2021
SSERVI ANNUAL REPORT

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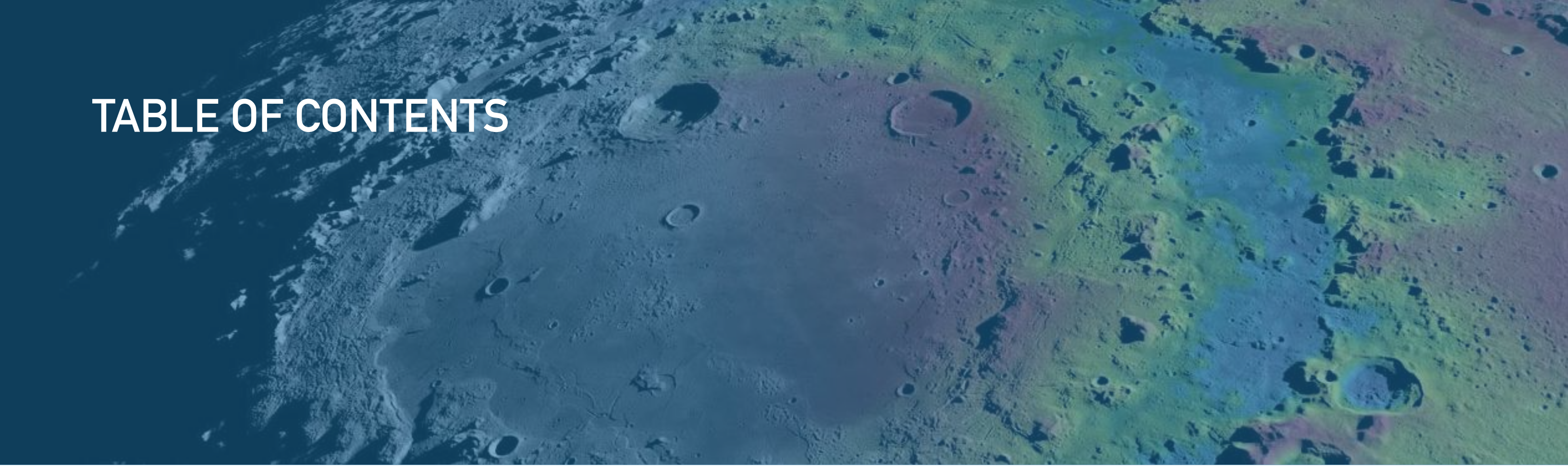
SOLAR SYSTEM EXPLORATION RESEARCH
VIRTUAL INSTITUTE



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FROM THE BRIDGE

Dear Exploration Science community,

We're delighted to present the 2021 SSERVI annual report. This report summarizes the SSERVI-funded work undertaken this year to advance human and robotic exploration of the Moon and other target destinations in support of Artemis and other NASA missions, as well as work undertaken by SSERVI international partner organizations. NASA is moving forward quickly with its plans for a lunar renaissance that includes the first human mission to the Moon in almost five decades, landing the first woman and first person of color on the Moon, engaging commercial space with the NASA Commercial Lunar Payload Services (CLPS), and the Volatiles Investigating Polar Exploration Rover (VIPER) that will go to the lunar South Pole to prospect for water ice and other resources, amongst many other activities that SSERVI is proud to be a part of.

The Agency is doing all of this in the context of an ongoing pandemic, and SSERVI continues to play an important role in connecting our community through virtual events, and by developing the tools and technology for virtual events of the future. SSERVI has a rich history of conducting hybrid meetings with in-person and virtual participants and continues to push the state-of-the-art by testing new collaborative technologies for exploration science. In 2021, innovations using platforms such as Zoom and Gather.Town resulted in a positive shift in the way our online meetings were conducted which broadened participation when circumstances didn't allow in-person attendance. For example, the combined NASA Exploration Science Forum (NESF) and European Lunar Symposium (ELS) had 3000 unique users from over 40 countries across its websites, posters, etc., with some participants calling it "one of the best online conferences to date." Lunar exploration is a global endeavor, and the virtual summit facilitated the cooperation of various NASA, European, and SSERVI partners. It also supported development of the next generation through representation on the Science Organizing Committee, Next Gen session co-chairs. throughout the meeting, a networking event and student poster competition, and through hosting the student-led LunGradCon forum. The new meeting format later served as a model for other virtual conferences, including the NASA Planetary Science Division's Lunar Surface Science Workshops. Through its research, SSERVI is also actively testing new rover concepts, the use of Augmented Reality/Virtual Reality (AR/VR) and the role of the 'metaverse' concept in scientific research, and will continue to develop collaborative technologies in support of the Lunar Exploration Advisory Group (LEAG) and other agency level groups and tasks.

At the request of NASA's Associate Administrators for the Science Mission Directorate (SMD) and Human Exploration Operations Mission Directorate (HEOMD, now the Exploration Systems Development Mission Directorate ESDMD), and in response to the mid-term Planetary Science Decadal Survey, a Senior Review Panel was tasked with conducting a comprehensive SSERVI Review in 2021 for the first time in the history of the institute, covering the period from the founding of NLSI in 2008 to the present. SSERVI Central submitted over 250 pages of data in response to the panel's specific questions in evaluating the progress made by the virtual institute, its impact on the advancement of planetary science and exploration, and its leadership in the field of planetary science. The Senior Review Panel findings were published in a report entitled "Enabling Planetary Science and Exploration" which provided helpful direction and unleashed potential ideas to help move SSERVI forward in the Artemis era. SSERVI embraces the panel's conclusions and looks forward to working with the community across directorates and agency stakeholders to implement these important findings.

We will not go to the Moon and beyond without winning the hearts and minds of the American public. SSERVI Central, SSERVI Teams, and SSERVI's international partners all conduct both individual and integrated outreach efforts in support of NASA's and other space agencies' overarching public engagement efforts. SSERVI strives to be an agent of change in science culture, and places a high priority on bringing compassion and inclusivity to the scientific community. We are proud to have an active Equity, Diversity, Inclusion and Accessibility (EDIA) focus group which has already begun to have impacts; we develop connections between career and next generation scientists to help young people get a positive start in their career journeys; we promote kindness, fellowship, and mentorship in science to increase empathy; and we do all this to empower others and build a more diverse and inclusive community. My hope is that in so doing, we can propel NASA's ambitious plans for the Moon and beyond while ensuring that space science and human exploration are for all people.

Ad astra,

Gregory Schmidt
SSERVI Director

SSERVI Central Office

As a virtual institute, SSERVI funds a range of U.S. teams and facilitates collaboration among teams, as well as commercial and international partners, to advance science and exploration. The SSERVI Central Office exercises overall leadership of the institute, setting strategic direction and managing domestic teams. It promotes the institute's research to NASA Headquarters and the planetary science and exploration communities. The SSERVI Central Office also supports the planetary science community, with a strong focus on the next generation and diversity, and actively advances Information Technology adoption and production for better virtual collaboration.

In support of these objectives, SSERVI Central has a team with a broad set of expertise that includes:

- Administration/Management
- Lunar & Planetary Science
- Data Visualization
- Partnerships
- Scientific & Technical Writing
- Facility Management
- Executive Administrative Support
- Training
- Public Engagement
- Virtual Collaboration Production
- Web Development
- Content Development / Graphic Design

PROMOTE

Science Exploration Support for SSERVI & Community

Administration for 12 P.I. Teams
Research Solicitation, Selection & Management
Collaboration Facilitation Through Executive Council & Site Visits
Focus Groups
Exploration Initiatives and Support
Advocacy & Reporting w/ SMD, HEOMD, & STMD
Strategic Vision / White Papers
Science Dissemination
NASA Exploration Science Forum / Focused Workshops
LEAG & SBAG Support
ELS / Pan-European Collaboration
Inclusion, Diversity, Equity, and Accessibility Initiatives
Mission Support (e.g. RP, ISEEE, LOIRP, ALSEP)
International Partnerships
Commercial Engagement
Solar System Treks Program Management
Regolith Testbed Facilities Management
Professional Research Travel Support

TRAIN

Next Gen Support

NASA Postdoctoral Program
Lunar and Small Bodies Graduate Conference (LunGradCon)
Next Generation Lunar Scientists and Engineers (NGLSE) Support
Student Internships and Analog Field Opportunities
Student Exchange / Travel
Teacher Training
Robotics Competition Support (Judging, Speaking)

INSPIRE

Public Engagement

Lead Coordination of SSERVI Team Public Engagement Working Group
Support and Advocacy for Fireballs in the Sky & Global Fireball Network Expansion
Student Engagement (K-Undergraduate)
Journey Through the Universe Support (Native Islander Program)
Student Science Clubs
Braille Books (Accessibility)
Special Event Support (e.g. 2017 Eclipse, InSight Launch, International Observe the Moon Night)
Public Engagement via Website & Social Media

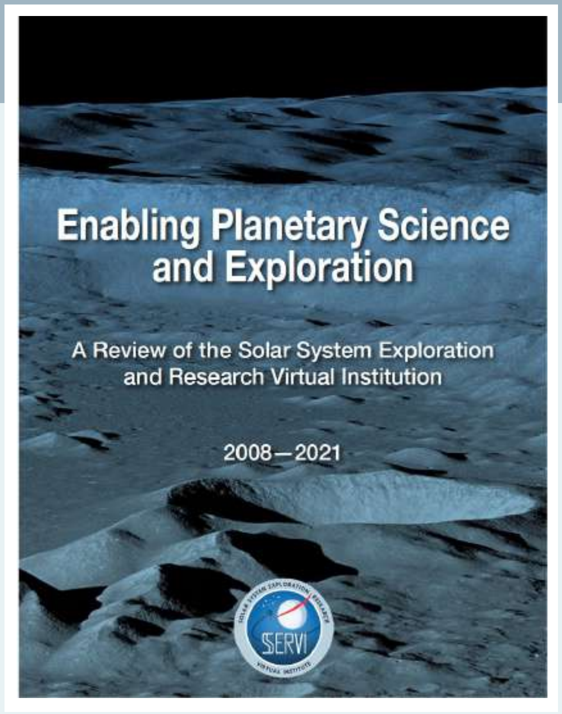
CONNECT

Collaborative Technology

Virtual Event Production for SSERVI Events & Teams
Exploration Science Forum
SSERVI Workshops Without Walls
Community Workshops (e.g. SBAG)
NASA HQ (SMD & HEO) (e.g. GER, NESSF Reviews, LSSW)
SSERVI Team Seminar Series
SSERVI & Community Website Development & Management
NASA IT Security Plan & Management
New Collaborative Technology Testing & Implementation
Silicon Valley Partnerships

SSERVI Senior Review

After a review of virtual institutes was recommended by the previous Planetary Decadal midterm review, an independent committee was chartered by the NASA Planetary Science Division (PSD) to comprehensively review SSERVI since its inception as the NASA Lunar Science Institute (NLSI). The committee was Chaired by Cindy Evans (JSC) and Chip Shearer (UNM) with NASA Headquarters oversight. SSERVI submitted over 250 pages of data in response to specific questions from the Committee and made a 5 hour presentation as they conducted the formal Institute Review. The Review Panel findings were published in a report titled “Enabling Planetary Science and Exploration: a Review of the Solar System Exploration and Research Virtual Institution,” which provided helpful direction and unleashed potential ideas to help move us forward in the Artemis era. Additionally, on invitation, SSERVI leadership presented an overview of SSERVI and provided information to the Moon and Mercury panel of the Planetary Decadal Survey; subsequent recommendations were in line with the SSERVI senior review recommendations.



The Committee report is available at: https://www.lpi.usra.edu/NASA-academies-resources/sservi-report-300-dpi-01072022.pdf

Key recommendations:

• SSERVI should continue, with support from both NASA’s science and human exploration enterprises

• The upcoming SSERVI CAN should have a focus on the Moon

NASA’s response to the Committee’s findings and recommendations can be found at: https://www.lpi.usra.edu/NASA-academies-resources/PSD-RESPONSE_FINAL.pdf

SSERVI continues working with its key stakeholders—including NASA’s Mission Directorates, research teams, and international partners—to advance the goals of Artemis and enable a new era of human exploration of the Moon.

Exploration Science enables human exploration or results from it. The guiding principle is **science enables exploration, exploration enables science[1].**

The Solar System Exploration Research Virtual Institute (SSERVI)

is a Virtual Institute at the intersection of science and exploration. It is comprised of a global network of dispersed, interdisciplinary researchers collaborating to address key fundamental science and human exploration questions. The scope of SSERVI research includes NASA's top destinations for human explorers, including NASA's bold plan to go forward to the Moon and beyond through the Artemis Program.

1.This phrase was first developed by Mark Robinson, P.I. for LROC, and popularized by Mike Wargo, former NASA ESMD Chief Scientist.

PROMOTE

A full-scale replica of an early design of NASA's Artemis water-hunting mobile Moon robot, the Volatiles Investigating Polar Exploration Rover, or VIPER. Credits: NASA/David Petri

SSERVI PRINCIPAL INVESTIGATORS

Prof. Daniel Britt
Center for Lunar and Asteroid Surface Science (CLASS)
University of Central Florida, Orlando

Prof. Jack Burns
Network for Exploration and Space Science (NESS)
University of Colorado, Boulder

Dr. Jeffrey Gillis-Davis
Interdisciplinary Consortium for Evaluating Volatile Origins (ICE FIVE-0)
Washington University in St.Louis

Prof. Timothy Glotch
Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2)
Stony Brook University

Dr. Jennifer Heldmann
Resource Exploration and Science of OUR Cosmic Environment (RESOURCE)
NASA Ames Research Center

Dr. Amanda Hendrix
Toolbox for Research and Exploration (TREX)
Planetary Science Institute

Prof. Mihaly Horanyi
Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)
University of Colorado, Boulder

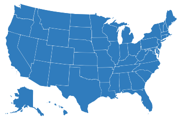
Dr. Rosemary Killen
Lunar Environment And Dynamics for Exploration Research (LEADER)
NASA Goddard Space Flight Center

Dr. David Kring
Center for Lunar Science and Exploration (CLSE)
Lunar and Planetary Institute

Prof. Thomas Orlando
Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)
Georgia Tech

Dr. Alex Parker
Exploration Science Pathfinder Research for Enhancing Solar System Observations (ESPRESSO)
Southwest Research Institute

Dr. Nicholas Schmerr
Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES)
University of Maryland



12 Domestic Teams

23% FEMALE
77% MALE

11 International Partners

CAN-2 + CAN-3 RESEARCHERS

457 Total Individual Team Members* (55 on multiple teams)

264 Individual Domestic Funded Researchers

139 Individual Domestic Collaborators (Unfunded)

54 International Collaborators (Unfunded)

*as proposed

23 VIRTUAL EVENTS

515 VIRTUAL PRESENTATIONS

SUPPORTED FOR SSERVI AND COMMUNITY

Virtual Events	
ECs	10
NESF + ELS	1
Focus Groups	3
Workshops / Seminars	1
LSSW	7
Town Hall	1
GatherTown Networking	2

Virtual Presentations	
NESF + ELS	184
Focus Group Meetings	30
Workshops / Seminars	25
LSSW	275
Town Hall	1
GatherTown Posters	222

SSERVI PUBLICATIONS
2014-2021

1138 SSERVI PEER REVIEWED PUBLICATIONS

23% student involved publication

14% cross team collaboration

22% international collaboration

WEBSITE ANALYTICS

243,230K Users on Main SSERVI Website

TWITTER FOLLOWERS

133.1K

SSERVI RESEARCH CONTRIBUTES TO:

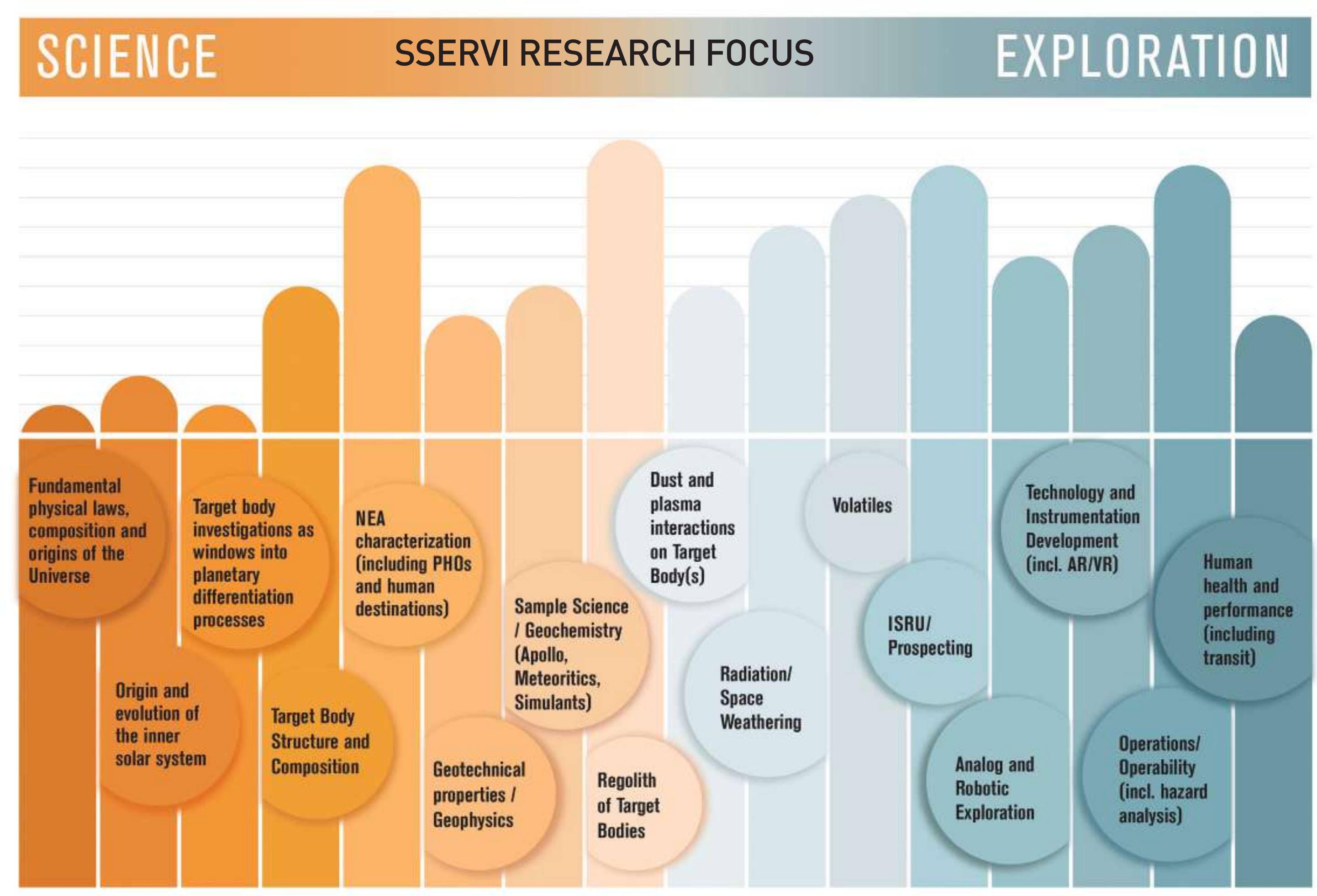
25 NASA MISSIONS

5 OTHER AGENCY MISSIONS

12 MISSION CONCEPTS

12 SPACEFLIGHT INSTRUMENTS

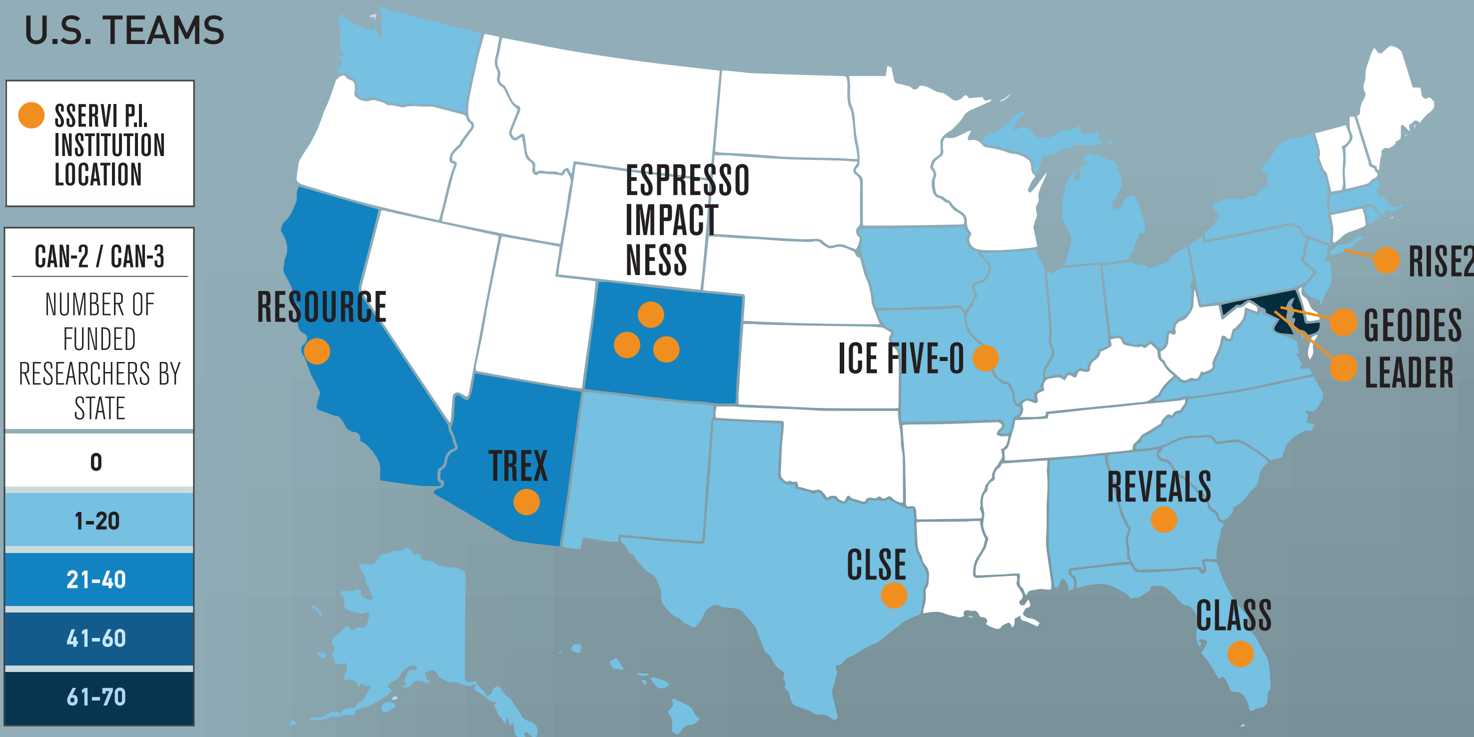
In addition, SSTP provides additional support for mission planning and proposals



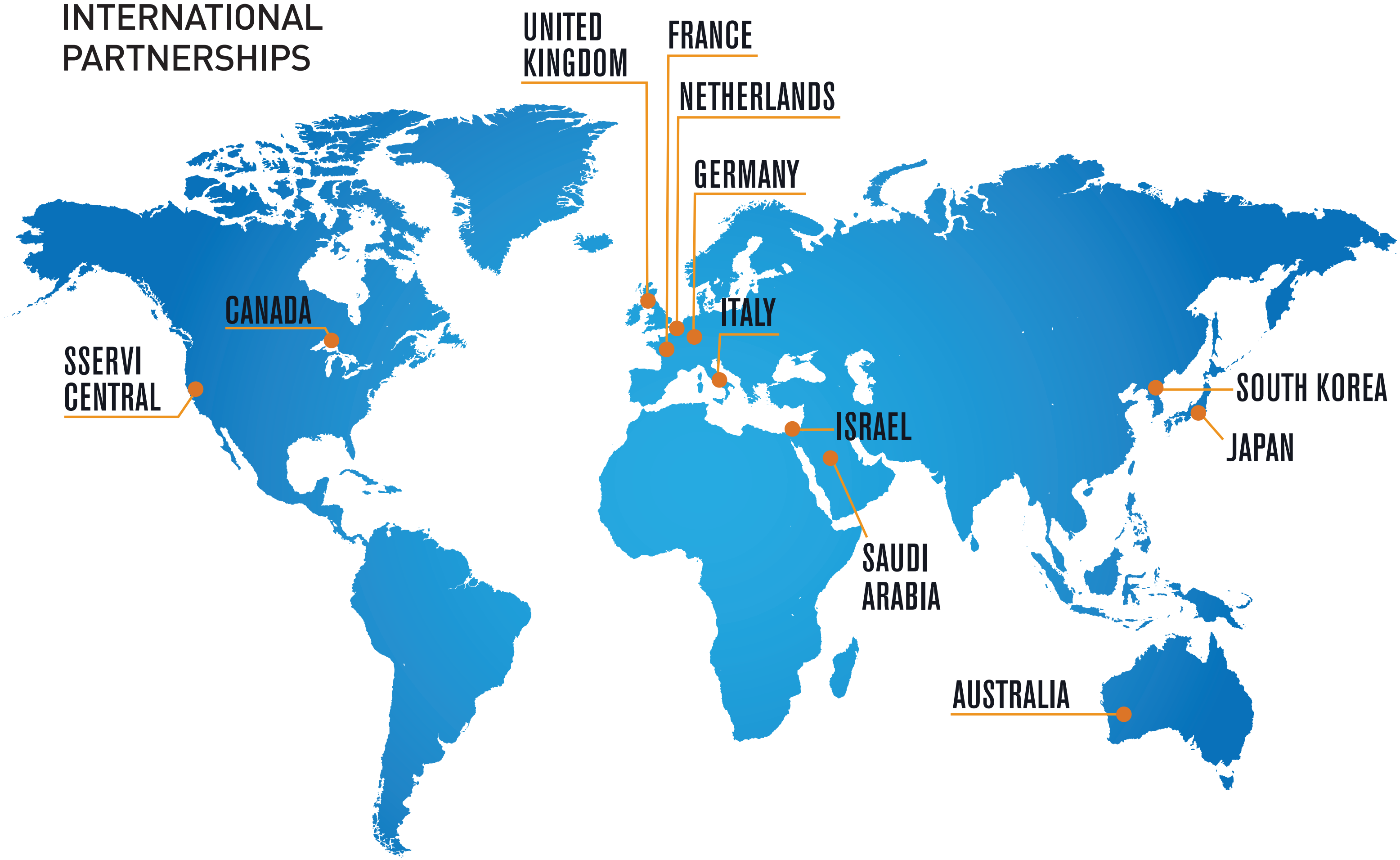
SSERVI research spans the spectrum of fundamental science to human exploration. This chart represents the research focus areas and the bar chart represents the number of SSERVI teams that are addressing a given research area as part of their proposed science.

Starting with the NASA Lunar Science Institute (NLSI), SSERVI has awarded 5-year cooperative agreements to selected teams. This graphic shows the historical timing of all previous CANs, and identifies the timing for the planned SSERVI CAN-4.

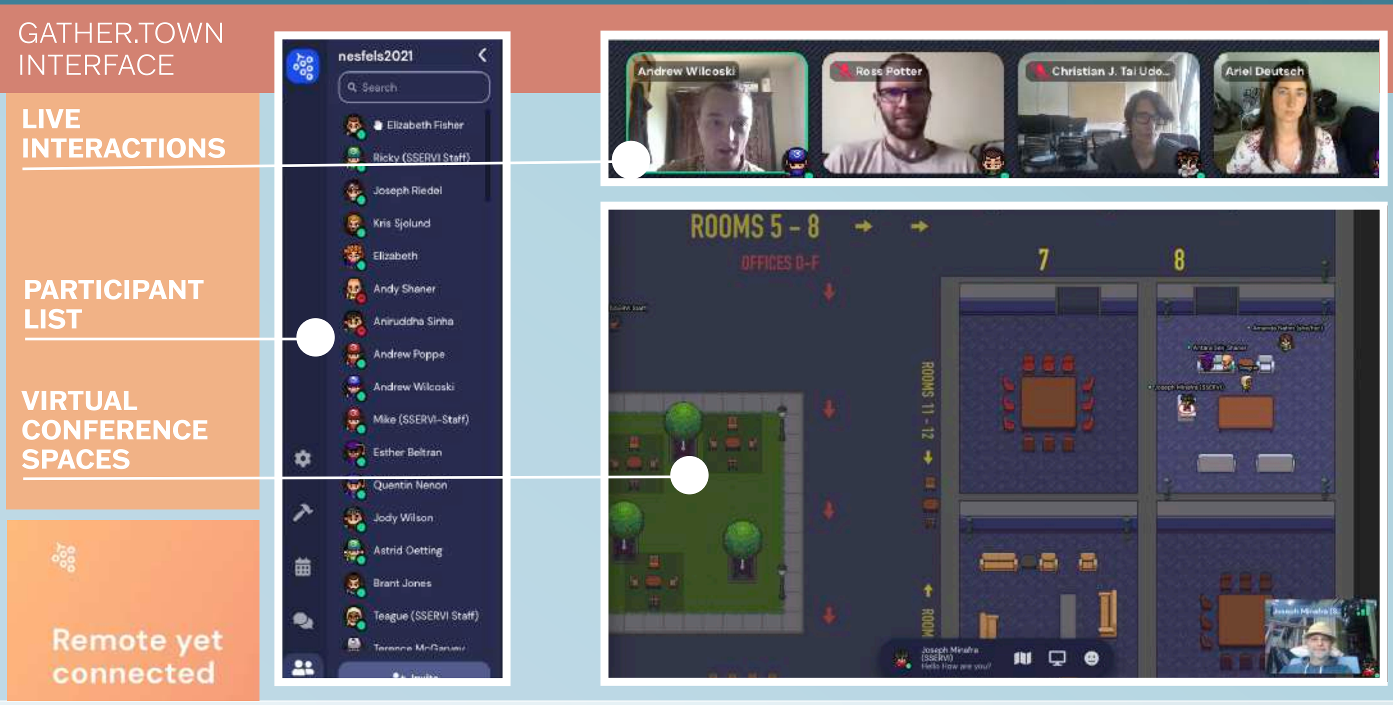
SSERVI U.S. TEAMS



SSERVI INTERNATIONAL PARTNERSHIPS



NASA EXPLORATION SCIENCE FORUM and EUROPEAN LUNAR SYMPOSIUM 2021



NASA EXPLORATION SCIENCE FORUM & EUROPEAN LUNAR SYMPOSIUM

The NASA Exploration Science Forum (NESF) is focused on sharing scientific discoveries that relate to human exploration, connecting scientists and engineers, and promoting the Next Generation of explorers. In addition, the NESF has provided a venue for the NASA Administrator, as well as directors of SMD/PSD and HEOMD/AES and the NASA Chief Scientist, to address the exploration science community. Annual highlights include talks from NASA officials, presentations and posters showcasing cutting-edge science, sessions focused on equity, diversity, inclusion and accessibility, professional awards and community recognition, international missions and contributions (eg, JAXA/ESA efforts), and NextGen professional development opportunities (serving as session chairs, student lightning talks, poster competition, travel awards, etc.).

With NASA's Artemis program engaging global partnerships, the opportunity for international collaboration has never been greater. This year the NASA Exploration Science Forum (NESF) was combined with the European Lunar Symposium (ELS) to bring the international exploration science communities together to share new, exciting results in a wide range of fields encompassing exploration science. SSERVI and its European partner organizations jointly co-hosted the 2021 NASA Exploration Science Forum & European Lunar Symposium as a virtual meeting, with a new virtual format to facilitate networking and collaborative opportunities for novel lunar science experiments.

A first look at the new virtual format revealed the Gather.Town Experience was not your average Zoom meeting. SSERVI was thrilled to host an immersive poster and networking experience through Gather.Town. During the poster sessions, each poster presenter had their own virtual space in Gather.Town. Our goal was to have a minimum of three people attend every poster and to make sure our student researchers had plenty of visitors.

EXPLORATION SCIENCE FORUM and EUROPEAN LUNAR SYMPOSIUM EVENT HIGHLIGHTS

WHAT HAPPENED, VIRTUALLY

- Scientific Exchange
- Bringing the Community Together in Novel Ways
- Promoting the Next Generation of Exploration Scientists
- Creating Bridges – Between Science and Exploration, and Between International Partners
- Opportunity for Discussion Regarding Equity, Diversity, Accessibility and Inclusion and Sustainable Exploration
- On-Demand Playback--Our production team made all individual talks and full-day recap videos available for on-demand playback

WEBSITE STATS

- NESF website viewed 17,000 times
- Poster pages have been viewed 1762 times
- 200+ additional social clicks
- 350 unique Gather Town users during NESF

Total Unique Users: 2,658

ATTENDEE DATA

7,200 attendees from the United States

652 attendees from the United Kingdom

422 attendees from Germany

418 attendees from India

318 attendees from Canada

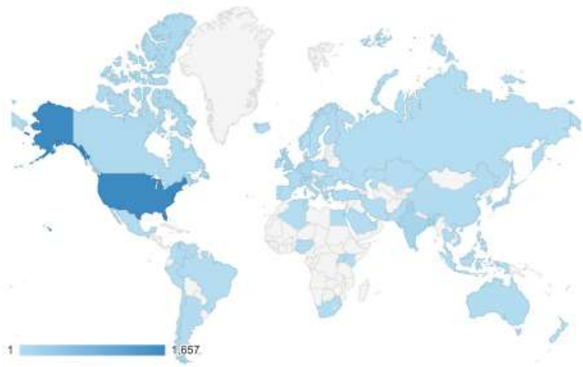
253 attendess from Italy

155 attendees from France

118 attendees from Netherlands

114 attendees from Australia

63 attendees from Japan



Once again in 2021, SSERVI Central Staff produced the Exploration Science Forum and European Lunar Symposium remotely

NASA EXPLORATION SCIENCE FORUM AWARDS

Each year at the NESF SSERVI presents awards as a means of honoring key individuals in the community: The Eugene Shoemaker Medal for lifetime scientific achievement, the Michael J. Wargo Award for outstanding achievement in Exploration Science, the Susan Mahan Niebur award for early career achievement, and the Angioletta Coradini Mid-Career Award.

AWARD NOMINATIONS

SSERVI awards are open to the entire research community; recipients need not reside in the U.S. nor be a U.S. citizen.

Nominations are welcome at any time at: https://sservi.nasa.gov/awards/submit but must be submitted by March 31st for consideration in that calendar year. Winners are formally presented with the awards at the annual Exploration Science Forum each summer.

More information on these awards and recipients, along with past awardees, can be found at:
https://sservi.nasa.gov/awards

Eugene Shoemaker Distinguished Scientist Medal

Paul G. Lucey

The 2021 Eugene Shoemaker Distinguished Scientist Medal, named after American geologist and one of the founders of planetary science, Eugene Shoemaker (1928-1997), is awarded to Paul G. Lucey for his significant scientific contributions throughout the course of his career. The award includes a certificate and medal with the Shakespearian quote "And he will make the face of heaven so fine, that all the world will be in love with night." Professor Paul G. Lucey is faculty at the Hawaii Institute of Geophysics and Planetology (HIGP) at the University of Hawaii, Manoa. His research in planetary science and remote sensing has been "instrumental" in developing imaging spectrometers for NASA. In addition to furthering human exploration of the solar system, he's also been busy at home saving planet Earth: when it was discovered that coral had a unique spectral signature or color, he helped map the abundance of living coral for every known reef in the world-- a revolutionary feat, like finally knowing how many trees are in the forest. He has served on many national review and advisory committees, has been the principal investigator of numerous NASA programs, and has gone on to use hyperspectral imagery to efficiently map lunar materials. Most recently his research on the composition of the lunar crust has led to quantitative modeling of near-IR spectra of the Moon, and he has closely studied diverse rock types detected in the lunar South Pole–Aitken Basin by the Chang'E-4 lunar mission. Dr. Lucey is a member of the SSERVI ICE FIVE-O team modeling the physical, chemical, and isotopic signatures around the lunar poles. He is an editor of the Journal of Geophysical Research, has published extensively with over 100 publications in prestigious journals, and is the co-inventor of multiple patents. Dr. Lucey's significant contributions across many disciplines--from engineering new instruments to scientific data analysis-- make him an admirable recipient of the 2021 Shoemaker Medal.

Michael J. Wargo Exploration Science Award

Darlene Lim

The Michael J. Wargo Exploration Science Award is an annual award given to a scientist or engineer who has significantly contributed to the integration of exploration and planetary science throughout their career. Dr. Michael Wargo (1951-2013) was Chief Exploration Scientist for NASA's Human Exploration and Operations Mission Directorate and was a strong advocate for the integration of science, engineering and technology. The 2021 Michael J. Wargo Exploration Science Award is given to Darlene Lim, research scientist at the NASA Ames Research Center. Dr. Lim has spent over 25 years conducting field research programs around the world, on land, and underwater, where she has piloted submersibles as a scientist and explorer. She graduated from Queen's University and received her PhD in Geology from the University of Toronto, Canada. She is currently the Deputy Project Scientist for the NASA VIPER Lunar Rover Mission, and also leads several NASA-funded research programs focused on blending field science with new Concepts of Operations for human and robotic teams. She is the Principal Investigator of the BASALT, SUBSEA, and Pavilion Lake research programs, Deputy PI for FINESSE, and Science Ops lead for RESOURCE. Her field science research programs are focused on developing human exploration tools, technologies, and concepts that serve to directly inform various NASA Design Reference Missions. She is blending field science research and exploration concepts that will enable scientists and future human explorers of the Moon and Mars. She has served on a number of NASA Mars Exploration Program Analysis Group committees and is currently serving on the NOAA Ocean Exploration Advisory Board, and the NASA Network for Ocean Worlds Steering Committee. We are very grateful she is part of this program and team; her efforts at integrating exploration and planetary science would make Mike Wargo proud!


Timothy Glotch

Angioletta Coradini Mid-Career Award

The SSERVI Angioletta Coradini Mid-Career Award is given annually to a mid- career scientist for broad, lasting accomplishments related to SSERVI fields of interest. Angioletta Coradini (1946-2011) was an Italian planetary scientist who has inspired astronomers around the world. The 2021 Angioletta Coradini Mid-Career Award is given to Dr. Timothy Glotch at Stonybrook University. Timothy Glotch is Professor of Geosciences and Associate Dean for Operations and Facilities, for the College of Arts and Sciences at Stonybrook University. He received his BA in astro-geophysics from Colgate University and his PhD in geological sciences from Arizona State University. He is a Co- Investigator on the Lunar Reconnaissance Orbiter Diviner Lunar Radiometer instrument and a Participating Scientist on the OSIRIS-REx asteroid sample return mission. He combines terrestrial analog field work, infrared remote sensing, and laboratory spectroscopy to better understand the composition of the crusts of Mars, the Moon, and small bodies. As a planetary scientist studying the formation and evolution of asteroids and the crusts of the Moon and Mars, he has used various NASA Mission data to enable a more quantitative analyses of remote sensing data for these planetary surfaces. His regolith research and spectroscopic measurements of terrestrial and extraterrestrial samples in simulated environments have substantially contributed to a quantitative remote sensing of the surfaces of the Moon, Mars, and small bodies. In addition, Dr. Glotch has been a Principal Investigator of two SSERVI teams (RIS4E and RISE2) and has led the effort of over 50 researchers and students in using state-of-the-art laboratory, theory, and field techniques to further NASA's science and human exploration goals. He exemplifies the teacher- scholar through the integration of outstanding research and education. Even mid-career, he has already received numerous NASA Group Achievement awards for his various mission involvement, as well as the National Science Foundation's prestigious Faculty Early Career Development (CAREER) program award. He has authored or co-authored more than 40 publications appearing in various journals, including: Science, Nature, Journal of Geophysical Research, Geology, Physics and Chemistry of Minerals, Earth and Planetary Science Letters, and has served as Associate Editor for JGR- Planets. He is most deserving of the 2021 Angioletta Coradini Mid-Career Award, congratulations!

Susan Mahan Niebur Early Career Award

The Susan Mahan Niebur Early Career Award is an annual award given to an early career scientist who has made significant contributions to the science or exploration communities. Recipients of the Susan M. Niebur Early Career Award are researchers who are no more than ten years from receiving their PhD, who have shown excellence in their field and demonstrated meaningful contributions to the science or exploration communities. Susan Mahan Niebur (1978-2012) was a former Discovery Program Scientist at NASA who initiated the first ever Early Career Fellowship and the annual Early Career Workshop to help new planetary scientists break into the field. This year the prize is jointly presented to Dr. Shuai Li, and Dr. Parvathy Prem.

Shuai Li

Dr. Shuai Li is an Assistant Researcher at the Hawaii Institute of Geophysics and Planetology at the University of Hawaii at Manoa. His research is wide- ranging, and has included lunar volcanism, petrologic evolution of the asteroid Vesta, mapping hydrated salts on Europa, the study of planetary surface compositions using hyperspectral remote sensing methods, and refining radiative transfer models for quantitative mineral mapping of planetary surfaces. He is a member of SSERVI's ICE Five-O team, where his research in the non-icy components of icy bodies in the outer solar system is providing clues about surface processes and their possible connections to the interior to improve our knowledge about the formation and evolution of the solar system. His research is helping to constrain and quantify lunar surface properties like the composition, retention, and distribution of water ice at spatial scales ranging from micrometers to kilometers, revealing surface processes possibly associated with the solar wind implantation, impacting of meteorites, comets, and interplanetary dusts, and interior degassing. His research on the distribution, variation, and origin of volatiles on the Moon and asteroids is improving our understanding about solar wind, volatile-delivering impacts, and magmatic and space weathering processes.

Parvathy Prem

Dr. Prem served as NESF Co-Chair this year. She is a science team member of NASA's Lunar Reconnaissance Orbiter (LRO) mission and SEAL payload, and is Co-Investigator on two SSRVI teams: LEADER and ICE Five-O. Her research focuses on applying computational methods to study solar system bodies and their interactions with the space environment. Current investigations include modeling the origin and transport of volatiles on the Moon, and developing radiative transfer models to aid in the interpretation of remote sensing data at radar, infrared and optical wavelengths. Her modeling is helping us gain a better understanding how comet impacts on the Moon could have delivered water and other volatile compounds to cold, permanently shadowed craters near the lunar poles. Congratulations to these two early-career researchers, and other 2021 NASA Exploration Science Award winners, for these outstanding contributions to the field of Exploration Science! The SSERVI awards are open to the entire research community and are presented with invited talks at the NESF. Nominations are welcome at any time but must be submitted in early March for consideration in that calendar year. Recipients need not reside in the U.S. nor be a U.S. citizen. Winners are formally presented with the awards at the NESF each summer. More information on these awards and past recipients can be found at: http://sservi.nasa.gov/awards.

2021

NASA Exploration Science Forum Student Poster Competition winners:

First place (tie) was awarded to **Faris Almatouq** for the poster *"Utilizing Hexagonal Boron Nitride and Graphene Field Effect Transistors for Neutron Dosimetry."*

First place (tie) was awarded to **Kristoffer Sjolund** for the poster *"Hybrid Dust Mitigation Brush Utilizing EDS and UV Technologies"*

Second place was awarded to **Dany Waller** for the poster *"Investigation of Magnetic Fields Associated with Various Lunar Swirls Observed in the Far-Ultraviolet."*

Third place was awarded to **Katerina Slavicinska** for the poster *"Analyzing the Polycyclic Aromatic Hydrocarbon Inventory of Carbonaceous Chondrites via High-Resolution Two-Step Laser Mass Spectrometry."*

Congratulations to these winners and to everyone who participated in the competition. We look forward to seeing additional innovative student research in the next Student Poster Competition!

2021 Exploration Science Forum Student Poster Competition Winners

SSERVI takes great pride in the annual student poster competition held each year at the NASA Exploration Science Forum. The Student Poster Competition provides motivation, encouragement, and most of all, recognition to the most promising scientists of the future. The contest is always very competitive with high-quality submissions.

Selection criteria include the originality of the research and its impact to science and exploration, the merit of the experiment design and rigor of results, the visual quality and clarity of the poster layout—including accessibility to the non-expert, and effectiveness in communicating the topic during the lightning talk. Winners receive a $1000 travel grant. Selections were made by votes of a committee of scientists and SSERVI management.

SSERVI Student Poster Competition Winners 2021. First place tie Faris Almatouq (top left) and Kristoffer Sjolund (top right). Second place Dany Waller (bottom left). Third place Katerina Slavicinska (bottom right).

SOLAR SYSTEM TREKS PROJECT

"Your Moon Trek tool was our primary source of information in checking sun elevation through the design reference mission, as well as a first pass of hazards at the planned landing site."

-Will Coogan, Chief Engineer – Firefly Lunar Lander

NASA's Solar System Treks (SSTP) is jointly funded by the Science and Technology Utilization Office (STU) office within HEOMD, the Planetary Science Division (PSD) of SMD, and the Science Engagement and Partnerships Division (SEPD) of SMD. It is managed through the SSERVI Central Office and is developed and operated by the project's team at JPL. SSTP provides a growing family of web-based portals and suites of interactive visualization and analysis tools enabling mission planners, lunar and planetary scientists, engineers, students, and the public to access geospatial data products from many different instruments aboard past and current lunar and planetary missions.

The portals facilitate distribution and usage of PDS data as well as data from partnering agencies and missions. Basic analytic features include distance measurement, elevation profiles, 3D print file generation, custom VR generation, and Sun angle calculation. Advanced analytics include lighting, electrostatic potential, slope, crater/boulder hazard analysis, and line-of-sight communications planning. Access to the portals' capabilities is maximized by the portals being web browser-based applications with nothing for the user to install. Visualization capabilities include interactive 3D visualization, custom VR generation, and stacking and blending of data products. During the past year, the project enhanced the technologies used in SSTP's existing portals, extended these technologies to additional planetary bodies, partnered with existing and future missions in mission planning, data visualization, and analytics, and played key roles in NASA's efforts in STEM engagement to learners of all ages. The project is supporting NASA's collaboration with its international space agency partners including JAXA (Japan), ESA (Europe), KARI (S. Korea), ASI and INFN (Italy), and AEM (Mexico). SSTP is also engaging with NASA's commercial partners through the Commercial Lunar Payload Services (CLPS) program. It has been tasked with providing detailed visualization and analysis capabilities for proposed future human and robotic landing sites on the Moon, and is an integral participant in NASA's Mars Human Landing Site Selection process.

At the beginning of FY21, in addition to the Solar System Treks home website (https://trek.nasa.gov), SSTP offered nine publicly released portals online:

Moon Trek: https://trek.nasa.gov/moon is the successor to NASA's Lunar Mapping and Modeling Project (LMMP) developed as part of the Constellation Program. New technologies, capabilities, and data products have resulted in a new portal updated to meet the needs of Artemis and a new generation of lunar missions.

Mars Trek: At the initial request of NASA's SEPD, the technologies we had developed for the Moon were extended to the planet Mars, making the wealth of NASA's current and historical Mars data readily accessible for STEAM engagement. At the direction of

NASA's PSD and HEOMD, the capabilities of the Mars Trek (https://trek.nasa.gov/mars) were extended to help meet the needs of the agency's Human Landing Site Selection (HLS2) efforts.

Ceres Trek and Vesta Trek: As the spectacularly successful Dawn mission drew toward its conclusion, mission management commissioned SSTP to create a portal (https://trek.nasa.gov/ceres) featuring its data gathered while in orbit around the dwarf planet Ceres. The mission had already commissioned a portal for Vesta (https://trek.nasa.gov/vesta) upon its earlier departure from the asteroid.

Titan Trek and Icy Moons Trek: With the completion of NASA's Cassini Mission's exploration of Saturn and its Moons, the management of the mission engaged SSTP to create two new portals providing access to and visualization of data gathered by Cassini from a number of Saturn's moons. Titan Trek (https://trek.nasa.gov/titan) featured a powerful new catalog and enhanced faceted search capabilities that are becoming the standard across the Trek portals. Titan Trek will continue to be updated in support of the upcoming Dragonfly mission. A unifying portal, Icy Moons Trek (https://trek.nasa.gov/icymoons), was developed to serve and visualize Cassini data from the moons Dione, Enceladus, Iapetus, Mimas, Phoebe, Rhea, and Tethys.

Mercury Trek: The Director of the Japanese space agency JAXA, the JAXA Project Scientist for the BepiColombo mission, and the NASA Chief Scientist jointly commissioned a portal (https://trek.nasa.gov/mercury) featuring MESSENGER data from Mercury that could be used to support mission planning for the joint JAXA/ESA BepiColombo mission, and could later serve data returned from the BepiColombo Mission.

Bennu Trek: At the request of the OSIRIS-Rex Mission, (https://trek.nasa.gov/bennu) provided visualization and data dissemination for the near-Earth asteroid Bennu. This initial release used the OSIRIS-REx PolyCam 5cm Global Mosaic basemap and DEM to represent elevation data. Additional data products include rock abundance and slope maps. In addition to global, polar, and 3D projection views, Bennu Trek features a special 3D Model view which provides optimized visualization of features with topological overhangs. Three guided tours provide detailed views and descriptions of areas of special interest.

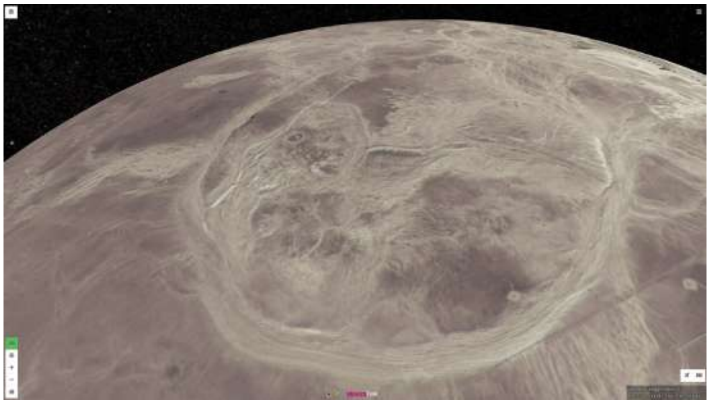
Ryugu Trek: At the request of NASA and JAXA management, SSTP produced and released a portal (https://trek.nasa.gov/ryugu) for the near-Earth asteroid Ryugu, providing visualization and dissemination of data from the Hayabusa2 mission.

Two new portals were added during the course of the year, addressing key upcoming targets for NASA scientific exploration.

Europa Trek: Both the Europa Clipper and JUICE missions have upcoming launches, so SSTP released a new portal for Jupiter's moon, Europa. The initial release features the Europa Voyager - Galileo Blend Color Mosaic as its basemap, with high-resolution data from Galileo. The new portal will play an integral role in our collaborations with NASA's Astrobiology Office and our European partners.

Europa Trek view of Europa's ridges and chaos terrain utilizing the Europa Voyager - Galileo Blend Color Mosaic basemap

Venus Trek: With the upcoming DAVINCI+ and VERITAS Discovery missions to Venus, SSTP developed and released the new Venus Trek portal using Magellan mission SAR data. The portal will promote understanding of the surface features of Venus and provide an important and timely enhancement to the Solar System Treks suite's capabilities for comparative planetology.



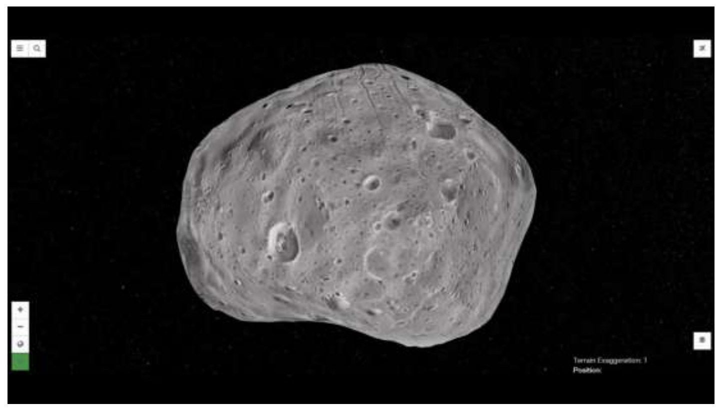
Venus' Artemis Corona visualized in Venus Trek

New Portals Under Construction

Barringer Crater on Earth as viewed in an Earth Trek prototype

Earth Trek: At the request of the Mars Program Office at NASA HQ, in collaboration with the Canadian Space Agency and Australia's Commonwealth Scientific and Industrial Research Organization, this new portal that will facilitate planning and execution of terrestrial analog studies as well as to visualize, analyze, and share data from such studies. The project is differentiated from other tools such as Google Earth and NASA WorldWind by specializing in topics of particular relevance to NASA SMD and HEOMD. It will support deployment and testing of instrumentation and equipment in the field and aid in the development and refinement of CONOPS. The portal is being developed to support both Martian and lunar terrestrial analog sites, as analog sites on Earth can enhance comparative planetology, to better understand similar features and processes on other worlds.

Phobos Trek: A prototype portal for Mars' moon Phobos is being developed in collaboration with the Japanese Space Agency in support of their upcoming MMX mission. This effort includes a number of international partners including ESA's Mars Express Mission.



Phobos with gravity contours in Phobos Trek prototype

FY21 Accomplishments Summary

Throughout the year, SSTP continued to advance its system and capabilities in support of NASA's science, exploration and public engagement strategic goals. Significant FY21 accomplishments include:

- Release of new capabilities / significant enhancement
  - -Line of Sight Tool initially implemented in Moon Trek for lunar communications and lighting planning
  - -Pixel Value Plot Tool for profiling various data sets on Moon Trek
  - -Authentication and Registration enhanced authentication and registration enhancement initially on Moon Trek for better user management and helping to increase user base and developing abilities for private/group work

-Country Mover Tool on Moon Trek and Mars Trek for public engagement

- Release of new data sets – Over 250 new products were ingested into various operational and prototype portals (e.g., Chang'E 2 south pole DEM and Mosaic, customized DIVINER temperature data sets, LRO NAC and Change'E 2 CCD Merge DEM, Lunar Mining for 3He)
- Planetary Science Decadal studies support for two Lunar missions focused on development of feasible and optimal rover path traversal
- Science and Exploration substantial support (e.g., DEM/Mosaics and analysis packages generation for mission planning and scientific research)
- Continuous and new Collaborations and Partnerships development
- Prototype development, research and capabilities under development

  -Earth Trek for analog studies

  -Generalized Feature Detector for detecting various planetary features

  -Interactive 3D path viewer

  -NAC Search Tool for finding NAC images available on PDS

  -Traverse pathing and supporting tools

  -Ray-traced lighting analysis in extreme high latitudes

- Release of new Trek portals

  -Europa Trek

  -Venus Trek

- Broader STEM Engagement
- Citizen_Science involvement

  -NASA Lunar data co-registration challenge

  -VIPER citizen science partnership

  -Continue to advance Equity Diversity and Inclusion

- Continous and new Working Groups (WG) support (e.g., additional WGs: SMD Catalog WG, SMD Web Modernation WG)
- Continous and new Meeting Presentations and Participation (e.g., submitted response to Planetary Data Ecosystem RFI and support their independent review)
- Independent_Evaluation of user experience through University of Gotherburg and University of Michicgan that led to user interface enhancements
- Major Infrastructure upgrade of system backend
- Open source and enhancement of Automated Data Pipeline for DEM/Mosaic production

MISSIONS

Many SSERVI Team members are involved with NASA space flight missions that are funded independently from SSERVI. Their roles range from instrument PI's, participants on mission science teams, or involvement in instrument or payload development, mission operations, or data analysis.

SSERVI-funded research further contributes to a number of NASA and International missions, instruments and programs. SSERVI researchers are fully integrated with mission efforts and connected to other contributing organizations (e.g., Lunar Surface Innovation Consortium [LSIC], Apollo Next Generation Sample Analysis Program [ANGSA], etc.) to synergistically connect NASA mission data to new scientific discovery. SSERVI scientists are using past mission data for new scientific discovery, and producing new data for upcoming Artemis mission planning. SSERVI scientists and integrated research teams work in both directions to enhance the science return of NASA's investments in existing missions while also producing results that can influence the preparation and analysis of future lunar science missions and data.

Additional details of team contributions to missions, instruments and programs are included in the individual team reports; select mission and instrument highlights from 2021 include:

MISSIONS:

- Artemis
- DART
- ESA VMMO
- FARSIDE
- Hera
- Hayabusa2
- Janus
- L-CIRIS
- LRO
- LUCY
- Luna-H Map
- Lunar Trailblazer
- LuSEE
- M3
- Mars 2020
- I-MIM
- MMX
- MRO
- MSL
- NEOS
- NEOWISE
- New Horizons
- OSIRIS-Rex
- PRIME-1
- ROLSES
- SunRISE
- VIPER

Images: NASA

INSTRUMENTS AND PAYLOAD DEVELOPMENT:

- COLDarm payload
- DALI
- Diviner
- Double Hemispherical Probe (DHP) instrument
- Electrostatic Lunar Dust Analyzer (ELDA) instrument
- ESA Comet Interceptor, MIRMIS
- Europa Clipper, MISE & SUDA
- I-SPI
- KPLO Gamma Ray Spectrometer
- LEXI
- LOLA
- LSITP MoonRanger flight project
- MRO CRISM
- Interstellar Mapping and acceleration Probe (IMAP) Interstellar Dust Experiment (IDEX)
- PRISM
- PRISM-2
- SEAL

REGOLITH TESTBED

The SSERVI-managed Regolith Testbed is available to the planetary science community, including CLPS and commercial developers. Thus far, the testbed has been used to conduct studies on optical sensing, drill testing, ISRU ID and extraction techniques, and remote robotic outreach activities. The testbed can accelerate innovation from idea generation through iterative testing and can quickly drive design improvements for science and technology projects. In addition, the testbed can help understand the basic effects of continued long-term exposure to dust in a simulated analog test environment.

The current facility contains two testbeds: the first has the largest collection (approximately 8 tons) of JSC-1A lunar lowlands regolith simulant in a testbed that measures 4m x 4m, and the second 65 ft x 14 ft testbed is filled with ~12+ tons of Lunar highlands simulant. The facility can be configured to suit the needs of the desired testing and is equipped for dust mitigation and safety oversight. Potential capability improvements (currently awaiting funding) include a lighting and video recording system and support structure.

VIPER researcher is testing a New Stereo Navigation System in our testbed

The Regolith Testbed is an excellent test environment for the next phases of the Artemis Program. Hardware and environmental testing scenarios include, but are not limited to, surface system interface and mobility, dust exposure and mitigation, terrain relative navigation sensors, regolith handling and sampling, additive printing and sintering technology development, electrical couplers and interfaces, granular mechanics, surface physics, and robotics integration. Future uses could include: testing ISRU methods for fuel, water and other resources; terrain-relative navigation sensor development, and testing robotic sensors using LIDAR, radar, and stereo vision to help robots maneuver safely in dusty environments. Robots are currently under development for regolith surface preparation to create landing platforms for landers, and the testbed could benefit research involving the extraction of metals from regolith using molten regolith electrolysis, regolith as a manufacturing feedstock for additive printing, sintering, and manufacturing using regolith.

Initiated by 2009 Centennial Challenge Regolith Mining Competition, Current and past users include: NASA VIPER Mission; Ames Research Center Intelligent Systems Division and Planetary Systems Branch; Universal Studios, and SSERVI Research Teams.

A wheel from the mockup for the VIPER mission to verify hazard camera beam pattern, placement and visual results from simulations

FACILITIES OPEN TO THE COMMUNITY

The following SSERVI-sponsored facilities can be made available to the broader scientific community. Interested parties should engage the facility POC to discuss scheduling time at the facility, along with any potential associated costs. Research activities that took place using team-supported facilities can be found in the individual team reports.

Dust Accelerator Laboratory (DAL) (U. of Colorado)

A 3 MV linear electrostatic dust accelerator which is used for a variety of impact research activities as well as calibrating dust instruments for space application.The 3 MV Pelletron generator is capable of accelerating micron and submicron particles of various materials to velocities approaching 100 km/s.

Contact: http://impact.colorado.edu/facilities.html

Ultra High Vacuum (UHV) & Ice and Gas Target Chambers (U. of Colorado)

Dedicated chambers that can be directly connected to the Dust Accelerator Laboratory for impact experiments requiring very clean conditions with exceptionally low background gas pressure, extreme cold temps, or various atmospheric gas pressures.

Contact: http://impact.colorado.edu/facilities.html

Reflectance Experiment Lab (RELAB) (Brown University)

Spectroscopic data can be obtained for compositional information relevant to planetary surfaces. High precision, high spectral resolution, bidirectional reflectance spectra of Earth and planetary materials can be obtained using RELAB.

Contact: http://www.planetary.brown.edu/relab/

Vibrational Spectroscopy Lab (Stony Brook University)

Spectroscopic tools allow examination of geologic materials similar to those that are present on Mars, the Moon, or other solar system bodies for better interpretations of remote sensing data.

Contact: http://aram.ess.sunysb.edu/tglotch/

Physical Properties Lab (U. Central Florida)

The density lab includes: (1) A Quantachrome Ultrapycnometer 1200. (2) A new custom-built pycnometer for larger samples. A special insert for thin slabs (up to ¼ in.). Both pycnometers have uncertainties of better than 0.5%. (3) ZH Instruments SM-30 magnetic susceptibility meter. (4) A fieldspec reflectance spectrometer with a wavelength range of 0.4-2.5 microns.

Contact: britt@physics.ucf.edu

GSFC Radiation Facility (NASA GSFC)

A dedicated 1 MeV proton beam line used to create radiation-stimulated defects in materials to help determine low energy H retention effects.

Contact: william.m.farrell@nasa.gov

Microgravity Drop Tower (U. Central Florida)

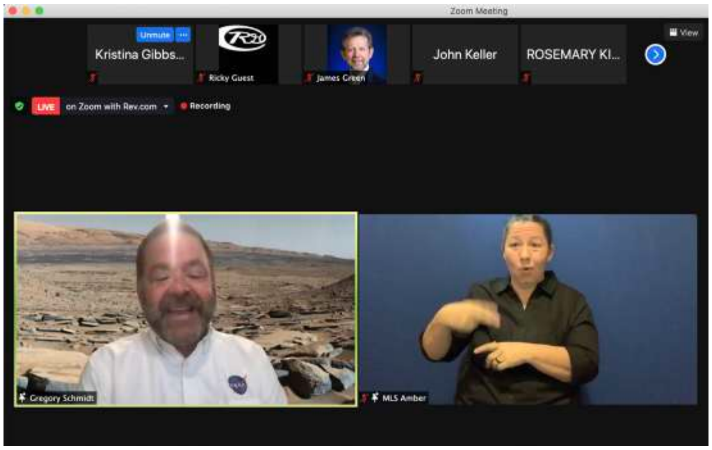
The drop tower provides a zero-G experience (0.7sec of freefall). An LED backlight helps track individual ejecta particles. Images are recorded with a high-resolution camera at 500 frames/second, which allows tracking of individual particles.

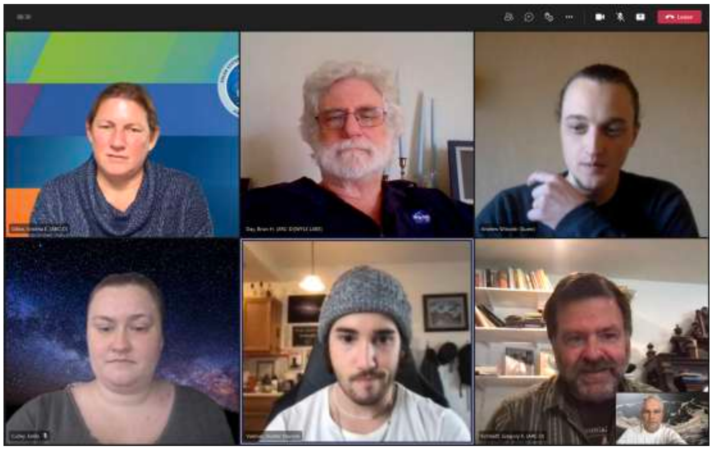
Contact: josh@ucf.edu

Regolith Testbeds (NASA's Ames and Kennedy Space Centers)

The 4m x 4m x 0.5m testbed at NASA Ames is filled with 8 tons of JSC-1A regolith simulant. Excellent for investigations in resource prospecting and regolith.

Contact: joseph.minafra@nasa.gov





As part of our mission to support the greater planetary science community, SSERVI provides a platform and technical support for community member led focus groups.

The Equity, Diversity, Inclusion and Accessibility Focus Group met 19 times in 2021. The recordings of the sessions can be found at https://sservi.nasa.gov/equity-diversity-and-inclusion-focus-group/. Some of the meetings hosted invited speakers who made presentations on a variety of topics, including "Geological & Historical Perspectives" (Barb Bruno), "Accessible Analogs: Creating an Inclusive Planetary Geology Field Course' (Anita Marshall), and "Ensuring all can thrive in STEM" (Lauren Edwards & Gretchen Goldman).

The Field Analog Focus Group met three times in 2021 and recordings of the sessions can be found at https://sservi.nasa.gov/analogs-focus-group/. Each session had a special topic with Lightning Round Talks and presentations by the following speakers:

- Dr. Gordon "Oz" Osinski: *"Preparing for the renewed robotic and human exploration of the Moon: Lessons learned from a decade of lunar analogue missions"*
- Dr. James W. Head: *"Antarctic Field Work: Lessons from the Dry Valleys for Human Exploration of the Moon and Mars, Part I"*

The Volatiles Focus Group was also very active in 2021. Recordings of the seven presentations can be found at: https://sservi.nasa.gov/volatiles-focus-group. During this year the group listened to presentations from Kevin Cannon, Kristen Luchsinger, OJ Tucker, Petr Pokorny, Prakash Chauhan, Apurva Oza, and Kathleen Mandt.

It should also be noted that focus groups are sometimes retired when the topic evolves or the group tasks are complete. One such group was the ALSEP data recovery Focus Group which was retired this year after the team was successful in recovering a trove of ALSEP Mission data. Ideas and requests for support from new focus groups are welcome, so please reach out to the Directors with new ideas.

In total there are currently 8 SSERVI focus groups:

Bombardment History of the Solar System

Chair: David Kring

The surfaces of the Moon, Mars, Phobos/Deimos, and asteroids have recorded and preserved the impact history of the inner Solar System since their formation. Studies of the impact record on planetary bodies can give valuable insights into the ultimate evolution of the Solar System.

Dust, Atmosphere, and Plasma (DAP)

Chairs: Jan Deca and Addie Dove

Understanding the dust and plasma environment on and near the surface of the Moon will allow us to better define requirements for surface operations, dust mitigation and radiation protection.

Equity, Diversity, and Inclusion (EDI)

Chair: JA Grier

The EDI Focus Group considers key issues in science and exploration of The Moon and asteroids that are related to equity, ethics, diversity, inclusion, and social justice. Examples of these issues include: diverse workforce development; equitable, beneficial, and just uses of space for all humankind, creating and maintaining a supportive professional culture, and inclusive representation of humans in science and exploration including race, disability, sexual orientation, gender, age, socio-economic status, and geographic distribution. Our group is open to all interested members (science, industry, government, university, non-profit, sociology, educators, science-communicators, etc.) of the broader lunar and asteroid communities. The main goal of the group is to identify and undertake specific actions to manifest immediate positive change.

Field Analogs Focus Group

Chairs: Tim Glotch, Darlene Lim, Jennifer Heldmann

Terrestrial analog field studies offer the unique opportunity to prepare for robotic and human planetary missions. Analogs provide the opportunity to conduct studies and tests related to science, mission operations, and technology in a relevant environment at relatively low cost and risk. The SSERVI Analogs Focus Group aims to bring together members of the community to discuss and review various aspects of fieldwork including, but not limited to, field sites, deployment logistics, field instrumentation, concepts of operations, software and hardware testing, etc. The NASA / SSERVI Analogs Focus Group also considers laboratory analyses of extraterrestrial analog materials and how quantitative laboratory analyses can be brought into the field.

Payloads and Instrumentation

Chair: Pamela Clark

This focus groups aims to support discussion on cutting edge science capability, through expanding the successful CubeSat model, developing core technologies through the Office of the Chief Technologist, and promoting the further development of 'microsized' instruments as well as instrumentation for larger mission concepts. We also aim to support essential instrument development and determining physical and cost limitations for broad categories of instrumentation. Potential mission and launch opportunities over the next several years is also discussed.

South Pole-Aitken Basin

Chair: Noah Petro

The South Pole-Aitken (SPA) Basin is the largest known impact basin in the Solar System. With a diameter of 2500 km, SPA provides great scientific potential for extracting native lunar mantle material and determining bulk lunar composition.

Space Commerce

Chair: Bruce Pittman

Continued exploration and scientific research produces emerging markets and new opportunities to expand human commerce to the Moon. Efforts spawned from the Google Lunar X-Prize offer significant new opportunities for the lunar science community.

Volatiles

Chair: Parvathy Prem

Water and other volatile constituents in and on the Moon and asteroids are resources for both science and exploration. They contain scientific records of processes and sources of volatiles in the distant past. They also are useful for producing propellant and life support for exploration initiatives.

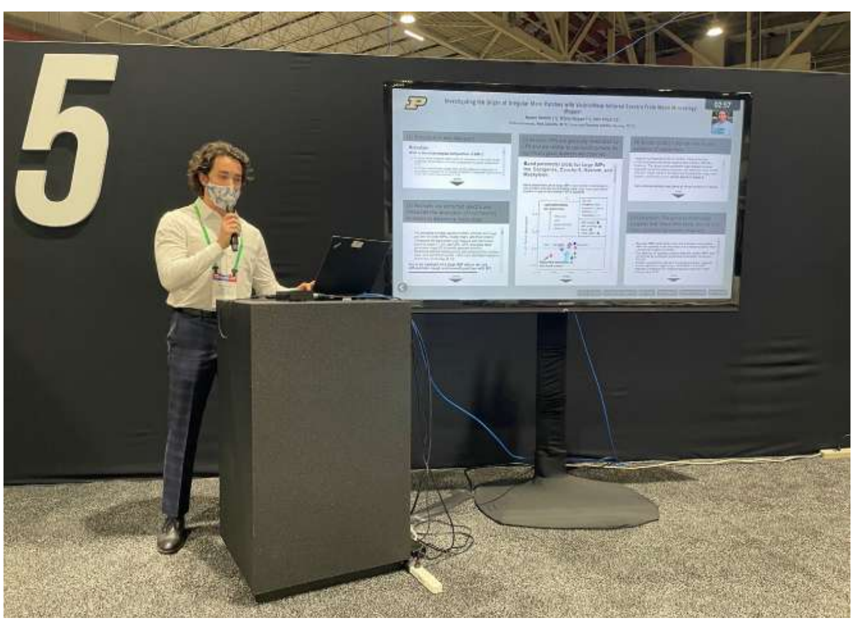
To join a SSERVI Focus Group please contact the Focus Group Chair.

THE MOON AND BEYOND
American Geophysical Union Fall Meeting

SSERVI hosted a special session at the American Geophysical Union (AGU) meeting on Thursday, December 16, 2021 entitled “The Science of Exploration: The Moon and Beyond,” which included oral presentations and lightning talks. In the broader context of the current Moon to Mars initiative, this session featured interdisciplinary, exploration-related science centered around airless bodies targeted as potential human destinations. Emily Culley and Andrew Wilcoski chaired the oral Sessions, Hunter Vannier (Purdue University) chaired the e-Lightning sessions, and Joseph Minafra supported solar system exploration at the NASA Exhibit booth.

