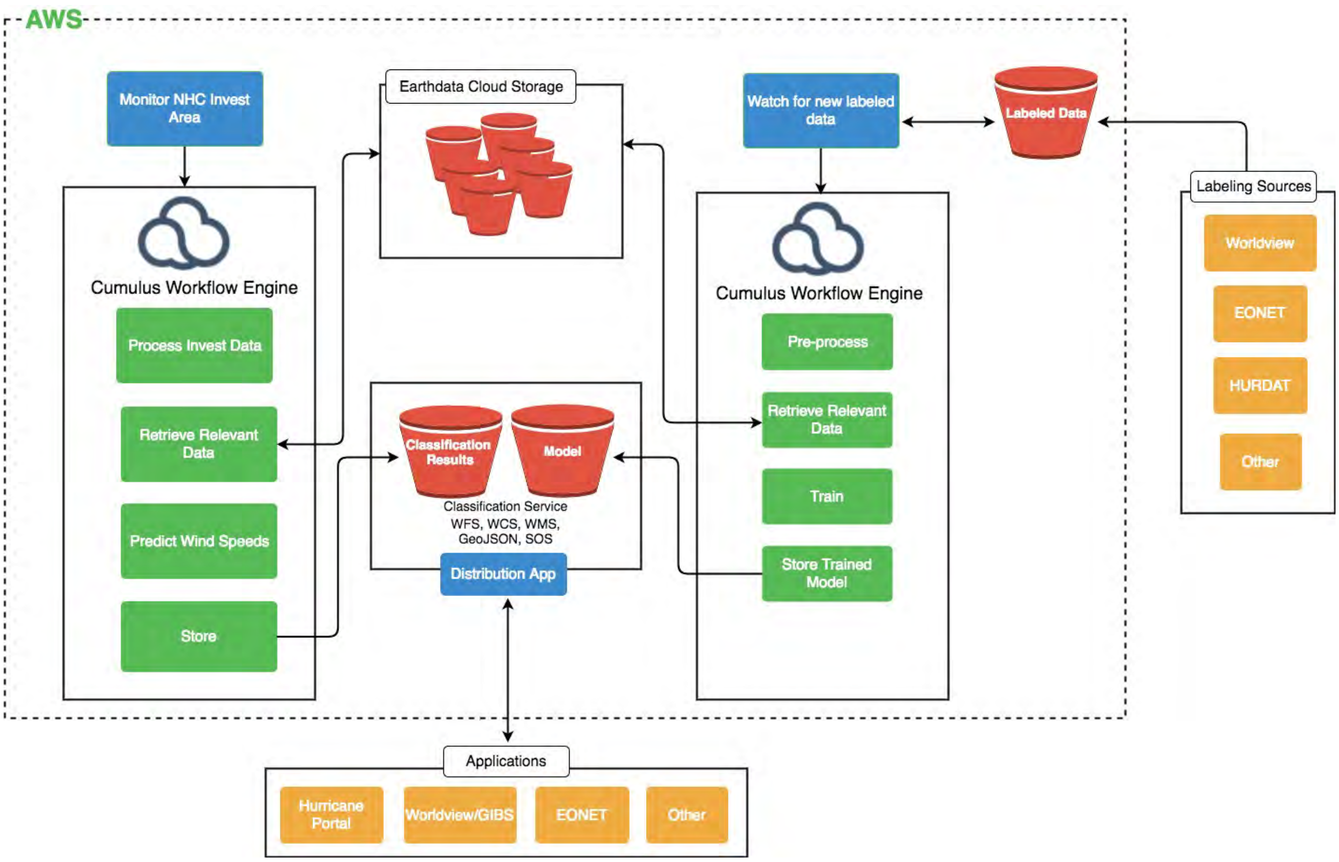


FIGURE 2. Cloud-based system architecture for deep learning-based tropical cyclone intensity estimation portal.

hurricane science experts for domain expertise and evaluation. Furthermore, we also collaborated with the NASA Short-term Prediction Research and Transition (SPoRT) Center to collect production requirements and engage the end user community. The system is trained using a custom convolutional neural network (CNN) on more than 100,000 images and matching wind speed information collected from various data sources. The output of the estimation is presented in a portal along with additional supplementary information. Figure 1 shows the portal interface being used during Hurricane Florence. Our method is completely objective and automated, and it has achieved higher accuracy than existing methods. Our system utilizes the NASA Cumulus cloud-based workflow framework running on Amazon Web Services (AWS), allowing the real-time workflow to be fully automated. The system includes a standard application programming interface (API) allowing external tools to utilize the estimation. The architecture of the system is illustrated in figure 2.

This is the first project that utilizes deep learning for objectively estimating tropical cyclone intensity. At the beginning of 2017, a prototype system was developed. The prototype demonstrated higher level of accuracy when compared to the literature, affirming the potential and paving the way for full system development. A case study for Hurricane Earl is shown in figure 2. Working towards an end-to-end system to forecast tropical cyclone intensity, the project has utilized NASA's Cumulus to listen to storm watches and forecast intensity information more frequently than currently being done. Furthermore, a design of a hurricane portal and web services are underway for end users and applications to interface.

SUMMARY

We have created and trained a custom deep CNN to objectively estimate tropical cyclone intensity with better accuracy. The estimations are generated every 15 min compared to the normal estimation interval of 3 to 6 hr. A cloud-based system that includes an interactive situational awareness portal provides a cost effective production environment for end users.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Manil Maskey

FUNDING ORGANIZATION: Science Mission Directorate

Interagency Implementation and Advanced Concepts Team

OBJECTIVE: *To enable cross-community collaboration by enhancing the entire scientific data lifecycle, including processes, policies, engineering and information communication.*

PROJECT DESCRIPTION

Since the launch of the TIROS-1 weather satellite in 1960, the availability of Earth observation and satellite remote sensing data has expanded significantly. The increased availability of Earth observation data has bolstered Earth science research and has provided new data for decision making and other societal applications. As the owner of the single largest open access repository of heterogeneous Earth observation data, NASA is committed to investing the effort and resources needed to ensure these data remain and will continue to remain available to all users. While NASA's data archives have traditionally been highly successful in upholding this commitment to the scientific research community, NASA recognizes that new strategies are needed in order to continue to meet the needs of the research community and to encourage the use of Earth observation data by a broader user base. First, there is a need to adapt to the rapid improvements in technology that are changing the way data is managed, distributed, and archived. Second, there is an ongoing need to improve the discovery, access, and use of NASA's Earth observation data beyond the scientific research community.

The Interagency Implementation and Advanced Concepts Team (IMPACT) addresses these needs by focusing on: (1) building partnerships with other Federal agencies, the applications community, decision makers, NGOs and other organizations to encourage the adoption of NASA's Earth observation data into their workflows and operational models; (2) enhancing NASA's existing data infrastructure, tools and services to encourage broader use of NASA's data for all users; and (3) enabling technology and innovation in order to lower the barriers to entry associated with using complex Earth observation data.

IMPACT supports the Earth Science Data Systems (ESDS) program mission in three areas with multiple projects supporting these areas. These are the three areas are described in detail:

1.) Manage interagency implementation: IMPACT serves as the ESDS program's designated point of contact (PoC) to other government agencies. IMPACT's PoC responsibilities include serving as a link between external agency interactions and NASA's Earth science data and by also supporting the Satellite Needs Working Group (SNWG). IMPACT supports the biennial surveys of participating agencies conducted by SNWG to assess their needs for U.S. government Earth observing satellite applications. IMPACT also designs and implements a systematic plan to assist other agencies in incorporating NASA Earth observation data into their workflows. One of projects in this area improves the discoverability of NASA Earth science data and other curated Earth observation data in trusted catalogs and platforms.

2.) Assessment and evaluation expertise: IMPACT provides the informatics, data systems, and domain science expertise needed to assess specific elements of the Earth Science Data and Information System (ESDIS) project and its existing processes. Assessments and evaluations are also informed, in part, by the IMPACT project's role as the primary data system PoC with other government agencies. IMPACT has several projects that support this task including one project that focuses on improving the discoverability, accessibility and usability of NASA's Earth science data holdings by ensuring all NASA collection and granule level metadata records in NASA's Common Metadata Repository (CMR) meet a minimum standard of quality and a second project that develops best practices for airborne data management and provides a knowledge base for airborne campaigns, data centers, managers, scientists and users.

3.) Develop advanced concepts: IMPACT provides strategic, technical, and management expertise

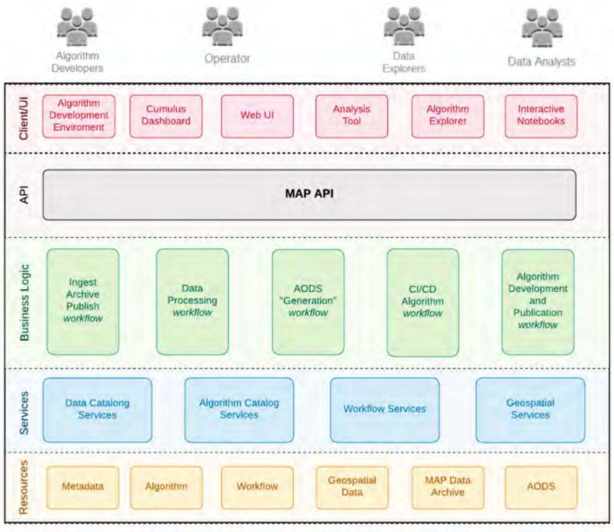


FIGURE 1. Notional Architecture for MAAP.

for rapid prototyping, development and testing of advanced concepts to further the evolution of the Data and Information System for Earth Observations by increasing the usage of data and the efficiency of operations. One of the projects in this area is the Multi-Mission Algorithm and Analysis Platform (MAAP). The MAAP is being jointly developed by NASA and ESA in order to establish a collaboration framework to share data, science algorithms, and compute resources for the purpose of fostering and accelerating scientific research. IMPACT is leading the data curation effort and the data systems component development for this project. See figure 1.

ACCOMPLISHMENTS

IMPACT published a paper titled "Recommendations to Improve Downloads of Large Earth Observation Data," in Data Science Journal on January 24, 2018. This paper provides guidelines to enable all cloud vendors (e.g., Amazon, Google, and Microsoft) to utilize a common methodology for bulk download of data from data centers, thus allowing the data providers to avoid the expense and complications of building custom capabilities to meet the needs of individual vendors.

IMPACT organized a workshop held in Annapolis, Maryland, to discuss the state of the art and accompanying challenges of performing analytics on NASA's Earth Observation data in the cloud. Over 3 days, presentations were given on machine learning, analytics algorithms and tools, analytics systems and architecture, and data systems architecture. Each of these presentations were followed by extensive discussions. A workshop report with findings and recommendations was delivered to NASA headquarters at the end of March.

A metadata review tool was developed by IMPACT and is being used by the Analysis and Review of CMR (ARC) team to review NASA EOSDIS collection and granule-level metadata in the CMR for correctness, completeness, and consistency in order to improve data discovery and accessibility. The tool was open sourced and made publicly available on NASA's GitHub.

SUMMARY

The value of Earth observation data will continue to increase as users leverage Earth observation data for novel new applications and as technology continues to offer innovative solutions for conducting research across large data volumes. Making these data and the accompanying technological solutions available to a broad range of users is a key goal for NASA. IMPACT helps NASA achieve this goal by monitoring trends in both the user community and the technology space to help develop effective data utilization solutions. IMPACT's cross-community collaborations, interagency partnerships, and technological expertise strategically places IMPACT at the center of research, applications, informatics, and data science.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Rahul Ramachandran

FUNDING ORGANIZATION: Earth Sciences Data Systems Program

High-Reliability Heliophysics Camera Design Assessments

OBJECTIVE: *To determine the feasibility of utilizing a successful heliophysics sounding rocket commercial-off-the-shelf design in satellite-based missions.*

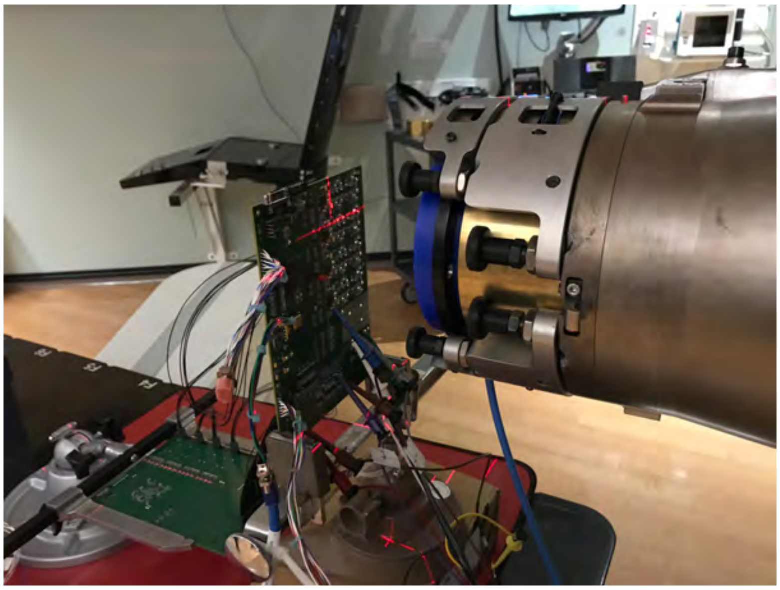
PROJECT DESCRIPTION

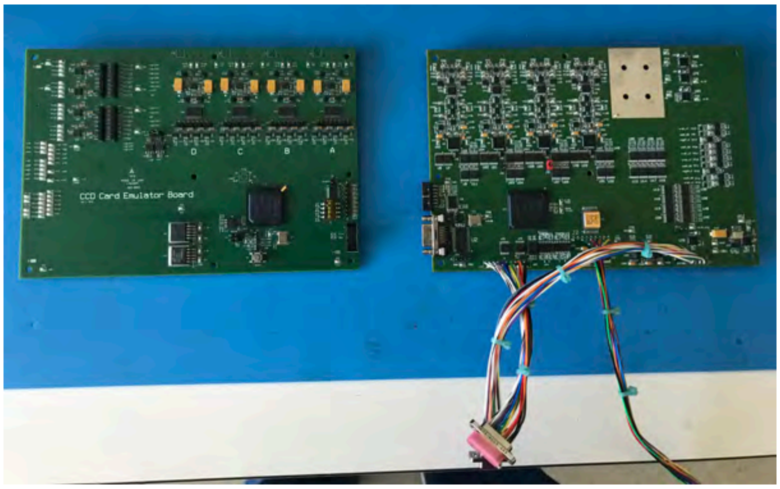
Current camera designs used on sounding rocket experiments make use of Grade 4 (low reliability) components to meet the required low-noise and high-speed parameters. In order to advance heliophysics instruments by supporting satellite-based missions with a minimum of 2-year durations, a reliable radiation tolerant instrument is required. This assessment encompasses the task of identifying possible alternatives and/or tests that would provide confidence in adapting it for use in an International Space Station environment.

The process for this effort is divided into two phases: parts research and parts testing. The initial phase assesses existing COTS components against the low earth orbit (LEO) environment. The first step is to determine if any radiation data exists on the current parts and if that data was sufficient for our environment. If sufficient data is not available, the next step is to identify possible rad-tolerant alternatives. If no alternatives are found, a second phase that includes radiation testing is needed to validate the existing COTs design. This step includes the assembly of supporting hardware, identification of possible test facilities, research into the type of testing needed and development of test plans.

ACCOMPLISHMENTS

The initial phase determined that alternatives exist for the digital section of the camera design; however, no radiation data existed on the critical analog path components, and no reasonable rad tolerant options were available due to the low noise and high-speed parameters. The analog section also has heritage on multiple sounding rocket missions, so a change of a single component would nullify this aspect. As a result, work began immediately on radiation testing options for the analog section. The primary challenge included assembling a procedure and test plan that would allow the hardware to be irradiated while providing a known image, and being able to monitor vital statistics real time that would provide insight into camera performance. For the testing configuration, the project decided to utilize existing sounding rocket analog-to-digital converter board (ADC) hardware, combined with a custom charge-coupled device (CCD) four-tap emulator that would need to be designed,





assembled, and tested at Marshall Space Flight Center (MSFC). VHSIC Hardware Description Language (VHDL) logic would also need to be developed for the emulator field programmer gate array (FPGA) that would serve as the controller for the board.

High-energy proton radiation testing was selected, as it provides insight into total dose effects, single-event upset characterization, and screens for parts with unacceptable low single-event latch-up tolerance. The Northwestern Medicine Chicago Proton Center was selected as the location for these tests. The sounding rocket ADC board, CCD emulator, and supporting hardware were assembled in a radiation chamber at the proton center with the monitoring station approximately 100 ft away. Fifteen different zones on the board that consisted of multiple integrated circuits (ICs) were irradiated with a various proton flux intensities and sizes to determine susceptibility to single-event effects (SEE) and total ionizing dose. Currents were monitored, images observed, and histograms examined in real time to evaluate the performance of these ICs in the proton environment. No SEEs were observed during approximately 10 hr of testing; however, it cannot definitively be ascertained that no upsets occurred. It can be deduced that if single-event upsets occurred, it did not result in a latch-up condition. It must also be noted that the functionality of the camera was verified during this test, not the low noise performance.

SUMMARY

Since no SEEs were observed in the analog section of the sounding rocket ADC, the assumption can be made that the multiple ICs tested are able to function successfully in the ISS environment. The results of this testing have provided the Coronal Spectrographic Imager in the Extreme Ultraviolet (COSIE) project confidence to move forward with the plan to utilize the existing sounding rocket COTS analog solution in the development of a TRL 6 low-noise camera.

A more detailed analysis of the accumulated data will be performed in the immediate future to provide estimates of TID of each analog section. This should provide even further confidence in the analog section performance.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Bryan Robertson, David Hyde

FUNDING ORGANIZATION: Center Strategic Development Steering Group

Predictive Thermal Control Technology for Stable Telescopes

OBJECTIVE: *To mature active thermal control technology to enable ultra-stable ultraviolet, optical, infrared space telescopes.*

PROJECT DESCRIPTION

Exoplanet science via coronagraphy requires ultrastable telescopes for multiple hour exposures. Predictive thermal control study (PTCS) matures technology to enable active thermally controlled ultra-stable telescopes required to make ultra-high contrast observations of exoplanets.

PTCS has three objectives: (1) validate models that predict thermal optical performance of real mirrors and structure based on their structural designs and constituent material properties, i.e., coefficient of thermal expansion (CTE) distribution, thermal conductivity, thermal mass, etc.; (2) derive thermal system stability specifications from wavefront stability requirements; and (3) demonstrate ability of a predictive thermal control thermal system to actively/predictively stabilize a mirror system's thermal environment.

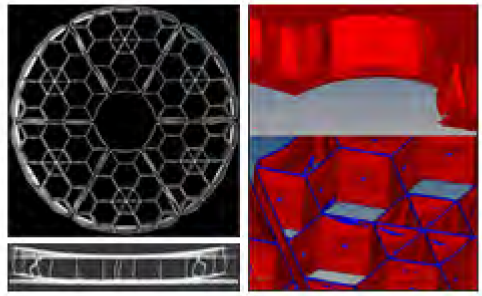


FIGURE 1. X-ray CT data converted into mechanical model.

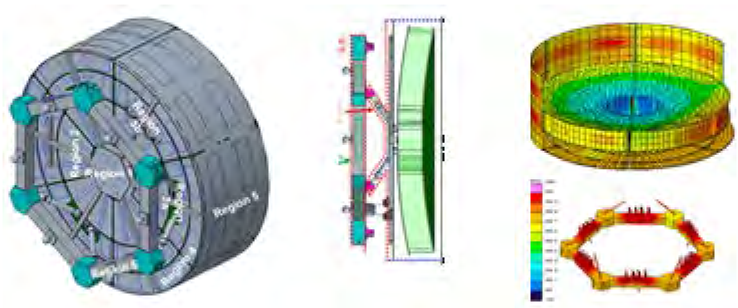


FIGURE 2. Thermal Control System with 26 zone control for AMTD-2 1.5-m ULE© mirror.

ACCOMPLISHMENTS

PTCS successfully progressed its objectives by accomplishing three of its five milestones: (1) created high-fidelity 'stop' model 0.5-m ULE® Advanced Mirror Technology Development (AMTD)-2 mirror, including 3D CTE distribution and reflective coating, that predicts its optical performance response to steady-state and dynamic thermal gradients. Structural model was created using 3D x-ray computed tomography (fig. 1), (2) derived specifications for thermal control system as a function of wavefront stability for a Vector Vortex Coronagraph, (3) designed and started fabricating thermal control system for AMTD-2 1.5m ULE mirror that senses temperature changes and actively controls mirror's thermal environment (fig. 2). Finally, PTCS results were presented in four papers at 2018 SPIE Conferences.

SUMMARY

PTCS is developing and demonstrating physics based active thermal control to enable ultra-stable telescopes required to make ultra-high contrast observations of exoplanets via coronagraphy.

PRINCIPAL INVESTIGATOR: H. Philip Stahl

CO-INVESTIGATOR: Thomas Brooks

PROJECT MANAGER: Michael Effinger

FUNDING ORGANIZATION: Science Mission Directorate

Carbon Nanotube Composite Sensor Using Advanced Manufacturing

OBJECTIVE: *To develop a wireless structural health monitoring sensor.*

PROJECT DESCRIPTION

The purpose of this project was to develop a carbon nanotube based composite wireless structural health monitoring sensor which could be use on spacecraft and aircraft structures for life of that structure. The material was developed to be piezoelectric in order to respond to strains in the material to which is attached.

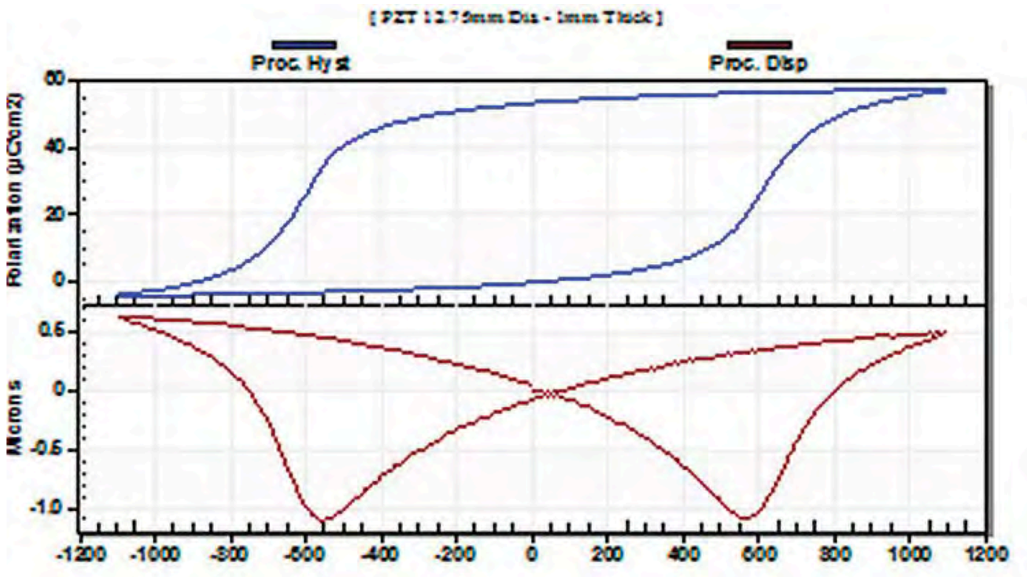


FIGURE 2. Piezoelectric Response Curves.

At the present time, strain sensors used on structures require external wires to a computer in order to measure strain. Also these strain sensors are quite brittle. Another type of strain sensor is a fiber optic with Fiber Bragg gratings etched into the material. Again, this limits the sensor to initial proof testing of the structural article. Thus, a material was developed which was piezoelectric and flexible and could be monitored wirelessly. We were able using a mixture of carbon nanotubes, polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE) polymer and lead zirconium titanate nanopowders to produce a 3D printable ink. This ink was then printed into strain sensors and the piezoelectric properties measured. The material showed excellent piezoelectric response and is flexible. A preliminary antenna design for the wireless transmission was also developed. We have a Technology Investment Plan (TIP) funded in which we will continue to fine-tune the piezoelectric properties through processing and 3D print an antenna on the sensor. We will finally test the system response by attaching the sensor to a composite bend specimen and measure the piezoelectric response as a function of bending stress.

FIGURE 1. Sensor with gold electrodes.

ACCOMPLISHMENTS

During this Center Innovation Fund (CIF) project, we successfully came up with the chemistry to successfully 3D print a structural health monitoring sensor. We successfully tested the piezoelectric properties and saw high piezoelectric response for this material. We also successfully designed a wireless antenna which can be 3D printed on the sensor.

SUMMARY

In summary, we have successfully 3D printed a composite system made up of carbon nanotubes, PVDF-TrFE polymer and lead zirconium titanate nanopowders. This system was shown through testing to have excellent piezoelectric properties. We have also successfully designed a wireless antenna which can be 3D printed on the sensor material.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Dennis S. Tucker, Curtis W. Hill

FUNDING ORGANIZATION: Center Innovation Fund

Piezoelectric Strainmeter for the Seismic Investigation of Planets

OBJECTIVE: *To develop of a seismometer instrument concept for planetary exploration.*

PROJECT DESCRIPTION

Seismology is a field uniquely suited to addressing both exploration and science goals. It can be used not only to ascertain the physical attributes of a planetary body's interior (which are relevant to its formation and evolution), but also to gauge the amount, magnitude, and distribution of seismicity that may present significant risk to future surface activities.

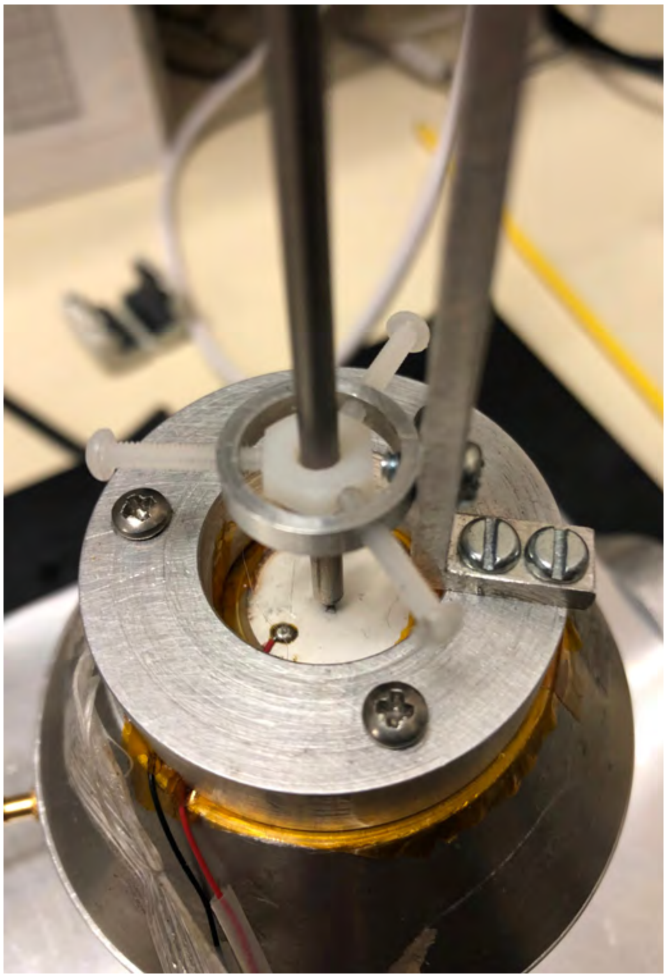


FIGURE 1. Piezo sensor mounted in test assembly.

The planetary seismology community has spent the last 20 years heavily advancing the development of very-broadband (VBB) seismic instruments. VBB instruments maximize scientific return in instances where only small numbers of instruments are able to be deployed, such as for the upcoming InSight mission to Mars. However, they are much heavier and more technologically complex than the instrumentation that is typically used in terrestrial field surveys. Consequently, new development efforts are exploring alternative technologies, including microelectromechanical systems, fluid seismometers, optomechanical geophones, and strainmeters.

This project sought to leverage existing NASA Marshall Space Flight Center (MSFC) capabilities in the development of a piezoelectric seismometer instrument concept for planetary exploration (fig. 1). The primary outcome of this work is a proof-of-concept demonstration that piezoelectric strainmeters are adaptable to seismic frequencies. The secondary outcome of this effort is the development of MSFC personnel such that their effectiveness to both current and planned future projects and missions is maximized (field deployment training).

Piezoelectric strain sensors are designed for measuring low strains characteristic of metal and composite-based structures. A typical sensor consists of a piezoelectric crystal oscillator similar to those employed in AM radios. The crystals are cut precisely to vibrate at a resonant frequency. When mechanical strain is applied, the resonant frequency of the crystal shifts. This electromechanical behavior can be monitored electronically in response to simulated or real seismic shaking. We obtained commercial electronic crystal oscillators and developed the procedures to disassemble them, mount them, apply mechanical strain, and monitor their electrical response. We also obtained a standard commercial optomechanical geophone and digital seismograph/data logger, and learned to operate, install, and downlink data in a real field deployment.

Piezoelectric technology is not currently considered mainstream in terrestrial seismology. However, it may port well to planetary implementations where small size, low power, robustness, and high sensitivity are

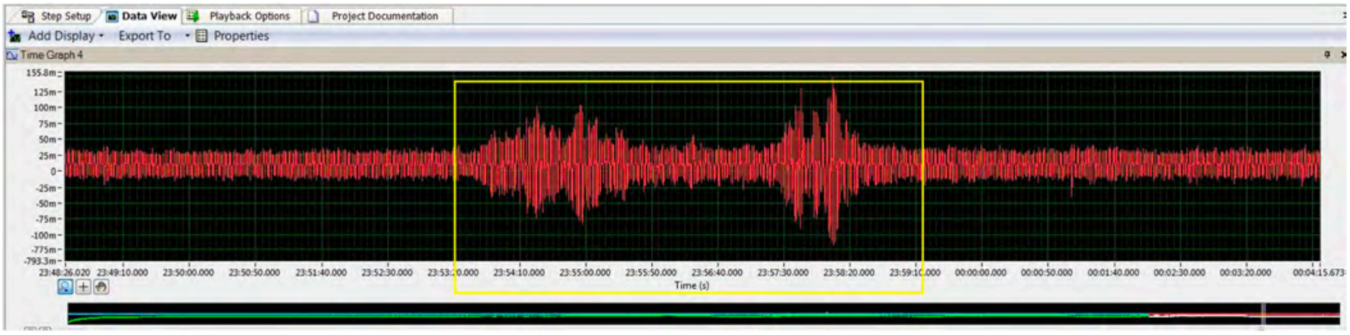


FIGURE 2. Seismogram of a large earthquake in Mexico as recorded by the prototype sensor in the basement of the NSSTC, Huntsville AL.

desirable. Commercial lunar landers in the immediate future will favor small, robust payloads that do not require the sophisticated operation procedures and deployment mechanisms currently required by state-of-the-art planetary seismometers. Logical next steps for this concept will be to field test the prototype in several different deployment configurations, especially including lander-integrated designs.

ACCOMPLISHMENTS

The project made the accomplished the following:

- developed test procedure.
- designed and built shake table adapter for sensor characterization.
- demonstrated detection of seismic signals with sensor prototype (fig. 2).
- learned to deploy commercial sensor in the field and gathered 1 month of continuous data in the Mars Yard at JPL (fig. 3).

FIGURE 3. Commercial sensor (left) and field set-up (right). The seismometer is buried under the rock in the foreground.

SUMMARY

Initiation of a seismometer development project at MSFC has enhanced competitiveness of both existing and planned efforts and has also positioned MSFC to be responsive to future mission Announcements of Opportunity. We are now providing scientific expertise to three different instrument development teams focused on the Moon and Europa. Knowledge gained through these competitive openings will be leveraged for future development of the piezoelectric concept with the ultimate goal of contributing to the next lunar geophysical network.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Renee Weber

FUNDING ORGANIZATION: Center Innovation Fund

The Chandra X-ray Observatory

OBJECTIVE: *To make fundamental scientific discoveries and contribute to our understanding of the universe.*

PROJECT DESCRIPTION

The Chandra X-Ray Observatory, one of NASA's Great Observatories, was launched on July 23, 1999. Its unique ability to provide high resolution, subarcsec x-ray images and high-resolution spectra have established it as one of the most versatile and powerful tools for astrophysical research in the 21st century. Chandra explores the hot, x-ray-emitting regions of the universe, observing sources with fluxes spanning more than 10 orders of magnitude, from the x-ray brightest, Sco X-1, to the faintest sources in the Chandra Deep Field surveys. Thanks to its continuing operational life, the Chandra mission also provides a long observing baseline which is opening new research opportunities. Chandra observations have contributed to all areas of astronomy and astrophysics, including but not limited to deepening our understanding of the coevolution of supermassive blackholes and galaxies, the details of blackhole accretion, the nature of dark energy and dark matter, the details of supernovae and their progenitors, the interiors of neutron stars, the evolution of massive stars, and the high-energy environment of protoplanetary nebulae, and even the interaction of an exoplanets with their stars.

The key to Chandra's success is the great advance in angular resolution. The mirrors produce images with half-power-diameter ≈0.5 arcsec for x-ray energies in the range $0.08<E<10$ keV. This angular resolution represents a 10-fold improvement over the two previous best x-ray telescopes, the US-led Einstein X-Ray Observatory (1978-1981) and the German-led Röntgensatellit (ROSAT, 1990–1999). The 10-m focal length high-resolution mirror assembly (HRMA) consists of four nested pairs (paraboloid-hyperboloid), grazing-incidence, glass-ceramic mirrors coated with iridium to enhance their reflectivity at x-ray wavelengths. The Observatory's highly eccentric orbit makes possible continuous observations of up to ≈185 ks with an observing efficiency ranging from 65% to 75%. The efficiency is limited primarily by the need to protect the instruments from particles, especially protons, during Chandra's passages through Earth's radiation belts.

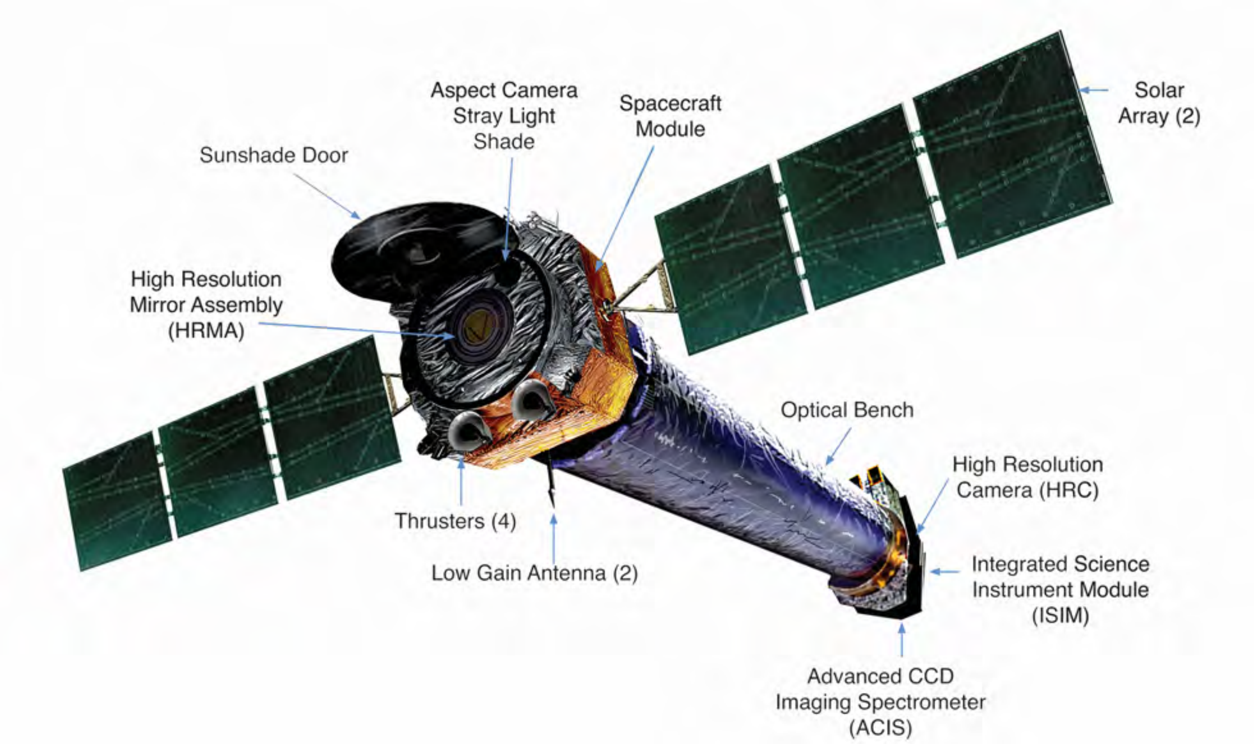


IMAGE CREDIT: JAMES VAUGHAN/CXC

FIGURE 1. Chandra X-ray Observatory showing major elements.

ILLUSTRATION: NASA/CXC/M.WEISS

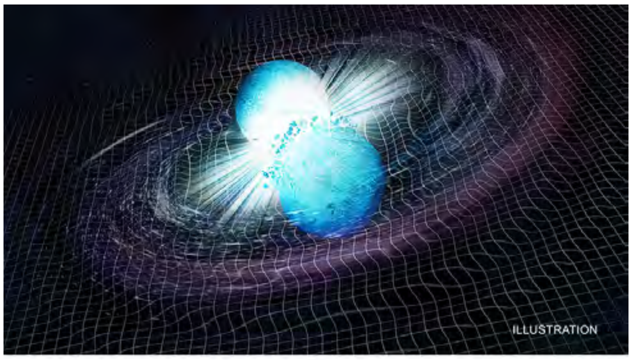


FIGURE 2: Artisit's conception of the merger of two neutron starts. Credit: NASA/CXC/ Trinity University/D. Pooley et al.

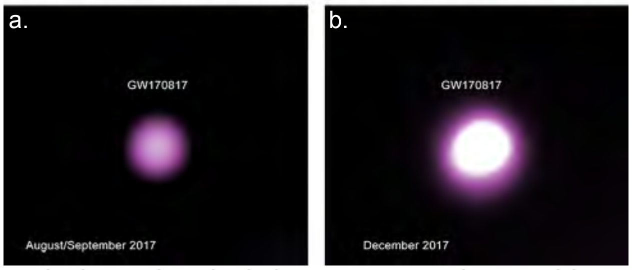


IMAGE CREDITS: NASA/CXC/TRINITY UNIVERSITY/D. POOLEY ET AL.

FIGURE 3. Chandra images of the increasing flux of x-rays from the vicinity of the black hole created in the merger: (a) August/September 2017 and (b) December 2017.

The observatory (fig. 1) consists of three principal elements: (1) the telescope comprised of the HRMA, two x-ray transmission gratings that can be inserted into the x-ray path, and a 10-m-long optical bench; (2) a spacecraft module that provides electrical power, communications, and attitude control; and (3) a Science Instrument Module that holds two focal-plane cameras, the advanced charged-coupled device (CCD) imaging spectrometer (ACIS) and the high-resolution camera (HRC), and mechanisms to adjust the camera's position and focus. The observatory is 13.8 m in length, has a mass of 4,800 kg, and the furthest ends of its solar panels are 19 m apart.

ACCOMPLISHMENTS

The project team accomplished the following in fiscal year 2018:

- celebrated its 19th anniversary of successful operation on July 23, 2018, even though it was designed for a 3-year mission with a goal of only 5 years.
- received 527 proposals this year from 25 countries requesting a factor of 5× more observing time than was available.
- continued an almost steady rate of ≈480 publications in referee journals per year.
- released 22 press and image releases.
- extended contract including options for operations until 2030.
- completed development and release of an upgraded observation request viewer, which reduced scheduling efforts by about 20 hr per week.

Note that Ricardo Giacconi (father of x-ray Astronomy and original proposer of Chandra) won the Nobel prize (2004).

SUMMARY

Chandra, aging gracefully, continues to operate successfully and provide the unique capabilities of the best angular resolution of any x-ray observatory, image-resolved spectroscopy, and a well-calibrated, long-lived facility for tracking the evolution of many astronomical systems on time scales now reaching the second decade.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Martin C. Weisskopf, Project Scientist

PARTNER: Chandra X-ray Center, Cambridge Massachusetts

FUNDING ORGANIZATION: Science Mission Directorate

The Imaging X-Ray Polarimetry Explorer (IXPE)

OBJECTIVE: *To measure the x-ray polarization of a wide variety of x-ray sources.*

PROJECT DESCRIPTION

The Imaging X-ray Explorer (IXPE) will be the next in the line of NASA's Small Explorer Missions. Selected in 2017 January, IXPE is planned to be launched into an equatorial orbit in April 2021. IXPE will study the x-ray polarization properties of dozens of sources per year, representing several source categories: active galactic nuclei (AGN); microquasars; radio pulsars and pulsar wind nebulae (PWNe); supernova remnants (SNR); magnetars; and accreting x-ray pulsars. Besides obtaining spectropolarimetry at moderate (proportional-counter) energy resolution, IXPE will conduct phase-resolved polarimetry of bright (isolated and accreting) pulsars, as well as imaging x-ray polarimetry of the brightest extended sources (e.g., PWNe and SNR). Figure 1 shows IXPE after deployment with major systems identified.

IXPE is the first-ever imaging X-ray Polarimeter. It relies on unique position- and polarization-sensitive detectors provided by our international partners in Italy. Coupled with these detectors, MSFC-built X-ray optics complete the critical elements of the scientific payload. Figure 2 is a schematic of the detector illustrating the principle of operation.

The detector is a position-sensitive proportional counter that is capable of imaging the entire track of the charge produced by the incident x-ray photo-ionizing the detector gas. The initial direction of the photoelectron is along the electric vector of the incident photon.

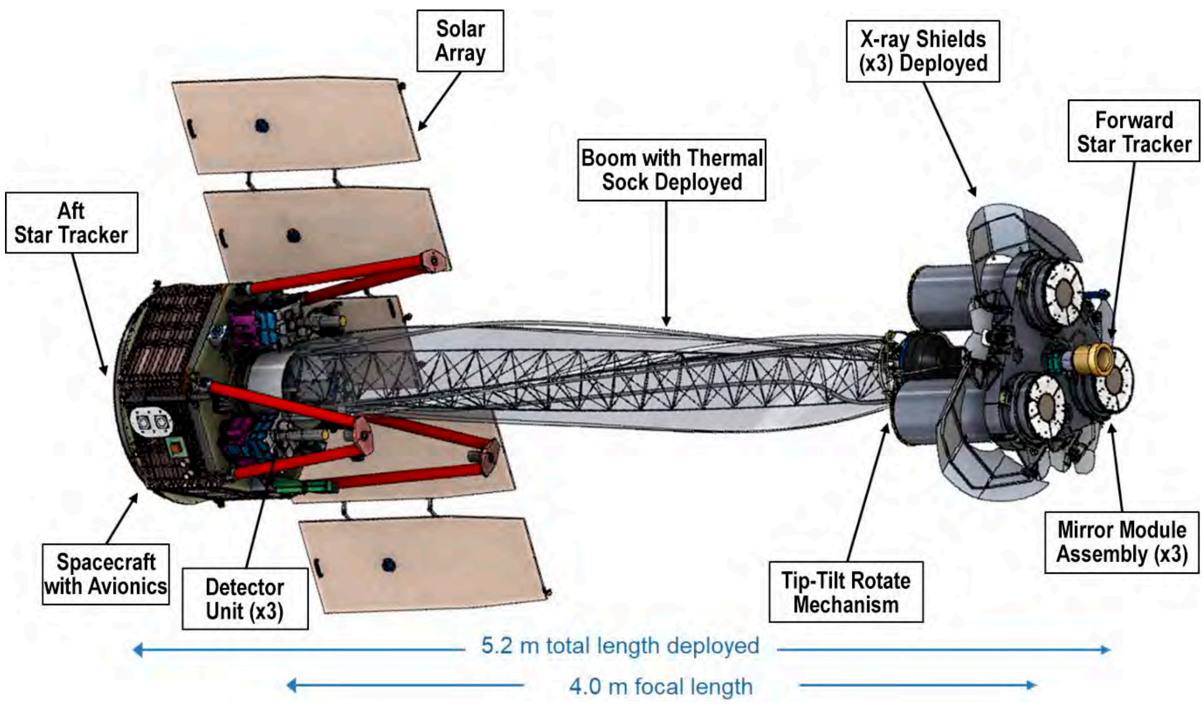


FIGURE 1. IXPE deployed.

ACCOMPLISHMENTS

- Held and passed five major requirements reviews: Instrument PDR, Spacecraft PDR, Payload PDR,

Instrument CDR & Mission PDR.

- Maturing major ICDs: Instrument to Spacecraft; Thermal Shields to Mirror Module Assembly (MMA); MMA to Mirror Module Support Structure; Mission Operations Center (MOC) to Malindi Ground station; Spacecraft to Malindi.
- Completed the third spacecraft design iteration.
- Completed boom demonstration testing with thermal sock and wire harnesses in place.
- With Spacecraft Simulator, confirmed data and electrical interfaces with the Instrument Data Services Unit breadboard in Italy.
- Completed assembly of the Engineering Unit of the MMA.
- Instrument/Gas Pixel Detector stability tests are on-going with good performance.
- Completed environmental tests of the Instrument/Filter Calibration Wheel Qualification Model.
- Accomplished the first delivery of flight-like hardware: MMA thermal shields from Japan.
- National Telecommunication and Information Administration Stage 2 has been approved.
- IXPE Project Service Level Agreement has been signed.
- IXPE Radio Frequency Interface Control Document for the Near Earth Network & Space Network has been baselined.
- MOC Preliminary Design Audit completed.

BENEFITS

IXPE is progressing as planned. Later this year there will be KDP-C which is the confirmation to allow IXPE to enter into phase C/D.

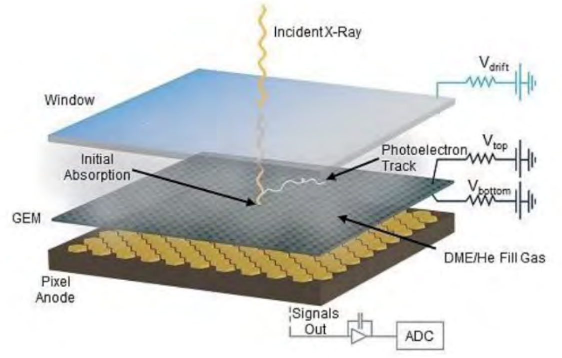


FIGURE 2. Schematic of the detector illustrating the principle of operation.