Joseph Minafra supporting the SSERVI at the NASA Exhibit booth at 2021 American Geophysical Union (AGU)

Emily Culley and Andrew Wilcoski Chaired the SSERVI The Science of Exploration: The Moon and Beyond I-II-III Sessions at 2021 AGU



Hunter Vannier Chaired the SSERVI The Science of Exploration: The Moon and Beyond IV eLightning Session at 2021 AGU

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TRAIN

FIELD TRAINING EXERCISE AT METEOR CRATER

On October 15-16, SSERVI technology lead Ricky Guest assisted CLSE PI David Kring in leading a lunar Extra Vehicular Activity (EVA) communication simulation at Arizona's Meteor Crater. Meteor Crater, located near Flagstaff, is the world's best preserved impact crater. The topographical terrain of the crater so closely resembles that of the Moon, NASA made it an official training site for Apollo astronauts.

The objective of this activity was to broadcast a simulated lunar EVA live over two days and interact with students guiding the EVA from a virtual Science Operations Center (SOC).

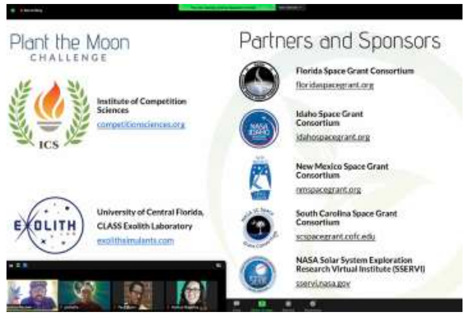
The event connected a distributed group of students who formed the SOC along with a designated SciComm, Debra Needham, who communicated instructions to Kring in the role of astronaut.

Students gave the 'astronaut' instructions for a three hour geologic traverse including station activities of the type that might be conducted on the lunar surface.

Carrying a mobile internet backpack with signal antennas, a mobile phone camera and gimbal stabilizer, SSERVI connected the student SOC and SciComm lead while also providing a live video feed referencing the topography and traverse via a Zoom connection to simulate the lunar exploration and communication for the EVA.

PLANT THE MOON CHALLENGE

The Plant the Moon Challenge supports NASA's Artemis Program to return to the Moon. Future missions to the Moon will prepare astronauts for the eventual manned exploration of Mars! Artemis plans will explore more of the lunar surface than ever before. However, returning humans to the Moon and planning to go to Mars is challenging in many ways. One of those challenges is how to feed your crew. Using local resources on the Moon could greatly enhance our capabilities to explore our celestial neighborhood.



SSERVI is a collaborator and Advisory Board Member of the Plant the Moon Challenge Competition.

SAN JOSE TECH MUSEUM

Lisa Incatasciato from the San Jose Tech Museum with the SSERVI Mars Touchstone on display at the San Jose Tech Museum

SSERVI Mars Touchstone on display at the San Jose Tech Museum

ROBORAVE TRAINING

Robotics are part of everyday life, from cellphones to self-driving cars to the satellites that orbit earth. To be successful in the 21st century students need to have an understanding of the robotics surrounding our everyday lives. RoboRAVE International is more than creating machines to perform tasks and win challenges, it's also about teaching students about science, technology, engineering, math and international collaboration skills.

Thousands of young people representing 27 countries are participating in the three-day education robotic competitions, competing in nine different challenges all around the world. These kids are learning and teaching themselves things about sensors and code and mechanics. SSERVI and RoboRave International together want to inspire our next generation work force to apply their science and technology and robotics, not just for competition, but to create new products, businesses and future space exploration efforts.

INSPIRE

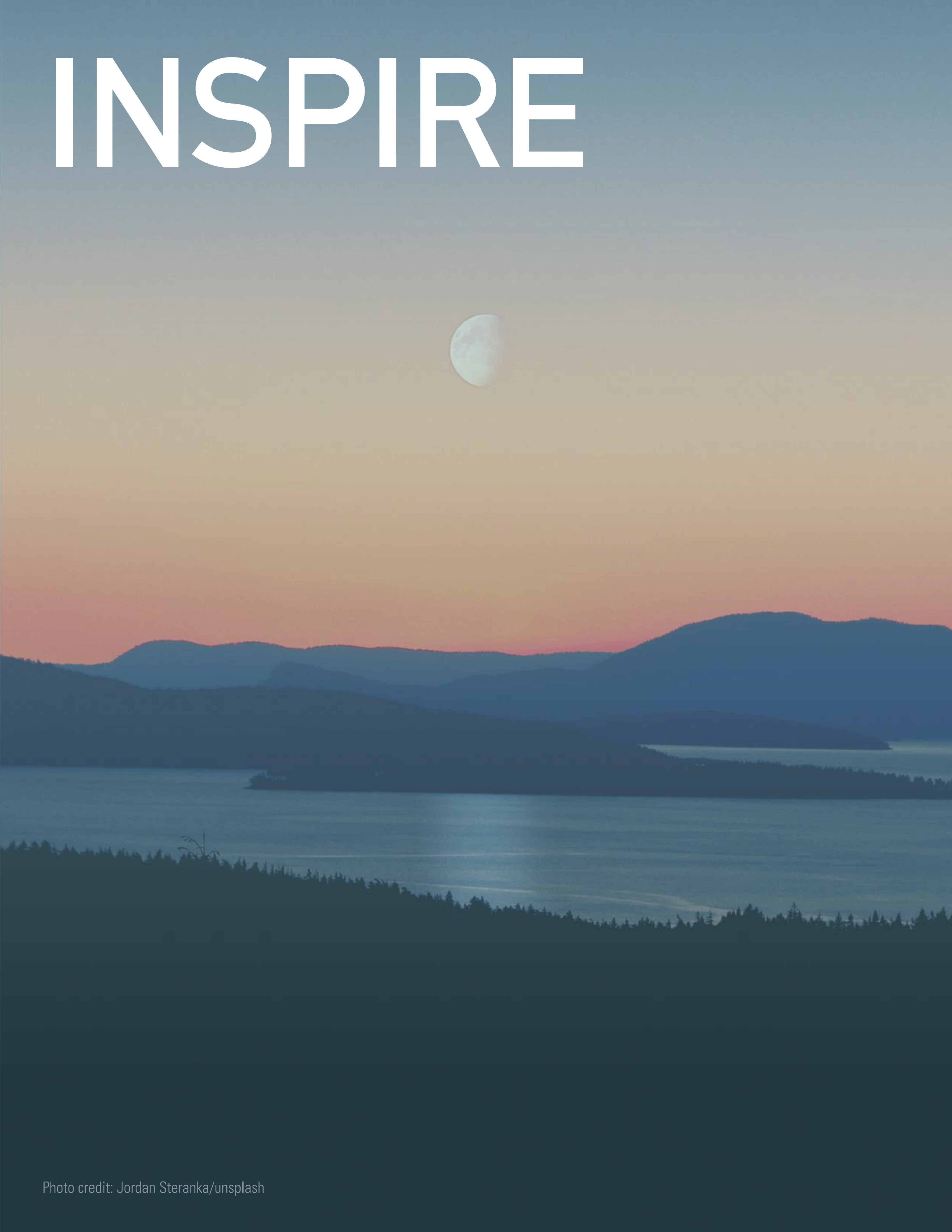


Photo credit: Jordan Steranka/unsplash

CLASSROOM VISITS

SSERVI Astromaterials virtual presentation to Navajo Nation elementary schools

Jen Baer reading her book to Navajo Nation Del Norte Elementary School. SSERVI NASA Careers Presentation for Navajo Nation Del Norte Elementary School in Gallup New Mexico.

Classroom from the NASA Career Day presentations to Navajo Nation Del Norte Elementary School

Joseph Minafra is virtually mentoring astromaterials to Liam Weesner who wants to be an Astrophysicist when he grows up.

DART MISSION LAUNCH

Public Exhibits and Apollo Sample and Meteorite Education Disk Certification

Newly certified teachers from the DART launch activities

Joseph Minafra exhibits at the DART launch public engagement day at John Hancock College

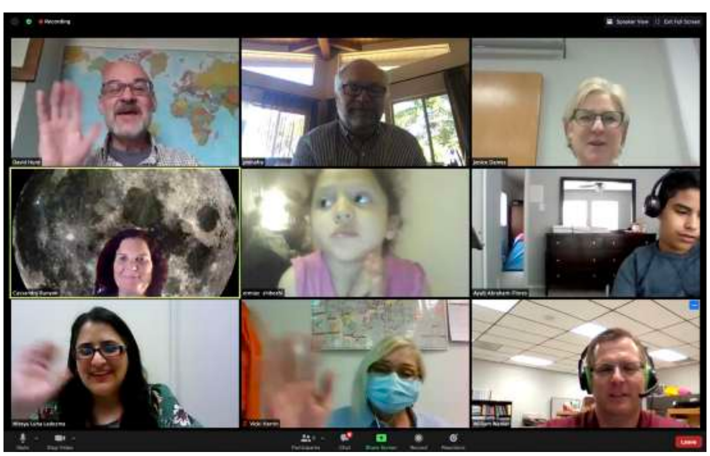
Brian Day giving pre DART launch introduction and mission objectives presentation from Hancock College

Teachers being certified to borrow NASA Apollo Lunar and Meteorite Education Disks

BRAILLE BOOKS

This year we designed another Braille Book for the Blind called "Earth A Tactile View of the Blue Marble" with production support From Kristen Erickson the Division Director of Science Engagment and Partnerships Division.

Getting a Feel for Eclipses books being used in Chile and Argentina



Virtual Presentation for Teachers of Students with Visual Impairments Northside Independent School District~ NISD Vision Program

APOLLO ANNIVERSARY AT U.S.S. HORNET

Apollo 50th Splash Down Event held in Alameda, California aboard the U.S.S. Hornet to commemorate the anniversary of the Apollo 15 mission. Between 650 to 700 public attended including a few local Star Wars Cosplay clubs.

Sharing lunar science information and astromaterials with local Star Wars JAWAS at the 50th Anniversary of Apollo 15 Splashdown event

SSERVI Lunar Exploration History Exhibit at the USS Hornet during the 50th anniversary of Apollo 15 Splash Down Event

Joseph Minafra presenting at the Bi-Annual Berkeley Innovation Forum at the Haas School of Business

SSERVI supported the NASA Ames Center Director and exhibited at the Modern Luxury Magazine "Innovation Summit" at the Ameswell hotel in Mountainview for a panel discussion to highlight NASA Ames contribution to innovation in Silicon Valley

Joseph Minafra exhibiting Astromaterials and SSERVI research information at Silicon Valley Innovation Summit

Brian Day has Saturn positioned in his telescope at the Silicon Valley Innovation Summit

SSERVI provided public presentations and certified teachers to borrow Apollo and Meteorite education disks at the Goldstone Apple Valley Radio Telescope (GAVRT) program is a partnership between NASA's Jet Propulsion Laboratory and the Lewis Center for Educational Research.

Teachers learning about planet building processes via various classroom activities during Apollo and Meteorite Education Disk Certification

SSERVI volunteering at annual Family Giving Tree Warehouse

CONNECT

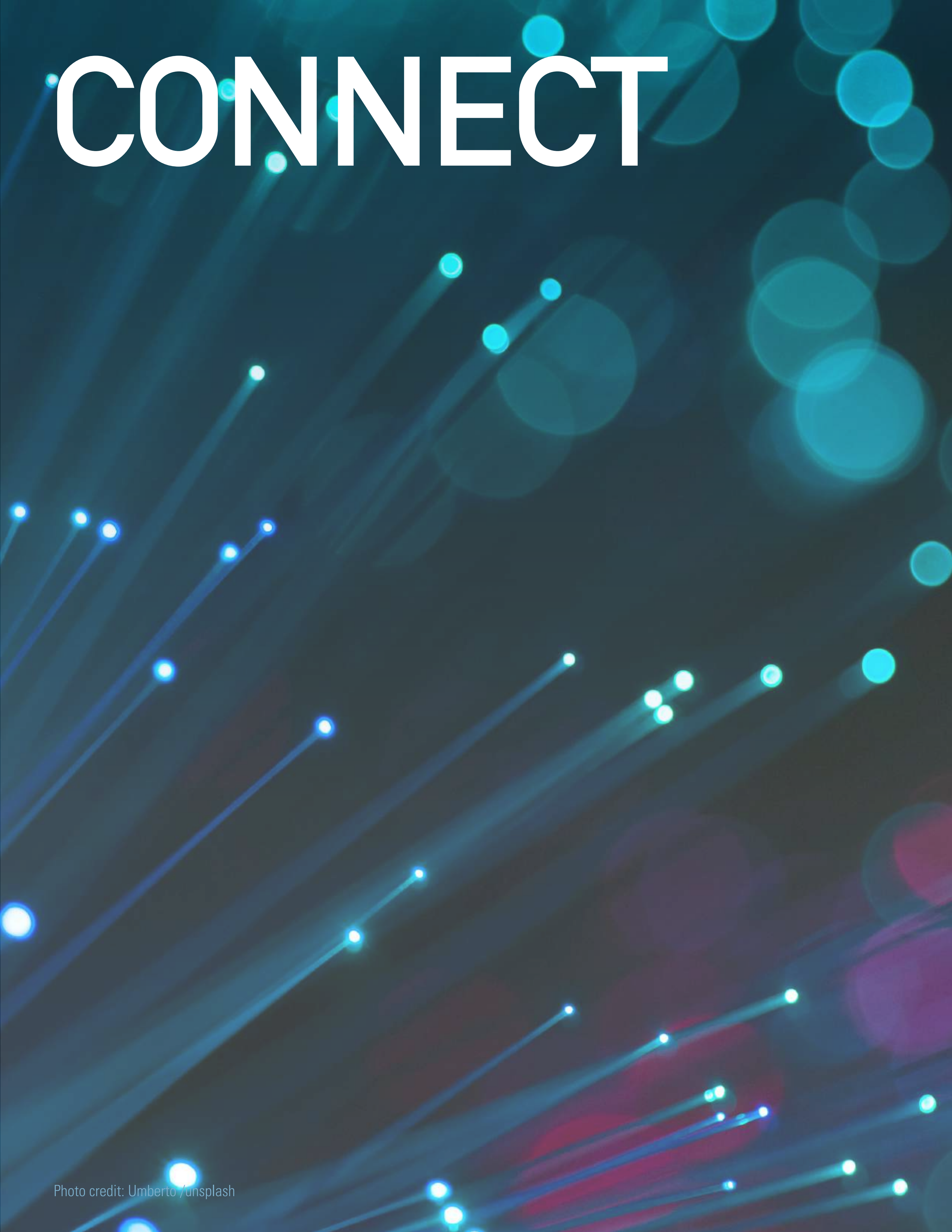


Photo credit: Umberto /unsplash

SSERVI collaborative technology capabilities emerged from humble beginnings but now play a key role in developing and applying innovative approaches to virtual collaboration and virtual meetings both internal and external of NASA. SSERVI is actively working with Agency leadership to move away from legacy, one-size-fits-all, monolithic enterprise architecture, to a modular set of modern and tailored technologies that meet the requirements of a geographically dispersed set of internal and external collaborators and partners. At first NASA enterprise capabilities such as WebEx supported internal-only participation equipped with a set of limited features not well-suited for dynamic virtual events. SSERVI quickly realized it needed to integrate and host a different array of technologies to enable success of its research community, the majority of which are external to NASA. SSERVI began identifying gaps in the enterprise technology portfolio with respect to document co-authoring, file sharing, and unified communications, and helped pioneer many analog-to-digital hybrid technologies to integrate legacy systems such as Polycom video-teleconferencing with then-leading digital meeting platforms like Adobe Connect. SSERVI worked to align effective audio/video and communication technologies and design strategies for teams and other organizations to use in creating their own on-premise meeting spaces and facilities. Given the tailored nature of these technologies, SSERVI facilitates end-user training to accelerate technology adoption as new platforms and capabilities arise to enable seamless collaboration experiences across organizations.

SSERVI also recognized that its teams and partners needed their own dedicated web presence, and created a process to design, build, and deploy tailored websites and web applications that are compatible with NASA standards. Leveraging modern web technologies, SSERVI introduced websites with mobile and other usable interfaces that were performant, secure, and scalable. In addition to emphasizing the end-user experience, a significant effort was made to improve the developer experience by using modern programming languages, frameworks, tools, and architecture principles to increase development, deployment, and maintenance efficiencies. Building on rich internal tools, the team developed scripts to automate data entry, workflows to automate event registration and attendee management, and sophisticated data management systems to collect, organize and filter data including publication metrics. Finally, SSERVI Central took its own web presence away from single-point-failure servers and moved to a NASA Ames managed data center. Over time, the institute's web strategy evolved but felt its deployment environment was falling behind and didn't have all the flexibility needed for hybrid virtual events and the future of web that we envisioned. Shifting to an entirely cloud-based environment has now allowed us to build a new array of websites and underlying systems in a more sustainable, more secure, and more performant fashion.

Finding new ways of collaborating virtually

Having focused on virtual meetings throughout its existence, SSERVI was well-poised to both continue its operations and assist the broad community when the COVID-19 pandemic hit in early 2020. New innovative developments with platforms such as Zoom and Gather.Town resulted in a refreshing shift in the way our online meetings were conducted and broadened the participation when circumstances didn't allow people to attend conference events in-person. The combined NASA Exploration Science Forum (NESF) and European Lunar Symposium (ELS) had 3000 unique users from over 40 countries across its websites, posters, etc., with some participants calling it "one of the best online conferences to date." These successes were enabled by our novel approach to building the technology behind these experiences; SSERVI deployed Gather.Town for participant interaction and virtual poster sessions -- a technology which was subsequently leveraged and deployed by other NASA groups and implemented for numerous non-NASA virtual conferences.

In 2021 SSERVI worked with Agency CIOs on the adoption and approval of numerous cloud-services (e.g.. Zoom, Slack, and Gather.Town) by introducing the tools to the agency, advocating awareness, underscoring their security considerations and overall compatibility within the Agency's existing framework. SSERVI demonstrated their usefulness and justified the need for such technologies in cases where no other Agency-approved tools would suffice.

Another excellent example of integrating collaborative technologies was in the Meteor Crater Field Training activities conducted in October 2021. SSERVI technology lead Ricky Guest assisted CLSE PI David Kring in leading a lunar Extra Vehicular Activity (EVA) communication simulation at Arizona's Meteor Crater—the official training site of the Apollo astronauts. The objective of this activity was to broadcast a live two-day simulation of lunar exploration with student-led EVA communication from a virtual Science Operations Center (SOC). By carrying a mobile internet backpack with signal antennas and a mobile phone camera and gimbal stabilizer, SSERVI was able to provide a live video feed referencing the topography and traverse via a web-based communication platform to connect the SOC and SciComm lead. This new paradigm was heralded as a terrific success that streamlined comms and required fewer personnel and equipment than previous technological approaches, resulting in efficiency and cost savings.

Pushing the boundaries of collaborative technology for the future

SSERVI is continuing to pursue its strategic interests in improving approaches to hybrid meetings as in-person meetings are once again able to take place. New cloud-based environments are improving not only the performance and security of the websites, but also the content and application development experience. By aligning NASA digital standards with leading-edge technologies and strategies for web applications, SSERVI is paving the way in modernizing legacy NASA web technologies and security postures. NASA is well-versed in single-source application development where a limited stack of technologies are used, enabling a lean and effective hosting environment. SSERVI is demonstrating the benefits and use-cases in using modern full-stack web technologies and principles to achieve a dynamic and modular architecture where tailored technologies or as-needed-services are deployed to keep hosting costs down. Moving away from server-dependent applications has significantly reduced server management burden including security and software updates. SSERVI leverages frameworks that enable streamlined website creation and deployment pipelines where cloud systems perform the heavy lifting once and intelligent caching is used to accelerate content delivery to users worldwide.

Having monolithic applications (e.g. Drupal or WordPress engines) at the core of a website introduces continuous security overhead with potential vulnerabilities across multiple exploitable vectors (it becomes harder to sustainably protect some of the layers); by decoupling these layers and configuring and hosting them in a tailored way, we can use each layer on an as-needed-basis and scale each independently over time. Decoupling our databases from monolithic applications also provides more granular control over data permissions and visibility.

In continuing its web architecture evolution, SSERVI brought forward a new web standard and demonstrated its features and benefits, how it improves the developer experience as well as the systems engineering components, alleviating security concerns and enabling us to build websites and web applications more efficiently for our customers, community, and external partners. NASA officials and subject matter experts -- primarily cloud-architects and system engineers -- recognized the benefits in how this new approach could save time and other resources while strengthening the Agency's website security posture. SSERVI is proud that this year, NASA offered Slack, Zoom and Gather.Town (as it looks to replace Communiqué Conferencing and other similar but inferior tools).

Now vs. Then: (above) Apollo era EVA communications required a dedicated truck with large support staff; (below) SSERVI PI David Kring and Ricky Guest demo modern comms that require only one person in the field with a portable backpack and mobile wireless communication system.

Looking forward, SSERVI will continue to consider how to best build the hybrid workplace of the future and increase the institute's autonomy to design and integrate custom solutions (e.g. conference rooms of the future, immersive collaborative technologies and tools, hybrid workplaces with both asynchronous and real-time collaboration, and other workplace and event production capabilities). How can SSERVI push the boundaries and operational modes of exploration science and cross-team collaboration? What new capabilities are needed? As an incubator leading the early adoption of collaborative technology for the Agency, we hope to make additional innovative contributions to NASA leadership. SSERVI Central serves as the lead for defining requirements for these technologies and has substantial involvement in coordinating and operating institute events while providing major assistance to Team and community events, as well as Agency events beyond SSERVI. SSERVI tech staff is actively helping the community select the best technologies to fit their needs and requirements and supports the adoption of these platforms through personalized training sessions. Please contact SSERVI IT (sservi-it@moonlight.arc.nasa.gov) with questions.

Website Development

In addition to the SSERVI and NESF websites, the SSERVI Tech team provided website support to other organizations within SSERVI and the community. Below is a table listing the main websites supported in 2021.

Website	Description	URL	YEAR
SSERVI	Defining the Institute while highlighting SSERVI research, related science, events/activities, and resources to the community.	sservi.nasa.gov	2013 - Ongoing
SSERVI Awards	The SSERVI Awards website highlights past winners of the distinguished Shoemaker Medal, Niebur, and Wargo Awards, while allowing the community to nominate candidates for the yearly distributed awards.	sservi.nasa.gov/awards	2014 - Ongoing
SSERVI Books	The SSERVI Books website was created to highlight the Institute's literary efforts, of which include "Getting a Feel for Lunar Craters" and "Getting a Feel for Eclipses".	sservi.nasa.gov/books	2014 - Ongoing
Lunar Surface Science Workshop	A workshop providing an open forum for the presentation, discussion, and consideration of various concepts, options, capabilities, and innovations to advance scientific discovery on the lunar surface. The website provides a dynamic comment system to capture feedback from community members on various themes while making recordings of sessions available for on-demand playback.	sservi.nasa.gov/lssw	2020-2021
2021 NASA Exploration Science Forum & European Lunar Symposium	Home of the combined 2021 NASA Exploration Science Forum (NESF) & European Lunar Symposium (ELS) where users found information on virtual logistics, registration, abstract submission, and on-demand playback of all live and archived presentations. NESF & ELS 2021 also featured Gather. Town that enabled live, interactive sessions for each poster author to connect with attendees.	sservi.nasa.gov/ nesfels2021	2021
SSERVI Focus Groups	SSERVI hosts researcher-led Focus Groups on a wide variety of topics. Some groups host seminars and those recordings are archived on the website for on-demand playback.	sservi.nasa.gov/focus-groups/	Ongoing
SSERVI Publication Database	SSERVI hosts a dedicated publication database for all its teams published publications.	https://sservi. pubdb.marqui.tech/ publications/	Ongoing

Event Production in 2021

SSERVI Central's Tech Team led the production and delivery of 75 events with over 500 presentations that were broadcast live and made available for on-demand playback. This valuable service makes important information widely available to the community; in 2021 SSERVI events had over 56,000 live-stream views and over 7,100 views of recorded sessions. Of these, 33 were in direct support of SSERVI's domestic Teams while 42 events supported SSERVI affiliated organizations both inside and outside of NASA. SSERVI continues to receive praise for its multimedia content delivery and technical production capabilities.

Some of the main events included:

• The combined 2021 NASA Exploration Science Forum and European Lunar Symposium produced 184 recorded presentations with over 15,000 live views and 1,500 on-demand playback views.

• The Lunar Surface Science Workshop was a series of 8 separate events covering topics related to lunar surface science. There were 257 presentations recorded over 8 days, which included over 35,500 live views, and over 1,600 views of the recorded content. These events culminated in the development of a summary document with community input for NASA leadership to reference as they build future planetary science programs.

Barringer Crater :

• Developed and implemented a communications plan for a lunar Extravehicular Activity (EVA) simulation training exercise led by CLSE PI David Kring at Arizona's Meteor Crater. The objective of this activity was to broadcast a simulated lunar EVA live and interact with students guiding the EVA from a virtual Science Operations Center (SOC). The event connected a distributed group of students who formed the SOC along with a designated SciComm, who communicated instructions to the 'astronaut.' Students gave the astronaut instructions for a three-hour geologic traverse including station activities of the type that might be conducted on the lunar surface. Carrying a mobile internet backpack, a mobile phone camera and gimbal stabilizer, SSERVI connected the student SOC and SciComm lead while also providing a live video feed referencing the topography and traverse via a web-based communication platform to simulate the lunar exploration and communication for the simulated EVA.

ACKNOWLEDGEMENTS

SSERVI would like to thank our supporters at NASA Headquarters for their leadership, funding and guidance as we prepare for Artemis and returning humans to the lunar surface. From the Science Mission Directorate (SMD) we thank Dr. Lori Glaze, Dr. Sarah Noble, Dr. Amanda Nahm and Dr. Shoshana Weider of the Planetary Science Division; Kristen Erickson of the Science Engagement and Partnerships Division; and Dr. Paul Hertz of the Astrophysics Division. From the Human Exploration and Operations Mission Directorate (HEOMD, now ESDMD) we thank Dr. Julie Robinson, Dr. Jake Bleacher, and Dr. Bette Siegel of the Systems Engineering and Integration Office. And from the Office of the NASA Chief Scientist, we thank former NASA Chief Scientist Dr. Jim Green and deputy chief scientist Dr. Dave Draper.

We extend a very special thanks to the hard work done by the NASA SSERVI Senior Review Panelists including co-chairs Dr. Cynthia Evans and Dr. Charles Shearer, panelists Dr. Justin Hagerty, Dr. Jose Hurtado Jr, Dr. Rosaly Lopes, and Dr. Clive Neal, and ex officio members Dr. Brad Bailey, Dr. Amanda Nahm (who also served as the HQ lead for the review), and Dr. Bette Siegel. The panel's guidance and recommendations are vital to making SSERVI a better institute and to connecting SSERVI contributions to exploration science, and we are in deep gratitude for the great deal of time spent in review of our institute by this panel.

In addition, we gratefully acknowledge the continued support from NASA Ames Research Center: Ben Varnell for his expert financial support and guidance, assisted by Michael Baumgarten and Delphina Turner; Barrie Caldwell, Bea Morales, and the NSSC teams for their outstanding procurement support, and Chris Wilson for his expert IT support.

We proudly acknowledge SSERVI CAN-2 and CAN-3 PIs and their teams for their exciting research, innovative techniques, and technological breakthroughs enabling human exploration, and the cadre of international researchers leading a global effort to expand human presence in space. We couldn't work with a more accomplished group of scientists both in our country and around the world.

SSERVI leadership is extremely appreciative of the hard work by its dedicated staff at SSERVI Central, including Prof. Carle Pieters, the SSERVI Distinguished Scientist. In addition, Brian Day and Emily Law (JPL) are acknowledged and thanked for overseeing the development and advances to the Solar System Treks Project.

Finally, we acknowledge everyone in the lunar science and exploration community who have endured all manner of hardships during an ongoing pandemic and yet sustained the field through these difficult years to make Artemis and the overall advancement of lunar and small body science a reality. In particular, we are confident that the next generation of brilliant researchers and explorers we've had the privilege to help and nurture will manifest a sustainable human presence on the Moon and beyond, and take humanity to places we can only dream of.

Ad lunam, ad astra!

Greg Schmidt
SSERVI Director

U.S. TEAM REPORTS

The SSERVI teams are supported through multi-year cooperative agreements with NASA (issued every 2-3 years) for long duration awards (5 years) that provide continuity and overlap between Institute teams. Each team is comprised of a number of elements and multiple institutions, all managed by a Principal Investigator.

CLASS **Center for Lunar and Asteroid Surface Science**
Daniel Britt, University of Central Florida, Orlando, FL

CLSE **Center for Lunar Science and Exploration**
David Kring, Lunar and Planetary Institute, Houston, TX

ESPRESSO **Exploration Science Pathfinder Research for Enhancing Solar System Observations**
Alex Parker, Southwest Research Institute, Boulder, CO

GEODES **Geophysical Exploration of the Dynamics and Evolution of the Solar System**
Nicholas Schmerr, University of Maryland, College Park, MD

IMPACT **Institute for Modeling Plasma, Atmospheres and Cosmic Dust**
Mihaly Horanyi, University of Colorado, Boulder, CO

ICE FIVE-O **Interdisciplinary Consortium for Evaluating Volatile Origins**
Jeffrey Gillis-Davis, Washington University, St. Louis, MO

LEADER **Lunar Environment and Dynamics for Exploration Research**
Rosemary Killen, Goddard Space Flight Center, Greenbelt, MD

NESS **Network for Exploration and Space Science**
Jack Burns, University of Colorado, Boulder, CO

RESOURCE **Resource Exploration and Science of OUR Cosmic Environment**
Jennifer Heldmann, NASA Ames Research Center, Mountain View, CA

REVEALS **Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces**
Thomas Orlando, Georgia Institute of Technology, Atlanta, GA

RISE2 **Remote, In Situ, and Synchrotron Studies for Science and Exploration**
Timothy Glotch, Stony Brook University, Stony Brook, NY

TREX **Toolbox for Research and Exploration**
Amanda Hendrix, Planetary Science Institute, Tucson, AZ

CAN-3 TEAMS
CAN-2 TEAMS

SSERVI U.S. TEAM EXECUTIVE SUMMARY REPORTS

CLASS

The Center for Lunar and Asteroid Surface Science (CLASS) team led by Dr. Dan Britt at the University of Central Florida studies the interaction between the surfaces of airless bodies and the space environment, exploration activities, and potential resource exploitation. Our research includes measuring and observing the physical and thermal properties of regolith material, observations of the mineralogy of primitive asteroids, the behavior of regolith in lunar and microgravity, the chemical reactions and reaction products that are part of space weathering, combined radar and optical characterization of asteroid surfaces, the cohesive forces on small asteroids including the interparticle forces and charging, analysis of the cohesive properties of meteorites, asteroids and bolides, development and launch of cubesats, and the use of regolith as a resource for construction, fuel, and life support consumables. One major focus is outreach to the NewSpace commercial community to provide the best science support for this innovative engineering startup sector. CLASS has several team-wide initiatives including on-line advanced planetary science education with six graduate-level seminar courses recorded for community access, the CLASS Exolith Laboratory which is the world leader in the development and production of lunar and asteroid regolith simulants, and the CLASS Planetary Landing Team which brings together the world's experts in rocket plume dynamics and surface interactions with the leaders of the growing commercial landing industry. CLASS is fundamentally an organization to bring the best science into the service of lunar and asteroid exploration. CLASS team members worked with graduate and undergraduate students at UCF and across member and external universities. Despite COVID restrictions, CLASS members were active in outreach programs, public presentations, and presentations to the media about ongoing lunar and asteroid mission activities.

CLSE

The Center for Lunar Science and Exploration (CLSE) team led by Dr. David Kring at the USRA Lunar and Planetary Institute and NASA Johnson Space Center studies impact history and processes, geochemistry of regolith, including volatile components, and ages of regolith materials on the Moon and other airless bodies. The bulk of CLSE's work this year was devoted to the geology of the lunar south pole, physical processes that may have affected the distribution of volatile elements in that region, and options for landing sites and extravehicular activities (EVAs) for the Artemis program. CLSE determined that a volcanic vent in the Schrödinger basin spewed tremendous amounts of gas, some of which migrated to the polar regions. Perhaps 12% of the vented water may have been deposited as ice in the shadowed regions of the Artemis exploration zone. CLSE continued to study the agency's potential Artemis landing sites, with a focus on scientific and in-situ resource opportunities that may be available during a 2 km walking EVA by Artemis astronaut crews. One of the potential Artemis landing sites CLSE studied was selected this year for the VIPER robotic mission. In parallel, CLSE's studies of the Schrödinger basin provided a strong foundation for an upcoming CLPS mission. Although the specific location of the CLPS landing site within the Schrödinger basin has not yet been selected, our studies of both the impact-generated peak ring and the subsequent eruption of a volcanic vent on the basin floor should provide important geologic context regardless of the selected landing site. Throughout the year CLSE trained a diverse suite of students, early career scientists, and mid-career scientists to support those upcoming robotic and human exploration missions. The team also used several types of events and artistic collaborations to engage the public in conversations about lunar science and exploration.

ESPRESSO

The Project for Exploration Science Pathfinding Research for Enhancing Solar System Observations (ESPRESSO) team led by Dr. Alex Parker at the SETI Institute and Dr. Kevin Walsh at SwRI works to develop new tools and techniques for improving the safety and efficiency of human and robotic exploration of the Moon and Near-Earth Asteroids. In 2021, they continued to refine the slate of novel instruments for characterizing the mechanical properties of asteroid and lunar regoliths in-situ, with the goal of enabling better-informed surface mobility and sample collection in these challenging environments. Team members also turned their attentions to understanding the interaction of the OSIRIS-REx spacecraft and the surface of Bennu, finding that packing fraction has a strong influence on the dynamics of the encounter. COVID-19 and several adverse weather events impacted progress due to restricted travel and laboratory access at key times in 2021. Several team members moved to positions at new institutes, resulting in substantial reorganization of team efforts. New members joined the ESPRESSO team to accelerate efforts to collect laboratory measurements of optical constants of lunar- and asteroid-relevant minerals and to fabricate and test new experimental hardware systems for exploring granular mechanics in reduced gravity and vacuum environments. New laboratory and fabrication facilities in Colorado and Washington state were commissioned in 2021. The Project ESPRESSO team hosted their NASA site visit during a virtual event in February 2021, resulting in numerous discussions with other SSERVI teams on prospective future collaborative cross-team efforts. ESPRESSO team members also supported the SSERVI senior review through timely delivery of materials requested by the review team.

GEODES

The Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES) team led by Dr. Nicholas Schmerr at the University of Maryland uses multidisciplinary geophysical investigations to explore a suite of natural resources on the Moon and other airless bodies. Geophysical methods are key tools for identifying resources on Earth and the Moon as they provide a means of characterizing and mapping the sub-surface using data gathered on and above the surface. In the second project year, our team has developed new geophysical modeling and experimental capabilities for subsurface exploration on the Moon and asteroids, expanded our publicly accessible database of planetary analog geophysical datasets, participated in developing new mission concepts for exploration of the Moon, and gave presentations at virtual scientific conferences and meetings reporting on the team's progress. Although the global pandemic still impedes the team's ability to get into the field, a small subset of the team with a focus on early career participants was able to visit and collect new geophysical data at Kilbourne Hole, New Mexico alongside our partner team RISE2. Our outreach and community building efforts have made significant progress in creating a new planetary division within the Society of Exploration Geophysicists, participation in the development of websites to educate and inform about the use of analog in planetary research, and participation in outreach activities such as International Observe the Moon Night. The GEODES team has been working in collaboration with RISE2 and the NASA GIFT program to develop field codes of conduct-- essential documents that outline the expected behavior of field expedition participants.

ICE FIVE-O

The Interdisciplinary Consortium for Exploring Volatile Origins (ICE Five-O) is a multidisciplinary team examining lunar volatiles from scientific and exploration standpoints. ICE Five-O researches volatile origins (e.g., H2O, CO, CO2, CH4, etc.), transport of volatiles to the poles, the role of the lunar regolith as a sink and a source for volatiles, and characterizes the potential for volatile-regolith interactions in the polar cold traps. In addition, we explore how volatile bearing samples can be collected, transported securely from the Moon, curated pristinely, and handled safely by astronauts and scientists. Experiments and modeling of Theme 1 samples constrain volatile origins and enhance our understanding of how the isotopes deuterium (D) and hydrogen (H) fractionate as they migrate and become sequestered at the lunar poles. A new NanoSIMS method devised as part of Theme 2 exemplifies the accuracy and precision in D/H measurements on a small-scale with which future return volatile bearing samples can be measured. This year we have initiated the flow of samples from laser irradiation experiments (Theme 1) to analyses via multiple analytical techniques (Theme 2), e.g., Transmission Electron Microscopy (TEM), ferromagnetic resonance, and visible-near infrared reflectance spectra. Also, as part of Theme 2, TEM observations of lunar particles found dry amorphous rims, which supports efficient steady-state desorption processes of volatiles from lunar regolith. TEM of chondritic Interplanetary Dust Particles fills in knowledge gaps regarding the potential interactions between rocky materials and volatile organics that are subjected to various kinds of irradiation. Research associated with Theme 3 serves to help clarify the interplay of reflectance and thermal emission, which will result in a more accurate characterization of the lunar hydration cycle by remote sensing. Theme 3 is also studying the detection and quantification of methane. Methane is a relatively simple molecule but could serve as a building block for more complex organic chemistry to further concentrate carbon in lunar polar regions. And lastly, the Five-O curation team focuses on experimental designs for critical measurements to understand the behavior of volatile-rich samples collected and returned by early Artemis missions.

IMPACT

The Institute for Modeling Plasmas, Atmospheres, and Cosmic Dust (IMPACT) team, led by Dr. Mihaly Horanyi at the University of Colorado Boulder, studies the effects of high-speed meteoroid impacts, plasma and ultraviolet (UV) charging, mobilization and transport of dust due to human/robotic activities, and natural processes, on the physical, chemical and geotechnical properties of regolith surfaces. They have continued to develop novel plasma and dust instrumentation for the lunar surface to resolve decades-old open questions about the origin of lunar swirls and the horizon glow, based on their ongoing series of small-scale laboratory experiments. Modeling efforts have helped to explain the plasma behavior near lunar magnetic anomalies and regolith evolution on small asteroids. The IMPACT dust accelerator facility enables researchers to explore the effects of meteoroid impacts into icy surfaces, develop new ways for in-orbit exploration of permanently shadowed regions, and assess the accessibility of their volatile content for future ISRU needs. New experimental electron beam setups have been developed for the safe and efficient removal of dust from space suits-- a critical element for mitigating dust hazards for future human presence on the lunar surface.

LEADER

Team LEADER is focused on investigating the many ways that the environment affects the lunar surface, exosphere and plasma and how human presence affects this system. Our subgroups focus on the exospheres, dust, plasma, and radiation environments as they are affected by and as they affect the human presence on the Moon. While at any given time, there are numerous ongoing investigations, the four areas of research that stand out in the last program year include: (1) The LEADER radiation team's prediction that the next solar cycle will be weak, with the sun producing far less magnetic outflux than nominal cycles. The impact on human explorers is the possibility of increased exposure to a correspondingly enhanced galactic cosmic ray environment. (2) The LEADER dust team's advancement in the understanding of grain triboelectric charging– which has been hypothesized by the LEADER plasma team to be the dominate astronaut and rover charging process in lunar shadowed regions. This work especially affects models predicting astronaut boot charging in shadowed (low plasma flux) regions. (3) Congruent with the tribocharging grain work, the LEADER plasma team has been involved with the JSC/xEVA and MSFC HLS teams in defining the lunar plasma environment in the polar regions and especially in assessing charging hazards that may possibly exist in terminator/polar regions. (4) LEADER plasma and exosphere teams together have been advancing the plasma-surface volatile connection, including advancing the modeling and lab work on understanding the solar wind implantation, OH formation, and H2 and water exospheric escape processes. They also have been considering the possibility that martian ionospheric ions implant into the moon Phobos and that the regolith from this body holds a record of the ancient martian atmosphere. This LEADER work has led to new mission and instrument concepts – including numerous CLPS instrument concepts – in the last year. The LEADER team also has active involvement in Equity, Diversity, Inclusion and Accessibility (EDIA) activities- including team members leading the LSSW workshop on inclusion. While the pandemic has created some roadblocks for mentoring, the LEADER team has met these challenges with continued student and early career participation in team activities. Overall, despite the obvious and ongoing pandemic-related challenges in collaborating, LEADER continues to be an exceptionally vibrant and active team.

NESS

The Network for Exploration and Space Science (NESS) team led by P.I. Jack Burns at the University of Colorado Boulder is an interdisciplinary effort that investigates the design and deployment of low frequency radio telescopes on the lunar surface. The purposes of these radio telescopes are cosmological and astrophysical measurements of neutral hydrogen at the end of the Dark Ages, during Cosmic Dawn, and at the onset of the Epoch of Reionization; radio emission from the Sun; and extrasolar space weather and exoplanets. NESS continues to advance instrumentation and a data analysis pipeline for the study of the first luminous objects (first stars, galaxies and black holes) and departures from the standard model of cosmology in the early Universe, using low frequency radio telescopes shielded by the Moon on its farside. The design of an array of radio antennas at the lunar farside to investigate the Dark Ages, Heliophysics, and Exoplanet Magnetospheres, is a core activity within NESS, as well as the continuous research of theoretical and observational aspects of these subjects. NESS is developing designs and operational techniques for teleoperation of rovers on the Moon's surface. New experiments, using rovers plus robotic arms and Virtual/Augmented Reality simulations, are being performed to guide the development of deployment strategies for low frequency radio antennas via telerobotics. Research supported by NESS has led to two NASA-funded CLPS missions that are scheduled to deploy the first U.S. radio telescopes on the Moon in 2022 (near side) and in 2025 (far side). For outreach, NESS published a new website to explain the Cosmic Dawn and Dark Ages to a general audience and recently completed a SSERVI-funded full-dome, feature-length planetarium film entitled Forward! To the Moon.

RESOURCE

The Resource Exploration and Science of OUR Cosmic Environment (RESOURCE) team is led by Principal Investigator (PI) Dr. Jennifer L. Heldmann and Deputy PIs Dr. Matthew Deans and Dr. Alexander Sehlke at NASA Ames Research Center. RESOURCE is focused on enabling In-Situ Resource Utilization (ISRU) near the sites of robotic and/or human missions to enable sustainable and affordable exploration of SSERVI Target Bodies. In 2021, RESOURCE work has focused on characterizing environmental and surface conditions of polar deposits on the Moon and airless bodies and determining correlations with volatile and ice content in these locations. RESOURCE has also evaluated novel depth cameras for lunar robotic use and integration into virtual and augmented reality platforms to optimize science and mission operations. RESOURCE partners at Honeybee Robotics have developed a new drilling system called Sensing, Measurement, Analysis, and Reconnaissance Tool (SMART) where the auger and bit are packaged with instruments that collect in-situ measurements of water ice, analyze volatile content, and answer key scientific questions about the properties of the lunar regolith. Hardware development at NASA Johnson Space Center has focused on developing and testing an ISRU water processing plant including the critical components needed to capture, clean, deionize, and electrolyze water as well as dry the oxygen and hydrogen gas products. A Special Issue was published in the journal Planetary and Space Science (PSS) as a collection of research papers focused on science and exploration results from our NASA-funded field analog campaigns. RESOURCE is also committed to Public Outreach as well as supporting Equity, Diversity, Inclusion, and Accessibility (EDIA) and has a robust portfolio of activities supporting these topics.

REVEALS

The Radiation Effects on Volatiles and Exploration of Asteroids and Lunar Surfaces (REVEALS) team focuses on understanding the role of solar wind and micrometeorite interactions with lunar and asteroid surfaces in the formation, sequestration and release of volatiles such as water, hydrogen, and methane. The team has measured the binding energies and transport coefficients of water and hydrogen on/in lunar regolith simulants and actual Apollo lunar samples. Numerical modeling and simulation directly assessed the importance of micrometeorite bombardment in the formation and transport of water in/on the lunar surface. The laboratory measurements were also used to develop models and technology platforms for water extraction using collected and focused solar radiation. With respect to EVA applications, reduced graphite and graphene-oxide composite materials have been developed and tested for use in dust mitigation strategies and radiation detection. Specifically, novel graphene-based meta-materials have also been explored as real-time passive radiation (x-ray and neutron) detectors with current efforts focusing on integrating the flexible substrate onto spacesuits for real time dosimetry. In addition, two other approaches to mitigating the potential deleterious effects of lunar dust using an electrodynamic dust shield brush assembly and an electrostatic microstructure array for spacesuit over-layers were investigated. Overall, the collective efforts address many SMD, STMD and HEOMD objectives associated with human exploration of near-Earth destinations.

RISE2

The Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2) team led by Prof. Timothy Glotch at Stony Brook University uses advanced field, laboratory, modeling, and remote sensing techniques to enable the safe and efficient exploration of the Solar System and to maximize the science return from missions to airless bodies in the Solar System. In Year 2 of our work, we have made substantial progress towards our goals through (1) the completion of simulated asteroid environment infrared spectra and analysis of the composition of the near-Earth asteroid Bennu using OSIRIS-REx Thermal Emission Spectrometer data; (2) near-field infrared (nano-IR) model development and data acquisition for carbonaceous chondrites, and the acquisition of a state-of-the-art nano-IR instrument at Stony Brook University; (3) initial development of a statistical comparison of the Hapke and Shkuratov radiative transfer models using a database of near-Earth asteroid visible/near-infrared spectra; (4) the first RISE2 field deployment at the Potrillo Volcanic Field, where we tested new hand-held instruments and software for field analog science and exploration; (5) continued software development for managing concepts of operations in the field and the use of augmented reality for field data visualization; (6) synthesis and experimental space weathering of high fidelity lunar analog regoliths; (7) reactivity, cytotoxicity, and genotoxicity tests of space weathered lunar analog materials; (8) completed hardware and methods development enabling microscale X-ray absorption fine structure (EXAFS) analysis of element valence states at the Argonne National Laboratory Advanced Photon Source; (9) scanning transmission electron microscope (STEM) analyses of space weathered and shocked grains from the asteroid Itokawa, returned by the JAXA Hayabusa mission, and (10) advanced X-ray absorption spectroscopy and STEM analyses, including nanometer-scale vibrational spectroscopy of chondritic insoluble organic matter. These scientific advances were supplemented by robust public engagement plan and were made possible by the contributions of 22 undergraduate students, graduate students, and postdoctoral scholars.

TREX

The Toolbox for Research and Exploration (TREX) team, led by Dr. Amanda Hendrix of the Planetary Science Institute, made great strides in science and exploration this year. TREX team members shared results and participated in numerous virtual workshops and conferences. Laboratory work progressed, toward the production of spectral libraries of terrestrial minerals and meteorite samples, ultimately for the analysis of remote sensing data of the Moon and small bodies, and for the characterization of those fine-grained surfaces in anticipation of human operations. TREX team members took part in numerous virtual public engagement activities. The dominant activity of the year was the preparation for and execution of our first field expedition, which took place in northern Arizona during two weeks in November. During the field exercises, rover-based software and instrumentation were used in various scenarios to test operational efficiencies. In these exercises, the TREX team used instrumentation (UV-MIR reflectance and GRS) to study two field sites and interpret data in terms of geologic history. The rover used the instrument data to autonomously choose its path across each site, using data to update geologic history information along the route. A scenario involving a proxy astronaut was used to assess efficiencies not only of adding in the keen eyes of the human, but of the benefit of added knowledge of an autonomous robot to the overall mission.

Center for Lunar and Asteroid Surface Science (CLASS)

Daniel Britt

University of Central Florida, Orlando, FL

CAN-3 TEAM

1. CLASS Team Report

1.1. Daniel Britt: CLASS P.I.: UCF

The CLASS Exolith lab remains the de facto world-wide standard for ISRU, lunar, Martian, and asteroid related engineering.

> In 2021, the Exolith lab shipped 37,770 kg of simulants to over 40 countries, a growth of >800% compared to the previous year.

The CLASS Exolith Lab supports a wide-range of planetary science missions to multiple target destinations (lunar, martian, asteroids, etc.) by delivering high-fidelity simulants to customers across the world.

The Exolith lab provides high-fidelity simulants of the lunar, martian, and asteroid surfaces, as well as custom simulants (e.g., Ceres, Phobos, Mercury) with development this year of additional lunar simulants focused on more accurately reproducing dust and agglutinates. In order to accommodate this demand, the Exolith laboratory moved into a new, larger location. The Exolith lab supports key exploration missions, including JAXA/NASA's planned MMX sample return mission at Phobos in 2024, and NASA's VIPER mission, where for the latter, more than 20 tonnes of lunar simulant have been delivered.

> The Exolith Lab has won a UCF internal competition for strategic investment and will be building a 10 x 10 meter regolith test bin equipped with gravity off-loading to simulate lunar surface regolith for testing NASA and commercial payloads.

CLASS collaborated with KSC Swamp Works on solar sintering of regolith and making simulated lunar regolith agglutinates from solar melted lunar regolith simulants. The agglutinates have been developed into an Exolith regolith product. Research into solar sintering as a lunar construction application continues.

Postdoctoral fellow, Leos Pohl, continues his work investigating asteroid regolith dehydration. This work has focused on cronstedtite, performing thermogravimetric analysis (TGA) and analyzing the samples after different temperature exposures via X-Ray Diffraction (XRD) spectroscopy in collaboration with CLASS Co-I Seal, and spectroscopy and FTIR spectroscopy, in collaboration with CLASS Deputy-PI Bennett. Dr. Pohl has also been developing computer algorithms to determine useful numerical outputs for ISRU in lunar polar regions (e.g., percentage of sunlight, duration of continuous darkness).

Postdoctoral fellow, Hannah Sargeant, has been leading the development of a Molten Regolith Electrolysis (MRE) reactor (Figure 1). We have demonstrated melting of lunar simulant through induction heating, and we have a complete design concept for a MRE terrestrial demonstrator. We are using thermodynamic models to predict how the lunar

Figure 1: 3D Rendering of the Molten Regolith Electrolysis (MRE) reactor being developed by Post-doc Hannah Sargeant working under PI Britt.

environment and surface materials will affect MRE performance. Hannah is also collaborating with colleagues at the United Kingdom SSERVI node on the development of a CFD-DEM simulation to predict the dust cloud produced when charged dust interacts with rover wheels. We are simulating interactions with past and future lunar rover wheel designs and are considering the effects of different surface charging conditions.

1.2. Adrienne Dove: Deputy PI: UCF

The Dove team are continuing experiments at the recently commissioned Stephen W. Hawking Center for Microgravity Research and Education. These include several microgravity experiments, most recently the GRIT chamber, designed by Wesley Chambers (graduated 2020) to study the interaction between a jet plume and regolith simulant. Development and testing of the ERIE experiment (funded for a Blue Origin Suborbital flight through NASA FOP) is ongoing. The Strata-2P parabolic flight campaign to study tool interactions with regolith in lunar/reduced gravity is under development, enabling the testing of technologies for investigating the formation and interaction of small particles and layered structures in low-gravity environments to inform robotic and human in-situ exploration.

1.3. Christopher Bennett: Deputy PI: UCF

Is working on the construction of an ultra-high vacuum chamber designed to study the visible to mid-infrared properties of regolith, minerals and ices exposed to space weathering agents. Graduate student Katerina Slavicinska worked with our collaborators at the University of Lille performing two-laser desorption mass spectrometry experiments on carbonaceous chondritic meteorites, which formed the basis of her master's thesis completed in December 2021. A paper from this work is currently under review. Graduate student Amy LeBleu-DeBartola is leading a paper on hyperspectral Raman mapping and Raman-induced damage of carbonaceous chondrites, anticipated to be submitted in Q2 2022.

1.4. Josh Colwell: Co-I: UCF

The suborbital flight experiment Collisions into Dust Experiment-3 (COLLIDE-3) flew successfully on May 22, 2021 on Blue Origin. The experiment was designed to study the response of CLASS-developed simulated asteroidal regolith to a low-velocity (< 50 cm/s) impact in a near-free-fall environment. The experiment functioned nominally, however, either vibrations within the experiment or a slight negative-g bias of the vehicle resulted in the material lifting out of the target tray so that there was no asteroidal surface to impact. The tray release mechanism has been re-designed to avoid this happening in future flights.

On July 7th graduate student Isabel Rivera defended her master's thesis based upon numerical simulations of the motion of particles launched off the surface of the Moon at speeds near lunar escape velocity and tracking the particles for weeks. These particles simulate the ejecta launched off the surface of the Moon as a result of lunar lander rocket exhaust. An example of these simulations is shown in Figure 2.

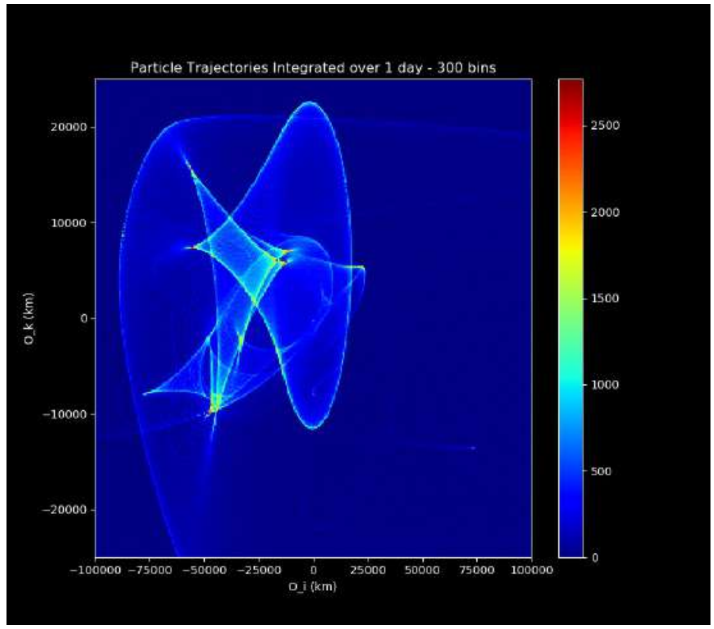


Figure 2: Simulation results showing distributions of dust launched off the Moon near escape velocity and integrated for one day. Brighter colors indicate regions where particles spend more time.

Drop-tower experiments under 1-g are being performed under vacuum to simulate the lunar environment. The intent is to characterize the fastest ejecta produced at these higher impact speeds and is motivated by interest in regolith characterization using charged dust detectors as well as scattered light dust detectors for CLPS missions.

1.5. Yanga Fernandez: Co-I: UCF

In a project led by graduate student Jenny Larson, the team is studying the dynamical behavior of ejecta liberated from the surface of an asteroid. This work will form the basis of Jenny's PhD, and a paper was published in February 2021 which describes how she augmented the Rebound Ejecta Dynamic (RED) Rebound simulation package. Jenny is now part of the DART mission investigation team and has been investigating the behavior of ejecta within the Didymos/Dimorphos environment after its impact by the DART spacecraft (Figure 3).

Graduate student Mary Hinkle leads our investigation of the thermal and scattering properties of the regolith of NEA (433) Eros as part of her PhD work. We are now looking to use Arecibo radar CW and delay-Doppler imaging data of

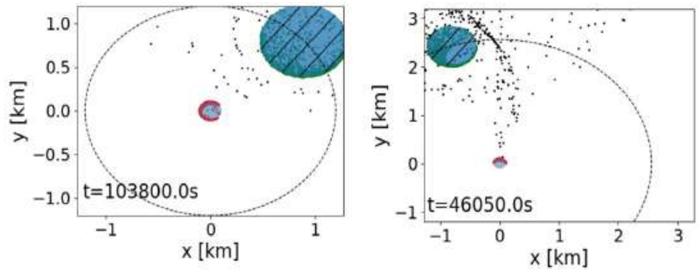


Figure 3: Snapshots from two simulated impacts in two Didymos-like systems. The only difference is the separation between the two bodies in the binary (1.2 km in the left figure, 2.56 km in the right figure). Dimorphos is in the middle, with Didymos the large blue, hashed circle. Particles that landed on Dimorphos are red, particles that landed on Didymos are green, and unlanded particles are black.

(433) Eros to tie cm-wave scattering properties of localized regions on the asteroid to the thermal emission mapping and visible-wavelength reflectance imaging. This would be the first time that data from these wavelength regimes will have been brought together to investigate Eros's regolith.

Undergraduate Daniel Davila led a paper recently published in the UCF Undergraduate Research Journal which investigated the assessment of hypothetical sungrazer comet families that may lie on an orbit with a small Earth-MOID and so could be potentially hazardous. The orbital elements that would place sungrazing comets on Earth-intersecting orbits were identified, and future work will determine whether observations could provide constraints on whether such sungrazer families exist.

1.6. Kerri Donaldson Hanna: Co-I: UCF

Co-Investigator Donaldson Hanna has been setting up an environment chamber capable of simulating near surface conditions of airless bodies in her laboratory at UCF. This chamber is connected to her FTIR spectrometer making it possible to collect spectral measurements under a range of environmental conditions.

Postdoc Mélissa Martinot has been working to combine visible to near infrared (M3) and thermal infrared (Diviner) observations of pure anorthosite regions on the Moon to better understand the formation of the anorthositic crust. Initial results from the analysis of select craters suggests the pure anorthositic regions are formed by highly-calcic plagioclase.

Graduate student Vanessa Lowry, jointly advised by CLASS Co-I Campins, has been using T-Matrix and Hapke scattering and radiative transfer algorithms to model thermal infrared spectra of Trojan asteroids (see Figure 4). Results suggest that fine particulate olivine (particle sizes < 5 microns) and lunar-like porosities (70-85%) can effectively model the 10-micron plateau observed in the TIR spectra.

1.7. Humberto Campins: Co-I: UCF

Co-I Campins has begun his new role in D.C. as a Jefferson Science Fellow. He remains heavily involved in the OSIRIS-REx mission, from helping to determine the sample selection site, to the spectroscopic characterization of the surface. A recent paper Co-I Campins co-authored suggests that the asteroid Bennu incorporates nanophase magnetite, which can form in the presence of Fe-bearing hydrated minerals (phyllosilicates) and will cause the carbonaceous asteroid to become spectrally bluer with increased exposure to space weathering agents, whereas in anhydrous carbonaceous asteroids, nanophase iron forms instead, which leads to reddening surface spectra with increasing surface age. Graduate student Anicia Arredondo successfully defended her PhD on 1st April 2021 after performing near-infrared spectroscopic surveys analyzing the spectral diversity of the inner belt primitive asteroid background population.

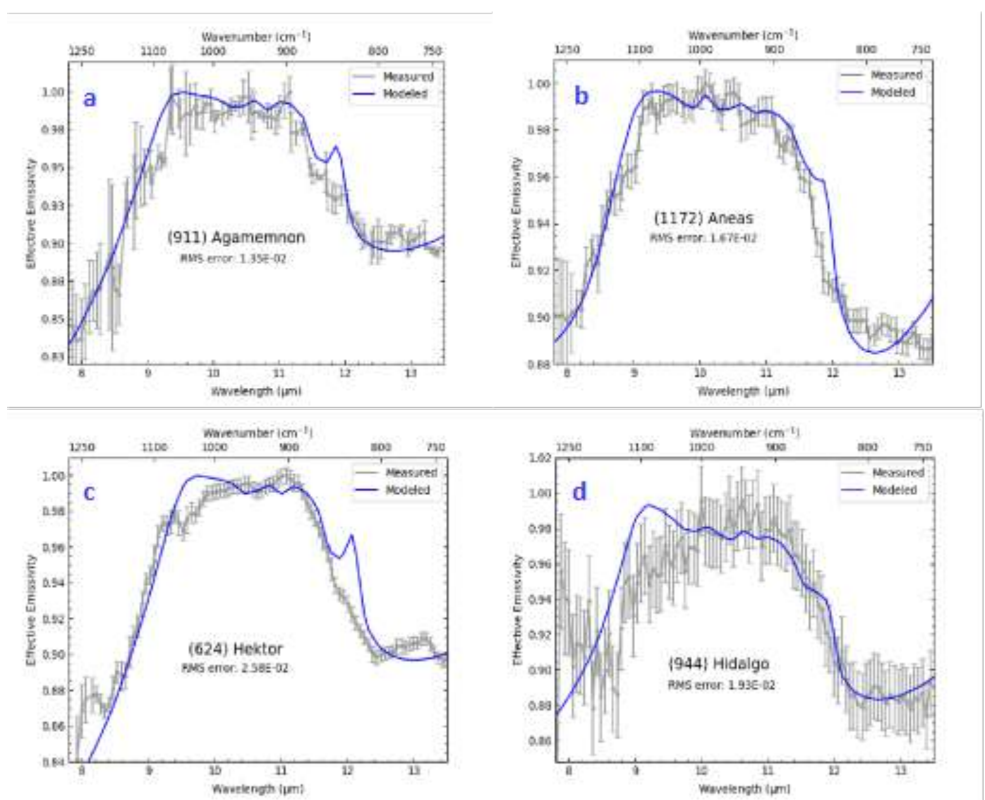


Figure 4: Model results for Trojan asteroids Agamemnon, Aneas, and Hektor, and asteroid Hidalgo.

1.8. Sudipta Seal: Co-I: UCF

In collaboration with Dr's. Britt, Pohl, and Bennett, we have been investigating how thermal effects induce alterations in minerals, such as cronstedtite by use of differential scanning calorimetry (DSC) and thermal gravimetric analysis (TGA) to different temperatures under either vacuum or ambient conditions (air or N2). The changes in morphology and structure are being analyzed primarily by x-ray photoelectron spectroscopy (XPS) and Fourier Transform infrared (FTIR) spectroscopy. Preliminary analyses indicate that when heated under vacuum conditions relevant to the space environment, cronstedtite samples showed a significant decrease in the Fe(II) to Fe(III) ratio, which will affect the reactivity of the surface.

The team has also developed an aerogel material using a combination of graphene oxide and antigorite to investigate how easy high specific surface area functional materials can be developed for ISRU applications, with applications to filtration and catalytic functionality. These materials can be reproduced through heating at 120 °C for 12 hours in an autoclave and then freeze-drying the aerogel product, as shown in Figure 5.

1.9. Phil Metzger: Co-I: UCF

CLASS Co-I Metzger has enhanced research and produced synergy from the crossover of several NASA research initiatives into lunar rocket plumes, including: 1) Analyzing Apollo 15 videography to determine quantity of blowing dust, which included developing new videography metrics, 2) Testing lasers on a Masten rocket blowing dust to quantify the dust-blowing physics, 3) Developing new methods to measure the entire particle size distribution in lunar dust clouds under a rocket using multiple laser wavelengths, 4) In analyzing large rockets landing on the Moon, developed a fast code (currently being formatting for distribution) that can be distributed to NASA researchers and contractors to enhance future efforts. 5) Analying deep cratering experiments by Masten Space Systems and its subcontractor to unravel the physics of these events, and 6) Integrating these diverse efforts to create a more complete understanding of the physics.

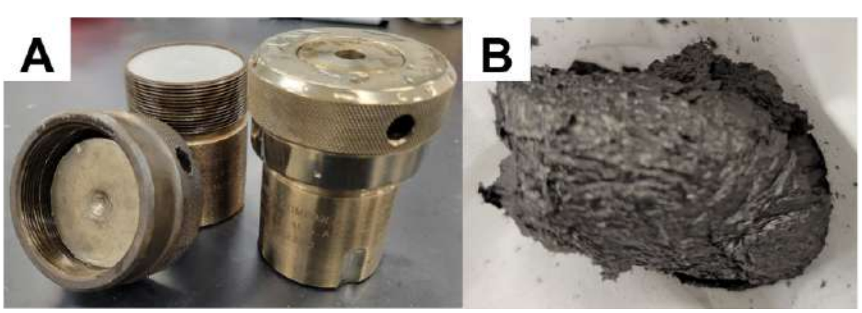


Figure 5: Hydrothermal synthesis of an aerogel made from graphene-oxide and antigorite.

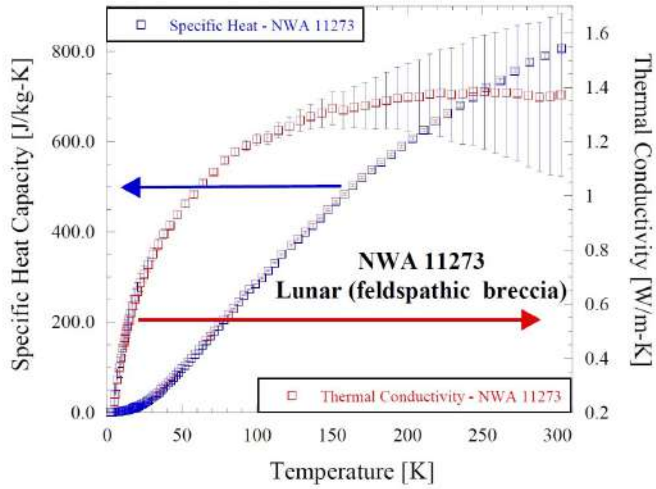


Figure 6: Example of specific heat and thermal conductivity measurements taken for lunar meteorite NWA 11273 as a function of temperature.

Co-I Metzger has also been performing magnetic and microwave susceptibility experiments on lunar soil and their mineralogical components, small-scale experiments of gas jets cratering granular media, and collaborating with computer simulation researchers to compare experiments.

1.10. Dan Scheeres: Co-I: University of Colorado

Over the last year we have had several asteroid-focused publications. Sanchez et al. is directly focused on regolith, and reports on a series of experimental tests on the properties of cohesive powders in vacuum. Li and Scheeres studied the properties of the Earth quasi-satellite 2016 HO3, which is a potential target for exploration. Recent theories have shown that this asteroid may be captured ejecta from the Moon. Three papers are focused on the effects of non-gravitational and gravitational forces acting on asteroids, including binary asteroid systems.

1.11. Cyril Opeil: Co-I: Boston College

The Opeil laboratory's CLASS-related research efforts focus on acquisition and preparation of meteorites and measuring their thermal properties, namely their heat capacity, thermal conductivity, and linear thermal expansion. This year, these measurements were made on the following materials: Lunar Meteorites: Lahmada 020, NWA 8022, NWA 8455, NWA 10401, NWA 11273 (shown in Figure 6), NWA 11303, NWA 13408, NWA 13788, NWA 13992, Touat 005; Martian Meteorites: NWA 7397, NWA 12262, NWA 12269, NWA 13187, NWA 13366; Carbonaceous Chondritic (CM2) Meteorites: NWA 11179, NWA 12184, NWA 12778, NWA 12861; Enstatite Meteorites: Al Haggounia 001, NWA 8552, NWA 974; Terrestrial Minerals: Anorthosite, Fused Silica, Kaolinite, CM2 simulant Block #28. This work

Figure 7: Testing with MTU-LHT-1A lunar simulant inside the DTVAC.

Figure 8: Testing T-REX on the first batch of in-house created MTU-LHT-1A lunar simulant.

has been presented at several international conferences with two manuscripts in preparation, with another in paper in preparation from four iron meteorites and two L class chondrites. But the most important scientific development of this year has been the collaboration and planning of thermal measurements of samples from Bennu 101955, which will be returned from the OSIRIS-REx mission.

1.12. Mark Boslough: Co-I: University of New Mexico

Co-I Boslough developed methods and ran simulations to model the Meteor (Barringer) Crater impact and other small terrestrial craters as a hybrid airburst/impact event, comparing identical simulations of crater formation with and without atmospheric effects, focusing primarily on distribution of ejecta using fragment tracking. These simulations include both 2-D axial and 3-D rectangular symmetry to explore the effect of the wake on distal ejecta velocity as a function of direction. Methods used to model nuclear weapons effects were applied to model blast wave propagation from airburst and impact events. Adaptive mesh refinement methods include using artificial viscosity at low altitude to refine only near the shock front in the atmosphere, which allows high-resolution blast modeling in very-large domain simulations. He is developing methods to generate transfer functions that will allow determination of the global distribution of mass and momentum, and seismic coupling due to reentry of the highest-velocity ejecta from large impact events (e.g., Chicxulub, Ries, Zhamanshin, and the Australasian tektite-forming event). This new methodology accounts for impact latitude and planetary rotation.

1.13. Paul van Susante: Co-I: Michigan Technical University

Co-I van Susante developed an in-house lunar simulant (MTU-LHT-1A) which has been well characterized in terms of mineralogy, glass content, particle size distribution (wet and dry), and hydrometer testing. So far, approximately 5,000 kg have been produced, with 50,000 kg needed to help support funded work. The team has been developing methods to create icy lunar regolith simulants, a 40ft frozen container facility to develop and produce frozen simulants, as well as the Dusty Thermal Vacuum Chamber (DTVAC; Figure 7) capable of conducting various regolith testing over the temperature range from -196 – 200 °C. Lunar simulant can now be routinely prepared with desired wt% hydration/ice levels, supporting several ISRU tests, as well as several NASA-funded grants (ESI, LuSTR, NIAC, NEXTStep, BIG, GCD). Ongoing research is underway on the wear on mechanical and electromechanical components operating with the lunar simulant, as well as a comparison of lunar regolith transport behavior under vacuum and atmospheric conditions. The T-REX rover that helped the team win NASA's Big Idea Challenge is shown scaling some of the MTU-LHT-1A simulant in Figure 8. The T-REX robot demonstrates a key requirement for lunar operations, to deliver power to dark craters on the Moon. In addition to helping with ice harvesting in those craters, it could charge other robots or host a router network to facilitate communication between devices in the field.

1.14. Robert Mueller: Co-I: Kennedy Space Center / Swampworks

KSC Swamp Works collaborated with SSERVI CLASS on solar sintering of regolith and making simulated lunar regolith agglutinates from solar melted regolith simulants. Parts were sourced and delivered to the Exolith lab. Weekly meetings with the student design team were held to provide consultation. NASA KSC's Environmental and Medical Contract (NEMCON) Industrial Hygiene Office performed bulk sampling of Serpentine for SSERVI CLASS and provided interim and final analysis reports in October and November.

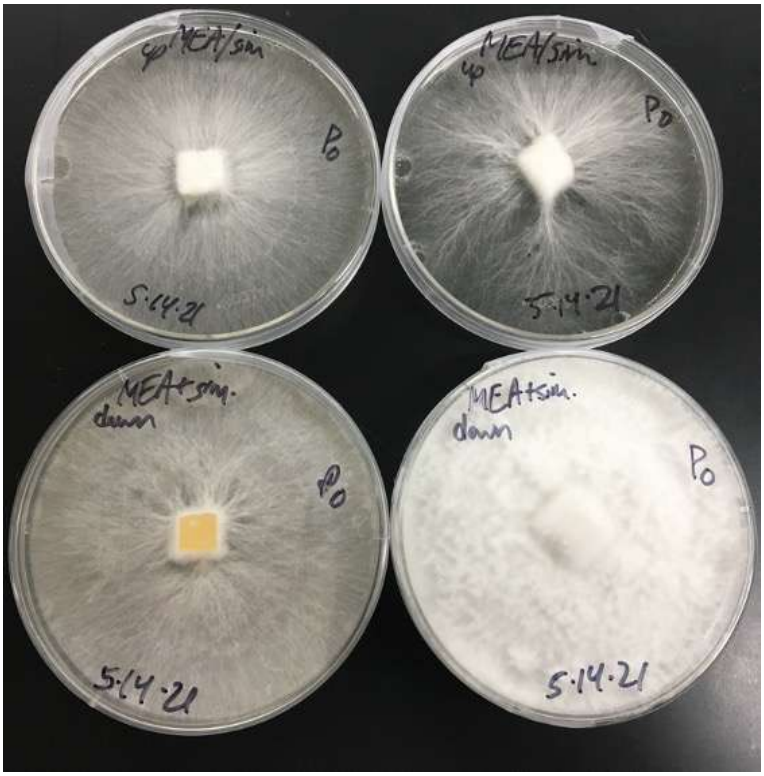


Figure 9: This image shows fungus development within different ratios of simulant to MEA. The bottom-left features the least simulant whereas the top-right has the highest simulant concentrations.