PRINCIPAL INVESTIGATOR: Martin C. Weisskopf

PARTNERSHIPS: THE ITALIAN SPACE AGENCY, Istituto di Astrofisica e Planetologia Spaziali/Istituto Nazionale di Astrofisica, Istituto Nazionale Fisica Nucleare, Ball Aerospace, Massachusetts Institute of Technology, Stanford University, University of Nagoya, Japan

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://ixpe.msfc.nasa.gov/

Fermi Gamma-Ray Burst Monitor (GBM)

OBJECTIVE: *To detect and characterize gamma-ray bursts.*

PROJECT DESCRIPTION

The *Fermi* gamma-ray burst monitor (GBM) is the secondary instrument on the *Fermi* satellite launched in 2008. *Fermi* GBM's primary objective is to detect and characterize gamma-ray bursts (GRBs) and other high-energy emissions from any point on the visible sky (excluding Earth blockage) over a broad energy range (8 keV–40 MeV). *Fermi* GBM was originally designed to extend the energy range of GRBs detected with the *Fermi* Large Area Telescope (LAT) to connect it to past observations. When GBM sees a GRB, the flight software triggers, sending a notice to the ground within several seconds. All events observed by GBM detectors are telemetered to the ground. This event-by-event data is searched for gamma-ray counterparts to gravitational wave events using algorithms developed in collaboration with the Laser Interferometer Gravitational Wave Observatory (LIGO) team. *Fermi* GBM is working closely with the LIGO/Virgo teams to find new counterparts to gravitational wave events.

ACCOMPLISHMENTS

On August 17, 2017, at 7:41 a.m. Central Daylight Time, *Fermi* GBM triggered on a short GRB that lasted about 2 s. This burst looked ordinary in the GBM data but was extraordinary in that it occurred 1.7 s after the first LIGO/Virgo detection of gravitational waves from a merger of two neutron stars. In fact, the automatic notice from *Fermi* GBM alerted the LIGO/Virgo team to take a closer look at their data because there was a large noise peak in one of their interferometers, so their automated searches did not immediately report the event. The probability of these two events occurring within 1.7 s of one another and in the same part of the sky by chance is 1 part in 20,000,000. Therefore, they are associated with one another. This association confirms that mergers of two neutron stars produce short GRBs. This particular GRB is unusual because it is the closest known, only 130,000,000 light years away, and that means it is 1,000 times fainter than the next faintest GRB with a known distance. This means that this GRB is likely viewed off-axis.[1] Using the time difference between the arrival of the gravitational waves and the GRB reveals that the speed of gravity is the same as the speed of light within one part in one quadrillion. The gravitational wave and GRB observations were followed by observations of this event across the entire electromagnetic spectrum, including gamma-rays, x-rays, ultraviolet, visible, infrared, and radio wavelengths. In 2018, the *Fermi* GBM team found another burst in archival data that closely resembled the characteristics of GRB 170817A, a short spike at higher energies with a longer tail at lower energies. This burst, called GRB 150101B, is also one of the closest GRBs detected, but is much shorter in duration and much brighter than GRB 170817A, suggesting that it is viewed more on-axis.[1] Gravitational waves were not observed from GRB 150101B because LIGO/Virgo was not operating in January 2015. *Fermi* GBM is the most prolific detector of GRBs, especially short GRBs, those lasting less than 2 s and that are associated with compact object mergers. This event is the dawn of a new era in astrophysics. When LIGO/Virgo resumes operations in early 2019, *Fermi* GBM will be looking for counterparts to new gravitational wave detections, using improved software to enhance its sensitivity to these events.

SUMMARY

Fermi GBM has become an important instrument for detecting counterparts to gravitational waves. In 2017, *Fermi* GBM was the first instrument to detect and localize a gamma-ray burst associated with gravitational waves. Looking back at earlier data, the team found a similar event, another likely example of a gravitational wave counterpart. The *Fermi* GBM team is improving their software to detect more of these events in the future.

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1. Goldstein, A.; Veres, P.; Burns, E.; et al.: "An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: *Fermi*-GBM Detection of GRB 170817A," *Astrophys. J. Lett.*, Vol. 848, No. 2, 14 pp., October 2017.

2. Abbott, B.P.; Abbott, R.; Abbott, T.D.; et al.: "Multi-messenger Observations of a Binary Neutron Star Merger," *Astrophys. J. Lett.*, Vol. 848, No. 2, October 2018

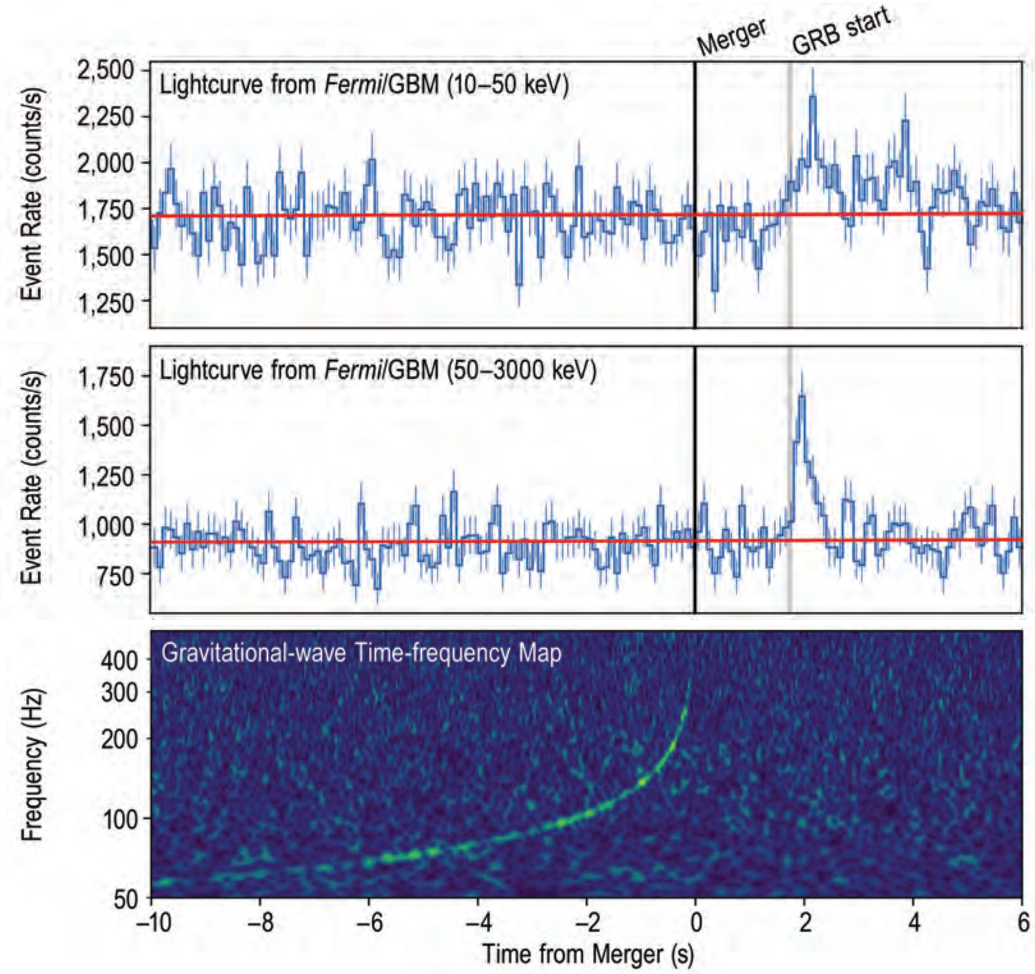


FIGURE 1. Joint Multimessenger detection of GW170817/GRB 170817A. Top panel: Fermi GBM light curve (intensity vs time) at lower energies (10–50 keV). Center panel: *Fermi* GBM light curve in the triggering energy range (50–300 keV). Bottom panel: The time-frequency map of GW170817 was obtained by coherently combining LIGO-Hanford and LIGO- Livingston.[2]

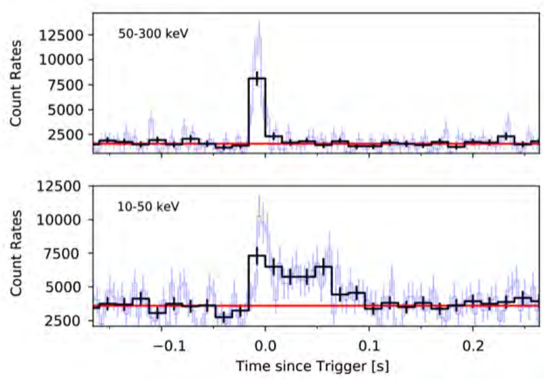


FIGURE 2. Fermi GBM Observations of GRB 150101B. Top panel: *Fermi* GBM light curve in the triggering energy range (50–300 keV). This band shows a short spike like GRB 170817A. (Bottom panel): Fermi GBM light curve at lower energies (10–50 keV). Like GRB 170817A, the emission in this band is longer in duration than at the higher energies.[3]

3. Burns, E.; Veres, P.; Connaughton, V.; et al.: "*Fermi* GBM Observations of GRB 150101B: A Second Nearby Event with a Short Hard Spike and a Soft Tail," *The Astrophysical Letters*, Vol. 863, No. 2, 9 pp., August 2018.

PRINCIPAL INVESTIGATOR: Colleen A. Wilson-Hodge

PARTNERSHIPS: University of Alabama in Huntsville, Universities Space Research Association, MPE, University of California-Davis, Bari, and NASA Goddard Space Flight Center

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://gammaray.msfc.nasa.gov/gbm/ and https://*fermi*.gsfc.nasa.gov

Strobe X

OBJECTIVE: *To probe the complex physical conditions and magnetic field of the Sun's chromosphere, while advancing the state of the art in ultraviolet spectropolarimetry.*

PROJECT DESCRIPTION

The Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (STROBE-X) is a probe class mission concept that will provide an unprecedented view of the X-ray sky, performing X-ray timing and spectroscopy over a broad energy band (0.2–30 keV) and wide range of timescales from microseconds to years. STROBE-X is made up of three instruments, two narrow field instruments and a wide-field monitor. The low-energy instrument (0.2–12 keV), the X-ray Concentrator Array (XRCA), is a follow-on to the Neutron star Interior Composition Explorer (NICER), currently onboard the International Space Station (Gendreau et al. 2016, Proc. SPIE 9905, 99051H, currently unavailable to the public), with 85–175 keV energy resolution and 100 ns time resolution and low background. The higher-energy instrument (2–30 keV) is an array of large area silicon drift detectors with a novel lightweight microchannel plate collimator, based on the European Large Observatory for X-ray Timing (LOFT) mission concept (ref. 1), with 300 eV energy resolution and 10 μs time resolution. The two pointed instruments are each an order of magnitude larger in effective area than their predecessors (NICER and the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array). The wide-field monitor (WFM), also based on LOFT, consists of coded mask cameras, sensitive to photons from 2–50 keV. This instrument acts as a trigger for the pointed instruments and provides high-duty cycle, high time-resolution, and good spectral resolution observations of the variable X-ray sky. The wide-field monitor is approximately 20 times the sensitivity of its predecessor, the RXTE All-Sky Monitor, enabling multi-wavelength and multimessenger investigations with a large instantaneous field of view. This mission concept was part of a NASA-funded study and will be submitted through NASA to the Astrophysics 2020 Decadal Survey for consideration. (Ray et al. 2018, SPIE, 10699, 1069919, unavailable to the public).

1. Feroci, M.; Stella, L.; van der Klis, M.; et al.: The Large Observatory for X-Ray Timing (LOFT), Experimental Astronomy, Vol. 34, No. 2, pp. 415–444, 2012.

ACCOMPLISHMENTS

In March 2017, STROBE-X was selected as one of NASA's Probe class mission studies. A science workshop was held in September 2017 to define the initial science requirements. Instrument and Mission Design Lab studies were performed at NASA GSFC in November 2017 and April 2018. The resulting design met all mission requirements, allowed for a 10° orbital inclination, used control moment gyros to achieve fast slew rates, employed TDRSS Ka band for high-rate data downlink, allowing event-by-event data for the brightest sources, with TDRSS S-band for autonomous burst and transient alerts, and achieved a mission cost of $<1B with a comfortable margin. The details of this concept was presented in June 2018 at the SPIE meeting in Austin, TX (Ray et al. 2018, SPIE, 10699, 1069919). The team is now finalizing the science case and the final report to NASA to be submitted in December 2018. NASA will submit the final reports to the Astrophysics 2020 Decadal Survey for consideration.

SUMMARY

The STROBE-X mission is defined by three key science drivers: (1) measuring the spin distribution of accreting black holes, (2) understanding the equation of state of dense matter, and (3) exploring the properties of the precursors and electromagnetic counterparts to gravitational wave sources. An exciting range of additional science is enabled by STROBE-X's capabilities including studies of the inner solar system to the high redshift universe.

PRINCIPAL INVESTIGATOR: Paul Ray, Naval Research Laboratory

AUTHORS: Colleen A. Wilson-Hodge

PARTNERSHIPS: NRL, U.S. Naval Research Laboratory, NASA Goddard Space Flight Center, Massachusetts Institute of Technology, Texas Tech University, University of Alabama in Huntsville

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://gammaray.nsstc.nasa.gov/Strobe-X/index.html

STROBE-X

IMAGE CREDIT: NASA/MIKE BAYSINGER ED04/ESSCA

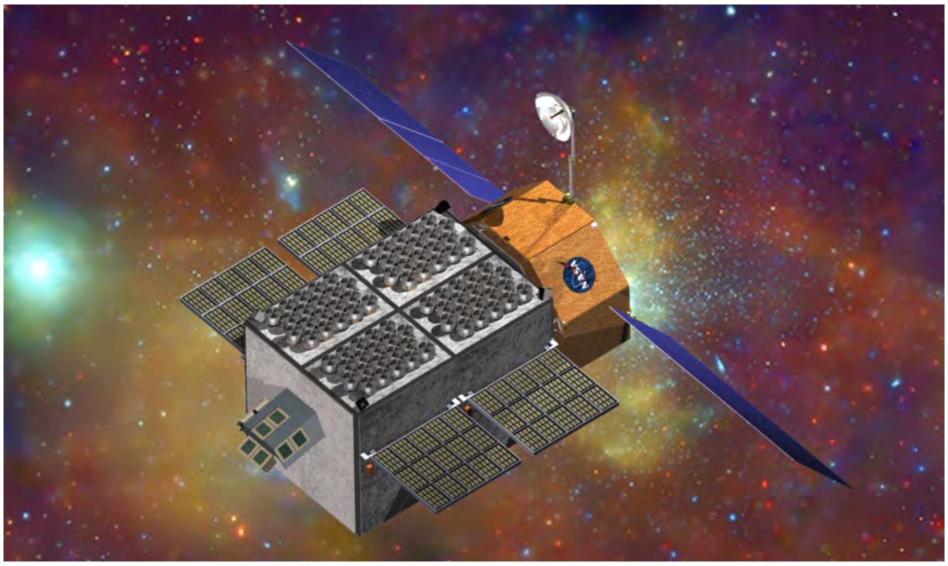


FIGURE 1. STROBE-X in space based on the design concept. STROBE-X will observe the X-ray sky with unprecedented effective areas of 2 and 5 m^2 with the XRCA and LAD, respectively.

FIGURE 2. STROBE-X comprises three instruments; the X-ray Concentrator Array (XRCA) consisting of 80 pairs of concentrating optics and detectors, divided into four quadrants; the Large Area Detector (LAD), consisting of 60 detector modules, with collimated silicon drift detectors in four panels; and the Wide Field Monitor (WFM) consisting of four pairs of coded mask cameras.

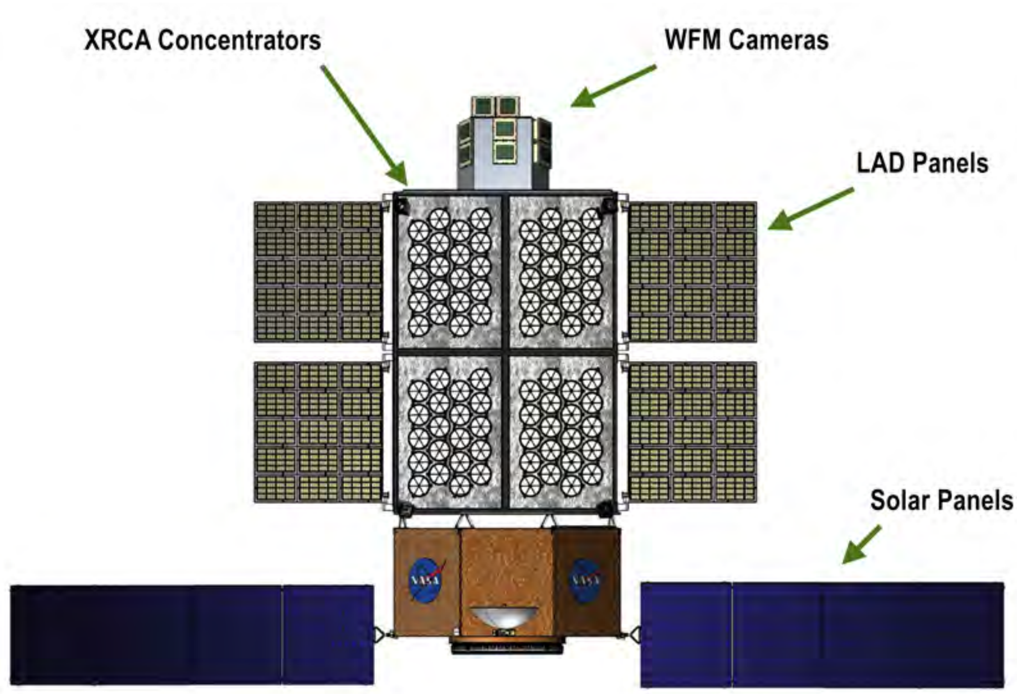


IMAGE CREDIT: NASA/MIKE BAYSINGER ED04/ESSCA

Transition of a MSFC Space Weather Product to the Operational Space Weather Community

OBJECTIVE: *To take a near real-time space weather product developed at NASA Marshall Space Flight Center and apply a unique research-to-operations paradigm as a 'proof-of-concept' approach to solving long-standing challenges of effectively transitioning experimental space weather products into operations.*

PROJECT DESCRIPTION

Space weather—including large flares and coronal mass ejections that accelerate energetic particles from the Sun and drive geomagnetic storms—have potentially wide-ranging impacts on society and its infrastructure. NASA operates satellites measuring solar output; however, successfully bridging the gap between derived products from these missions and operational forecasters has proven challenging. The goal of this project is to demonstrate that the unique research-to-operations/operations-to-research (R2O/O2R) paradigm developed for terrestrial weather applications by the Short-term Prediction Research and Transition (SPoRT) Center can be used to transition experimental space weather products to the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center SWPC, who is responsible for alerting the public to pending space weather events.

To demonstrate this proof of concept, output from the NASA Marshall Space Flight Center (MSFC)-developed Magnetic Forecasting (MAG4) model has been transitioned to Space Weather Prediction Center (SWPC). MAG4 is an all-clear space weather forecasting tool that provides probabilities that solar active regions will produce harmful space weather. MAG4 can run in near real-time, but the past generation of the product has been subject to periodic, lengthy downtime that has limited its utility as an operational forecasting tool. To make the product more suitable for operations, MAG4 has been integrated into the robust operational data processing stream at SPoRT and is now disseminated via a dynamic website developed in conjunction with the forecasters.

This effort complements work by other space weather applications groups, including the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center (GSFC), who perform model validation and engage with the space weather community to expose them to new tools available for transition. The work performed here demonstrates an approach to take products identified as mature and value-added and accelerate them into operations through integration into decision support tools, development of training, and assessment to improve experimental products. MSFC is engaged in an agency-level initiative called the Space Weather Science Applications Project (SnAP), which is pulling together all of NASA's space weather groups to develop a national strategy for responding to challenges with space weather R2O/O2R. Lessons learned will be used to inform the SnAP strategy. This work will also be extended to the Space Radiation Analysis Group at NASA Johnson Space Center, who makes decisions regarding space radiation hazards for astronauts.

ACCOMPLISHMENTS

The MAG4 code was successfully integrated into the SPoRT operational data processing stream through the development of real-time scripts that allow for automated execution of the software. The primary output of the MAG4 code is an annotated magnetogram, which is a pictorial representation of the spatial variations in strength of the solar magnetic field used by space weather forecasters to identify active regions (fig. 1). MAG4 objectively analyzes active regions and assigns the probability of producing a solar flare, representing an improvement over current operational forecasting techniques that use subjective analysis to determine flare probability. Through a series of teleconferences with SWPC forecasters, a collaboratively designed website was developed to present the real-time magnetograms. Tabular output of event rates and flare probabilities that match thresholds used by SWPC for addressing flare threat were automatically produced and presented—an innovation over previous attempts to present MAG4 on the web. MAG4 output was provided

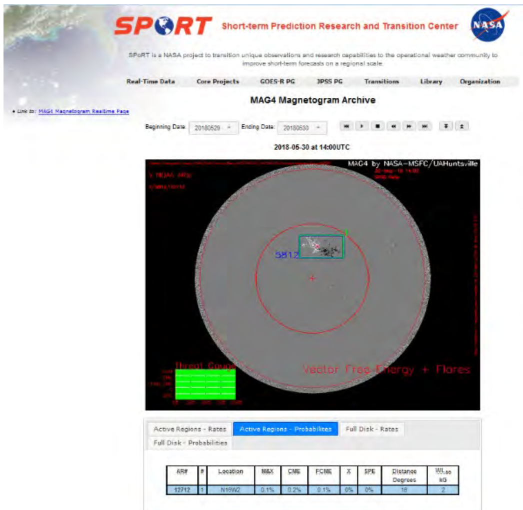


FIGURE 1. MAG4 decision support website.

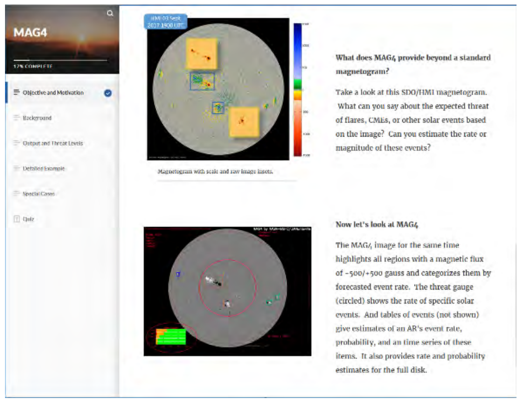


FIGURE 2. MAG4 user-focused training.

with hourly cadence on separate real-time (previous 48 hr) and archive (previous 28 days) websites allowing forecasters to loop the magnetograms and tabular probabilities to track the evolution of active regions. The real-time website can be viewed at <https://weather.msfc.nasa.gov/cgi-bin/sportPublishMAG4.pl?dataset=mag4realtime>. A key lesson learned is that codeveloping forecasting solutions with an end-user will increase the likelihood of use.

Another innovation in the space weather R2O/O2R community that was demonstrated through this effort was the development of targeted, end user-specific training using instructional design concepts (fig. 2). Previous training delivered on space weather products has used a presentation-style training approach, which describes what a product is but is limited in describing how a product is beneficial to the operational forecaster process. Using specialized training software, a web-based training module was developed describing both the details of MAG4 and ways that this product can complement other operational products. The training also included a tutorial on how to interpret the imagery and how to use the new website. The training website can be viewed at <https://rise.articulate.com/share/eYcOvSE4Ly3-AlqHCRHNJ7XleTr3QyYT#/?_k=xm-knkk>. A key lesson learned is that training users on how to use experimental products alongside current operational tools is key to having those users adopt an experimental product into operations.