1.15. Joel Sercel: Co-I: TransAstra

Several experiments are in progress to determine the efficacy of using fungus in regolith to create soils for large habitats. Several species have been evaluated, with the 3 most promising being pursued further. Figure 9 shows four example plates where different gradients of simulant to malt extract agar (MEA) in which fungi have been grown. In plates with lower concentrations of MEA, the mycelium appears to compensate for the lack of nutrition by creating "hyphal highways" (i.e., filamentous/rhizoid) whereas the nutrient-rich media leads to more densely colonizing and fluffy mycelium (i.e., tomentose). This work was completed as part of a SBIR Phase I study. We performed a study to determine the relationship between continuous power vs. water content of lunar regolith in extracting 100 tonnes/yr of water, as a function of power generation efficiency. This study highlights the ISRU requirement that regolith with higher water content would be vastly more efficient when considering <5wt% content.

As part of our NIAC phase III, TransAstra has also continued developing the Mini Bee ground demonstration project; mirror alignment is underway for the Mini Bee Reflector system, where a large primary mirror is used to collect light, while a second mirror suspended above it reflects and focuses the light into a third mirror, which redirects the light into the interior of the spacecraft bus towards either the optical mining head or OmnivoreTM thruster propulsion systems currently in development. The OmnivoreTM thruster has been successfully tested at CSM using the same high-power light source as the optical mining platform.

1.16. Chris Dryer: Co-I: Colorado School of Mines

The team at the Colorado School of Mines continued to improve the Optical Mining Testbed (OMTB). Improvements include a mass spectrometer to monitor gas composition during mining tests, improvements to integrated mass gauging to monitor sample mass changes during testing, optical shutters, improved reflector mount, and careful alignment of the optical system. Peak beam intensity at focus is 900 W/cm2 using a 15-kW electrical bulb with up to 3.3-kW optical power delivered to sample surfaces. A total of eight spalling tests were conducted in 2021 on simulants of C-type asteroids containing 15wt% water, where optical mining rates of 1-2 kg/hr and water capture rates of 0.05 kg/hr have been observed, the latter corresponding to about 5wt% by mass.

1.17. Robert Jedicke: Co-I: University of Hawaii at Manoa

Co-I Jedicke has been developing software to support the Sutter survey and Sutter ultra missions, in collaboration with TransAstra. Software to generate realistic synthetic image containing stars at correct locations and magnitudes as well as synthetic ISRU targets have been developed so we are now focusing on optimizing filters to characterize and identify specific ISRU targets. At this time, two of the four telescopes have been purchased and mounted for the Sutter ground test and the software testing has demonstrated that our matched filter algorithm can process the projected data stream in real-time. This project has been partially funded by a NIAC phase II grant.

1.18. Barbara Cohen: Co-I: GSFC

Co-I Cohen has been researching the near-surface rock distribution on the Moon. This will help ultimately inform design choices for a prototype sample carousel being developed in collaboration with Honeybee robotics to deliver samples to a proposed Potassium (K) - Argon (Ar) Laser Experiment (KArLE) instrument prototype intended to provide in-situ dating in planetary missions.

1.19. Noemi Pinilla-Alonso: Co-I: Florida Space Institute

With the departure of Co-I Anne Virrki, Noemi now also serves as the Deputy Principal Scientist at the Arecibo Observatory (AO). As part of the CLASS Graduate Seminar series, Co-I Pinilla-Alonso helped prepare an agenda of classes that would put together all the science value of that observatory for radio astronomy, planetary science, and space and atmospheric science. The class also included a presentation of a concept for a new radio and radar telescope at the

Arecibo Observatory and of the Big Data Office successfully implemented in 2020. All the videos can be viewed on the CLASS website and SSERVI YouTube channel.

Co-I Pinilla-Alonso has been focused on publishing papers of observations and releasing data from the PRIMASS-L study to the small bodies PDS node, partially funded through CLASS (DOI: 10.26033/xnfh-np39, https://sbn.psi.edu/pds/resource/primassl.html).

This fall, we also welcomed a new graduate student, Brittany Harvison, who will be working with Co-I Pinilla-Alonso under CLASS.

1.20. Clive Neal: Co-I: Notre Dame University

We are investigating the trafficability of lunar regolith and the ability of different rover wheel designs to transverse it. Three rover wheels were recently obtained to conduct tests on lunar highlands regolith simulant LHS-1 to test the trafficability of the regolith (i.e., will repeated rover traverses create smaller particles and, therefore more dust?). The wheels are from the Astrobotic rover, a replica wheel from the Lunar Roving Vehicle (from Glenn Research Center) used during Apollo, and a VIPER-like wheel (from Johnson Space Center). The test bed for these wheels has been designed and is being constructed in Q1 2022 at Exolith Lab. A cone penetrometer, similar to that used on the lunar surface by the Apollo astronauts, was purchased and used in further defining the geotechnical properties of highlands regolith simulant LHS-1.

2. Inter-team/International Collaborations

CLASS team members have submitted proposals with several SSERVI teams and commercial space partners, which include Honeybee Robotics, Masten Aerospace, TransAstra, Colorado School of Mines, University of Notre Dame, etc.

2.1. Inter-Team Collaborations

2.1.1. SSERVI Central: Our Education and Public Engagement team (led by C. Runyon) continues to work closely with Joe Minafra and Maria at SSERVI Central.

2.1.2. CLSE: CLASS Co-I Mark Boslough is working with David Kring & Don David (a space artist) to develop Science-based Meteor Crater impact illustrations.

2.1.3. SEEED: CLASS Co-I Mark Boslough is working with Doug Schmitt, Jonathan Delph, Brandon Johnson (Purdue), Brandon Schmandt (UNM), and Gareth Collins (Imperial) on a Meteor Crater seismic survey.

2.1.4. IMPACT: CLASS Co-I Dreyer is a member of the SSERVI IMPACT team.

2.1.5. REVEALS: CLASS Co-I Bennett is a member of the SSERVI REVEALS team; he and D. Britt, L. Pohl, B. Jones and T. Orlando are collaborating on Thermo Gravimetric Analysis (TGA) and space weathering of volatile-rich asteroidal regolith materials.

2.1.6. UNITED KINGDOM: CLASS Post-doc Hannah Sargeant is helping develop the ProSPA instrument for the Luna-27 mission, as well as studying rover wheel interactions with lunar regolith.

2.2. International Collaborations

- Bennett and graduate student Katerina Slavicinska are collaborating with Univeristé de Lille analyzing the spatial distribution of organics within meteorites using two-laser desorption mass spectrometry.
- Co-I Opeil has been working with C. Avdellidou (Laboratoire Lagrange, Université Côte d'Azur, Nice, France) and & Landsman (CLASS Exolith Lab/Florida Space Institute) on the thermal conductivity & heat capacity measurements of a CM2 simulant sample.
- Co-I Opeil and PI Britt collaborations with G. Consolmagno (SSERVI/CLASS CoPI- Spec. Vaticana) and B. Macke (SSERVI/CLASS CoPI- Spec. Vaticana) continue on thermal & physical properties of meteorites.
- Co-I Boswell is collaborating with Christian Koeberl (U. Vienna) on tektite formation, cratering mechanics, and airbursts. Koeberl is a visiting professor with seminars (postponed until 2022 due to covid); they were introduced to one another through SSERVI connections.
- Co-I Boswell is working with Ania Losiak (Polish Acad. Sci.) & Vance Holliday (U of Arizona) on modeling and fieldwork associated with Odessa Crater.
- Co-I Abdell is an advisor to the European Commission Near-Earth Object Modelling and Payloads for Protection (NEO-MAPP) project. This activity is led by Patrick Michel at the Nice Observatory.
- Britt is jointly advising a grad student at the University of Grenoble in ISRU related studies. Sebastien Cohoner will split his time between Grenoble and UCF in Orlando. He is currently performing experiments at Dr. Britt's lab in Orlando.
- Britt is working with Co-Is Chrysoula Avdellidou and Marco Delbo (Observatoire de la Côte d'Azur) on impact experiments using asteroid simulants, thermal cycling of regolith investigations, and physical properties investigations.
- Britt is partnering with Serkan Saydam of the University

of New South Wales to integrate planetary science and ISRU into their very strong mining curriculum.

- Britt is working with Hideaki Miyamoto (University of Tokyo) on the development of simulants to support the JAXA MMX mission.

3. Public Engagement Report

CLASS regularly participates in high school events, science fairs, and public outreach/talks within the local community.

3.1. Daniel Britt:

- We held a perseverance rover exhibition for space week offered at Daytona's Museum of Art and Sciences.
- CLASS supported NASA's Plant the Moon Challenge by providing over 2 tons of lunar/martian simulants to grade schools for education, so that they can help answer the question "Can we grow good sustainably in a Lunar or Martian environment?"
- Exolith Lab provided opportunities for 12 high-school students to gain research and volunteer experience assisting in making regolith simulant.
- Working closely with Plant the Moon, a program that distributes lunar and martian regolith simulant to schools across the country for students to run plant growth experiments over a 10-week period.

3.2. Mark Boslough

- Asteroid Day: Recurring event (June). Webcast panel member (see Moment of Outreach Youtube video)
- Asteroid Hunters (IMAX): Film finally premiered this year, but I was unable to attend due to covid.
- Near-Earth Object Rapid Response Team founder/leader
- Published two planetary impact-related articles in Skeptical Inquirer (both reprinted by Asteroid Day).
- Multiple science news media interviews about planetary impacts and airbursts.

3.3. Paul Abdell

- Night Sky Network Webinar about the DART Mission and Planetary Defense on October 21, 2021 (Virtual).
- Lafayette Geological Society Presentation about DART and Planetary Defense on October 20, 2021 (Virtual).
- Astranova School presentation about DART and Planetary Defense on December 10, 2021 (Virtual)

3.4. Yanga Fernandez

Organized and ran an outreach program that made use of UCF's Robinson Observatory. We engaged the public in lunar and small-body science at many of these events. Due to the pandemic, we limited attendance to minimize crowding, but had 4 events and with about 60 people attending each event. About 75 people attended our "International Observe the Moon Night" event on October 16.

3.5. Kerri Donaldson Hanna

- Center for Health & Wellbeing Digital Education Program, Public lecture entitled 'Asteroids, NASA, and the Health Benefits of Stargazing', June 2021.
- Mars2020 Landing Party Panel, Fernbank Science Center and Jim Cherry Memorial Planetarium, February 2021.
- Astronomy & Geophysics Article, 'Playing TAG with Bennu', Volume 62, doi:10.1093/astrogeo/atab038, February 2021.
- Ivanhoe Broadcast News, 'Study Science: A Giant Leap Forward for Women', September 2021.
- UCF Today, 'A First-of-its-Kind Camera to Investigate the Moon's South Pole', March 2021.
- News 6 Click Orlando, 'UCF Professor Among Team Working with One-of-a-Kind Camera Going to the Moon', March 2021.
- Fox 35 Orlando, 'UCF Professor Teams Up with NASA to Create Camera Going to the Moon', March 2021.
- Spectrum News 13, 'Perseverance Rover Lands Safely on Mars', February 2021.
- Spectrum News 13, 'UCF researchers aid in Earth's first planetary defense mission', November 2021.

3.6. Cass Runyon

- Three Zoom sessions with elementary and middle school students who are blind, from El Paso School District, El Paso, Texas. Sessions also included their teachers and parents.
- Worked closely with members of the Landsat 9 Team to create and publish a tactile book on Earth and an introduction to climate change: Earth: A tactile Guide to the Blue Marble (NASA SP-2021-08-01-ARC; www.sservi.nasa.gov/books)
- Presented 55 virtual field trips on space science and exploration to over 1,500 middle school students using Stellarium planetarium program and tactile books. Some programs were held live at the Coshocton High School Planetarium in Coshocton, Ohio.
- Presented SSERVI science and the upcoming Artemis mission to 24 educators at Spartanburg Science Center in Spartanburg, SC.
- Field testing of tactile books and associated activities highlighting light pollution in Earth: A Tactile Guide to the Blue Marble. This was done in conjunction

Figure 10: Co-I Runyon published Earth: A tactile view of the Blue Marble. NASA SP-2021-08-01.ARC.

with University of Kentucky graduate classes and personnel at the Kentucky School for the Blind, June 2021.

- Panelist and invited presenter for the SciAccess International Workshop, hosted by Ohio State University.
- Participant and presenter for NASA 508 Task Force hosted by NASA Marshall Space Flight Center.
- Sharing CLASS science and technology as a part of the NASA Mission Design class who is designing the Observation, Research at Cratered Lunar Environments (ORACLE) mission at College of Charleston. CofC science students work closely with engineering senior design students at the University of Alabama Huntsville.
- Sharing CLASS science and technology as a part of Planetary Geology at the College of Charleston.
- Ongoing discussions with multiple Schools for the Blind across the nation, all of whom have received copies of our tactile books.
- Presentation and delivery of the tactile books to the Etelman Observatory, University of the Virgin Islands, St. Thomas, USVI; North Dakota School for the Blind, Vermont School for the Blind; Ohio School for the Blind; and New York School for the Blind.
- Great Lakes Planetarium Association annual meeting, Grand Rapids, Michigan, November 2021. Collaboration with University of Minnesota Duluth, Delta College, and Stiftung Planetarium, Berlin Germany regarding tactile astronomy resources and science accessibility issues.

3.7. Joel Sercel

- Presented on Asteroid Mining At 2020 Free Market Forum https://youtu.be/Wp4C7F76YVE

3.8. Clive Neal

- Invited panelist, AAS Goddard Symposium: The Moon is not just a place to learn how to go to Mars. 5 May 2021
- United States Congress: Invited seminar to congressional staffers – The Value of our Moon (27 April 2021)
- Continued development of my CE-30555 Living and Working on the Moon undergraduate class (55 Students registered in the class for Spring 2022).
- 5 March 2021: Dr. David Livingston, Broadcast 3654 Dr. Clive Neal. https://www.thespaceshow.com/show/05-mar-2021/broadcast-3654-dr.-clive-neal
- 22 March 2021: Brendan O'Shaughnessy, University of Notre Office of Public Affairs and Communications: A Fan of the Moon: Clive Neal searches for new resources in lunar rocks. https://www.nd.edu/stories/the-fan-of-the-moon/
- 26 March 2021: Jeff Foust, Space News - NASA looking for earlier launch of lunar orbiter SmallSat mission. https://spacenews.com/nasa-looking-for-earlier-launch-of-lunar-orbiter-smallsat-mission/
- 4 May 2021: Eric Berger, Ars Technica: NASA has selected its deep space hardware – now comes the fun part. https://arstechnica.com/science/2021/05/nasa-has-selected-its-deep-space-hardware-now-comes-the-fun-part/
- 9 September 2021: Paul Voosen, Science Magazine – The coming lunar armada: A fleet of NASA-funded startups will soon begin to land on the Moon. https://www.science.org/content/article/nasa-funded-startups-will-soon-put-fleet-landers-moon

3.9. Phil Metzger

- Very active on twitter with 85.2k followers and 52.7k tweets.

3.10. Josh Colwell and Addie Dove

- Continued with the "Walk about the Galaxy" podcast: http://walkaboutthegalaxy.com/
- Produced 32 planetary and astrophysics-related podcasts during 2021. For example, this one is about the Perseverance rover on Mars: http://walkaboutthegalaxy.com/2021/02/perseverance-cache-me-while-you-can/

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

4.1. Cass Runyon

- We continue to make sure that all EPE activities and resources are fully accessible to all audiences. We are working closely with educators of the Blind, Deaf and other special needs to test and refine our tactile books, online content and hands on activities. We will continue to work with Title 1 schools and underrepresented populations at public events as COVID permits.
- Working closely with the IDEAS team and the education video production team at NASA Langley Research Center to adapt NASA education activities for use with all audiences. The activity and adaptation videos are

Figure 11: Group of minority-student undergraduate interns assembling the mini-RASSOR platform.

currently in final edit. Videos will include ASL/Deaf interpreters.

- New staff hire, Ms. Maria Royle, Stall High School. Maria is a science teacher and ESL Coordinator helping to ensure that all of our EPE activities are fully accessible in support of EDIA.

4.2. Rob Mueller

- Mentored a group of minority undergraduate interns who worked on manufacturing and assembling the Mini-RASSOR platform (see Figure 11).

4.3. Kerri Donaldson Hanna

- Ivanhoe Broadcast News, 'Study Science: A Giant Leap Forward for Women', September 2021.
- UCF honored Women in Space during their SpaceU football game held on October 22nd where CLASS Deputy Co-I Addie Dove, and Co-I's Donaldson Hanna and Pinilla-Alonso were honored. See Figure 12.

4.4. Cyril Opeil

- Recruiting Katrina Donahue to work on meteorites is a first for my laboratory. Undergraduate women in physics are rare in my university and although this may not seem like a triumph to all, Katrina is only the third woman to work in my lab in the last eighteen years. Providing opportunities for women in science research is a personal priority for me.

4.5. Yan Fernandez

Fernandez collaborated with a group of students in UCF's Technical Communication MS program to assess how to broaden outreach possibilities at the campus observatory. Part of the group's work was to advise us on how we can provide a more welcoming experience for all demographic groups, including those traditionally underrepresented in STEM. The group wrote a report, and we are now in the process of implementing the recommendations in our outreach work.

5. Student/Early Career Participation

Undergraduate Students

1. Anna Metke, UCF, Exolith Director of Operations
2. Christian Sipe, UCF, Exolith Lab, lead ISRU engineer
3. Anna Paula Dovali, UCF, Exolith Lab
4. Makayla Peppin, UCF, Exolith Lab, Geotechnical Research Associate
5. Parks Easter, UCF, Exolith Lab
6. Joshua Conway, UCF, Exolith Lab
7. Lucas Weber, UCF, Exolith Lab
8. Alexander Madison, UCF, Exolith Lab
9. Konrad Krol, UCF, Exolith Lab
10. Catherine Millwater, UCF, Exolith Lab
11. Sheina Rodriguez, UCF, Exolith Lab
12. Riley Havel, UCF, Exolith Lab as well as spectral characterization of Martian soils and computation of spectral properties of molecules in Deputy-PI Bennett's

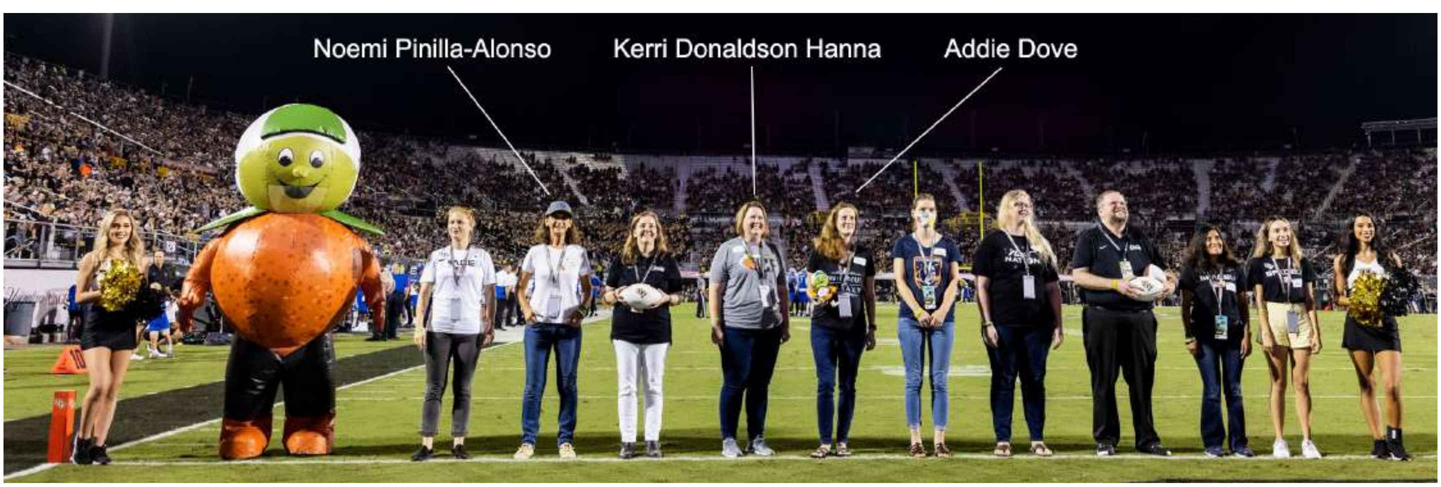


Figure 12: CLASS Co-Is being honored at UCF's SpaceU game.

laboratory (see Big Bang Box under awards).

13. Alexander Wasilkoff, Boston College, working with Co-I Opeil. Performed computational analysis on meteoritic heat capacity, thermal conductivity, and linear thermal expansion data. How a first-year PhD student at Boston University.
14. Katrina Donahue, Boston College, working with Co-I Opeil. Assisted in meteorite sample preparation and thermal/physical measurements.
15. Maxwell Korman, Boston College, working with Co-I Opeil. Assisted in meteorite sample preparation and thermal/physical measurements.
16. Bobby Lawrence, MTU, Icy Regolith production/ characterization. Lunar transport behavior.
17. Chuck Carey, MTU, Icy Regolith production/ characterization. Lunar transport behavior.
18. Nathan Miller, MTU, Icy Regolith production/ characterization. Lunar transport behavior.
19. Megan Harwell, LANL, worked with Mark Boslough but now a PhD student at UC Davis (Stewart group).
20. Daniel Davila, UCF, undergraduate student, working with Co-I Fernandez on hazards from sungrazing comets.
21. Adam Bedel, UCF, working with Co-I Donaldson Hanna on building a vacuum chamber capable of simulating lunar and asteroid conditions for measuring CLASS regolith simulants.
22. Luis Santori, UCF, working with Co-I Donaldson Hanna on creating LROC NAC digital terrain models of pure anorthosite regions on the Moon and analyzing resulting photometric observations.
23. Cheyenne Harper, UCF, working with Co-I Donaldson Hanna on sample preparation and testing temperature sensors in CLASS lunar regolith simulants.
24. Reece Hammond, College of Charleston, Working with Co-I Runyon.
25. Giulliana Rasua, UCF, working with Co-I Seal.
26. Julian Salkin, U. Hawaii, working with Co-I Jedicke on development of optimized filters for ISRU target identification.
27. Sarah Heckel, CSM, working with Co-I Dryer supporting optical mining testbed.
28. Jonathan Pearce, CSM, working with Co-I Dryer supporting optical mining testbed.
29. Joseph Erigat, CSM, working with Co-I Dryer supporting optical mining testbed.
30. Caleb Kracke-Bock, Purdue, Working with Joel Sercel at TransAstra.
31. Ty Krieger, Trinity University, Working with Joel Sercel at TransAstra.
32. Sammie Van Blaricom, Cal Poly San Luis Obispo, Working with Joel Sercel at TransAstra.
33. Ivan Mak, University of Wisconsin-Madison, Working with Joel Sercel at TransAstra.
34. Alexander James Love, Trinity University, Working with Joel Sercel at TransAstra.

Graduate Students

1. Kārlis Šļumba, UCF, Exolith Laboratory.
2. Katerina Slavicinska, UCF, working with Dr. Bennett on the analysis of carbonaceous chondritic meteorites using two-laser desorption mass spectrometry.
3. Amy LeBlue-DeBartola, UCF, working with Dr. Bennett on the analysis of carbonaceous chondritic meteorites using Raman spectroscopy.
4. Mary Hinkle, UCF, graduate student, working with Dr. Fernandez on thermal modeling of asteroids.
5. Jennifer Larson, UCF, graduate student, working with Dr. Fernandez on dynamical modeling of ejecta clouds from asteroids.
6. Vanessa Lowry, UCF, graduate student, working with Dr. Donaldson Hanna on modelling thermal infrared spectra of asteroids, Trojan asteroids, and lunar soils, working with Dr. Tim Glotch (RiSE) on T-matrix radiative transfer algorithms.
7. Ryan Galinkin, UCF, graduate student, working with Dr. Donaldson Hanna on laboratory measurements of highly porous analog samples to constrain surface porosities of airless bodies.
8. Nick Piskurich, UCF, graduate student, working with Dr. Donaldson Hanna on remote sensing analysis of the irregular mare patches on the Moon.
9. Autumn Shackelford, UCF, graduate student, working with Dr. Donaldson Hanna on characterizing the effects of cold and 'wet' conditions on grain morphologies in CLASS lunar regolith simulants.
10. Miguel Coto Villanueva, Colorado School of Mines, Space Resources Program was mentored by scientists and engineers at SwampWorks.
11. Cole Pazar, Colorado School of Mines, Space Resources Program was mentored by scientists and engineers at SwampWorks.
12. Travis Vazansky, Colorado School of Mines, Space

Resources Program was mentored by scientists and engineers at SwampWorks.

13. Caitlin Milera, University of North Dakota, Working with Co-I Runyon.
14. Marissa Saad, University of North Dakota, Working with Co-I Runyon.
15. Tori McIntosh, University of North Dakota, Working with Co-I Runyon.
16. Carig J. Neal, UCF, Working with Co-I Seal.
17. Yifei, Fu, UCF, Working with Co-I Seal.
18. Tomifey Broslav, CSM, working with Co-I Dryer supporting the optical mining testbed.
19. John Schmit, CSM, now lab manager/research engineer working with Co-I Dryer supporting the optical mining testbed.
20. Wellington Froelich, Purdue, Working with Joel Sercel at TransAstra.
21. Seth Krieger, University of Southern California, Working with Joel Sercel at TransAstra.
22. Derek Janoski, University of Southern California, Working with Joel Sercel at TransAstra.

Postdoctoral Fellows

1. Jared Long-Fox, UCF, Exolith Lab, Chief Geomechanics Specialist, Geotechnical Analysis.
2. Zoe Landsman, UCF, now Exolith Lab Chief Scientist.
3. Leos Pohl, UCF, working with Dan Britt on asteroid physical properties.
4. Mélissa Martinot, UCF, working with Dr. Donaldson Hanna on remote sensing analysis of pure anorthosite regions on the Moon and laboratory measurements of lunar analogs.
5. Hannah Sargeant, UCF, working with Dan Britt on molten regolith electrolysis reactor and interactions between dust and rover wheels.
6. Michael Lucas, University of Notre Dame, Working with Dr. Neal on lunar trafficability.

New Faculty Members

1. Ms. Maria Royle, Stall High School. Maria is a science teacher and ESL Coordinator helping to ensure that all of our EPE activities are fully accessible in support of EDIA.

6. Mission Involvement

1. Lucy, D. Britt, Leader of the Interior and Bulk Properties Working Group, Co-Investigator. This directly builds on SSERVI small bodies research. Lucy was launched October 16, 2021.

Figure 13: Launch of the Lucy spacecraft from Cape Canaveral

2. New Horizons, D. Britt, Co-Investigator.
3. OSIRIS-REx, C. Opeil, leveraging an introduction through CLASS/SSERVI connections, Dr. Opeil will have an opportunity to measure the thermal properties of samples returned from 101955 Bennu. SSERVI is supporting his measurements of meteorite thermal properties which led to this opportunity.
4. Hyabusa2, P. Abell, Facilitating interactions among Japanese and US team members and as an agency liaison to JAXA on behalf of NASA. Since Hyabusa2 has conducted multiple surface operations at asteroid 162173 (Ryugu) with touchdowns, rovers, impactors, and the first return samples from a carbonaceous asteroid, this role facilitates interactions between the mission and CLASS/SSERVI research interests.
5. Double Asteroid Redirect Mission (DART), P. Abdell, is a participant on the ground-based observations working group, and the impact modeling, ejecta, and proximity science working groups. CLASS researchers are involved in ground- and space-based observations of asteroids, modeling of impacts and ejecta, as well as the DART mission itself.
6. Near-Earth Surveyor Mission (NEOSM), P. Abdell, is participating as an investigation team member for identification of small body targets with low delta Vs, which is of interest for NASA's resource utilization and exploration objectives. He is also participating on the comet working group to help model the numbers of comets that may be identified by NEOSM and the proportion of these objects that represent an impact hazard to the Earth. The mission will survey much of the NEA population with emphasis on the 140-m and larger populations and through SSERVI, CLASS researchers will be directly linked to details about the mission, the science and potential future collaborators.
7. Hera Mission, P. Abdell, is participating as a US member on the Hera mission investigation team to aid the characatization of the Didymos and Dimorphos post-DART impact. This mission has direct ties to CLASS/SSERVI research since it will be the first

rendezvous mission to a binary NEA and will gain clues not only about the impact effects of DART, but also about the characteristics and formation history of this binary NEA system. Binary NEAs represent 1/6 of all NEAs and are therefore common among the NEA population.

8. DART, UCF Graduate student Jenny Larson, participant on the investigation team. DART is a NASA space mission launched in October 2021 to test planetary defense methods for near-Earth objects by nudging an asteroid away from a collision course with Earth.
9. NEOWISE, Y. Fernandez, collaborator in the mission's comet group. NEOWISE continues its infrared sky-survey, and it discovers and characterizes numerous NEAs and comets, including potentially hazardous ones.
10. NEOSurveyor (NEOS): Y. Fernandez, Co-I and Investigation Team member. NEOS is run out of the NASA PDCO office and will be a follow-on mission to NEOWISE. We are currently in Phase B. NEOS is expected to find and characterize a significant fraction of the NEOs (asteroids and comets) that are at least 140-meters in diameter and so help achieve the goals of the Brown Act.
11. Lunar Reconnaissance Orbiter, Diviner Lunar Radiometer, K. Donnaldson Hanna, Co-Investigator (2014 – present).
12. OSIRIS-REx, K. Donaldson Hanna, Participating Scientist (2017 – present).
13. Lunar Compact InfraRed Imaging System (L-CIRIS), K. Donaldson Hanna, Co-Investigator (2019 – present).
14. Lunar Trailblazer, K. Donaldson Hanna, Co-Investigator.
15. ESA Comet Interceptor, MIRMIS, K. Donaldson Hanna, Instrument Team Member (2019 – Present).
16. COLDarm payload for NASA CLPS, R. Mueller, The Cold Operatble Lunar Deployable Arm (COLDarm) leverages technology used for the Mars Ingenuity Helicopter to perform a variety of tasks in extremely cold temperatures (-173 °C) without the need for a water heater. This includes tasks like scooping and analyzing lunar soil, deploying instruments, and capturing photos of the lander's surroundings. Jared Long-Fox (CLASS) has been collaborating on this project, providing geotechnical expertise to the COLDarm scooping experimental design. This involvement directly flows from SSERVI's support of the Exolith Lab and research into the geotechnical properties of simulants.
17. Martian Moon eXploration (MMX) Mission, R. Mueller, Technical advisor on PlanetVac Regolith Sampling Technology Demonstration. Rob Mueller at NASA Kennedy Space Center & SSERVI CLASS member is the technical advisor for the pneumatic sampler being provided by NASA to JAXA. Valuable scientific information was provided by Dr. Dan Britt (CLASS) to inform sampling strategies and the sampler design. The JAXA MMX mission is proceeding to the Preliminary Design Review (PDR) milestone and has full funding for the pneumatic sampler which is due to fly on the JAXA MMX spacecraft in 2024.
18. Landsat 9, C. Runyon, the new tactile book, Earth: The Blue Marble, connects the various imagery being collected by the new Landsat 9 mission to sea level rise, climate change science, penguin colonies and more.
19. Janus, R. Jedicke, science team member providing ground-based observational support. The Janus mission will characterize and contrast the properties of two binary asteroid systems of different taxonomies, 1996 FG3 (C) and 1991 WH (Sk).
20. Masten Mission 1 (SAMPLR Instrument), C. Dreyer, Instrument Co-I of a robotic arm mounted penetrometer.
21. Luna-27, H. Sargeant, ProSPA, Science Team Member. The instrument is being built at The Open University (part of the United Kingdom SSERVI node) and will be conducting ISRU studies in a south polar region of the Moon.
22. Mars International Ice Mapper, H. Sargeant, Measurement Definition Team Member.
23. Lunar Geophysical Network, C. Neal., A New Frontiers 5 Proposal. Request for Information sent out to 33 different entities (NASA centers and commercial companies) in order to build the Mission Team. Thirteen responses received and seven partners were invited to form the Mission Team.

7. Awards

1. Astronaut Scholar, Riley Havel, Undergrad working with Dr. Bennett, and in the Exolith Lab.
2. Goldwater Scholar, Riley Havel, Undergrad working with Dr. Bennett, and in the Exolith Lab.

Figure 14: "I know in STEM we often face imposter syndrome, and it might hold us back at times, but receiving the astronaut scholar has just made me a lot more ambitious and think that my career goals aren't as lofty as I once thought — that I can do it." – Riley Havel, Astronaut Award recipient in 2021.

3. Co-I Paul van Susante and his team won (Artemis award) for NASA 2020 BIG IDEA Challenge in January 2021, for their work on the Tethered – permanently shadowed Region EXplorer (T-REX).
4. Co-I Paul van Susante and his team won NASA's Watts on the Moon Challenge Grand Prize (scenario #2, tasked teams with delivering power from the power plant to a water extraction plant inside the crater) in May 2021, for their proposed system of tethered rovers that unspool superconducting wire into the crater.
5. Co-I Paul van Susante and his team won (runner-up) prize for NASA's Break the Ice Challenge in August 2021, in collaboration with team LIQUID (Altadena, California).
6. 10 CLASS Co-Is and Collaborators were honored by the IAU and the WG on Small Bodies Nomenclature. The new named asteroids include:

   (26435) Juliebrisset = 1999 XS241

   (27082) Donaldson-Hanna = 1998 TT30

   (27409) Addiedove = 2000 EJ135

   (29605) Joshuacolwell = 1998 QF54

   (35646) Estela = 1998 KO66

   (36329) Philmetzger = 2000 LU35

   (39256) Zacny = 2000 YE120

   (39290) Landsman = 2001 CC29

   (45846) Avdellidou = 2000 RA96

   (46308) Joelsercel = 2001 OZ104
7. Three CLASS post-docs were awarded Preeminent Postdoctoral Program Scholarships from UCF: Dr. Hannah Sargeant (working with PI Britt), Dr. Leos Pohl (working with PI Britt) and Dr. Craig J. Neal (working with Co-I Seal).
8. Co-I Noemi Pinilla-Alonso was awarded UCF's Women's History Month Honoree (in March 2021). An award from the Office of Excellence at UCF for women in recognition to their impact on students and UCF's campus community: https://provost.ucf.edu/news/faculty/2021-womens-history-month-honorees/
9. UCF honored Women in Space during their SpaceU football game held on October 22nd where CLASS Deputy Co-I Addie Dove, and Co-I's Donaldson Hanna and Pinilla-Alonso were honored. Co-I Pinilla-Alonso also received the space football in representation of the Florida Space Institute (see Figure 16).

Figure 15: Artemis Award for NASA's 2020 BIG Idea Challenge.

10. As part of the World Space Week, UCF promoted and highlighted the work of both CLASS PI Dan Britt and his involvement in the Lucy mission, as well as CLASS Co-I Pinilla Alonso who showed leadership in establishing UCF as a major user of the James Webb Space Telescope, helping UCF researchers secure more than 100 hours of telescope time in the first round of competed time: https://www.ucf.edu/news/ucf-celebrates-world-space-week-all-october-long/
11. Co-I Campins has been named a Jefferson Science fellow and from Nov 21st, 2021, has been reporting to Washington D.C. where he will be advising the U.S. Department of State. No more than 15 of the nation's most distinguished faculty are named fellows each year.
12. Co-I Neal was the recipient of the inaugural LEAG Service Award in 2021.
13. Kārlis Šļumba, Graduate student from Lativa was awarded a Fulbright Graduate Fellowship. He is working with PI Britt.


Figure 16: CLASS Co-I Noemi Pinilla-Alonso being handed the space football at UCF's SpaceU game alongside UCF's citronaut mascot.

Center for Lunar Science and Exploration (CLSE)

David Kring

Lunar and Planetary Institute, Houston, TX

CAN-3 TEAM

1. CLSE Team Report

1.1. Science and Exploration

1.1.1. A Source of Polar Volatiles

The CLSE team has been investigating the lunar volatile cycle, which begins with the initial delivery of volatile materials from impacting asteroids and comets when the Moon accreted (e.g., Barnes et al., 2016a); followed by the processing of that material in the lunar interior that we detect with Apollo and lunar meteorite analyses (e.g., Robinson et al., 2016; Barnes et al., 2016b); the venting of that material in volcanic eruptions (e.g., Kring, 2014), which may have produced transient atmospheres (Needham & Kring, 2017); the addition of late accreting volatiles by impactors (Joy et al., 2020); and the collective transport of those indigenous and exogenous volatile materials to the lunar poles where they can potentially be recovered for in-situ resource utilization.

Expanding on those previous studies, this year CLSE focused on the largest indigenous source of volatiles in the south polar region (Kring et al., 2021), which is an immense volcanic vent on the floor of Schrödinger basin. That vent was produced when basalts deep within the lunar interior were transported to the surface (Fig. 1), spewing water and other volatile constituents into a transient gas-rich cloud whose components were transported across the lunar surface in a series of hops until trapped in cold polar locations (Fig. 2).

Our study began by showing that lunar pyroclastic vents across the lunar surface repeatedly generated 1012 to 1015 g of H_2O and $CO+CO_2$ for pyroclastic volumes of 10 to 500 km3 (Fig. 3) early in lunar history, particularly during the first billion years. Some of those volatiles migrated to the lunar poles where they could be trapped in permanently shadowed regions (PSRs).

The largest indigenous source of volatiles in the south polar region was volcanism that erupted on the floor of the Schrödinger impact basin. Using crater counting chronological methods, we found the vent eruption ceased ~3.70 +0.02-0.03 Ga. To estimate the volume of gas liberated by that eruption, the team used Lunar Reconnaissance Orbiter Camera (LROC) and Lunar Orbiter Laser Altimeter (LOLA) data to measure the volume of erupted magma. The team then integrated those volumes with vented volatile estimates using analyses of similar

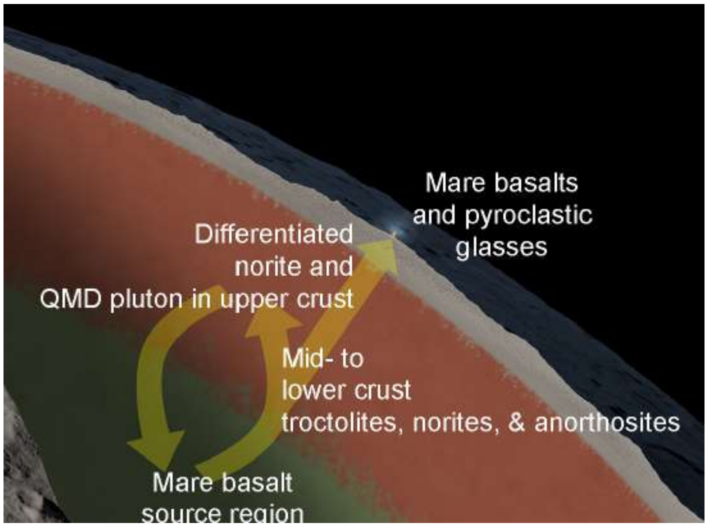


Fig. 1: The lunar volatile cycle includes the processing of accreted volatiles within the lunar interior and the venting of those volatiles at the surface in volcanic eruptions. The erupting basalts that fed the Schrödinger volcanic vent came from the lunar mantle.

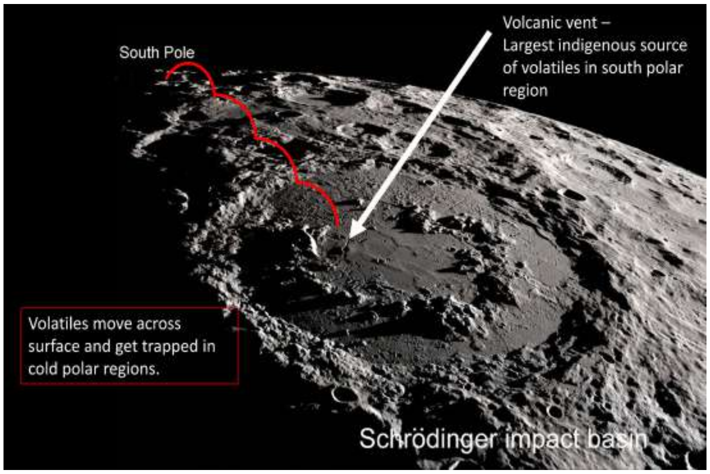


Fig. 2: Volatile materials vented in the Schrödinger basin hopped across the lunar surface where they could be trapped in cold polar regions of the Moon. Background image produced from LRO data by NASA GSFC\SVS.

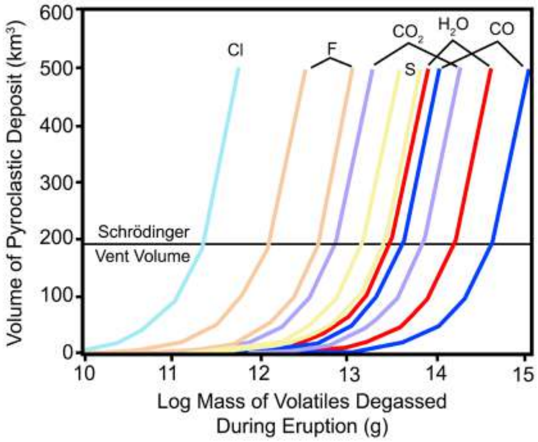


Fig. 3: Minimum and maximum mass of volatiles degassed during eruptions producing pyroclastic deposits with volumes up to 500 km3. A single curve for Cl represents maximum values; the minimum is zero. The volume of the Schrödinger vent and the correlated mass of volatiles degassed are shown along a horizontal line.

types of pyroclastic material collected by Apollo 15 and 17 astronauts. Using those integrated data, CLSE calculated the volumes of H2O, CO-CO2, F, S, and Cl vapor species released, including calculated values of 3.0 × 1013 to 1.6 × 1014 g H2O (Fig. 3). Those results were then entered into a model of the transport of volatiles across the lunar surface and a model of volatile deposition in polar cold traps. Those models suggest 1.1 × 1010 kg of the water vented in the Schrödinger basin were trapped in the Artemis exploration zone (Table 1).

1.1.2. Implications for Artemis and Commercial Lunar Payload Services (CLPS) Missions

The study's results suggest that missions designed to measure volatiles in the Artemis exploration zone should have the capability to analyze volatile deposits derived from volcanic vapors and, ideally, chemically and isotopically distinguish a volcanic source from other sources of volatiles.

The study's results also suggest a mission to the Schrödinger basin is needed to test the volatile production function. Such a mission would either measure volatile contents of in-situ glasses or by collecting samples for return to Earth for analyses.

The volcanic vent in Schrödinger basin was one of the initial NASA Exploration Space Mission Directorate's targets for the Lunar Reconnaissance Orbiter mission. The Schrödinger basin has since been the focus of several landing site and traverse studies by the CLSE team (O'Sullivan et al., 2011; Kramer et al., 2013; Kumar et al., 2013, 2016; Hurwtiz & Kring, 2015; Potts et al., 2015; Steenstra et al., 2016; Kring et al., 2016, 2017) and other colleagues in the community (Mest, 2011; Bunte et al., 2011; Morse et al., 2021). Because the Schrödinger basin's volcanic vent is a potential target for human exploration, we note that this source of volatiles is far larger than the Sunset Crater and SP Mountain volcanic vents (Fig. 4) often used for astronaut training and lunar mission simulations (Fig. 5).

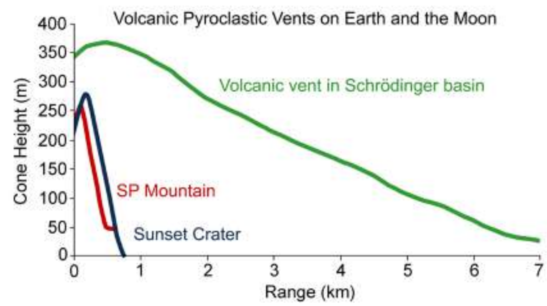


Fig. 4: Comparison of the topographical profiles of the pyroclastic vent in the Schrödinger basin and two lunar analogue vents on Earth, SP Mountain and Sunset Crater. The centers of the cones are along the vertical axis.

Fig. 5: Volcanic vents, like SP Mountain in northern Arizona, were exploration targets in Constellation-era lunar mission simulations. Shown here are CLSE PI Kring, in the roll of senior field geologist, and a Lunar Electric Rover safety engineer, during a D-RATS lunar mission simulation. Astronauts in the rover are moving towards the SP Mountain volcanic vent seen in the background.

Table 1
Masses of vented molecular species trapped in lunar polar regions, percentage of source that is trapped, and percentage relative to water.

Species	North Pole	South Pole
H_2O	4.5×10^8 kg (0.5%) (100%)	1.1×10^{10} kg (12%) (100%)
OH	1.1×10^6 kg (0.003%) (0.24%)	1.4×10^8 kg (0.5%) (1.3%)
CO_2	1.2×10^9 kg (3%) (267%)	8.0×10^9 kg (21%) (73%)
CO	6.8×10^5 kg (0.003%) (0.15%)	8.8×10^7 kg (0.04%) (0.8%)

The Schrödinger impact basin has also been selected to be the landing site of a CLPS mission. While the exact landing site within the basin has not yet been determined for that mission, the results provided by this year's CLSE research suggest the volcanic vent is an attractive target.

The CLSE team also examined a portion of the Schrödinger impact basin's peak ring, produced a geologic map of the area (Fig. 6), and developed three notional traverses (Czaplinski et al., 2021) that address science objectives outlined by the National Research Council (2007). Such a geologic location would allow a mission to address different science questions than those accessible around the volcanic vent. Thus, the CLSE team's research results this year should assist the upcoming CLPS mission regardless of the selected landing site.

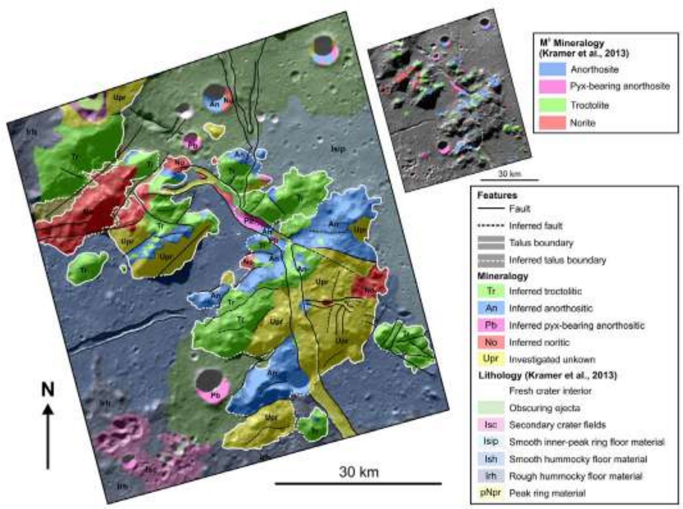


Fig. 6. Geologic map of a portion of the Schrödinger impact basin's mountainous peak ring.

1.1.3. Potential Artemis Landing Sites

CLSE is examining potential Artemis landing sites identified by the agency. Thus far, CLSE has provided assessments of nearly a dozen sites (Fig. 7) and evaluated different types of surface traverses. Some studies assume crew are limited to a 2-kilometer walking EVA limit, while some studies assume crew will have access to a rover that extends traverse distances during 14- to 42-day-long surface missions. Most of the landing sites are on topographical summits, either on top of a massif (such as the Malapert massif) or the uplifted rim of an impact crater (such as Shackleton crater). Those landing sites are attractive to the agency because of their ability to provide solar power >50% of the time while, in some cases, also being located close to PSRs where volatile substances might be recovered for human consumption, radiation shielding, and rocket propellant.

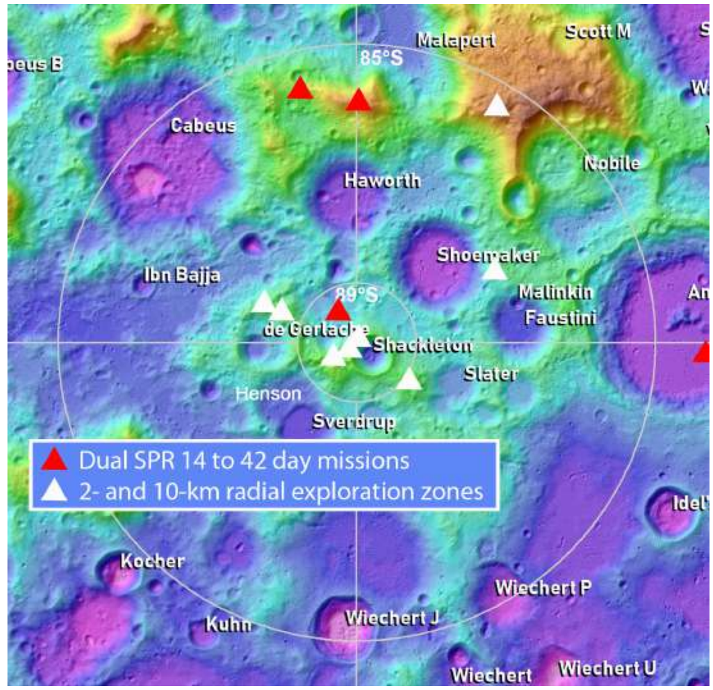


Fig. 7: Locations within 6° of the lunar south pole, the initial Artemis exploration zone, that the CLSE team has studied for different types of human mission scenarios, including 2-km-diameter walking EVAs, 10-km-diameter unpressurized rover EVAs, and greater distance traverses using dual small pressurized rovers.

This year CLSE took a closer look at potential Artemis landing sites 001, 004, 007, 011, 102, and 105. To illustrate that work, we direct readers to a spectacular three-dimensional oblique view of lunar surface sites 001 and 004 that we created by draping Lunar Reconnaissance Orbiter Camera (LROC) images over Lunar Orbiter Laser Altimeter (LOLA) topography (Fig. 8). The south pole is located on the rim of Shackleton crater, which is 21 kilometers in diameter. That impact event excavated material from a massif (mountain) that had been uplifted by the South Pole-Aitken basin. The view in Figure 8 is looking along a ridge on top of that massif. Site 001, which is on the massif, and site 004, which is on the rim of Shackleton crater, are both covered with impact ejecta from Shackleton crater. Our analyses of those landing sites indicate the debris is rich with anorthosite, which may be remnants of an ocean of magma that used to surround the Moon. The Shackleton impact event also excavated older ejecta blankets, some of which we see layered on the far side of the crater (Gawronska et al., 2021). Thus, samples of Shackleton ejecta may contain impact melt from the South Pole-Aitken (SPA) basin and other pre-Nectarian and Nectarian-aged impacts, plus cryptomaria from SPA. Collectively, samples of Shackleton ejecta may provide a 1.5 billion-year-long record that includes information on the bombardment that produced the Moon's giant impact basins and at least one period of intense volcanism.

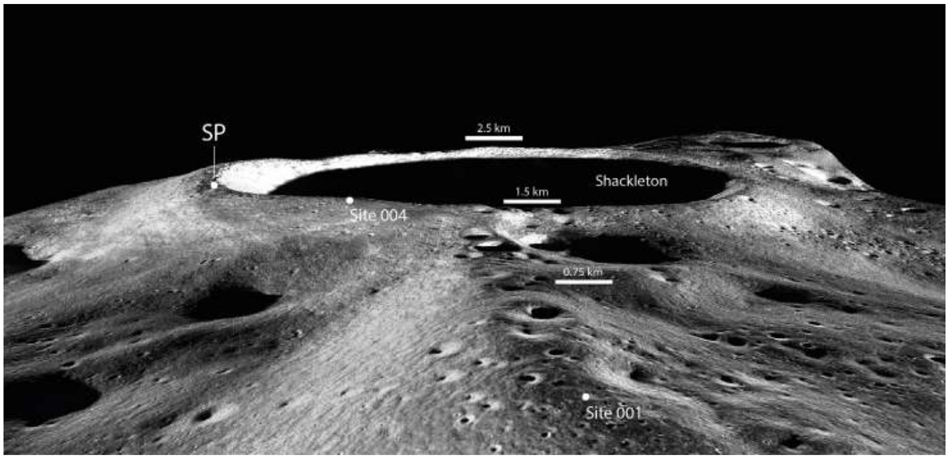


Fig. 8: Oblique view of a ridge adjacent to Shackleton crater looking towards the rim of Shackleton crater. The scale varies with distance from the viewer. The ridge is >700 m above the adjacent terrain. Shackleton crater has a 21 km diameter. SP = south pole. Rendered by international collaborator Valentin T. Bickel by draping LROC NAC images over LOLA topography.

Those geological outcomes may be augmented with studies of volatile substances within small PSRs that dot the area. Model calculations (Siegler et al., 2016) suggest several areas are thermally stable for water ice within 2.5 m of the surface. Initial assessments of potentially volatile-bearing regolith in small PSRs (such as a boulder shadow or small crater) or along the edges of larger PSRs on the Moon should be designed to (i) measure volatiles in their natural state, unaffected or minimally affected by sampling protocols, and (ii) evaluate the modification of volatile substances by impact cratering processes that constantly garden the lunar regolith. Volatile substances, in contrast to rock samples, lend themselves to in-situ analyses. Thus, initial analyses using deployable instruments, which have heritage use throughout the solar system, could be used to measure the chemical and isotopic composition of any volatile material.

One of the Artemis landing sites we studyied (site 102) was selected late in 2021 as the landing site for the VIPER robotic mission. The site is located on the top of a towering massif that was informally called Leibnitz ß during the Constellation era. CLSE studied the site using LOLA, LROC WAC, and LROC NAC data available on the PDS. Those data were analyzed in the summer of 2021 by our graduate student interns (G. R. L. Kodikara, M. A. Kopp, M. L. Meier, R. V. Patterson, F. B. Wróblewski, K. R. Frizzel, K. M. Luchsinger, A. Madera, T. G. Paladino, C. J. Tai Udovicic). Although the location is on a massif summit, it is also within an impact-cratered terrain where it will be essential to assess regolith modification by impact processes. Our student-led team mapped 12,146 craters with diameters >10 m in the area, which will likely affect the geologic context of VIPER operations and subsequent analyses of the mission's analyses.

In a complimentary project led by international collaborator Myriam Lemelin, the CLSE team examined the entire Artemis exploration zone for sites suitable for volatile deposits and investigations recommended by the National Research Council (2007). The study integrated an analysis of potential volatile deposits, determined using several different methods, the availability of nearby landing sites, and the accessibility of those deposits along paths with suitable slopes. The integrated product led to a prioritization of landing sites (Lemelin et al., 2021) that can be used in a multi-mission international robotic exploration program.

1.1.4. Preparing for Lunar Surface Science Operations

CLSE responded to agency requests for lunar surface EVA input, providing, for example, briefings to the Exploration EVA (xEVA) Operations Team and the broader JSC EVA community through its Open EVA Research Forum.

CLSE also responded to several agency requests for assistance through its series of Lunar Surface Science Workshops. We collated results from previous CLSE studies to (i) described the value of an integrated science and flight operations control room, (ii) an exploration operations system, and (iii) issues to be addressed in an initial assessment of volatile-bearing regolith during Artemis missions.

The concept of integrated science and flight operations was developed and tested during the Constellation era in a series of field-based lunar mission simulations. Those simulations drew staff from the Flight Operations Directorate's Astronaut Office and Extravehicular Activity (EVA) Group, Human Factors, and the science community, including the CLSE team. Furthermore, the simulations used and developed flight-like hardware, including mobility assets, technical adaptations to suits. An important advance made during those simulations was the integrated science and flight operations control room. The flight control room in JSC Bldg. 9 for the first remote field simulation evolved to a field-deployed Mobile Mission Control Center (MMCC) (Fig. 9, top) and then to a next-generation flight control room that was finally installed in JSC Bldg. 30 as NASA's Mission Control Center (Fig. 9, bottom). From those flight control rooms, crew missions were conducted at Moses Lake, WA (2008) and the Black Point Lava Flow, AZ (2008-2011). The latter site provided a lunar-like terrain where realistic science activities under demanding field conditions could

Figure 9: (top) Integrated flight control room in a Mobile Mission Control Center. (bottom) Integrated flight control room in JSC Building 30, NASA's Mission Control Center. Note that Artemis Astronaut Jessica Watkins, then a student, is sitting at an EV2 camera science console in the flight control room.

be conducted, and a flight control room that integrated flight and science personnel supported lunar surface activities. The simulations demonstrated that an integrated flight and science operations architecture greatly enhances mission productivity and provides crew with lunar surface expertise when engaged in lunar surface activities. It is important to develop a new series of those simulations for the Artemis era, so that science and flight operations staff have an opportunity to work with crew and hardware providers to develop the skills necessary to work as a team during a lunar surface mission.

Drawing on Apollo and Constellation lessons, we also noted several useful features of a successful exploration system: integrated science & engineering; lunar surface operations crafted in the framework of an exploration plan; integrated robotic & human exploration; well-trained crew (Sidebar); crews with appropriate sampling tools; integrated lunar surface mission simulations; collection of lunar samples, which are the key to transformative lunar science; and engaged university and international communities.

> The south pole resides on the rim of Shackleton crater. That impact event excavated 4 × 1011 m3 and nearly a billion metric tons of rock that were deposited on the crater rim and the surrounding terrain. Knowing which rock samples to collect from those deposits takes skill that will need to be developed.

Finally, we suggested through the Lunar Surface Science Workshop series that trenching is an important component of any initial evaluation of volatiles by Artemis crews. A trench will provide a baseline needed to understand the context of any in-situ analyses or of any core sample returned to Earth. Ideally, trenching should occur before a site for in-situ analyses or core recovery is selected. A trench will provide answers to several important questions: Do the abundances and compositions of ices vary along a spatial gradient? For example, do the relative abundances of dry ice and water ice vary with depth or laterally through the regolith? Do ices occur along grain and clast boundaries, in pore spaces, or both? Are ices concentrated along lithologic boundaries, such as the boundary between regolith layers, between ejecta layers, or along faults, that may have been pathways for volatile element movement? Have impact cratering processes produced breccias that mixed ice-bearing clasts with ice-free matrix or vice versa? Did the subsequent thermal equilibration of clasts and matrix cause diffusion of volatile material between those components and through the regolith? Is there any evidence of post-breccia diffusion that might reflect a modified thermal regime due to a modified depth of burial? Observations that allow those questions to be addressed will provide the means to test existing models of volatile evolution in regolith and, thus, the resource potential (RP) of that regolith. Those observations will also greatly enhance the value of any chemical and isotopic analyses.

CLSE responded to a request for similar information about volatile sampling from the agency's Contamination and Research Integrity (CaRI) team, submitting a brief report titled "Artemis Crew Core Sample of Potentially Volatile-bearing (Icy) Regolith."

While most of CLSE's products are packaged for delivery to the agency, we note that the university community has a very important role in developing surface science operations. For that reason, we gladly provided a briefing to a science and engineering group at Arizona State University about human and robotic mobility assets suitable for lunar surface operations.

1.1.5. Training for Lunar Surface Science Operations

The NASA Administrator asked our organization for input for anticipated lunar surface science operations. We responded with a summary of lessons learned during the Apollo and Constellation eras in a report titled Training for Lunar Surface Operations. The report was assembled by CLSE PI Kring and three EVA experts (Chris A. Looper, Zane A. Ney, and Barbara A. Janoiko) on the CLSE team who participated in Constellation-era lunar mission simulations. Notably, Apollo Flight Director and former Johnson Space Center Director Gerry Griffin wrote a forward for the document. The report was delivered to the agency at the end of the previous year. After the report had time to circulate through channels within the agency, it was released to the entire lunar and planetary science community in 2021. The report is accessible at https://www.lpi.usra.edu/lunar/strategies/Artemis-Major-Skills-Training_DV1_2_w_appendix.pdf.

One of the lessons captured in the report is that science staff need to be trained to work in a human flight operation environment. CLSE PI Kring, working with Flight Operations Directorate (FOD) and EVA staff, developed and implemented this year a course titled Space Flight Resource Management (SFRM) Training for Science Operations. The course used the LPI and flight operations training facilities at JSC. Participants learned SFRM skills, learned to develop and share situational awareness in a complex mission environment, learned to develop better active listening skills, learned communication protocols, learned how to package comm-loop calls, and learned problem solving skills relevant to a human mission environment. In addition, participants discussed Gateway-related operations, including a required tele-operation element, the evolving Design Reference Mission (DRM) for lunar surface landing sites and traverses, and an introduction to EVA ops that uses the new Exploration Extravehicular Mobility Unit (xEMU) for astronauts. Several early- to mid-career scientists participated in the program. Additional editions of the program are planned for 2022 and beyond, so that a pool of talent is available for the implementation of Artemis lunar surface missions.

1.2 Training & Education

CLSE provided additional training and education for students engaged in lunar surface exploration, although adjustments had to be made to accommodate pandemic-driven restrictions.

1.2.1 EVA Exercise at Meteor Crater

CLSE developed a 2-day course titled EVA Exercise at Meteor Crater that involved 20 students. We had to develop a communication system that simulated a lunar mission, with communication occurring within a science ops team, between the science ops team and a science communicator (SCICOM), and a closed loop between SCICOM and crew. In a very important collaboration, SSERVI Central staff at the NASA Ames Research Center developed a communication architecture, assembled the necessary components, and then deployed to Meteor Crater to support the EVA exercise. The innovative communication architecture (Fig. 10) was a huge success and far more compact than the system used during Apollo EVA exercises at Meteor Crater. The EVA Exercise at Meteor Crater training activity was not part of our original 5-year plan, but was so successful that we will be looking for ways to repeat the activity in future years.

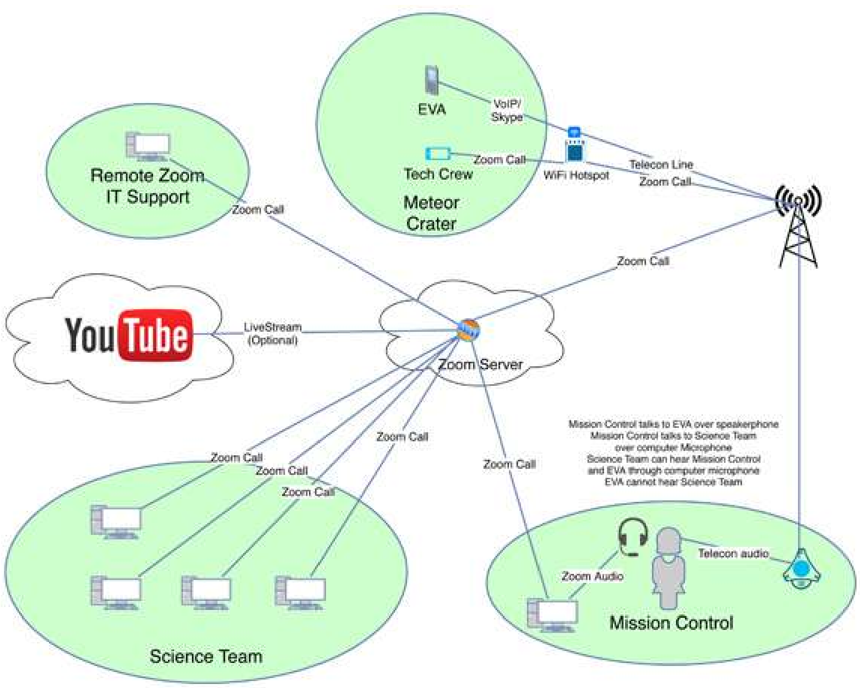


Figure 10: Communication architecture between EVA subject, Houston SCICOM, and remote Science Operations Center (SOC), Meteor Crater, October 15-16, 2021. NASA SSERVI Illustration (Ricky Guest and Ashcon Nejad).

1.2.2 Exploration Science Summer Intern Program

Due to pandemic-related restrictions, we had to modify our Exploration Science Summer Intern Program. Selected students were unable to travel to our training and research facilities in Houston. Moreover, facilities at both LPI and JSC were closed. Thus, we instituted for a second year a special "virtual" edition of the program. Despite being separated by more than a thousand miles, the team of students produced wonderful geologic insights about three potential landing sites in the lunar south polar region.

The students began by examining potential Artemis landing sites 102 and 105, both of which were also being considered for the VIPER robotic mission. The students then examined the terrain between the rim of Shackleton crater and Shoemaker crater, including intercrater plains. Finally, the students developed a computer model that captures the consequences of impact-generated ballistic sedimentation, showing that the process can dramatically affect the deposition and preservation of ice-bearing deposits in the Artemis exploration zone. Those results were briefed to LPI and JSC scientists in Houston and will be presented at the 2022 Lunar and Planetary Science Conference. Two full-length journal articles are also in preparation.

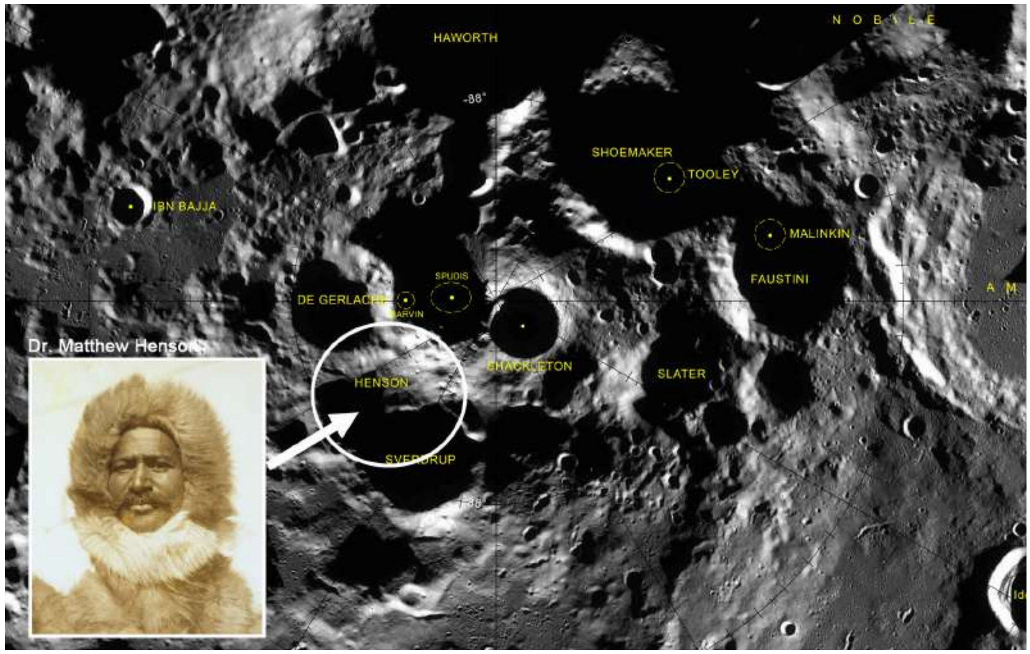


Fig. 11. Mosaic image of the south polar terrain with location of the newly named Henson crater featured.

1.3 Community Service

In addition to providing products for the agency, the CLSE team supports the broader lunar community with several services.

1.3.1 Lunar Science and Exploration Portal

CLSE continued to add data and documents to the online Lunar Science and Exploration Information Portal that is often described as the 'go-to' place for lunar information. This year additions were made to the collection of strategic lunar architecture documents and the library of classroom illustrations.

1.3.2 Lunar South Pole Atlas

CLSE continued to contribute products to the LPI Lunar South Pole Atlas. One of this year's contributions is a new topographic map, produced by team collaborator Julie Stopar, that includes the Malapert massif and the informally named Leibnitz ß massif. The summit of the Leibnitz ß massif is the location of the VIPER lunar landing site.

1.3.3 New Geographic Names

The CLSE team, largely through student-led initiatives, has been mapping potential Artemis landing sites identified in NASA's Plan for Sustained Lunar Exploration and Development. Our mapped areas contain several, fairly large craters that are unnamed. We have been referring to them as unnamed crater #1, unnamed crater #2, etc., but that is awkward and conflicts with other investigators using similar informal nomenclature for different craters.

We identified a small number of craters that, if named, would facilitate discussion of south polar geology. One of our graduate student interns, Jordan Bretzfelder, led a proposal to name one of those craters Henson (Fig. 11), in recognition of Dr. Matthew Henson's pioneering exploration of the north polar region of Earth. The proposed name was approved by the IAU Task Group for Lunar Nomenclature. NASA Headquarters and Ames Research Center distributed the news of Henson crater, recognizing the name reflects the Artemis axiom "first woman and first person of color" on the Moon (https://www.nasa.gov/feature/ames/henson-crater).

As Jordan noted, "Creating an inclusive community and achieving equity in the sciences begins by recognizing the contributions of people from all backgrounds. It felt like a disservice that Henson hasn't been appropriately recognized for his contributions to polar science, and I'm proud to be a part of rectifying that."

2 Inter-team/International Collaborations

2.1 Science and Exploration Research

CLSE obtained valuable input about lunar regolith simulants from the University of Central Florida SSERVI team and its Exolith lab.

CLSE provided modest input to a study by a University of Central Florida SSERVI team postdoctoral researcher.

CLSE studies of lunar volatiles were greatly enhanced by contributions from international partners in the United Kingdom.

CLSE studies of lunar polar geology and lunar farside geology were greatly enhanced by work done by international partners in Germany.

Fig. 12. Clarissa Tossin and her jacquard tapestries of the Moon.

Fig. 13. Astrophysicist Dr. Fatoumata Kébé who promotes science careers for girls and is using CLSE input with one of her educational projects.

3 Public Engagement Report

CLSE has a public engagement program that proactively takes advantage of new opportunities, while also providing a stable platform for two long-standing, successful education and public engagement programs: Exploration of the Moon and Asteroids by Secondary Students (ExMASS) and International Observe the Moon Night.

3.1 New Opportunities

On the anniversary of Apollo 14, CLSE staff spent an evening "virtually" with Atlanta's Fernbank Museum and its members. We had a live audience of 640 connections, which is an excellent response that illustrates the public's interest in lunar exploration.

CLSE assisted artist Clarissa Tossin (Fig. 12) who was developing public art commissioned for the Brochstein Pavilion at Rice University in Houston. The work of art titled The 8th Continent is a set of digital loom jacquard tapestries with metallic thread that are based on lunar images and illustrations. The installation premiered September 24 and will remain at the pavilion for one year.

The LPI was contacted by the French Embassy in Houston. The embassy hosted a 2021 visit by Dr. Fatoumata Kébé (Fig. 13), who is a well-known astrophysicist in France. Dr. Kébé is also a prominent contributor to the Éphémérides project. As she noted in a recent New York Times article, that project is designed to promote science to girls between the ages of 8 and 18 and remove biases that push girls away from professional science careers. Dr. Kébé asked for our support with another educational project. During a visit to the LPI, we reviewed 'big ideas' in lunar science (e.g., the giant impact hypothesis and lunar magma ocean hypothesis) and explored ways to teach that science to students and the public. Dr. Kébé is using the information discussed with the CLSE team to design an exhibit to be constructed in France. She is also translating educational materials previously developed by the LPI and CLSE for distribution in France.

3.2 Exploration of the Moon and Asteroids by Secondary Students (ExMASS)

The Exploration of the Moon and Asteroids by Secondary Students (ExMASS) program engages high school students in authentic, inquiry-based (student-led), lunar/asteroid research projects. Selected teams are paired with a professional scientist to guide them through the research process.

2021 ExMASS Program Overview

Ten schools were selected in spring 2021 to participate in the 2021-2022 ExMASS program (Fig. 14). Approximately 40 students began the program in August 2021. Because the ExMASS program is virtual by design, the ongoing pandemic has not had a significantly negative effect on the program's logistics. Student teams will present their research in the spring of 2022, competing for a chance to present at the 2022 Exploration Science Forum. In addition, the Moon 101 activity completed by students during the first months of the program is being revamped to use the NASA Moon Trek portal.

3.2.1 Science Education Research Studies

In the previous year, CLSE began collaborating with science education researchers at the University of Houston-Clear Lake and the University of Louisiana, Monroe to examine the impact of the ExMASS program on students, teachers, and advisors. Researchers presented preliminary results of their investigation into characteristics of the scientist-student team relationship during the 2021 Exploration Science

Forum. The researchers are currently working to submit a paper discussing their analyses of communications between advisors and students/teachers to further characterize the scientist-student relationship. ExMASS lead Shaner continues to analyze post-program survey data in an ongoing effort to evaluate the program's impact on participants' attitudes toward science and science careers (Shaner et al., 2018).

Fig 14. Locations of 2021-2022 ExMASS schools.

3.3 International Observe the Moon Night

CLSE engagement lead Shaner assisted with planning the global 2021 International Observe the Moon Night event as well as LPI's virtual event. After serving 11 years on the event's coordinating committee, Shaner, a founding member, stepped down from his position following the 2021 event. During this time, he led efforts to translate event documents into multiple languages and brought on multiple new partners including World Space Week, The Planetary Society, and the Astronomical League. He also initiated conversations with commercial lunar companies including Astrobotic, Intuitive Machines, and Masten Space Systems.

4 Student/Early Career Participation

Due to the pandemic, CLSE had to make adjustments to its Exploration Science Summer Intern Program. A virtual edition of the program was designed to give the students a positive experience while generating output to assist the exploration of the lunar south pole. CLSE supported ten students in that program. Due to the pandemic, field-based student activities at Meteor Crater were canceled. They were replaced by an innovative virtual EVA Exercise at Meteor Crater. CLSE supported twenty students in that program. Four students participated in both programs.

Graduate Students

1. Jordan Bretzfelder (University of California, Los Angeles)
2. Frédéric Diotte (University of Sherbrooke, Canada)
3. Krystyna Doran (Rutgers University)
4. Katelyn Frizzell (Rutgers University)
5. Thomas Früh (University of Münster, Germany)
6. Aleksandra Gawronska (Miami University, Ohio)
7. Cosette Gilmour (York University, Canada)
8. Elise Michelle Harrington (University of Oslo)
9. Elisha Jhoti (University of California, Los Angeles)
10. Megan Kopp (Boston College)
11. Gayantha Loku Kodikara (University of Wisconsin-Milwaukee)
12. Stefano Lannini Lelarge (University of Pisa, Italy)
13. Kristen Luchsinger (New Mexico State University)
14. Alissa Madera (Rutgers University)
15. Maree McGregor (University of New Brunswick, Canada)
16. McKayla Meier (University of Idaho)
17. Aaron Morrison (University of Missouri)
18. Tyler Paladino (Idaho State University)
19. Ruby Patterson (University of Houston)
20. Leah Sacks (University of Western Ontario, Canada)
21. Jahnavi Shah (University of Western Ontario, Canada)
22. Tara Sweeney (University of Texas, El Paso)
23. Christian Tai Udovicic (Northern Arizona University)
24. Bennett Wilson (York University, Canada)
25. Frank Wroblewski (University of Idaho)
26. Bidgong Zhang (University of California, Los Angeles)

Postdoctoral Fellows

1. Dr. Katharine Robinson (USRA-LPI)

6. Mission Support

CLSE is assisting the agency with studies that support the Artemis program (see sections 1.1.3-5 above) and its CLPS robotic lander program, including the 2024 CLPS mission to the Schrödinger basin. CLSE's study of potential Artemis landing site 102 provides baseline geologic context for the VIPER landing site. CLSE"s study of the ridge between landing sites 001 and 004 provides a baseline geologic context for the delivery of NASA's PRIME-1 payload.

7. Awards

CLSE Co-I Amy Fagan and Collaborator Lisa Gaddis received a NASA Group Achievement Award for their participation in the Artemis III Science Definition Team.

Exploration Science Pathfinder Research for Enhancing SS Observations (ESPRESSO)

Alex Parker
Southwest Research Institute, Boulder, CO

CAN-2 TEAM

1. ESPRESSO Team Report

COVID-19 continued to present severe challenges to execution of numerous planned Project ESPRESSO activities in 2021. As one of our guiding themes is improving operational safety, we have strongly prioritized team safety and the safety of their families and communities. While laboratory capabilities were re-centralized after the dispersal to team members' homes in 2020, a series of adverse weather events caused significant damage to several ESPRESSO lab facilities. In the following sections, we highlight the areas and efforts that have made the most progress under these conditions in 2021.

1.1. Testing Models of Impacts into Lunar and Asteroid Regoliths

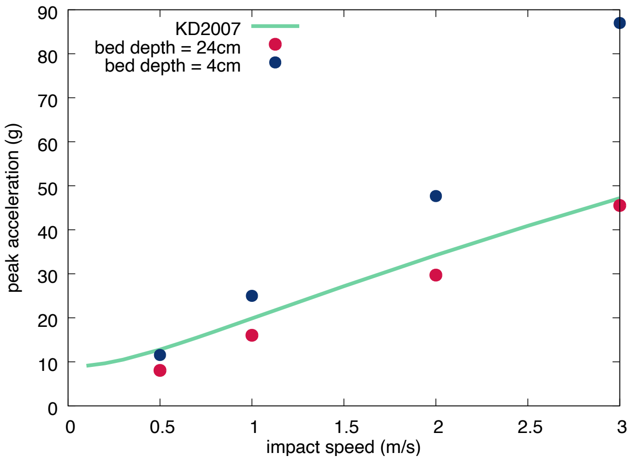
1.1.1. Low-speed Impacts and Interactions with Low-g Surfaces

Project ESPRESSO's efforts to conduct low-speed impacts into granular media is driven by the goal of being capable of anticipating spacecraft-surface interactions in low-g environments and to develop low-cost, disposable nano-impactors to test surface properties before committing a spacecraft, rover, or astronaut to a traverse, landing, or other activity that might destabilize a surface.

In 2021, we conducted simple impacts into intentionally shallow regolith beds to measure and describe how the measured forces deviate from expectations derived from standard theory. We aim to provide a framework to interpret acceleration profiles of impactors into stratified regolith, or layered materials, at low speeds with minimal prior knowledge of the surface material properties.

For a series of impacts where the depth of the target bed is 3×Dimpactor (24cm) the peak acceleration (averaged from over ten impacts for each data point), trends closely with predictions from the Katsuragi and Durian (2007) force law. Accelerations were measured by 3-axes accelerometers embedded within the impact probe. The peak accelerations diverge substantially when the bed is reduced to 0.5×Dimpactor (4cm). This intuitive trend describes the effect of solid bottom of the bed pushing the acceleration profile to diverge from expectations (see Fig 1 left panel, with low bed depths in blue, and deep beds in red with predictions the aqua line).

The other exploration that was done in depth this year was that regarding the shape of the impactor. The peak force and shape of the force profile could be critically important for



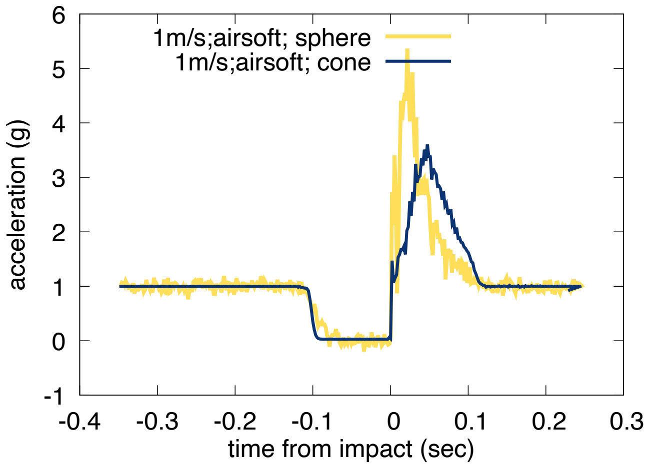


Fig 1. Left panel: Peak acceleration during impact of a spherical impactor into a granular bed of two depths, compared to predictions from the Katsuragi & Durian (2007) force law. Right panel: Influence of impactor shape on acceleration profile.

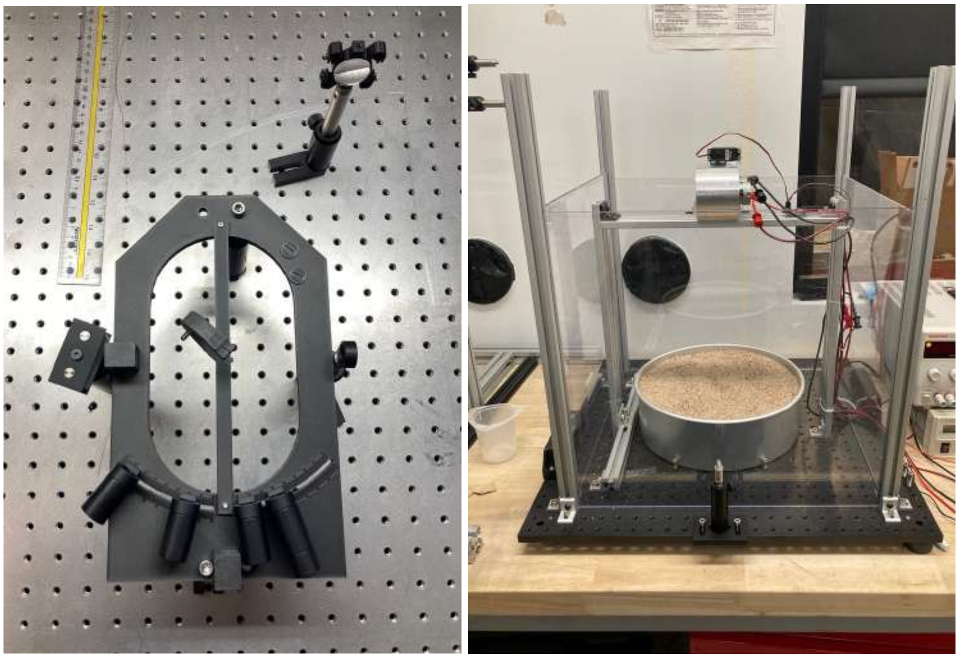


Fig 2. Left panel: Flight-like GraVeTAS sensor with filtered photodiode angular array (bottom). Right panel: Gassless GraVeTAS projectile launcher (top) in impact testbed.

different mission designs and strategies. Here, we find that moving from a simple spherical impactor to a 60º conical impactor decreases the peak force and shifts the peak force reading back in time (Fig 1, right panel). This should result in a change to the inertial draft portion of the force law governing these impacts into granular materials.

Team members also conducted studies of force laws relevant to the interaction between the NASA OSIRIS-REx spacecraft and the surface of asteroid (101955) Bennu during the touch-and-go sample acquisition maneuver (TAG-SAM). Multiple granular mechanics codes were used to numerically simulate the interactions between the spacecraft and the surface and comparing their results to predictions of penetration depth from traditional force laws and scaling relationships (Ballouz et al. 2021).

1.1.2. High-speed impact experiments in reduced gravity and vacuum

A key goal of the ESPRESSO effort is developing and deploying a reduced-gravity system for characterizing impact ejecta from medium- and high-speed impacts into simulated lunar and asteroid regoliths under vacuum and relevant gravity environments. This requires development of three key sub-systems, which have reached a high level of maturity in 2021. The first is the Grain Velocimetry and Tomagraphy Analysis System (GraVeTAS), which is a laser-based system for characterizing the size, shape, and 3D velocity vector of individual dust grains traveling at high speed through free space. New beam masks encoding a quasi-chirp pattern into the illumination laser have been demonstrated to enable non-degenerate direction and speed measurements with a stationary beam pattern. Detector electronics and signal analysis software have been developed and underwent testing in late 2021.

The second subsystem is a gassless projectile launcher for high-speed impact experiments under vacuum. A flywheel-based accelerator was developed, fabricated, and tested by new team member Zane Meyer as a senior undergraduate at UTSA and later as an engineer on staff at SwRI Boulder. This projectile launcher includes a magazine system enabling multiple shots to be taken without breaking vacuum. This system is shown in Fig 2.

The final required subsystem for these experiments developed in 2021 is the vacuum housing and regolith bed, designed to encapsulate loose regolith between parabolas and rotate to provide fresh surface for multiple impacts within a single chamber during a given flight. Chamber systems have been fabricated and are undergoing testing. Final integration of all three subsystems and end-to-end testing is to commence in early 2022 before a planned late spring flight campaign.

1.2. ESPRESSO Facilities in 2021

1.2.1. Lab Access Challenges

COVID-19 has continued to hamper access to shared laboratory spaces at several ESPRESSO partner institutions, resulting in limitations in in-person collaboration. Further, storms in both Texas and Colorado resulted in significant damages to ESPRESSO laboratory facilities; all of the primary labs and shops used by ESPRESSO team members in Boulder were flooded during an extreme rainfall event on July 25-26, 2021, resulting in complete lab shutdown. Partial roof collapse at a Texas facility during the February ice storm further limited laboratory access for ESPRESSO team members.

1.2.2. SETI Rapid Prototyping Facility

As part of Parker's transition to SETI Institute, a new rapid-prototyping facility has been set up in Washington state to support ongoing ESPRESSO efforts. The primary efforts in 2021 were development and testing of ultra-lightweight rocket-borne vacuum systems for suborbital flight (the rocket-borne space environment chamber RSEC) and the large-scale lightweight vacuum vessels for reduced gravity parabolic flights (the airborne space environment chambers ASEC) in 2022.

Rocket-borne chambers have been designed to accommodate Blue Origin New Shepard Single- and Double-Locker form factors, as well as an extremely large (120-liter) concept design for a full payload stack configuration. These chambers have already been requested by community members proposing to the NASA Flight Opportunities program. Inspired by the success of the BORE-II experiment in 2020, such chambers can enable long-term (several minute) high-quality microgravity experiments under vacuum conditions.

Other efforts supported by the new facility include ongoing development of magnetic anchoring and regolith manipulation technologies, fabrication and field testing of mesh-networked seismic and environmental sensors, and maintenance and upgrading of the Open Telerobotics Rover for the 2022 field season. Facilities include large-format SLA and multi-material, high-temperature FDM 3D printers, laser cutters, CNC mills, electrical component assembly equipment, and welding equipment.

> Ultra-lightweight Rocket-born Space Environment Chambers can provide high-quality microgravity and vacuum conditions for technology maturation.

1.2.3. SwRI Spectrophotometry and Optical Constants lab

A new spectrophotometry laboratory facility at SwRI Boulder under the direction of ESPRESSO Co-I Dr. Silvia Protopapa has been fully commissioned, and staff trained in instrument operation. This facility complements the JHU spectrophotometry facility led by Prof. Sarah Hörst for ESPRESSO efforts to create a catalog of optical constants for lunar- and asteroid-relevant minerals.

2. Inter-team/International Collaborations

Co-I Molaro is assisting TREX team members in developing a series of SciArt workshops: "Making Space: A Workshop on Space, SciArt, & Society. Workshop concept developed in 2021, with three workshops planned throughout 2022. In 2021, Co-I Molaro also worked with a team of researchers in France to build computational models of thermal shock experiments in meteorite mineral matrices. This work extends the efforts under Project ESPRESSO to understand the propagation of heat, stress, and fractures through mineral matrices and their impact on the evolution of lunar and asteroid regoliths.

Co-I Nowicki has taken a new position as a Senior Program Manager at Oxford University's Atmospheric, Oceanic and Planetary Physics Department. In this role he will be leading a group developing instrumentation for planetary exploration. He will maintain his role as a Project ESPRESSO team member and collaborator, continuing development of the numerous instrument systems under his purview as the former lead of the Boulder Laser Ablation of Standoff Targets for Exploration Research Laboratory (BLASTERLab). We anticipate that this collaboration with the Oxford University group will be fruitful and enable us to build deeper ties with international missions and flight instruments.

All development of lightweighted vacuum chamber systems for operation in reduced gravity aircraft is being conducted in collaboration with Canada's NRC-CNRC Flight Research Laboratory, as their Falcon 20 reduced gravity research aircraft is our primary platform for lunar- and microgravity experiments.

3. Public Engagement

3.1. Virtual Education and Public Outreach Presentations

Project ESPRESSO EPO lead McKinnon conducted a variety of virtual events for public engagement in 2021. These include a "Quarantine Conversation" podcast hosted by the Pacific Museum of Earth, and the "Storytime with Mika" video series hosted by the SETI Institute during World Space Week (October 4-10 2021). McKinnon's skills as a communicator, community organizer, and disaster mitigation expert were tapped extensively in 2021 during the BC fire season and subsequent landslides during winter rains.

3.2. Launch of ESPRESSO Medium blog

Updates managed by Project ESPRESSO EPO lead McKinnon, including posts on the open telerobotics rover and successful test flight of ESPRESSO-developed Clockwork Starfish asteroid sampling mechanisms.

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

AstroAccess Zero-G Flight, AstroAccess (ESPRESSO Co-I Molaro at PSI). Co-I Molaro assisted in the organization of an October 2021 Zero-G flight for AstroAccess, an organization advancing disability inclusion in space and spaceflight. The flight brought a team of people with mobility, vision, and hearing disabilities into zero-gravity and hyper-gravity environments to explore design for accessibility in space for all. Co-I Molaro is supported by ESPRESSO to consolidate the findings of this flight for further research in advancing accessibility in space.

Figure 3: The 12 Ambassadors of AstroAccess' Flight 1 in front of Zero G Corporation's G-Force One aircraft on the tarmac of Long Beach Airport. From left to right, back row: Mary Cooper, Cheri Wells-Jensen, Eric Shear, Apurva Varia, Sina Bahram, Zuby Onwuta, Mona Minkara, Viktoria Modesta. Front row: Sawyer Rosenstein, Dana Bolles, Eric Ingram, Centra Mazyck. Image credit: Al Powers for Zero Gravity Corporation.

in OSIRIS-REx. Co-Is Walsh and Molaro are both leveraging their SSERVI efforts to better understand the environment at Bennu, including the processes of thermal fracturing of boulders on Bennu's surface and the interplay of regolith granular mechanics and spacecraft mechanisms during the TAG-SAM maneuver.

Co-I Lewis was selected as a Co-Investigator on the NASA VIPER mission to the lunar south pole. Prof. Lewis' will lead a geophysical traverse at the lunar south pole with the VIPER accelerometers, building on past work with the accelerometers on board the NASA Curiosity rover on Mars, and further expanding the Project ESPRESSO team's work on using commercial- and industrial-grade accelerometer systems for exploring planetary surfaces. This effort also includes collaboration from GEODES team members.

5. Student/Early Career Participation

Undergraduate Students

1. Zane Meyer, UTSA, graduated in 2021 and joined SwRI Boulder office as a full-time engineer working on ESPRESSO instruments and experimental facilities.

Postdoctoral Fellows

2. Annika Gustafsson, SwRI, small body surfaces properties.

3. Christopher Cline, NASA JSC, impact processes.

New Faculty Members

4. Professor Kevin Lewis, Project ESPRESSO Co-Investigator at Johns Hopkins University, was awarded tenure and promoted to associate professor.
5. Dr. Keith Nowicki, Project ESPRESSO Co-Investigator, now a Senior Programme Manager at Oxford University's Atmospheric, Oceanic and Planetary Physics Department.
6. Dr. Akbar Whizin, Project ESPRESSO team member at SwRI, promoted to Senior Research Scientist.
7. Dr. Alex Parker, Project ESPRESSO director, now a Principal Investigator at SETI Institute.

6. Mission Involvement

Ongoing Project ESPRESSO experimental and modeling efforts complement multiple team members' involvement

7. Awards

2022 Emerging Scholar for trailblazing research and mentorship by Diverse: Issues in Higher Education magazine. Cristina Thomas, Co-I, NAU.

UTSA senior Zane Meyer was instrumental in developing the high-speed projectile launcher for GraVeTAS experiments, and since graduating has joined the Boulder team as an engineer on SwRI staff.

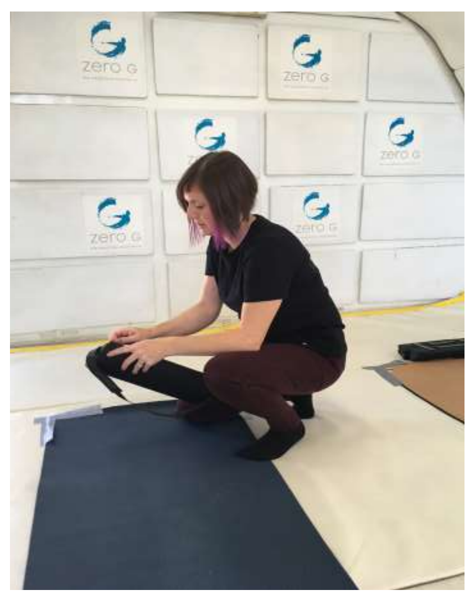


Figure 4: ESPRESSO Co-I Molaro conducting staging operations on board G-Force One before the AstroAccess Flight 1.

Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES)

Nicholas Schmerr
University of Maryland, College Park, MD

CAN-3 TEAM

1. GEODES Team Report

During its second year, GEODES has continued to adjust our efforts under the effects of the global pandemic and the challenges associated with making sure that our team members can have safe and healthy working environments. Fortunately, the new virtual environment has allowed our team activities to flourish, with new interaction spaces becoming readily available and accessible. In this new paradigm, GEODES has focused on geophysical modeling and experimental research across our four themes of void spaces, regolith, subsurface volatiles, and magma-tectonic resources. New findings from the team have been presented in over 40 abstracts submitted to virtual scientific conferences and workshops, and our scientific output is growing steadily with at least 5 new publications, and more to come from three graduate students who completed GEODES-supported research projects in the past year. We were able to complete our first field expedition late in 2021 at Kilbourne Hole, New Mexico in collaboration with the RISE2 SSERVI team. Our outreach and community engagement has also been growing, with the development of a new Field Code of Conduct, and other activities under way. The GEODES team continues to expand, we have added 9 new graduate students and postdocs, and 6 new collaborators to the team, and we expect to add many more in the coming years.

1.1. Regolith Joint Modeling

Radar and seismic techniques can provide information about the character of a planetary regolith. GEODES graduate students, Linden Wike (UMD) and John Coonan (USF), and members of the Regolith Theme [Becky Ghent (PSI), Ved Lekic (UMD), Sarah Kruse (USF), Jacob Richardson (GSFC), and Doyeon Kim (ETH)] are studying ways to synergistically employ spatially coincident shallow seismic and ground penetrating radar (GPR) techniques to gain quantitative information about the physical properties of the lunar regolith. One of our team's goals is to use these complementary techniques in concert to reduce ambiguity in recovery of important physical regolith properties, particularly when little or no a priori ground truth information is available. Currently we are testing numerical simulations of seismic and electromagnetic wave propagation through a common set of model spaces. Ultimately, we intend to use these simulations to validate methods, and determine optimal acquisition geometries for joint analysis of regolith containing voids, suspended rocks, or other scatterers.

These modeling efforts are allowing our GEODES team to understand the effects of void spaces and complex porosity on both seismic and GPR modeling software. In our initial work, we demonstrate the methodology using a single void: a semicircle of 25m radius, with its ceiling located at 25m depth. This void structure is placed within a basaltic composition matrix: a 300m by 100m prism for the seismic approach and a 130m by 90m prism for the GPR approach (Fig. 1). We propagate simulated electromagnetic and seismic waves through the models containing the basaltic medium and vacuum-filled void, compute CMP-stacks, and migrate both records. This is work that will be presented at the Lunar and Planetary Science Conference (Wike et al., LPSC 2022).

1.2. Measuring Seismic Velocity in the Lunar Regolith

The lunar subsurface is a primary science target for future missions to the Moon and serves as a potential host location for resources such as water ice, void spaces for astronaut

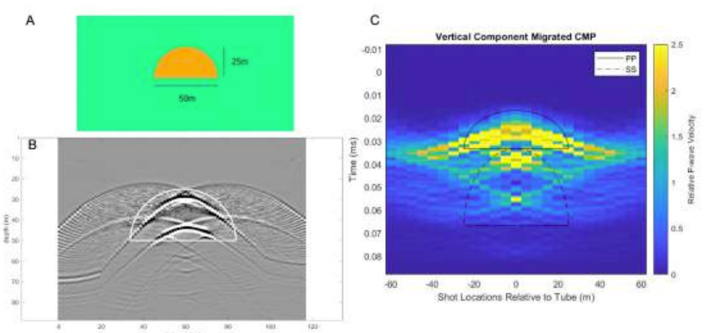


Figure 1. Simulations that show how seismic and radar waves interact with a subsurface void space. A) Model space geometry used. B) Synthetic gprMAX migrated GPR waveforms for a source array situated above the void. C) Synthetic SPECFEM2D migrated seismic waveforms for a station array situated above the void.

shelter, and important ore-bodies for in-situ manufacturing and building materials. The first tens of meters of the lunar subsurface are characterized by a poorly sorted, loosely consolidated, granular mixture of impact ejecta fragments, shattered local rocks, and dust. Understanding variations in the structural properties of the deeper regolith requires a geophysical approach; the GEODES team is investigating how the seismic signature of the regolith environment is affected by changes in material properties, such as when frozen in ice. This will be key for the subsurface exploration in future lunar surface missions.

The Properties of Regolith from Experiments at Small Scale in Seismic Simulants (PORES4) experiment is being led by GEODES graduate student Casey Braccia, and her GEODES Co-I mentor Dr. Wenlu Zhu, with assistance from a University of Maryland undergraduate, Aniqa Islam. They have assembled a seismic test chamber (Fig. 2) capable of measuring the seismic properties of the lunar regolith at low pressure (~10 millibar) in a volume of ~19 liters. We use cork to simulate the grain boundary forces experienced by regolith materials at lowered lunar gravity. Our seismic source consists of a 5 mm metal ball bearing dropped at vacuum by releasing it from a magnet attached to the top of the container. The seismic source imparts ~5 mJ of energy that is recorded by 100 Hz geophones embedded in the regolith materials. The experiment performance is being tested against various lab environments and calibrated against a range of simulant materials. The goal of the experiment is to generate the capability to measure both dry and frozen materials at low pressure and identify the effects of water ice present in regolith at the lunar poles, a science priority under our Regolith and Volatiles themes.

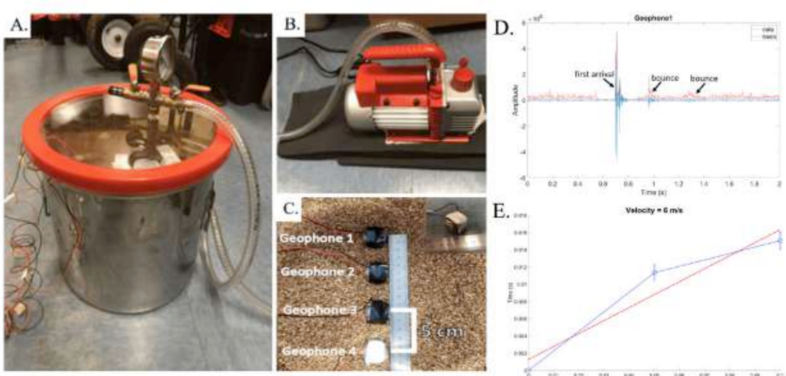


Figure 2. Geophysics test chamber for measuring seismic velocity of lunar regolith analog materials. A) Vacuum chamber. B) Vacuum pump system. C) geophones arranged in test chamber filled with cork. D) results from a ball bearing source. E) results for measured seismic velocity of the core (8 m/s). From Braccia et al., LPSC 2022.

1.3. Tomo-XRF Prototype Testing

GEODES has been partnering with Dr. Huapeng Huang at Advanced Analyzer Labs who is creating a compact, low-power, in-situ X-ray imaging (CT) and X-ray Fluorescence (XRF) system (TOMO-XRF). The instrument package was developed under NASA SBIR Phase II support with contract # 80NSSC19C0163, via collaboration with Dr. William Brinckerhoff at NASA GSFC, and, by Advanced Analyzer Labs, Inc. and Industry Vision Automation, Corp. The GEODES team provided Dr. Huang with an opportunity to field test his TOMO-XRF equipment in a lunar analog setting. The TOMO-XRF package provides non-destructive sample imaging with the sample unaltered and undamaged. The instrument package is equipped with a 12W compact X-ray source, a 20mm x 30mm image sensor, and an SDD detector. The image sensor has a pixel size of 20 µm with a 2-D image and 3-D reconstruction resolution of ~100 µm. The entire system is portable with all the components integrated into a standard carry-on luggage case with a total mass of ~10 kg. The total operational power is less than 35W and the packaging is fully radiation proof and safety certified. In the current prototype, a scan takes 25 minutes for a full X-ray image (91 frames) and several minutes for a XRF spectrum. The 3D reconstruction can be accomplished in <1 minute. The first prototype of the compact X-ray CT system was successfully beta tested in November 2021 at the GEODES/RISE2 Potrillo Volcanic Field Expedition outside El Paso, TX (Fig. 3).

1.4. MOLASSES Modeling

GEODES Co-Is Chuck Connor, Laura Connor (USF), and Jacob Richardson (GSFC) have developed a

Figure 3. The TOMO-XRF instrument being tested in the field at Kilbourne Hole, NM. A) Dr. Huang and GEODES graduate student Casey Braccia operating the instrument on the rim of the volcanic crater. B) a caliche-covered root sample being scanned by the instrument. C) Tomographic reconstruction of the sample showing the internal structure of the sample and porosity within the caliche.

lava flow emplacement model to forecast flow emplacement over planetary surfaces. This MOdular LAva Simulation Software for Earth Science (MOLASSES) model uses lava flow morphology parameters to forecast ultimate lava flow runouts. GEODES is now applying this flow model to lunar landscapes to understand the construction of volcanic fields and mare on the Moon. Successful modeling of these terrains can help describe the variety of the morphologies, volumes, and related eruption parameters of the ancient lavas that built them. Examples of MOLASSES lava flows at the Marius Hills are shown in Figure 4. Simulated flows with different parameters can mimic thin flows and lava domes and flows respond to topographic highs and lows [Richardson, NESF 2021].

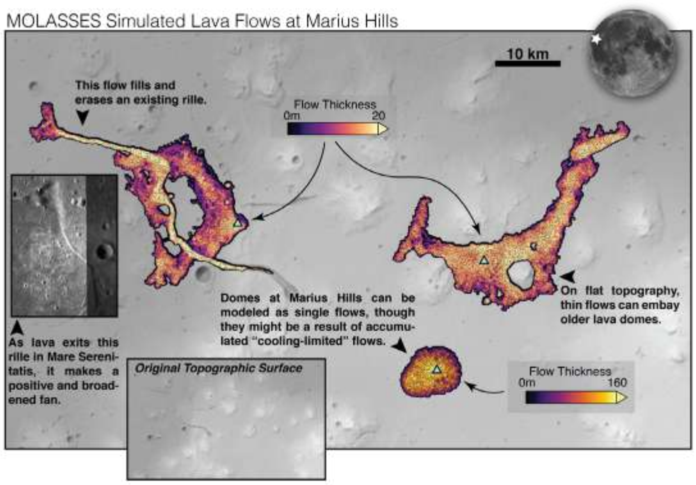


Figure 4. Three MOLASSES flows with different eruption parameters (e.g., total volumes, effective flow thickness) are modeled in a single region of the lunar Marius Hills from user-defined vent locations (blue triangles). Flow color represents thickness. Basemap is the ~512 pixel per degree SLDEM2015 topography dataset by Barker et al. [2015]. left inset: an example NAC mosaic image of a lava flow in southern Mare Serenitatis. bottom inset: an un-annotated topographic map of the same map extent without simulated flows. Lighter shades in basemaps

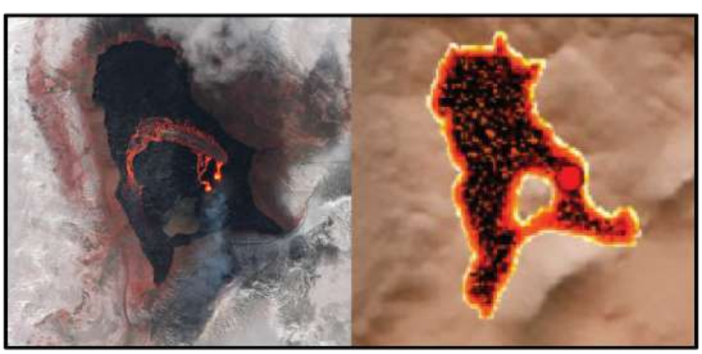


Figure 5. In both reality (left) and simulation (right), lava in the Fagradalsfjall region erupted in the enclosed Geldingadalir Valley and quickly filled it until spilling over into neighboring valleys to the southeast. This example comparison shows the lava flow extent after the first week of eruption. Satellite image credit: Planet Labs (March 26, 2021).

During the 2021 Fagradalsfjall eruption in southwestern Iceland, GEODES Co-Is also simulated the lava flow extent with an ArcticDEM basemap downsampled to similar resolutions as the SLDEM topographic basemaps used for ongoing lunar studies. The simulated flow is compared to a satellite image of the real flow extent on March 26, 2021, shown in Figure 5. A user interface to run a simple version of the MOLASSES code for multiple lunar terrains, including the Aristarchus Plateau, Marius Hills, and the Hertzsprung impact basin, are available at: https://gscommunitycodes.usf.edu/geoscicommunitycodes/public/welcome/GEODES.php

2. Inter-team/International Collaborations

2.1. Joint RISE2/GEODES Field Expedition to the Potrillo Volcanic Field

Eight members of GEODES joined a RISE2 field expedition to the Potrillo Volcanic Field in southern New Mexico. At the site, GEODES team members conducted a series of co-located 2-D seismic, GPR, and magnetic profiles, along with geological sampling of the different units on the rim of the Kilbourne Hole Volcanic Crater (Fig. 6). Our goal was to determine the geophysical properties of the eruption deposits, both in-situ in the field and in the hand sample in the laboratory through experimental rock physics. The geophysical surveys were designed to be analogous to

Figure 6. The GEODES team in the field at Kilbourne Hole, NM.

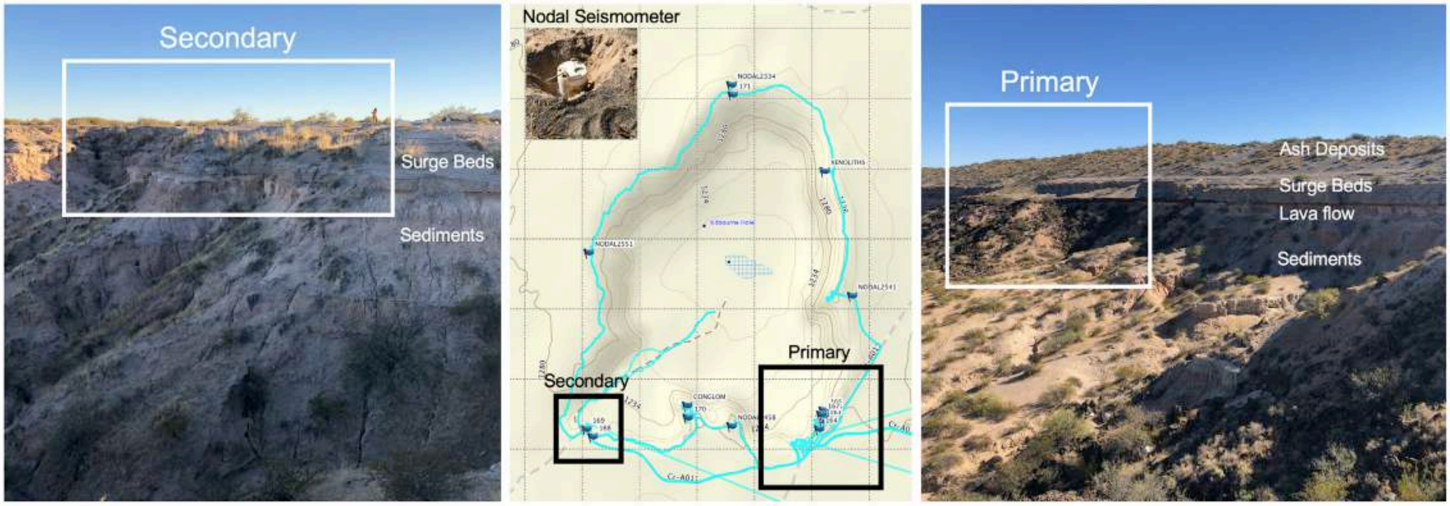


Figure 7. Locations of the two GEODES study sites on the rim of Kilbourne Hole. The left and right panels show photographs of the investigation areas and indicate local geological units, the center panel shows GPS tracks collected around the field area over a background topographic map. During the field expedition, we also deployed 4 nodal seismometers that recorded the activities of the SSERVI teams in the area, as well as local and teleseismic seismicity that occurred during the field expedition.

similar surveys that might be conducted in future missions to the Moon and served as an opportunity to familiarize astronauts training participants from RISE2 with geophysical equipment, methods, and active sounding techniques. The expedition also allowed several GEODES graduate students to get their first experiences in the field collecting data and interacting with both the GEODES and RISE2 field teams.

Collaboration with RISE2 on the data collection included placing our geophysical lines inside the scan areas of LiDAR and drone photogrammetry conducted by team members of RISE2 (Fig. 7). We plan to exchange data with the RISE2 team and further coordinate visualization products and digital elevation maps into our data analysis. We also hosted a prototype field instrument, Tomo-XRF, a joint micro-computed tomography and X-ray fluorescence 3-D scanning system (see Section 1.3). The data generated by these activities will be shared in the Online Planetary Analogs Geophysical Database and Digital Repositories at the University of Maryland.

2.2. A Probabilistic Seismic Hazard Assessment for the Moon (GEODES/TREX)

The GEODES team has partnered with the TREX team to construct a probabilistic seismic hazard assessment (PSHA) for future lunar exploration. This partnership includes Maria Banks (NASA-GSFC/TREX), Lisa Schleicher (USGS/GEODES), Shelby Bensi and her graduate student Constantinos Frantzis (UMD/GEODES) and Tom Watters (SI/GEODES). Probabilistic seismic hazard analysis (PSHA) has been widely adopted to assess the frequency and severity of ground motion (GM) hazards on Earth and to inform engineering decisions and design criteria. As long-term crewed outposts on the Moon become a priority, PSHA provides the quantitative framework to assess lunar seismic hazards that may affect facilities.

The Apollo-era seismometers recorded 28 shallow moonquakes during the approximately seven years of operations. Recent studies indicate these events may be associated with lobate fault scarps that have been detected in images from the Lunar Reconnaissance Orbiter Camera (LROC). Data from the Apollo seismic stations coupled with recent lunar reconnaissance and mapping efforts and high-fidelity numerical modeling provide a foundation for the development of a lunar PSHA. Our research team seeks to leverage this data along with physical process models, statistical assessments, and machine learning methods to develop a preliminary lunar PSHA.

This group's efforts to date have focused primarily on developing a source model and global-scale magnitude recurrence relationship (Fig. 8a). We have considered two potential source model interpretations. The first considers individual lobate scarps as potential sources of seismic events. The second uses a clustering algorithm to group scarps as pseudo faults (Fig. 8b). We have used kernel density estimation to create a conditional epicentral probability density function based on scarp locations under both potential interpretations. We then update the density function using Bayesian updating and information about potential epicentral locations for the recorded shallow moonquake events (Fig. 8c). We have further developed a global Gutenberg-Richter magnitude recurrence distribution of lunar seismic events using the estimated magnitudes of the 28 shallow moonquakes detected by the Apollo era seismometers. Our future work will focus on refinement of source models, as well as development of other components of the preliminary PSHA, including ground motion prediction

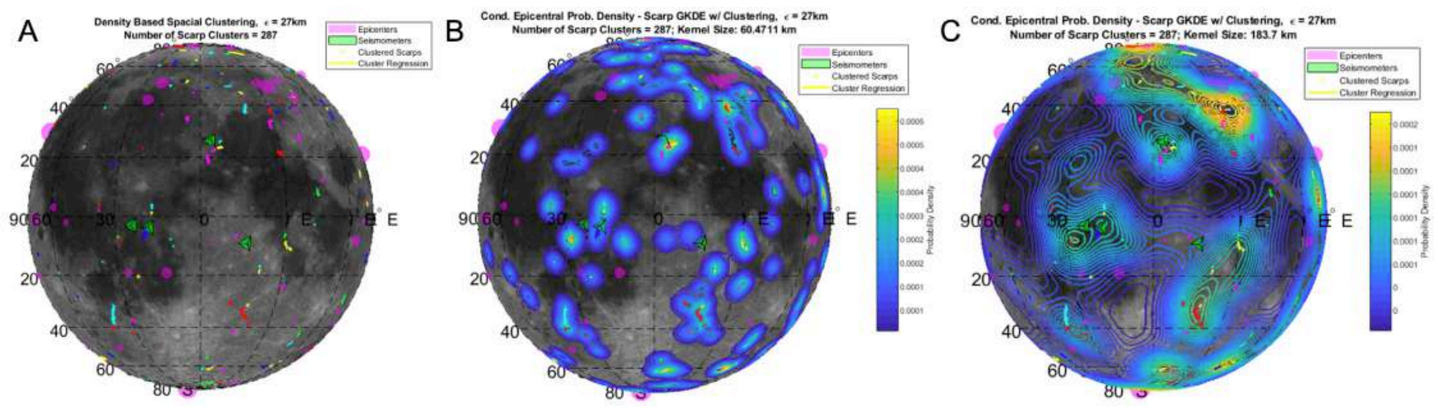


Figure 8. Lunar PSHA source model derived from Apollo-era seismicity. A) Density-based scarp clusters computed with DBSCAN. B) Conditional epicentral PDF with prior bandwidth – clustered model. C) Conditional epicentral PDF with posterior bandwidth – clustered model.

and site response models, and was presented in (Frantzis et al., AGU, 2021).

2.3. NASA Planetary Analogs Website (GEODES/RISE2)

The GEODES team partnered with RISE2 to develop content for a new section on the NASA Solar System website, https://solarsystem.nasa.gov/, specifically for Planetary Analog Field Research. This public resource, led by RISE2 SA/CS/PE Lead Caela Barry and GEODES SA/CS/PE Lead Molly Wasser and former GEODES Co-I Nicole Whelley, includes an overview of planetary analogs (https://solarsystem.nasa.gov/planets/planetary-analogs/) as well as an “Analog Explorer” gallery (https://solarsystem.nasa.gov/planets/analog-explorer/) with sliding images of analog sites on Earth and their planetary counterparts. The section launched on February 1, 2021. In 2022, Barry and Wasser plan to add content on even more analog projects, especially those concerning ocean worlds, and conduct a social media campaign with the NASA Solar System and NASA Earth social media accounts to highlight analog work.

2.4. EDIA Activities: Field Code of Conduct (GEODES/RISE2/GIFT)

Field research provides unique opportunities to expand planetary science knowledge, develop the next generation of researchers, and build productive connections between teams. The immersive nature of the field work environment enables strong cooperation and can catalyze progress towards common goals. It also makes problematic behavior difficult to escape or de-escalate, presenting specific, inherent challenges which include and go beyond physical hazards.

Thorough safety planning and clear behavioral expectations are vital tools for improving inclusivity in field work. GEODES has partnered with RISE2 and NASA’s Goddard Instrument Field Team (GIFT) to develop community resources designed to promote safety and inclusivity in field expeditions. The resources are structured as three related documents: 1) Field Safety Plan, 2) Field Code of Conduct, and 3) Field Bill of Rights. This effort has been led by Caela Barry (RISE2) with additional contributions from Nicole Whelley (GEODES), Jacob Richardson (RISE2, GIFT, GEODES), Patrick Whelley (RISE2/GEODES), Tim Glotch (RISE2), Kelsey Young (RISE2, GEODES, GIFT), Amy McAdam (RISE2, GIFT), and Nicholas Schmerr (GEODES) (see Barry et al., LPSC 2022).

These documents are intended to be fine-tuned in advance of each field expedition and shared with all field participants, who are expected to review, discuss, and agree to the terms of the documents before travel. Collaborative expectation-setting across project boundaries facilitates communication and follow-through on trips that include members of multiple teams. During expedition debriefs, team members are invited to provide feedback on their field research experience. Comments related to community documents are taken into consideration for future reference. During the planning process leading up to each expedition, the field leadership team revises the text to reflect team feedback and current best practices, attend to worksite-specific adjustments, and update perishable items such as contact information. Although there is much that could go into a Code of Conduct, our teams have found that it is best to keep this document readable and brief, and accompany it with more in-depth resources.

3. Public Engagement

3.1. International Observe the Moon Night

International Observe the Moon Night (https://moon.nasa.gov/observe) is an annual worldwide public science festival of lunar science and exploration. SA/CS/PE Lead Molly Wasser serves as Deputy Director of the program. In

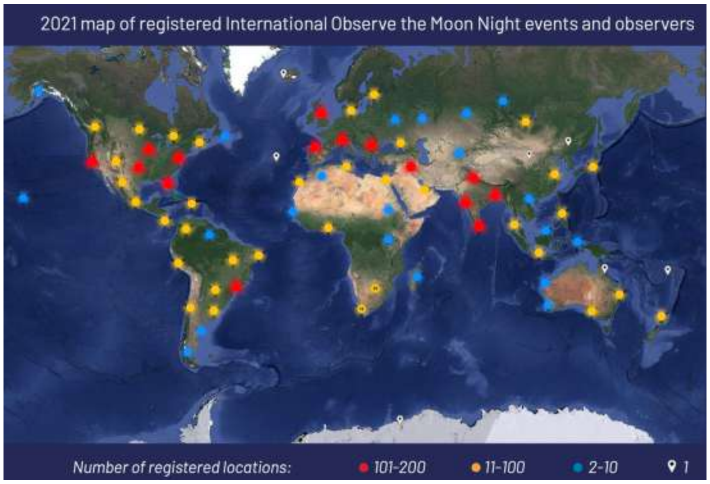


Figure 9 Map of 2021 registered International Observe the Moon Night events and individual observers.

2021, nearly 4,000 events and individual lunar observers registered to participate from all 50 states, 122 countries, and all 7 continents (Fig. 9). 94% of surveyed participants reported an increased interest in planetary science and exploration after celebrating International Observe the Moon Night.

3.2. Virtual Engagement

Wasser also co-leads NASA's official fieldwork social media accounts, NASA Expeditions. The accounts feature "takeovers" from different NASA-funded teams over a week, describing the science, logistics, and daily life of field work. Recruiting SSERVI participation was a focus in 2021 and we are pleased to report that the accounts featured takeovers from the TREX node's expedition to Arizona to test a rover (https://twitter.com/i/events/1471135526220484609) and the RISE2 and GEODES co-expedition to Potrillo Volcanic Field in New Mexico.

In late 2020 and early 2021, GEODES co-created NASA's public-facing website for planetary analogs, (https://solarsystem.nasa.gov/planets/planetary-analogs/). Former GEODES Co-I Nicole Whelley and RISE2 SA/CS/PE Lead Caela Barry developed an overview of planetary analogs and the "Analog Explorer" gallery (https://solarsystem.nasa.gov/planets/analog-explorer/) with the aid of many field scientists from the RISE2 and GEODES teams. The section launched on February 1, 2021.

3.3. Community Engagement

The GEODES team is dedicated to in-reach within the planetary science community. GEODES PI Schmerr is a member of a Society of Exploration Geophysicists (SEG) Planetary Exploration Task Force that is formulating a new planetary section within the SEG, which primarily serves the terrestrial oil and gas communities. This exciting effort will build a bridge between the resource exploration community and the planetary science community, allowing the resource exploration community to offer its extensive knowledge and wisdom as the planetary science community prepares to explore worlds other than Earth.

4. Student/Early Career Participation

In the second year of the GEODES project, our team added 14 new science collaborators that span the early career spectrum. This diverse group of new team members is collaborating across the team's various resource themes (identified below), has built GEODES connections to other SSERVI teams, and has expanded our geophysical expertise to new realms of research.

4.1 GEODES Undergraduate Students

1. Kris Laferriere (Astronomy, advisor: Jessica Sunshine), University of Maryland, Ice Deposits, calibrated, optimized the thermal removal, and analyzed Deep Impact data collected over the Moon's South Pole (now studying planetary science at Purdue University w/ Dr. Ali Bramson).
2. Aniqa Islam (Geology, advisor: Nicholas Schmerr), University of Maryland, Ice Deposits, Regolith Themes, helping to develop a lunar geophysical test chamber.

4.2 GEODES Graduate Students

1. Edward Williams (Geology PhD candidate, advisor: Laurent Montési), University of Maryland, Tubes/Voids, Magma-tectonics Themes, modeling of fracture occurrence and density within lava tubes on the Earth and the Moon.
2. Brianna Mellerson, (Geology Masters candidate, advisors: Ved Lekic and Nick Schmerr), University of Maryland, Tubes/Voids Theme, magnetic and gravity modeling of lava flows.
3. Joseph DeMartini (Astronomy PhD candidate, advisor Derek Richardson), University of Maryland, Regolith Theme, computer simulations of shaking and the Brazil Nut Effect for asteroids and the Moon.
4. Casey Braccia (Geology PhD candidate, advisor Wenlu Zhu), University of Maryland, Volatiles Theme, Ice Deposits, Tube/Voids Themes, rocks physics experiments with planetary surface materials and microtomographic imaging of pore space.
5. Linden Wike (Geology PhD candidate, advisor Nick Schmerr), University of Maryland, Tubes/Voids, Ice Deposits, Regolith Themes, seismology and wave interactions with pore space and cavities, scattering and wave propagation simulations.

6. Yisha Ng (Mech. Eng. PhD candidate), Arizona State University, Tubes/Voids Theme, engineering and field instrumentation design and operations.
7. John Coonan (Geology Masters, advisor Sarah Kruse), University of South Florida, Regolith, Tubes/Voids Themes, GPR interactions with pore space and cavities, scattering and wave propagation simulations.
8. Cosmo Varah-Sikes (Astronomy PhD candidate, advisor Jessica Sunshine), University of Maryland, Ice Deposits, Regolith Themes, spectral and spatial mapping of a unique, spinel-rich lunar deposit on the nearside of the Moon.
9. Naya Deykes (Geology Masters candidate, advisor Ryan Porter), Northern Arizona University, Tubes/Voids, Magma-tectonics Themes, understanding of shallow subsurface structures and compositional properties of cinder cones.
10. Mackenzie White (Geology PhD candidate, advisor Matt Siegler), Southern Methodist University, Tubes/Voids, Ice Deposits, Regolith Themes, studies using GPR and an IR camera inside terrestrial lava tubes.
11. Angie Martinez (Geology PhD candidate, advisor Matt Siegler), Southern Methodist University, Tubes/Voids, Ice Deposits, Regolith Themes, constraining the thermophysical parameters that influence volatile stability in near-polar lunar craters.
12. Troy Berkey (Geology Masters, advisor Chuck Connor), University of South Florida, Magma-tectonics Themes, potential field modeling methods for identification, evaluation, and characterization of features associated with volcanic systems.
13. Orion Hon (PhD candidate, advisor Lynn Carter), University of Arizona, Magma-tectonics, Regolith Themes, remote sensing data to study lunar volcanic deposits and their emplacement, as well as modeling lunar pyroclastic eruptions.

4.3 Postdoctoral Fellows

1. Doyeon (DK) Kim, University of Maryland, Tubes/Voids, Magma-tectonics, Regolith Themes, joint inversion methods, seismology and forward wave propagation models.
2. Sajad Jazayeri, University of South Florida, Regolith Theme, ground penetrating radar data analysis and modeling of void space GPR signatures.
3. Ernest Bell, Goddard Space Flight Center, Tubes/Voids, Magma-tectonics Themes, geophysical field techniques and operations, modeling of lava tubes and subsurface tectonic structure.

4.4 New Collaborators

1. Michelle (Shelby) Bensi, University of Maryland, Magma-tectonics, lunar probabilistic seismic hazard analysis modeling.
2. Lisa Schleicher, US Geological Survey, Magma-tectonics, lunar probabilistic seismic hazard analysis modeling.
3. Tom Watters, Smithsonian Institution, Magma-tectonics, lunar tectonics and fault mapping.
4. Maria Banks (TREX), Goddard Space Flight Center, Magma-tectonics, fault scrap mapping and fault process modeling.
5. Harry Lisabeth, Lawrence Berkeley National Laboratory, Ice Deposits, Regolith Themes, micro-scale acoustic experiments and geophysical properties of sample.
6. Huapeng Huang, University of Maryland, Ice Deposits, Regolith Themes, micro-scale acoustic imaging of hand samples with in-situ X-ray fluorescence and micro-CT scanner.

4.5 Dissertations and Theses

1. Ernie Bell (University of Maryland, PhD) “Geophysical Exploration of Terrestrial and Lunar Volcanic Fields” Dr. Bell will begin a postdoctoral position at NASA Goddard Space Flight Center in the fall working with Kelsey Young (GSFC), and continue to work on GEODES.
2. Edward Williams (University of Maryland, Masters) “Deformation and Failure of Lunar Lava Tubes” Edward has continued on as a PhD student at the University of Maryland working with Laurent Montesi on modeling the stability of lava tubes and other void spaces.
3. Troy Berkey (University of South Florida, Masters) “Three-Dimensional Intrusion Geometries in the Monogenetic San Rafael (Utah) Sub-volcanic Field Revealed by Nonlinear Inversion of Magnetic Anomaly Data.”

4.6 Promotions

1. In November 2021, GEODES Deputy PI Dr. Jacob Richardson became a research scientist civil servant in the Science and Exploration directorate at NASA Goddard Space Flight Center.

5. Mission and Instrument Involvement

5.1 GEODES Activity Associated with Missions and Mission Development

1. Lunar Environmental Monitoring Station (PRISM), Nicholas Schmerr (Deputy PI), PI: Mehdi Benna, Lunar Commercial Lander Payload Systems proposal.

GEODES provided support for mission development and the preparation of a mission proposal to NASA.

2. Far Side Seismic Suite (PRISM), Mark Panning (PI), Renee Weber (Co-I). This mission will deploy a geophysical package at Schrödinger crater on the lunar farside in 2024.
3. Volatiles Investigating Polar Exploration Rover Participating Scientist Program (VIPER), Nicholas Schmerr (Co-I), PI: Kevin Lewis, GEODES is providing FTE to support Schmerr's role as a Co-I on the project. We will use the VIPER IMU to conduct gravity and seismic science experiments on the mission.

5.2 GEODES Activities Associated with Instrument Development

1. TOMO-XRF (NASA SBIR Phase II), Huapeng Huang with contract # 80NSSC19C0163, points of contact Dr. William Brinckerhoff at NASA GSFC, and, Huapeng Huang, Advanced Analyzer Labs, Inc. and Industry Vision Automation, Corp.
2. Lunar Environmental Monitoring Station (LEMS; DALI), Nicholas Schmerr, Seismometer Instrument, Role: Co-I; GEODES is providing opportunities for instrument field testing to the project and enabling analog experiments to determine deployment strategies for the seismometer instrument.
3. SUBsurface Lunar Investigation and Monitoring Experiment (SUBLIME; DALI), Nicholas Schmerr, Seismometer Instrument, Role: Co-I; Terry Hurford, Seismometer Instrument Development, Role: PI. GEODES is providing opportunities for instrument field testing to the project and enabling analog experiments to determine deployment strategies for the seismometer instrument.
4. Seismometer for a Lunar Network (SLN; DALI), Nicholas Schmerr, Seismometer Instrument, Role: Co-I; GEODES is providing opportunities for instrument field testing to the project and enabling analog experiments to determine deployment strategies for the seismometer instrument.

6. Awards and Honors

1. Chuck Connor (University of South Florida) was elected last year as a Fellow to the American Association for the Advancement of Science (AAAS). This well-deserved honor recognizes him for his "distinguished contributions to the field of geosciences, particularly for advancement of volcanology and natural hazard assessment through development of numerical models of volcanic phenomena."
2. Joe DeMartini (University of Maryland) a PhD candidate working with Dr. Derek Richardson at the University of Maryland, was awarded a NASA FINESST grant for his proposal "Surface processes on low-gravity bodies with irregularly shaped particles."

Interdisciplinary Consortium for Evaluating Volatile Origins (ICE FIVE-O)

Jeffrey Gillis-Davis
Washington University, St. Louis, MO

CAN-3 TEAM

1. ICE FIVE-O Team Report

1. ICE Five-O Project Report

The Moon's volatile deposits record a complex, multistage evolution that includes their origin, transport, sequestration, processing, and fractional loss. Potential volatile sources include the solar wind, impactors of all sizes, and gases expelled during volcanic eruptions. To determine volatile source(s), chemical measurement interpretations must account for preferential isotope loss (i.e., fractionation) caused by transport and radiation-induced chemical reactions. Team Five-O endeavors to understand these processes and their indelible mark on the volatile record. To this end, we designed four vertically integrated themes to advance the understanding of lunar volatile deposits in the context of science and exploration. These themes are: (1) Experiments and Modeling; (2) Analytical Characterization of Volatile Exposed Materials; (3) Remote Sensing, and; (4) Sample Handling and Curation. In the following sections, we highlight the team's effort and areas of progress.

Understanding the source of lunar volatiles is critically important to NASA science and exploration. ICE Five-O investigates volatiles' origin, transport, and isotopic modification through experiment, modeling, and analyses.

1.1. Theme 1: Experiments and Modeling

This theme uses innovative experimental and modeling approaches to investigate interactions involving space weathering and possible reactions between volatiles and lunar regolith.

1.1.1. Next Generation Laser Space Weathering: Jeffrey Gillis-Davis (PI)

In principle, the lunar polar regolith is similar to the equatorial regolith. In reality, remote sensing data indicate that polar regolith may have different physical, spectral, and potentially chemical properties. Regolith processing by micrometeorites was simulated in the laboratory using lasers. A short pulse (6-7 nanoseconds) and a long pulse laser (100 nanoseconds) were combined for the first time to produce agglutinate-like melt structures, which overcomes a significant hurdle in laser space weathering. Based on analyses from Theme 2, the novel dual laser weathering technique generates regolith-like products that behave spectrally, physically, magnetically, and chemically like equatorial lunar regolith.

The next steps will be to conduct these experiments at polar relevant temperatures and in the presence of volatiles. The dual laser irradiation method will be combined with an enhanced laser space weathering chamber to investigate multiple factors that could give rise to measurable differences in remotely sensed data between polar and equatorial regions (e.g., temperature, porosity, and volatile content). We are currently testing the capabilities of the enhanced laser space weathering chamber.

1.1.2. Radiation Processing of Volatiles and Volatile Covered Surfaces: Gerardo Dominguez (Co-I and Theme 1 Lead)

Postdoc Caroline Caplan and Co-I Dominguez have carried out electron beam irradiation experiments (Figure 1).

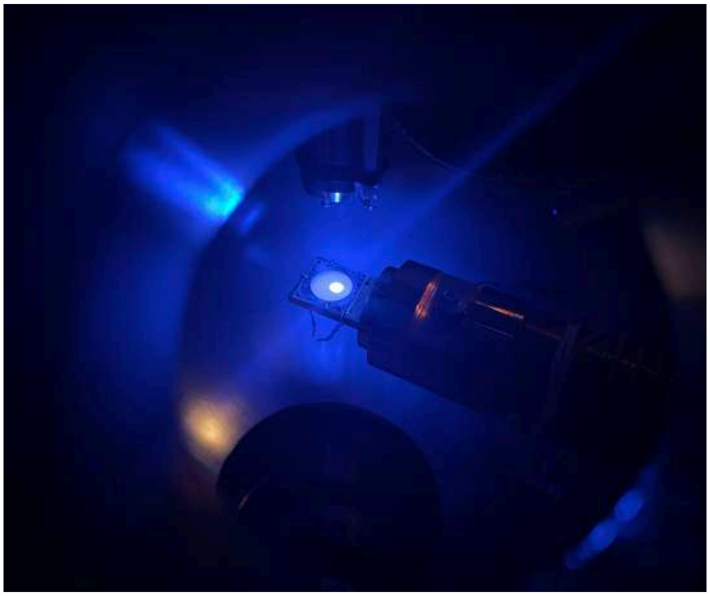


Figure 1. Phosphor screen image of 5 keV electron beam, which is used to focus the beam. Photo by Dr. Caroline Caplan.

The electron experiments lay the groundwork for future proton (H+) irradiations as both use essentially the same equipment: the UHV system, He cryostat, NanoIR to look for nanofluid inclusions, SIMS instrumental analyses, and post-SIMS data reduction and analysis. The H+ irradiation experiments aim to help us understand the origins of water on the Moon. If found, inclusions could be analyzed by Co-I Ogliore (Theme 2) to determine their D/H and 18O/16O and 17O/16O compositions. An extension of this effort, sublimation experiments, will provide fundamental data to understand surface isotopic fractionation factors needed for transport modeling by Co-I Prem.

Comparison between isotopic measurements of experimental samples and Deuterium/Hydrogen predicted from transport modeling will fill knowledge gaps in our understanding the origin of lunar volatiles.

1.1.3. Isotopomer Surface Lifetimes: Impacts on Transport and Composition: Parvathy Prem (Co-I)

Research by Applied Physics Laboratory undergraduate interns (June 2020-21) led to a student-led presentation on isotopic fractionation of water during exospheric transport at LPSC 2021. The interns conducted three simulations for an episodic, globally distributed source of water: (a) H_2O; (b) HDO, assuming the same activation energy as H_2O; and (c) HDO, with a slightly higher activation energy than H_2O, consistent with its higher mass. In comparing volatile transport between models (a) and (b), the students found that more HDO molecules than H_2O molecules were cold-trapped, leading to a slight enrichment at both poles in the ratio of Deuterium/Hydrogen (Deuterium is a heavy form of hydrogen with a proton and a neutron in its nucleus, whereas hydrogen has only a single proton in its nucleus). In simulation (c), it took longer for HDO to reach the cold traps than simulation (b) but, ultimately, almost the same amount of HDO was sequestered in permanently shadowed regions. Currently modeled loss processes for HDO and H_2O are slow compared to the rate of ballistic transport. Hence, model results indicate that more prolonged exposure to the space environment does not affect how much HDO is ultimately cold-trapped.

Model results help to characterize the fractionation of hydrogen isotopes in water during transport to the cold traps. Experiments in Task 1 will provide constraints on key model parameters.

Ongoing work—synergistic with VIPER mission and CLPS payloads—includes code modifications to model transport and cold-trapping of multiple volatile species (such as carbon dioxide) in addition to water. These modifications include using a distribution of activation energies for adsorbed molecules and incorporating high-resolution surface temperature maps.

1.1.4. Alteration of Lunar Samples in Response to Exposure to Volatile Deposits: Bradley Jolliff (Co-I) and Alian Wang (Co-I)

"SSERVI support also enabled me to contribute to capstone papers reviewing the lunar community's current understanding of lunar volatiles (e.g., Lucey et al., 2021 and Schörghofer et al., 2021)"
Parvathy Prem

Drs. Jolliff and Wang are developing two instruments (WIR and MIR3100) for our laboratory analysis of materials mixed with, and affected by, interaction with frozen volatiles. The WIR is the near-InfraRed (IR) detector, operating in the range 1.25–2.5 μm, and the MIR3100 operates in the near IR (2.5–5 μm) and the mid IR (5.5–11 μm). These instruments are used in our experiments to measure mineralogy and detect surface alteration of those materials as they interact with volatiles during surface weathering processes.
The effort on the combined WIR-MIR3100 detectors has enabled us to participate in proposals for Commercial Lunar Payload Services (CLPS) mission applications (via the PRISM calls). These detectors will be especially suitable for detecting volatile-altered minerals or volatile-bearing materials (ices, glasses). We reported on MIR3100 developments at the 2021 American Geophysical Union meeting (Wang et al. 2021).*

These instruments for in-situ analysis of materials mixed with and affected by interaction with ices in lunar polar environments are relevant to recent PRISM calls (Payloads and Research Investigations on the Surface of the Moon)

* Wang, A., P. Sobron, O. Pochettino, E. J. Eshelman, H. Qu, B. L. Jolliff, and J. J. Gillis-Davis (2021) MIR3000 for lunar mineralogy and volatile detection, American Geophysical Union Fall Meeting 2021, New Orleans, LA.

1.2. Theme 2: Analytical Characterization of Volatile Exposed Materials

Theme 2 uses analytical instruments capable of nm-scale spatial resolution and high spectroscopic sensitivity to examine space weathering alteration effects that occur on the nanometer to micron length scale.

Themes 2 and 3 aim to disentangle the regolith's role in the water cycle from the micro-scale measured by instruments to the kilometer scale observed by remote sensing.

1.2.1. Electron Microscopy on Interplanetary Dust Particles (IDPs) and Theme 1 Experimental Materials: Hope Ishii (DPI, Theme 2 Lead), John Bradley (Co-I), and Kenta Ohtaki (Postdoc)

Functional testing of our SSERVI-funded analytical double-tilt cryo-transfer Scanning-Transmission electron microscopes (TEM) holder is complete. The cryo-transfer holder enables immobilization and study of volatiles and sensitive organics by keeping volatile-rich samples frozen during TEM analyses. A new heating stage was tested for simulating diurnal and pulse heating.

We searched for hydroxyl (–OH) and/or water (H2O) in still-sealed vesicles in space-weathered rims on a lunar anorthite grain and silicates in extraterrestrial interplanetary dust particles (IDPs). Electron energy loss spectroscopy (EELS) did not reveal –OH and/or H2O in the lunar rims, unlike in rims on silicates in IDPs.

The observed dry amorphous rims on lunar particles support efficient steady-state desorption processes from lunar regolith.

We carried out monochromated EELS on terrestrial organics and extraterrestrial chondritic (carbon-rich) IDPs—Access to TEMs at the Molecular Foundry in Berkeley, CA, through an active user proposal allows us to take advantage of advanced capabilities on TEMs that are not available on our University of Hawaii microscope. We analyzed terrestrial type IV kerogen (inertinite) because it is reported to be most like meteoritic organic matter. These analyses revealed differences in the aliphatic/aromatic ratio and nitrogen content between the kerogen and organics in carbon-rich IDPs, indicating significantly different molecular chemistry. Among the C-rich IDPs, we found a lower N/C ratio in "fusion crust" organics on the particle exteriors, which signifies organic processing during atmospheric entry. We also observed different N/C ratios in organics closely associated with glassy grains than matrix organics contained in the IDPs, suggesting differing chemistry, potentially from the processing of different generations of precursor ices. We are preparing to examine the interaction of inertinite with various minerals during simulated solar wind irradiation. We plan to look for evidence of molecular variations associated with mineral surfaces using monochromated EELS.

The significance of directly measuring chondritic IDPs is that it may help us unravel the details of the potential interactions between the inorganic substrates and the icy precursors to organics when they are subjected to various kinds of irradiation.

Electron transparent thin sections of laser-irradiated olivine (Theme 1), a component of the lunar highlands, were prepared for TEM analyses. Bright field and dark field imaging, elemental chemistry, and oxidation state mapping show an amorphized and oxidized damage layer and formation of npFe0 near the crystal interface. Nanoparticulate reduced Fe (npFe0) is abundant, and we observe surprising segregation of Ca within the silicate substrate, possibly a shock effect (Figure 2). These processed minerals are relevant to understanding the behavior of inorganic materials prior to adding volatiles and organics into the system.

1.2.2. NanoSIMS Measurements of Water and OH in Meteoritic Materials: Ryan Ogliore (DPI) and Lionel Vacher (Postdoc).

We advanced our new NanoSIMS technique to accurately and precisely measure hydrogen isotopes (D/H) of extraterrestrial

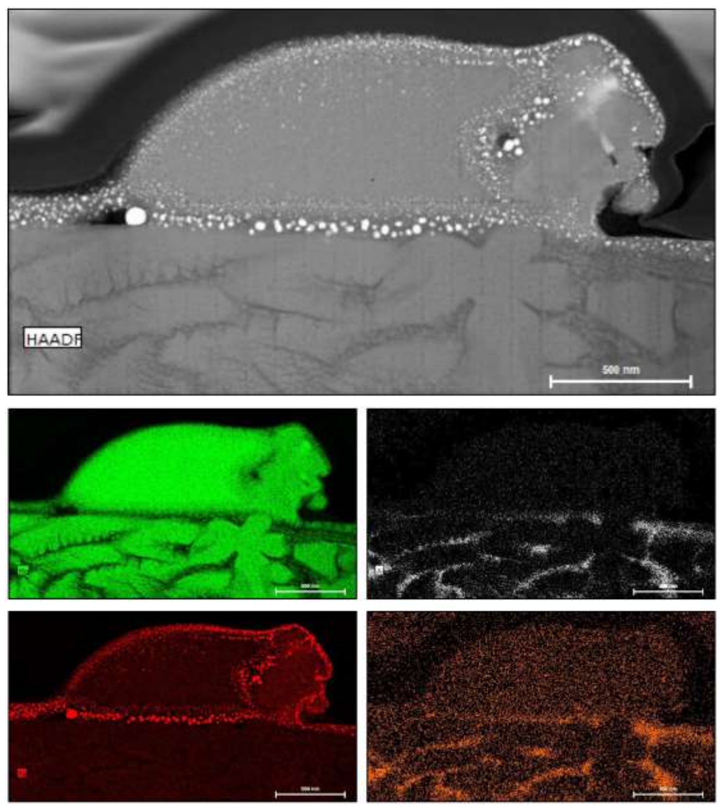


Figure 2. Darkfield image (top) and corresponding EDX maps showing the distributions of Mg (green), Al (white), Ca (orange) and Fe (red). The surfaces of the grain are decorated with nanophase Fe0 as seen in the darkfield image and Fe map. In the bulk olivine crystal, Al and Ca have segregated from Mg (and Si). Scale bars are 500 nm.

water. Our improved methods allow us to measure D/H in minute samples such as microscopic hydrated inclusions. The new method of using a generalized linear-mixing model can also minimize the effects of contamination. We have confirmed the accuracy of this technique by measuring D/H in Maribo (CM2). We used this method to study small-scale D/H variability in matrix and small hydrated inclusions in meteorites (e.g., Isheyevo (CH/CB) and Tagish Lake (CI)) and found variable ratios. In addition, our approach can be used for the isotopic characterization of Theme 1 experimental materials and future volatile-rich lunar samples, which will require efficient analyses of a small amount of material.