SUMMARY

The SPoRT team has successfully demonstrated the R2O/O2R paradigm for application to space weather forecasting using the MSFC-developed MAG4 product. This was accomplished through integrating the software into a mature data processing infrastructure, developing a dynamic website, and producing training resources using instructional design concepts. The MAG4 product and SPoRT R2O/O2R paradigms have both advanced in readiness for use in space weather operations and lessons learned will help to shape a NASA strategy for space weather R2O.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Bradley Zavodsky

PARTNERS: National Oceanic and Atmospheric Administration Space Weather Prediction Center, University of Alabama in Huntsville, Jacobs Engineering Group

FUNDING ORGANIZATION: Technology Investment Program

ENTRY, DESCENT, AND LANDING

Lander Technologies

OBJECTIVE: *To target a sustainable return to the lunar surface through a combination of participation in and support of commercial lander development, technology development and risk reduction activities, and in-house lander design efforts.*

PROJECT DESCRIPTION

In 2018, the Lander Technologies program, under Advanced Exploration Systems (AES)/Human Exploration and Operations Mission Directorate (HEOMD), with support from the Science Mission Directorate (SMD) and the Space Technology Mission Directorate (STMD), conducted a wide range of lunar-lander-related development activities, including providing engineering design, analysis, and test support to companies participating in the Lunar Cargo Transportation and Landing by Soft Touchdown (CATALYST) initiative, designing a NASA-led pallet lander targeted toward delivery of mobile payloads to the lunar surface, early mission architecture studies for potential human missions back to Moon, and maturation of key technologies critical to these and future lander efforts.

FIGURE 1. Astrobotic Peregrine lander.

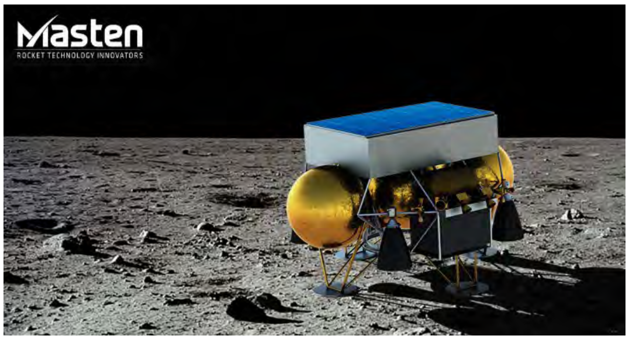


FIGURE 2. Masten Space Systems lander.

FIGURE 3. Moon Express lander.

A unique aspect of Lander Technologies is the relationship between the CATALYST companies and the NASA lander team. In this portion of the Lander Technologies portfolio, NASA works side by side with three small companies, Astrobotic, Masten Space Systems, Moon Express, (see figs. 1–3), performing critical activities to develop each company's lander design. These activities are tailored to each company's specific needs and NASA's interests. This year, for example, these tasks included the design, fabrication, and integration of the primary lander structure and propellant tanks for a lander test bed, core flight software development of Guidance Navigation and Control applications; advanced thruster and engine development; avionics design, fabrication, and test; and various discipline analyses and simulations efforts. It is important to point out that these activities are commercial partner-driven, which is a different role for NASA.

Another portion of the Lander Technologies portfolio is the development of in-house (internal NASA) lander designs. This includes early detailed design and analysis of a pallet lander for near-term robotic missions as well as mission architectural and conceptual design efforts targeted toward returning humans to the Moon. These efforts not only increase the design maturity of NASA's landers in anticipation of and preparation for upcoming science and exploration missions, but also strengthen the lander team capabilities, identify potential risks and technology gaps, and educate future NASA exploration planning. Targeted milestones for this year were requirements and early design reviews for the pallet lander shown in figure 4.

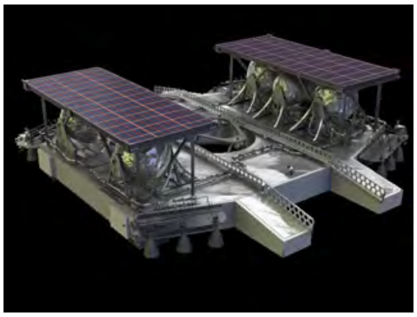


FIGURE 4. NASA's Lunar Pallet Lander.

As the name implies, a third and key portion of the Lander Technologies portfolio is the maturation of critical technologies to enable and enhance future lunar landers. This year, technology efforts have included the design and testing of advanced in-space and descent thrusters for both storable, bi-prop and cryogenic propellants; design and environmental testing of a Navigation Doppler Lidar to enable precision landing; thermal analysis and brassboard testing of a propellant liquification approach to enable future lunar and mars in situ propellant production; thermal testing of thin film solar cells for lunar application; and development and flight testing of advanced high heat rejection turn-down ratio thermal techniques for surviving the lunar night.

ACCOMPLISHMENTS

With a portfolio as broad as that described above, there were numerous accomplishments in 2018; too many to comprehensively list here. However, a few notable CATALYST items included completing the delta-PDR and initiating avionics testing for Astrobotic's Peregrine lander, completing the integration of structure and tanks for Masten's XL1T terrestrial test bed lander (fig. 5), along with development of Core flight software based GNC applications for multiple partners. For the pallet lander, the lander team completed an Internal Design Data Package report and review documenting the current design state and a variety of associated analyses and positioned the lander to be used on an upcoming SMD mission targeted for a 2022 launch. Technology development and risk reduction achievements included the following:

- a successful PDR for the Deep Space Engine (by Frontier Aerospace), a compact MMH/Mon25, pulsed thruster planned for use on the Astrobotic Peregrine and NASA's pallet lander;
- environmental testing of key components of the NDL;
- initiation of liquification brassboard testing;
- hot-fire testing of a lander class, cryogenic LOX/Methane engine, and completion of a thermal vacuum test; and
- an ISS test effort on advanced passive thermal control system designed for lunar night survival.

FIGURE 5. Integrated Structure and Propellant Tanks for Masten's XL1T terrestrial bed lander.

SUMMARY

2018 was a productive and exciting year for Lander Technologies that saw significant progress across the program's portfolio of lander development activities. Each CATALYST partner made strides on their landers; NASA's pallet lander design was refined and targeted for an upcoming science mission to lunar poles; several technologies took significant maturation steps; and Lander Technologies has evolved into a new program under formulation, currently called Advanced Cislunar Surface Capabilities within AES/HEOMD. This program will continue to support CATALYST companies and risk-reduction and technology activities and will also substantially increase activities toward a future sustained human lunar exploration and utilization campaign.

PROJECT MANAGERS: Greg Chavers

FUNDING ORGANIZATION: Advanced Exploration Systems

Simulation of Mars Lander Plume-Induced Cratering and Debris Transport

OBJECTIVE: *To advance the capability by simulating engine plume and regolith interaction to full scale production level for Large Robotic and Human Class Landers. This goal was met and exceeded during a Technology Investment Plan (TIP); subsequently, this TIP has attracted new business to simulate the upcoming landing of Mars InSight.*

PROJECT DESCRIPTION

Planned human-class and large robotic landers with propulsive engines of significantly more power than historical landers will lead to unprecedented regolith liberation and rock-and-regolith momentum transfer. This extreme plume-regolith interaction leads to several risks: formation of craters, which contributes to a tilted and hazardous landing platform, high-energy debris contamination that damages vehicles and other critical assets, and particulate clouds that hinder landing telemetry. The plume-induced craters will alter the degree and direction of reflected plume forces on the lander vehicle as it descends, thereby affecting Guidance, Navigation and Control authority. To address these risks, the MSFC Fluid Dynamics Branch predicts spacecraft plume induced surface crater formation and regolith particle debris transport towards the vehicle and surrounding assets. During a fiscal year (FY) 2018 Technology Investment Project (TIP), this prediction capability was matured: From a two-dimensional axisymmetric (2D-axi) single-engine lander and landing zone to a three-dimensional (3D), multi-engine lander on a full-scale landing zone (size on the order of football field).

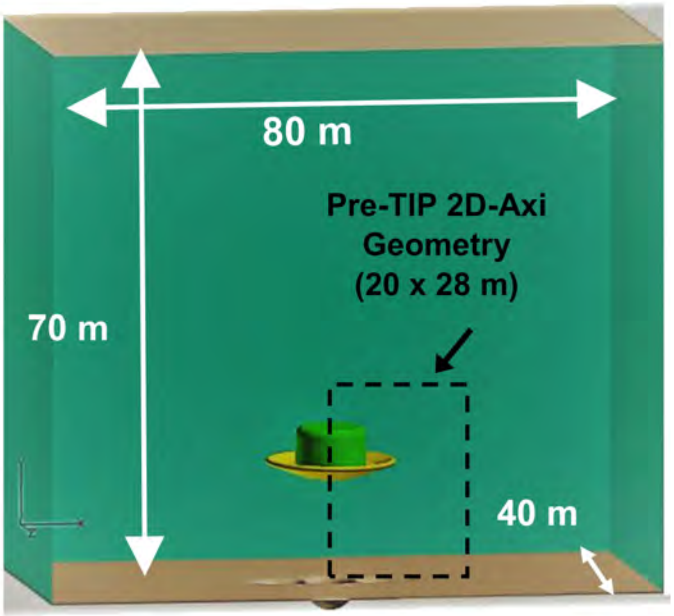


FIGURE 1. Pre-TIP 2D Axi-symmetric simulation geometry outline overlaying current 3D Simulation capability: 80 x 40 m, with a height of 70 m.

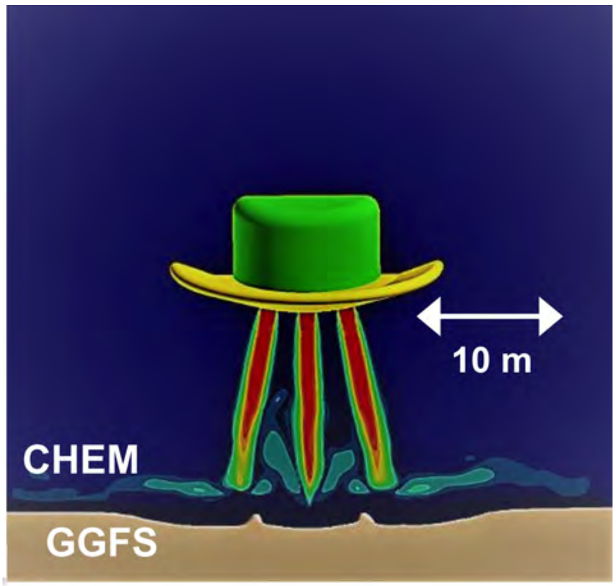


FIGURE 2. Engine Plumes from descending Lander impinge on regolith and create craters. CHEM and GGFS Domains indicated.

A major TIP Program objective of bringing in new MSFC business has already been accomplished. Most notably, the simulation framework enhanced during this TIP will be used to predict crater formation of Mars InSight, before it lands on the planned date of November 26, 2018. Post-landing simulations of the Mars InSight landing informed by camera landing data will also be conducted. These simulations are funded by the Science Mission Directorate (SMD) for Mars Insight Reconstruction. Furthermore, Entry, Descent, and Landing, (EDL) simulations that incorporate plume-surface interaction on Mars human landers and large robotic landers will be funded by the Mars Study Capability (MSC) Team.

The approach taken during this project was to enhance an integrated three-component simulation framework used to predict plume-regolith interaction; this phenomena leads to the risks of crater formation, debris transport, and cloud formation. The three components of the simulation framework are the Loci/CHEM computational fluid dynamics (CFD) tool, the gas-granular flow solver (GGFS), and the debris transport analysis (DTA) toolkit. CHEM simulates full 3D multi-plume effects and vehicle descent as it approaches the native regolith, capturing the physics of regolith debris lofted

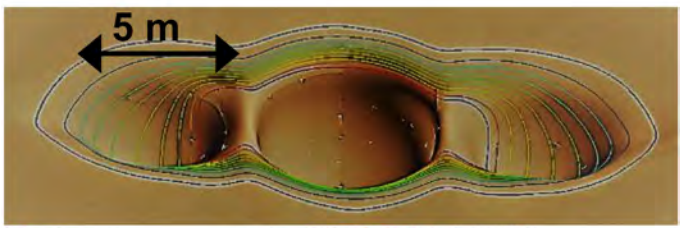


FIGURE 3. Magnified view of 5-m-diameter plume-induced craters, highlighted with pressure contour lines.

from the surface and accelerated to high velocities and high kinetic energy levels. CHEM also simulates time-dependent 6-degree-of-freedom (6DOF) vehicle motion. Engine thrust modulation through throttling and time-dependent gimbaling of engines are also innate features of CHEM. The GGFS multiphase flow computational tool implements a two-fluid model with fluid representation of the gas and granular phases to avoid the need to model billions of particle interactions. As with the gas phase, the granular phase is modeled as an Eulerian fluid with constituent physics closure models that capture the complex, nonlinear granular particle interaction effects. The computational solution is then post-processed in the NASA-developed DTA toolkit to determine the transport of debris particles originating from the regolith surface.

The main challenges were scale-up of geometric landing zone size and numerical stability of the solution algorithms. The innovations accomplished were to dramatically increase domain size and resolution and to successfully achieve numerical stability for high Mach number and high-temperature plume flow, thus bringing simulation capability to production-level readiness of realistic vehicle geometry and lander engine flow conditions. At the beginning of the TIP, 2D-axisymetric geometry with CFD grid size on the order of hundreds of thousands of computation cells was feasible. Mach number was limited to approximately 3.0. The CHEM-GGFS-DTA framework can now simulate 3D, realistic geometry and realistic plume flow conditions (Mach > 6.0) on NASA Ames Super-Computers, with CFD grid size on the order of tens of millions of computation cells. The amount of scale-up achieved far exceeded what was considered feasible at the beginning of the project.

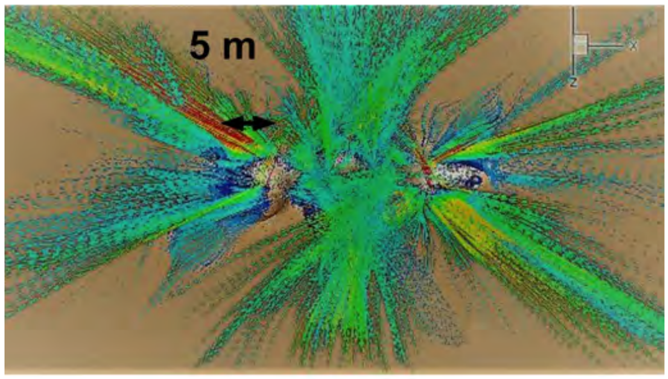


FIGURE 4. Particle paths colored by velocity. The plume and induced particle trajectories are modified by the craters, in both magnitude and direction.

Via a currently-funded Small Business Technology Transfer (STTR) contract, the next step is to increase the parallel processing efficiency of the GGFS tool. In addition, a separate and unique FY 2019 funded TIP will increase the functionality of GGFS by giving it the capability to model multi-size, multi-shape regolith particles, beyond its current capability for a single-size spherical particle.

ACCOMPLISHMENTS

Several technical hurdles were overcome during this TIP, contributing to meeting the high-priority TIP Program objective of attracting new business: Mars InSight and MSC EDL. Specific accomplishments include:

1.) development of a density-based projection method algorithm for the GGFS Eulerian-Eulerian tool, for added numerical stability,

2.) improvements in GGFS Energy equation formulation, also for stability,

3.) enhanced communication and coupling between CHEM and GGFS at the common interface to allow very high Mach number plume simulation,

4.) improved communication between CPU processors within GGFS for enhanced parallel scalability,

5.) improved data input/output algorithms within GGFS to allow domain size scale-up, and

6.) enhanced usability of the CHEM-GGFS-DTA framework: beyond tool developers.

The major milestone accomplished was simulating a three-engine lander descending toward an 80-by-40-m landing zone (nearly the size of a football field) and to fully simulate the landing from ≥40 m high, with three 5-m-diameter craters formed. The CHEM mesh has approximately 25 million cells, and the GGFS mesh has 20 million cells. Simulation with a GGFS mesh of 65 million cells was shown to be feasible; therefore, higher fidelity simulations can be accomplished for large domains.

SUMMARY

A multicomponent integrated simulation framework (CHEM-GGFS-DTA) has been significantly enhanced, beyond project expectations, to provide simulation of plume-surface interaction for full-scale landers with multiple engines and realistic high Mach number plumes, and full-size landing zones. Follow-on work will include increasing the parallel processing efficiency and functionality of GGFS, and with outside project funding, EDL simulations of Mars InSight and for the MSC Team will be conducted.

PRINCIPAL INVESTIGATOR: Douglas G. Westra

CO-PRINCIPAL INVESTIGATOR: Peter A. Liever

CO-PRINCIPAL INVESTIGATOR: Jeffrey S. West

DEVELOPER: Manuel Gale

PARTNER: Tara T. Polsgrove, Sponsor

FUNDING ORGANIZATION: Technology Investment Program

MODELING, SIMULATION, IT

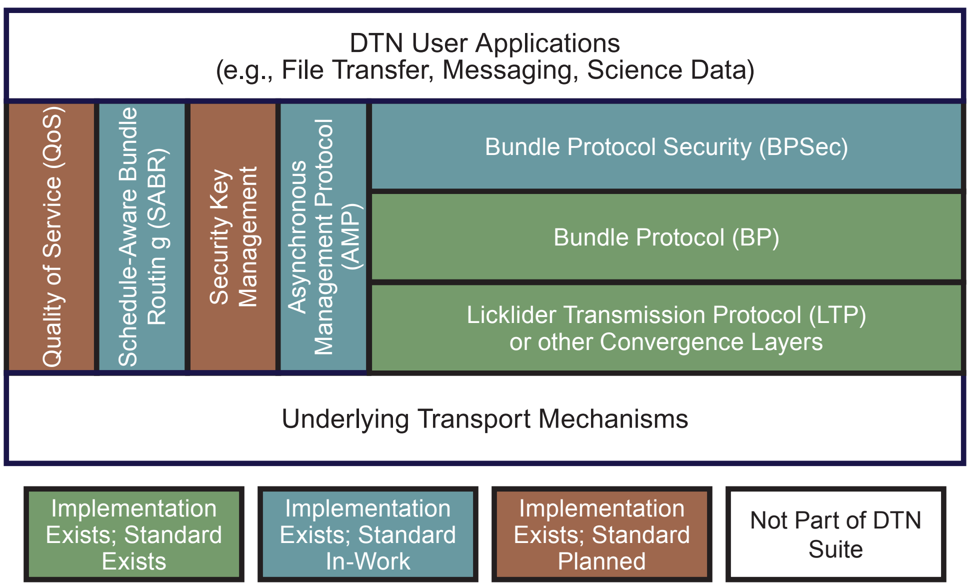
Delay/Disruption Tolerant Networking

OBJECTIVE: *To extend Internet-like services to space in support of current and future space missions and as a basis for the Solar System Internetwork.*

PROJECT DESCRIPTION

Delay/disruption-tolerant networking (DTN) is a combination of protocols that are being developed to extend the terrestrial Internet into Low Earth Orbit (LEO) and deep space to help form the backbone for future space communications project support. The Advanced Exploration Systems (AES) DTN Project will prepare DTN technologies and operations concepts for infusion into the next generation of human spaceflight missions via adoption by AES projects, Exploration Systems Division (ESD) programs, and the International Space Station (ISS). ESD programs include Orion/Multi-Purpose Crew Vehicle (MPCV), Space Launch System (SLS), and SLS Exploration Mission 1 (EM-1). CubeSat payloads, including Lunar IceCube, Lunar Flashlight, BioSentinel, and Near Earth Asteroid Scout (NEAScout), and numerous ISS experiments are utilizing DTN for data transfers as user interest in this capability continues to grow. Emphasis has been placed on developing implementation-ready sets of DTN components and operations concepts to support rapid update and infusion of DTN into NASA's space communication architecture. Additionally, emphasis has been and continues to be placed on international standardization of DTN through the Internet Research Task Force (IRTF), the Internet Engineering Task Force (IETF) and Consultative Committee for Space Data System (CCSDS) Standards.

While NASA's DTN-related activity is expected to continue through the operational deployments of DTN on future missions, the focus of the AES DTN project is to transition away from a developmental role and into



an infusion-and-mission-support role for the technology elements reaching maturity. Additionally, the focus of the AES DTN Project is on human space exploration, but the DTN protocols being developed should also benefit other NASA missions such as robotic deep-space, LEO, near-Earth object, and terrestrial applications.

A key technical challenge over the last year was upgrading the original DTN Gateway Server onboard ISS to another platform. NASA Marshall Space Flight Center and NASA Johnson Space Center ISS engineering and operations teams participated in detailed testing, including payload users to ensure the upgraded NASA Interplanetary Overlay Network (ION) DTN implementation, as well as the hardware platform and operating system, did not introduce issues for existing and new ISS Payload users. The technology upgrade provided the ability to increase the DTN downlink rate from 15 Mbps to 30 Mbps with growth to 50 Mbps expected in the middle of fiscal year (FY) 2019.

ACCOMPLISHMENTS

Infusion of DTN technology on ISS:

The Huntsville Operations Support Center (HOSC) collaborated with JSC ISS flight and ground engineering teams to deploy a DTN architecture supporting ISS operations and payload teams. This activity was started in late 2014, and the hardware and software were deployed to support real-time ISS operations on May 5, 2016. Since initial deployment, the ISS onboard DTN Gateway Server was recently upgraded (hardware and Operating System) to provide higher data downlink rates (from 15 to 30 Mbps). Telemetry downlink rate will eventually grow to 50 Mbps in FY 2019. There are many Payloads onboard ISS that are utilizing DTN, and many more that plan to utilize this protocol in the near future.

SUMMARY

DTN allows ISS Payload Developers (PD) the capability to automate and streamline their control center operations. The technology enables automatic retransmission of payload telemetry that may have been disrupted by space link issues. This cuts down on the number of playbacks the payload developers would have to perform to fill these gaps, which also helps maximize the bandwidth utilization on the space link between ISS and ground.

LEAD PROJECT MANAGER: Brenda Lyons, JSC

MSFC SUPPORTING PROJECT MANAGER: Gary Knickerbocker, MSFC

PARTNERS: Applied Physics Laboratory, Glenn Research Center, Goddard Space Flight Center, Jet Propulsion Laboratory, Johnson Space Center

FUNDING ORGANIZATION: Advanced Exploration Systems

FOR MORE INFORMATION:

http://www.nasa.gov/feature/new-solar-system-internet-technology-debuts-on-the-international-space-station/

https://www.youtube.com/watch?v=0gCMIiJdYPQ

https://www.youtube.com/watch?v=HV8CHoWP9-o

https://www.youtube.com/watch?v=nWtRTzXJvtI

MATERIALS, STRUCTURE, MECHANICAL SYSTEMS, AND MANUFACTURING

Additive Manufactured Throttleable Pintle Injector

OBJECTIVE: *To find novel ways to take advantage of additive manufacturing to produce a pintle injector for a liquid oxygen/liquid methane engine and other rocket engine systems.*

PROJECT DESCRIPTION

NASA Marshall Space Flight Center (MSFC) has pursued multiple successful technology tasks since 2005 to develop components that can be used for relevant liquid oxygen/liquid methane (LO_2/LCH_4) engine systems in the 100–25,000 lbf thrust range. The efforts at MSFC have included multiple coaxial and impinging injector designs that have offered good performance and stability. However, limited throttle range testing has been pursued on these injectors with LO_2/LCH_4. Since in-space applications for LO_2/LCH_4 may require a high throttle range to maximize the mission capability of available engine designs, a pintle injector offers a potential solution. Pintle injectors inherently offer high throttle range compared to coaxial and impinging injector designs. Evaluating such injectors for LO_2/LCH_4 systems may significantly improve the capability and operating range of the in-space engines that MSFC is pursuing. Developing and evaluating a LO_2/LCH_4 pintle injector in this continuing effort will provide results that support multiple near-term engine applications for NASA and commercial opportunities. This injector design and development will facilitate a separate aerospike engine design that RocketStar is pursuing. RocketStar plans to fabricate the injector with additive manufacturing (AM) to optimize and/or enhance design features that have not been available with traditional fabrication techniques.