1.2.3. Ferromagnetic Resonance Measurements of Theme 1 Experimental Materials: Andrew Ichimura (Co-I)

Ferromagnetic resonance (FMR) measurements of dual laser weathered San Carlos olivine (9.5 wt.% FeO) samples from Theme 1 indicate an abundance of nanophase iron. The FMR intensities of the laboratory weathered samples compare to the FMR intensities of mature lunar soils. Although the laser weathered samples appear mature based on FMR and optical spectroscopy, the apparent surface exposure indices determined for the samples is lower than expected with IS/FeO values of <30. For comparison, the lunar soil maturity index, IS/FeO, ranges from immature <30; submature 30-60, and mature >60. Future work will look at explaining this discrepancy in maturity index values between the laser weathered olivine and Apollo samples. Two areas of future work to explain this difference include: (1) Simulating the FMR spectra of dual laser weathered San Carlos olivine and Apollo soils with similar FeO wt.% to reveal the differences in the magnetic properties of the nanophase iron; and, (2) Determining the size and distribution of the npFe for the San Carlos olivine laser weathered samples with TEM data. Correlating npFe size and distribution with IS/FeO surface exposure index will help assess the fidelity with which laser weathering mimics the effects of space weathering.

1.2.4. Principal Component Analyses of Theme 1 Experimental Materials: Heather Kaluna (Co-I)

Principal Component Analysis (PCA) and spectral characteristics (e.g., mean reflectance, spectral slope, and band area ratios) were used to perform a comprehensive spectral comparison between dual laser irradiated samples and spectra of naturally weathered soils from the Lunar Soil Characterization Consortium. Dual laser irradiated material followed spectral trends more similar to lunar soils than did single short pulsed laser irradiated materials. Principal Component 1 (PC1) was found to be 100% correlated with albedo (mean reflectance), PC2 and PC3 are largely influenced by spectral slopes and band area ratio respectively. When comparing PC1 and PC4, there are two distinct clusters, one of which is dominated by naturally weathered samples, and the other experimentally weathered samples. We are still in the process of determining which spectral characteristics dominate PC4. We are also in the process of separating the visible and near-infrared regions of the spectra to run our PC analyses and further investigate the ability to emulate the wavelength dependency observed among naturally weathered samples.

1.3. Theme 3: Remote Sensing

Understanding the interplay of reflectance and thermal emission to accurately characterize the lunar hydration cycle, and studying the detection and quantification of organics.

> This Theme aims to improve confidence in conclusions regarding the distribution and behavior of water on the Moon, which are substantially different based on methods for deriving solar emission in the key wavelength region near 3 microns.

1.3.1. Address Issues of Mixed Thermal and Reflected Signal in Infrared Spectroscopy: Paul Lucey (Co-I, Theme 3 Lead), and Abigail Flom (Graduate Student)

We continue to work on models that incorporate more pragmatic assumptions to improve confidence in results regarding the distribution and behavior of water on the Moon. For example, realistic models of subpixel temperature variations and explicit solutions to subpixel photometric behavior. We also take a new approach by observing the Moon at 3 microns, which includes the important vibrational water bands, from the NASA Infrared Telescope Facility at Maunakea Observatory during a partial lunar eclipse. During a lunar eclipse, the Earth blocks a portion of the Sun as viewed from parts of the Moon, decreasing the illumination and reducing lunar surface temperature. The lower

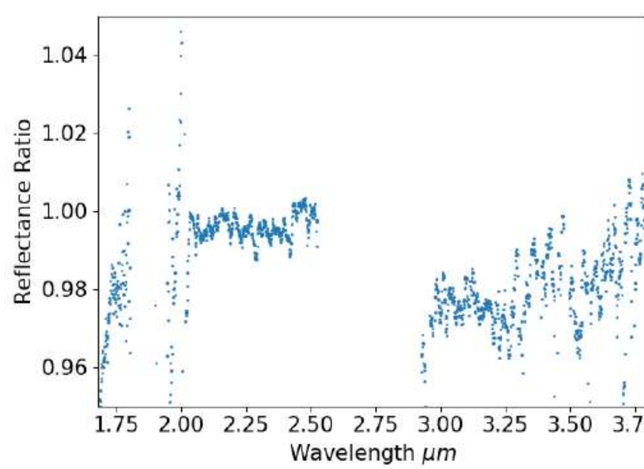


Figure 3. Ratio of the spectrum of the Chang'E 5 landing site taken during partial eclipse (45% illumination) to that taken in full illumination. A clear 3-micron band has emerged due to a drop in lunar surface temperature.

temperature causes thermal blackbody emission to shift to longer wavelengths, which mitigates the need to correct for the thermal emission signal in the 3 micron region. We found that in comparing data collected at 45% illumination to data collected out of eclipse a 3 micron band does emerge at the Chang'E 5 landing site, which is dry according to data from the Moon Mineralogy Mapper (Figure 3). Whether the 3-μm band has emerged with the drop in temperature is due to the reduced thermal component or actual temperature depending on variation in water or hydroxyl concentration is under investigation.

1.3.2. Establish Detection Limits for Organic Materials

We have also begun a new project to understand cold trapping of methane (CH4) in regions of permanent shadow at the lunar poles. The lunar atmosphere contains methane, conjectured to be produced in chemical reactions in the surface between solar wind hydrogen and carbon. We are mining a large telescopic data set that includes 3.4 micron wavelengths where organics, like CH4, can be detected and might reflect organics in lunar soil agglutinate glass. Observed from equatorial orbit, methane cold traps on the lunar nightside and is subsequently released into the exosphere shortly after dawn. As this liberated methane migrates through the exosphere, a portion could be permanently trapped in regions of permanent shadow. The total surface area of lunar soil that is available for adsorption of CH4 is large enough that. If, across the entire lunar surface, the total surface area of soil is saturated with adsorbed CH4, about 50 ppm of hydrogen in the form of methane could be trapped. This concentration is small with respect to expected water abundances, but methane could constitute a feedstock for organic chemistry in the polar regions that might further concentrate carbon. We are building a methane adsorption chamber to investigate if methane could be detected spectroscopically from orbit in regions of permanent shadow at the lunar poles or by the lunar polar rover mission VIPER.

Figure 4. Co-I Julie Mitchell (left) and team member Amber Turner (right) preparing cryogenic lunar volatile simulants.

We investigate if methane could be detected spectroscopically from orbit in regions of permanent shadow at the lunar poles or by the lunar polar rover mission VIPER.

1.4. Theme 4: Handling and Curation

Theme four addresses curation protocols for sample return and the evolution of volatiles, or low-boiling point compounds, and minerals within long-duration, curated samples.

> ICE Five-O has significantly accelerated the development of simulants, methods, and instruments needed to support Artemis sample return.

1.4.1. Volatile-rich Lunar Simulant Procedure Development: Julie Mitchell (Co-I and Theme 4 lead) and Amber Turner (Co-I)

The Theme 4 Curation Team prepared its new laboratory, the Planetary Exploration and Astromaterials Research Laboratory (PEARL), for testing that directly supports lunar exploration missions. The new lab allowed the curation team to focus on making a specific, reproducible procedure by which previously JSC-developed volatile-rich lunar simulants can be made in laboratories across the world (Figure 4). Theme 4 now has a laboratory procedure and is currently refining it for use in mission-critical experiments on lunar volatile-rich simulants to facilitate Artemis sample return. After these experiments are complete, we plan to publish the simulant preparation procedure for community benefit.

1.4.2. Volatile Storage Experiments: Julie Mitchell (Co-I and Theme 4 lead), Ernest Lewis (Co-I), Cecilia Amick (Co-I), and Amber Turner (Co-I)

The objective of this task is to measure the degree of phase change and chemical alteration in lunar volatile-rich simulant samples at a range of temperatures. We integrated a Parr high-pressure, hermetically sealed vessel with a Universal Gas Analyzer (UGA). This arrangement allows for real-time analysis of gases that separate from the solids and become trapped in the vessel during controlled warming of volatile-rich materials. The Parr vessel and UGA are being used to assess the alteration of a volatile-rich sample that is returned without a flight freezer, providing a critical measurement for understanding the behavior of volatile-rich samples collected by early Artemis missions. After two years of preparations, we will begin our first experiment at the end of January 2022. The result of our testing will inform mission planners in the development of a flight freezer and will provide critical baseline data for planning for lunar volatile sample curation.

The effort of Theme 4 helps meet the Artemis III Science Definition Team priorities for the need to have cryogenic sampling capabilities, which will bring precious volatiles from the Moon's permanently shadowed regions to Earth for meticulous studies.

The team has also assessed the need for characterizing returned lunar volatile samples using both destructive (mass spectrometer) and non-destructive (reflectance and transmission spectroscopic) techniques. A Gas Chromatograph-Mass Spectrometer and Fourier-Transform InfraRed spectrometer were recently purchased, and both instruments are in the process of being brought online. These two new instruments will complement the UGA and a cavity ringdown spectrometer that are currently in the PEARL at JSC.

2. Inter-team/International Collaborations

2.1. ICE Five-O and TREX (PI: A. Hendrix)

Five-O Team members are working with TREX PI Hendrix comparing the UV signature of dual and single laser irradiated materials. Experiments with dual laser irradiation uses both long (100 ns) and short (7 ns) pulse lasers, while single laser irradiations only use the typical short pulse laser.

2.2. ICE Five-O and RISE4 (PI: T. Glotch)

Both teams have a common interest in measuring space weathering effects with near-field FTIR. Gillis-Davis and Glotch have jointly submitted a NASA Postdoctoral Program announcement related to spectroscopic measurements and spectral modeling of experimentally space weathered lunar analogs, chondritic meteorites and meteorite analog materials. Gillis-Davis also serves on the Ph.D. dissertation committee of Donald Hendrix, a RISE4 graduate student.

2.3. ICE Five-O, RISE4 (PI: T. Glotch), and SEEED (PI: C. Pieters)

Members of the three teams (e.g., Gillis-Davis, Glotch, Pieters, Mustard) are working with Graduate student Chris Kremer on infrared spectra of olivine in the 4-8 µm "cross-over" range as a tool for determining the Mg# of olivine.

2.4. ICE Five-O and LEADER (PI: R. Killen)

Dr. Prem is a joint Co-I on the LEADER/ICE Five-O teams. Results from ICE Five-O work on isotopic fractionation will inform LEADER models of past, present, and future lunar volatile transport.

2.5. ICE Five-O and CLSE (PI: D. Kring)

Dr. Stopar is bridging volatile science, exploration, and planning for future polar observations from the surface as an ICE Five-O Co-I and CLSE team member. Dr. Stopar generated a new quick-look map product of the lunar south pole that features Malapert peak. This map joins a large collection of related products on the LPI website that include contributions from CLSE interns, LPI's RPIF, and external sources. https://repository.hou.usra.edu/handle/20.500.11753/1756

2.6. ICE Five-O and Reveals and LEADER (Orlando, Farrell)

Dr. Lucey (Co-I and Theme 3 lead) produced a lunar volatiles review paper that included Prem (ICE Five-O) and SSERVI co-authors Orlando and Farrell.

2.7. ICE Five-O and Artemis

Co-I and Theme 4 lead Dr. Mitchell and her team are currently collaborating with members of the Artemis mission development teams, including the EVA sample collection tools team, the cold stowage team, and several spaceflight vehicle teams.

2.8. International Collaboration

PI Gillis-Davis is collaborating with Dr. Aleksandra Stojic of the Institute for Planetology, Westfälische Wilhelms Universität, Münster, Germany. We are studying how single thin layers behave on a mineral grain surface when zapped by a laser and whether incipient surface effects would result in measurable spectral signatures.

3. Public Engagement

Public engagement is a core Team mission. Public engagement is vital to raising awareness of the questions SSERVI science is tackling to understand the Universe. Increasing consciousness of the many gaps that exist in scientific knowledge fosters inclusion and inspiration because people are actively seeking the information they need to help fill those gaps—They want to be part of Team NASA.

3.1. Science Activities Liaison and Community Engagement Lead Dr. Barbara Bruno (Co-I)

Throughout 2021, Co-I Bruno has worked to (1) foster a long-term partnership with the Interpretation Staff (Park Rangers who focus on Education & Outreach) at Haleakalā National Park, building on the strong foundation established during 2020; and (2) forge a new partnership with the Interpretation Staff at Hawai'i Volcanoes National Park. With both National Parks, it is their needs that drive the partnership activities. At Haleakalā, at their request, the partnership focuses on providing training for Interpretation staff and assisting with development and review of outreach materials. Dr. Bruno organized and/or led nine trainings during 2021. ICE Five-O PI Gillis-Davis and other team members also participated in some of the trainings.

Figure 6. Zoom-based conversation with teenage participants of the YEP based out of CSUSM about being a college graduate and scientist from a similar background to their own.

3.2. Public Engagement by Other Co-Is

Dr. Gerardo Dominguez did a Zoom presentation and Question and Answer with National Latino Research Center's (NLRC) Youth Empowerment Program (YEP), which is run by MyUniversity at CSUSM (Summer of 2021, See Figure 6)

Dr. Parvathy Prem has participated in multiple public engagement activities:

- Research advisor and guest lecturer for the 2021-22 LPI/SSERVI Exploration of the Moon and Asteroids by Secondary Students program.
- Skype a Scientist—virtual classroom visits with five elementary/middle schools in TX, MD, IL, Kazakhstan, and Canada.
- Community scientist virtual visits with Howard County, MD public schools (Grades 2–4).
- Invited talks given at Georgia Tech, Providence Women's College (Calicut, India), Taiwan Space Union (Taiwan).

Dr. Mitchell gave a virtual talk to the Stem Enhancement in Earth Science (SEES) program for high school students. The title of the talk was, "Curation and Science for the Artemis Generation." She also gave a pre-recorded talk at the public EVA Exploration Workshop 2021, entitled, "Artemis Sample Science and Curation."

Dr Hope Ishii (DPI) was a guest on Canadian Broadcasting Corporation/Radio Canada's Quirks & Quarks science-focused weekly radio show (December 2021). She discussed solar wind generated water in extraterrestrial regolith and its contribution to Earth's oceans. She was also interviewed for a Hawaii Public Radio news segment.

Dr. Ryan Ogliore (DPI) was interviewed on KMOX and 97.1 FM Talk radio (Nov 28 and Dec 21). Topics included DART, asteroid impacts, the movie Armageddon, and related subjects.

Dr. Gillis-Davis (PI) gave two invited presentations. The first to the St. Louis Astronomical Society was titled, "The Travel Moon: Returning to the Moon, Our Destiny of Tomorrow" (10/15/21). He brought the Lunar Disk to a second public outreach event and talked about the Moon at a star party for International Observe the Moon night at Eastern Central College (10/16/21).

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

1. Parvathy Prem (Co-I): Co-Chair, NASA Lunar Surface Science Workshop Session #13: Inclusive Lunar Exploration.
2. Parvathy Prem participated (as a panelist and facilitator) in the Indigenous & Anticolonial Views of Human Activity in Space seminar series organized by the Space Enabled Research Group at the MIT Media Lab.
3. Jeffrey Gillis-Davis: Member of the Physics Department EDIA committee. We work to make physics a more Diverse, Equitable, Inclusive, and Accessible community.
4. Prem and Gillis-Davis helped with LPSC Early-Career Presenters Help Desk. Students, post-doctoral fellows, and other early-career scientists were invited to stop by the virtual Help Desk for assistance in planning their oral or poster presentations. Experienced scientists provided feedback on presentation content before Early-Career Presenters submitted their files for the conference (2/19-2/24/2021).
5. Prem and Gillis-Davis are members of the SSERVI EDIA focus group, which meets bi-weekly.
6. Hope Ishii (DPI) served as an Instructor for the 2021 EP'IK (Earth, Planets, 'Ike, and Kuleana) Summer Camp for Hawaii high school students. A key objective is to promote awareness in the geosciences by integrating elements of 'ike Hawai'i (Hawaiian knowledge) and kuleana (responsibility), enhanced by purposeful connections of indigenous stories and science. Ishii focused on connections to the cosmos.
7. Co-I Julie Mitchell provided inputs to the Johnson Space Center EDIA Plan.
8. Throughout the year, Co-I and SA/CE-lead lead Barb Bruno worked to modify the Individual Development Plan (IDP) model developed for the 'Ike Wai project for a national audience. This entailed broadening

the Hawaii-centric place and culture module to a more general Diversity, Education and Inclusion (DEI) module. Our goal is to institute IDPs throughout the ICE Five-O institutions, and possibly more broadly across all NASA SSERVI nodes, as discussed with Greg Schmidt, Kristina Gibbs and the NASA EDIA committee.

5. Student/Early Career Participation

Undergraduate Students

APL CIRCUIT Undergraduate Interns, Academic Yr 2020–21, effort by Parvathy Prem:

1. Christopher Alfaro (UMBC, Chemical Engineering)
2. Katherine-Ann Carr (UMBC, Mechanical Engineering)
3. Oluchi Azubuike (UMBC, Information System)
4. Courtney Carreira (JHU, Physics, Applied Math & Statistics)
5. Alyse Tran (JHU, Mechanical Engineering)

Graduate Students

6. Oscar Gravador III, Washington University, space weathering.
7. Abigail Flom, University of Hawaii, remote sensing.
8. Chiara Ferrari-Wong, University of Hawaii, remote sensing.

Postdoctoral Fellows

9. Caroline Caplan, California State, San Marcos, geochemistry/cosmochemistry.
10. Lionel Vacher, Washington University, cosmochemistry/isotopic analysis.
11. Emily Costello, University of Hawaii, impact gardening
12. Kenta Ohtaki, University of Hawaii, TEM analyses and geochemistry
13. Lizeth Magaña, Applied Physics Laboratory/John's Hopkins University, lunar polar volatiles.

Promotions

14. Kenta Ohtaki, University of Hawaii at Manoa, materials science. Dr. Ohtaki played a key role in the analysis of Theme 1 materials. He was promoted to a staff position during 2021.
15. Gillis-Davis promoted to Research Professor
16. Co-I Mitchell promoted to Portfolio Scientist in the Astromaterials Research and Exploration Science Division at NASA-JSC.
17. Lionel Vacher has taken a postdoc at the Institute for Planetary sciences and Astrophysics, University of Grenoble.

6. Mission Involvement

1. LRO (Mini-RF, Diviner), Parvathy Prem, science team member, her work focuses on understanding the near-surface thermal environment (an important boundary condition for my ICE Five-O volatiles transport work) and her Mini-RF work is aimed at understanding the distribution and form of polar ice.
2. VIPER, Parvathy Prem, Co-I, selected Dec 2021, understanding how exhaust volatiles are transported.
3. Surface and Exosphere Alterations by Landers (SEAL) and Peregrine Ion Trap Mass Spectrometer (PITMS) (NASA-provided lunar payloads), Parvathy Prem, science team member, understanding how exhaust volatiles are transported.
4. Hayabusa 2, sample analyses team, Hope Ishii, John Bradley and Kenta Ohtaki participated as members of the initial sample analysis team studying space weathering features. Initial publications have been submitted.
5. Artemis, Sample Return and Curation, Team members: Julie Mitchell (NASA), Ernest Lewis, Cecilia Amick, Chris Harris, and Amber Turner (Jacobs/JETS). The SSERVI studies of the curation of lunar polar volatile samples is directly related to the major Artemis goal of returning samples from the lunar south pole, including samples from Permanently Shadowed Regions (PSRs) which could be rich in a unique combination of volatile compounds. Due to the unprecedented nature of this type of sample, a significant amount of laboratory studies are needed to adequately prepare for the return of this kind of sample. ICE-Five-O has significantly accelerated the development of simulants, methods, and instruments needed to support Artemis sample return.
6. Artemis, Julie Mitchell is the Artemis Curation Lead for the Internal Science Team.
7. LRO, LOLA and Diviner, Paul Lucey, Co-I, modeling subpixel temperature variations.
8. ManitobaSat-1, Ed Cloutis (Collab. Univ. Winnipeg), science payload will carry meteorites and lunar analogs into LEO to see how space weathering affects them by monitoring any color changes. Laser weathering experiments (Theme 1) of meteorite and analog materials will provide a basis for observations and a check to experiments.
9. Volatile & Mineralogy Mapping Orbiter Mission is an ESA funded cubesat. Ed Cloutis, used a three-band lidar (532, 1064, and 1560 nm) to look for ice in

permanently-shadowed regions. Measurements of ice/regolith mixtures (Theme 3) will help interpret VMMO results.

10. I-SPI, FROST, and LunaR are three Canadian Space Agency-funded Phase 0 studies that are examining the use of infrared spectroscopy (I-SPI and FROST) or Raman spectroscopy (LunaR) to search for water ice in permanently-shadowed regions. Ed Cloutis (Collab, Univ. Winnipeg) is Science Team Lead for I-SPI and FROST, and PI for LunaR.

7. Awards

1. Shoemaker Award, Paul Lucey, Co-I
2. Susan Mahan Niebur Early Career Award, Parvathy Prem, Co-I
3. University of Hawaii Presidential Citation for Outstanding Service, Bar

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)

Mihaly Horanyi
University of Colorado, Boulder, CO

CAN-3 TEAM

1. IMPACT Team Report

1.1 Dust Accelerator Experiments

1.1.1. Testing of SUDA Flight Model

The Surface Dust Analyzer (SUDA) instrument is set to launch in October 2024 aboard the Europa Clipper mission. The instrument was developed by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado and was tested and calibrated in the IMPACT dust accelerator. SUDA will characterize the composition of Europa's surface by measuring the composition, size, speed, and spatial distribution of dust in the vicinity of this moon, and will provide a spatially resolved compositional map of Europa for the regions along the ground tracks of the orbiter's flybys. The SUDA flight model (Fig. 2, left next page) is pictured in the IMPACT cleanroom after a calibration run at the dust accelerator.

1.1.2. Modeling and Interpreting Antenna Signals from Dust

Impacts on Spacecraft

Space missions often carry antenna instruments that are sensitive to dust impacts, yet the understanding of signal generation mechanisms has remained incomplete for the past nearly five decades. We developed an analytical signal generation model which agrees well with our laboratory measurements. The model is based on the direct and induced spacecraft charging from the collected/escaping

The IMPACT dust accelerator facility (Fig. 1), continues its unique position as a facility to study hypervlocity (>> 1 km/s) dust impacts for basic physics studies, and to enable flight instrument development. We have served multiple space missions for dust impact damage studies, testing and calibration for NASA's Cassini, New Horizons, Solar Probe Plus, Europa Clipper, IMAP, and ESA's Destiny Plus missions. The facility is open to the US and international lunar, space, and planetary sciences communities.

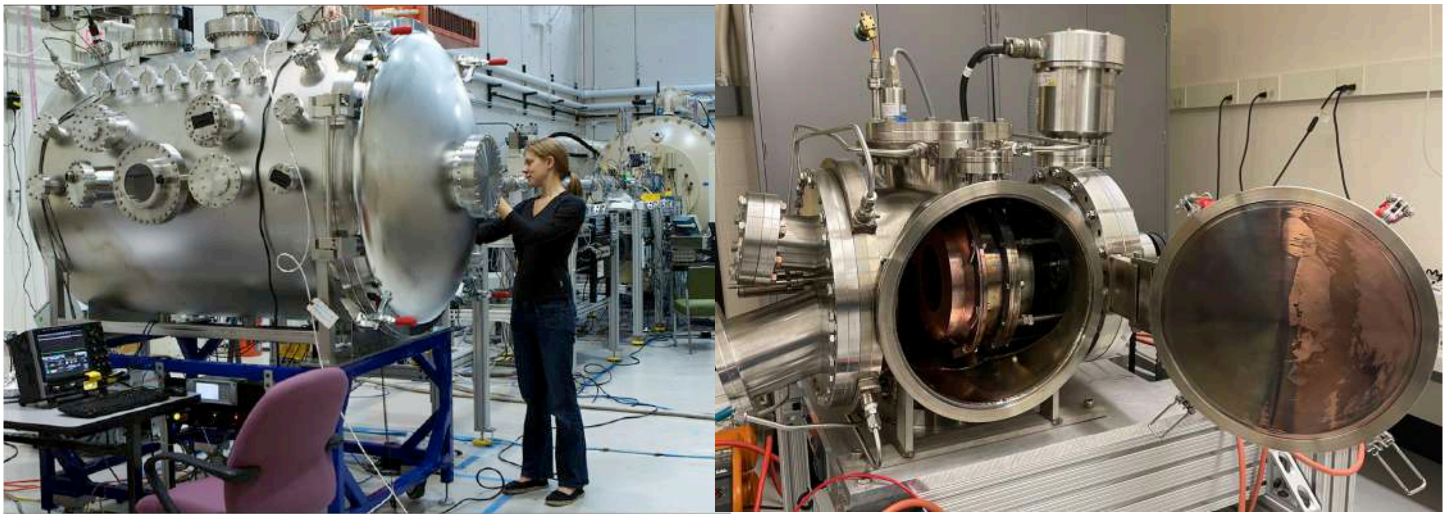


Figure 1. The IMPACT dust accelerator facility (left) makes use of various specialized target chambers, including a) a gas target for meteoroid ablation studies; b) a cryogenic target for ice impact experiments, c) a large impact chamber that can accommodate experiments that need rotational and/or translational staging in the dust beam, in addition to specialized single user chambers. The on-site class 10,000 clean room supports instrument development efforts for space flight. IMPACT also recently developed a dust coating facility (right), which enables in-house metal-coating of a wide variety of grain materials for use in the accelerator, as well as the development of more exotic core-shell microparticles.

free charges in the impact-generated plasma cloud. A set of laboratory experiments was performed using a 20:1 scaled down model of the Cassini spacecraft in the dust accelerator (Fig. 2, right). (SSERVI-2021-011 M.-H. Shen, Z. Sternovsky, M. Horanyi, H.-W. Hsu, and D. Malaspina, J. Geopys. Res. - Space 126, e2020JA028965, https://doi.org/10.1029/2020JA028965, 2021 and SSERVI-2021-XXX M.M. Shen, Z. Sternovsky, A. Garzelli, D.M. Malaspina, J. Geopys. Res. – Space 126, e2021JA029645 https://doi.org/10.1029/2021JA029645, 2021).

1.1.3. Differential Ablation of Micrometeoroids Impacting a Gas Target

Micrometeoroids entering the atmosphere lose mass through ablation, with the more volatile components differentially ablating first. To study this phenomenon, we shot olivine particles coated in polypyrrole, an organic conducting polymer, into a gas target at speeds of 10 – 20 km/s. Our measurements suggest that organics ablated from micrometeoroids may produce sufficient charge to be detectable by radar. The apparent large size of the ablating molecules also suggests that meteors may be able to deliver complex organics into the atmosphere that could have been useful building blocks for life on the early Earth. (SSERVI-2021-XXX M. DeLuca, Z. Sternovsky, S. P. Armes, L. Fielding, M. Horanyi, D. Janches, Z. Kupihar, T. Munsat, and J.M.C. Plane, J. Geophys. Res. - Planets, submitted, 2021).

1.1.4. Cryogenic Ice Target Experiments

We have performed a set of unique impact experiments into H2O ice targets which include known concentrations of complex organic molecules in one experiment and known ratios of Deuterium (D) to Hydrogen (H) in another. In order to create uniform ice targets, we developed a novel air-spray method to deposit ice uniformly onto a cryogenic substrate while preventing the migration of dopants during freezing.

Detection of complex organic molecules on/above the surface of icy airless bodies will answer significant questions about the chemical evolution of such bodies, and survivability and detectability of these molecules provides a critical proof-of-concept of these experiments. At the dust accelerator, H2O ice doped with histidine was bombarded with hypervelocity dust. Time-of-flight (TOF) mass spectroscopy analysis of the impact plume demonstrated that the amino acid survived the impact process at velocities below about 7 km/s and can be measured directly. At higher velocities, fragmentation products appear, which may enable their use to identify the parent molecules. Similar experiments were performed with ice created with a known D-H ratio, demonstrating the proof-of-concept that the D-H ratio can be determined correctly with this method.

1.2. Laboratory-Scale Experiments

1.2.1. Electrostatic Dust Mobilization Experiments

Electrostatic dust lofting has been suggested to explain a number of unresolved phenomena on airless planetary bodies such as the lunar horizon glow, the dust ponds on asteroid Eros, and the radial 'spokes' in Saturn's rings. We performed experiments in which we lofted dust in the laboratory using energetic electrons and/or UV illumination, and measured the size distribution of the grains (N. Hood*, A. Carroll*, X. Wang, and M. Horányi, ICARUS, accepted, 2021). Measurements of the size distribution in the 1 to 40 µm diameter range demonstrated agreement with the "patched charge model" from our previous work.

Experiments were also performed on dust mobilization in laboratory models of lunar magnetic anomalies, in which it was found that mobilization is correlated with the orientation of the magnetic field and is inhibited in certain regions. We developed an explanation based on ambient electrons collected in photoemitting areas precipitating changes in the emission and re-absorption of photoelectrons inside microcavities between dust particles. The magnetic field controls the movement of the ambient electrons, resulting in active and inactive regions. Computer simulations show that areas of ambient electron accumulation as imposed by the magnetic field agree with experimentally observed

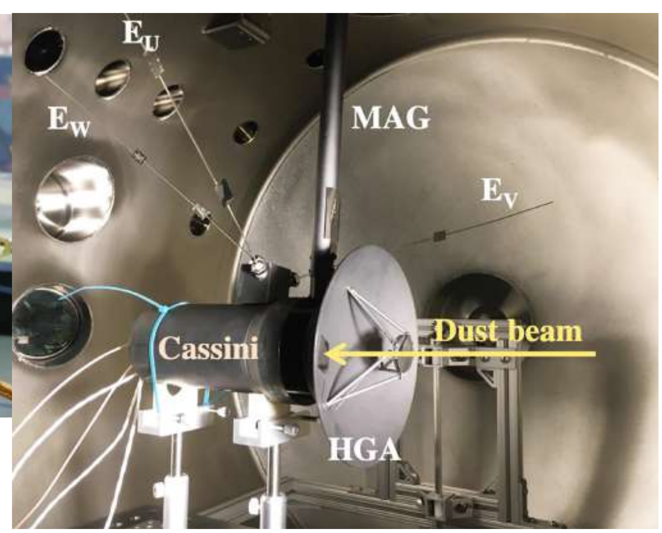


Figure 2. (Left) The SUDA flight model undergoing testing in the IMPACT cleanroom. (Right) Scale model of the Cassini spacecraft undergoing dust impact studies to interpret antenna signals from impact plasma production.

patterns of dust mobilization (Yeo L.H., N. Hood, J. Schwan, X. Wang, and M. Horanyi, Phys. Rev. Lett., submitted, 2021).

1.2.2. Laboratory Simulation of Solar Wind Interaction with Lunar Magnetic Anomalies

Magnetic anomalies on the surface of the Moon interact with the solar wind plasma, resulting in both magnetic and electrostatic deflection/reflection of charged particles. Consequently, surface charging in these regions differs from regions without magnetic fields. This interaction was studied with the Colorado Solar Wind Experiment, using a high energy flowing plasma (100-800 eV beam ions) incident upon a magnetic dipole embedded beneath an insulating surface. At low ion beam energies, the surface potential (in Volts) reached the ion beam energy (in eV), due to magnetic exclusion of electrons in the lobe regions. At high beam energies, the surface potentials in the electron-shielded lobe regions remained significantly lower than the expected magnitude, which guided a test particle simulation indicating that secondary electrons induced by the high energy impinging ions can enter the shielded regions (L.-H. Yeo, J. Han, X. Wang, G. Werner, J. Deca, T. Munsat, M. Horányi, J. Geophys. Res. - Space, submitted, 2021).

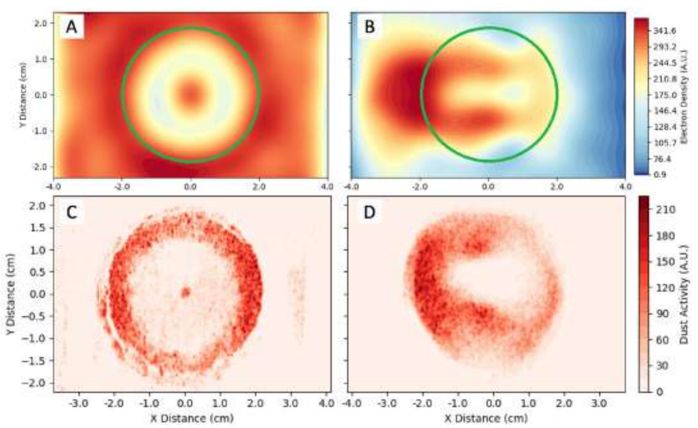


Figure 3. Simulated electron landing patterns (A, B), compared to measured dust activity levels (C, D). In each case a magnetic dipole is located just below the surface, with its magnetic moment perpendicular to the surface (A, C) and parallel to the surface (B, D), respectively. The green circles indicate the area of the dust bed in the experiment.

1.3 Data Analysis and Modeling

1.3.1. Plasma Environment Surrounding the Reiner Gamma

Magnetic Anomaly

The Reiner Gamma region on the lunar surface hosts a set of brightness variations ("swirls") that are co-located with a prominent crustal magnetic field. We analyzed the distinct plasma regimes that a mission to this region may encounter along its trajectory, such as the Moon's crossing through the Earth's magnetosheath and a set of different solar wind directions. We simulated the electron, proton, and He2+ dynamics with computational particles and included

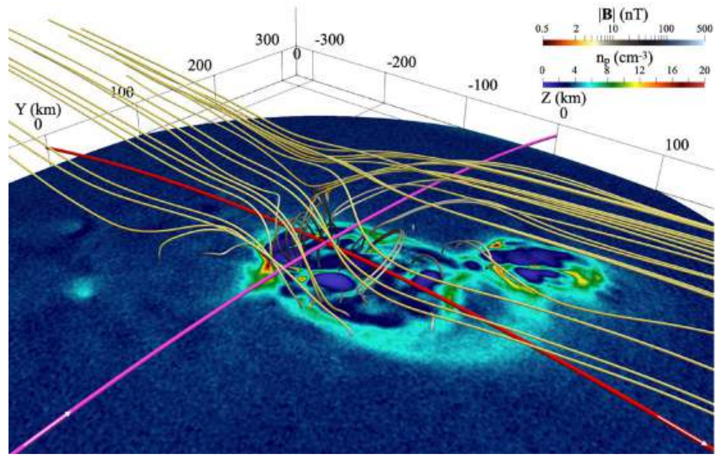


Figure 4. Overview of the simulated region surrounding the Reiner Gamma magnetic anomaly. The solar wind incidence angle is 45° and the IMF is chosen parallel to the surface (a sample of field lines is shown for illustration). Two trajectories are indicated crossing the center of the main anomaly at 15 km above the spherical lunar surface. The polar and equatorial orbit are colored in magenta and red, respectively. np is the proton number density, shown here at the lunar surface. |B| is the magnetic field magnitude.

the Reiner Gamma magnetic field using a model developed from Kaguya and Lunar Prospector measurements. We found that the plasma environment is vastly different at different altitudes and depends critically on the upstream plasma parameters. Our models are essential to help define the measurement requirements for future endeavors to magnetized regions on the lunar surface, such as Reiner Gamma. (J. Deca J., A. R. Poppe, A. Divin, and B. Lembège, JGR-Space 126, https://doi.org/10.1029/2021JA029180, 2021).

1.3.2. Fine-Grained Regolith Loss on Sub-km Asteroids

Fine-grained regolith has been considered a common element of the surfaces of airless bodies that determines their spectral and thermophysical properties. Surfaces of asteroids visited by recent sample return missions are dominated by centimeter- to meter-sized boulders, indicating an active fine-grained regolith removal process at work. To understand regolith size distribution on small asteroids, we applied experimental results to simulate regolith fragmentation processes, loss by impact ejecta, and electrostatic removal of fine-grained regolith. Our results indicate that a coarse, boulder-rich scenery likely occurs on km-sized and smaller asteroids within a few million years, as the removal of fine-grained regolith by electrostatic dust lofting dominates production by fragmentation. The short regolith removal timescales suggest a competition between electrostatic erosion and space weathering shaping the reflectance spectra of small asteroids. (H.-W. Hsu, X. Wang, A. Carroll, N. Hood, and M. Horanyi, Nature Astronomy, submitted, 2021).

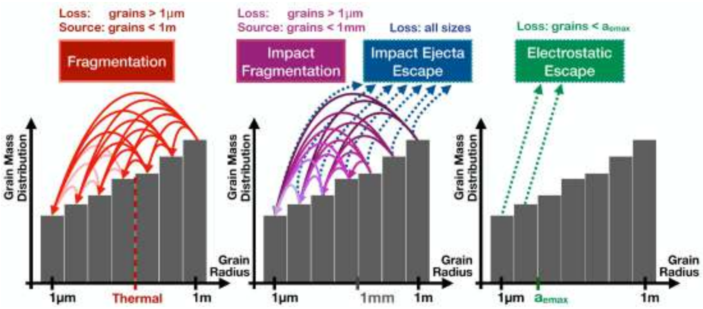


Figure 5. Schematic of the three primary processes considered in shaping the regolith size evolution on airless bodies.

1.3.3. Lofted Dust, Ejecta Clouds, and Exospheres on the Moon and other Airless Planetary Bodies

We have performed several studies which model phenomena observed in laboratory or mission data. For example, we have modeled the lofting dynamics of dust grains on small bodies, using initial conditions obtained from recent laboratory results. From a complex interplay between the grain size, gravity, initial charge, and the various charging currents, we show that micron-sized dust grains can be lofted to high altitudes and even escape from smaller bodies. (Yeo L.-H., X. Wang, J. Deca, H.-W. Hsu, M. Horanyi, Icarus 366, 114519, https://doi.org/10.1016/j.icarus.2021.114519, 2021). A related study expanded previous models of ejecta cones observed with LDEX plume crossings, and implemented a global lunar model fitted to LDEX measurements of the sporadic background to constrain the product of meteoroid impactor fluxes and ejecta mass yield per source. We found that if βmeteoroids are responsible for the day/night asymmetry, they must have an impact ejecta yield of at least 103 (E. Bernardoni, M. Horanyi, and J. Szalay, Planetary Sci. J. 2, 67, https://doi.org/10.3847/PSJ/abea7c, 2021).

IMPACT investigators also contributed to a review of progress made over the past decade concerning our understanding of meteoroid bombardment on airless solar system bodies as one of the sources of the formation of their exospheres (D. Janches, A.A. Berezhnoy, A.A. Christou, et al., Space. Sci. Rev., 217-50, https://doi.org/10.1007/s11214-021-00827-6, 2021), as well as a study of Na and K Mercury and Moon exospheres (Leblanc F., Schmidt C., Mangano V., et al., Space Sci. Rev., submitted, 2021).

1.3.4. Modeling Meteoroid Impacts on the Juno Spacecraft

Events which meet certain criteria from star tracker images onboard the Juno spacecraft have been proposed to be from impacts of >10 μm interplanetary dust particles on its solar arrays. We compared the reported event rates to expected dust impact rates using dynamical meteoroid models for the four most abundant meteoroid/dust populations in the inner solar system and found that the dust impact rates predicted by dynamical meteoroid models are not compatible with the Juno observations. We also investigated the hypothesis of dust leaving the Martian Hill sphere originating either from the surface of Mars itself or from one of its moons, and again found inconsistency with the Juno observations. We concluded that the star tracker observations are unlikely to be the result of instantaneous impacts from the Zodiacal Cloud. (P. Pokorny, J.R. Szalay, M. Horanyi, and M.J. Kuchner, The Planetary Sci. J, in press, 2021).

1.4 Exploration: Dust Hazard Mitigation

Lunar dust has been a concern for human exploration since the Apollo era. Dust can be stirred up by robotic and/or human activities and released by natural processes such as micrometeoroid impacts and electrostatic lofting. As learned from the Apollo missions, lunar dust can readily stick to all surfaces, causing damage to spacesuits, degradation of thermal radiators and optical components, and failures of mechanisms. Also, lunar dust in human living quarters could lead to health risks from inhalation. An overview of the dust environment of the Moon was provided in M. Horanyi, E.A. Bernardoni, A.M. Carroll, N.F. Hood, H-W. Hsu, S. Kempf, P. Pokorny, Z. Sternovsky, J.R. Szalay, and X. Wang, in: The Impact of Lunar Dust on Human Exploration, editor: J.S. Levine, Cambridge Schol. Pub., ISBN:1-5275-6308-1, 2021. In the lab, we continued our work on electron-beam-based dust mitigation technology (B. Farr, X. Wang, J. Goree, I. Hahn, U. Israelsson, M. Horanyi, Acta Astronautica 188, https://doi.org/10.1016/j.actaastro.2021.07.040, 2021). We also carried out a series of experiments to demonstrate a simple technique for restoring light transmission of dusty glass surfaces in space (A. Doner, M. Horanyi, J. Faller, J. Fontanese, T. Munsat, Advances in Space Res., https://doi.org/10.1016/j.asr.2021.07.020, 2021).

1.5 Exploration: In Situ Resource Utilization (ISRU)

1.5.1. Temperature Modeling of the Permanently Shadowed Regions (PSRs) of the lunar poles

Models of temperature vs. depth were developed for cold traps in PSRs at the lunar poles where ISRU equipment will operate to prospect, collect, and extract volatile resources. 2-D models (e.g. Fig. 6) were created for a wide range of

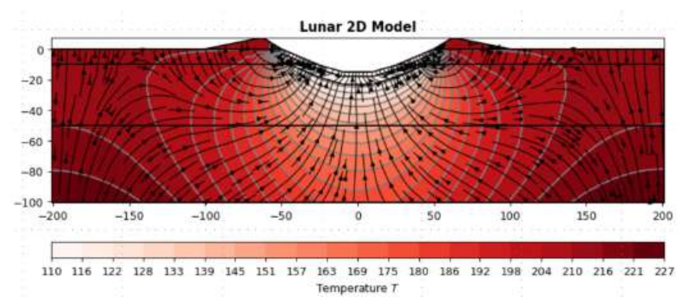


Figure 6. The calculated temperatures with depth and heat flow streamlines are based on the input PSR thermophysical model. X and Y axis units are meters.

crater sizes, incorporating actual topographic surface profiles of medium to large PSRs near the lunar south pole. In addition, some models included zones of icy regolith in PSRs. Ice has a higher thermal conductivity than dry regolith, and icy regolith is expected to have intermediate thermal conductivity proportional to the percentage of ice content.

1.5.2. Terramechanics Modeling of Soil and ISRU Instrument Interactions at the Lunar Poles

We applied the IEP to two physical configurations of possible ISRU instruments, a blade and a wheel interacting with regolith simulant. This work resulted in a collaboration with Outward Technologies (OT), which led to an additional NASA SBIR project. Experimental results obtained with the IEP were used by OT to calibrate a Discrete Element Method model. Tests were conducted in air and in vacuum, with lunar simulants GRC-3, GRC-3 with synthetic agglutinates, and cenospheres (paper in preparation).

1.5.3. SAMPLR Lunar Mission Payload

In collaboration with Maxar, CSM is using the IEP to design a penetrometer equipped with a force-torque sensor at the end of a robotic arm to collect data on surface penetration and relaxation forces. This will provide estimates of bulk relative density, cohesive behavior, and surface strength of the lunar regolith. The CSM-Maxar collaboration led to a project supported by the NASA LSITP program. A Masten Space Systems lander will deploy and operate the robotic arm and penetrometer on the lunar South Pole (near Haworth crater) in 2024, as part of the NASA Commercial Lunar Payload Services (CLPS) program (M. A. Seibert, et al., 51st Lunar and Planetary Science Conference, paper 2564, 2020).

2. Inter-team/International Collaborations

2.1. Inter-Team Collaborations

Lunar Environment and Dynamics for Exploration Research (LEADER, PI: R. Killen): longstanding successful collaboration on vapor and plasma release due to micro-meteoroid impacts and plasma modeling. Collaboration on the new lunar reference book New Views of the Moon, chapter on The Dust, Atmosphere, and Plasma at the Moon by Farrell, et al.

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS, PI: T. Orlando): common projects include dust charging, tribo and impact-induced prebiotic chemistry, as well as a jointly mentored NPP Fellow (M.J. Schaible).

Interdisciplinary Consortium for Evaluating Volatile Origins (ICE FIVE-O, PI: J. Gillis-Davis): Joint proposal to investigate origins of nanophase Fe in regolith grains in the laboratory.
Toolbox for Research and Exploration (TREX, PI: A. Hendrix): ongoing collaborations on laboratory efforts, IMPACT provides space and technical assistance for the TREX UV spectroscopy setup.

2.2. International Partnerships

IMPACT has built active ongoing relationships with its international partners from Germany, Canada, Norway, and Japan.

Germany: Long-term close collaborations exist between the Cosmic Dust Research Group at the University of Stuttgart, led by Prof. Ralf Srama. We have an active exchange program for students, postdocs and researchers. The University of Colorado and the University of Stuttgart have an active Memorandum of Understanding to set the framework for collaborations in lunar and space research.
We have a close collaboration with Prof. Bernd Abel at the Wilhelm-Ostwald-Institute for Physical and Theoretical Chemistry and Institute of Chemical Technology of the University Leipzig. This collaboration is focused on the development of a novel ice-particle accelerator to be housed at IMPACT.

Theoretical and experimental work on regolith characterization is continuing in collaboration with the dust group at the Technical University, Braunschweig, led by Prof. Jurgen Blum. Impact experiments involving mass spectroscopy are part of an ongoing collaboration with the group at the Free University of Berlin led by Prof. F. Postberg. Prof. Postberg is spending a sabbatical year at IMPACT (8/2021-7/2022), working closely with IMPACT projects on the analysis and interpretation of time-of-flight mass spectra from icy surfaces, developing new approaches to the assessment of the ISRU potential of the lunar permanently-shadowed polar regions using IMPACT developed dust instruments onboard polar orbiting spacecraft.

Canada: We have common projects with the group at the University of Alberta, led by Prof. R. Marchand on modeling plasma surface interactions.

Norway: Ongoing collaborations with the group at the University of Oslo led by Prof. W. Miloch address new instrument ideas. We have received funding from the Partnership Program with North America, Norway, that pays all travel and living expenses of IMPACT students visiting Oslo, and the Norwegian students visiting us.

Japan: We have been collaborating with the group at the Kobe University led by Prof. Y. Miyake on modeling of plasma - surface interactions to enable a better analysis and interpretation of existing observations and laboratory experiments at IMPACT, and the design of future landed surface experiments to explore the charging, mobilization, and transport of lunar dust.

3. Public Engagement Report

IMPACT remained the leading group to organize the 12th annual Lunar and Small Bodies Graduate Forum (http://impact.colorado.edu/lungradcon/). It was held virtually on July 15th and 16th, 2021, with a pre-conference social event the evening of July 14th, preceding the 2021 NASA Exploration Science Forum and European Lunar Symposium, which were also held virtually. Following the broad interests of SSERVI, the scope of LunGradCon included both lunar and small body science. As in the past, LunGradCon provided an opportunity for grad students and early-career postdocs to present their research on lunar and small body science in a low-stress, friendly environment, being critiqued only by their student and recent graduate peers. In addition to pre-recorded oral presentations, the forum presented opportunities for professional development and networking with fellow grad students and postdocs, as well as senior members of SSERVI.

As in previous meetings of the Space Resources Roundtable (SRR) organized by the Center for Space Resources at Colorado School of Mines, an opportunity was provided again this year for graduate students to present their research results to a forum of international experts in this field. They did so in a dedicated session held on June 10, 2021, for students who are involved in space resources research. In addition, faculty, and students from other SSERVI nodes had the opportunity to present their ISRU related work at the SRR.

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

The CSM Space Robotics Challenge (Colorado School of Mines)

The Center for Space Resources at CSM hosted the Space Robotics Challenge on September 3-5, 2021 (see Figure 7), which was sponsored by the Rocky Mountain Section of AIAA, the Colorado Space Grant Consortium, Northrup Grumman, Ursa Major Technologies, EyasSat, Blue Foot Engineering, and Atomos Space. It is well known that the aerospace industry suffers from a diversity and inclusion problem. Therefore, a diverse group of undergraduate students came together to learn about the potentials of a career in aerospace and explore their role in this industry. The mission of the event was to increase participation and retention of students in underrepresented groups in aerospace, through hands-on experiences, building relationships with like-minded students, and networking with industry professionals. These professionals conducted several panels and Q&A discussion sessions with the students to make them aware of the status of EDIA in aerospace and the need for improvement in this area. It is our intention and hope that starting collaborations across all genders, ethnicities, and races at the undergraduate level, followed later in graduate school, will ultimately result in enhancing diversity in the space sector. The theme of the competition revolved around IMPACT ISRU research, including the interaction of excavation and resource extraction robotic equipment on planetary surfaces.

5. Student/Early Career Participation

Undergraduate Students

1. Thomas Corbett, Univ. Colorado, Accelerator Support
2. Michael Creager, Univ. Colorado, Ion Spectra Analysis
3. Brandon Cyrus, Univ. Colorado, Impact RGA Experiment, UHV Facilities
4. Destry Dewitt, Univ. Colorado, Ion Spectra Analysis
5. Erick Diaz, Univ. Colorado, Dust Coater
6. Luke Eberwein, Univ. Colorado, EDA Dust Dropper Chamber
7. Ben Farr, Univ. Colorado, Dust Mobilization, Plasma Studies
8. Evan Indge, Univ. Colorado, Ion Spectra Analysis
9. Hunor Kovacs, Univ. Colorado, Solar Wind Simulation Experiments
10. Zuni Levin, Univ. Colorado, SimIon Modeling
11. Gwyneth Lowry, Univ. Colorado, Ion Spectra Analysis
12. Elena Opp, Univ. Colorado, Plasma Chamber

Figure 7. The Space Robotics Challenge at Colorado School of Mines was organized to increase EDIA awareness and opportunities among a diverse group of students (September 3-5, 2021).

Development

13. Kelyan Taylor, Univ. Colorado, Plasma Studies

14. Allesandro Verniani, Univ. Colorado, Ion Spectral Analysis

15. Michael Voss, Univ. Colorado, Impact Ionization and Solar Wind Experiments

Graduate Students

16. Ethan Ayari, Univ. Colorado, Ion Spectra Modeling

17. *Edwin Bernardoni, Univ. Colorado, Dust Measurements at Solar System Bodies

18. David Chaparro, Univ. Colorado, Cryogenic Dust Impact Experiments

19. Hunter Danque, CO Sch. of Mines, Lunar Cold Trap Modeling

20. Alex Doner, Univ. Colorado, SDC, IDEX target, moon PVDF

21. Allesandro Garzelli, Univ. Colorado, Impact Ejecta Experiments

22. Bill Goode, Univ. Colorado, SUDA Flyby Analysis/ Planning

23. Rebecca Mikula, Univ. Colorado, Ion Spectra Analysis

24. David Purcell, CO Sch. of Mines, ISRU experiments

25. Ben Thrift, CO Sch. of Mines, ISRU experiments

26. *Zach Ulibarri, Univ. Colorado, Cryogenic Dust Impact Experiments

27. *LiHsia Yeo, Univ. Colorado, Electrostatic Dust Mobilization Experiments

* Ph.D. completed

New Faculty Members

28. Prof. Jordy Bouwman, University of Colorado, Dept. of Chemistry, Specialty.

29. Prof. Kevin Cannon, Colorado School of Mines, Planetary Geology/Space Resources

6. Mission Involvement

1. **NASA New Horizons**, Student Dust Counter, PI: M. Horanyi, IMPACT dust accelerator experiments are being used to extend the calibration data base of this instrument for oblique dust impacts (M. Piquette et al., Calibration of Polyvinylidene Fluoride based dust detectors in response to varying grain density and incidence angle, Rev. Scientific Instruments 91, 023307, 2020, https://doi.org/10.1063/1.5125448).

2. **NASA PICASSO** program supports the technology development of the Double Hemispherical Probe (DHP) instrument, PI: X. Wang. The initial laboratory demonstration of the DHP was supported by SSERVI. DHP is designed to improve space-based plasma density and temperature measurements, especially in flowing plasmas, regions with UV illumination, and to minimize the effects of spacecraft charging on the analysis and interpretation of the data (J. Samaniego et al., JGR-Space 125, article id. e28508, 2020, 10.1029/2020JA028508)

3. **NASA DALI** program supports the development of the Electrostatic Lunar Dust Analyzer (ELDA) instrument, PI: X. Wang. ELDA was initially designed based on SSERVI supported laboratory experiments. An updated version (EDA) is part of a PRISM 2021 payload proposal. EDA would measure the properties (mass, charge, speed) of electrostatically mobilized and transported dust on the lunar surface.

4. **Europa Clipper, Surface Dust Analyzer (SUDA)**, PI: Sascha Kempf. This impact plasma ionization time-of-flight dust instrument has been initiated by SSERVI funded accelerator experiments. SUDA will provide a compositional surface map of Jupiter's moon Europa, by analyzing the makeup of ejecta particles generated from its surface by the continual impacts of interplanetary micrometeoroids.

5. **NASA Interstellar Mapping and acceleration Probe (IMAP)**, Interstellar Dust Experiment (IDEX), PI: M. Horanyi. IDEX will measure the composition of interplanetary and interstellar dust. Similar to SUDA, this instrument development was enabled by SSERVI supported initial experiments at our dust accelerator facility.

IMPACT's initial motivation for developing impact plasma ionization time-of-flight composition analyzers was to extend the capabilities of the Lunar Dust Experiment (LDEX) flown on NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission in 2013-2014. LDEX itself was originally developed by SSERVI's predecessor, the NASA Lunar Science Institute (NLSI). LDEX discovered a permanently present dust exosphere engulfing the Moon, sustained through the continual bombardment by interplanetary dust particles. Incoming particles also generate ejecta from permanently shadowed regions, and a SUDA/IDEX type instrument could be used to explore the makeup of their volatile content from a polar orbiting spacecraft and assess the accessibility of their volatile content for future ISRU needs.

Lunar Environment And Dynamics for Exploration Research (LEADER)

Rosemary Killen
NASA Goddard Space Flight Center, Greenbelt, MD

CAN-3 TEAM

1. LEADER Team Report

1.1 LEADER Exosphere Theme

The LEADER Exosphere Theme team's work spans a range of computational, experimental, and data analysis work that aims to illuminate interactions between exospheric volatiles and the lunar surface and space environment and identify implications for science and exploration.

> Building on prior work, LEADER team members continued efforts to model the alteration of the exosphere during and after the descent and landing of mid-sized lunar landers, such as those applicable to the CLPS program, and to determine the long-term alteration of the environment.

Co-Is William Farrell, Parvathy Prem, O. J. Tucker, and Dana Hurley, led a study of the evolution of a local exosphere from exhaust water vapor deposited in the vicinity of the landing site. LEADER Co-Is William Farrell, Jason McLain and O. J. Tucker continue to advance scientific understanding of how solar wind and micrometeoroid interactions with the lunar surface contribute to the lunar volatile cycle – developing important, testable predictions for future observational studies.

> Co-I McLain published a laboratory study demonstrating that lunar regolith could convert incident 2 keV H2+ beam ions into surface hydroxyl, with results showing increasing levels of OH production with increasing ion beam flux levels (McLain et al., JGR: Planets, 2021) (Figure 1).

Co-I Tucker's efforts this year included investigating the relative roles of solar wind implantation and impact vaporization in generating lunar H2 and H2O exospheres (Figure 2), through numerical modeling incorporating results from flash heating desorption experiments carried out by Co-I McLain (Tucker et al., LPSC, 2021). In ongoing work, LEADER intern Khari Fletcher (Howard University) and Co-I Tucker are analyzing H2 data measured by LADEE-NMS to further understand the response of the H2 exosphere to magnetospheric shielding of solar wind plasma (Fletcher et al., NESF-ELS and DPS, 2021).

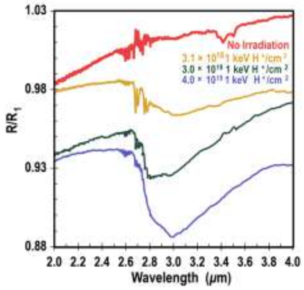


Figure 1. DRIFTS (Diffuse Reflectance Infrared Fourier Transform Spectroscopy) spectra of 78421 before and after proton irradiation. The spectra from top to bottom correspond to the unirradiated 78421 (back of sample) and after fluences of 0.31 ± 0.07, 3.0 ± 0.7, and 4.0 ± 1.0 × 1019 1 keV H+/cm2. The sample irradiated to a fluence of 3.0 ± 0.7 × 1019 1 keV H+/cm2 was from a follow-up experiment with an unused portion of the 78421 sample. The spectra have been vertically offset for clarity.

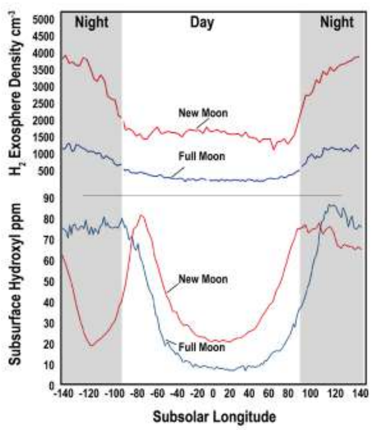


Figure 2. Modeled diurnal equatorial OH surface concentration (bottom) and H2 exosphere density (top) due to solar wind implantation during new Moon (red) while exposed to the unperturbed solar wind, and during full Moon (blue) while shielded in the Earth's magnetotail (Tucker et al. 2021).

Co-I Menelaos Sarantos investigated the competition of adsorption, desorption, and diffusion inside a granular material to understand the timescale of outgassing from a regolith (Figure 3) (Sarantos and Tsavachidis, ApJ Letters, 2021). Using computer-generated spherical packings to simulate regolith microstructure, this research demonstrated that the complex diffusion paths could prolong the lifetime of adsorbed volatiles on the lunar surface.

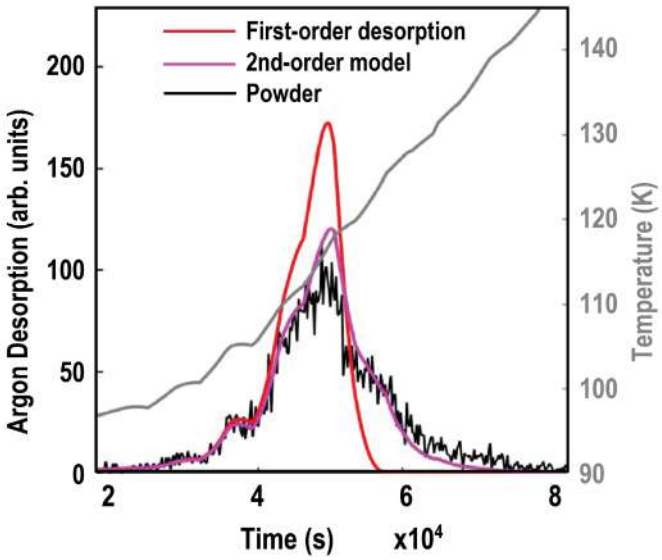


Figure 3. From Sarantos and Tsavachidis (2021), this plot shows the release of adsorbed argon over time as the temperature of a porous medium is increased. Desorption from a powder (black line) does not resemble first-order desorption (red line), as is often considered, because of diffusion into the porous, granular medium. A second-order desorption model provides a better fit. This slower release of gas has implications for long-term volatile retention in the lunar regolith

This work indicates that a broad distribution of desorption activation energies at the lunar surface (or the diffusion phenomena investigated by Co-I Sarantos) could give rise to a lingering local water exosphere, which could be sensed by mass spectrometers onboard the Astrobotic lander slated to visit the Lacus Mortis region in 2022–23 (Farrell et al., Icarus, 2022). Co-Is Farrell, Hurley, Prem, and Tucker are providing science support for these NASA-provided lunar payloads.

LEADER support also enabled several Co-Is to contribute to papers (Lucey et al., Geochemistry, 2021; Schörghofer et al., Space Science Reviews, 2021) reviewing our current understanding of lunar volatiles and looking ahead to the next decade of discovery.

1.2 Plasma Environment

The LEADER plasma team continued its successful campaign to understand lunar plasma-surface-object interactions. The LEADER team focuses on answering the question: "How does plasma interact with the lunar surface, its tenuous atmosphere, and exploration systems for past, present, and future conditions?" To answer this question, the LEADER plasma team investigated the environments of the Earth's Moon and other moons in our solar system, addressing topics ranging from large scale plasma interactions to small-scale surface interactions and the interconnections between these disparate scales.

> At the largest scales, LEADER addressed the interaction of the Moon with the terrestrial magnetosphere.

Unlike in the solar wind, the plasma derived from the lunar exosphere has comparable density to that of the ambient plasma in the magnetotail. As a result, the presence of the Moon and its exosphere appreciably perturbs the terrestrial magnetotail environment, leading to the formation of a draped magnetic field structure, accelerating lunar ions via magnetic forces, and creating unique electron cyclotron harmonic waves. Xin Cao, Melanie Peters, and Michael Kistler addressed this unique interaction and how it is controlled by the upstream solar wind and magnetospheric activity indices [Kistler et al., 2021]. In related work, William Farrell and Anthony Rasca investigated the disturbed lunar environment in the geomagnetic tail during a CME passage [Rasca et al., 2021a].

> At medium scales, LEADER studied lunar plasma interactions in the wake and near magnetic anomalies.

William Farrell continued studies of the wake and its formation region immediately downstream of the terminator/polar region. This work led to the publication of a cubesat mission concept called Terminator Double Layer Explorer (TerDLE) that would examine the wake formation region near the terminator [Farrell et al., 2021]. Meanwhile, Feng Chu led a study of the electron heating in lunar magnetic anomaly regions, showing that it is correlated with the occurrence of small-scale electrostatic structures, which are

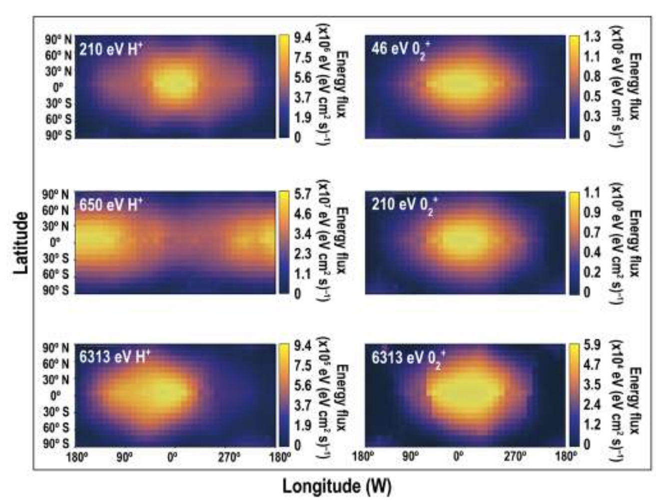


Figure 4. The long-term averaged flux of solar wind and Martian ions that impact the surface of Phobos, as observed by MAVEN. a–f, Long-term averaged precipitating flux of protons and Martian O2 (Nenon et al. 2021). Positive ions at each location on the surface of Phobos: 210 eV H+ (a); 650 eV H+ (b); 6,313 eV H+ (c); 46 eV O2+ (d); 210 eV O2+ (e); 6,313 eV O2+ (f). The west longitude of 0 faces Mars; 180 is anti-Mars.

likely produced by two-stream instabilities and the electron cyclotron drift instability [Chu et al., 2021]. In related work, Andrew Poppe was a co-author on a modeling study of lunar magnetic anomaly interactions [Deca et al., 2021].

LEADER continues to investigate the influence of the plasma on the tenuous lunar exosphere and its formation and loss, with close ties between the plasma and exosphere teams. Ionization of exospheric constituents leads to the formation of a plume of pickup ions in the solar wind. Given the statistically significant 10-year database from the THEMIS-ARTEMIS mission, we can now investigate how the flux of pickup ions depends on lunar phase, solar wind and solar inputs. Lexi Leali and Jasper Halekas developed methods for identifying candidate pickup ion events, excluding signatures from reflected protons, and isolating the pickup ion fluxes for statistical analysis.

At the smallest scales, LEADER studies the plasma interaction with the regolith, which is intimately tied to both space weathering, and the formation of the exosphere.

Dr. Quentin Nénon used MAVEN measurements of martian ionospheric plasma and the TRIM.SP Monte Carlo model to quantify the rate and depth of implantation of martian ionospheric material into the regolith of Phobos [Nénon et al., 2021]. This work (Figure 4) predicted that Phobos' regolith may hold an invaluable record of the ancient martian atmospheric composition, which will be tested via the return of Phobos surface samples by the JAXA Mars Moon Exploration (MMX). Dr. Nénon also investigated the flux of solar wind and terrestrial magnetospheric ion populations to lunar polar craters, showing that permanently shadowed regions at the lunar poles are subject to a non-negligible ion flux originating from both the shocked (and heated) solar wind in the terrestrial magnetosheath and plasma found in the terrestrial magnetotail, with implications for the budget of implanted volatile material in the lunar poles [Nénon and Poppe, 2021]. Finally, Andrew Poppe showed that micrometeorite impacts can affect lunar surface charging in the magnetotail [Poppe et al., 2021].

Tying the magnetospheric plasma interaction, the surface-plasma interaction, and the exosphere themes together, O.J. Tucker led a study of proton implantation during periods when the Moon was in the geomagnetic tail, finding that an extended region of depletion of implanted protons/OH is expected to exist over a large portion of a lunation, as a residual effect from passing through the proton-depleted geomagnetic tail [Tucker et al., 2021]. In related lab work, Jason McLain published a laboratory study showing that lunar regolith could convert incident 2 keV H_2^+ beam ions into surface hydroxyls, with the OH levels increasing with increasing ion beam flux levels [Mclain et al., 2021].

LEADER also continues to provide inputs to exploration activities. William Farrell was involved in the updates of the description of the lunar plasma environment found in the Design Specification for the Natural Environment (DSNE) document, which was used by a team at JSC to examine the expected charge build-up on the xEMU space suit. He also assisted in reviewing the results of this suit charging model procured by the JSC/xEVA team members, ensuring that the correct plasma conditions and triboelectric charging models were employed.

1.3 Dust Theme

Dr. Hartzell's LEADER task focuses on understanding triboelectric charging of regolith. Due to complications in hiring a student to work on this task in Year 1, a postdoctoral researcher (Dr. Yun Zhang) was hired and began work in November 2021. Dr. Zhang is working to computationally model the exchange of charge between regolith grains using LIGGGHTS, an open-source Discrete Element Method simulation that models the interactions of hundreds of thousands of grains. The goal is to replicate the Dr. Hartzell's tribocharging experiment test stand in LIGGGHTS to enable validation of the tribocharging model and LIGGGHTS implementation. It is anticipated that Dr. Zhang will be working on LEADER for at least two years, providing continuity

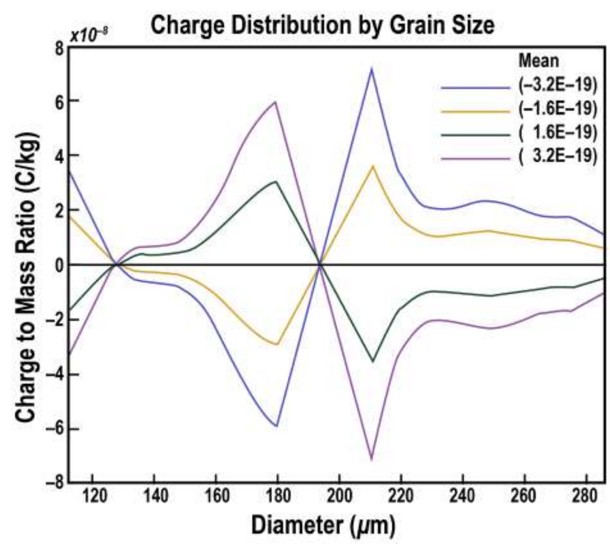


Figure 5. Mean of the charge distribution as a function of grain size for a range of transferred charge magnitudes and polarities (in units C). Tribocharging might be caused by ions or electrons - it's a point of uncertainty in the community in this field. Imagine you have some mixture of grains - they have a size distribution. Now, suppose you looked at all the grains that are 100 microns in size and find the average charge (Q) on those 100micron grains. This plot is showing the average Q/m for grains of a given size. The different lines show the average Q/m when you assume that the charge carrier to has different charges (+1e, +2e, -1e,-2e).

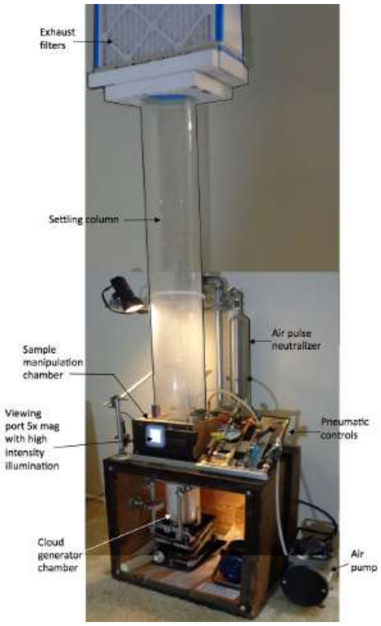


Figure 6. Experimental test stand developed by Dr. Marshall to investigate the role of interparticle forces in aeolian detachment of dust particles.

on this task. Prior to Dr. Zhang's start, another postdoctoral researcher, Dr. Liam Morrissey, completed a short-term contract to investigate the effect of charge carrier magnitude, polarity, and number density on simulations of charge transferred between two species of dielectric grains (Figure 5). Prior investigations have suggested that triboelectric charging may be caused by the transfer of ions or molecules rather than electrons. Figure 5 investigates the sensitivity of our existing charge transfer model to variations in the charge carrier polarity and magnitude. This investigation has been documented in an LPSC abstract.

Dust, although tiny, is purportedly harder to lift by wind than much larger sand grains.

Dr. Marshall has been investigating the relationship between adhesion and aeolian dust mobilization. Interparticle forces are the primary cause of this resistance. However, Mars displays frequent and vigorous dust lifting. We believe that the key to understanding this issue lies with the degree of sediment compaction. Compaction of undisturbed dust deposits is primarily a function of settling conditions. To shed light on this more than 80-year-old enigma, Dr. Marshall has constructed an experimental test stand that controls this critical settling parameter (Fig. 6). It creates a 2-m tall dust cloud of controllable density, which then settles out gently on to sampling plates (as it would do naturally). These plates are then optically inspected at magnification while a tiny horizontal air stream is applied to the surface of the settled material. The strength of the stream is recorded when dust-motion threshold occurs.

1.4 Radiation Theme

The radiation environment of the Moon is dominated by galactic cosmic rays (GCRs) and solar energetic particles (SEPs). LEADER continues to enhance our understanding of the radiation environment of the Moon and its effects. Our colleagues at the Community Coordinated Modeling Center (CCMC) have been working quite actively on forecasting SEPs (solar energetic particles) (https://sep.ccmc.gsfc.nasa.gov/probability/) See their website, A Joint SRAG/CCMC Collaboration to Improve Space Weather Prediction for Crew Protection during Near-Term Lunar Surface and Cis-Lunar Missions (https://ccmc.gsfc.nasa.gov/isep/).

SEPs can alter lunar soil through a process called dielectric breakdown ("sparking"), and both GCRs and SEPs can affect the radiation exposure of astronauts on or near the Moon.

1.4.1 Evidence for Dielectric Breakdown Weathering on the Moon

Building on work from Year 1 of LEADER [i.e., Jordan, 2021], Co-I Andrew Jordan has led work that has found further evidence for SEPs causing dielectric breakdown in cold soil on the Moon [Jordan et al., 2022]. Jordan revisited the work of Sim et al. [2017], who discovered that crater walls show east-west asymmetries in space weathering and that these asymmetries depend on longitude. Sim et al. argued that these asymmetries show that the magnetotail inhibits weathering by the solar wind, but their solar wind model was unable to explain the longitudes of the peak asymmetries. Instead, the longitudinal dependence is better explained by a space weathering that occurs on the nightside and is affected by the magnetotail. Only dielectric breakdown can explain this: the magnetotail can deflect SEPs, and breakdown occurs on the nightside. In addition, Jordan [2022] has shown that breakdown weathering may be important on other airless bodies in the Solar System, particularly the moons orbiting in Jupiter's radiation belts.

As NASA plans to return astronauts to the Moon, a critical question is the future radiation environment.

1.4.2 Predicting the Next Solar Cycle

GCR fluxes reached space-age record highs during solar cycle 24, and it is important to know what the fluxes will be in the new cycle 25. Co-I Fatemeh Rahmanifard has developed an innovative technique to show that the Sun has moved into a new period of persistently low solar activity—a secular solar minimum [Rahmanifard et al., 2022]. This technique leverages the fact that the flux of GCRs at 1 AU samples the state of the full heliosphere over the past cycle, and the resulting hysteresis in GCR flux can be used to predict the strength of the next solar cycle. Rahmanifard et al. [2022]

predict that cycle 25 will be as weak as or weaker than cycle 24, which means that the Sun has moved into a secular minimum and that GCR fluxes will again be high (Fig. 7). This is important for planning crewed missions to the Moon, and Rahmanifard will use this prediction to determine the possible radiation environment during this new solar cycle.

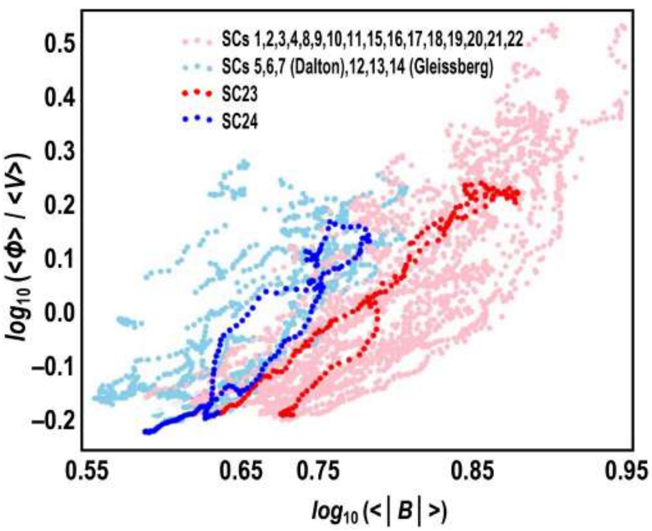


Figure 7. The last 24 solar cycles (year 1755 to present) showing the monthly relation between the heliospheric modulation potential (high Φ means low GCR flux), solar wind speed (V), and heliospheric magnetic field strength (B). At the end of cycle 23 (red), the Sun transitioned from the secular maxima to the secular minima. Cycle 25 will likely also be a weak cycle (black arrow shows cycle 24 leading into 25), thus GCR fluxes at the Moon will be at least as high as those observed during cycle 24. (Adapted from Figure 1, Rahmanifard et al. [2022].)

2. Inter-team/International Collaborations

Andrew Poppe has an on-going collaboration with Jan Deca of the IMPACT team on plasma modeling of the Reiner Gamma anomaly. See e.g.: http://research.ssl.berkeley.edu/~poppe/papers/Deca_et_al_2021.pdf

Dana Hurley is collaborating with David Kring's team, CLSE, and with Jennifer Heldmann's team, RESOURCE.

Jason McLain is collaborating with Thomas Orlando's team REVEALS. Micah Schaible is collaborating with us on the reactivity of dust grain surfaces due to space weathering and dust charging.

3. Public Engagement

- Caela Barry is preparing the new "Moon and Sun" web page for moon.nasa.gov. Andrew Jordan provided useful presentation materials for reference, and Liam Morrissey addressed some science questions.
- Micah Schaible has volunteered to act as a research advisor to high school students through the ExMASS program led by Andy Shaner.
- Menelaos Sarantos spoke to students of the sixth grade of the Charles E Smith Jewish Day School today on the topic "Does the Moon have an Atmosphere?"
- P. Misra - Judge for the Outstanding Student Paper Award (OSPA): reviewed and judged virtual posters and oral talks at the AGU 2021 Fall Meeting, December 13-17, 2021.
- P. Misra – Graduate Research Fellowship Program, Physics II Reviewer & Panelist, National Science Foundation (NSF), December 2021 – January 2022.
- P. Prem -Invited Speaker, Planetary Science and Astrobiology Seminar, Georgia Tech, Sept. 2021.
- P. Prem - Invited Speaker/Panelist, Indigenous & Anticolonial Views of Human Activity in Space Seminar Series, Space Enabled Research Group, MIT Media Lab, August, and October 2021.
- P. Prem - Seminar, Department of Physics, Providence Women's College (Calicut, India), July 2021.
- P. Prem -Invited Speaker, Mini-Moon Seminar Series, Taiwan Space Union and National Central University, Taiwan, December 2020 and February 2021.
- P. Prem - Invited Presentation, Future In-Space Operations Telecon, January 2021.
- P. Prem - LPI Exploration of the Moon and Asteroids by Secondary Students (ExMASS) program. Student presentation judge for 2020-21 program, research advisor for 2021-22 program.
- P. Prem - Skype a Scientist (November 2020; February, March, April, May, and September 2021). Virtual classroom visits with nine classrooms (Grades 5-9) in PA, OR, NYC, TX, MD, IL, and Canada.
- P. Prem - Community Scientist Visits with Howard County Public Schools (Grades 2–4), February 2021.

4. Equity, Diversity, Inclusion and Accessibility (EDIA) Activities

- Reading and Discussion Series, SSERVI EDIA Focus Group, Caela Barry
- NESF Science Organizing Committee Co-Chair Prem, implementation of EDIA recommendations.
- NASA Lunar Surface Science Workshop Session #13: Inclusive Lunar Exploration. P. Prem, Co-Chair.
- Tavares, F., Treviño, N. B., Ravanis, E., Prem, P., and Buckner, D., Ethical exploration, and the role of planetary protection. 34th IAA Symposium on Space Policy, Regulations and Economics, 2021.

5. Student/ Early Career Participation & Retention Within the Field

5.1 Undergraduate Students

1. Melanie Peters (Iowa State University, mentor Halekas), Physics student, has been working on electron cyclotron harmonic waves near the Moon observed in the Earth's magnetotail [Kistler et al., 2021].
2. Khari Fletcher (Howard University, mentor Tucker), Physics, [Fletcher, K.M. et al., Analysis of LADEE measurements of H2 in the lunar exosphere].
3. Giovanni Bacon (Embry-Riddle Aeronautical University, mentor Killen), engineering physics, helped to reduce observations of the lunar exosphere from the Goddard Coronagraph at Sonoita, Arizona [Killen, et al. 2021, Icarus, 355], and has been running the SDTrimSP Code for a sensitivity study of sputter parameters [Bacon et al., SDTrimSP Simulations of Solar Wind Sputtering on Mercury: A Sensitivity Study to Establish a Best-Practice, MExAG, Abstract 9031]. Accepted to the graduate program at Purdue University, Dept. of Earth, Atmospheric and Planetary Sciences.
4. Dennis Herschbach (Vanderbilt University, mentor Killen) was an intern at GSFC as a high-school senior and is now a sophomore at studying physics and computer science at Vanderbilt. He is one of the eight recipients of the 2021 NASA College Scholarship.
5. Irima Ajang (Howard University, mentor Killen) is now a first-year medical student at Howard Univ.
6. Mary Poltrak (US Naval Academy, mentor Killen) graduated from the US Naval Academy in Annapolis and is now fulfilling her obligation as a Naval Officer.
7. Lexi Leali (Iowa State, Mentor Halekas) worked on pickup ions/ plasma in the lunar environment.

5.2 Graduate Students

1. Alexandra Cramer (Boston University, mentor Sarantos), now a fourth-year graduate student at Boston University (Cramer, A. G. et al., 2020, J. Geophys. Research: Space Physics, 125, e2020JA028518)
2. Heidi Halivand (Greg Delory and Andrew Poppe) obtained her PhD and is now at MSFC.
3. Stephanie Howard (graduate student of Jasper Halekas) now a post-doc at Goddard SFC.
4. Anastasia Newheart (Collier) now a graduate student at Rice (Space Physics) planning to graduate with her PhD in May 2022.

5.3 Early Career Scientists Who Obtained Permanent Positions

1. Dr. Liam Morrissey, Post Doctoral Fellow for LEADER at Goddard Space Flight Center, has accepted a tenure track faculty position at The Memorial University of Newfoundland beginning September, 2022.
2. Dr. Quentin Nenon, Post-Doctoral Fellow at SSL, Berkeley, with Dr. Andrew Poppe, took a Civil Service position, CNRS, France, Sept. 2021.
3. Dr. Philip Quinn (formerly at UNH) took a position at JSC's Space Radiation Analysis Group (SRAG))
4. Dr. Dov Rhodes (Post Doctoral Fellow for LEADER at Goddard Space Flight Center) took a position at a nuclear energy research facility.
5. Dr. Wouter deWet, formerly Research Scientist at UNH, accepted a permanent position at Oak Ridge National Laboratory.

5.4 Early Career Scientists Currently on LEADER

1. Anthony Rasca GSFC, plasma
2. Micah Schaible, Georgia Tech, sputtering/ laboratory work
3. Paul Szabo, Berkeley SSL, sputter calculations/ SDTrimSP
4. Phillip Phipps, GSFC, radiation/ lunar poles
5. Jason McLain, GSFC, laboratory measurements of sputtering and surface damage
6. Fatemeh Rahmanifard, UNH, Galactic Cosmic Rays, exposure rates
7. Ramin Lolachi, GSFC, Simulations of light scattering from dust.
8. Prabal Saxena, GSFC, early Moon evolution, surface exposure
9. Yun Zhang, UMD, dust/ laboratory studies
10. Colin Joyce, UNH, energetic particles in the heliosphere
11. Liam Morrissey, GSFC, sputter calculations, molecular dynamics and SDTrimSP

6. Mission Involvement and Concepts

- LEXI, Collier, M., PI, The Lunar Environment heliospheric X-ray Imager is a wide field-of-view soft X-ray telescope to image the Earth's magnetopause from the lunar surface. LEXI will be one of ten Commercial Lunar Surface Payloads (CLPS) hosted by the Firefly Aerospace Blue Ghost Mission 1.
- ROLSES, Farrell of CLPS ROLSES radio team (PI:

MacDowall). Instrument delivered to Intuitive Machines (IM) and am working on ConOps. ROLSES proposal was justified based on Farrell et al 2013 paper on the photoelectron sheath. Launch is scheduled for March 2022.

- PITMUS, Farrell, Prem, Tucker, of CLPS mass spectrometer teams (PITMUS (PI: Cohen)
- SEAL, Farrell, Prem, (PI: Benna)). Instruments delivered to Astrobotics (AB) in the last month. SEAL and PITMS teams (selected NASA-provided lunar payloads due to fly in 2022).

  Note that LEADER models on the exosphere were used in the original proposal win.

  -Farrell of CLPS MAG team (PI: Purucker). Instrument delivered to AB.

  -Farrell of a CLPS PRISM-2 proposal team.

- PRISM (Gruithusien Gamma and South Pole), Prem provided expertise on redistribution of exhaust volatiles.
- LRO ESM-5, Prem provided expertise to potentially observe exhaust water vapor released during future lunar landings.

The 'Lingering exosphere' prediction paper cited above is in support of PITMUS and SEAL, but is paid for by LEADER.

Leveraged NASA Grant Award:

Raman Cube Rover (R3R) for Enabling Lunar Science and Exploration: Integrating Technology Development with STEM

None of these teams are paying for science support since they are still in the build phase, so our involvement in ops discussions, instrument papers, etc. is actually being charged primarily to LEADER.

Engagement, NASA Award#: 80NSSC21M0301, PI: P. Misra (Howard University), Co-PIs: Shahid Aslam (GSFC), Blanche Meeson (GSFC), and Dina Bower (University of Maryland/GSFC), NASA MUREP Space Technology Artemis Research (M-STAR) Program, 9/1/2021-8/31/2023.

Proof-of-concept design and implementation of an efficient optical telescope and relay system for a Raman Cube Rover-coupled-lander system is currently being pursued.

7. Awards

Susan Mahan Niebur Early Career Award, July 2021, Parvathy Prem.

NASA Special Act Award, William Farrell, for participation on the Decadal committee.

Robert H Goddard Award, 2021, O. J. Tucker for science.

Robert H Goddard Award, 2021, Menelaos Sarantos for leadership.

Robert H Goddard Award, 2021, Michael Collier for supervisory excellence.

Network for Exploration and Space Science (NESS)

Jack Burns

University of Colorado, Boulder, CO

CAN-2 TEAM

1. NESS Team Report

1.1. Primordial Hydrogen Cosmology

One of the principal goals of our collaboration is to study how low-frequency radio telescopes in the lunar environment will reveal the earliest phases of the Universe's history to learn about exotic physics (such as dark matter and primordial black holes) and the formation of the first stars, black holes, and galaxies. The best method to do this is with the "spin-flip" transition of neutral hydrogen, which pervades the early Universe and is sensitive to its properties on large scales. The lunar environment is an ideal platform for these efforts, because it is free of terrestrial (human and ionospheric) interference.

One of the challenges of such modeling efforts is ensuring that theoretical predictions are not based too strongly on our expectations, given the many uncertainties in this early era. Mirocha et al. (2022) have developed a phenomenological approach to modeling the spin-flip background that bypasses many of the assumptions of galaxy-based prescriptions. In this paper, the framework was applied to the reionization era, but it will also be applied to the era of the first stars and black holes that will be studied with lunar radio telescopes. Additionally, in Trapp & Furlanetto (2022) it was demonstrated that next generation galaxy surveys can measure the large-scale environments of survey fields, which will improve cross-correlations with the spin-flip background and enable new physical probes.

1.1.1. Theoretical Predictions of the 21-cm Signal

We describe our progress in designing such telescopes below, but central to the effort is improving our understanding of how the spin-flip signal can be harnessed optimally in order to learn about these processes, which requires theoretical modeling of the expected signals. Co-I Furlanetto worked to improve predictions of galaxy populations during this era, which are essential to predicting the spin-flip background. In Furlanetto & Mirocha (2021), bursty star formation in small galaxies was explored along with the effects of the buildup of stellar mass during the Cosmic Dawn. It was demonstrated that such bursts can have substantial effects on the earliest phases of galaxy formation, which will be a prime discovery area for lunar radio telescopes. Furlanetto is continuing to improve these models with two UCLA undergraduate students. Anna Tsai is exploring how globular cluster formation during this bursty phase may affect galaxy formation, while Natsuko Yamaguchi is studying how chemical enrichment with heavy elements occurs in this era (which has strong implications for the transition from exotic "first stars" to normal galaxy formation).

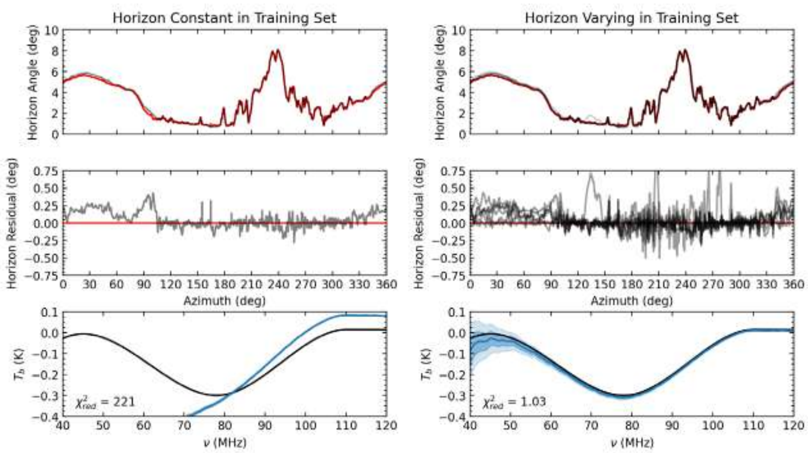


Fig. 1 - Top: Horizon profiles from the Schrodinger Basin on the lunar surface used for the simulated data realization (red) and the foreground training set curves (grey). Middle: Residuals between the horizon profiles used to create the foreground training set (grey) and the fiducial horizon used to create the data realization (red). Bottom: Simulated extracted 21-cm signal compared to the input (black). When our training set formalism is not used for modeling the horizon, the signal extraction is poor (left). When a horizon training set is fully incorporated in the analysis, the signal extraction is precise and unbiased (right).

1.1.2. Experimental Progress

Experimental teams seeking to detect the 21-cm signal have gained considerable experience with pathfinder instruments over the last decade. It has become apparent that instrumental and calibration effects need to be included directly in science data analysis. This can be done by modeling the instrumental and calibration effects, and simultaneously fitting models to the observations that include both astrophysical components and calibration components. Bayesian analysis provides a robust framework for implementing this integrated strategy. Collaborator Steven Murray, working with Co-I Bowman, has been implementing a fundamental overhaul of the analysis of EDGES global 21-cm observations, developing an open-source calibration and analysis software pipeline that is focused on enabling Bayesian inference. Bayesian forward modeling allows for the rigorous propagation of instrumental uncertainties through the entire analysis chain, and facilitates comparison of models and datasets in a statistically rigorous way. This is of increasing importance as multiple experiments are now yielding results that must be evaluated in tandem. This work has motivated new laboratory tests to better identify errors and uncertainties in calibration measurements for EDGES.

1.1.3. Data Analysis Pipeline for Global 21-cm Signal Experiments

The fourth and final paper (Tauscher et al. 2021) in the series describing the framework of the NESS 21-cm global signal data analysis pipeline was published in the Astrophysical Journal. Paper IV describes how instrumental effects introduced by electronic receivers can be rigorously accounted for using a technique termed analytical marginalization of linear parameters (AMLP). This paper and the corresponding additions to the pipeline software are crucial for extracting the global 21-cm signal from data produced by real instruments.

In another paper (Bassett et al. 2021), the effect of the shape of the landscape horizon on low frequency global signal observations was examined. Published in the Astrophysical Journal, the paper shows how incorrect assumptions on the shape of the (Earth or lunar) horizon can produce significant biases in the extracted signal, particularly when analyzing multiple correlated spectra, which we have shown previously to produce the most precise constraints on the global signal (Tauscher et al. 2021a). Fig. 1 shows the importance of fully modeling the horizon using our training set framework for simulated observations from the Schrodinger Basin on the lunar farside. In conjunction with the paper, an open source Python package, SHAPES, which is able to calculate the apparent horizon for any location on the lunar surface using LRO LOLA elevation data, was publicly released.

Fig. 2 - Test setup for measuring the dielectric constant and loss tangent of the ceramic material used in the patch antenna. Inset shows a sample of the material mounted on the fixture.

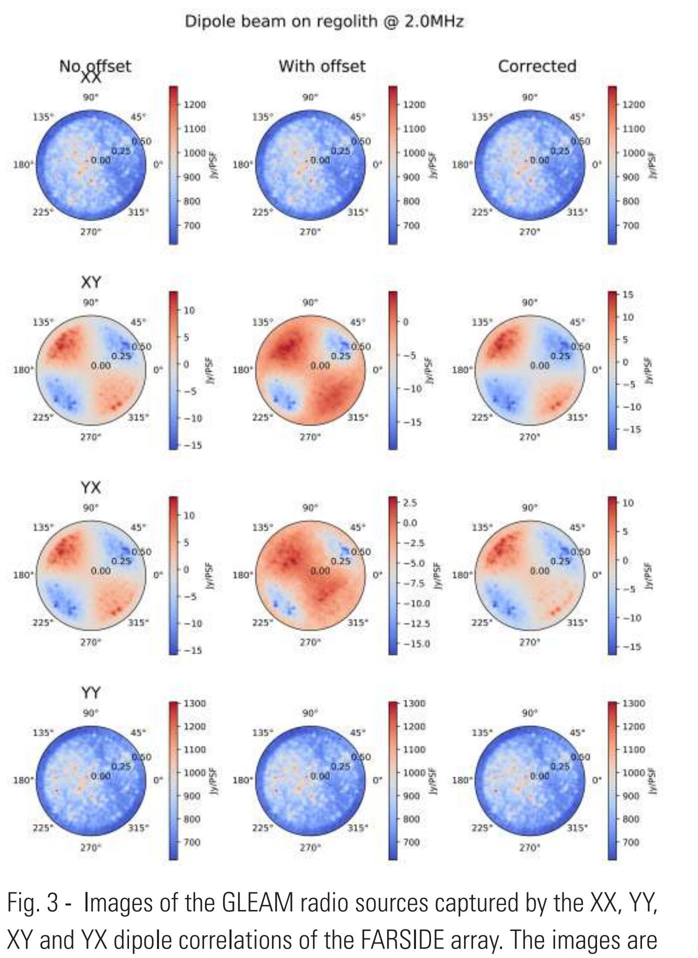


Fig. 3 - Images of the GLEAM radio sources captured by the XX, YY, XY and YX dipole correlations of the FARSIDE array. The images are produced by the custom interferometric simulation pipeline. Three cases are shown: (left) no offset between the orthogonal dipoles in the array, (middle) 50m offset between the dipoles and (right) correction applied to the images of the offset case. The offset case changes the image produced by the XY and YX correlation and the correction applied restores the image to the original case.

1.1.4. Instrument Development

1.1.4.1. Antenna and Advanced Receiver Development

Work over the past year, led by Co-I Bradley and his team, has focused on four areas of instrument development: patch antenna, receiver front-end with calibration, pilot tone circuitry, and various antenna simulations. The patch antenna consists of a stacked structure containing a dielectric material having a relative dielectric constant of 4.5. A solid polymer with this value would be too massive, so a composite approach was adopted. Three 1:15 scale versions were fabricated and evaluated, the last containing 130 small pieces of high dielectric constant ceramic material embedded into a foam substrate. The mass of the full-size antenna would be reduced to about 10 kg. A report on the ceramic evaluation was written. A receiver front-end board consisting of three amplifiers, one filter stage, and FET switches was also developed and evaluated together with a calibration board containing thermal noise sources. A prototype pilot tone injection system consisting of a direct digital synthesizer, power detector, and controller was developed and the circuit board layout completed. Electromagnetic study for the high-band composite dielectric patch antenna design as well as the low-band stacer antenna with the lunar lander were performed using commercial 3D electromagnetic simulation software, CST Microwave Studio. The error budget for the science result was estimated by constraining the variations on the antenna radiation pattern due to lunar environmental effects, such as, relative errors in the simulated antenna radiation patterns at different combinations of lunar regolith properties (in terms of dielectric permittivity and loss tangent values).

1.1.4.2. FARSIDE Concept Instrumentation

Mahesh, Bowman et al. 2022 (in prep.) performed a detailed study of the expected polarization imaging performance of the FARSIDE array on the lunar surface. A custom interferometric simulation pipeline was developed that incorporates the beam patterns of the dipoles on the regolith and the uv-coverage of the array (projected baselines on the sky). The pipeline was used to estimate and quantify the effect on the polarization performance of FARSIDE's novel dipole arrangement, which has non-collocated phase centers of the orthogonal dipoles. For this study, a mock sky created using the GLEAM catalog of low-frequency radio sources was used. A correction to be applied on the image products was formulated to adjust the results for offset errors.

In Hegedus, Burns, Hallinan et al. 2022 (in prep) a simulated FARSIDE array was laid out and used to observe the redshifted 21-cm signal from the frequency range 10-80 MHz. The output of a 300 Mpc 21cmFAST run was used as ground truth and translated to a small field of view imaging simulation. Astropy was used to estimate the angular sizes of 300 Mpc structures at a given redshift. Two versions of the ground truth were made: a version using a vanilla 21cmFAST cosmological model to generate the 21-cm signal, and a toy exotic physics version where a 0.1 k/Mpc wave was injected into the data to simulate the presence of fractionally ionized dark matter in the early universe. A custom CASA pipeline was used to simulate the visibility response of the 256 element FARSIDE array, then the widefield imaging software WSCLEAN was used to image and deconvolve the data in total intensity (Stokes I). The recovered FARSIDE images were then analyzed as a function of spatial spectral power, revealing that FARSIDE can successfully discern between the two models. An example of this analysis for simulated FARSIDE observations at 40 MHz is shown in Figure 4. This will lead into future work where simulated recovered FARSIDE observations will be put through the NESS 21-cm pipeline. The pylinex code will allow us to recover the exact set of cosmological parameters behind the recovered 21-cm signal, which will be separated from a realistic galactic background.

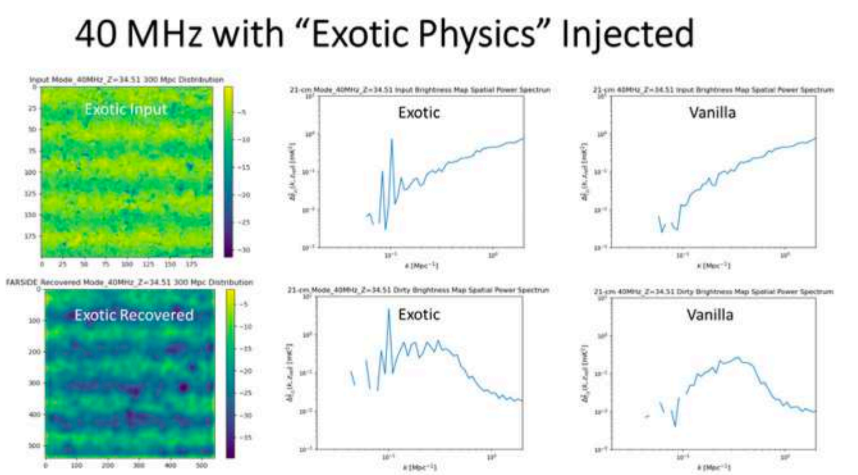


Fig. 4 - Top left: Exotic ground truth of the redshifted 21-cm signal at 40 MHz made from an altered 21cmFAST run. Top middle: Spatial power spectrum of top left, spike at 0.1 k/MPc showcasing the added "exotic physics" from fractionally ionized dark matter. Top right: Spatial power spectrum of vanilla output of 21cmFAST with no exotic physics injected. Bottom left: FARSIDE recovered image of exotic physics scenario. Bottom middle: Spatial power spectrum of bottom left, with visible spike still at 0.1 k/MPc. Bottom right: Spatial power spectrum of recovered FARSIDE image of the vanilla physics scenario, lacking the 0.1 k/MPc spike.

1.1.4.3. Development of CLPS Missions: ROLSES and LuSEE Instrumentation

In anticipation of upcoming NASA-funded CLPS missions, Radio wave Observations at the Lunar Surface of the photoElectron Sheath (ROLSES, scheduled to land in mid-2022) and Lunar Surface Electromagnetics Experiment (LuSEE, scheduled for the farside in 2025), NESS team members conducted detailed modeling of the effects on the antenna beam from the electromagnetic properties of the lunar subsurface. Numerical modeling of antenna beams was conducted with CST Microwave Studio (see above). Electrical properties of the lunar subsurface were varied within reasonable bounds such that the beams could be compared over a range of parameter space. The beam simulations were then fed through the analysis pipeline described in Sec. 1.1.3 in order to study how the lunar soil properties might influence recovery of the 21-cm global signal from lunar observations. One key finding of this analysis was that the relative permittivity of the soil was far more influential than the dielectric loss in terms of its influence on the antenna beam. Ongoing work in this area incorporates more complicated soil models including inhomogeneous subsurface structure.

Burns, MacDowall, Bale, Hallinan, Bassett, Hegedus published a paper in a special lunar-oriented issue of the Planetary Science Journal on “Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions” which described the ROLSES and LuSEE radio astronomy instruments along with FARSIDE.

1.2. Lunar Exploration and Surface Telerobotics

NESS contributions to lunar exploration efforts involve research on teleoperation of rovers on the lunar surface for deployment and construction of low frequency radio telescope arrays. The NESS team continued to research new methods to support low-latency, interactive telerobotics for future lunar missions. To examine the capabilities that augmented, virtual and mixed-reality interfaces offer for improving telerobotic performance, the team studied the effectiveness of providing both 1st person (egocentric) virtual control rooms and 3rd person (exocentric) cyber-physical configurations. To examine the benefits of high-fidelity simulation for robotic operations, the team implemented a “virtual recovery sandbox,” which is a recreated, manipulable virtual space representation of a robot’s state and its operational environment.

To study the capabilities that virtual and mixed reality (VAM) technologies can provide for lunar surface robotics, NESS team members are exploring multi-perspective augmented virtuality head-mounted display (HMD) interface designs. This research is led by graduate student Michael Walker, supervised by Professors Dan Szafir and Jack Burns. To mitigate the nauseating effects of directly streaming stereo video feeds to HMD Interfaces, two augmented virtuality HMD Teleoperation Interface paradigms have arisen from state-of-the-art research in the VAM Human-Robot Interaction field: Virtual Control Room (robot egocentric) and Cyber-Physical Interfaces (robot exocentric). In both interface styles, the user’s point-of-view is decoupled from the robot’s point-of-view to remove the proprioception system conflicting cues. By placing the user in an augmented virtuality environment, the user’s eyes are represented by virtual cameras in the virtual space that move freely with the user’s head and body movements. This decoupling method helps mitigate nausea caused by communications/hardware delays and/or imperfect mappings between user head motion and robot head motion. In this research, we looked to combine both the egocentric (1st person) and exocentric (3rd person) designs to examine the overall effectiveness and optimal use cases for our hybrid design paradigm. The hypothesis is that our combined style of interface will offer significant operational advantages for remote navigation and manipulation teleoperation and supervision tasks if a robot operator can simultaneously use or switch at-will between both egocentric and exocentric perspectives. Additionally, our hybrid Cyber-Physical Virtual Control Room (Figure 5) can facilitate multi-user collaboration for joint robot teleoperation, supervision, and data analysis via real-time virtual avatar streaming.

NASA is planning to create a sustainable presence on the Moon during this decade. This includes the construction of the Lunar Gateway which will allow for low-latency communications on the Moon’s surface. This would be useful in missions like FARSIDE, which will require rovers to deploy a radio array on the farside of the Moon. If an autonomous assembly failure occurs, operators will need to teleoperatively recover from the failure. To aid with the

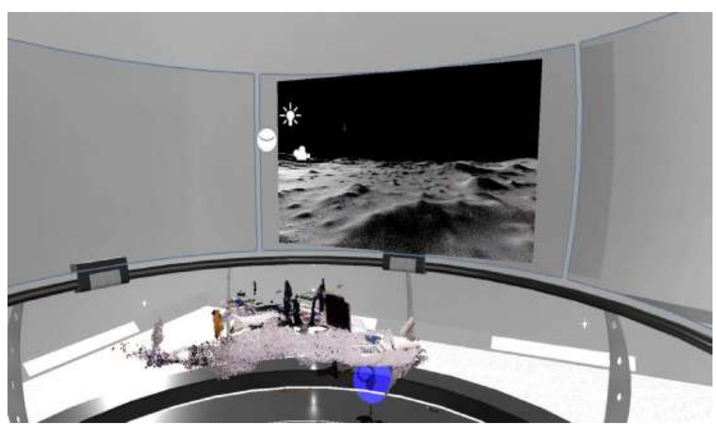


Fig. 5 - The NESS hybrid augmented virtuality interface design unifies concepts from both cyber-physical and virtual control room interfaces by providing mobile space robot operators with egocentric (live 3D video stream) and exocentric (3D dense point cloud environmental constructions) perspectives to enhance telepresence and situational awareness.

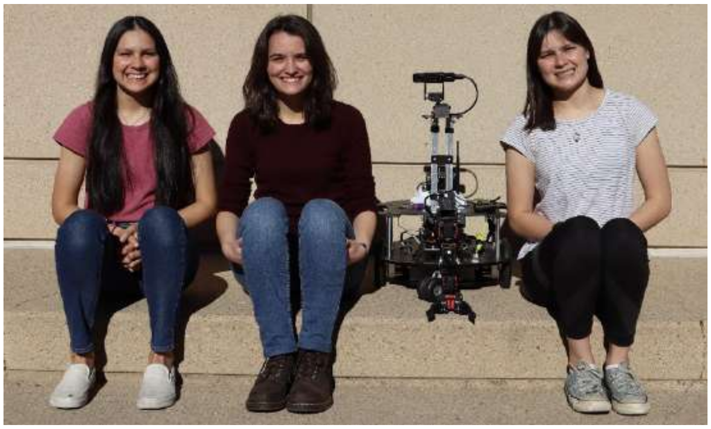


Fig. 6 - Undergraduate members of the NESS Telerobotics Lab team along with the Armstrong rover. From left to right: Madaline Muniz, Phaedra Curlin, and Alexis Muniz.

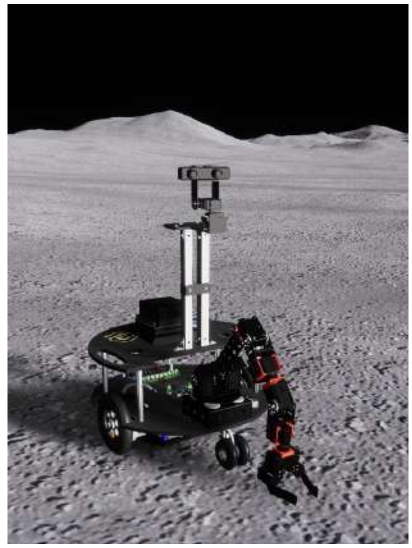


Fig. 7 The digital twin of the NESS Armstrong rover and mechanical arm on the simulated lunarscape within NESS's VR construct.

troubleshooting process, members of the NESS Telerobotics Laboratory at the University of Colorado Boulder (Figure 6) have created a virtual reality (VR) platform that includes a digital twin of our rover in a simulation of its environment that currently functions with the lab's physical rover + mechanical arm called Armstrong (Figures 6, 7). The VR twin is CAD-accurate and uses the same control interface as the physical one. The virtual rover also takes advantage of novel technologies on Armstrong like its stereoscopic camera that lets the teleoperator see from the rover's perspective and move the camera with head movements. The simulated environment can use point-clouds generated from this camera or use real-world measurements and imaging. The VR platform is similar to physical duplicates traditionally used on Earth for troubleshooting rovers but is risk-free, resettable, and portable. A baseline experiment is under development to evaluate the effectiveness of the VR platform for troubleshooting. A successor experiment will compare the VR platform to the use of a physical twin for recovery from deployment failures.

1.3. Heliophysics

Work on the Heliophysics mission Sun Radio Interferometer Space Experiment is progressing nicely, with Co-I Kasper and Collaborator Hegedus pushing forward on the operational design and science analysis pipeline for the mission. An alpha version of the SunRISE Science Data System pipeline is now complete, with simulated data going from uncalibrated spectra, to calibrated spectra, to cross correlated visibilities, to images and gaussian fits on the sky. Simulated SunRISE radio data was made by translating Wind/WAVES data into SunRISE sensitivities, with the location of any fit signal over the background originating from the 12 o'clock angle. An example of these final gaussian fits for a type III radio burst is shown in Figure 8. On the left are the fit emission location and sizes for the 2 hours of data including a type

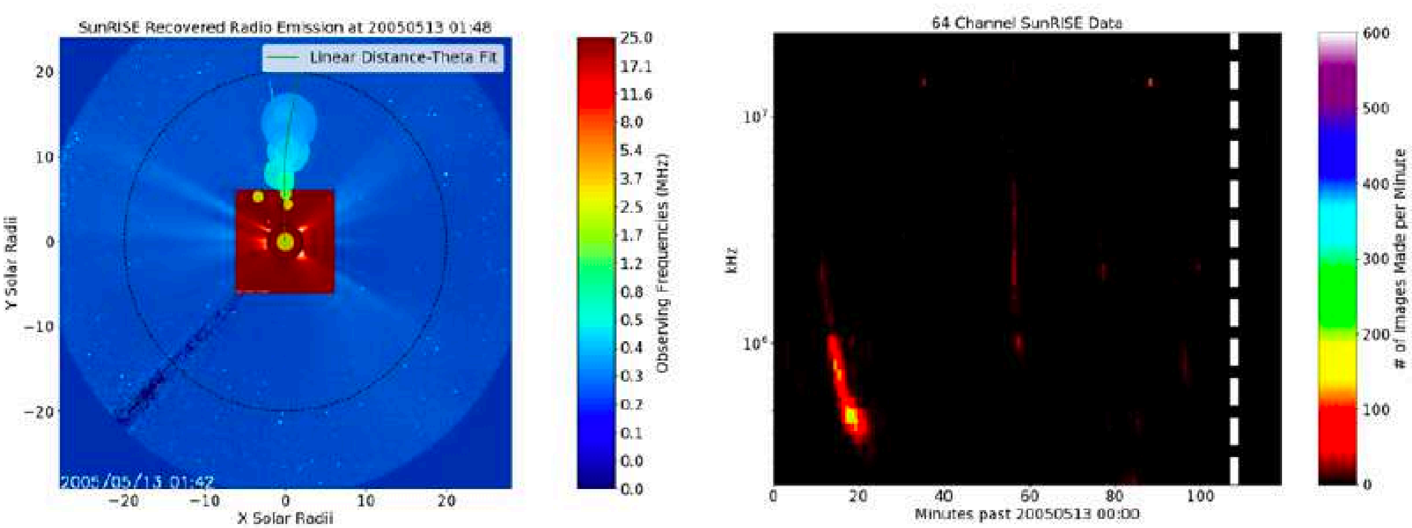


Fig. 8 Left: SunRISE summary plot showing localizations of radio emission over LASCO C2 & C3 coronagraphs. Right: The number of images made across frequency and time, indicating the fit signal above background levels, with the type III burst showing up bwtween 15-20 minutes into the simulated data.

III burst, plotted over LASCO C2 & C3 coronagraph data. The recovered emission lies along the 12 o'clock angle, matching the input location for each frequency. The right panel shows the number of images made across frequency and time, indicating the fit signal above background levels, with the type III burst showing up between 15-20 minutes into the simulated data.

The development of the SunRISE science processing pipeline will continue to mature over the next 2 years as SunRISE works towards launch in mid-2024. In particular, all the ground-based calibration data that will be generated over the coming years will be integrated into the science pipeline.

1.4. Extrasolar Space Weather

The detection of exoplanetary radio emission, as well as the detection of stellar radio bursts indicative of coronal mass ejections (CMEs) and stellar energetic particle events (SEPs), is critical for diagnosing planetary habitability and understanding the role that planetary magnetospheres play in shielding their atmospheres from the space weather environments of their host stars. Current ground-based low-frequency arrays are paving the way for future lunar-based low-frequency radio telescopes, such as FARSIDE, which will be vital for expanding our reach to the terrestrial-like magnetospheres that can only be detected from space.

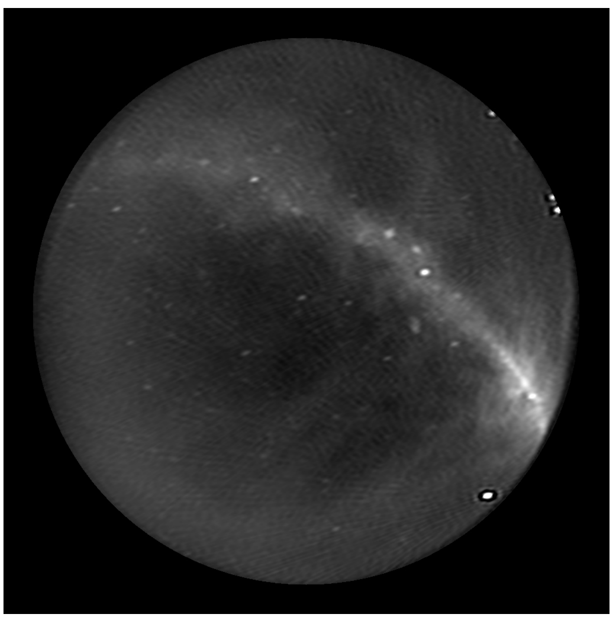


Fig. 9 - All-sky image with the OVRO-LWA, taken on January 12, 2022, from commissioning observations, as part of the ongoing upgrade of the array. At the time of these commissioning observations, just under half of the antennas were operational, all of which are in the central 200-m diameter "core" of the array. This image spans 34–84 MHz, with a spatial resolution of approximately 1 degree. The arc of diffuse emission crossing the center of the image is synchrotron emission from the Milky Way; the Sun can be seen setting towards the horizon in the bottom-right corner of the image.

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA, led by NESS Co-I Hallinan) is one such ground-based array serving as a pathfinder for future lunar-based arrays like FARSIDE, providing a framework for the operation and design of a survey targeting extrasolar space weather science from the lunar surface. OVRO-LWA targets nearby stellar systems to monitor for stellar CMEs and SEPs, as well as radio signatures of planetary magnetospheres – specifically, the Jovian-like magnetospheres that are detectable from within Earth's ionosphere. The OVRO-LWA is a 352-element dipole array in California, operating at sub-100 MHz frequencies and imaging the entire viewable hemisphere at 10-second cadence. This allows for the simultaneous monitoring of thousands of stellar sources for radio emission indicative of space weather events.

In the last year, significant progress has been made in the ongoing upgrade of the OVRO-LWA, which, when completed, will expand the array from its previous 288-element configuration to the final 352-element configuration spanning a 2.6 km diameter area. The upgrade also features a full redesign of the analog and digital signal processing systems, as well as efforts to measure and characterize all 352 antenna beams via multiple methods (including via drone). Precise knowledge of the dipole beam patterns will be essential for achieving the sensitivity necessary for detecting stellar and planetary radio emission. Demonstrating this capability with a ground-based array like OVRO-LWA will impact strategies employed by lunar-based arrays like FARSIDE.

2. Inter-team/International Collaborations

Burns continued to collaborate on an ESA-funded concept study proposal called LunarLOFAR. This is a low frequency radio array from the lunar farside with elements in common to the NESS FARSIDE concept. We are planning to do a joint workshop in 2022 on science with lunar farside low radio frequency arrays.

3. Public Engagement

3.1. From Cosmic Dark to Cosmic Dawn: An Outreach Website

With former UCLA undergraduate Erika Hoffman, Co-I Furlanetto released an outreach website (https://cosmicdawn.astro.ucla.edu/) highlighting the science of the first galaxies. The NESS/UCLA website highlights the key insights we hope to learn about the Cosmic Dawn and Dark Ages as well as the instruments that are studying it. This first version of the website is targeted toward the interested layperson (aiming for a Scientific American level). It allows exploration of the era on several levels, from quick summaries of the key science topics to in-depth exploration of some of the key observables. Lunar radio observatories receive a special focus, with science pages discussing exotic physics during the Dark Ages, the formation of the first stars and black holes, and the 21-cm spin-flip background itself, as well as a page about low-frequency radio observatories and about telescopes on the Moon (Figure 10).

Fig. 10 - Screen shot of the NESS/UCLA outreach website on the early Universe and lunar radio telescopes.

3.2. Planetarium Show: Forward! To the Moon

NESS and the Fiske Planetarium at the University of Colorado, in collaboration with TEND Studio, SSERVI, and Lockheed Martin, will premiere a feature length, full dome film titled Forward! To the Moon at CU-Boulder in February 2022. This production features the NASA Artemis (Figure 11) and Commercial Lunar Payload Services (CLPS) Programs, along with the development of surface telerobotic deployment and construction that will be critically important to exploration and science investigations of the Moon and for advancing on to Mars. In addition to the Fiske premiere, special events are also being planned for the San Francisco Bay Area, Houston, Huntsville, and other locations. The film will be distributed for free to planetariums around the globe.

3.3. Public Talks

Fig. 11 - Frame from Forward! To the Moon illustrating Orion leaving Earth heading to the Moon.

- "Study for FARSIDE," presented by Nivedita Mahesh, East Valley Astronomy Club, Arizona. March 2021.
- "FARSIDE: Exploring the Cosmos from the Moon," presented by Nivedita Mahesh, Saguaro Astronomy Club, Arizona. January 2022.
- Public talk to the Astronomy Club of Asheville, NC on "Taking Silicon Valley to the Moon," July 15, 2021, presented by Jack Burns.
- Public lecture to Secular Hub in Denver, "Taking Silicon Valley to the Moon," December 11, 2021, presented by Jack Burns.

4. Student/Early Career Participation

Undergraduate Students

1. Erika Hoffman (UCLA): outreach website designer
2. Anna Tsai (UCLA): theoretical 21-cm studies
3. Natsuko Yamaguchi (UCLA): theoretical 21-cm studies
4. Phaedra Curlin (University of Colorado Boulder): surface telerobotics
5. Mason Bell (University of Colorado Boulder): surface telerobotics
6. Madaline Muniz (CU-Boulder): surface telerobotics
7. Alexis Muniz (CU-Boulder): surface telerobotics

Graduate Students

8. Adam Trapp (UCLA): theoretical 21-cm studies
9. David Bordenave (Department of Astronomy, University of Virginia): experimental 21-cm studies
10. Neil Bassett (University of Colorado Boulder): 21-cm data analysis studies
11. Joshua Hibbard (University of Colorado Boulder): 21-cm data analysis studies
12. Michael Walker (University of Colorado Boulder): surface telerobotics
13. Nivedita Mahesh (Arizona State University): experimental 21-cm studies

Technicians

14. David Lewis (Arizona State University, part-time technician): experimental 21-cm studies

Postdoctoral Fellows

15. Alexander Hegedus (University of Michigan): simulating space-based radio arrays
16. Marin Anderson (California Institute of Technology, Jet Propulsion Laboratory): extrasolar space weather
17. Steve Murray (Arizona State University): 21-cm data analysis studies

18. Jordan Mirocha (McGill University): theoretical 21-cm studies
19. Bang Nhan (National Radio Astronomy Observatory): experimental 21-cm studies
20. Keith Tauscher (University of Colorado Boulder, until July 2021): 21-cm data analysis studies

5. Mission Involvement

1. SunRISE: In the past year the Sun Radio Interferometer Experiment (SunRISE) mission passed its Integrated Design Review, a major milestone that led the mission into Phase C of operations, where implementation of the mission accelerates. Co-I Kasper and Collaborator Hegedus presented the mission overview and the implementation of the science data system respectively. The SunRISE mission has an estimated launch date of mid-2024, and a primary mission length of 12 months.

2. ROLSES: This will be the first NASA-funded radio astronomy payload to land on the Moon as part of the first CLPS mission (using the Intuitive Machine (IM) NOVA-C commercial lander). One exciting recent development is that we will be able to observe for ~12 hrs during the lunar night at the end of the mission. IM has completed the so-called FlatSat testing twice, and the ROLSES NPLP was finally delivered to IM late in June 2021. The current NOVA-C lander launch date is in June 2022. The goals for this mission include: determine the photoelectron sheath density from ~1 to ~3 m above the lunar surface; demonstrate detection of solar, planetary, & other radio emission from lunar surface; measure reflection of incoming radio emission from lunar subsurface and below; measure Galactic spectrum at <30 MHz; aid in the development of lunar radio arrays. NESS Deputy PI MacDowall is PI of ROLSES, and Burns and W. Farrell (NESS collaborator) are Co-Is.

3. FARSIDE: The Dark Ages of the early Universe was singled out by the Astro2020 Decadal Survey as THE discovery area in cosmology for the next decade. The Dark Ages, along with detecting radio emission from nearby exoplanets, are the primary science goals for this array of 256 dipole antennas. FARSIDE was identified by Astro2020 as one possible Probe-class mission. Work on further development of FARSIDE was described above. Burns is the PI and Hallinan is Deputy PI of the FARSIDE concept.

4. LuSEE (includes input from the NASA-funded DAPPER concept study): LuSEE is now fully funded by NASA, with partnership from DOE, as the first NASA radio astronomy payload for the lunar farside. It is scheduled by the NASA ESSIO office to fly as CS-3 on a separate lander, in conjunction with the deployment of a lunar comms satellite, in 2025. It will carry sufficient batteries to permit operations during the lunar night. This will enable the first truly sensitive observations of the 21-cm signal from the Dark Ages. Antenna and receiver designs continue to advance based, in part, on previously funded work by NESS. NESS Collaborator S. Bale is the PI of LuSEE, and Burns and MacDowall are Co-Is.

5. VIPER: During this past year, NESS Co-I Fong served as the deputy rover lead for the Volatiles Investigating Polar Exploration Rover (VIPER) mission. To support NESS research and outreach activities, Fong actively worked to disseminate VIPER developed data, including the VIPER Environmental Specification and synthetic terrain digital elevation models of lunar sites (Hermite-A, Nobile, Shackleton Ridge). Fong also served on the Independent Assessment Team for the “Moon Ranger” lunar rover mission (SMD PRISM program), providing robotics expertise to the CDR and Delta CDR reviews.

6. Awards

Jack Burns was elected in 2021 to the International Academy of Astronautics, headquartered in Paris.

7. Equity, Diversity, Inclusion & Accessibility

Equity, diversity, inclusion, and accessibility are core values of the NESS team and our home institutions. Two EDIA initiatives were pursued by NESS in this past year. First, one of our goals is to increase women and minority participation in fields that have traditionally been underserved. Robotics is a prime example. In our NESS telerobotics lab, we have recruited three women, two of whom are persons of color (Fig. 6). All three are engineering majors. Phaedra Curlin was promoted in 2021 to Lab Manager. She is graduating this Spring and will begin graduate school at CU in the Fall. In addition, an astrophysics/instrumentation Ph.D. student at ASU supported by NESS and mentored by Co-I Bowman, Nivedita Mahesh, is graduating and will begin a postdoc this Fall at Caltech mentored by NESS Co-I Hallinan. Second, as part of our outreach project to develop the feature length planetarium program Forward! To the Moon, diversity was foremost in our planning. The film shows a new generation of astronauts, many women and persons of color are part of the 21st century Artemis class of astronauts. We included interviews from a diverse group of young students who are excited by space and travel to the Moon and Mars. Our goal in this show that will be seen by tens of thousands in planetariums world-wide is that space careers are open to everyone.

Resource Exploration and Science of Our Cosmic Environment (RESOURCE)

Jennifer Heldmann
NASA Ames Research Center, Mountain View, CA

CAN-3 TEAM

1. RESOURCE Team Report

1.1. Morphology of Ice Stability Zones

1.1.1. Lunar Poles

RESOURCE scientific research focuses on characterizing polar regions on airless bodies which harbor volatile deposits (including water ice) which are of interest to both science and exploration communities. In new research we quantify surface roughness inside and outside of ice stability zones at the lunar poles. Through analysis of lunar data, we observe surfaces where ice is stable that are smoother than neighboring warmer surfaces. Interestingly, these comparatively smooth surfaces are observed in both craters that host surface water-ice exposures and those that do not, suggesting that the presence of subsurface ice, rather than surface ice, may be responsible for the reduced surface roughness.

NASA directly benefits from understanding the roughness of planetary surfaces. Roughness is a key metric for determining the safety and traversability of a surface, and is a critical parameter when planning future robotic and human operations on the lunar surface.

> "Constraining the locations and environments of anomalous surface textures may provide insight into the locations of ice on the Moon for future in-situ resource utilization."

1.1.2. Craters on Mercury

When correlations of surface roughness and ice content observed on the Moon were extended to analyze the surface texture of six ice-bearing craters in the polar regions of Mercury, we found that the presence of ice creates a smoothing effect on the surface by filling in the underlying topography. However, the magnitude of this smoothing effect is dependent on the initial roughness of the underlying topography. The ice deposits appear to be smoothest along their edges, suggesting the ice may be thickest at the edges, or that small impacts that cause texture variations may disappear more quickly at the ice edges.

> "The texture of Mercury's ice provides important information regarding the physical nature of the ice, and how this ice has been modified over time in the space environment."

1.2. Depth-Data Collection Techniques for In-Situ Geological Analysis

The RESOURCE team at Massachusetts Institute of Technology (MIT) has focused on advanced technologies and operations techniques to enable human and robotic mission operations in support of science and exploration. This year the MIT team completed testing of various depth-data collection techniques in a geologic analog environment to assess the benefits and deficits of these techniques for in-situ geological analysis, as well as testing reconstruction algorithms. We compared stereophotogrammetry, time-of-flight, and RGB (color) imagery and video, and assessed these data acquisition techniques for depth-of-view, field-of-view, bandwidth requirements, lighting conditions, and basic processing requirements. The different cameras were mounted on the Boston Dynamics Spot robot which provided an advanced roving platform that was operated on an unstable beach with geological points of interest that could be approached remotely with the robot (Figure 1). Based on this analog fieldwork, we found that a combination of time-of-flight and color imagery data provided the most appropriate resolution for a lunar south pole lighting condition.

Figure 1A. Boston Dynamics Spot robot equipped with multiple payload elements on RESOURCE 2021 deployment.

Informed by this fieldwork, we selected a commercial-off-the-shelf (COTS) camera with time-of-flight and color imagery capabilities to modify for lunar rover missions. We are currently working on multiple risk-reducing experiments for this camera to prepare for a possible Commercial Lunar Payload Services (CLPS) mission in 2023. An experiment to test the camera in lunar dust conditions will be flown on a Zero-G flight with the MIT Space Exploration Initiative in May of 2022. This Zero-G experiment is in development now and will assess the camera's capabilities when exposed to lunar regolith simulant with lunar lighting conditions. The lunar regolith will be disturbed by a rotating rover wheel while monitoring the resolution from the COTS camera of a 3D printed rock wall. The dust kickup dynamics of the wheel in microgravity will also be studied by creating a laser wall to visualize a single slice of the 3D space. A video will allow for particle image velocimetry (PIV) to best characterize the paths and velocity of the particles (Fig 2).

The raw data from the field experiments were also analyzed with several reconstruction algorithms to render the sites in virtual reality and determine which method leads to the most error-free field site models and can use low bandwidth data. We are currently working on collection methods that optimize data collection for the chosen Open3D reconstruction. The low-resolution models were then implemented in a real-scale VR environment (Fig 3). The next segment of work will be to implement measurement tools into this VR interface, improve 3D model generation, and start usability tests with expert users.

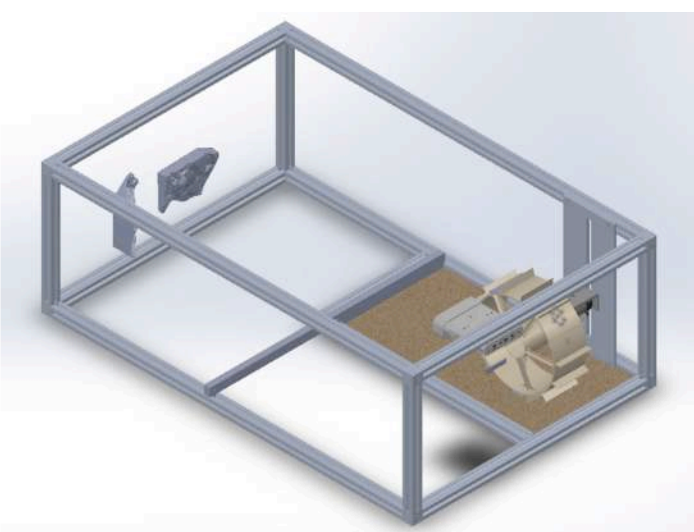


Figure 2: Zero-G flight experimental setup

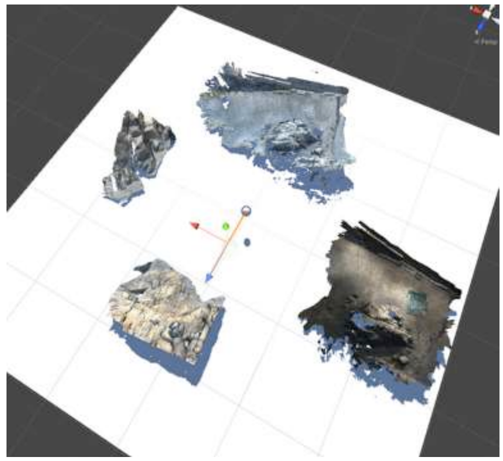


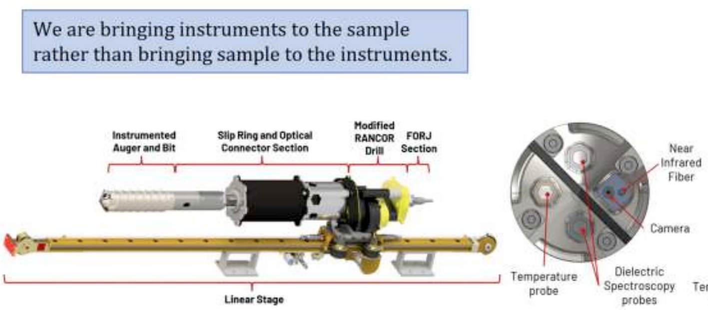
Figure 3: Depth-data reconstruction

1.3. Lunar Drilling Technologies

In 2021, the RESOURCE team led by Honeybee Robotics has been focused on developing the next-generation lunar drilling systems which include integrated science instruments within the drill itself. This method allows for in-situ measurements where the instrument is brought directly to the sample. To achieve this goal, the RESOURCE team has developed a new drilling system called Sensing, Measurement, Analysis, and Reconnaissance Tool (SMART) for ISRU investigations on the Moon. SMART's auger and bit are packaged with instruments that look for water ice, analyze volatile content, and answer key scientific questions about the properties of the lunar regolith. SMART is the natural evolution of the TRIDENT drill, which uses the auger to move drill cuttings up to the surface for instrument analysis on the upcoming VIPER and PRIME-1 missions to the Moon. Unlike TRIDENT, SMART brings instruments to the sample rather than bringing samples to the instruments.

> "RESOURCE is developing the next-generation hardware and operations for planetary drilling by integrating scientific instruments within the drill itself, allowing for in-situ measurements and eliminating the need for sample handling and transfer."

SMART is instrumented with five sensors in a 5 cm (2 inch) diameter auger and bit assembly: (1) a near infrared spectrometer for volatiles and mineralogical information, (2) a neutron spectrometer for hydrogen detection, (3) a dielectric spectroscopy probe for electrical properties, (4) a temperature sensor and heater for thermal gradient and thermal conductivity measurements, and (5) a camera for visible light images and surface texture (Figure 4). The drill is also an instrument, as drilling power and penetration rate can be used to determine regolith strength.



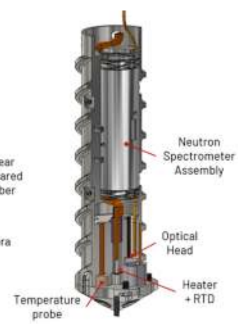


Figure 4. Components of the next-generation SMART drill prototype.

Honeybee Robotics has designed and built the SMART prototype to demonstrate instrument functionality. The system is composed of the instrumented auger and bit, a slip ring and fiber optic rotary joint section to pass the power and signals to the avionics, a drill head to provide rotary percussive drilling, and a linear stage to advance the drill into the subsurface (Figure 5).

Figure 5. SMART drill prototype at Honeybee Robotics.

The SMART prototype is capable of demonstrating instrument functionality in relevant environments.

We will continue to collaborate with instrument experts from NASA Ames Research Center and the Jet Propulsion Laboratory (JPL) to develop the technology. This year we will focus on testing the drill and individual instruments in relevant lunar environments.

1.4. ISRU Water Processing Plant

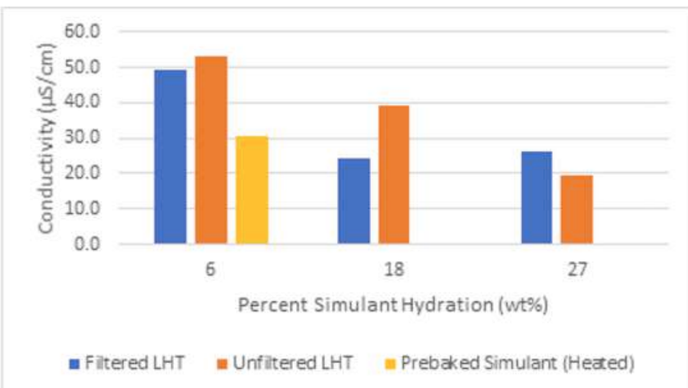
The RESOURCE project, led by NASA's Johnson Space Center (JSC), is working to process extracted water in an ISRU plant and demonstrate an integrated test of the critical components needed to capture, clean, deionize, and electrolyze water as well as dry the oxygen and hydrogen gas products.

The leading technology for water electrolysis is based on proton exchange membranes (PEM). In order to feed water into a PEM electrolyzer, the conductivity must be less than 1 μS/cm. Therefore, any water derived from the lunar surface will likely require purification and deionization before it can be electrolyzed. In order to determine the size of a water cleanup and deionization system, we need to determine the conductivity of product water as a function of both volatiles and particulates. Year 1 test results showed that a half micron filter strategically placed within the vessel that performs the heating of simulant was sufficient to yield product water with a particle count that was within acceptable limits of a PEM electrolyzer. The chemical analysis showed that the levels of calcium, iron, and magnesium detected in the product water were within the acceptable limits of a space-qualified electrolyzer (International Space Station Oxygen Generation Assembly). However, the chemical analysis also revealed significant levels of ammonium ions that had a direct correlation to the product water conductivity. The presence of ammonium ions in the product water prevented the team from being able to derive a direct correlation between particulate and conductivity.

The goal of RESOURCE Year 2 testing was to remove ammonia as a source of contamination so that a correlation between particulate and conductivity in the product water could be determined. The approach involved pre-baking the simulant (LHT-2M) to 150 degrees for 3 hours, before adding deionized water to the simulant. The results showed that the pre-baking step was effective at reducing the ammonium ions, but was not sufficient to completely remove the ions from the product water (Figure 6). After sharing the results with the simulant development team, it was suggested to flush the simulant with deionized water without heating and analyze the water used to flush the simulant. The flush test showed that the deionized water did not pick up ammonium ions when passing through the simulant. This indicates that the source of ammonium ions is caused by a combination of LHT-2M simulant, water and heat.

Since ammonia was one of the volatiles detected from the LCROSS impact, it is one of the known contaminants that will need to be accounted for when developing large-scale water cleanup systems for ISRU applications. However, the generation of ammonia from a terrestrial simulant was unexpected and may need to be accounted for. Testing to date has been performed with LHT-2M simulant, but a new simulant developed by Exolith Lab called Lunar Highlands Simulant-1 (LHS-1) has been acquired by the NASA JSC ISRU team for large scale water extraction testing in support of the Lunar Auger Dryer for ISRU (LADI) project. This year, tests will be repeated with Lunar Highlands Simulant-1

RESOURCE hardware development and testing at NASA Johnson Space Center provides the capability to process extracted water in an ISRU plant.



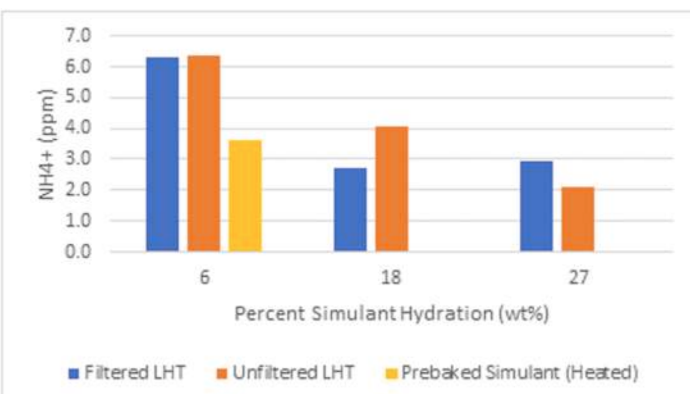


Figure 6. Laboratory analysis results showing hydration levels of lunar simulant undergoing multiple ISRU processing steps.

1.5. Terrestrial Analog Field Studies

In 2021, a Special Issue was published in the journal Planetary and Space Science (PSS) and edited by Co-I Lim and PI Heldmann (Figure 7). This Special Issue is titled "Analog research and comparative planetology related to the scientific exploration of volcanic and hydrothermal systems in our Solar System" and is a collection of research papers focused on science and exploration results from our NASA-funded field analog campaigns.

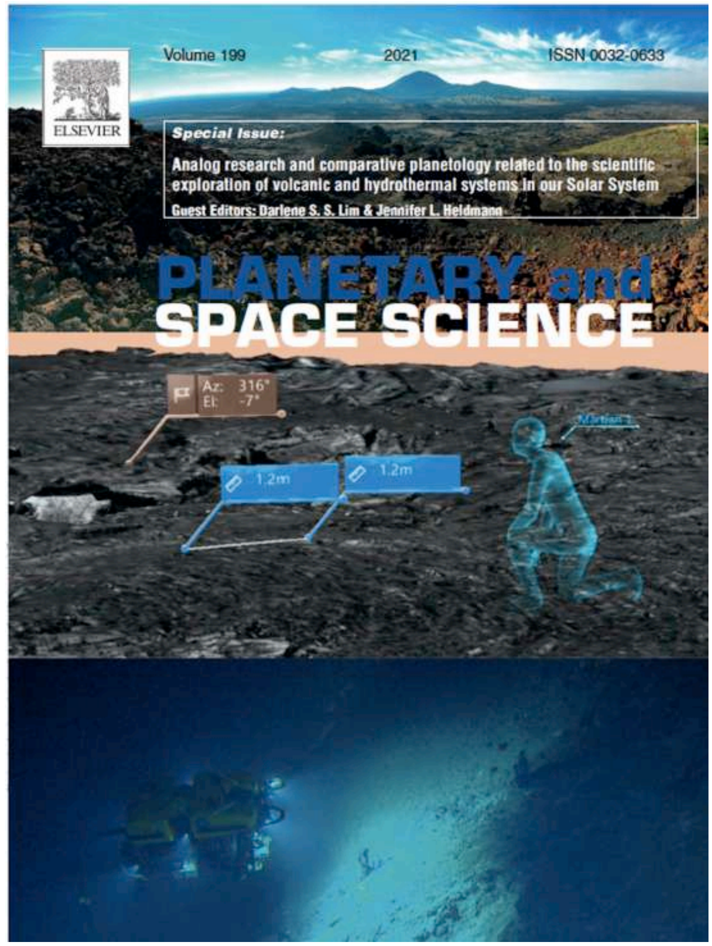


Figure 7. Cover of Special Issue of Planetary and Space Science journal (2021) featuring a compilation of research papers based on our NASA-funded terrestrial analog field campaigns.

2. Inter-team/International Collaborations

RESOURCE is pleased to partner with multiple inter-team and international SSERVI partners. These partnerships have led to important contributions to the RESOURCE portfolio.

2.1. International Collaborations

2.1.1. Canadian Lunar Research Network, University of Western Ontario.

RESOURCE works closely with team member Dr. Gordon Osinski at the University of Western Ontario (UWO) as the lead of the Canadian Lunar Research Network, an official SSERVI international partner. RESOURCE specifically capitalizes on the expertise of UWO in terms of ice and volatile characteristics and behavior in cold environments to understand ice deposits on the Moon. UWO has also contributed to RESOURCE planning for terrestrial analog testing of science, operations, and technologies as relevant for ice characterization, and provides key inputs for terrestrial analog deployments.

2.1.2. (Korea Institute of Geoscience and Mineral Resources (KIGAM)

RESOURCE Collaborator Dr. Kyeong Kim is a researcher with the Korea Institute of Geoscience and Mineral Resources. Kim's research focuses on lunar science and the applications of XRF analysis on planetary surfaces. Kim is also the PI of the gamma ray instrument slated to fly onboard the Korean Pathfinder Lunar Orbiter and has involved RESOURCE team member R. Elphic as a Co-I with KPLO.

2.1.3. Curtin University, Perth, Australia

RESOURCE Collaborator Dr. Phil Bland provides a direct connection between the RESOURCE team with the Australian mining industry. In particular, RESOURCE capitalizes on Australia's vast mining industry regarding best practices and technologies for optimal mining protocols to enable planetary ISRU.

2.1.4. Open University, United Kingdom

RESOURCE Collaborator Dr. Mahesh Anand is a recognized expert in lunar ISRU. Specifically, Dr. Anand's expertise is valuable for assessing mineral and chemical resources on the Moon.

2.2. SSERVI Inter-Team Collaborations

2.2.1. RISE2

The RESOURCE PI has coordinated with RISE2 PI to establish and run the NASA / SSERVI Analogs Focus Group. This Focus Group capitalizes on the expertise of these two SSERVI teams and integrates the capabilities and needs of the broader community to provide a forum for timely discussion and advancement of analog field activities to support both human and robotic exploration of SSERVI Target Bodies.

3. Public Engagement Report

3.1. Storylines

In 2021, pre-service educators from Howard University's School of Education designed and implemented lessons that connect the problems and innovations the RESOURCE mission is tackling to empower conceptual storylines. Storytelling through culturally relevant engineering design challenges can broaden the participation of Black and Latinx students. Using this methodology, the students can access the material in culturally relevant ways that are authentically connected to their interests and worldviews. The educators implemented these lessons virtually and in-person in Washington D.C. and Prince George's County Public Schools in Maryland – both districts serve majority Black and Latinx students.

Storytelling can: 1.) Engage student's interests and worldviews; 2.) Connect to broader social justice issues; 3.) Center Subject Matter Experts of Color; 4.) Create engineering design challenges that are anchored in students' experiences. This work was presented at the July 2021 Exploration Science Forum session "Building Better Worlds (EDIA/Public Engagement)." Figure 8 below is a slide from the presentation showing an instance of storytelling engagement around accessing lunar ice.

Additional student engagement included four virtual classroom visits by Dr. Matiella Novak to Old Mill South Middle School in April 2021. The presentation included highlighting RESOURCE science and exploration as well as broader Solar System science and exploration.

3.2. Public Outreach

RESOURCE team members have conducted a multitude of outreach events over the past year to share the excitement of this project and NASA's ISRU-relevant activities. Here are examples of RESOURCE outreach and community engagement. PI Heldmann delivered a virtual presentation to Friends High School students (Wynnewood, PA) regarding planetary science and robotic exploration. PI Heldmann is also a Subject Matter Expert (SME) for the NASA Science Activation Team led by the SETI Institute titled "SETI Community College Network" which aims to connect NASA science research with community colleges across the country.

Public talks and podcasts by RESOURCE team members are also available online. In March 2021 Co-I Lim was featured on an episode of "NASA Science Live!" to discuss terrestrial analog fieldwork. PI Heldmann was an invited guest on the U.S. Space and Rocket Center podcast titled "Dare to Explore" in Spring 2021. PI Heldmann also supported the SSERVI TREX team by participating in an outreach event for Almaden Country Day School in San Jose as part of their Expanding a Dynamic and Gifted Education (EDGE) day.

3.3. Community Activities

RESOURCE team members have been engaged in a plethora of community activities over the past year. Several RESOURCE team members have been involved with the National Academies of Science Engineering and Medicine (NASEM) Decadal Survey for Planetary Science and Astrobiology 2022-2023. PI Heldmann serves on the Panel for the Moon and Mercury and as Co-Chair of the Human Exploration Working Group (HExWG).

In addition, Co-I Colaprete (NASA Ames) served on the NASEM Committee on Planetary Protection and Co-I Hurley (JHU/APL) was invited to speak to this Planetary Protection committee.

PI Heldmann also served on NASA's Artemis III Science Definition Team which issued a report on high priority science activities for the first Artemis human landing near the south pole of the Moon (https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf). Heldmann has served as a member of NASA's Science Mission Directorate Contamination and Research Integrity (CaRI) Team as the authoritative SMD body for input and analysis relevant to human exploration capabilities and architectures for Artemis. Heldmann was invited by the NASA Headquarters Exploration Science Strategy Integration Office (ESSIO) to present her terrestrial analog research at a technical interchange meeting (TIM) facilitated by NASA with the United Arab Emirates (UAE) personnel from the Mohammed Bin Rashid Space Centre (MBRSC).