For the last several years, aerospace companies have been examining ways to use AM, or 3D printing, to aid the production of rocket engines. Using AM allows design features not available with traditional fabrication techniques. It can also help to reduce the number of parts in engine components, thus speeding up production and lowering costs. While initially developing the TrailBlazer Technologies, RocketStar approached MSFC with the goal of using their research to consider using AM to produce a potential pintle injector design. Using AM in their design considerations opened up opportunities of design freedom, and removed traditional barriers to design and manufacturing. So, the goal of this research was to design an injector, build it with 3D printing technology, and eventually test the component at MSFC on existing thrust chamber hardware.

ACCOMPLISHMENTS

With the assistance of propulsion combustion devices engineers at MSFC, RocketStar engineers were able to design a pintle injector. Five main pintle injector modules were designed to facilitate testing at MSFC. Both the injector aft end and forward end incorporated 14-in diameter 1.25-in thick flange to mate with MSFC's test facility and supporting thrust chamber hardware.

A plastic model of the injector was printed and fit checked at MSFC. The fit check provided a successful and convenient way to identify necessary changes to the hardware interfaces, prior to investing in and fabricating the actual injector. MSFC engineers provided inputs for the necessary corrections, which can easily be implemented in the injector's final design. RocketStar will use this information to finalize the injector design and pursue fabrication of the test ready hardware. Testing of the injector at MSFC will be considered, pending fabrication results and available funding.

SUMMARY

The primary objective of this research was to additively manufacture a pintle injector for a high throttle range LO_2/LCH_4 rocket engine. The commercial partner, in conjunction with NASA engineers, designed the injector to meet interface requirements in order to potentially test the injector at MSFC's Test Stand 115, which is used to test moderate thrust liquid rocket engine components. Upon completion of the design, the partner printed a plastic version of the injector and brought that prototype to MSFC to fit-check the component at MSFC. Although the printed version was not an exact fit, the prototype unit allowed the team to successfully identify the necessary changes to the injector interfaces, prior to pursuing the fabrication of the actual hardware. Testing of the actual hardware is on-hold pending additional funding that will be used to manufacture the injector and fund the tests at MSFC.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Sandra Elam-Greene, Reginald Alexander

PARTNER: RocketStar

FUNDING ORGANIZATION: Cooperative Agreement Notice

FOR MORE INFORMATION: http://rocketstar.nyc/

The Fabrication of Lightweight Full-Shell Replicated Optics by 3D Printing

OBJECTIVE: *To offer a new approach to x-ray optics fabrication by replacing a portion of the thickness of traditional nickel cobalt electroformed optics with a lightweight printed ceramic. This approach offers the potential to achieve a larger collecting area for a given mass budget in comparison to traditional electroformed optics.*

PROJECT DESCRIPTION

The goal of the project was to demonstrate a method for reducing the mass of traditional nickel cobalt (NiCo) electroformed optics by replacing a portion of the replicates thickness with a lighter-weight ceramic. The approach leverages NASA Marshall Space Flight Center's expertise in mandrel fabrication, metrology, and electroforming. The new technological element presented here is related to the use of additive manufacturing (AM), which is utilized to provide a lighter-weight alternative to electroforming while also offering the potential to fabricate high-resolution optics without the need for secondary processes currently needed to improve the optic's imaging resolution. This approach also potentially enables the integration of mounting and alignment mechanisms onto the optic during the manufacturing process. The approach is a hybrid method that utilizes NiCo-replicated optics, which are traditionally electroformed and then released from a precisely formed mandrel. The electroforming process produces replicates with the required smooth-surface quality needed to achieve good specular reflectivity at x-ray wavelengths. The replicate, however, must be thick enough to provide the necessary flexural strength to the optic to preserve its figure, but this adds weight and limits the collecting area of the optical assembly for a given mass budget. Our approach is to replace a significant portion of the NiCo thickness with a much less dense (nearly a factor of three) ceramic material. In this way, the lighter-weight ceramic composing the bulk of the optic provides the necessary flexural strength, while the thin layer of electroformed NiCo provides the smooth optical surface necessary to achieve acceptable x-ray reflectivity.

ACCOMPLISHMENTS

In the first year, we were able to demonstrate the principle of the electroformed/ceramic hybrid on a flat mandrel. (See figure 1.) The process involved electroforming of a 50-µm-thick layer of NiCo on a 2-in-diameter polished flat. We then utilized an industry partner (HotEnd Works) to deposit a 1-mm-thick boron carbide (B_4C) layer on the back surface of the NiCo utilizing a process (binder jetting) that selectively deposits a liquid-binding agent onto a ceramic powder. Our approach was to first heat treat the ceramic at low temperature, ≈150 °C, in order to sufficiently harden the ceramic to allow the removal of the hybrid replicate from the mandrel. We were able to successfully remove the replicated hybrid from the mandrel and found that the high frequency surface roughness of the replicate (≈10 Å) was preserved after the ceramic printing ss (i.e., no 'print through'). However, the low-frequency error (i.e., 'waviness') of the sample was not as promising.

To fully densify the ceramic, however, it must be sintered at high temperature. We found that upon further heat treatment at modestly higher temperature (≈500 °C), the samples delaminated between each printed lamina. It became clear after this result that it would be better to investigate alternative methods of ceramics AM, rather than to continue paying for additional samples using the binder jetting process. AM ceramics are typically consolidated from powders by high temperature sintering. By starting with powders, consolidation to a dense part is an almost insurmountable challenge, and residual porosity is typically unavoidable. Furthermore, many additive processes introduce large thermal gradients that tend to cause

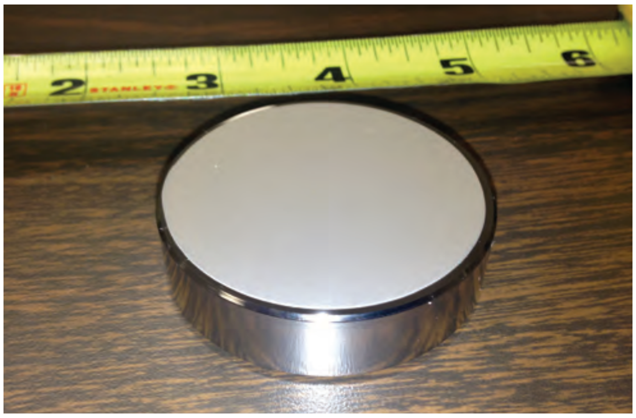
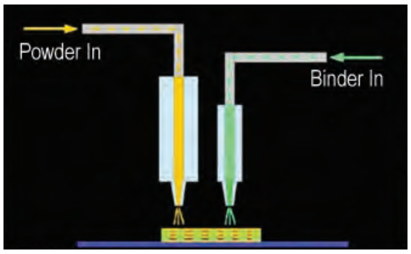
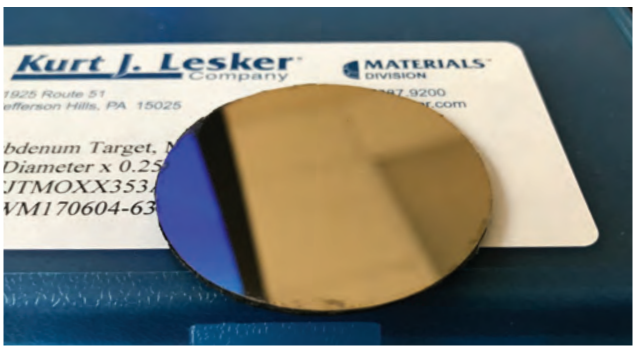
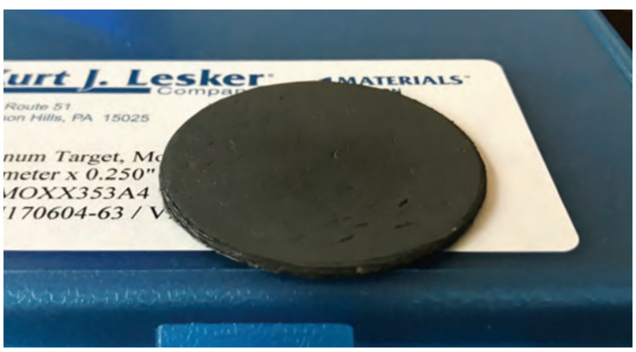


FIGURE. 1. The first hybrid ceramic optic was produced on a 2-in-diameter *z*-flat. The sample showed promising high frequency surface roughness. The low-frequency figure of the sample appeared to be negatively influenced by the shrinkage mismatch between the ceramic and electroformed NiCo, however.







cracks in ceramics. Pores, cracks, and inhomogeneities are responsible for low strength and poor reliability of AM ceramic parts. We are therefore investigating a new ceramic AM process called polymer-derived ceramics (PDC) developed by HRL Labs. The polymer contains a preceramic resin system that can be cured with ultraviolet (UV) light in commercially available stereolithographic 3D printers, allowing for complex shapes. The AM of ceramics using PDC has shown to have superior mechanical characteristics in comparison to binder jetting methods. Polymer structures have been formed and then pyrolyzed to a ceramic with uniform shrinkage, low porosity, and which are absent of cracks and other defects.

We are actively investigating an alternative hybrid approach using polymer derived ceramics developed by HRL Labs. This approach will utilize AM figured substrates which have been fully sintered prior to the deposition of a conductive thin film to facilitate electroforming a cladding layer of NiCo. The electroformed NiCo is then polished to the necessary surface finish to achieve high specular x-ray reflectivity. This process leverages MSFC's expertise in the fabrication and polishing of highly figured NiCo x-ray optics. HRL Labs has signed a nondisclosure agreement, and work is planned to test this method on flat ceramic samples in the near future.

FIGURE. 2. Ceramic hybrids cracked after further heat treatment at ≈500 °C.

SUMMARY

We investigated the use of a ceramic AM process called pressurized spray deposition (PSD) developed by an industry partner HotEnd Works. The process utilizes a powdered ceramic and the selective application of a binding agent to produce complex 3D shapes. To achieve full densification, the printed ceramic must be fully sintered at a temperature ≈1,000 °C. Our intent was to combine our traditional NiCo electroforming process with this ceramic AM process to produce a lightweight hybrid x-ray optics. We found, however, that this AM process resulted in substantial cracking failures when heat treated at even modest temperatures of ≈500 °C. We therefore have abandoned this AM approach and are now exploring an alternative method of ceramic AM developed by HRL Labs called polymer derived ceramics. Polymer-derived ceramics have been shown to be superior to powder-based ceramics, producing denser and crack-free ceramics that exhibit low porosity. The polymer-derived ceramics developed by HRL Labs contains a pre-ceramic resin that can be cured with UV light and utilized in commercially available stereolithographic printers. Our refined approach will start with fully sintered figured optics composed of silicon carbide that have been formed using HRL's process. The figured ceramic optic will then be clad with a thin layer (≈50 µM) of electroformed NiCo and subsequently polished to a surface finish suitable for achieving highly specular x-ray reflectivity. This process leverages MSFC's expertise in the fabrication of electroformed NiCo x-ray optics. HRL Labs has sign a nondisclosure agreement, and we anticipate to begin this work in the near future.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: David Broadway

FUNDING ORGANIZATION: Center Innovation Fund

Utilizing Bosch Generated Carbon for Additive Manufacturing

OBJECTIVE: *To successfully generate Bosch-Carbon ABS filament and to determine the mechanical properties and effects of carbon on the matrix of Bosch-Carbon ABS samples.*

PROJECT DESCRIPTION

The primary objective of this proposal is to successfully generate Bosch-Carbon acrylonitrile-butadiene-styrene (ABS) filament and to determine the mechanical properties and effects of carbon on the matrix of Bosch-Carbon ABS samples. For long-duration life support missions, oxygen recovery from metabolic carbon dioxide (CO_2) is essential. Currently, the International Space Station (ISS) oxygen recovery system is capable of recovering approximately 50% of the oxygen from metabolic CO_2. However, for long-duration manned missions, a minimum of 75% with a target of 90% of oxygen recovery is required. Theoretically, the Bosch process can recover 100% of oxygen from metabolic CO_2, making it a desirable technology for oxygen recovery for long-duration missions. The Bosch process reacts CO_2 with hydrogen (H_2) to produce water (H_2O) and elemental carbon in the presence of a catalyst. The water that is produced in the Bosch process is fed to the Oxygen Generation Assembly (OGA) where it is then electrolyzed to form gaseous H_2 and O_2. Hydrogen is recycled back to the Bosch process, and O_2 is returned to the atmosphere. Carbon builds up and fouls the catalyst at a rate of 1 kg per day.

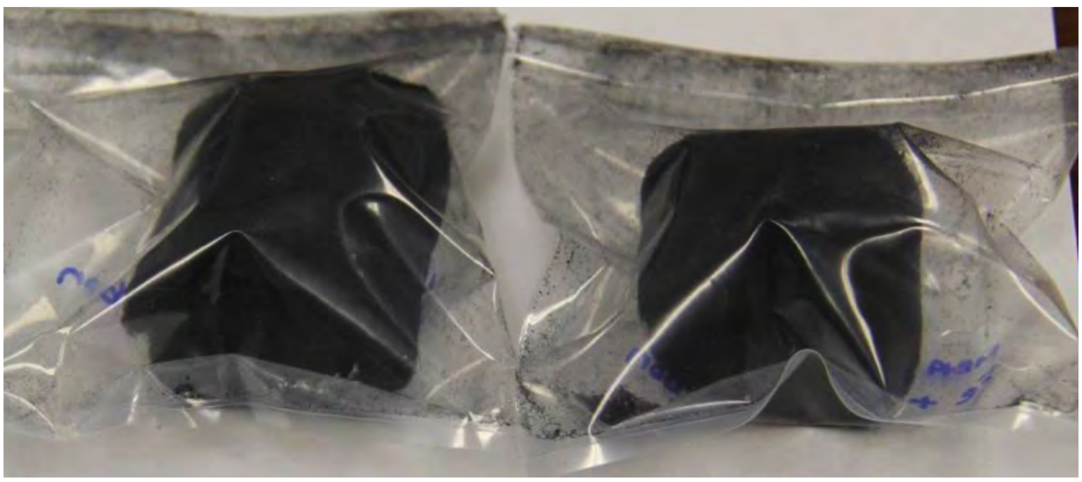


FIGURE 1. Carbon-coated Iron wool catalyst generated from the Bosch process from previous Bosch catalyst development testing.

Finding useful ways to utilize the carbon produced in the Bosch process would be very beneficial. One area of particular interest is additive manufacturing. Additive manufacturing onboard ISS provides the ability to manufacture parts on demand allowing for critical replacement parts and tools to be manufactured without the need to wait for them to arrive. ABS filament is used on ISS for additive manufacturing, and although ABS is a relatively strong plastic, when ABS manufactured parts are used as tools, there is a great chance of the manufactured parts to fracture. The addition of carbon to the ABS filament is likely to solve this issue. A material's physical, electrical, and optical characteristics can be improved by the addition of carbon. Carbon has long been used in industry as a reinforcement providing structural strength to materials. The addition of Bosch carbon to ABS filament could greatly increase the structural strength of manufactured parts allowing for more durable and reliable parts to be printed, as well as utilizing a waste product of the Bosch reaction.

This project aligns with the Agency-designated NASA Marshall Space Flight Center's (MSFC's) roles and responsibilities for the Environmental Control and Life Support System (ECLSS) and additive manufacturing as well as MSFC's Strategic Management Agenda, "A Plan to Thrive," to directly enhance MSFC's technology and system development efforts in the human exploration of our solar system. This project also directly aligns with the Agency's Mission Pull for advanced manufacturing and ECLSS as well as NASA's Technology Roadmaps/Strategic

Technology Investment Plan: Technology Area (TA) 6 (Human Health, Life Support, and Habitation Systems) and TA 12 (Materials, Structures, Mechanical Systems, and Manufacturing).

For long-duration manned missions, oxygen recovery is essential. Currently, the ISS the oxygen recovery system recovers approximately 50% of the oxygen from metabolic CO_2. Future missions will require a minimum oxygen recovery of 75% with a target of greater than 90% which will allow for limited resupply mass and logistical requirements. Theoretically, the Bosch process can recover 100% of oxygen from metabolic CO_2. The Bosch process reacts CO_2 to form H_2O and solid carbon (C(s)) in the presence of an iron, nickel, or cobalt catalyst. For space flight, the Bosch process would be combined with water electrolysis which would convert the H2O from the Bosch process into H_2 and O_2. The H_2 would be recycled back to the Bosch process, and the O_2 would be released into the cabin for crew consumption. There are three reactions that occur during the Bosch process that ultimately converts CO_2 into water and solid carbon:

RWGS	$CO_2 + H_2 \leftrightarrow H_2O + CO$	(1)
CO Hydrogenation	$CO + H_2 \leftrightarrow H_2O + C(s)$	(2)
Boudouard	$2CO \leftrightarrow CO_2 + C(s)$	(3)
Bosch Process	$CO_2 + 2H_2 \leftrightarrow 2H_2O + C(s)$	(4)

The carbon that is produced in the process coats and fouls the catalyst at a rate of 1 kg per day. Figure 1 shows carbon-coated iron wool generated from the Bosch process. Historically, the carbon and catalyst have been discarded as waste product. In the interest of limiting storage and mass, it would be beneficial to utilize the carbon produced during the process.

The ability to manufacture on demand is a capability that has endless possibilities for the future of space exploration. This allows for repairs of critical parts without the need to wait for replacement parts to arrive and also for the construction of critical tools needed for installation of new manufactured hardware, which will be beneficial for long-duration missions beyond low-Earth-orbit. Additive manufacturing capabilities are currently available on the ISS in which ABS filament is being used. Replacement parts and tools need to be reliable, and while ABS is a relatively strong plastic, manufactured ABS parts are likely to fracture under certain stresses and conditions. The addition of carbon to the ABS filament is likely to solve this issue.

The addition of carbon can greatly improve a materials physical, electrical, and optical characteristics. In industry, carbon has long been used as a reinforcement agent providing structural strength to materials. It has been shown that carbon-filled materials have comparable properties to metals; therefore, the addition of Bosch carbon to ABS filament could greatly increase the structural strength of manufactured parts. Recycling Bosch carbon would also increase the amount of additive manufacturing material available. By creating the filament in space, it may be possible to recycle additional materials to further reduce weight, such as using soft stowage support or packaging made from ABS. Bosch-carbon ABS filament will allow for more durable and reliable parts to be printed as well as utilizing a waste product of the Bosch reaction.

FIGURE 2. 3D-printable filaments made from the combination of ABS (blue beads) and Bosch carbon.

ACCOMPLISHMENTS

In addition to this project, we were awarded a Collective Agreement Notice award to continue this project. In this initial stage, we will perform a detailed characterization of the Bosch carbon provided by NASA. Analytical techniques that will be used include a combination of x-ray powder diffraction (XRD) (to estimate graphitic content), Raman spectroscopy (also to estimate graphitic content), sieve analysis (to measure particle size), contact angle measurements (to estimate surface energy), and scanning electron microscopy (SEM) (to estimate particle size and particle morphol-

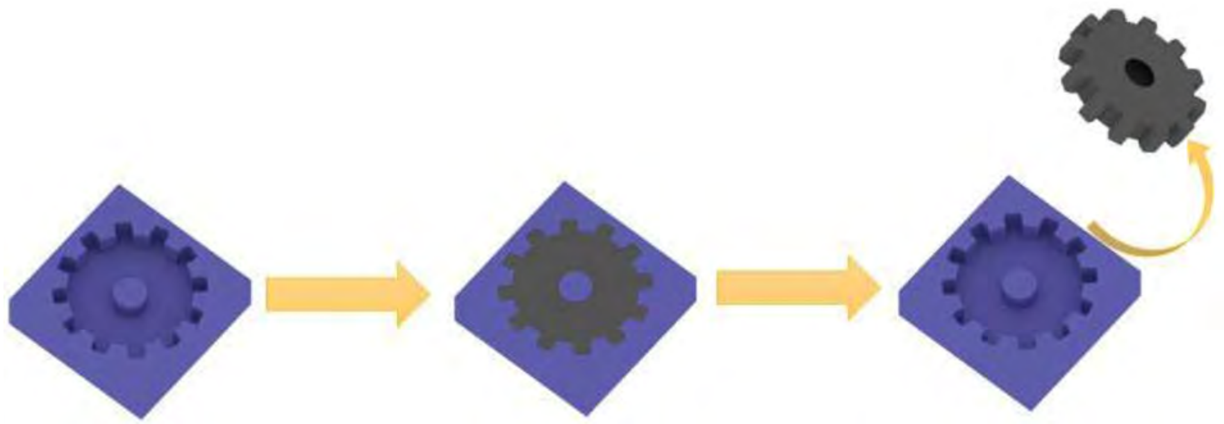


FIGURE 3. Reusable 3D-printed mold to cast thermosets filled with Bosch carbon.

ogy). These techniques will allow us to understand the composition of the Bosch carbon and monitor how the Bosch carbon is altered though various treatments.

ABS will be combined with Bosch carbon through mechanical mixing and extruded into filaments using the 3DEvo advance extruder in Professor Bara's laboratories (figure 2). The Bosch carbon loading will be varied, and the impact on the printing properties of the ABS will be examined. A potential difficulty of using Bosch carbon as a filler is that ABS is known to become brittle at higher carbon loadings (i.e., >20%). Therefore, a focus of this research will be to probe the maximum Bosch carbon content in ABS while maintaining suitable mechanical properties. Follow-up work will include testing of Bosch carbon in other thermoplastics, such as polylactic acid (PLA), polyether ether ketone (PEEK), and the ionic ultra-high pressure (UHP) polymers. In addition to exploring Bosch carbon in thermoplastics, we will look at the incorporation of Bosch carbon as filler in thermosets (figure 3). Although FDM is not typically performed with thermosets, NASA's desire for fused deposition modeling (FDM)-based 3D printing capabilities can still be utilized by first printing reusable molds for the thermosets, a practice widely used in device prototyping. Room-temperature vulcanizing (RTV) silicone will be used as a model thermoset, as its behavior with carbon black (CB) filler is widely understood. In addition, the elastomeric properties of RTV silicone are complimentary to those of ABS and will allow for the production of flexible/compressible/deformable parts not possible with ABS (e.g., gaskets). The envisioned process works by first 3D printing molds from ABS, then filling these molds with the RTV silicone + CB mixture, which is allowed to cure times on the order of minutes to hours). The cured RTV silicone + CB part is then cleanly removed from the ABS mold, and the mold can be reused many times. In addition to RTV silicone, other Bosch carbon filled resins, such epoxies, can also be examined in the future.