RESOURCE has also contributed to multiple NASA Lunar Surface Science Workshops (LSSWs). PI Heldmann co-chaired LSSW #4 regarding Lunar Planetary Protection and Permanently Shadowed Region Classification and wrote the subsequent LSSW report. Multiple presentations were given at LSSW #8 (Structuring Real-Time Science Support of Artemis Crewed Operations") including presentations by Heldmann et al. ("Guiding Principles to optimize real-time scientific productivity during Artemis crewed missions to the Moon"), Lim et al. ("Tactical and strategic science support for crewed Artemis missions: Lessons learned from the BASALT research project"), and Osinski et al. ("Mission control structure and strategies: Lessons from the CanMoon lunar sample return analogue mission"). LSSW #8 also included RESOURCE graduate student Ferrous Ward (MIT) as a workshop facilitator.

3.4. Analogs Focus Group

The SSERVI Analogs Focus Group was established by RESOURCE PI Heldmann, RESOURCE Co-I Lim, and RIS4E PI Glotch. Terrestrial analog field studies offer the unique opportunity to prepare for robotic and human planetary missions. Analogs provide the opportunity to conduct studies and tests related to science, mission operations, and technology in a relevant environment at relatively low cost and risk. The SSERVI Analogs Focus Group aims to bring together members of the community to discuss and review various aspects of fieldwork including, but not limited to, field sites, deployment logistics, field instrumentation, concepts of operations, software and hardware testing, etc. This Group currently hosts quarterly virtual seminars which are recorded and posted on the SSERVI website for later viewing. An Analogs Focus Group seminar was given by RESOURCE Collaborator Osinski (Western University, Canada) in April 2021 titled "Preparing for Renewed Robotic and Human Exploration of the Moon: Lessons Learned from a Decade of Lunar Analogue Missions"). More information can be found on the SSERVI Analogs Focus Group website at https://sservi.nasa.gov/analogs-focus-group/.

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

RESOURCE has a firm EDIA commitment and shares EDIA thoughts and strategies with the broader community. Below is a brief summary of EDIA-relevant activities within the RESOURCE team this year.

1. PI Heldmann, served as a Subject Matter Expert (SME) for NASA Commercial Space Capabilities Office (CSCO) to review Established Program to Stimulate Competitive Research (EPSCoR) proposals focused on research and development of interest to commercial spaceflight companies with a focus on water ice exploration. EPSCoR focuses on 25 states and three territories (Guam, U.S. Virgin Islands, and Puerto Rico); these 28 EPSCoR jurisdictions combined receive less than 10% of available federal research funding.
2. Multiple RESOURCE team members regularly support the SSERVI EDI Focus Group by attending biweekly EDI meetings and participating in associated activities.
3. Support Women in Space Speaker Series and relevant

EDIA talks such as presentation by MIT researchers Katlyn Turner and Danielle Wood (MIT) titled “Towards Intersectional Equity in Complex Sociotechnical Systems.”

4. Led by Howard University, RESOURCE has developed PowerPoint slides highlighting ~20 NASA/Planetary scientists of color. This resource offers teachers a “complete” curriculum outlining the technical aspects of ISRU, where the RESOURCE tasks/sub tasks are linked to content standards, social justice/community issues, and personal relevance. The curricular resources are a living document that can then be updated by teachers as they adapt or implement lessons with their students.
5. At the AIAA ASCEND meeting (December 2021), RESOURCE Collaborator Lopez (Astrobotic) organized a panel discussion (CLB.PNL-58: Redefining Aerospace – Cultivating Diversity in a New Space Era) where Collab. Lopez and PI Heldmann served as panelists to discuss EDIA in the space industry.

5. Student/Early Career Participation

Undergraduate Students

1. Sofia, Kwok, Caltech, Mechanical Engineer
2. Trent, Piercy, MIT Aeronautics and Astronautics
3. Eman, Yasin, Howard University, School of Education, Special Education and Biology (K-12)
4. Zhakiya, Bangura, Howard University, School of Education, Elementary STEM Education

Graduate Students

5. Alexandra, Forsey-Smerek, MIT Electrical Engineering and Computer Science
6. Cody, Paige, MIT Aeronautics and Astronautics
7. Ferrous, Ward, MIT Aeronautics and Astronautics
8. Don Derek Haddad, MIT Media Lab
9. Jessica Todd, MIT Aeronautics and Astronautics
10. Lindsay Sanneman, MIT Aeronautics and Astronautics
11. Nora, Shapiro, University of Michigan, Environmental and Sustainable Engineering
12. Tanya, Rogers, Rice University, Chemical and Biomolecular Engineering
13. Tiana, Woolard, Howard University, School of Education, and Prince George’s County Public Schools, Elementary Education

Postdoctoral Fellows

14. Ariel, Deutsch, NASA Ames Research Center

Figure 9. Cody Paige with the Boston Dynamics Spot rover at MIT.

Student Spotlight: Cody Paige (MIT)

Cody Paige is a fourth year Ph.D. student at MIT working on advanced technologies to optimize robotic and human space missions to the Moon. She is testing hardware and assessing software developments to integrate near field-of-view depth data integrated into a virtual reality platform for science and mission operations. She conducts theoretical, laboratory, and terrestrial analog fieldwork to develop the use of a time-of-flight depth camera as a low-cost alternative to stereophotogrammetry for depth-data collection on lunar rover missions with a specific focus on near field-of-view (up to 5 m depth with sub-cm-scale resolution) scientific and geologic analysis capabilities. This year she also designed an experiment to test the camera in lunar dust conditions to be flown on a Zero-G flight in collaboration between RESOURCE and the MIT Space Exploration Initiative to reduce risk and optimize performance for the camera for future lunar flight opportunities.

6. Mission Involvement

1. VIPER, Jennifer Heldmann, Science Team, Mission Operations
2. VIPER, Anthony Colaprete, Project Scientist
3. VIPER, Darlene Lim, Deputy Project Scientist
4. VIPER, Matthew Deans, Robotics
5. VIPER, Ross Beyer, Ground Data Systems
6. VIPER, Joshua Coyan, Geostatistics Lead
7. VIPER, Julie Kleinhenz, ISRU
8. VIPER, Zara Mirmalek, Mission Operations
9. VIPER, Kris Zacny, TRIDENT drill PI
10. VIPER, CLPS, Dan Hendrickson, Astrobotic lander systems

11. VIPER, CLPS, Jennifer Lopez, Astrobotic lander systems
12. LRO, Dana Hurley, LRO LAMP Science Team
13. LRO, Ross Beyer, LRO LROC Science Team
14. LRO, Richard Elphic, Diviner Imaging Radiometer Team
15. LRO, Alexandra Matiella Novak, Mini-RF Science Team
16. LUNA-H Map, Anthony Colaprete, Science Team
17. KPLO, Kyeong Kim, KGRS PI (KPLO Gamma Ray Spectrometer)
18. CLPS 19C, Anthony Colaprete, Instrument PI
19. CLPS 19C, Richard Elphic, Instrument PI
20. CLPS 19C, Kris Zacny, Instrument PI
21. PRIME-1 mission, Janine Captain, Instrument PI
22. Mars Moon eXplorer (MMX), Richard Elphic, MEGANE Gamma Ray and Neutron Spectrometer Team
23. Mars Science Laboratory (Curiosity rover), Chris McKay, Science Team
24. Mars Science Laboratory (Curiosity rover), Kris Zacny, Instrument Team
25. Mars Reconnaissance Orbiter, Alexandra Matiella Novak, CRISM Mission Operations
26. Mars 2020, Anthony Colaprete, Mastcam-Z Science Team
27. Orion spacecraft, Michael Downs, Test and Recovery Operations
28. DART, Andrew Rivkin, DART Investigation Team Lead

Mission Acronyms:

VIPER: Volatiles Investigation Polar Exploration Rover

CLPS: Commercial Lunar Payload Services

LRO: Lunar Reconnaissance OrbiterL

LUNA-H Map: Lunar Polar Hydrogen Mapper

KPLO: Korea Pathfinder Lunar Orbiter

PRIME-1: Polar Resources Ice Mining Experiment-1

MMX: Mars Moon eXplorer

DART: Double Asteroid Redirection Test

7. Awards

1. NASA SSERVI 2021 Wargo Award for Integration of Science and Exploration, Co-I Darlene Lim
2. APEX award (Ames Project Excellence Development Program), PI Heldmann, Collaboration between NASA Ames Research Center Entry Systems & Technology Division and Planetary Systems Branch.
3. Association of Women Geoscientists (AWG) Professional Excellence Award 2021, PI Heldmann
4. Fellow of the Institute of Space Commerce, Co-I Dava Newman, MIT
5. HST Observer Program: Analysis of Low-Albedo Asteroids Observed through JWST Guaranteed Time, Co-I Rivkin, JHU/APL
6. NASA Ames Group Achievement Award, Co-Is Colaprete, Lim, Mirmalek, Coyan, Deans, Beyer, Elphic, Kleinhenz, Zacny, PI Heldmann, VIPER (Volatiles Investigating Polar Exploration Rover)
7. NASA Ames Center Innovation Fund (CIF), THEIA – Thermal History Exploration Instrument for Artemis, PI Heldmann, Deputy PI Sehlke
8. New appointment to Board of Directors, Satellogic, Co-I Dava Newman, MIT
9. 2021 Barringer Award, Meteoritical Society, Collab. Osinski, Western University

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)

Thomas Orlando
Georgia Institute of Technology, Atlanta, GA

CAN-2 TEAM

1. REVEALS Team Report

1.1. Meteoroid Stimulated Water Synthesis on the Moon

It is well accepted that water and water-equivalent hydrogen are present on the Moon but the sources, distributions, and the absolute amounts present are still not known. The REVEALS team has proposed that water formation can occur by a process known as recombinative desorption (RD) of the hydroxyl groups produced by solar wind bombardment. Shown below in Figure 1 is a snapshot of water production rates from recombinative desorption and from melt associated with meteoritic impacts after 200 lunar days at full illumination. The maximum rate of water production from RD due solely to solar thermal heating occurs at the equator and subsolar point where the temperature is the greatest. Conversely, the production rate from temperature jumps accompanying meteoritic impacts is slightly offset from the subsolar point. RD mediated water formation via normal thermal excursions and local temperature increases due to micrometeorite impact events can produce a quasi-continuous source of water that will eventually be trapped in craters and permanently shadowed regions (PSRs).

Water from the sum of RD and impact melts contribute about 200 ppm on average to the surface grains within PSRs at a linear water accumulation rate of ~ 0.3% of a monolayer per year. At this rate, pure molecular water ice should be visible in the PSRs. However, impact gardening will ensure that there is no build-up of pure water ice, instead ensuring a rocky/ice mixture.

1.2. Measuring and Modeling H2O Transport and Interactions with Lunar Simulants and Apollo Samples at Conditions Relevant to In-situ Resource Utilization

Water and molecular hydrogen evolution from Apollo sample 14163 and lunar regolith simulants LMS-1 and LHS-1 were examined using Temperature Programmed Desorption (TPD) in ultra-high vacuum. LMS-1, LHS-1, and Apollo 14163 released water upon heating (Figure 2), whereas only the Apollo sample directly released measurable quantities of molecular hydrogen.

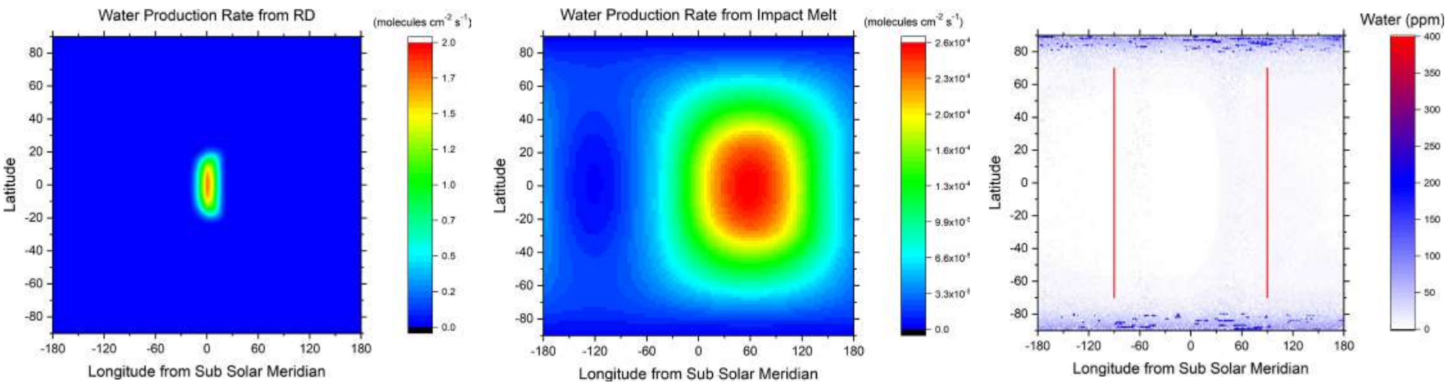


Figure 1: Snapshots of water on the Moon at full illumination. Water production from RD is shown on the left, with peak production at the equator and at the subsolar point after 200 lunar days of solar wind bombardment. The middle displays the production of water from the melt of meteoritic impacts. Frozen water accumulation is shown on the right after 1000 years of water production from both RD and impact melt.

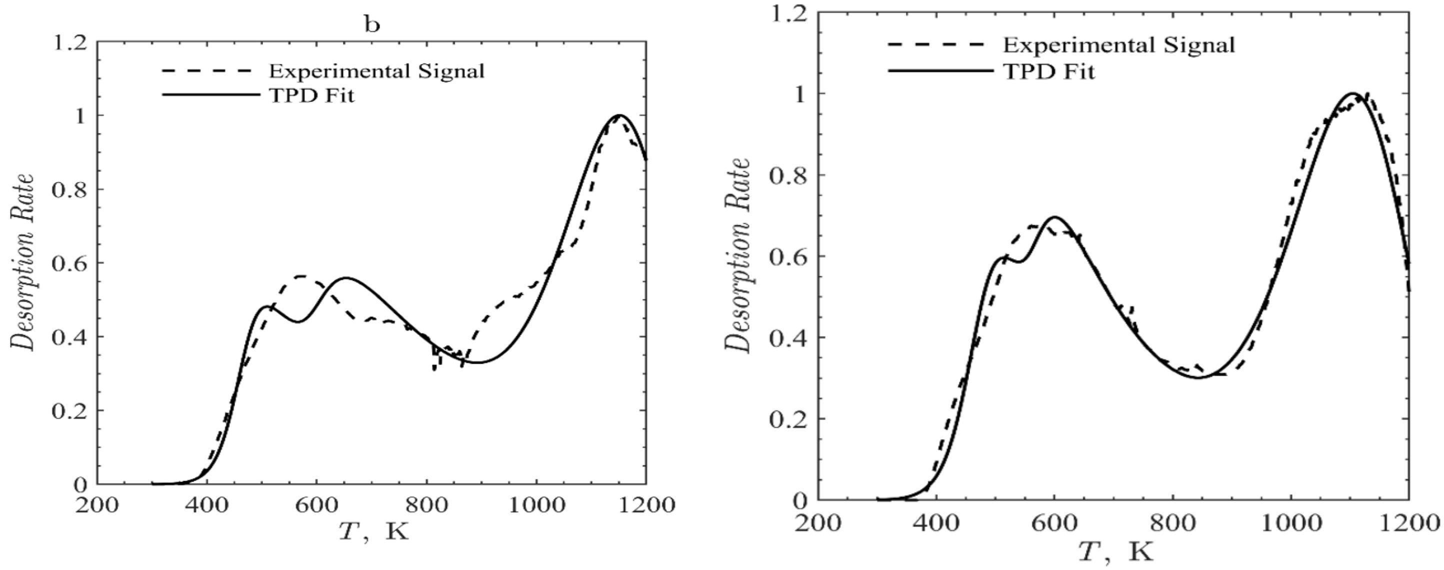


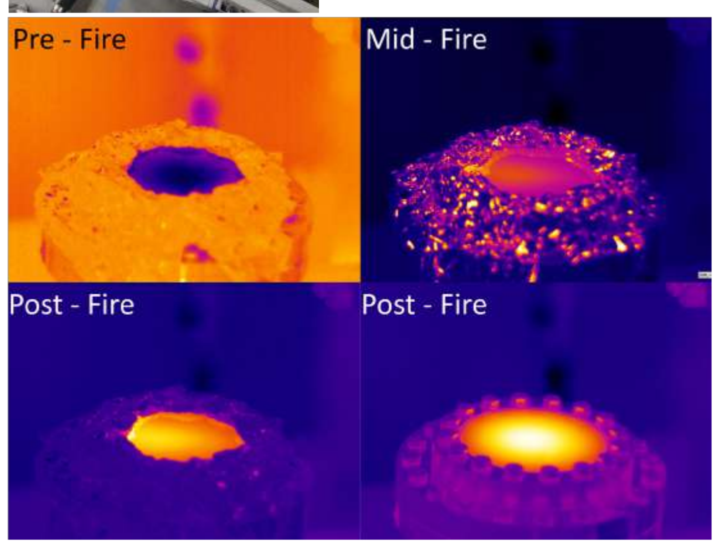
Figure 2: The normalized experimental H2O TPD signal and model fit. For LHS-1 simulant (left frame) and Apollo 14163 highland sample (right frame). These behave similarly though the Apollo sample is space weathered.

Since essentially no molecular hydrogen was observed from the simulants, the results indicate that LMS-1 and LHS-1 display water surface binding and transport interactions similar to actual regolith but not the desorption chemistry associated with the implanted hydrogen from the solar wind.

Overall, these terrestrial surrogates are useful for understanding the surface and interface interactions of lunar regolith grains, which are largely dominated by the terminal hydroxyl sites under both solar wind bombardment and terrestrial preparation conditions.

Experiments were performed to study H2O(v) transport through a packed bed of JSC-1A at temperatures and pressures relevant to in-situ resource utilization (ISRU). The results were modeled with a piecewise function to capture the transition and Knudsen flow regimes. This work was expanded to study lunar highland (LHS-1) and lunar mare (LMS-1) simulants from the CLASS SSERVI node. The normalized diffusivity measurements approach the predicted Knudsen diffusivity for both simulants. Water extraction from lunar regolith was also modeled using a three-dimensional thermal and gas diffusion model. Both surface heating and the insertion of heated drills were investigated for various heating power levels and expected soil ice fractions. The calculations rely on the use of the Crank-Nicolson finite difference method for the diffusion equations.

Figure 3: Experiments are underway examining the feasibility of extracting volatiles from the regolith using solar power. The principle of operation is shown in the top left figure. The simulator was calibrated to a thermal radiative flux of 35 kW/m2. Figure below documents the temperature of the apparatus. The low flux is necessary to avoid damaging the quartz window.



1.3 Development of an Indirect Solar Receiver for the Thermal Extraction of H2O(v) from Lunar Regolith: Experimental Testing

An indirect solar receiver for thermal extraction of water from lunar regolith was modeled, assembled and tested. Specifically, two solar selective and non-selective reactor surfaces were investigated to estimate thermal extraction efficacy for comparison. Based on these results, a test chamber, shown in Figure 3, was fabricated to allow a SiC absorber, imbedded in a bed of frozen lunar simulant with 0 – 7.5 wt% H2O(s), to be directly irradiated with a high flux solar simulator. The subsequent H2O extraction rate was measured with mass spectrometry. A desiccant H2O(g) trap was used with a moisture analyzer to integrate over the partial pressure curves coupled to overall evolved H2O mass to determine a transient sublimation rate.

> The modeling and test results indicate that substantial amounts of water vapor can be extracted using this process and should be easy to scale. The final lunar water extractor pod will be mechanically robust and likely more stable than polymer tents.

1.4 BIG IDEAS Challenge: Dust Mitigation Using EDS,UV Photoelectric Charging and Microarrays

Dust accumulation can be harmful to the physical health of astronauts by excessive inhalation and irritating sensitive sensory organs (eyes, ears, mouth, nose, airway, etc.). Dust can also be harmful to the mission itself by damaging and effecting the performance of essential equipment and disturbing experiments conducted by the astronauts. NASA launched a Big IDEAS challenge in 2021 to directly address the lunar dust issues NASA will need to solve for the planned Artemis mission, with specific attention towards mitigating damage to spacesuits. REVEALS team members contributed to two Big IDEAS Challenge teams, "Shoot for the Moon" at Georgia Tech and "Lunar Dust Mitigating Electrostatic Micro-Textured Overlay (LETO)" at the University of Central Florida. The GT project developed a hybrid dust mitigation brush using an electrodynamic dust shield (EDS) and photoelectric charging via ultra-violet (UV) radiation, as shown in Figure 4.

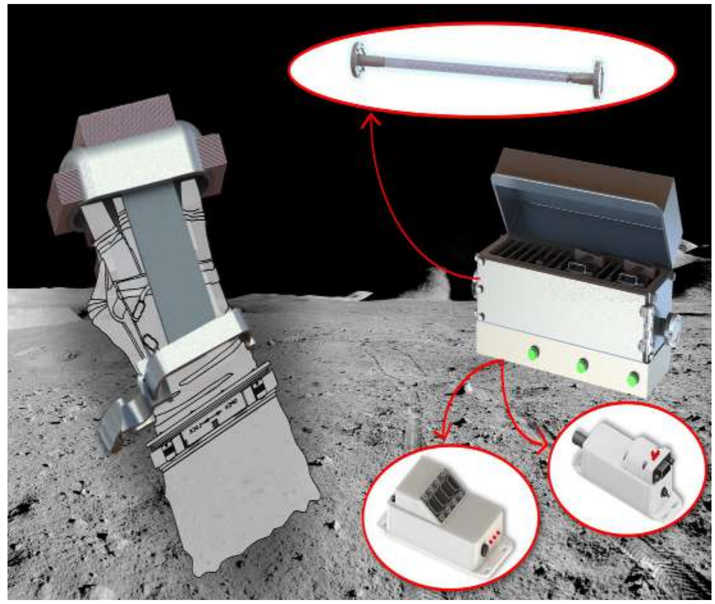


Figure 4: GT-EDS hand held brush with dust collection bin and plug-in power system.

The astronaut-centric ergonomic brush used a multi-stage dust mitigation process that consisted of 1) collecting dust between the bristles and electrodes by brushing, 2) using a UV radiation chamber to charge present dust particles, and 3) activating the EDS and thereby repelling the charged lunar dust. Dust adherence experimentation successfully replicated lunar dust lodging within the Thunderon brush bristles under high vacuum conditions and 2D EDS experiments using an interdigitated chip verified the electrostatic removal of LHS-1 simulant dust. UV exposure of lunar dust atop a 2D EDS chip removed the dust at a lower voltage.

> This materials science-based effort received the Best Technical Project award.

> A patent disclosure was filed on overall design concept and applied voltage forms and the project received the Best Human Factors Project.

The UCF LETO project focused on producing a spacesuit overlayer containing microstructure arrays that would repel dust passively as well as with the use of an applied electric field.

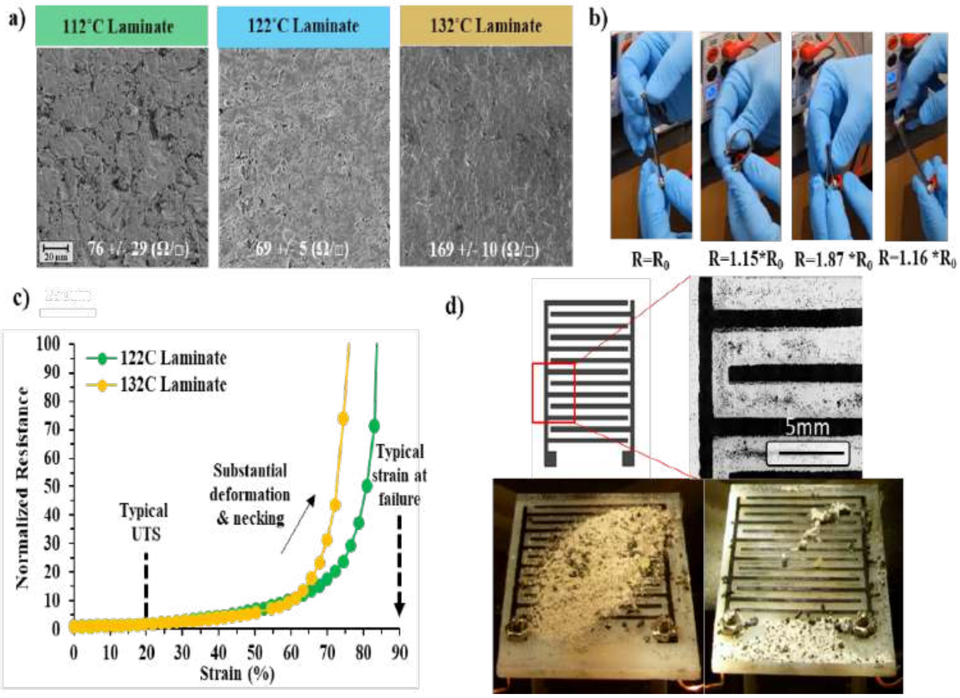


Figure 5: a) SEM images of processed laminates. b) Sequential images of a bend test performed on laminated material showing an increase in resistivity with bending and a recovery upon unbending. c) Normalized resistance as a function of strain for laminated samples. d) 2D EDS design and patterned laminate system showing removal of lunar simulant.

1.5 Graphene Polymer Composites for EVA Applications

A scalable method to produce chemically modified reduced graphene oxide (CMrGO) with high electrical conductivity (≈400 S/cm) and processability was developed. Previous work demonstrated good miscibility of these nanomaterials with space-relevant polymers (HDPE) and processing flexibility due to dispersibility in numerous solvents. Laminated composites, shown in Figure 5a, have reduced roughness and porosity, as well as improved consistency and high conductivity. Additionally, as shown in Figure 5b and c, these composites are mechanically robust to tension and flexion and maintain conductivity up to the substrate's mechanical limits. They therefore appear to be good candidates for spacesuit and inflatable applications. The flexibility of the processing technique also allowed us to create and test the prototype 2D EDS system as shown in Figure 5d.

1.6 Graphene FET and Metamaterials for Neutron Dosimetry

Using electron-beam lithography, several gFET prototypes were fabricated, with graphene stacked under or above thin hexagonal boron nitride (hBN) layers. Monoisotopic h10BN and h11BN single crystals were grown in-house and exhibit high quality (characterized by x-ray photoelectron spectroscopy, Raman spectroscopy, and UV-Vis absorption measurements). These stacked metamaterial devices (graphene on hBN) were fabricated as test prototypes for sensitive neutron detectors based on radiation-induced changes in resistivity. Real-time resistance measurements of these prototypes using the D-D neutron generator (2.5 MeV, ~5E10 neutrons/sec) in Georgia Tech's Radiological Science and Engineering Lab demonstrated functional responses.

1.7 Effects of Cooling Garment on Radiation Protection and Astronaut Performance

The REVEALS Team is investigating effects of a spacesuit cooling garment on radiation protection, exercise performance and perceived exertion. The project incorporates a layered approach to spacesuits combining radiation protection and thermoregulation. Next steps are to increase internal water distribution for increased protection of vulnerable

> The aim is to use on-board additive manufacturing to create metamaterial devices for resistive sensing of radiation and for radiation shielding. Such metamaterials, at least partially sourced via ISRU, would be useful for lunar construction and beyond, e.g., in the Moon to Mars Planetary Autonomous Construction Technologies program (MMPACT).

Figure 6: Dr. Dunn, REVEALS team testing the functionaly of the cooling garmet design at Johnson Space Center.

and sensitive organs from Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs) that pose serious health risks to astronauts. Performance testing was also carried out to determine thermal stress baselines on human performance. Certain materials, such as the graphene composite materials developed by REVEALS can help to reduce radiation intake and improve heat transfer from the body. For all these materials to come together, system requirements need to be analyzed. This includes the understanding of heat loss from the body and which region produces the most heat, as well as understanding which parts of the body are at the most risk from radiation poisoning.

REVEALS team members are also examining the neuromuscular mechanisms mediating human performance under extreme conditions. Their work has highlighted the application of a cooling garment discussed above on exercise performance, cognition, and neuromuscular function. Understanding the influence of acute ischemic hypoxia and systemic hypoxemia on muscle and cognitive function are important for astronaut health during long duration spaceflight.

2. Inter-team/International Collaborations

CLASS Collaborations: Regolith Shielding, Volatile Transport and Dust Mitigation

Collaborations with Britt (UCF) continue on understanding the thermal production, transport and release of water and other volatiles from lunar and asteroid simulants. These are developed in the CLASS EXOLITH lab and are being used by several REVEALS team members in measurements of diffusion and transport coefficients of volatiles such as hydrogen and water in regolith. Britt (CLASS-PI) is also a member of the REVEALS advisory board.

LEADER, RISE2 and IMPACT Collaborations: Health Effects of Charged Dust Grains

Schaible is working with IMPACT and LEADER in developing an apparatus and testing protocol to examine the effects of grain charging on health. Specifically, the program mainly examines the interaction of charged grains with surrogate lung membrane surfactants. The program is generally geared towards understanding and controlling grain charging effects on chemistry. It is continuing with shared support for Schiable involving LEADER. Note Farrell (LEADER Co-I) is also a member of the REVEALS advisory board. Schiable and Orlando have also been interacting with RISE2 with respect to characterizing and understanding the surface defects and reactivity on lunar simulant grains.

LEADER Collaboration: Micrometeorite Formation of Water

Jones and Orlando are working with Sarantos (LEADER) to examine and model the formation of water from micrometeorite impact events. This uses the known micrometeorite impact rates and the activation energies and transport rates measured by the REVEALS team.

University of Georgia, Department of Physics

Abate's group probes the optical properties of meta materials with scanning probe FTIR and scanning photoluminescence in the nanoscale. A collaboration with Orlando and Schiable on examining space weathering effects at the single grain level has been carried out on terrestrial samples and on several lunar samples with various degrees of maturity.

NASA-MSFC

Based on a SSERVI sponsored US Provisional Patent, a NASA-MSFC cooperative agreement began in Sep. 2021 leveraging REVEALS-developed IP. The aim is to create metamaterials for resistive sensing of radiation and for radiation shielding, using novel 2D and topological materials. Chemically-modified reduced graphene oxide combined with commercial hexagonal boron nitride nanoparticles are under investigation as the basis for additive manufacturing of neutron sensors and shielding. Such metamaterials, at least partially sourced via ISRU, would be useful for the Moon to Mars Planetary Autonomous Construction Technologies program (MMPACT).

3. Public Engagement Report

3.1. Student Summer Programs:

The "Structural Engineering Summer Program: Truss Me, Designing Structures is Fun!" was held July 1- 14, 2021. The camp used the app "Truss Me" developed by Rimoli, which was designed as a virtual lab to help students understand concepts of structural mechanics usually difficult to convey with traditional teaching approaches. The app is based on a state-of-the-art simulation engine to provide the most realistic experience. It was also presented within a gaming environment to keep students engaged. The format of the camp was virtual (online) and delivered by imoli and two graduate students, a Latino male and one female, to provide diverse role models to the students. Student demographics in total: 16 rising 8th- through 12th-grade students from Lovejoy High School (n=5), Paul Duke STEM High School (n=3), Meadowcreek High School (n=3), McClure Health Science High School (n=1), Johns Creek High School (n=1), Tucker High School (n=1), Lilburn Middle School (n=1), and "LMS" (n=1) attended this online summer program. Approximately 62% of the students were male and 38% female. Approximately 50% of the students were Hispanic or Latino, 37% African American, and 13% white.

The "STEAM Research Academy" was held in July 1-18, 2021. This focused on preliminary designs and testing of a lunar lander equipped with a robotic sampling scoop/arm. Students were afforded opportunities to learn about real-world engineering problems and upcoming lunar missions, alongside scientists in the mist of conducting current research. Students also competed in an end-of-camp tournament luncheon judged by REVEALS facilitators and experts in the community. The program was well received and celebrated by both parents and community partners.

Students in both camps were also afforded a virtual opportunity to learn about the upcoming Artemis Mission from professional staff associated with the Artemis Team Chat – organized by Pris Johnson-KSC. This was an unique opportunity for students to get first-hand knowledge of the planned Moon explorations efforts directly from Artemis team members.

3.2. K-12 School Presentations and Tutoring

Beltran contributed to the stem CONNECT program in Florida 4-8th grade classrooms, a program particularly involved in targeting underserved communities, and at the Women in Science Club, California middle schoolers, January, 2021.

Brant Jones has been providing academic support to underserved youth at A+ Squash in Atlanta, GA. A+ is a community program designed to help students graduate high school and grow into exemplary leaders. This is accomplished through physical fitness, academic growth and civic engagement.

Media Attention: The ongoing work between Beltran and Hill has received media attention. Specifically, the NASA-related work performed by Hill and his laboratory on cooling garments has received university-wide attention (https://www.ucf.edu/news/ucf-researcher-aims-to-preserve-astronauts-muscle-function-in-space/) and their work has been televised (https://www.mynews13.com/fl/orlando/news/2021/04/18/ucf-muscle-research-needed-to-help-send-astronauts-to-mars).

The Georgia Tech Big Ideas "Shoot the Moon" team effort on developing a dust mitigation brush was featured on the Atlanta 11Alive TV News Coverage. It was also posted on the NASA SSERVI web-site https://www.11alive.com/article/news/community/georgia-tech-students-designing-space-technology/85-8b227d44-4386-4fea-b0e6-cb422c539564

Figure 7: STEAM Research Academy students engaged in summer camp and simulating lunar landings.

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

STEAM Research Academy: Freedom Middle School: Approximately 30 students participated in the Robotics competition and Truss-Me summer camps with the latter hosted at Georgia Tech. This STEAM Research Academy is situated at Freedom Middle School in DeKalb County. The academy was operated during the pandemic and provided a learning and nurturing environment for under-privileged students The school's population is one of the most diverse in the nation. Over 54 countries and 100 languages are represented within the student body. Freedom has Title 1 status; 100% of students receive free or reduced lunch. However, enrollment was open to all metro students, including those in private schools.

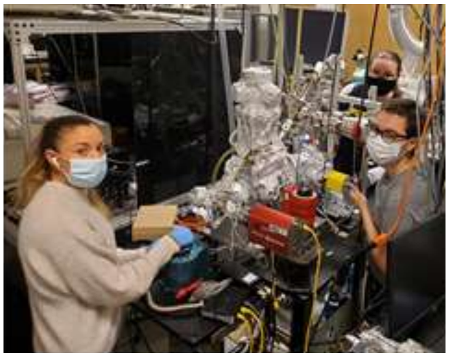
5. Student/Early Career Participation

Undergraduate Students

1. Josh Fisch, University of Chicago, Astrophysics/Pre-med. Summer Internship; partially sponsored by REVEALS and Florida Space Grant Consortium (FSGC). Simulations, background research.
2. Kathryn Carrieri, University of Central Florida, Mechanical Engineering. Senior Project Design.
3. Jacob Carver, University of Central Florida, Mechanical Engineering. Senior Project Design: Simulations/testing for EVA design of radiation/cooling vest.
4. Dennis Corraliza, University of Central Florida, Mechanical Engineering. Senior Project Design: Simulations/testing for EVA design of radiation/cooling vest.
5. Cody Hagemes, University of Central Florida, Mechanical Engineering. Senior Project Design: Simulations/testing for EVA design of radiation/cooling vest.
6. Grant Spence, University of Central Florida, Mechanical Engineering. Senior Project Design: Simulations/testing for EVA design of radiation/cooling vest.
7. Brandon Ortiz, University of Central Florida, Materials Engineering. Senior Project Design: Simulations/testing for EVA design of radiation/cooling vest.
8. Ryan Valmonte, University of Central Florida, Materials Engineering. Senior Project Design: Simulations/testing for EVA design of radiation/cooling vest.
9. Michael Pacocha, Georgia Institute of Technology, Physics. Laboratory assistant.
10. Patrick Connolly, Georgia Institute of Technology, Nuclear & Radiological Engineering. Simulations.
11. Nikolai Simonov, Georgia Institute of Technology, Physics. Laboratory assistant.
12. Burhanuddin Bhinderwala, Georgia Institute of Technology, Physics. Laboratory assistant.

Graduate Students

13. Hannah Lyons, University of Florida, Medicine. Summer Internship; sponsored by REVEALS and Florida Space Grant Consortium (FSGC). Analog Research, background research. (Partial support).
14. David Fox, University of Central Florida, Chemistry (nanotechnology). Testing nanomaterials for lunar regolith dust. NASA Big Idea Challenge. Laboratory assistant (Partial support).
15. Alex-Burnstine-Townley, University of Central Florida, Chemistry (nanotechnology). Testing nanomaterials for lunar regolith dust. NASA Big Idea Challenge. Laboratory assistant. (Full support).
16. Chris Proppe, University of Central Florida, Physiology. Laboratory assistant. Simulations/testing for EVA design of radiation/cooling vest.
17. Paola Rivera, University of Central Florida, Physiology. Laboratory assistant. Simulations/testing for EVA design of radiation/cooling vest.
18. Connor Westcott, University of Central Florida, Computer Engineering. Simulations. Laboratory assistant.
19. Kristoffer Sjolund, Georgia Institute of Technology, Physics. Graduate student, School of Mechanical Engineering, Big IDEAS EDS Brush project lead (full support).
20. Emily Ryan, Georgia Institute of Technology, School of Materials Science and Engineering, Ph.D. candidate, 2D meta-materials synthesis and characterization (full support).
21. Christina Buffo, Georgia Institute of Technology, School of Chemistry and Biochemistry, Ph.D. candidate in Chemistry. IR spectroscopy of radiation-processed icy lunar grains (full support).
22. Ashley Clennenden, Georgia Institute of Technology, School of Physics, Ph.D. candidate in Physics. Formation and release of water and oxygen from lunar regolith. (full support).
23. Aintzane Castarlenas, Georgia Institute of Technology, School of Chemistry and Biochemistry, MS candidate. Formation and release of water from solar wind implantation (full support).



Graduate students Aintzane Castalenas, Ashley Clennenden and Christina Buffo assembling the REVEALS solar wind irradiation chamber at Georgia Tech. The proton irradiation source is used to implant protons into surrogate and actual Apollo samples under ultrahigh vacuum conditions followed by thermal heating to produce molecular water.

Chris Proppe and Paola Rivera, working on simulations/testing for EVA design of radiation protection/cooling vest at Dr. Hill's lab, UCF. It has received media attention, featured on UCF News and on TV. Peer-reviewed papers to journals have been submitted and published.

24. *Garret Schieber, Georgia Institute of Technology, School of Mechanical Engineering, Ph. D. in Feb. 2021- Thesis work: ISRU modeling, measurement and technology design (full support). Garrett accepted a postdoctoral fellowship with CLASS and then accepted a full-time appointment with Blue Origin.
25. Faris Almatouq, Georgia Institute of Technology, School of Physics. gFET radiation sensors (fellowship support).
26. Zachery Enderson, Georgia Institute of Technology, Scholl Physics. 2D COF materials (partial REVEALS support).

Postdoctoral Fellows

27. Joshua Lehman, University of South Florida, Emergency Medicine. Subject Matter Expert, NASA-Flight medical team. Consultant. Partial support.
28. *Zach Siebers – Georgia Institute of Technology. Zach accepted a position with Exponent- role is to increase materials science efforts for space exploration applications.

New Faculty Members

29. Julie Brisset, University of Central Florida/FSI, Engineering/Physics. Simulation testing for lunar water extraction/ISRU.
30. Ethan Hill, University of Central Florida, Kinesiology/ Physiology. Simulations for EVA design of radiation/ cooling vest.
31. Rosario Gerhardt, Georgia Institute of Technology., Materials Science, Dielelectric function measurements of icy regolith.
32. Yohannes Abate, Univ. of Georgia, High resolution optical mapping spectroscopy and physics of 2D materials.

6. Mission Involvement

Karl Hibbitts at APL is Deputy PI of the Mapping Imaging Spectrometer for Europa (MISE) instrument onboard NASA's Europa Clipper spacecraft. The SSERVI work on lunar polar regions is relevant to Hibitt's efforts on Europa ice and non-ice material. Orlando and Jones are working with the PRIME-1 and VIPER MSOLO team on modeling transport and release of water from lunar regolith. Beltran is working with the VIPER team on outreach/citizen science projects. Schaible was involved with the JAXA MMX mass spectral analyzer (MSA) instrument team. The collaboration built on work started as part of the SSERVI DREAM2 led Phobos Regolith Ion Sampling Mission (PRISM) SmallSat mission concept study.

7. Awards

1. Doctoral student Rivera awarded "Best in Category" for her NASA REVEALS-related work. Dr. Hill's student Ms. Paola Rivera wins UCF award for research presentation, "Local versus systemic hypoxia: differences in neuromuscular function during exercise."

2. GT, School of Physics, Doctoral student, Faris Almatouq, won first place (tie) in the 2021 NASA NESF/ELS Student Poster Competition. "Utilizing Hexagonal Boron Nitride and Graphene Field Effect Transistors for Neutron Dosimetry," F. Almatouq, Z. Jiang, P. N. First, and T. M. Orlando, NASA Exploration Science Forum (NESF) & European Lunar Symposium (ELS), [VIRTUAL due to Covid-19], July 20-23, 2021.

3. GT, School of Mechanical Engineering Graduate Student Kristoffer Sjolund, et. al, won first place (tie) in the 2021 NASA NESF/ELS Student Poster Competition. "Hybrid Dust Mitigation Brush Utilizing EDS and UV Technologies," NASA Exploration Science Forum (NESF) & European Lunar Symposium (ELS), [VIRTUAL due to Covid-19], July 20-23, 2021.

Remote, In-Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2)

Timothy Glotch
Stony Brook University, Stony Brook, NY

CAN-3 TEAM

1. RISE2 Team Report

1.1. Theme 1 – Preparation for Exploration: Enabling Quantitative Remote Geochemical Analysis of Airless Bodies

In Year 2, the RISE2 Theme 1 team continued work on several projects relating laboratory spectroscopic measurements to remote sensing data. Our work has focused on continued application of simulated airless body environment (SAE) spectroscopy for direct comparison between laboratory thermal infrared (TIR) spectra and remote sensing data from the Moon and asteroids and near-field infrared (nano-IR) model development and data acquisition for ordinary and carbonaceous chondrites. We have also begun work to directly compare and test the abilities of the commonly used Hapke and Shkuratov models for analysis of visible/near-infrared (VNIR) spectra of asteroids.

1.1.1. Simulated Airless Body Environment Spectroscopy

Working with PI Glotch, Stony Brook graduate student Laura Breitenfeld completed a laboratory study designed to provide a training set for a multivariate machine-learning based analysis of OSIRIS-REx Thermal Emission Spectrometer (OTES) data. Because Bennu's surface is a complex mixture of coarse and fine particulates, standard TIR linear mixing models do not provide accurate estimates of the asteroid's mineralogy. Breitenfeld acquired TIR spectra of hundreds of mineral mixtures similar in composition to CI and CM chondrites in a simulated asteroid environment. She then applied a machine learning model based on these data to the average OTES spectrum of Bennu and benchmarked the model using spectra of CI and CM chondrites with known mineralogies. The results of this study are summarized in Figure 1, which shows the derived compositions of Bennu and several chondrite meteorites. Overall, the model predicts that samples of Bennu will have similar phyllosilicate abundances, higher carbonate and magnetite abundances, and less pyroxene than most meteorite analogs in our sample collection.

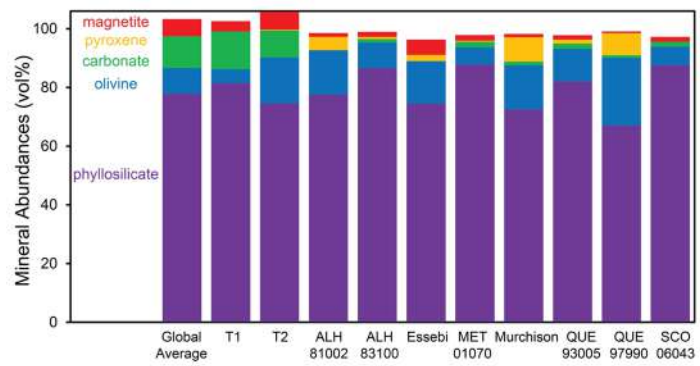


Figure 1. Mineral abundances (vol%) of the global average, Type 1, and Type 2 OTES spectra from machine learning predictions compared to carbonaceous chondrite abundances from quantitative X-ray diffraction data.

1.1.2. Near-field Infrared (Nano-IR) Spectroscopy and Model Development

Co-I Mengkun Liu and postdoctoral researcher Xinzhong Chen have continued working in Year 2 to refine models of the near-field interaction of sample surfaces and the nano-IR atomic force microscope (AFM) probe tip that enables infrared measurements at 20-30 nanometer spatial scales. Due to the strong electromagnetic interaction between the AFM tip and sample surface, nano-IR spectra are typically distorted and shifted compared to their traditional far field reflectance or absorbance counterparts. Their work advanced in Year 2 by incorporation of machine learning models to the analysis of interactions between the sample surface and AFM probe tip and the investigation of sample anisotropy on nano-IR spectra. The latter project is particularly important for interpreting nano-IR analyses of minerals, most of which are anisotropic. Mineral anisotropy causes light to interact with samples in different ways depending on the mineral's crystal orientation. This results in nano-IR spectra that vary as a function of the crystal's orientation in the sample. A major effort in the coming year will be to more fully characterize the variability of nano-IR spectra of common minerals to understand the potential impacts on spectral interpretation. In year 2, PI Glotch installed a state-of-the-art nano-IR imaging and spectroscopy instrument in his lab at Stony Brook University. This instrument, partially supported by

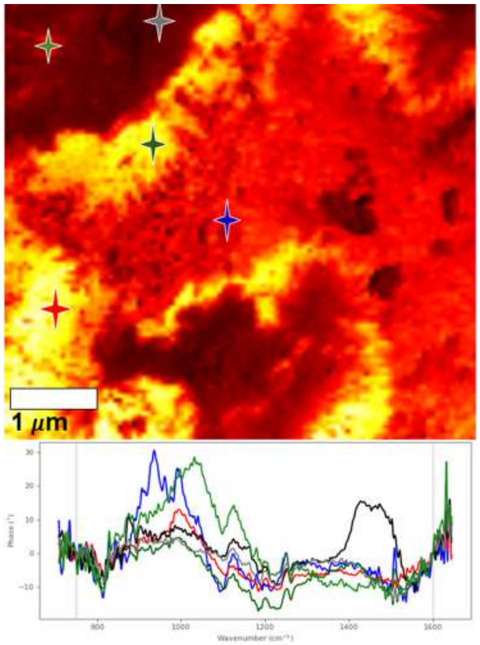


Figure 2. Broadband nano-IR image (top) and phase spectra (bottom) of a portion of CM2 chondrite NWA 12748. The image and spectra demonstrate compositional variability in the meteorite at <100 nm spatial scales.

SSERVI, is allowing us to substantially improve the quality and quantity of nano-IR measurements of extraterrestrial materials that we have been conducting. Our previous measurements were acquired at the Advanced Light Source synchrotron facility and were limited to about 10 days per year. Initial measurements of CM2 chondrite NWA 12748 made with the new instrument (Figure 2) show that while the meteorite is heavily altered, primary igneous minerals (pyroxene; blue, green, and red spectra) are still present in close proximity to chemically altered carbonate minerals (black spectrum).

1.1.3. Test of Hapke and Shkuratov Radiative Transfer Models

Co-I's Elizabeth Sklute and Tom Burbine have begun working with PI Glotch and Stony Brook graduate student Olive Koren to perform a statistically meaningful test of the Hapke and Shkuratov radiative transfer models using a set of VNIR reflectance spectra of hundreds of near-Earth and main belt asteroids made available by Co-I Burbine and Collaborator Rick Binzel. The Hapke and Shkuratov models are both commonly used by planetary scientists for the quantitative mineralogical analysis of remote sensing spectroscopic data. However, they make very different assumptions and simplifications in their solutions of the radiative transfer problem. To date there has been no systematic comparison of the models on a large data set. Co-I Sklute has been coding the models with input from Co-I Burbine and PI Glotch and graduate student Koren have begun to gather the necessary mineral optical constants that will be used as primary inputs into the models. In the coming year we expect to execute the first comparisons of the models to determine how they differ in the mineralogies that they predict.

1.2. Theme 2 – Maximizing Exploration Opportunities: Development of Scientific Field Methods for Human Exploration

The Theme 2 team has been hard at work to accomplish both our science and exploration objectives. Scientifically, we seek to constrain the eruptive history of the Kilbourne Hole (KH) maar crater in the Potrillo Volcanic Field (PVF), New Mexico, using field observations and a combination of in situ science instruments. Operationally, we seek to define Exploration Protocols and Concepts for Operation (ConOps) for how to deploy science instruments successfully during human exploration, especially with upcoming NASA Artemis missions.

1.2.1. Science Objectives: Distinguishing Volcanic Events with Portable Instruments

RISE2 objectives at KH seek to reconcile two different formation mechanisms for maar craters (single eruption

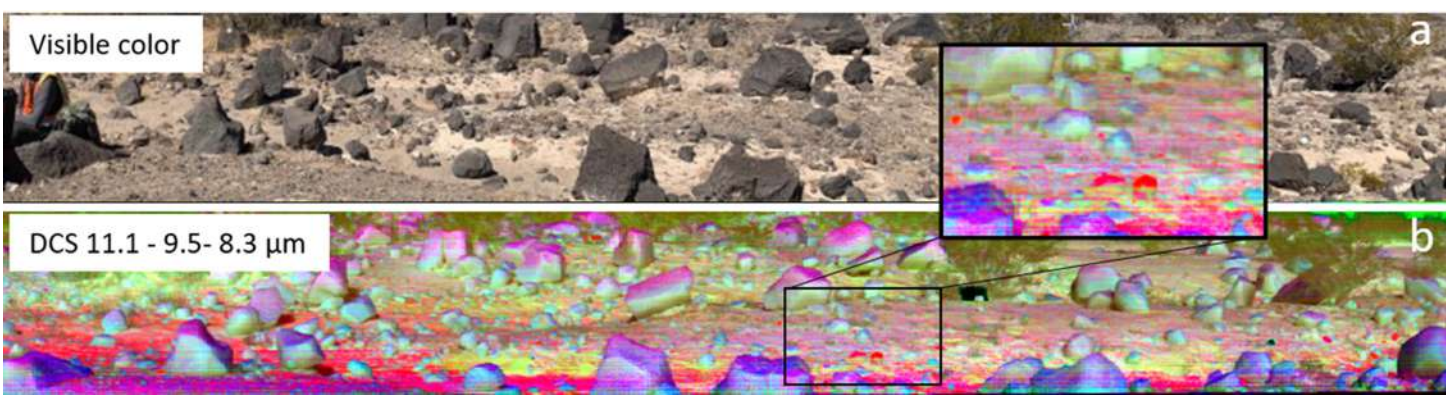


Figure 3. KH field data collected with the RISE2 hyperspectral imager (Lead: A.D. Rogers) during Nov 2021 field campaign. Data like this is used for both scientific and exploration objectives. (a) Visible panorama of boulders, small clasts, soils, desert pavement, and sparse vegetation. (b) Decorrelation stretched (DCS) image using radiance at 11.1, 9.5, and 8.3 µm displayed as red, green and blue. Color variations indicate compositionally distinct materials. Area in inset is ~10 m distance from sensor. Abundant olivine and pyroxenite xenoliths (cyan) and silicic clasts (red) are found among larger basaltic boulders (purple and pink).

versus incremental growth), as well as determine the eruptive history of KH specifically. By obtaining field data on bedding, stratigraphy, grain size, mineralogy, and chemistry, we seek to constrain this history. Through fieldwork conducted at KH in November 2021, our team was able to conduct critical data in all these areas from multiple key locations around KH. Fieldwork included scouting for the most scientifically fruitful areas of KH, as well as working in field subteams structured around a) Geochemistry/Mineralogy, b) Topography (including LiDAR and Mapping), c) Uncrewed Aerial Vehicles (UAVs), d) Data (to feed our Operations objectives), e) Operations (to feed Operations objectives, f) Geophysics (a close collaboration with the GEODES SSERVI node), and g) Public Engagement. These subteams used not only field observations and measurements (such as mapping, stratigraphy, grain size, etc.) but also in situ science payloads (LiDAR, GPR, magnetometry, hyperspectral imager, VNIR, XRF, LIBS, and a variety of UAVs) to collect data to aid in eruptive history interpretation (Figure 3). The team is now hard at work analyzing these data in 2022 to answer these RISE2 scientific questions.

1.2.2. Exploration Objectives

RISE2 exploration objectives include both developing a ConOps for scientific human exploration with in situ science instruments and developing recommendations for science data processing, assimilation, visualization, and management. The November 2021 field campaign was the first RISE2 fieldwork (due to COVID). The data collected, described above, are critical for not only RISE2 science objectives but also for these exploration objectives. As our scientists are hard at work processing and interpreting field data in 2022, our Data and Exploration sub-teams are equally hard at work preparing for our 2022 objectives, which will include evaluating processed data products that are critical for not only future Artemis astronaut crews completing lunar surface scientific exploration but also planning future exploration scenarios that will form the basis of our RISE2 exploration work. 2022 will include fieldwork designed to prepare for these lunar surface simulations, with our scientists working in tandem with not only software developers but also human exploration engineers and flight controllers.

1.2.3. Other Accomplishments

Completing fieldwork during the COVID-19 pandemic has been a big challenge. Our RISE2 team has worked very hard to ensure the November 2021 fieldwork was conducted safely, and we worked with the GEODES and TREX SSERVI teams to compare COVID field safety plans. Additionally, our RISE2 field leadership worked with GEODES and the NASA Goddard Instrument Field Team to develop critical field safety documents, including a Field Safety Plan (including COVID planning), a Code of Conduct, and a Field Bill of Rights. Taken together, these documents ensure all field team members are safe and conduct fieldwork in an inclusive and welcoming environment. RISE2 will continue this work in future years.

1.3. Theme 3 – Protecting our Explorers: Understanding how Exposure to Lunar and Asteroid Regolith Impacts Human Health

In our second year, we focused on further evaluation of the toxicity of reduced lunar surface materials. This included, materials synthesis, reactivity analysis, and toxicological studies.

1.3.1. Synthesis and Analysis of Reduced Lunar Regolith Analog Materials

In Year 2, we focused on synthesizing, "space weathering," and characterizing individual components of lunar regolith, specifically olivine, ilmenite, and the vapor deposits formed during ilmenite basalt degassing (Apollo 74220 orange glass composition), while continuing to provide reduced LHS-1 and LMS-1 for toxicological studies. Olivine (Fe,Mg)2SiO4 is common in the lunar fines, so we have synthesized a spectrum of olivine compositions and roasted some of them in a stream of hydrogen at high temperature for use in reactivity and toxicological studies. We also synthesized ilmenite (FeTiO3), as it is another Fe-bearing mineral in the lunar fines that may pose a health hazard. Figure 4 shows the potential effect of space weathering, that is, effective reduction of ferrous Fe and its mobilization from ilmenite and the production of rutile (TiO2). Both ilmenite and the reduced products will be used for toxicological studies.

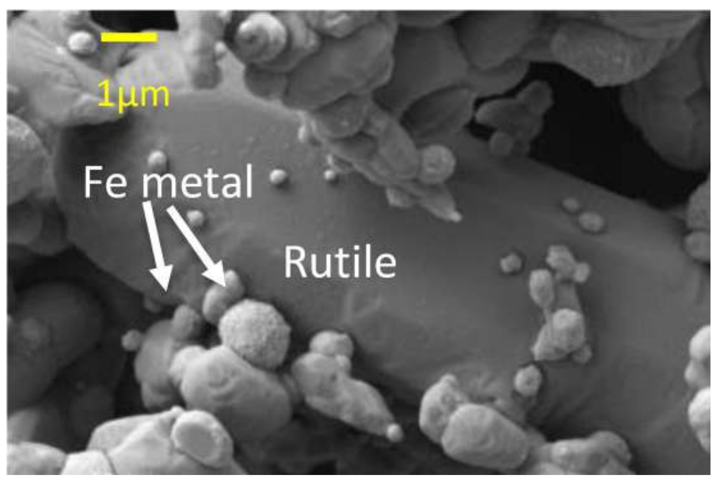


Figure 4. SEM image of products of reduction of synthetic ilmenite.

In order to assess the toxicity of vapor-deposited material that could be in the regolith in regions of high concentrations of pyroclastic glass beads, we simulated lunar fire fountaining of a magma of the composition of Apollo 74220 orange glass. The materials precipitated by the cooling magmatic gas simulate the types of fine-grained materials that were

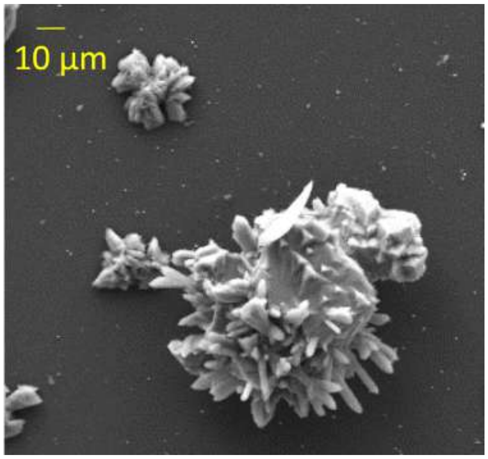


Figure 5. SEM image of vapor-deposited large magnetite crystal coated with Ge-rich Fe-silicate clusters.

added to the regolith fines during fire fountaining. Figure 5 shows an example of the vapor-deposited phases. The presence of magnetite (Fe2+Fe23+O4), an oxidized phase, as a vapor deposit from a reduced lunar magma is consistent with the discovery of magnetite in the lunar highlands that may be attributable to fumarolic activity. Further analysis will allow for the development of a set of materials produced by vapor-deposition for toxicological studies.

1.3.2. Lunar Regolith Analog Reactivity and Toxicity

In Year 2, we have finished measuring the OH* generation of lunar simulants, including heat treated/reduced samples, in deionized water, simulated lung fluid (SLF), and artificial lysosomal fluid (ALF). A significant decrease in OH* radicals were measured in both SLF and ALF which was attributed to either the interaction between generated OH* and amino acids in solution or the prevention of Fenton chemistry (OH* generation) via chelation of electrolytes to the surfaces of lunar dust grains. We have also measured OH* generation of synthetic olivine samples across the olivine solution series in both deionized water and in EDTA solution. Incubation in EDTA exhibited a substantial increase in OH* generation for all olivine samples except for forsterite (Fe-free olivine), which seems to indicate the possibility that Fe plays a substantial role in the generation of OH*.

We have continued our efforts to assess the impact of lunar regolith simulants on lung cell survival, DNA integrity, and mitochondrial function with new assays. We also began investigating whether Glutathione (GSH), a known antioxidant that can eliminate most free radicals, would affect the chemical (oxidative) damage caused by LMS-1 and LHS-1 simulants. Figure 6 shows the results when cells were pretreated with the indicated concentration of GSH for an hour, and then 0.5 mg/cm2 of dust load was added for 1-hour cell exposure. We have found a significant rise in cell survival in all groups.

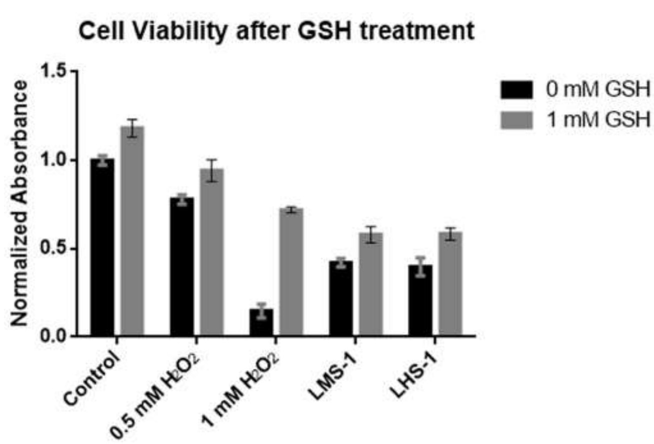


Figure 6. Cell viability when pretreated with glutathione (GSH) and loaded with 0.5 mg/cm^2 of dust. The cell viability is measured with a absorbance-based MTT (3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay and controls are normalized to 1. 0.5 and 1 mM hydrogen peroxide are used here as a positive control for the GSH treatment

1.4. Theme 4: Maximizing Science from Returned Samples: Advanced Synchrotron and STEM Analysis of Lunar and Primitive Materials

The Theme 4 team is dedicated to developing and applying new technologies for analysis of returned samples using microbeam methods.

1.4.1. X-ray Absorption Fine Structure (XAFS) Analysis of Element Valence States

In Year 1, we reported how we have implemented and tested the high energy-resolution fluorescence detection XAFS (HERFD-XAFS, 1-3 eV) system at beamline 13-ID-E, led by Theme 4 team members Tony Lanzirotti, Steve Sutton, and Darby Dyar, as well as GSECARS beamline scientist Matt Newville. This HERFD-XAFS system uses crystal analyzer spectrometers for measuring the fluorescence XAFS (1-3 eV resolution) rather than the energy dispersive solid-state detectors typically used (~130 eV resolution). In Year 2, we have begun using the new system to acquire HERFD Eu L-edge XAFS spectra from a suite of synthetic basaltic glass standards (synthesized by collaborator Molly McCanta, Univ. of Tennessee), synthesized at variable oxygen fugacity (fO_2). Spectra collected from these glasses demonstrate the improved energy resolution of spectra collected using this methodology, with spectral changes consistent with expected valence variability. These data will be used to develop new calibration models using Eu LαHERFD-XAFS for valence state oxybarometery, particularly applicable to lunar and martian igneous systems.

1.4.2. Investigation of Space Weathering, Coatings, and Impact Effects

Co-I Burgess and postdoctoral fellow Brittany Cymes continued to study variable effects of space weathering on mineral phases in lunar and asteroid return samples. Comparing Apollo 17 soils with different exposure conditions, they found that the abundance of npFe0 varies with exposure, and even detected solar wind He inside vesicular npFe0 grains with EELS. Olivine frequently shows Si-rich glassy rims containing npFe0, while Mg-rich rims are found on Ca-plagioclase and ilmenite. Other unusual space weathering features in these samples include Ca-Al-rich rims, spherical particles with unusual geochemistry, oxidized npFe+, and crystallinity-controlled npFe0 formation in pigeonite-augite exsolution lamellae (Figure 7). In addition, Co-I Burgess began analysis of space weathering rims of Hayabusa2 return samples from asteroid Ryugu, with preliminary results submitted for publication in early 2022.

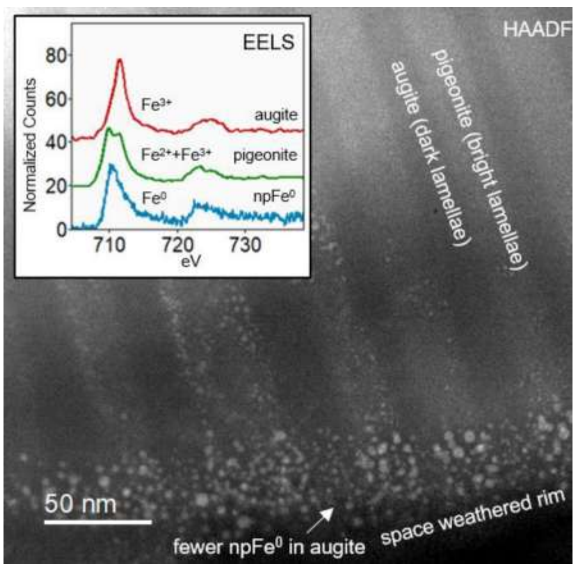


Figure 7. HAADF-STEM image of a space weathered rim of an exsolved pyroxene grain from Apollo sample 71501. EELS spectra (inset) reveal the Fe oxidation state of each phase.

1.4.3. Advanced X-ray Absorption Spectroscopy (XAS) and Scanning Transmission Electron Microscopy (STEM) Measurements of Returned Samples

In Year 2, Co-Is Stroud and De Gregorio refined their sample preparation and analysis protocols for working with regolith particles using crushed particles and insoluble organic matter (IOM) residues of carbonaceous chondrite meteorites. This expertise was applied to Ryugu samples to generate transmission electron microscopy (TEM) sections and other sample mounts for the Hayabusa2 IOM Initial Analysis Team. Subsequent scanning transmission X-ray microscopy-X-ray absorption near-edge structure (STXM-XANES) and STEM-electron energy loss-energy dispersive spectroscopy (EELS-EDS) measurements of these samples confirmed the sample preparation protocols successfully minimized contamination and damage while producing high quality sections for analysis. Preliminary results from these measurements were submitted for publication in early 2022.

2. Inter-team/International Collaborations

2.1. Inter-team Collaborations

The RISE2 team is dedicated to the concept of inter-team collaboration within the overall structure of SSERVI. Our experiences have provided evidence that the whole of SSERVI is greater than the sum of its parts.

2.1.1. Collaborations with the GEODES Team

During the fall of 2021, the RISE2 team successfully executed a field expedition to the Potrillo Volcanic Field in New Mexico. Members of the GEODES team participated in the field work and added their geophysical expertise to the RISE2 science and exploration efforts. The goal of this collaboration was to conduct a 2-D seismic, gravity, GPR, and magnetic profile of Kilbourne Hole to determine the nature of the subsurface dike that supplied the eruption with magma. The survey was designed to familiarize astronauts and participants with geophysical equipment and active sounding techniques.

As described in Section 5, we also worked with leadership of the GEODES team in the drafting of documents governing expectations of behavior in the field. These documents, including a Field Work Code of Conduct, a Field Safety Plan, and a Field Work Bill of Rights, are available to any other teams considering field work in the future.

2.1.2. Collaboration with the RESOURCES Team

PI Glotch continued work with RESOURCES PI Jennifer Heldmann and Darlene Lim to operate the SSERVI Analogs Focus group. This group now has over 100 members on its email distribution list. It hosts focus group meetings at the annual NASA Exploration Science Forum and, with the support of SSERVI Central's technical staff, runs quarterly seminars related to analog activities. These seminars are recorded and available for playback by any member of the public or scientific community. During 2021 PI Glotch organized and led a set of Laboratory Analogs lightning round talks for one of the seminars.

2.1.3. Collaboration with the REVEALS Team

We have been working with REVEALS team members to better understand the surface chemistry of pulverized and weathered minerals to better link minerals surface speciation to reactivity and chemistry. This collaboration has helped Stony Brook graduate student Donald Hendrix to interpret the results of mineral reactivity experiments. We have also begun work with the ICE-FIVE-O team, who will experimentally space weather lunar simulants using nanosecond pulse lasers and provide the materials to us for future reactivity and toxicity analyses.

2.2. International Collaborations

Drs. Gordon Osinski (University of Western Ontario) and Ed Cloutis (University of Winnipeg) have continued as RISE2 collaborators. Osinski is the PI and Cloutis is a team member of Canadian Lunar Research Network (CLRN), providing a link between the two teams. Osinski and his former student (now postdoctoral researcher) Gavin Tolometti will be key collaborators on RISE2 Theme 2 field work and Cloutis continues to collaborate with RISE2 Theme 1 team members on infrared spectroscopy of extraterrestrial and terrestrial analog materials. Osinski and Cloutis will again host (in person or virtually) undergraduate researchers funded by the RISE2 team during the summer of 2022.

Dr. Mehmet Yesiltas from Kirklareli University (Turkey) continues as RISE2 collaborator, working with PI Glotch on Raman and nano-IR spectroscopic measurements of ordinary and carbonaceous chondrites. He is a co-author on two papers by Glotch's former grad student Jordan Young that are currently in review in Meteoritics & Planetary Science and Journal of Geophysical Research – Planets. He has led several papers in the last year with Glotch as a co-author that are focused on nano-IR analyses of carbon and minerals in carbonaceous chondrite meteorites.

Dr. Neil Bowles (University of Oxford) is a RISE2 collaborator, providing a link to the UK and broader European Solar System science and exploration communities.

3. Public Engagement Report

In 2021, RISE2 connected with school groups and members of the public through a combination of virtual and in-person channels, significantly expanded its online presence by creating a team website and contributing to NASA's Planetary Analogs web content and worked throughout the year to prepare for the Spring 2022 Science Journalism Program at Stony Brook University.

3.1. Talks, Visits, and Events

Graduate students in Stony Brook University's RISE2-funded GradEdOutreach program, led by Laura Breitenfeld and Ella Holme, worked together with 5th graders at Nathaniel Woodhull Elementary to build model rovers in anticipation of Perseverance's landing on Mars. This project represents one installment in a sustained collaboration between GradEdOutreach and local schools in New York, including a series of Mars-science-themed interactions with classes at Nathaniel Woodhull.

Tom Burbine presented 'The Golden Age of Asteroid Observations' for the UCLA Meteorite Gallery Lecture Series on 11/21/2021. Ed Cloutis gave an invited lecture, 'Work at the University of Winnipeg's Planetary Spectrophotometer Facility', at the Royal Astronomical Society of Canada Winnipeg Branch on 9/10/2021. Caela Barry joined students in grades 3-8 at Kopernik Observatory in Vestal, NY for a STEM-career-focused discussion on 11/11/2021. Barry also serves year-round on the International Observe the Moon Night Coordinating Committee (https://moon.nasa.gov/observe). International Observe the Moon Night 2021 took place on October 16 and included an estimated 500,000 observers in 122 countries on all 7 continents.

3.2. RISE2 and Cross-Team Web Content Development

The RISE2 website, launched in 2021 (https://www.stonybrook.edu/commcms/rise2/) provides a high-level overview of each RISE2 science theme and a running list of peer-reviewed publications. Additional development is ongoing. Throughout the year, team members also contributed to the development of new public-facing NASA web content focused on geologic analogs in planetary science (https://solarsystem.nasa.gov/planets/planetary-analogs/), led by Barry and former GEODES SA/CS/PE lead Nicole Whelley. The NASA Planetary Analogs landing page launched in February 2021, followed by an interactive gallery which invites visitors to compare analog field work sites side-by-side with similar environments on other worlds.

Figure 8. Tweet highlighting collaboration between Stony Brook University and Nathaniel Woodhull Elementary.

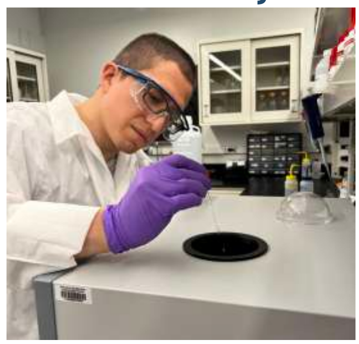
Figure 9. Screenshot of an interactive image pair comparing research sites in Hawaii and on the Moon, from NASA's Analog Explorer gallery.

3.3. Training the Next Generation of Science Journalists
PI Tim Glotch, SBU Professor Zachary Dowdy, and public engagement lead Caela Barry worked with representatives of each science theme to integrate RISE2 research into the curriculum of Stony Brook's Spring 2022 Science Journalism program. This course connects undergraduate students with scientists through guest lectures, virtual lab visits, and an in-person field expedition opportunity. Course participants will come away with an understanding of the science research process, including aspects of funding and logistics systems. Students will hone their science journalism skills by reporting on RISE2, and their stories about the team's work will be publicly available online.