3D printing and the subsequent mechanical testing of filaments, printed parts, and cast thermosets, will be performed using mechanical testing equipment (e.g., Instron) available at both NASA and The University of Alabama. Samples will also be provided to NASA for thermal analysis.

SUMMARY

We are continuing to synthesize different variations of these Bosch carbons and characterize these polyimides with different thermal characterization techniques:

- differential scanning calorimetry
- therogravimetric Analysis
- mechanical Properties Testing
- XRD
- scanning electron microscopy.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Brittany Brown (MSFC/ES62)

CO-PRINCIPLE INVESTIGATOR: Enrique Jackson, (MSFC/EM22)

PARTNERSHIP: Paul Rupar, The University of Alabama

FUNDING ORGANIZATION: Center Innovation Fund

Composite Technology for Exploration (CTE)

OBJECTIVE: *To advance composite technologies with a focus on weight-saving, performance-enhancing bonded joint innovations for heavy-lift launch vehicle-scale applications to support future NASA exploration missions.*

PROJECT DESCRIPTION

The Composite Technology for Exploration (CTE) project is developing and demonstrating critical composite technologies for future NASA exploration missions with a focus on composite joint technologies for Space Launch System (SLS)-scale hardware. CTE will improve the analytical capabilities required to predict failure modes in composite structures. It supports SLS payload adapters and fittings by maturing composite bonded-joint technology and analytical tools to enable risk reduction. Composite joints can account for significant increases in cost and weight. Through materials characterization studies, advanced analysis tools, and the design, manufacturing, and testing of lightweight composite bonded joint concepts, CTE is producing weight-saving, performance-enhancing composite bonded joint technologies. CTE is developing and validating high-fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints. By applying this comprehensive approach, CTE will progress and improve bonded-joint failure load and mode predictions to help reduce knockdown factors and increase overall confidence of bonded joint composite structures.

FIGURE 1. One of four full-scale bonded joints on the Payload Adapter Manufacturing Demonstration Article (PLA MDA).

When properly designed, composite structures have many potential benefits over traditional metallic structures, including lower mass, better fatigue resistance, lower part count, and reduced life-cycle cost. NASA plans to advance composite technologies that provide lightweight structures to support future exploration missions. Due to the large 8.4-m diameter of a heavy-lift type launch vehicle and the unavailability of large autoclaves for curing composite structures, individual large composite panels must be manufactured separately and then joined together. The state-of-the-art method for joining launch vehicle composite panels and structures is metallic joints that are both heavy and labor intensive. Through CTE, NASA is gaining experience on developing lightweight composite joints and analysis techniques specifically applicable to large-scale composite structures.

CTE has designed a bonded (no fasteners) longitudinal joint. Joint test coupons have been fabricated and tested. Large-scale longitudinal-joint tests will follow. Another challenge with a much larger payoff includes designing and testing a bonded circumferential joint. CTE has down-selected several analytical programs and failure theories to analyze the circumferential joint designs. Results of the different joint tests will be used to evaluate analytical approaches. When complete, a tailored approach for the reduction of factors of safety for composite discontinuities and for highly accurate failure prediction capabilities will be published.

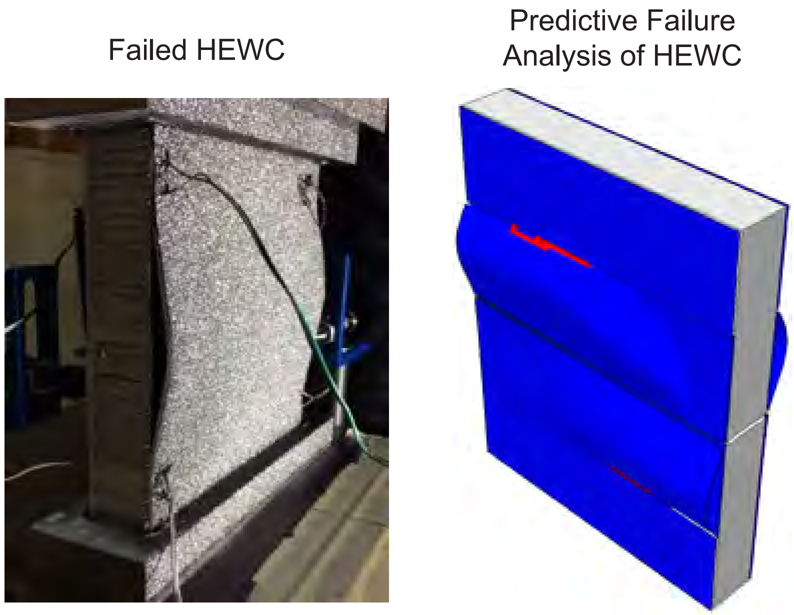


FIGURE 2. Predictive failure analysis (PFA) of a hoop edgewise compressions (HEWC) coupon and a failed HEWC coupon. Pretest predictions were within 9% of testing results.

ACCOMPLISHMENTS

The project demonstrated CTE double-lap longitudinal-joint design and an out-of-autoclave, cured, bonded composite joint through design, analyses, manufacturing, and test. The CTE project developed longitudinal-joint detailed designs, test article designs and NDE standards. It evolved manufacturing process parameters to produced repeatable and reliable longitudinal joints and fabricated 12 jointed panels with these processes at NASA Marshall Space Flight Center (MSFC) and manufactured 49 joint test articles at NASA Goddard Space Flight Center (GSFC). The 49 test articles were tested in primary loading conditions, in both pristine and damaged conditions. Pristine and damaged joints met CTE load requirements with 2.0 factor of safety. CTE evaluated cohesive zone in-plane continuum damage model (COSTR) for longitudinal joint specimen failure predictions and established a nonlinear approach resulting in pretest predictions within 9%. The results of the joint tests are being used to evaluate the down-selected several analytical programs and failure theories. CTE also completed four full-scale joints on the Payload Adapter Manufacturing Demonstration Article (PLA MDA). Next, the project will design, manufacture, and test a bonded circumferential joint, a much bigger challenge, but much bigger payoff. It includes advanced 3D woven-joint design methodology and learning how to communicate design intent among designer, manufacturer, and analyst to received 3D woven parts as needed to structurally perform.

SUMMARY

The potential benefits of CTE's composite joints technology development activities include weight savings, cost savings, and improved performance with increased reliability compared to metallic structures/joints. The project will enable the technology infusion of lightweight composite joints into future exploration missions. CTE is working to achieve these potential benefits by developing and validating high-fidelity analytical tools and standards for predicting failure and the residual strength of composite bonded joints. This allows for a tailored approach to reducing the safety factor for composite discontinuities while still reducing risks and increasing confidence in composite joint technologies.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: John Fikes

PARTNERS: Game Changing Development Program, SLS Spacecraft and Payload Integration/Evolution (SPIE) Office, Langley Research Center, Goddard Space Flight Center, Glenn Research Center

FUNDING ORGANIZATION: Game Changing Development

Low-Cost Upper Stage-Class Propulsion (LCUSP)

OBJECTIVE: *To use additive manufacturing to develop high-pressure/high-temperature combustion chambers and nozzles with copper and nickel alloys.*

PROJECT DESCRIPTION

Low-Cost Upper Stage-Class Propulsion (LCUSP) is developing the process of using selective laser melting (SLM) of copper-alloy GRCop-84 and electron beam free form fabrication (EBF^3) with nickel-alloy Inconel 625 to produce a regen-cooled rocket combustion chamber. By utilizing SLM and EBF^3 additive manufacturing techniques, the manufacturing cost and schedule are greatly reduced. Performing a hot-fire test in a relevant environment demonstrates the performance and compatibility of a GRCop-84 chamber liner with an EBF^3 Inconel 625 chamber jacket.

The LCUSP program was designed to develop processes and material characterization for the GRCop-84 copper-alloy commensurate with powder-bed additive manufacturing, evaluate bimetallic deposition of Inconel 625 onto GRCop-84, and complete testing of a full-scale combustion chamber.

FIGURE 1. Combustion chamber showing the bimetallic bond of GRCop-84 liner and the Inconel 625 structural jacket and manifolds.

Thrust chamber assemblies must withstand both extremely high heat loads and high pressures as they generate thrust from chemical energy. The LCUSP project focused on advancing two manufacturing processes to improve fabrication: (1) SLM of GRCop-84 and (2) bimetallic bonding of GRCop-84 and Inconel 625 using EBF^3. SLM sinters layers of fine GRCop-84 powder to form the copper-alloy liner. The liner has complex integral coolant passages to properly cool the walls and address the high heat loads the chamber experiences during operation. GRCop-84, a NASA Glenn Research Center (GRC) developed material, provides excellent heat conduction. EBF3, under development by the NASA Langley Research Center, was used to additively manufacture a nickel-alloy structural support jacket to the GRCop-84 liner that provides structural support to the chamber during operation. In addition, materials scientists from GRC in Cleveland, Ohio, performed extensive analysis and materials characterization of the rocket part. These technologies allow engineers to tailor designs and include custom geometries that were costly or impossible to realize in parts before this technology was developed.

ACCOMPLISHMENTS

During the last year, LCUSP successfully completed the project milestones by demonstrating the performance and compatibility of a select laser melting (SLM) manufactured GRCop-84 chamber liner with electron beam free form fabrication Inconel 625 jacket integrated with a SLM manufactured nozzle with ten hot-fire tests.

The full-size thrust chamber, Unit 3.0, was successfully hot-fire tested on February 22, 2018, at NASA Marshall Space Flight Center. The test was conducted at 100% power for 20 s and reached 1,460 psia chamber pressure with a thrust level of 29,100 lbf. The project also tested the shorter thrust chamber, Unit 2.2, on March

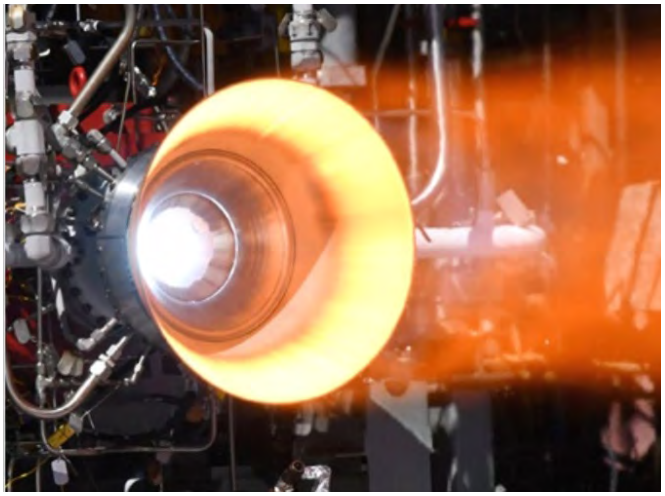


FIGURE 2. An LCUSP hot-fire test was conducted at 100% power.

2, 2018, at 100% for 25 s. This test produced 26,700 lbf of thrust with a chamber pressure of 1,420 psia. This test series was very successful demonstrating through hot fire testing, the performance and compatibility of a SLM manufactured GRCop-84 chamber liner with EBF^3 Inconel 625 jacket integrated with an SLM manufactured nozzle. LCUSP also went one step further by demonstrating the integrated system with a carbon-carbon nozzle extension. This marks a technology first for the successful hot-fire test of a liquid oxygen/hydrogen regen-cooled GRCop-84 copper-alloy 3D-printed combustion chamber with an integral EBF^3 deposited nickel-alloy structural jacket.

SUMMARY

While LCUSP has focused on thrust chamber components, the capabilities to additively manufacture with copper-alloys and perform bimetallic deposition is applicable to a variety of applications. Processes and parameters are available to industry partners to enable a long-term supply chain of copper combustion chambers. LCUSP is part of a strong base of novel manufacturing techniques upon which the Rapid Analysis and Manufacturing of Propulsion Technologies (RAMPT) project can build and further evolve the advanced manufacturing work performed by NASA. The RAMPT project will develop and advance large-scale, lightweight multimetallic freeform-manufacturing and composite overwrap techniques and analysis capabilities required to implement them to reduce design-and-fabrication cycles for regen-cooled liquid rocket engine components.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: John Fikes

PARTNERSHIPS: NASA Langley Research Center, NASA Glenn Research Center

FUNDING ORGANIZATION: Game Changing Development

Space Environmental Effects on Additively Manufactured Parts

OBJECTIVE: *To modify space environment simulators for higher fidelity to actual space environment and characterize the improved performance by testing additively manufactured materials samples.*

PROJECT DESCRIPTION

A 3D printer was installed on the International Space Station (ISS) in 2014 and has printed over two dozen parts. This technology is maturing with stronger materials, including rocket engine parts that, for an Exploration mission, may be exposed to space for weeks and months, not just minutes. Eventually, either on ISS or on manned missions elsewhere in the solar system, there will be a need to replace a part that will be exposed to space. This effort gives the data needed on how durable 3D-printed materials might be in the space environment. During the 3D-printed part testing, improved ultraviolet (UV) radiation sensors were also exposed, and the UV radiation simulator was better characterized. One of the UV radiation sensor designs and a variety of additively manufactured material specimens were launched in April 2018 as part of the Materials International Space Station Experiment (MISSE)-9 array of experiments. The planned exposure on orbit is 1 year.

Simulated low-Earth-orbit exposures included 5 eV atomic oxygen and UV radiation. These tests provided the erosion yield, or the rate a polymeric material is damaged by atomic oxygen, and also changes in thermo-optical properties for these materials. The electrical resistivity of the electrostatic-dissipative polyether-ketone-ketone (ESD-PEKK) was measured before and after exposure. While the resistivity did increase due to atomic oxygen exposure, the material was still electrostatic dissipative. The technology advanced from no data available to test readiness level (TRL) 5 for some of the materials. Once the flight samples are returned, the full set of control samples and ground test samples will be mechanically tested. This will provide data on embrittlement due to UV radiation and any effects of thermal cycling.

ACCOMPLISHMENTS

Simulated space exposure is complete on a number of polymeric and metallic additively manufactured samples. Currently exposed to space onboard the ISS are samples of Inconel, polyetherimide (Ultem 1010 and 9085), ESD-PEKK (fig. 1). A duplicate set of samples, plus polycarbonate biocompatible per ISO 10993 USP Class VI (PC-ISO) is planned for launch in November 2018 as part of the MISSE-10 complement of experiments (fig. 2). The improved UV sensors are flying on the ram, wake, and zenith sides of the MISSE Flight Facility (MISSE-FF). Also studied were polyphenylsulfone (PPSF) and NASA Glenn Research Copper 84 alloy (GRCop-84).

SUMMARY

This project was a two-year effort to provide data on the durability of additively manufactured materials in the space environment, to help develop in-space manufacturing capabilities, and to advance towards more sophisticated parts. Polymeric and metallic samples were manufactured at NASA Marshall Space Flight Center, while 3D printer manufacturers Stratasys Inc., and Made in Space, Inc., participated in this effort so as to compare different vendors and printing setups. At the same time, laboratory simulators were improved for better fidelity to the space environment. The new UV sensors are small enough for flight not only on MISSE-FF but also CubeSats.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Miria Finckenor

FUNDING ORGANIZATION: Center Strategic Development Steering Group

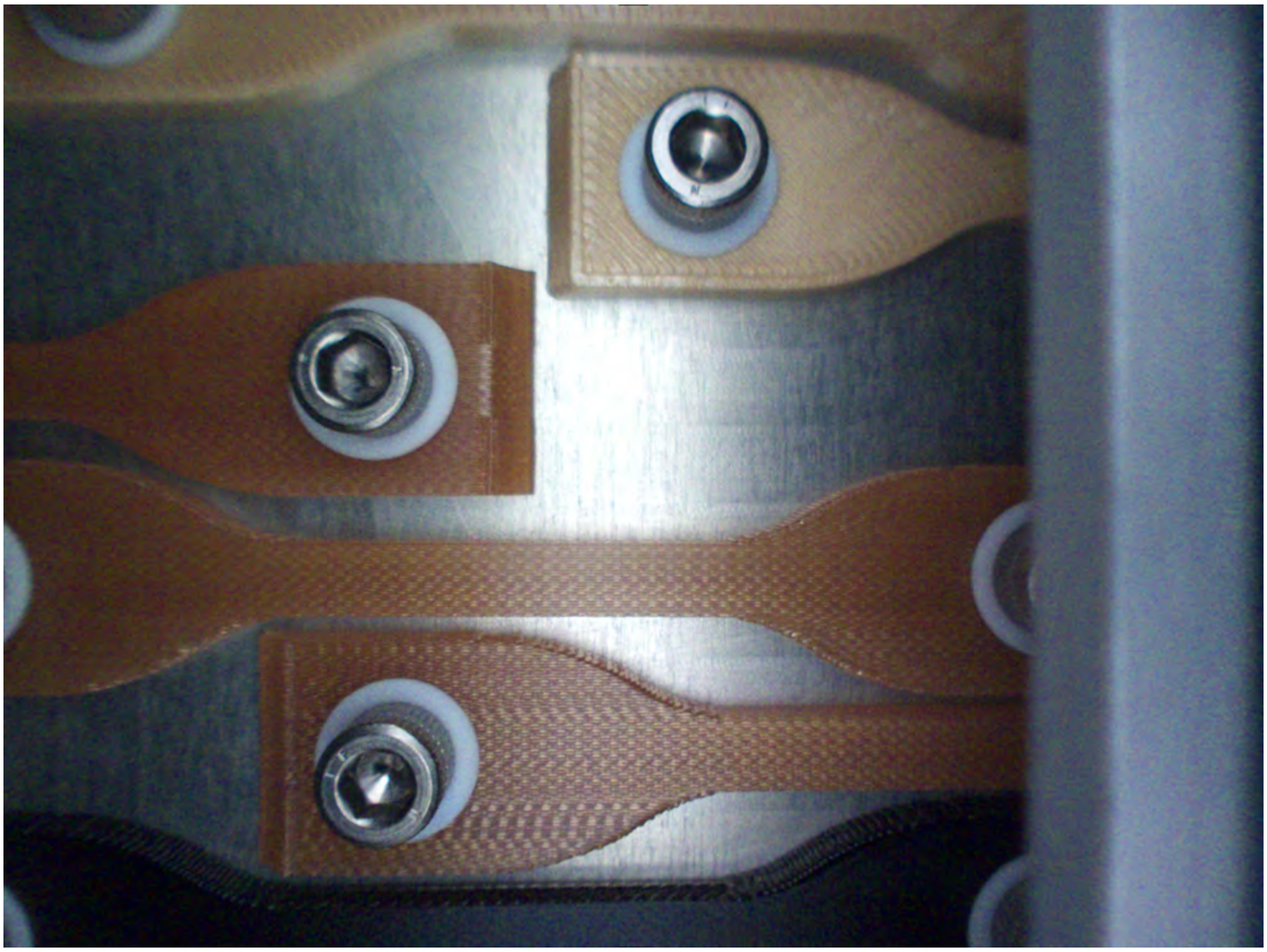


PHOTO COURTESY OF ALPHA SPACE AND NASA

FIGURE 1. On-orbit photo of MISSE-9 additively manufactured materials.

PHOTO COURTESY OF ALPHA SPACE AND NASA

FIGURE 2. MISSE-10 additively manufactured materials experiment.

Ionic Polyimides: New High-Performance Polymers for Additive Manufacturing

OBJECTIVE: *To determine the relationship between molecular structure, thermal properties, and performance of ionic polyimides.*

PROJECT DESCRIPTION

The primary objective of this proposal is to determine the relationship between molecular structure, physical properties, and performance of ionic polyimides. Further, the team seeks to determine their utility as materials suitable for additive manufacturing of components used in aerospace vehicles, with an emphasis on characterizing and simulating their thermal behaviors and properties. This proposal addresses the need for fundamental research on a customizable polymer-filament feedstock for 3D printing with tailor-made properties, potentially making it superior to the commercial blends offered in industry today. The deliverables for this project are the creation of a database that will detail the relationships between the molecular structure and physical properties for the ionic polyimide of interest (e.g., glass transition temperature (T_g)/melting point (T_m) relative to different ionic polyimide structures). This new database will provide a 'road map' to the development of the first generation of materials and ultimately proof of concept.

a.

b.

FIGURE 1. Photographs of the first-generation ionic polyimide films: (a) neat and with ≈25 wt% 'free' [C_2mim][Tf_2N] content and (b) the difference in optical clarity when 'free' IL is present illustrated.

The proposal is a continuation and aligns with the advanced manufacturing fiscal year 2017/2018 focus domain. This research will focus on additive manufacturing to develop in-space manufacturing capabilities for space exploration. The innovation is revolutionary because, unlike any material currently available for 3D printing, ionic polyimides retain the robust nature of polyimides, while displaying the ease of processing and conductivity of ionic liquids (ILs). Figure 2 shows an example structure of an ionic polyimide produced from commercially available starting materials by the research group of Professor Jason E. Bara at The University of Alabama (UA).

The unique combination of functionalities and properties is not found in conventional polyimides or other engineering polymers. The use of these materials will allow for potential aerospace applications such as valves, O-rings, seals, and gears. Bara's group has already demonstrated that their first-generation ionic polyimides can be extruded, pelletized, and molded at ≈220 °C, which is consistent with modern fused deposition modeling (FDM) 3D printers (fig. 3).

Thus, it is imperative to rapidly begin to elucidate the thermal behaviors of these materials to gain an understanding of the key structural variables that must be manipulated to develop further generations of application-specific materials. The benefits associated with ionic polyimides are the following:

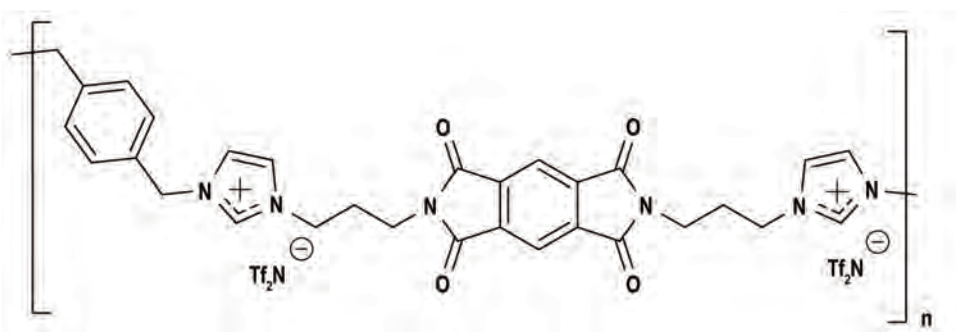


FIGURE 2. Example of ionic polyimide molecular structure.

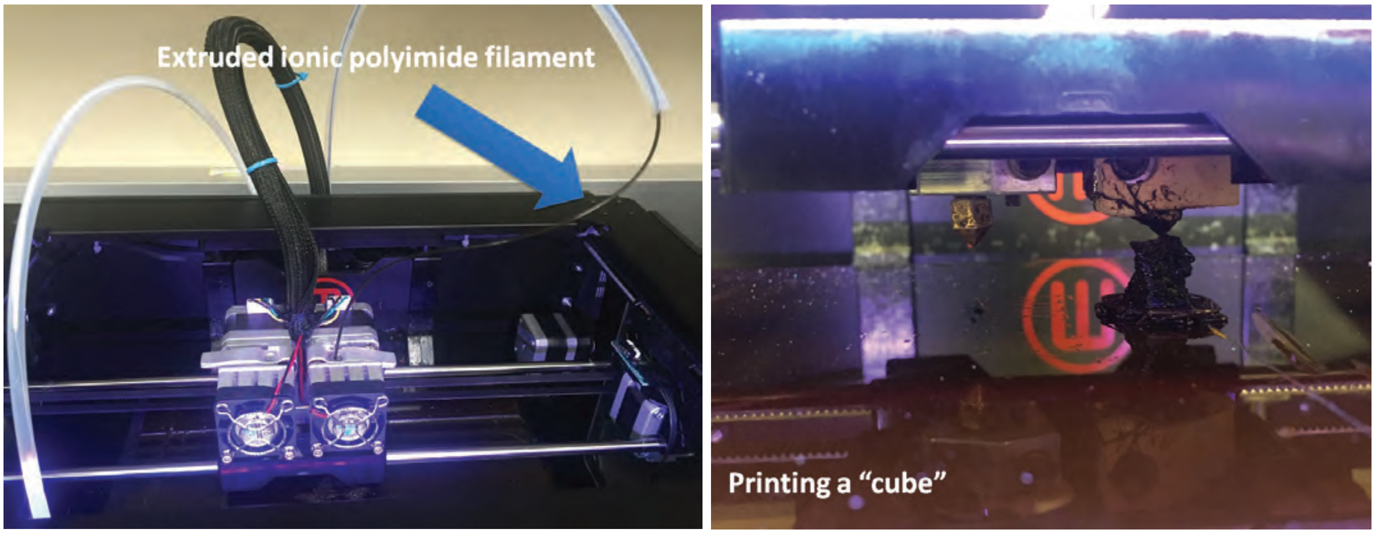


FIGURE 3. Proof of concept in using ionic polyimide material in FDM 3D printing.

1.) Ionic polyimides provide better control over chemical, conductive, and mechanical properties during the production of polyimide materials.

2.) The ionic polyimides can bind ionic liquids within their structures, which allows for enhanced control of material properties and performance.

3.) Straightforward synthesis/production process:
   (a) results in low-cost fabrication and
   (b) finished material could likely garner a premium price due to the enhanced material functionality.

ACCOMPLISHMENTS

Much to our surprise, the ionic polyamide materials synthesizing in Bara's lab at UA exhibited shape memory properties. Without any special thermal or chemical processing, the ionic polyamides were observed to behave as thermoplastic elastomers. This behavior was discovered through recovery of ionic polyamide during drying in a vacuum oven. While attempting to pull the ionic polyamide from a glass dish at 150 °C, a student in Bara's group discovered that the polymer could be processed into a coil shape by wrapping it around a 0.25-in-diameter stainless-steel rod. Upon cooling to room temperature, the coil was observed to be deformable through stretching with rapid recovery to the original size within 1–2 min. Further experiments were performed to produce discs of the ionic polyamide. These discs (≈1/8-in thick and 2-in diameter) could be folded in half but would rapidly spring back to their original fully extended state.

As mentioned, these materials were not expected to have shape memory behavior, and they were originally produced as a comparative study to Bara's ionic polyimide materials which also show promise for 3D printing applications. However, although they are also highly thermally stable and amenable to a variety of processing techniques, the ionic polyimides do not exhibit such shape memory behavior. It is hypothesized that the additional H-bonding sites on the ionic polyamides are responsible for the shape-memory behaviors, as there is very little difference in the chemical compositions of ionic polyimides and ionic polyamides other than the H-bonding donor and acceptor sties. When sliced/cut/shredded, the particles of the ionic polyamides also exhibit self-healing behavior and will fuse back together over short time scales (seconds to minutes).

We are not aware of 3D printing of shape-memory, self-healing thermoplastic elastomers in either commercial or research applications. As such, these ionic polyamides represent a truly unique class of materials and first-of-a-kind opportunity to produce flexible and durable parts for a variety of applications including those related to plan missions beyond Earth.

Resources for this effort will be used to collaborate with the Co-Principal Investigator Professor Jason Bara (UA), and Kendall Byler a Computational Chemist from the University of Alabama in Huntsville. Jason Bara and his research group will continue to synthesize ionic polyimides and being to extrude filaments, and Kendall Byler will continue to conduct molecular dynamic simulations of each of the polyimide structures.

SUMMARY

We are continuing to synthesize different variations of these ionic polyimides and characterize these polyimides with different thermal characterization techniques:

- differential scanning calorimetry,
- Fourier transform infrared spectroscopy, and
- thermogravimetric analysis.

We will also continue modeling ionic polyimides via *ab initio* calculations. In addition to this project, we were awarded a Cooperative Agreement Notice Award to continue this project. Finally, we will develop filament feedstock materials from these ionic polyimides and ILs to additively manufacture parts from these materials for aerospace applications.

PROJECT MANAGER AND/OR PRINCIPLE INVESTIGATOR: Enrique Jackson

PARTNERSHIPS: Jason Bara, The University of Alabama; Kendall Byler, University of Alabama in Huntsville

FUNDING ORGANIZATION: Center Innovation Fund

Print Assisted Photovoltaic Assembly (PAPA)

OBJECTIVE: *Reduce touch labor, enable large scale production, and work towards in-space manufacturing of thin-film solar panels.*

PROJECT DESCRIPTION

Print-Assisted Photovoltaic Assembly (PAPA) uses advanced additive electronics manufacturing to print flexible paneling components around commercial off-the-shelf (COTS) solar cells. This builds a fully functional solar panel via an automated process. Currently, both state-of-the-art (SOA) and advanced-concept (e.g., thin-film) space solar panels are manufactured via the compilation of piece parts by hand. In contrast, PAPA automates the entire labor-intensive paneling process. The advantages are twofold: (1) near term, solar panel cost reduction and enablement of large-scale production and (2) long term, capability for in-space solar panel manufacturing. In this Center Innovation Fund work, Principal Investigator John Carr, who has an extensive background in photovoltaics and thin-film solar panels, joined Co-Investigator Furman Thompson, who has extensive background in advanced manufacturing and additive electronics, to develop this process. Custom pick-and-place tooling, a programmable robotic arm, and various additive electronic print heads were utilized to bring PAPA to life.

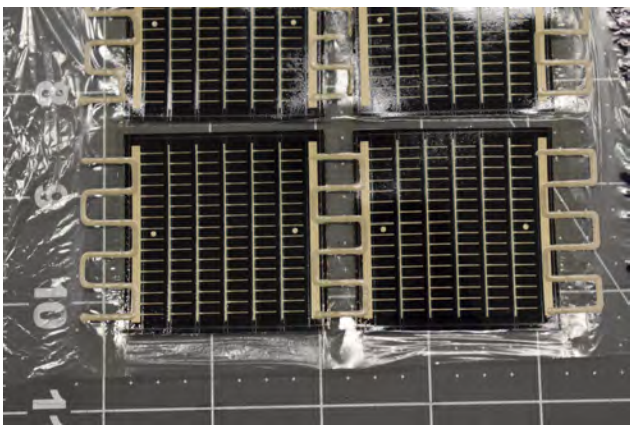


FIGURE 1. Complete PAPA solar panel assembly.

During this work, PAPA was taken from concept to prototyped process. All tooling was designed and fabricated utilizing 3D print manufacturing. This included custom solar cell pick-and-place vacuum tool heads, material spray-and-dispensing valve tool heads, solar cell trays, and tool change stations. This tooling was coupled to a Universal Robots robotic arm which was programmed with RoboDK to assemble prototype two- and four-cell, fully flexible solar panels or subcoupons.

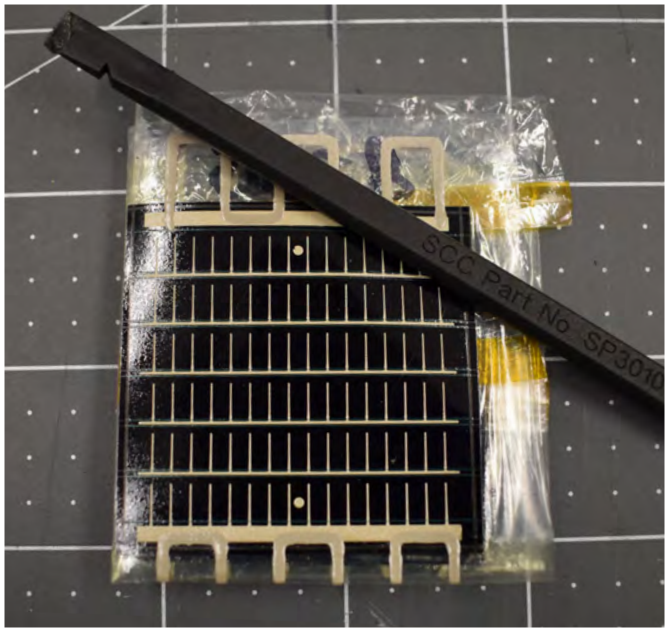


FIGURE 2. Folded PAPA.

ACCOMPLISHMENTS

In order to successfully print and assemble the subcoupons, several fabrication steps were developed during this work. These included cell-to-polyimide substrate adhesion, cell-to-cell and cell-to-bus bar electrical interconnection, as well as panel encapsulation. Each step was optimized in the RoboDK code; then, an integrated process program was created. During the integrated process creation, the individual steps were again optimized as step-to-step interactions were found. The PAPA fabricated subcoupons were successfully tested for electrical power generation under Air Mass 0. The subscoupons were then folded, unfolded, and retested without degradation. The subcoupons were also subjected to 15 rapid thermal shock cycles from –65 °C to +110 °C and again retested without degradation.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: John A. Carr, Furman Thomposon

FUNDING ORGANIZATION: Center Innovation Fund

Additive Construction with Mobile Emplacement (ACME)

OBJECTIVE: *To advance additive construction technologies that enable deep space exploration architectures and improve life on Earth.*

PROJECT DESCRIPTION

Additive Construction with Mobile Emplacement (ACME) is the process of utilizing in situ materials for the construction of large-scale structures like habitats, berms, landing pads, and roads using an autonomous, additive layering technique, often referred to as 3D printing, for the protection of people, hardware, and electronics while on the surface of an extraterrestrial body like the Moon or Mars.

ACME is focused on developing the technologies required to sort and process in situ materials into construction materials. ACME consists of subsystems that process, mix, and continuously feed concrete material through a nozzle mounted on a mobility system. Along with advancing the additive construction process, material research and development includes characterizing materials, developing new binders, and understanding different mixture compositions that could be compatible with the additive construction process. The US Army Corps of Engineers (USACE) is interested in additive construction to reduce building time, material cost, and personnel exposure in hazardous environments. Structures built using additive construction could aid in quickly and efficiently providing the military with protection and accommodations overseas, building of emergency housing after a disaster, and utilizing native materials in remote areas.

ACME has demonstrated the ability to build straight and curved walls using a concrete recipe composed largely of Portland cement, a less-expensive testing material that could potentially be created using lunar regolith. Developing binders from in situ resources that are compatible with in situ aggregates to meet process and structure requirements is one of the greatest challenges facing in-space construction. Material research and development has occurred to perform the tasks mentioned in the previous paragraph. Testing included hypervelocity impact tests, compression strength tests, simulated environment curing tests, and printability characterization.

NASA Kennedy Space Center (KSC) provided the Material Delivery System (MDS). The system measures and supplies the needed dry ingredients (e.g., cement, aggregate, sand) and liquid materials (e.g., water, additives) into a hopper. The wet concrete mix is then transferred to the Gantry system. NASA Marshall Space Flight Center (MSFC) provided the Gantry system that allows for x-, y-, and z-translational movement and z-rotation of the printhead. The Gantry system was designed to autonomously manufacture a 32 × 16 × 10-ft tall structure using less than six individuals in 24 hr or less.

ACCOMPLISHMENTS

KSC enhanced the MDS to meet USACE request to resolved hopper flow problems with wet sand. KSC invented and developed a bristle agitator device to transport damp sand in the feed system. A full B-hut print was completed using the enhanced MDS with the US Marines operating it.

Benchtop motor testing was performed at MSFC and allowed the team to address electrical, controls, and software open work at MSFC prior to implementation at USACE. Implementation of the findings from the benchtop motor testing showed controllable and repeatable movement in both the x- and y-axes. Controlled movement of the carriage and trollies/ towers was also demonstrated. Work is expected to be complete with a demonstration in early fiscal year 2019.

FIGURE 1. Through an Interagency Agreement, NASA and USACE are collaborating to advance the additive construction process. USACE's Automated Construction of Expeditionary Structures (ACES-3) gantry system will enable structures to be built within 1/8inch accuracy using six or less people in under 24 hr.

FIGURE 2. Verification and validation testing on the integrated MDS was performed in Champaign, Illinois, with the U.S. Marines operating it.

SUMMARY

The vision of ACME is to enable science and human exploration by utilizing in situ resources that feed additive construction technologies to efficiently build needed infrastructure. By using in situ materials, the mass launched from Earth to a destination could be reduced by as much as 90%. Additive construction can be used to build both terrestrial and extraterrestrial structures, reduce the time and cost required to transport materials by using in situ materials, and reduce waste when compared to traditional construction techniques.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: John Fikes, Mallory Johnston (Deputy)

FUNDING ORGANIZATION: Game Changing Development

FOR MORE INFORMATION: techport.nasa.gov/view/17558

Wear-Resistant Coatings to Enable Friction Stir Welding of Higher-Temperature Materials

OBJECTIVE: *To demonstrate deposition of tungsten rhenium coatings on friction stir welding tool materials and measure wear performance.*

PROJECT DESCRIPTION

Friction stir welding (FSW) is a solid-state joining technique developed at The Welding Institute (TWI) in 1991. The process was first used at NASA to weld the super lightweight external tank for the Space Shuttle. Today, FSW is used to weld fuel tanks for launch vehicles and structural elements of crew capsules. While it is largely a mature process for aerospace-grade aluminum alloys, a current focus of FSW research is to extend the process to higher temperature materials (such as metal matrix composites, steel, and titanium). Properties of solid-state welds typically show improvement over fusion welds in steel and titanium alloys since FSW occurs below the melting point of the workpiece. Thus, deleterious phases which may result from melting and resolidification do not form in joints produced by FSW. Application of FSW to higher temperature, harder materials has historically been impeded by rapid wear of the welding tool, a consequence of the discrepancy in hardness between the tool and the workpiece material as well as heat wear. The current state of the art in tooling for higher-temperature applications are tools made of tungsten-rhenium (W-Re) or polycrystalline cubic boron nitride (PCBN). For many applications and users, these tools are prohibitively expensive and limit the expansion of the FSW process beyond aluminum alloys. This effort seeks to evaluate the potential of coating lower cost base tool materials (HSS and MP159 are both standard tool materials for FSW) with W-Re as an alternative to bulk tool fabrication from W-Re or PCBN.

Plasma Processes, LLC, a small business in Huntsville, AL, will develop process parameters for plasma vacuum spray deposition of W-Re on HSS and MP 159 substrates. This coating process is distinct from the chemical vapor deposition processes traditionally used to coat tools and can produce a denser coating with better adhesion to the substrate. Coatings will be deposited on FSW tools made of HSS and MP159, specifically the portions of the tool (shoulder and pin surface) which contact the material during the welding process. The 'shoulder' is the cylindrical surface of the tool which rotates on the surface of the material being welded, generating frictional heating that is sufficient to plasticize (but not melt) the workpiece material. The 'pin' is the smaller cylinder which protrudes from the shoulder and plunges in to the material to stir it during the welding process. As a proof of concept, W-Re coated tools of both base materials (HSS and MP159) will be used to weld a metal matrix composite (aluminum-359 reinforced with 20% silicon carbide). Wear of the tool with successive weld passes will be monitored using optical comparison methods (the tool can be etched to remove residual aluminum which adheres to tool surfaces during welding and wear can be gauged using a high-resolution microscope). Wear characteristics of coated tools will be compared against the uncoated tools which serve as the performance baseline. Delamination of FSW tool coatings deposited under process forces is common, but the dense coatings possible with vacuum plasma spray may uniquely guard against this or at least delay it. Microscopy can be used to assess the integrity of the coating after welding.

ACCOMPLISHMENTS

This project received funding in late fiscal year (FY) 2018. FSW tools of MP159 and HSS are currently being fabricated. Substrate materials are at Plasma Processes to facilitate development of process parameters for the coating process. Sample FSW tools are with the surface metrology group at MSFC to determine best practices for wear measurement in this specific application. Coating of the tools will take place in early FY 2019, and welding trials (initially of metal matrix composites) with successive measurement of wear will begin shortly thereafter.

SUMMARY

FSW of metal matrix composites, titanium, and steel is a major thrust area for applied research in the aerospace, aviation, oil and gas, maritime and defense sectors. Tool wear has consistently impeded expansion of the FSW process to materials beyond aluminum alloys. Dramatic wear of the FSW tool in welding of higher temperature alloys is common. This project is intended to provide an initial proof of concept for the efficacy of W-Re coatings in mitigating tool wear in FSW of higher temperature alloys. If successful, a follow-on program further exploring this approach could yield a low-cost solution to mitigating or eliminating wear of the tool in these applications. Vacuum plasma spray deposition has demonstrated success in depositing hard coatings for propulsion components and the deposition process should be readily extensible to coating FSW tools and other machine tools (ex. cutting tools) with appropriate substrate selection and accompanying parameter development. Even in conventional FSW applications (HSS tools welding aluminum alloys), thicker materials can result in fatigue of the tool, leading to fracture. In these instances, W-Re coatings may also allow tools to be used longer before replacement.

PROJECT MANAGER AND/OR PRINCIPAL INVESTIGATOR: Tracie Prater

PARTNER: Plasma Processes

FUNDING ORGANIZATION: Seedling Investment Program

Performance Optimization of 3D-Printed Hybrid Rocket Fuel Materials

OBJECTIVE: *To develop custom filament blends to improve combustion performance of additively manufactured hybrid fuel grains for small satellite propulsion systems.*

PROJECT DESCRIPTION

While characterizing the performance of acrylonitrile-butadiene-styrene (ABS) produced by fused deposition modeling (FDM) as a potential replacement for conventional hybrid rocket fuels, Utah State University (USU) discovered that the layered material structure of 3D-printed thermoplastic material has the ability to concentrate minute electrical charges between material layers when subjected to a low-wattage inductive spark. This charge accumulation results in a strong electrostatic surface-arc, and the resulting Joule heating (the process by which the passage of an electric current through a semiconductor releases heat) causes fuel pyrolysis. Combustion results when this pyrolysis occurs simultaneously with the introduction of an oxidizing flow.

USU has developed a simple, low-wattage, on-demand hybrid ignition system with a moderately-high technology readiness level (TRL) and has recently begun testing very small-scale, low-mass-flow hybrid rockets for space propulsion applications, including demonstration of the technology on a sounding rocket flight from NASA Wallops Flight Facility in 2018. These inherently safe, 'green' propulsion technologies represent a potential low-cost replacement for many hydrazine-based systems.

To date, the feedstock used to manufacture the fuel grain has been based only on commercially available filaments. These materials are optimized for strength, durability, and printability rather than combustion performance. In fact, many commercial feedstocks incorporate additives which function as burn retardants. Thus, there exists the potential to develop custom blends of feedstocks for this application.

The addition of materials containing hydrogen may significantly improve the filament's performance in rocket fuels while still maintaining sufficient structural integrity to prevent collapse of the fuel grain during the burn. The focus of this research is the addition of low-density polyethylene (LDPE) and high-density polyethylene (HDPE) to ABS filament in order to increase burn properties. Once the baseline fuel material combustion properties were established, compatible performance additives were incorporated into filament using commercial-off-the-shelf filament-making units (the Filabot and Protocycler). Fourier-Transform infrared spectroscopy (FTIR) analyses as well as complementary results of differential scanning calorimetry (DSC) tests were used to derive the chemistry of the 'alloyed' materials. DSC established the glass transition temperatures of the blended material and provided an indication of the level of crystallinity. Combustion performance was measured via testing at ambient and vacuum conditions.

ACCOMPLISHMENTS

A standard shape for the fuel grain was created using a computer-aided design program. ABS fuel grains were printed and evaluated via testing to establish a baseline for combustion performance. To manufacture LDPE and HDPE filament, pellets of each material were passed through a commercially-available Filabot® extruder. The Filabot creates a filament by heating pellets that are fed into the hopper and squeezing them out of a small-orifice nozzle, producing a 1.75-mm-diameter filament that is compatible with desktop 3D printers. The culmination of the research in manufacturing methods under the Cooperative Agreement Notice (CAN) was the creation of the mixed ABS and LDPE fuel grain.

NASA Marshall Space Flight Center (MSFC) also explored filament making in parallel with USU's work using the filament manufacturing unit. In this work, ABS and LDPE and ABS and HDPE were blended together by dissolving pellets of these constituent materials into a slurry with a solvent. The resulting slurry was solidified, chopped up into pellets, and extruded using the Protocycler unit. Ultimately, this filament showed poor consistency in terms of diameter and was not suitable for printing. Additionally, the feedstock blends exhibited poor homogeneity, which would likely create undesirable variability in combustion performance along the printed fuel grain. Filaments produced with the process described above to date (70% ABS, 30% HDPE and 50% ABS, 50% HDPE) were analyzed with differential scanning calorimetry (DSC) and FTIR. This filament blending technique shows potential, but ultimately issues with diameter control and homogeneity of the resulting material must be addressed before it can be effective in producing materials for this application.

Under this CAN, MSFC completed testing of Stratasys ABS, Filabot ABS, Makerbot ABS, HDPE, LDPE, ABS/LDPE, ABS/HDPE, Pink Poly blends, HIPS, and HIPS/ABS. Testing included Fourier Transform analysis and DSC. DSC tests conditions to determine heat capacity for a polymer sample, as well as determining glass transition temperature and/or heat of fusion for melting crystalline regions in the sample. FTIR provides a summary of functional chemical groups present in the specimen and their relative concentrations. USU characterized performance of several of the blended alloys via combustion testing.

SUMMARY

To date, the feed stock used to print the fuel grain in this propulsion application has been based only on commercially available products. The objective of this work was to explore blending of constituent feedstock materials to significantly improve their performance as rocket fuels while still maintaining sufficient structural integrity. A well-characterized 38-mm hybrid motor system was used to characterize the performance of the blended alloy, with comparisons against the base LDPE and ABS constituents. Although the mix of LDPE and ABS tested did not perform better than LDPE or ABS, this result is likely due to the different stoichiometric oxidizer-to-fuel (O/F) ratios of the respective fuels. Because blended material burns between O/F ratios which are significantly below the optimal O/F ratio for LDPE, the overall blended fuel performance is lower. This effect may be adjusted for by increasing the ABS content and reducing the LDPE content of the blended feed stock in future work. A key unanticipated result of this test series is that it may be possible to blend material ratios in such a manner so as to reduce or completely eliminate O/F shifts during the burn.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Tracie Prater, Marshall Space Flight Center; Stephen Whitmore, Utah State University

FUNDING ORGANIZATION: Cooperative Agreement Notice

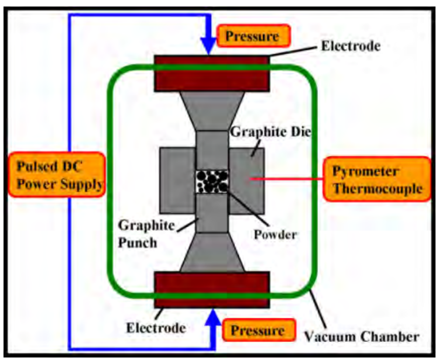
Advanced Processing Techniques to Produce Tooling Materials for Friction Stir Welding of Heat-Resistant Materials

OBJECTIVE: *To evaluate spark plasma sintering processing for producing a fine-grain, single-phase tungsten-25% rhenium alloy.*

PROJECT DESCRIPTION

Through this study, alternative methods for consolidating tungsten-25% rhenium (W-25%Re) alloys were investigated to produce low-cost friction stir welding (FSW) tooling for joining heat resistant materials. The spark plasma sintering (SPS) equipment at the NASA Marshall Space Flight Center (MSFC) provided the opportunity to retain the fine grain size of the starting powders in a rapid consolidation process, thereby overcoming the difficulty and costs associated with hot forging these high-strength and wear-resistant materials. This study has laid the ground work for effective consolidation and processing of W-25%Re alloys for fabricating FSW tooling materials to support the production of improved weld quality and high strength joints in heat-resistant materials such as titanium, nickel-based superalloys and steels.

a.



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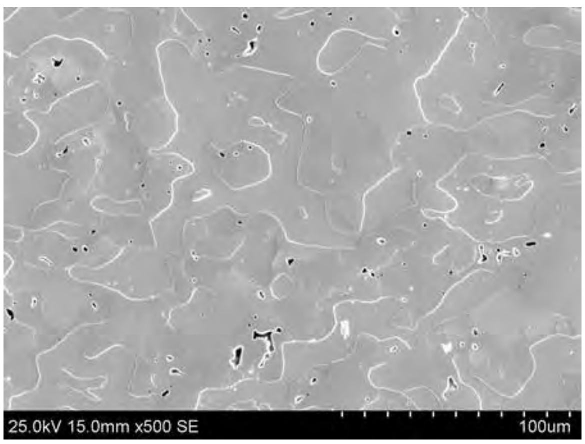


FIGURE 1. Overview of the SPS Process and (b) microstructure of W-25% Re consolidated using the SPS process at 1800 °C for 30 min to achieve 97%TD.

W-25%Re alloys used in high-temperature applications rely on a fine grain size and strengthening achieved by formation of a single solid phase. Past efforts to produce this material relied on high temperature forging and swaging operations to form the single solid phase and refine the microstructure. This processing results in a cost of $1,000 per inch of material, which was limited to diameters of 1.5 in. To promote the use of this alloy for applications such as tooling for FSW processes, a more cost-effective approach must be demonstrated without size limitations. Use of the SPS processing is known for retaining the fine grain size of the starting powders. This project explored the feasibility of using SPS to retain the fine grain size in a single solid phase as a low-cost processing route.

The powders used in this project were provided by in-kind contributions from Re Alloys. Table 1 summarizes the steps taken to evaluate various processing routes and the outcome. While the rapid consolidation of SPS produced fine grain specimens with a density >97% of theoretical density (TD), insufficient time at temperature precluded the formation of the single-phase tungsten-rhenium. The difficulty in forming the single solid phase results from the slow diffusion rate of rhenium into the tungsten phase. Approaches taken to overcome this limitation are summarized in table 1. The next step of this process is to evaluate the use of HIP processing to fully consolidate the material while providing the homogenization heat treatment.

ACCOMPLISHMENTS

While the formation of a single solid phase of W-25%Re was not demonstrated following SPS consolidation, the fine grain size was retained. Postprocessing

Task	Outcome
1) Develop baseline sintering parameters for 45 µm diameter powders.	97% TD at 1,800° C for 30 min produced significant amounts of σ phase.
2) Coat rhenium onto the tungsten powders.	No change from baseline processing.
3) Ball mill powders to refine grain size from 45 to 20 um and shorten the diffusion distance.	Using baseline sintering, a decrease was observed in the amount of σ phase.
4) Repeated application of ball milling with heat treatment of the powders for pre-alloying.	Pre-alloying was demonstrated, although the single phase decomposed following SPS.
5) Post SPS heat treatment at lower temperature to homogenize into single phase.	Pre-alloying was demonstrated, although the single phase decomposed following SPS.

TABLE 1. Summary of processing schemes evaluated.

at 2,350 °C for 5.25 hr was sufficient to homogenize the σ phase to form the desired single-solid phase. Figure 2 shows a summary of the typical phase progression using x-ray powder diffraction (XRD) for the starting powder, SPS consolidated specimen, and after homogenizing treatment at 2,350 °C for 5.25 hr. While the data shown is for the rhenium-coated tungsten powder consolidated to 95% TD, it is typical of the phase evolution in the other samples summarized in table 1.

SUMMARY

Given the effectiveness of homogenizing heat treatment of the SPS consolidated sample, the next step would be to lower the SPS temperature and consider a hot isostatic press (HIP) heat treatment to achieve 100% TD. By lowering the SPS temperature, improvement is obtained in the life of the graphite dies. Achievement of at least 94% TD in specimens consolidated at 1,600 °C for 10 min could be effectively densitified and homogenized in a subsequent HIP process. Shortening the time at this temperature would assist with retention of the fine grain size in a fully consolidated specimen.

The final specimens prepared using SPS have been sent to Re Alloys who will do the HIP processing. If this is effective, a die will be made in the shape of the FSW tool and consolidated using SPS. This will allow characterization of the wear properties during the FSW process of materials such as Incone.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Dennis Tucker, Marshall Space Flight Center; Judy Schneider, University of Alabama in Huntsville

PARTNERSHIP: VRe Alloys (in-kind contributions of powders)

FUNDING ORGANIZATION: Cooperative Agreement Notice

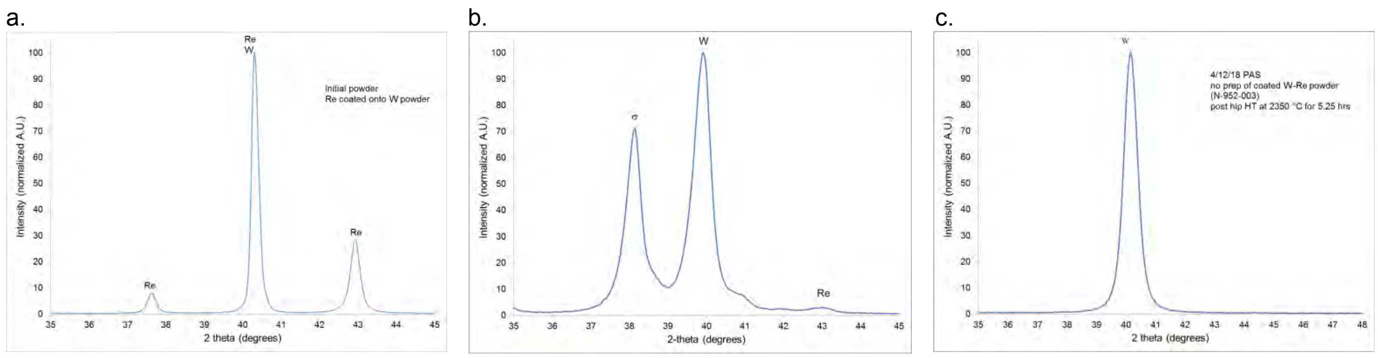


FIGURE 2. (a) XRD analysis of the starting powders, (b) after SPS processing at 1,800 °C for 30 min, and (c) following homogenization heat treatment at 2,350 °C for 5.25 hr.

3D Motion Magnification

OBJECTIVE: *The goal is to create an imagery system and software tools that can be used to determine the motion of a structure during vibration testing.*

PROJECT DESCRIPTION

Traditional structural testing relies on accelerometers and strain gauges to measure the motion due to some applied force. These sensors are accurate, but they only gather data at discrete locations on the test article. One method of gathering the full-field motion data of the structure is through the use of video cameras. A new technique called motion magnification allows for easy measurement and visualization of the static or dynamic structural response. The goals of this project are (a) to develop a time-synchronized stereoscopic imagery system that captures the structural motion data for a large space structure and (b) to create a set of software tools that enable the measurement and easy visualization of the motion.

Examples of motion magnification capabilities are shown in figures 1 and 2. Figure 1 shows the post-buckling deformation of a cylinder. Figure 2 shows the second bending mode of a slender beam captured with an off-the-shelf stereoscopic camera.

Measuring the structural response of a test article requires a group of time-synchronized cameras to measure the motion in all three dimensions. The machine vision cameras used for this project are triggered using a square wave signal from an Arduino electronics platform. The 3D measurements are then combined to measure and visualize the structural motion.

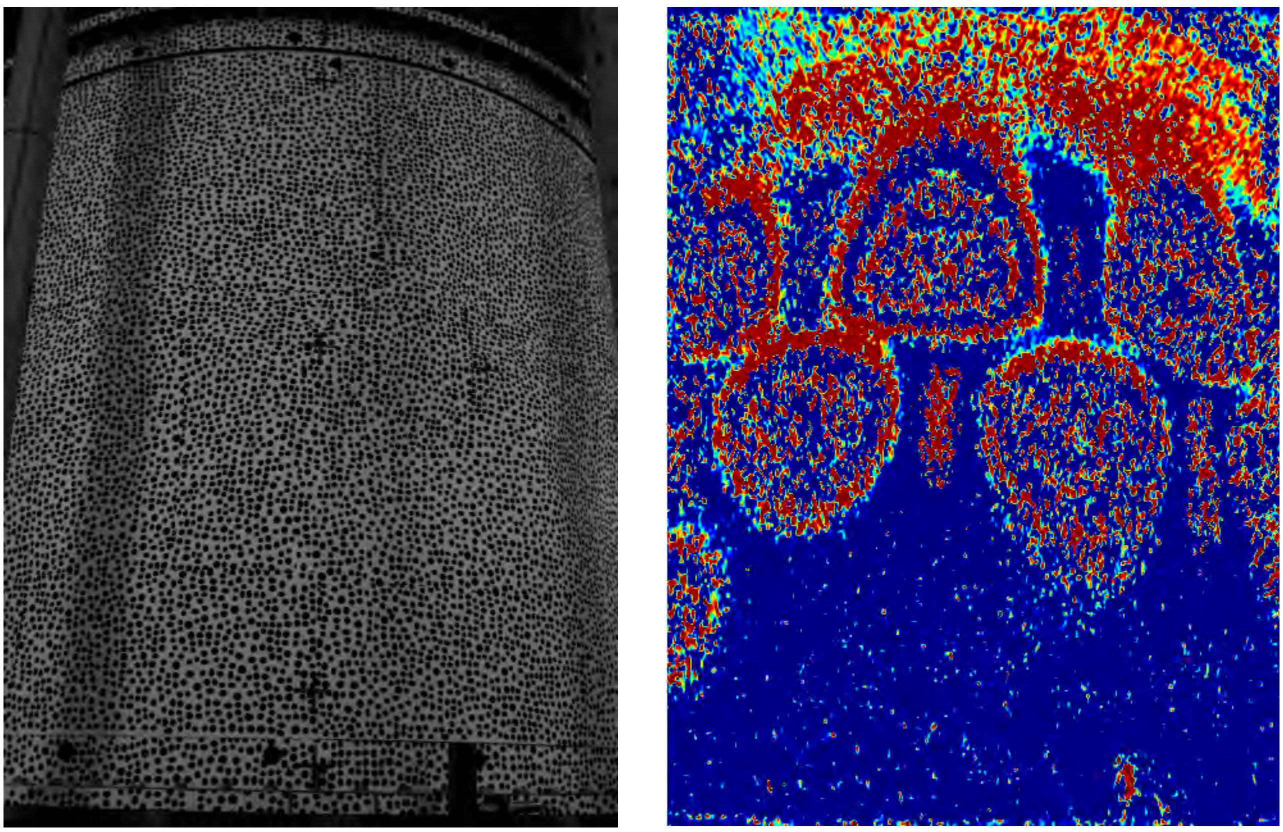


FIGURE 1. Measurement of structural deformation of a large cylinder during failure. Original image (left) compared with the Motion Magnification of the image (right).

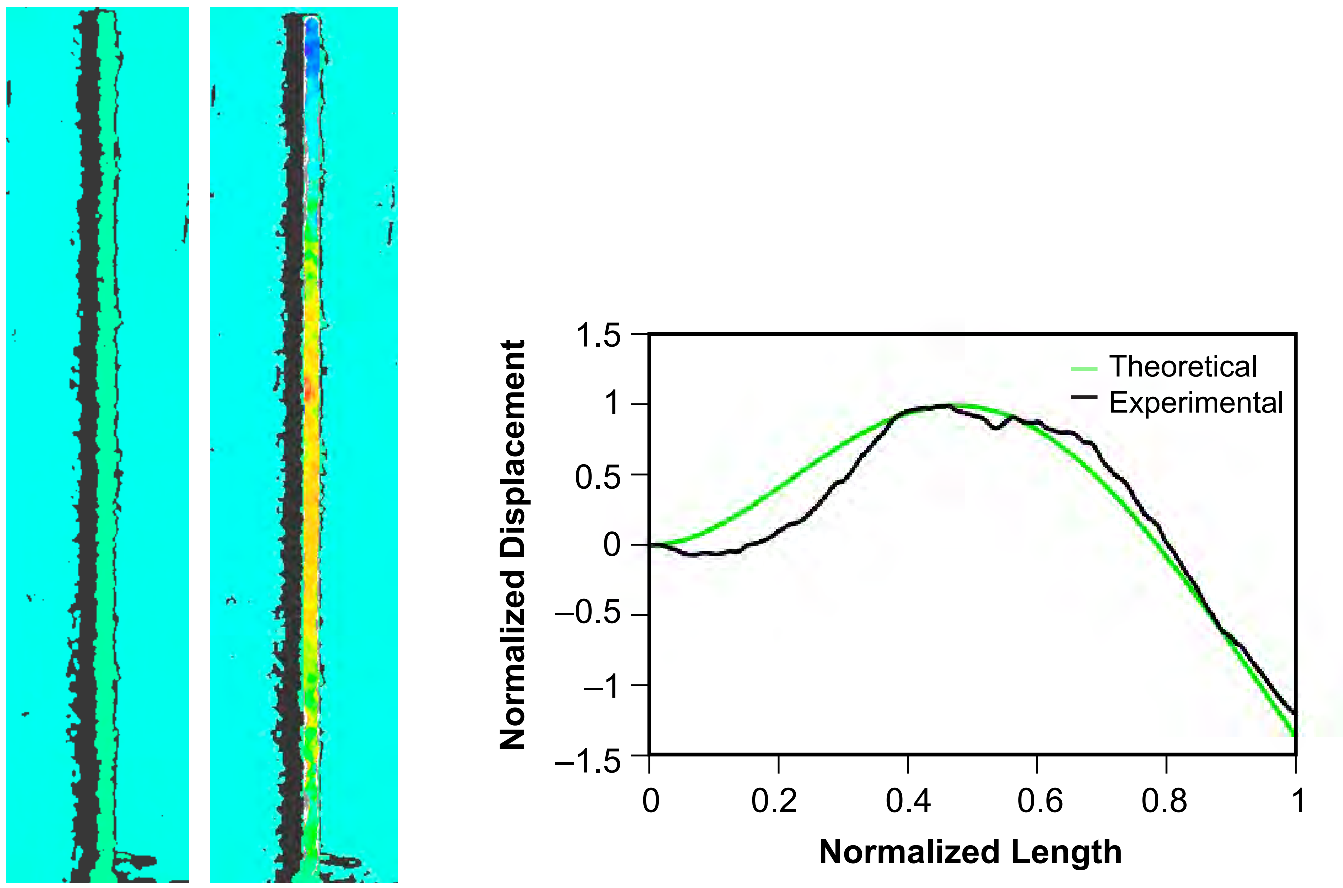


FIGURE 2. Measurement of the vibrational mode of a beam using stereoscopic camera. Original depth measurements (left), depth isolated and magnified about a frequency (middle), and comparison to theoretical results (right).

The visualization of the subpixel motion of the structure will be performed using Motion Magnification. Motion magnification uses a complex steerable pyramid to determine the local spatial phase change between images. The local spatial phase is used to determine the motion of the structure, and it can be amplified and added back into the video so that the structural motion is 'magnified' and easily visualized. Amplification of the local spatial phase has not previously been performed in 3D nor with multiple cameras.

After motion magnification for stereoscopic imaging, we want to implement motion magnification for an array of cameras in any arbitrary orientation relative to the structure. This will allow for measurement of large structures where obstacles prevent line-of-sight measurement of the entire test article.

PROJECT MANAGERS AND/OR PRINCIPAL INVESTIGATORS: Eric C. Stewart

FUNDING ORGANIZATION: Seedling Investment Program

GROUND AND LAUNCH SYSTEMS

Distributed Vibration Suppression Technology

OBJECTIVE: *To design, develop, and prototype distributed vibration suppression technology and compare its vibration mitigation performance to standard tuned mass damper technology.*

PROJECT DESCRIPTION

Distributed vibration suppression (DVS) utilizes NASA's award-winning phased mass (PM) technology. It employs multiple PM units distributed throughout a given structure. This distributed approach yields a high-performance, lightweight vibration mitigation system that addresses NASA's needs by managing launch vehicle structural dynamics problems such as thrust oscillation, wind induced vibration, and propellant slosh. In addition, DVS addresses national needs such as earthquake mitigation in buildings and bridges.

This Tech Tank-funded DVS development project will empirically and analytically compare the mitigation performance of DVS technology to standard tuned mass damper (TMD) technology in a 15-ft-tall scaled launch vehicle/building model. TMD and PM embodiments will be optimized and parametrically tested in multiple configurations to validate analytical models. Low, upfront NASA expenditure will leverage existing PM research supported by multiple subject matter experts (SMEs).

State of the art vibration mitigation systems include large mass TMDs and active control systems that can be heavy and exhibit multiple failure modes. PMs have been shown to perform significantly better than TMDs for vibration mitigation. NASA missions that will benefit from DVS technology include large space structures such as: International Space Station, Mobile Launcher, Space Launch System, and space observatories.

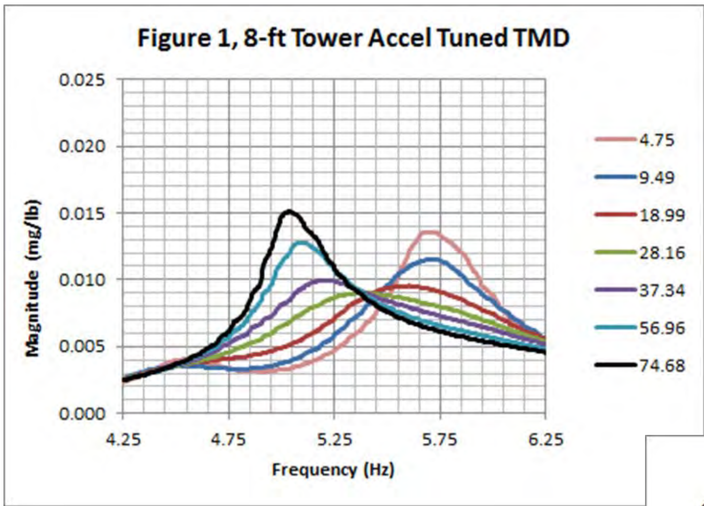
In Los Angeles, California, recent laws have stipulated that 15,000 structures must be modified to improve earthquake survivability. These new laws have created a $1.5 billion market. Two examples of the impact earthquakes can have include the 1994 Northridge earthquake and the 1976 Tangshan earthquake. Northridge was a 6.7 magnitude event that injured 8,700 people and led to 57 deaths. Property damage was approximately $50 billion. Tangshan was a 7.8 magnitude event that severely injured an estimated 164,000 people and led to approximately 650,000 deaths. Property damage was approximately ¥10 billion.

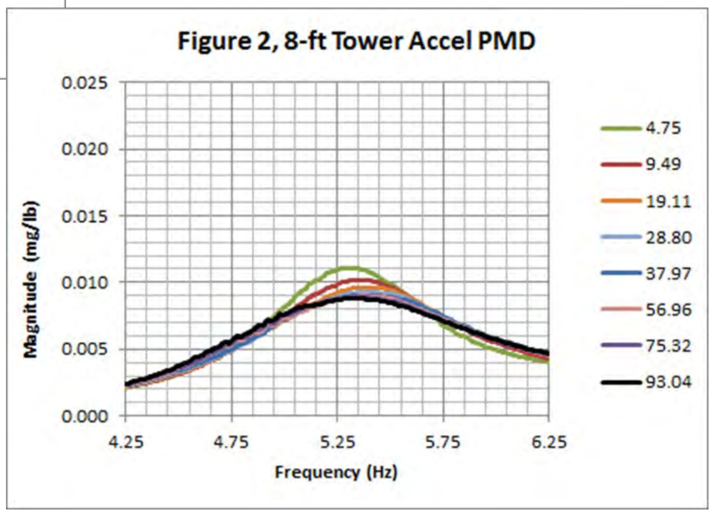
ACCOMPLISHMENTS

Initial activities have been focused on the development of a new phased mass damper (PMD). The new concept employs a hybrid damping approach that relies on a combination of damping mechanisms to achieve optimal vibration mitigation performance at low, medium, and high-vibration amplitudes. Standard TMD attenuators can be an effective vibration suppressor when optimally tuned. However, performance of the standard TMD attenuator is severely limited when exposed to extreme excitations that vary significantly over time in magnitude and contain a wide range of excitation frequencies. The damping element of the PMD is very different than the damping element used in a standard TMD. This new damping concept allows the PMD to remain in an optimum configuration throughout small, medium, large, and huge displacements.

Multiple PMD embodiments have been assembled and evaluated in an existing eight-ft-tall mini tower structure. Parametric force linearity sine-sweep testing techniques were used to characterize the modal response characteristics of the mini tower across a wide range of excitation force magnitudes. Acceleration over force frequency response functions were recorded. Modal parameters such as frequency and damping along with the peak mgs/lb quantified damper vibration mitigation performance.

Figures 1 shows a series of frequency-response function results of the force-linearity sine sweeps tests conducted with the mini tower configured with standard TMD mitigation, while figure 2 details the PMD-equipped mini tower. Each trace on the plots corresponds to a specific sine sweep peak-to-peak excitation force measured in pounds. The plots clearly show how the system response characteristics change as





excitation force increases. Because it is a narrowband device, the conventional TMD system performs with optimum attenuation at only one excitation amplitude. TMD attenuation performance rapidly degrades as excitation amplitude increases. The PMD system, on the other hand, remains at optimum attenuation performance across the entire range of excitation amplitude.

Over the next 4 months, the PMD embodiments will be miniaturized and the 15-ft-tall test structure will be assembled. Multiple PMDs will be then integrated into the structure, and force-linearity sine sweep tests will be conducted.

SUMMARY

Significant progress has been accomplished to develop viable PMD technology for this Tech Tank-funded research activity. In fact, the project has only been active for 2.5 months, yet multiple PMD embodiments have been empirically investigated. Early tests results are promising and the overall activity is on schedule. Near-term actions will involve the assembly of the 15-ft test tower along with integration of four PMD embodiments.

PRINCIPAL INVESTIGATOR: Jeff Lindner, Linc Research, Inc.

FUNDING ORGANIZATION: Seedling Investment Program

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Many of NASA's missions would not be possible if it were not for the investments made in research advancements and technology development efforts. The technologies developed at Marshall Space Flight Center contribute to NASA's strategic array of missions through technology development and accomplishments. The scientists, researchers, and technologists of Marshall Space Flight Center who are working these enabling technology efforts are facilitating NASA's ability to fulfill the ambitious goals of innovation, exploration, and discovery.

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