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

1. Field Safety and Bill of Rights Documents, Stony Brook University, University of Maryland, NASA Goddard Space Flight Center. We worked with representatives from several field teams to develop field safety and bill of rights documents that will be required for all team field activities undertaken by RISE2, GEODES and the Goddard Instrument Field Team (GIFT).
2. Deanne Rogers and Tim Glotch (Stony Brook University Department of Geosciences) co-founded the Department of Geosciences EDI committee in 2020 and continued to serve as chair (Glotch) and faculty committee member (Rogers).
3. Rhonda Stroud (Naval Research Laboratory) participated in a virtual panel discussion at the Women in Microscopy Conference, March 8, 2021, hosted by Northwestern University.
4. Kate Burgess (Naval Research Laboratory) participates in meetings of the NRL Inclusion and Diversity Council.
5. Tom Burbine (Mount Holyoke College) participated in graduate school and undergraduate internship panels hosted by the College.
6. As VEXAG Chair, Darby Dyar (Mount Holyoke College/PSI) is currently involved in an active push to get LPSC to rotate out of Texas to make it more geographically accessible to a wider portion of our community, and to find a venue where are attendees can have a sense of personal safety.
7. Reading and Discussion Series, SSERVI EDIA Focus Group. Public engagement lead Caela Barry organized and facilitated a Reading and Discussion Series for the SSERVI EDIA Focus Group. This included four small-group discussions, plus an end-of-series debrief, to support informal learning about EDIA topics. Meetings took place between April and July 2021. Themes and featured content (publications and other media) were selected based on suggestions from the Focus Group. Participants in the final discussion assembled a set of recommendations for improving accessibility at SSERVI's virtual NESF 2021.

5. Student/Early Career Participation



Student Profile: Donald Hendrix
Donald Hendrix is a 6th year Ph.D. student at Stony Brook University working with Prof. Joel Hurowitz as part of the RISE2 Theme 3 group. Donald's work has consisted of using chemical methods to understand the hazards of lunar dust exposure to prepare future lunar astronauts for travel to the lunar surface. For the Apollo missions in which dust was a nuisance, it was reported that dust emanated a "gunpowder-like" smell. The dust irritated astronauts' skin and eyes and induced allergy-like responses upon inhalation. Because lunar dust represents a health and safety hazard, steps must be taken to both prevent exposure and understand the health and safety implications of lunar dust exposure.

To elucidate the mechanisms associated with lunar dust toxicity, Donald has pursued several avenues of research. His work initially used terrestrial minerals that are closely analogous to lunar mineral compositions. These samples were then milled into a fine-dust powder similar in size to what a human may inhale and accumulate in the lungs upon exposure to lunar dust. These mineral samples were then assessed for their ability to generate toxic chemical compounds in water-based solutions as a proxy for the chemical release behavior upon contact with lung fluid, which resulted in the determination that iron-rich lunar minerals may cause the most damage to human lungs upon exposure. Later work centered around olivine, a common mineral found on the Moon, and the dissolution over time in a salt and organic liquid mixture meant to replicate human lung fluid. A one-micron particle was calculated to dissolve in approximately 24 years if the particle is not cleared from the human lungs. Donald further increased the fidelity of his experiments by processing simulants with a heat treatment procedure to add metallic iron to the simulant particles. Donald found that the levels of toxic compounds generated by these artificially space weathered samples are far higher than those that have not undergone the process. This process allows for quick and cost-efficient means of generating samples similar to what are found on the Moon without the need to obtain precious Apollo samples or relying on “as-received” lunar simulants without the critical metallic iron component.

Student Profile: Laura Breitenfeld

Laura Breitenfeld is a 4th year graduate student at Stony Brook University working with Profs. Tim Glotch and Deanne Rogers as part of the RISE2 Theme 1 group and the OSIRIS-REx Spectral Analysis Working Group (SAWG) team. Laura’s work has pushed forward the state-of-the-art in using machine learning models to quantify mineral abundances from infrared remote sensing data. As a member of the RISE2 and OSIRIS-REx teams, Laura created a set of hundreds of carefully prepared mineral mixtures with compositions similar to those of CI and CM chondrites, which are spectrally similar to Bennu, the OSIRIS-REx target asteroid. She acquired thermal infrared emission spectra of each of the mineral mixtures under simulated lunar environment conditions using Stony Brook’s Planetary and Asteroid Regolith Spectroscopy environment chamber (PARSEC). Through the course of Laura’s work, she uncovered details of the thermal characteristics of very dark carbonaceous asteroid regoliths under vacuum conditions.

Laura’s laboratory work provided the basis for machine learning-based quantitative spectral unmixing of OSIRIS-REx Thermal Emission Spectrometer (OTES) data. Because the surface regolith of Bennu is a complex mixture of boulders and coarse and fine particulates, OTES spectra cannot be analyzed using traditional linear least-squares models. Instead, Laura’s laboratory data have been used in a nonlinear multivariate partial least squares (PLS) model to predict the abundances of individual minerals and mineral groups that comprise Bennu’s surface regolith. Laura’s results show that the surface regolith of Bennu is composed of ~80% phyllosilicates—primarily Mg- and Fe-bearing serpentine, which is in line with meteorite analogs. Her model also showed that Bennu’s regolith contains a greater amount of carbonate minerals and magnetite (an Fe-oxide) than typical CM carbonaceous chondrites, along with generally smaller amounts of pyroxene and olivine. The results of Laura’s model will be tested when OSIRIS-REx returns its sample of Bennu in September, 2023.

Laura’s initial work determined mineral abundances of Bennu’s regolith from average spectra acquired during different parts of the OSIRIS-REx remote sensing mission. She is currently working to determine the spatial distributions of minerals and mineral groups on the surface to provide a better understanding of the relationships between mineral composition and surface features on Bennu.

Undergraduate Students

1. Iman Khanan, Mount Holyoke College, VNIR spectroscopy.
2. Deepika Kumawat, Mount Holyoke College, VNIR spectroscopy.
3. Sydney Wallace, Mount Holyoke College, machine learning algorithms for asteroid classification.
4. Kim Vu, Stony Brook University, VNIR spectroscopy of chondrite-relevant mineral mixtures.

Graduate Students

5. Laura Breitenfeld, Stony Brook University, Outreach with local New York elementary schools, high schools, and community colleges.
6. Tristan Catalano, Stony Brook University, Synthesis of space weathered lunar regolith simulants.
7. Hsing-Ming (Jamie) Chang, Stony Brook University, Assessing the genotoxic and cytotoxic effects of lunar dust simulants on human lung cells.
8. Leonard Flores, Stony Brook University, Raman and nano-IR spectroscopy of CI and CM chondrite meteorites.
9. Marina Gemma, Columbia University, Simulated asteroid environment spectroscopy of ordinary chondrites.
10. Donald Hendrix, Stony Brook University, Assessment of the reactivity of lunar regolith simulants.
11. Reed Hopkins, Stony Brook University, Visible/near-IR spectroscopy of experimentally space weathered minerals.
12. Olive Koren, Stony Brook University, Development of mineral optical constants and light scattering models for quantitative characterization of infrared remote sensing data.
13. Gregory Smith, Stony Brook University, In vivo (intratracheal) exposure of mice to lunar regolith simulants.

14. Connor Tinker, Stony Brook University, Development of a dust deposition chamber for infrared analyses of dust-coated surfaces.
15. Zhouyiyuan Xue, Stony Brook University, Assessing the genotoxic and cytotoxic effects of lunar dust simulants on human lung cells.
16. Jordan Young, Stony Brook University, Raman and nano-IR spectroscopy of chondrite meteorites (now a Machine Learning Engineer at DataBook).
17. Wenjun Zheng, Stony Brook University, Near-field model calculations and simulations.

Postdoctoral Fellows

18. Xinzhong Chen, Stony Brook University, Near-field model calculations and simulations.
19. Brittany Cymes, Naval Research Laboratory, Study of space weathering features of Apollo 17 regolith samples via scanning transmission electron microscopy (STEM).
20. Casey Honniball, NASA Goddard, infrared spectroscopy and lunar remote sensing.
21. Zachary Morse, Howard University at NASA Goddard Space Flight Center, Geochemistry and mineralogy in analog environments, augmented reality to enhance human exploration.
22. Cheng Ye, Stony Brook University, Mineral optical constants and light scattering theory (moved to postdoctoral researcher position at Northern Arizona University with Co-I Christopher Edwards).

6. Mission Involvement

1. VERITAS, Venus Emissivity Mapper (VEM), Darby Dyar, Deputy Principal Investigator, use of machine learning algorithms developed with SERVII funding to interpret laboratory spectra that are analogs of the Venus surface.
2. OSIRIS-REx, Timothy Glotch, OTES, Participating Scientist Co-I, use of simulated asteroid environment spectroscopy techniques developed in part with SSERVI funding, for analysis of OSIRIS-REx Thermal Emission Spectrometer data.
3. OSIRIS-REx, Deanne Rogers, OTES, Participating Scientist Collaborator, use of simulated asteroid environment spectroscopy techniques developed in part with SSERVI funding, for analysis of OSIRIS-REx Thermal Emission Spectrometer data.
4. Hayabusa2, Brad De Gregorio, Organic Macromolecule Initial Analysis Team, performed ultramicrotomy and FIB sample preparation of Ryugu samples for several team members and performed STXM/XANES measurements on the same samples. Used sample preparation and measurement protocols developed directly from SSERVI work to accomplish these goals.
5. Hayabusa2, Rhonda Stroud, Organic Macromolecule and Sand Initial Analysis Teams, performed aberration-corrected STEM measurements of Ryugu samples for both teams. SSERVI research on meteorite analogs helped to ensure that this characterization could be performed without damaging these precious samples.
6. Hayabusa2, Kate Burgess, Sand Initial Analysis Team, performed aberration-corrected STEM measurements to characterize the mineralogy of Ryugu samples. SSERVI-developed knowledge was used to search for space weathering effects in space-exposed sample surfaces.

7. Awards

1. SSERVI Angioletta Coradini Mid-Career Award, Timothy Glotch, Stony Brook University, PI
2. National Science Foundation CAREER Award, Mengkun Liu, Stony Brook University, Co-I
3. Stony Brook Geosciences David E. King Field Work Award, Reed Hopkins, Stony Brook University, Graduate Student
4. Presidential Dissertation Completion Fellowship, Donald Hendrix, Stony Brook University, Graduate Student
5. Advanced Photon Source Users Organization Arthur H. Compton Award, Stephen Sutton, University of Chicago, Co-I. https://www.aps.anl.gov/APS-News/2021-03-31/rivers-and-sutton-of-gsecars-named-winners-of-2021-apsuo-compton-award/2021-03
6. Women in Aerospace Outstanding Achievement Award, Amy McAdam, NASA Goddard Space Flight Center, Co-I
7. Barringer Medal and Meteoritical Society Fellow, Gordon “Oz” Osinski, University of Western Ontario, Collaborator
8. Fellow, Microscopy Society of America, Rhonda Stroud, Co-I
9. J. F. K. Heinrich Award, Microanalysis Society, Katherine Burgess, Co-I

Toolbox for Research and Exploration (TREX)

Amanda Hendrix
Planetary Science Institute, Tucson, AZ

CAN-2 TEAM

1. TREX Team Report

The year 2021 was a successful year for the TREX team, as we continued in the pursuit of answers to science and exploration questions! TREX team members shared results and participated in numerous virtual workshops and conferences. Laboratory work progressed, toward the production of spectral libraries of terrestrial minerals and meteorite samples, ultimately for the analysis of remote sensing data of the Moon and small bodies, and for the characterization of those fine-grained surfaces in anticipation of human operations. TREX team members took part in numerous virtual public engagement activities. The dominant activity of the year was the preparation and execution of our first field expedition, which took place in northern Arizona during two weeks in November.

1.1. The TREX Fine-Particle Spectral Library

TREX Theme 1 focuses on spectral measurements, covering ultraviolet (UV) through mid-infrared (MIR) spectral ranges, of fine-particle (<10 βm) terrestrial minerals, meteorite and lunar samples, measured under planetary conditions (under vacuum and at appropriate temperatures). TREX labs at Univ. Winnipeg (UW), Planetary Science Institute (PSI), the Laboratory for Atmospheric and Space Physics (LASP) at Univ. Colorado, Mt. Holyoke, and DLR in Germany are all contributing measurements to this effort.

> The prime objectives of this study of fine particles are to
> 1) better interpret remote sensing data sets, and
> 2) take steps to characterize the dusty conditions at the Moon.

1.1.1. Terrestrial Minerals & Meteorites

The creation of the spectral library of 28 terrestrial minerals (Table 1) was nearly completed in 2021, with the continued production of “Frankenspectra” - i.e., composite spectra composed of UV to MIR datasets from the TREX labs (DLR, PSI, UW, LASP). These final spectra will be archived and published in 2022. These data are the first comprehensive suite of laboratory spectra under planetary conditions covering this wide spectral range.

In 2021, the remainder of the 12 TREX-requested meteorite samples (Table 2; slabs and chips of each) were received from JSC. Smaller slabs and particulates (<25 um and 63-125 um) were prepared. These samples were sent to RELAB (for VNIR and MIR reflectance measurements) and to Stony Brook University (for MIR reflectance and MIR emissivity measurements) (in lieu of traveling to DLR (Germany) during the COVID-19 pandemic). Other TREX labs (UW, PSI, Mt. Holyoke) will make measurements in 2022. Measurements at SBU were largely handled by RISE2 student Nandita Kumari.

TERRESTRIAL MINERALS:	
Forsterite Globe SSERVI	Ilmenite AA-30
Forsterite SC SSERVI	Kaolinite KGa-1b
Bytownite CB SSERVI	Labradorite ARSAA
Labradorite - Chihuaha SSERVI	Ca Montmorillonite STx-1b
Diopside - Herschel SSERVI	Na Montmorillonite SWy-3
Augite - Harcourt SSERVI	Nontronite NAu-2
Albite AL-1	Oldhamite AA-14
Anorthite AN-G	Palygorskite PFI-1
Enstatite Zen-1	Phlogopite Mica-Mg CRPG
Fe metal AA-70	Pyrite SA-25G
Graphite 7-11 um	Serpentine SMS-16
Hectorite SHCa-1	Serpentine UB-N
Hematite AA-30	Spinel ARSAA
Hematite SA-500G	Zinnwaldite ZW-C

Table 1. Terrestrial minerals, prepared in <10 micron grains, measured in TREX laboratories under vacuum at UV-MIR wavelengths

METEORITES:	
ALH 76001 (L6)	LAR 12326 (howardite)
ALH 83102 (CM2)	MAC 88102 (mesosiderite)
EET 79002 (diogenite)	MIL 07010 (L impact melt)
GRA 95205 (ureilite)	MIL 090001 (CR2)
LAP 10014 (EL6)	WSG 95300 (H3.3)
LAR 04316 (aubrite)	

Table 2. Meteorites measured, as slabs and particulates (<25 and 63-125 micron grains) in TREX laboratories under vacuum at UV-MIR wavelengths

1.1.2. UV Standards

Work on the platinum calibration standards continued in 2021. Co-I Holsclaw finished getting four glass disks coated in platinum (Fig. 1) at Univ. Colorado. These four disks vary in roughness, from a mirror-like surface to graduating coarser grit; however, studies of the scattering characteristics showed that they were not Lambertian, and thus not ideal for standards. Simultaneously, Co-I Clark prepared roughened three aluminum calibration targets; Holsclaw had these coated in platinum (Pt) at Univ. Colorado and then measured the scattering properties and found them to be more Lambertian than the glass disks. One of the Pt-coated Al disks was sent to TREX Collaborator Pearson at PSI who measured it versus Spectralon, aluminum, and gold. Work on the Pt standard is being finalized before manufacturing more for use by the community. We expect that these standards will be more reliable and stable than Spectralon in the UV.

Figure 1. A sample glass disk coated in platinum, an excellent calibration standard for UV-visible wavelength measurements.

1.2. Lunar and Small Bodies Studies

The Moon is the only Solar System body humans have visited, and a likely future human destination. As such, TREX goals are to characterize lunar grain size, mineralogy, thermal attributes, space weathering effects, and high priority geologic features with an overall aim of addressing ISRU, future instrument development needs, and informing future human and robotic lunar surface exploration. Furthermore, Near-Earth Objects (NEOs) and the martian moons are potential ISRU and human destinations. They evoke a number of critical questions regarding the diversity of their compositions and dynamical histories. Thus, the TREX team aims to characterize their regolith grain size, mineralogy, thermal attributes, and space weathering effects – with an overall goal of addressing ISRU and future instrument development needs.

1.2.1. Lunar Particle Size Map

TREX Co-Investigators Rebecca Ghent and Norbert Schorghofer, along with Collaborator Michael Aye, have been working on creating a map of lunar grain size - a non-trivial task. In 2021 they achieved an important milestone: they have finally developed an end-to-end procedure for calculating grain size by matching Diviner nighttime temperature observations to thermal model predictions for the very large Diviner dataset. They have also included the effects of local topography, which have a significant effect on the results. Michael has managed to streamline, optimize, and speed up this process to make it tractable. Steve Wood (PSI) is now working with them, contributing new conductivity expression from Wood (2020). They have successfully run two tests already and are now beginning additional model runs for a denser range of effective particle diameter values to further assess the results. This is a big project that will be wrapped up in 2022.

1.2.2. Ryugu Sample Measurements

As a Co-Investigator on the Hayabusa-2 mission, TREX DPI Faith Vilas had long been awaiting the arrival of Ryugu samples. This task came under the umbrella of the TREX project as it was decided to make UV measurements of the Ryugu samples. Preparation for sample studies proceeded throughout 2021, with tentative plans to go to Japan to measure samples in the UV in the June timeframe. Due to COVID-19, that plan was scrapped - but happily our Hayabusa-2 colleagues in Japan agreed to send us samples (unexposed to air!) so that we could make UV measurements of individual grains at our TREX partner labs at Univ. Illinois (see also Sec 6). Faith Vilas, Amanda Hendrix and grad student Camilo Jaramillo made UV-visible spectral measurements of 5 Ryugu grains, prior to being exposed to air, Sept 6-9, 2021. Analyses of the data are underway, along with further lab measurements of unexposed candidate materials to interpret the Ryugu data.

Jaramillo’s vacuum suitcase design allowed for the unprecedented UV-visible spectral reflectance measurements of individual Ryugu grains that had never been exposed to Earth’s atmosphere.

1.2.3 Other Projects

TREX Co-Investigator Tom Prettyman is carrying out simulations to support compositional corrections used in the determination of lunar hydrogen concentrations. Prettyman expects to wrap up the modeling work in the first few months of 2022. He plans a publication on the distribution of hydrogen in the Procellarum KREEP Terrane.

In their Lunar Accretion Model, TREX Co-Investigators Amy Mlinar and Ed Rivera-Valentin are creating a fully three-dimensional model of the growing Moon, including heating from impacts, deposition of heated ejecta, and cooling via radiation. The model will tell us the thickness of the initial magma ocean and how it depends on the accretion timescale for the Moon.

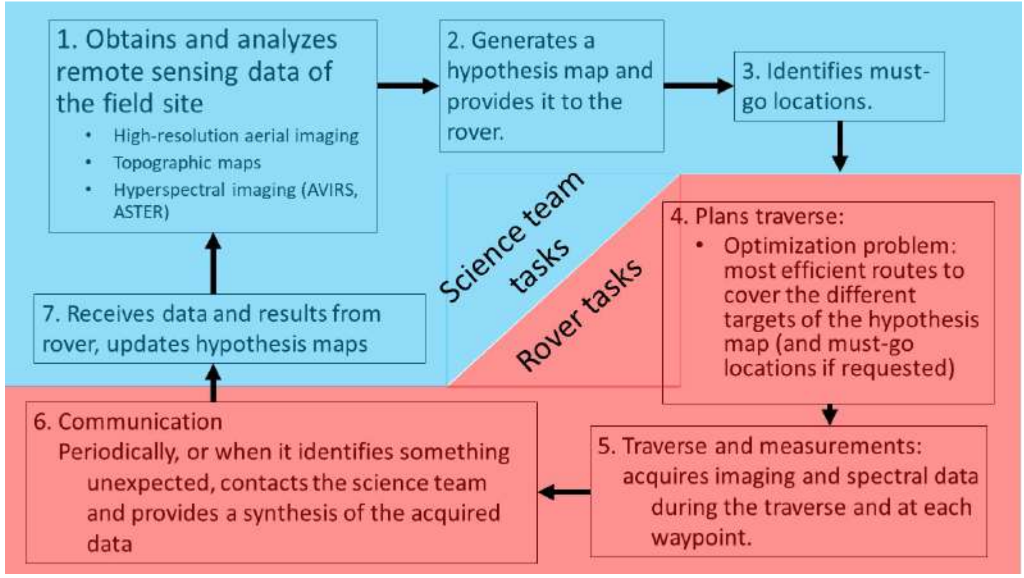


Figure 2. Graphical representation of the tasks of the science team and rover during TREX field exercises.

1.3. TREX Fieldwork

The TREX team originally planned on our first field expedition in April of 2020, and (due to the pandemic) it finally happened over the course of two weeks in November of 2021. TREX fieldwork was designed to investigate tools and techniques to improve operational efficiency and science yield of future rover missions to the Moon or small bodies. During field exercises, the team used a rover to explore both autonomously and interactively with a proxy astronaut. The rover (Zoë) runs advanced science analysis software (Tetracorder), analyzing and interpreting science data from several instruments to autonomously derive composition and geologic origin of the terrain over which it is traveling. Zoë makes onboard decisions about what it has found, where to go next and what route it should take. The intent of the field exercises is to compare the science yield and operations efficiency of

1) current robotic exploration strategies
2) a semi-autonomous robotic system and
3) an astronaut-in-the loop strategy (how can astronaut efficiency be maximized by the use of a robot?)

In preparation for the field activities, the TREX team performed a week-long Operational Readiness Test (ORT) in July 2021. During the ORT, we tested the fully integrated system, including rover operations and science room exercises. The test was designed to allow the science and rover teams to work together in a mock deployment to test out the rover's capabilities and train the teams on the use of tools that would be used in the actual field deployment. We tested our readiness to execute the tasks (Fig. 2), which describes the flow of activities pertaining to the rover and the science team. We also tested the ability of the rover to autonomously interpret spectroscopic observations as it performs measurements, and assess diverse formation hypotheses based on the spectroscopic interpretations. During the ORT, the rover and Carnegie Mellon-based rover team operated in a field site in Pennsylvania, while the science team operated remotely; communication between the field and science teams was primarily via Slack.

For the field work, the TREX team studied two field sites in northern Arizona. In preparation for the field work, the science team was tasked with performing a remote-sensing study of each of the field sites using hyperspectral data from AVIRIS and high resolution (< 1 m/pixel) images of the sites. The study resulted in the production of a hypothesis map. The hypothesis map represented the basis for decision-making and reporting undertaken by the robot. It contained a set of hypotheses to be explored (e.g., the geologic history of a field site), and observables that allowed these hypotheses to be weighted (e.g., mineralogy) as measurements were acquired and interpreted. Given this map and its associated uncertainties, the rover calculates and executes a traverse profile that optimizes for uncertainty resolution, terrain, and resources. Throughout the traverse, the rover performs observations with its instrument suite and interprets the data, stopping to contact the science team at predetermined waypoints or when it makes unanticipated findings.

Three operational scenarios were executed for comparison purposes at each field site:

Scenario 1) standard rover exploration paradigm where the science team chose waypoints. The rover was commanded to go to each waypoint, but chose autonomously the route to get there. At each waypoint, the science team (located at a science operations center in Flagstaff) chose imaging and where locally to obtain contact spectra, XRD measurements, microscopic images and other contact instrument data, based on what was seen in the rover camera images.

Scenario 2) The rover was set up for autonomous rover exploration, where it was commanded to go to a final destination waypoint, but chose the route and chose intermediate waypoints based on the hypothesis map supplied by the science team before field operations. At each waypoint the science team could request data from any of the instruments, based on locations selected in rover camera images.
Scenario 3) Autonomous rover operations as in Scenario 2 but with an astronaut deployed alongside the rover. The astronaut could explore independently and request data from the various instruments at outcrops.

TREX fieldwork broke new ground in 2021 in studies of autonomous robotic exploration for maximizing efficiency of human missions.

The two field sites were selected based on their traversability. The first site (Fig. 3) provided both the science and rover teams a training ground in which to practice operations and science analysis. It was selected for its geologic simplicity, and the existence of extensive literature on the geology of the rock units present at the site. The second site (Site 2) was more challenging from both operational and scientific perspectives and provided a more robust test of the autonomous science system.

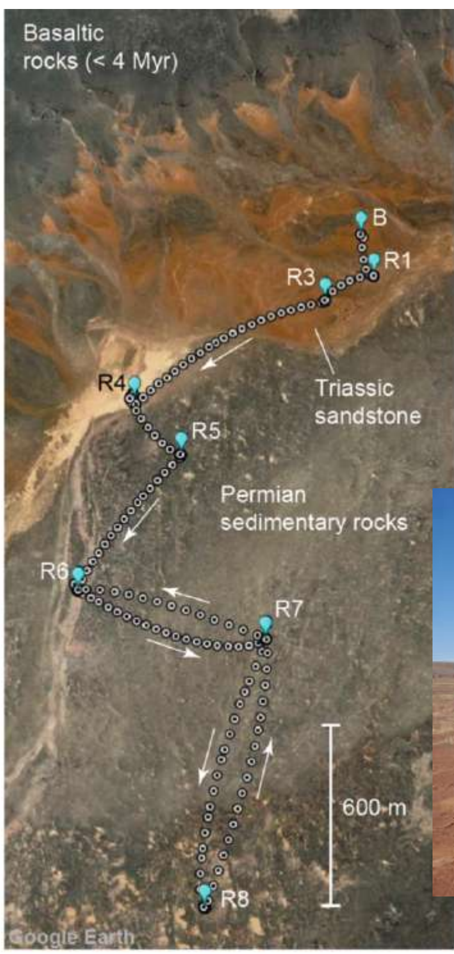


Figure 3. Field Site 1: The path of the rover (circles) and locations where the rover was approximately stationary (blue pins with labels) are shown. The study area, which is bounded to the north by basalts, contains a mixture of sandstone and limestone deposits.

The instrument suite (some integrated on the rover and some hand-held) includes spectrometers observing in the 0.2–14 μm range – a spectral region containing a broad range of mineralogically diagnostic features. A “microscopic” RGB color imaging camera provided close-up images of the locations where contact spectra were obtained (the “microscopic imager” was a cell phone camera). An X-ray diffraction (XRD) field unit was used to determine sample mineralogy at selected locations. Finally, a Gamma Ray Spectrometer (GRS) measured the radioelements K, Th, and U at regular intervals along the rover traverse. A central server was set up so that the rover and rover support field instruments could upload all operation and science data to the server so that the remote science team could monitor incoming data.

The automation achieved in these first field tests were successful. The automated science results from spectroscopy were a clear help in understanding mineral composition at each location in rapid time. In Scenario 2, the autonomous rover chose waypoints that were different than what the science team chose using the same beginning point and end point. In Scenario 3, the astronaut provided additional eyes on the ground, human experience and interpretation, enabling additional insights that the science team might miss based on limited data.

2. Inter-team/International Collaborations

- TREX team members Faith Vilas, Amanda Hendrix and Deborah Domingue are working with JAXA partners on the Hayabusa-2 mission to study samples from Ryugu in TREX labs on Earth. Initial measurements were made in August 2021; further measurements will be made in 2022.

- TREX Co-I Maria Banks is working with the GEODES team on a probabilistic seismic hazard analysis framework for the Moon; they are looking at lobate scarp thrust faults as potential targets for science investigation and especially as potential hazards. This work led to an abstract submitted to the first Lunar Surface Science Workshop, and led to a scarp location in the abstract being added as one of the Artemis landing sites under consideration.

Figure 4. The TREX field team with the rover Zoë at Site 1.

- TREX and RISE2 are collaborating on laboratory measurements (MIR reflectance) of TREX mineral and meteorites samples.

- TREX benefitted from the use and adaptation of the GEODES/RISE2 Fieldwork Code of Conduct.

3. Public Engagement Report

TREX Public Engagement Lead Sanlyn Buxner has taken advantage of this period of social distancing to organize several virtual public engagement activities. Here we outline a number of the outreach activities undertaken by the TREX team in 2021.

3.1. Howard University

The TREX team worked with Professor Marcus Alfred at Howard University to continue the program (started in 2020) of bi-weekly lunchtime meet-and-greet sessions with physics students. Members of the TREX team (listed below) met with interested students in the Department of Physics and Astronomy, to talk about what planetary scientists do and the different career paths that we each have taken.

February 12: Daniel Wolf Savin

April 2: Tom Prettyman

April 9: Deborah Domingue

April 16: Eldar Noe Dobrea

April 23: Becky Ghent

3.2. UP Workshops for Chabot Space and Science Center

The TREX team did training sessions with Galaxy Explorer volunteers at Chabot Science in Oakland, CA throughout the spring.

March 6: Amanda Hendrix - Water on the Moon??

March 13: Daniel Wolf Savin- The Genesis Project: Forming the First Star

March 20: Shawn Wright/Sanlyn Buxner - Surface Processes on the Earth, Moon, and Mars

March 27: Pamela Gay - Where is Water in the Solar System

April 3: JA Grier How Scientists Know “When Something Happened”

April 10: Deborah Domingue: Variety in Asteroid Surfaces

April 24: Tom Prettyman: Planetary Cores: Asteroid Connection

3.3. Other Outreach Activities

May 14: Tom Prettyman and Amanda Hendrix (and Brian Day and Jen Heldmann!) – Virtual “space exploration” outreach event for Almaden Country Day School in San Jose - Expanding a Dynamic and Gifted Education (EDGE) day

June 11: Dr. Becky Ghent gave a virtual presentation on June 7, 2021 for 18 students in Indigenous Physical Geology (GLG 101) at Diné College (Instructor Dr. Kevin Webster of PSI)

June 7: Sanlyn Buxner – In person presentation for youth 4 – 15 years; Mentally Ill Kids In Distress (MIKID), Tucson AZ, Hands-on Meteorites and Connections in the Solar System

June 30: Tom Prettyman – Virtual featured speaker for Asteroid Day hosted by Chabot Space and Science Center

July 12: Sanlyn Buxner presented at the Arizona Science Teacher Association Symposium

October 16: International Observe the Moon Night – support of local events various dates throughout the spring and summer: Amanda Hendrix organized the Planetary Outreach program at the Boulder County Farmers Markets

Fieldwork EPO: The TREX team engaged the public via Twitter during our field work, and “took over” the NASA Expeditions Twitter account in early December. Also, the TREX team invited NASA videographer Franklin Fitzgerald out in the field to capture the action on film. Franklin is currently assembling a piece on TREX fieldwork for NASA TV; the piece can also be cut up and used for outreach.

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

1. The SSERVI EDI Focus Group is led by TREX Co-investigator JA Grier. Several TREX team members regularly attend the Focus Group meetings (often held on Friday in 2021).
2. The TREX Fieldwork Code of Conduct placed great emphasis on inclusiveness and accessibility, which are very important to the TREX team.
3. TREX Co-I Lynnae Quick helped plan the 2021 National Society of Black Physicists (NSBP) meeting and arrange talks for the Earth and Planetary Systems Sciences section.
4. TREX Co-I JA Grier continues planning for the TREX Workshop for Disabled Writers, now planned for June 2022.
5. Several TREX EPO activities (Sec 4) are geared toward EDIA, including our Howard University program and our Chabot Space and Science Center program.

6. TREX Co-I Ed Cloutis has applied to host First Nations students in spectroscopy-related research this summer through University of Winnipeg programs designed to attract First Nations STEM students to the university and to provide them with opportunities to engage in research.

5. Student/Early Career Participation

Undergraduate Students

1. Brent Lorin, Johns Hopkins University, Whiting School of Engineering
2. Evan Lonsdale, Univ. Colorado, Electrical Engineering
3. Sophia Woznichak, Appalachian State University, modeling solar wind ion irradiation
4. Sahejpal Sidhu, Univ. Winnipeg
5. Stephanie Connell, Univ. Winnipeg
6. Alexis Parkinson, Univ. Winnipeg

Graduate Students

4. Alberto Candela, Robotics Institute, School of Computer Science, Carnegie Mellon Univ. (graduated Aug 2021)
5. Srinivas Vijayarangan, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.
6. Camilo Jaramillo, Nuclear Engineering Dept., Pennsylvania State Univ. (working in laboratory at Univ. Illinois)
7. Abigail Breitfeld, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.; worked with TREX team during fieldwork
8. Margaret Hansen, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.; worked with TREX team during fieldwork
9. Madison Borrelli, Arizona State Univ.; worked with TREX team during fieldwork
10. Cece Thieberger, Northern Arizona Univ.; worked with TREX team as a remote fieldwork documentarian
11. Wilson Jean-Baptiste, Howard University, Physics Ph.D. student (summer 2021); he worked on a project entitled: "Characterization of Cryogenic Muds on Ceres"
12. Daniel Applin, Univ. Winnipeg, Master's student
13. Nathalie Turenne, Univ. Winnipeg, Master's student

Post-Docs

14. Caitlin Ahrens, GSFC; worked with TREX team as a remote fieldwork documentarian

New Faculty Members

15. Alberto Candela, Jet Propulsion Laboratory, Robotics.
16. Kevin Edelson, graduated with MS from Robotics Institute, School of Computer Science, Carnegie Mellon Univ. in Dec 2020; currently working at JPL; may go back for PhD

Penn State graduate student Camilo Jaramillo designed and fabricated a "vacuum suitcase" for use in TREX laboratory experiments. Samples are loaded in an inert environment and sealed to contain the environment within the inert environment suitcase, which then can be transported. In 2021, Camilo's vacuum suitcase was used for a somewhat unexpected application: specialized UV Ryugu sample measurements. Each Ryugu grain was loaded into the suitcase in a glovebox to enable UV measurements of the grains without ever exposing them to the oxidizing Earth atmosphere. (left) Camilo (holding vacuum suitcase) with TREX PI Amanda Hendrix and DPI Faith Vilas; (right) a Ryugu grain in the vacuum suitcase.

6. Mission Involvement

- TREX Co-I Maria Banks was selected to serve as Project Scientist for CLPS Task Order 19D. For this Task Order, Firefly Aerospace will fly their Blue Ghost lander to Mare Crisium in 2023 with 10 NASA sponsored payloads (scientific instruments and tech demos). Banks is responsible for ensuring the success of the payload scientific investigations and objectives and is responsible for planning the surface operations ConOps and contingency plans, among other things. Banks is also supporting our return to the Moon as an invited member of several technical assessment teams within the over-arching Cross-Artemis Site Selection and Analysis Team (CASSA). NASA developed CASSA to ensure that the proper technical analyses are completed in order to identify a location for Artemis landings and the future development of a Base Camp. Banks supports the Human Landing System (HLS) Site Availability, Science Objectives, and Basecamp Site Planning and Logistics teams, and is co-leading the Data Assessment team. Banks' experience as a TREX Co-Investigator and Theme 1 helped lead to her CLPS involvement.
- The development work on Tetracorder (the expert

system for autonomous spectral identification of measured minerals) for TREX fieldwork helped clean up some aspects of the code and that has helped with other missions, including EMIT and MRO CRISM. Furthermore, work on past mission data sets has been improved. Specifically, new mapping of M3 data for the Moon is improved via Tetracorder development; a paper on this topic is in work (Clark et al.).

- Lavabug is a submitted PRISM2 mission proposal that followed closely from TREX work (Hendrix, Vilas, Clark, Banks, Prettyman); with REASON team members Tony Colaprete and Rick Elphic, and LEADER Co-I O.J. Tucker)
- Work developing autonomous navigation capabilities for TREX field experiments directly benefited knowledge and skills development and provided valuable test data and experience for the NASA LSITP MoonRanger flight project. Specifically, students and staff involved in both projects were better able to contribute to the flight program given their TREX experience.
- TREX-related work on spectroscopy of meteorites (and lunar samples in 2022) led to the success of co-investigator Ed Cloutis' team in proposing a CubeSat mission to study space weathering by exposing lunar samples and analogues and meteorites to the low-Earth environment and looking for any space weathering-related changes in spectral properties. The satellite will launch later this year.
- TREX-related work on spectral properties of samples led to Ed Cloutis' team being invited to join the upcoming PRISM Vertex mission to Reiner Gamma in 2024.

7. Awards

2021 AAS/DPS Harold C. Urey Prize, Lynnae C. Quick, TREX Co-investigator

The 2021 Harold C. Urey Prize for outstanding achievement in planetary research by an early career scientist is awarded to Dr. Lynnae C. Quick (NASA Goddard Space Flight Center). Dr. Quick's innovative scientific work focuses on geophysical processes writ large, reaching from the inner solar system, through the asteroid belt, to ocean worlds, and into the exoplanetary realm. She has revisited modeling of (cryo) lava domes on Venus and Europa, was the first to model the formation of Ceres' *bright spots* via the transport of material from a deep brine reservoir to the surface, has repeatedly provided new insights into plumes on Jupiter's moon Europa, and shed light on the abundance of extrasolar ocean worlds. In addition to her scientific pursuits, Dr. Quick is exceptionally engaged in the broader research community through her proactive leadership as a Co-Investigator on several space missions, as a member of the Outer Planets Assessment Group steering committee, the Planetary Science Decadal Survey 2023-2032 panel on ocean worlds and dwarf planets, and the National Society of Black Physicists. Dr. Quick's advocacy work to diversify the field is particularly notable. She has mentored many early career planetary scientists and is leading the Dragonfly Student and Early Career Investigator Program. Every aspect of Dr. Quick's career represents a positive outlook for the future of our community.

SUMMARY OF INTERNATIONAL COLLABORATIONS

SSERVI's International Partnerships Program provides collaboration opportunities for researchers within the global planetary science and human exploration community, working both on development of new science and technical approaches and communicating this science to the public. International partners are invited to participate in all aspects of the Institute's activities and programs. In addition, SSERVI's Solar System Treks Project (SSTP) has played a significant role in the institute's international partnerships and collaborative efforts are outlined in the sections below.

Non-U.S. science organizations can propose to become either Associate or Affiliate partners of SSERVI on a no-exchange-of-funds basis. Affiliate partnerships are with non-government institutions (e.g., universities and other research institutions). Associate partnerships are government-to-government agreements including those between NASA and international space agencies.

While SSERVI did not enter into an agreement with new partners in 2021, collaborations with the existing 11 international partners continued, although somewhat hampered by the worldwide COVID pandemic. SSERVI has active partnerships that include: Australia, Canada, France, Germany, Israel, Italy, Japan, Netherlands, Saudi Arabia, South Korea, and the United Kingdom. In addition, looking forward to 2022, SSERVI will be looking at strengthening existing partnerships and building new partnerships in conjunction with NASA's efforts to join with other nations through the Artemis Accords.

Below is a summary of the collaborations between SSERVI and the International Partners, followed by reports from some of the partners.

European Lunar Symposium

Due to the COVID-19 pandemic, the European Lunar Symposium was held jointly with the NASA Exploration Science Forum as a virtual conference. The meeting was held in July 2021. This meeting built upon the European Lunar Symposiums (ELS) held in Berlin (2012), London (2014), Frascati (2015), Amsterdam (2016), Muenster (2017), Toulouse (2018) and Manchester (2019), virtual (2020) as well as the global interest in new missions to the Moon. The meeting was held under the umbrella of SSERVI and the European SSERVI teams.

The science organizing committee was a blend of researchers from both the US and Europe. The presentations were also a blend of representatives from both regions. Due to joining the meetings, there was an increase in presentations and posters. There were a total of 239 virtual presentations made over two and a half days (124 orals + 115 posters).

NESF and ELS 2021 Co-Chairs: Greg Schmidt, SSERVI and Mahesh Anand, Open University

Photo Credit: ELS organizers

Japan: SSERVI's Solar System Treks Project (SSTP) continued its ongoing collaborations with SSERVI's Japanese international partner consisting of the Japan Aerospace Exploration Agency (JAXA) and its Institute of Space and Astronautical Science (ISAS). At JAXA's request, SSTP used its Ryugu Trek portal to create data visualizations for JAXA to use in its Hayabusa2 mission presentations at the Japan Geoscience Union conference. SSTP also used its Mercury Trek portal to create data visualizations for JAXA for the first flyby of Mercury by the BepiColombo spacecraft on October 1, 2021. SSTP used its Moon Trek portal to create custom lunar data visualizations for JAXA's participation in International Observe the Moon Night and for a Japanese museum exhibition.

Italy:

SSERVI's Central Office collaborated with our Italian partners by co-hosting a virtual mini-workshop in 2021. The topic was Robotic Moon Exploration Cooperation Opportunities and featured presentations from both the US and Italy. The meeting was considered highly productive by representatives from both regions as new collaborations were identified during the meeting. The success of this meeting also prompted additional workshops that were planned for 2022. SSERVI's Central Office also partnered with NASA's Planetary Missions Program Office and Allan Hancock College in planning and conducting the public program for the launch of the Double Asteroid Redirection Test (DART) mission from Vandenberg Space Force Base in November, 2021. SSERVI's international partner, the Italian Space Agency (ASI), is a participant in the DART mission through its contribution of the Light Italian CubeSat for Imaging of Asteroids (LICIACube) spacecraft launched as an integrated payload with DART. Because of this, SSERVI collaborated with ASI to facilitate their participation in the public launch program and provide a public lecture about LICIACube by ASI's Simone Pirrotta as part of the program.

RoboRave International:
Working with RoboRave International SSERVI's Central Office has inspired students from around the world to develop STEAM related skills in preparing for jobs crucial for space exploration. SSERVI has worked with RoboRave International for over 11 years to expand international partnerships, increase international participation (currently 27+ countries participate each year), and help influence economic, educational, and workforce development programs in many countries. In 2021, travel was limited but SSERVI Central made a virtual presentation to the event in Estonia. The U.S. Speaker Program continues to offer SSERVI an opportunity to engage with new audiences, expand their networks, and exchange ideas with professionals across the globe in support of international exchange. RoboRave International competitions are conducted in person and through virtual engagement platforms and focus on key topics including climate change, advancing workforce development and economic prosperity, expanding educational diplomacy, and fostering open collaboration and civil society.

Developing Partnerships
Mexico: Ongoing discussions continue with Mexico's Agencia Espacial Mexicana (AEM) for it to become a SSERVI international partner. During those discussions, we have been conducting a number of preliminary collaborations. Mexico's COLMENA lunar rovers are scheduled to be deployed on the lunar surface as part of the CLPS 1 mission to Lacus Mortis. SSTP worked with AEM to prepare a video tour of Lacus Mortis as an outreach tool for COLMENA. AEM is also an organizer of the Noche de las Estrellas, or Night of the Stars, annual public engagement event. Along with the Universidad Nacional Autonoma de México (UNAM), AEM has continued to bring together hundreds of thousands of attendees yearly throughout Mexico and Central America at annual Noche de las Estrellas celebrations. SSERVI has been a participant at these events in Mexico in the past. But it has been a long-time goal of SSERVI and AEM to expand the program into Latin American communities here in the United States. That goal was realized on November 13, 2021 with the first U.S. Noche de las Estrellas celebration. This event, held at the Norton Science and Language Academy in Riverside, CA, was a collaboration between SSERVI, the Lewis Center for Educational Research, AEM, and UNAM, and hosted over 1000 in-person attendees observing COVID protocol precautions. We look forward to continuing and expanding this collaboration in years to come.
The Latin American and Caribbean Space Agency (ALCE) was established in 2021 with the objective of coordinating the space cooperation activities of Latin American and Caribbean countries for the peaceful use and exploration of outer space, the Moon and other celestial bodies. Mexico has assumed the pro tempore presidency of ALCE and is the site for ALCE headquarters. As the organization and initial activities of ALCE ramp up, and as SSERVI's collaboration with AEM progresses, AEM has agreed to be SSERVI's point of contact with ALCE and to help facilitate future interactions.

1. CANADA Team Project Report

1.1. University of Alberta and MacEwan University
Drs Christopher Herd and Erin Walton have contributed to the lunar science community through their studies of lunar meteorites, which focus on the mineralogy and petrology of unbrecciated basalts and regolith breccias. Their work combines electron microscopy to quantify mineral composition and microtextures, and Raman spectroscopy to characterize mineral structures. Drs Herd and Walton are currently co-supervising two MSc students, Tatiana Mijajlovic and Radhika Saini. Tatiana's work focuses on shock metamorphism recorded as deformation and transformation of host rock minerals including olivine, pyroxene plagioclase and silica. Shock metamorphism of unbrecciated samples is presumably associated with impact events that eject rocks into Earth-crossing trajectories. The conditions of shock metamorphism are calibrated by shock recovery experiments. By characterizing shock effects in the samples, the pressures and temperatures of impact can be constrained, which in turn tells us about the size of the source crater. This type of work can help us to find locations on the lunar surface from which meteorites originated. Radhika's project looks at minerals that have crystallized from melt in the matrix of regolith breccias. The pressure-temperature stability of these minerals can tell us about the processes by which unconsolidated near-surface materials (regolith) may be assembled to form coherent rocks on planetary bodies lacking an atmosphere.

1.2. Carleton University
Dr. Alex Ellery and his team at Carleton University in Ottawa have been exploring long-term in-situ resource utilization (ISRU) on the Moon on the basis that any short-term strategy should be informed by long-term goals. Their motivation is to ensure that we adopt sustainable approaches to using space resources – sustainable with respect to both the Moon and Earth. Their goal is to push ISRU as far as possible by determining how an entire spacecraft (nominally a solar power satellite module), lunar launch system and lunar base can be constructed from lunar resources sustainably. For example, they favor the extraction of LOX from lunar minerals rather than LH2/LOX from water due to the waste products of such processes. They are developing: (i) end-to-end ISRU payload concept with technology demonstration converting regolith to test product; (ii) lunar industrial ecology of interlinked (electro)chemical processes that yield minimal waste (concept achieved); (iii) 3D printing as universal manufacturing method including electric motors

(demonstration achieved); (iv) in-situ resourced energy system (concept achieved); (v) in-situ resourced 3D printed magnetron; (vi) in-situ resourced lunar base (concept achieved).

Figure 1. Space MRI Team P.I. Gordon Sarty, left, and graduate students Pallavi Bohidar (at the computer) and Farnaz Zohourparvaz (front right), with the MRI located between them, prior to takeoff on a recent test flight on NRC's Falcon 20 jet. Photo credit: Duff

1.3. University of Saskatchewan

In 2021, Dr. Gordon Sarty (Department of Psychology and Health Studies at the University of Saskatchewan) and the Space MRI Team completed a zero-g test flight of an ankle-size prototype of a space capable magnetic resonance imager (MRI) (Figure 1). You may find a video of the flight at: https://news.usask.ca/articles/research/2021/sartys-usask-team-tests-technology-for-mri-in-space.php

Their test flight was a big step forward in the development of MRI technology for use by astronauts on the lunar surface, beginning with a wrist-size MRI for the Artemis lander to demonstrate the technology and to acquire some of the first hard data on the response of the human body to living in lunar gravity.

1.4. Université de Sherbrooke

Dr. Myriam Lemelin and her students at the Université de Sherbrooke, Quebec have focused on projects studying lunar volatiles and pyroclastic volcanism. During 2021, Dr. Myriam Lemelin has published a first-author publication on investigating the location of water-ice-bearing PSRs near the Moon's south polar region using data acquired by NASA's Moon Mineralogy Mapper instrument. Two of her graduate student's thesis work strongly support lunar volatile and polar exploration research. For example, her master's student Samuel Bouffard works towards identifying a promising landing site for the Canadian micro-rover that will travel to the lunar South Pole in 2025, and her master's student Frédéric Diotte focuses on using laser-induced breakdown spectroscopy to identify and quantity lunar volatiles. In addition to being first-author, Myriam is also a co-author on three papers studying lunar surface processes using remote sensing datasets (Černok et al., 2021; Clabaut et al., 2021; Trang et al., 2022). Myriam's students all study different aspects of lunar science and exploration. Most recent work by her master's student Samuel Gagnon was on determining if the relative radiance of lunar impact melt deposits is due to the presence of glass (Gagnon et al., 2022).

1.5. University of Winnipeg

Dr. Ed Cloutis at the University of Winnipeg is leading a Canadian Space Agency (CSA) funded Science, Technology, Engineering, and Mathematics (STEM) program to introduce K-12 students to STEM via Moon-based educational materials and hands-on activities. Dr. Ed Cloutis is involved in numerous proposals and programs including being a Co-I on the NASA PRISM Vertex lander mission, Co-I on a number of NASA PRISM proposals for lander mission to the Gruithuisen Domes, PI on a CSA Lunar Exploration Accelerator Program (LEAP) project to investigate the utility of a Raman spectrometer for future lunar landed missions, a Co-I on multiple CSA LEAP projects to investigate and advance the science and technology readiness levels of various Canadian-developed instruments for future lunar landed missions, Co-I on the Canadensys-led Lunar Rover Mission concept study, and a Science PI on the CSA and European Space Agency (ESA) funded Phase A study of a 12-U CubeSat to explore for water ice in permanently shadowed regions in the south pole region of the Moon. Ed is also part of a science team for the CSA University CubeSat program to orbit a satellite called Iris (ManitobaSat-1) to investigate how the space environments affects the surface of the Moon.

1.6. University of Western Ontario

Drs Gordon Osinski and Roberta Flemming have been conducting studies on impact cratering, shock metamorphism, and petrology of lunar materials. Dr Gordon Osinski and his research team of students and postdocs are focused on lunar surface processes. Three students (two undergraduates and one graduate) are using optical microscopy and crystal-size distribution (CSD) analysis to study the petrography and composition of shocked and impact melt-bearing Apollo samples in an attempt to re-

Lunar science in Canada received a significant boost with the award of two 5-year Canadian Space Agency Lunar Exploration Accelerator Program (LEAP) Planetary Science Investigation Grants to the Canadian community. One of these went to CLRN PI, Dr. Osinski (University of Western Ontario), and is entitled "A Canadian Lunar Research Network for Geology, Geophysics, and Prospecting ($900,000). Co-Investigators on this grant are Drs. Flemming, Neish, and Tornabene from Western; Dr. Herd from the University of Alberta; Dr. Lemelin from L'Université de Sherbrooke; and Dr. Walton from MacEwan University.

evaluate the nomenclature of lunar impactites in the Apollo collection. In addition, Dr Osinski's team are seeking to better constrain the pressure and temperature conditions of impact melt deposits by studying the crystallography and microstructures of zircon grains and zirconia crystals in impact melt samples from the Mistastin Lake (Tolometti et al., in review) and West Clearwater impact structures located in Canada. In September 2021, Dr Osinski led a field expedition to Mistastin Lake (Figure 2) to acquire more samples for the research project in conjunction with astronaut geology field training for the CSA and NASA.

Dr Roberta Flemming has also been co-supervising a graduate student who has focused on analyzing the petrology and shock conditions of lunar meteorites using a combination of optical microscopy and micro-X ray diffraction (e.g., Li et al., 2022).

Figure 2. Western team studying impact melt deposits at the lunar analogue site, the Mistastin Lake impact structure.

In further Apollo sample-based research, Tianqi Xie, a PhD student under the co-supervision of Drs. Sean Shieh and Gordon Osinski completed and published a Raman microscopy study of samples from all 6 Apollo missions (Xie et al., 2021). They documented a variety of shock features recording low to moderate shock levels, including fractures, deformed twins, undulatory extinction, planar features, and partially isotropic plagioclase. A notable non-observation was the absence of planar deformation features or completely isotropic (i.e., diaplectic) glass in this suite of samples.

Dr Catherine Neish and her research team have focused on studying the physical properties and composition of lunar surface features using a plethora of remote sensing data sets acquired from spacecrafts (e.g., radar, thermal infrared, reflectance spectra, and high-resolution imagery). Her lab has a strong focus on impact cratering, in particular understanding the emplacement conditions of lunar impact melt flows, the breakdown of lunar impact melt deposits, the surface properties of dark halo craters, and the surface characteristics of permanently shadowed regions in the lunar south pole. In 2021, Dr Catherine Neish published her work on understanding the spectral properties of lunar impact melt flows using the NASA Moon Mineralogy Mapper instrument (Neish et al., 2021) (Dr Roberta Flemming is a co-author). Her current students and recently defended PhD student Gavin Tolometti have been submitting their work to planetary science conferences such as the 53rd Lunar and Planetary Science Conference (e.g., Thaker et al., 2022; Tolometti et al., 2022).

Additional remote sensing studies of lunar impact craters were published by PhD student Morse (now at NASA GSFC and part of the SSERVI RISE2 team) under the supervision of Dr. Osinski. In the first contribution, they carried out morphologic mapping and interpretation of ejecta deposits from Tsiolkovskiy Crater (Morse et al. 2021a). These results provide a better understanding of the effects of impact angle on ejecta emplacement and also provide evidence for two main stages for ejecta emplacement; namely, ballistic sedimentation and radial flow following by late-stage melt-rich flows. In the second contribution, the focus was on generating the most detailed geological map to-date of the interior of the Schrödinger Basin, coupled with travserse planning for a rover-based sample return mission (Morse et al. 2021b).

Drs Tim Newson and Gordon Osinski and their teams have been conducting geological and geotechnical research on several lunar simulants to better understand their mineralogical, chemical, and physical properties (Newson et al., 2021). Led by MSc student Zhang, they recently created a prototype simulant created from shocked anorthosite and impact melt rock to investigate whether this will result in a more realistic simulant.

Work at Western is also focused on instrument development, with an ongoing CSA-funded project to develop an Integrated Vision System (IVS) (Pilles et al. 2021). This is a prototype stand-off instrument designed to be mounted on a rover mast and appropriate for both scientific characterization of the lunar surface and rover guidance, navigation, and control (GNC). Several versions of IVS are currently in various stages of development, with various types of multispectral imagers (e.g., 400 – 1700 nm and 300 – 2500 nm) and a LIDAR system incorporating multiple laser wavelengths.

2. Inter-team/International Collaborations

Dr. Peter Brown (Western) is part of the Center for Lunar and Asteroid Surface Science (CLASS2) team.

Dr. Cloutis at the University of Winnipeg is a member of four NASA SSERVI networks: TREX, ICE Five-O, RISE2, and CLASS2.

Dr. Osinski (Western) is part of the Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2) and Resource Exploration and Science of OUR Cosmic Environment (RESOURCE) teams.

3. Public Engagement Report

3.1. University of Saskatchewan

For 2021, the Space MRI Team's test flight was posted to the University of Saskatchewan's news website (https://news.usask.ca/articles/research/2021/sartys-usask-team-tests-technology-for-mri-in-space.php) and the P.I. Dr. Gordon Sarty made a presentation, complete with hardware, to the Saskatoon chapter of the IEEE at their AGM. A planned presentation for the local Centre of the RASC is on hold until COVID-19 restrictions lift.

3.2. University of Winnipeg

This year the University of Winnipeg securied a two-year grant from the CSA for lunar focused K-12 education, entitled Manitoba Lunar and Planetary Science (MLaPS). As part of this grant, Dr Ed Cloutis gave a talk on lunar science and exploration at the Royal Astronomical Society of Canada Winnipeg Branch monthly meeting on September 10th, 2021

3.3. University of Western Ontario

During the 2021, the Institute for Earth and Space Exploration at University of Western Ontario participated in the annual International Observe the Moon Night virtual event. The event was comprised of staff and graduate student volunteers from the Department of Physics and Astronomy, and the Department of Earth Sciences, with a series of speakers set up to talk about topics such as the history of lunar exploration and lunar geology. Dr Gordon Osinski, with support from a CSA LEAP grant, created new lunar rock kits (Figure 3) containing samples of terrestrial rocks that are analogous in texture and composition to Apollo samples. Dr Osinski opened these kits for public requests to be used in K-12 classrooms across Canada. In addition, he worked with Western Space to produce a lunar surface environment world on Minecraft (named Mooncraft) for outreach education.

Figure 3. Example of the lunar kit created by Dr Gordon Osinski. Samples include impactites from Mistastin Lake and simulated lunar regolith.

3.4. Indus Space

The social enterprise Indus Space (founded by Dr. Bhairavi Shankar in 2018) located in Canada has focused on public engagement, particularly for K-12 youths. Over the past year, Indus Space has organized events as part of several national initiatives in addition to regular programming. On May 8th 2021, Indus Space took part in Science Rendezvous (part of Science Odyssey), and participated in the Science Chase. They provided 5 short self-paced space themed challenges for K-8 youth to compete in a day. From September 20th to 23rd, Indus Space participated in two Science Literacy Week organized events. On October 1st to 3rd, Indus Space participated in the NASA Space Apps Hackathon. Throughout 2021, they hosted multiple "Meet a Space Professional" speaker series, where guests were able to share what they do related to space exploration and field questions. Currently, Indus Space is collaborating with a local community organization to provide Moon themed programming with partial support from the Canadian Space Agency (see: https://www.astrostemlabs.com/moon). As part of the Moon themed initiative, Indus Space hosted International Observe the Moon Night on October 16th. They hosted 98 participants over 5 hours of programming, speakers, and virtual observing with the Royal Astronomical Society of Canada – Toronto Centre.

In September 2021, 13 students participated in the CLRN – Western Impact Cratering Short Course and Field School held at the ~200 km impact structure in Sudbury, Ontario formed 1.85 billion years ago. During this intensive week-long short course and field training program students conducted field research and were introduced to impact cratering processes and products.

4. Student/Early Career Participation

Undergraduate Students

- Stephanie Connell, University of Winnipeg.
- Brynn Dagdick, University of Winnipeg.
- Jack Hostrawser, University of Western Ontario.
- Jesse Kuik, University of Winnipeg.
- Cain Lambert, University of Winnipeg.
- Marc Mechem, University of Western Ontario.
- Alexis Parkinson, University of Winnipeg.
- Mary Ramiez, University of Winnipeg.

Figure 4. Students getting a close look at an outcrop at the base of the Sudbury Igneous Complex.

Graduate Students

- Daniel Applin (Masters), University of Winnipeg: Lunar Science and Exploration.
- Pallavi Bohidar (PhD), University of Saskatchewan: Building prototypes for portable MRI scanners, using innovative technology to monitor astronaut health in space missions.
- Samuel Bouffard (Masters), Université de Sherbrooke: Identifying promising lunar landing sites for the Canadian micro-rover that will travel to the lunar south pole in 2025.
- Neeraja Chinchalkar (PhD), University of Western Ontario: Impactites of West Clearwater impact structure, Quebec, Canada.
- Frédéric Diotte (Masters), Université de Sherbrooke: Laser-induced breakdown spectroscopy to identify and quantify volatiles and highly siderophile elements in the lunar regolith.
- Faezeh Ebadollahi (Masters), University of Saskatchewan: Biomedical and medical engineering.
- Hammed Ejalonibu (PhD), University of Saskatchewan: Engineering novel optical sensors for magnetic field sensing applications.
- Samuel Gagnon (Masters), Université de Sherbrooke: Mapping of impact melts at the lunar south pole.
- Rohit Gaikwad (Masters), Carleton University: Fresnel lens solar concentrators.
- Cailin Gallinger (PhD), University of Western Ontario: 3D structure and breakdown of lunar impact melt deposits from thermal infrared and radar remote sensing.
- Jamie Graff (PhD), University of Western Ontario: Examining physical characteristics of impactites and impact crater ejecta.
- Alex Gmerek (Masters), Carleton University: TDLAS water/volatile detection prototype development.
- Elizabeth Lymer (PhD), University of Winnipeg: Lunar Science and Exploration.
- Tatiana Mijajlovic (Masters), University of Alberta: Shock metamorphism and lunar basaltic meteorites.
- Farnaz Zohour Parvaz (PhD), University of Saskatchewan: Space MRI Lab.
- Aaron Purchase (PhD), University of Alberta: Biomedical MRI and superconducting magnets.
- Christopher Sedlock (PhD), University of Alberta: Oncology.
- Hongwei Sun (PhD), University of Alberta: Health and medical physics.
- Ashka Thaker (Masters), University of Western Ontario: Multiwavelength analysis of lunar radar dark halo craters.
- Bertrand Thibodeau (Masters), Carleton University: Chemical pre-processing of anorthite into pure oxides.
- *Gavin Tolometti (PhD), University of Western Ontario: Physical properties of volcanic and impact melt flows on Earth and the Moon.
- Nathalie Turenne (Masters), University of Winnipeg: Lunar Science and Exploration.
- Xavier Wall (PhD), Carleton University: Electrochemical reduction of metal oxides.
- Abdul Wasae (Masters), Carleton University: Carbon recycling using the Sabatier process.
- Zayn Wolf (Masters), University of Winnipeg: Lunar Science and Exploration.
- *Tianqi Xie (PhD), University of Western Ontario: Shock effects in plagioclase feldspar using Raman microscopy.

*Now postdocs at Western.
**A previous PhD student from Western, Zachary Morse, is now at NASA GSFC and is part of the RISE2 team.

Postdoctoral Fellows

- Christy Caudill, University of Winnipeg and University of Western Ontario.
- Emmanuel Lalla, University of Winnipeg.
- Sebastien Manigand, University of Winnipeg.
- Jennifer Newman, University of Winnipeg.
- Sandra Potin, University of Winnipeg.
- Gavin Tolometti, University of Western Ontario.
- Tianqi Xie, University of Western Ontario.

6. Mission Involvement

Various CLRN researchers are involved in the development of concepts and prototype instruments for future missions.

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1. ITALY Team Project Report

The recent renewed global interest in lunar exploration stimulated ASI to activate dedicated initiatives for Italian national research and industrial communities: in the past months, several meetings and workshops have been held to survey technological capabilities and scientific interests and infuse them into the ASI vision and strategic plan, in order to elaborate on an ambitious and sustainable roadmap. The view and priorities of the scientific community have been collected in a White Paper prepared by the National Institute of Astrophysics (INAF), where the continuity in sectors with consolidated leadership (planetary spectrometers and radars, subsurface access by drilling and sampling, observation of the Universe through X/gamma ray detectors, cosmic rays detectors, etc) is accompanied by innovative proposals. The White Paper collected proposals ranging from the characterization of the lunar environment, surface and internal structure, to the identification and characterization of possible sites able to host future human outposts, to the search and extraction of volatile resources, to the exploitation of the Moon as a unique platform for the observation of the Universe or as a laboratory to perform experiments (e.g. in life science). At the same time, the first studies have been promoted both for robotic and manned missions, to be implemented as domestic initiatives, or in the framework of Italian participation in ESA activities, or also in bilateral cooperation, like possible contributions to the NASA Artemis program.

In 2021, the Italian space community also confirmed its desire to keep lunar exploration as one of the highest priority sectors; the interest in destinations like Moon, Martian moons and Near Earth Asteroids has been confirmed with a push at different levels. The scientific community was extremely active, as demonstrated by a relevant participation in major international conferences, including the 43rd COSPAR Scientific Assembly (held virtually, January 28 –February 4), Europlanet Science Congress 2021 (held remotely September 13 – 24) and also the European Lunar Symposium, which was jointly and virtually co-hosted with the 2021 NASA Exploration Science Forum by NASA SSERVI and its European partner organizations on July 20–23. The following report summarizes of the main achievements of the most active research group for exploration.

1.1. INFN-LNF (Italian National Institute for Nuclear Physics - Frascati National Laboratories)

The INFN-LNF Team (led by Dr. S. Dell'Agnello), in Joint Lab with ASI-CGS (Italian Space Agency - Center for Space Geodesy), and together with the co-investigating team at the University of Maryland - College Park (hereafter UMD, led by Prof. D. G. Currie), is working full steam on the objective of deploying single, large, next generation CCRs (Cube Corner Retroreflectors) of uncoated fused silica developed over the past 15+ years for the first missions to the Moon in 2023.

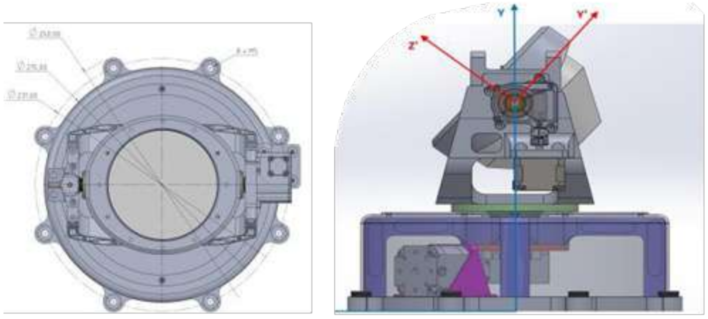
> "The deployment on the Moon of single, large next-generation cube corner retroreflectors will start by 2023."

These instruments share a common optics design heritage from Apollo Laser Retroreflector Arrays (LRAs), and currently consist of American and European payload implementations approved for NASA Commercial Lunar Payload Services (CLPS) missions in late 2023 and early 2024, respectively: Next Generation Laser Retroreflector (NGLR) by UMD, funded by NASA, and Moon Laser Instrumentation for General relativity/geophysics High-accuracy Tests (MoonLIGHT) by INFN, funded by ESA and ASI.

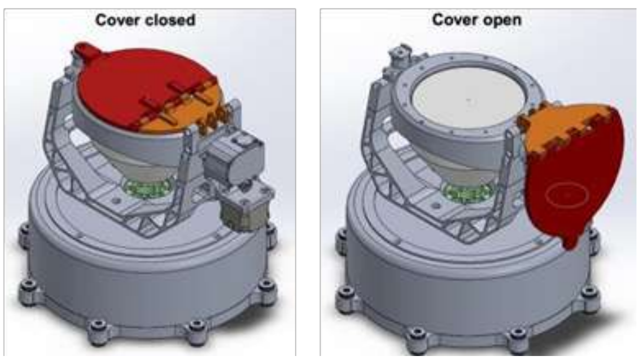
Single, large next-generation CCRs will significantly expand the Apollo legacy and open the path to improved tests of General Relativity, like the weak and strong equivalence principle, geodetic precession, inverse-square force-law, and more stringent constraints on possible time changes of the gravitational constant G.

NGLR 10-cm solid reflector next to an Apollo 38-mm CCR (left; credit: D. G. Currie) next to a Martian microreflector like the ones onboard Perseverance and ExoMars (middle; credit: ASI-INFN). Side view of a MoonLIGHT in a fixed-pointing mount with pre-launch selectable elevation (right; credit: ASI-INFN).

Apollo LRAs were aligned by astronauts using the center of the Earth and taking into account the lunar libration pattern. With the MoonLIGHT Pointing Actuator (MPAc) funded by ESA, this alignment will be performed robotically by two actuators.



Above two figures: top and side views of next-gen CCR integrated into MPAc. Below two figures: next-gen CCR + MPAc with the robotic removable dust cover shown closed and open. Credit: ESA.



The first NGLR (with fixed pointing) will be launched with a NASA-CLPS mission dubbed Ghost Blue on the Firefly lander. The launch is scheduled for Q4 2023 and the landing site will be the Mare Crisium. The first MoonLIGHT (equipped with MPAc and the robotic dust cover) will be launched with the NASA-CLPS/PRISM1A (CP-11) mission on the Intuitive Machines lander. The launch is scheduled for Q1 2024 and the landing site will be the Reiner Gamma swirl region.

"NGLR will be launched by a NASA-CLPS's Firefly mission towards the Mare Crisium in 2023. MoonLIGHT, with MPAc and the robotic dust cover, will be launched by a NASA-CLPS's Intuitive Machines mission towards the Reiner Gamma swirl region in 2024."

The science return of cube corner retroreflectors on the Moon will continue for the following decades because CCRs are passive, long-lived instruments, as demonstrated during the past 50+ years by Apollo and Lunokhod LRAs. Since all existing LRAs are north of the lunar equator, we recommend one or more southern landing or roving sites, especially towards the limbs or the south pole, as they would be most helpful both for lunar science and for fundamental physics.

MoonLIGHT, with MPAc and a robotic dust cover, is a cost-effective, science-effective, compact and light instrument (<2kg, dust cover included) that will serve the lunar science community for decades to come.

1.2. INAF – Istituto Nazionale di Astrofisica

The Italian National Institute of Astrophysics - INAF team is deeply involved in preparing for lunar exploration activities, especially as part of the ESA PROSPECT Team. The Italian science team is composed by a wide group of scientists, all of them involved or with strong interest in the lunar science and exploration. The Prospect Team was selected by ESA with the aim to define and ensure the scientific requirements of PROSPECT, to consolidate PROSPECT science objectives, to ensure PROSPECT is operated effectively at the lunar surface, and to increase the scientific return of the expected data. The main purpose of PROSPECT is to support the identification of potential resources on the Moon and to assess the utilization of those resources. Water and other volatiles found at the lunar surface could provide a major potential asset for future exploration and represents a vital consumable for human explorers in the source of oxygen for life support systems. Moreover, hydrogen and oxygen can be extracted from lunar soil and used as fuel.

Some members of the INAF Team are leads or team members for different ESA Topical Teams in the context of European Large Lunar Lander missions, and are in charge of preparing a plan that could be used as the basis for scientific investigations and payloads for ESA's future lunar exploration activities. This was intended to begin with the selection of a pool of payloads for potential flights in the 2022-2025 timeframe. In particular, we are studying a geological mission to investigate lunar volcanism and a polar mission investigating volatiles and ice. The intention of this plan is to define the European science community's priorities for lunar exploration that can be addressed by missions to the lunar surface in the coming years.

Moreover, in the last year IAPS – INAF was heavily focused on investigating extraterrestrial differentiated material. Researchers are investigating ungrouped achondrites, within the aims of OL-BODIES project (ASI-INAF agreement 2018), analyzing the effect of spectral properties on material with different olivine abundance and composition to address our ability to detect the main composition and mineral phases of asteroids. This was done in collaboration with colleagues from the University of Florence, University of Pavia and IGG-CNR in Pavia where research on different aspects related to mineral and bulk composition is conducted. Also, they have started the spectral analysis of some lunar meteorites related to the MELODY project (INAF-PRIN 2019). The origin of water in the proto-Moon and the Early Earth has been investigated through the study of hydrogen abundance and isotopic composition in nominally anhydrous minerals (NAMs) in Apollo samples. This study started at the Open University (UK) and resulted in a paper currently under review in Nature Communications. This study led to the development of the POSEIDON proposal (MarieSkłodowska -Curie H2020 of Alice Stephant) which aims to analyze a range of primitive achondrite meteorites and determine the water content and hydrogen isotopic composition in nominally anhydrous minerals (NAMs), using a combination of techniques (i.e., transmission infrared spectroscopy, reflectance spectroscopy, nano secondary ion mass spectrometry). The leading goal is to estimate bulk-parent body volatile abundances of achondrites, which were among the first planetesimals formed in the Solar System, to develop a robust understanding of the distribution and source(s) of water in the inner Solar System. This project involves active collaborations with The Open University (UK) and Buseck Center for Meteorite Studies (USA) for sample loan and analyses.

1.3. Politecnico di Milano

In the frame of Moon Exploration, Politecnico di Milano is continuing work on In Situ Resources Utilization ISRU framework, with particular attention on water production from lunar regolith. The experimental plant in PoliMi labs has been finalized and functionally tested, with process tests that began in Q4 2020. The possibility of extracting oxygen from the regolith oxides with no feedstock melting, through carbothermal Reduction (CRB) processes was demonstrated and the expected yield in water production has been experimentally confirmed. Activities were carried on in synergy with ESA, ASI, and OHB company during August 2021 and continued as internal research up to now (Q2-2022). A correlated set of activities is related to Lunar South Pole soil simulant characterization in thermal vacuum conditions. In fact, reproducing a planetary soil simulant bed has proven to be a tough challenge, with the need for repeatable procedures to prepare soil with the desired physical properties, and the need to ensure preservation during thermal-vacuum operations, which is even more important with the presence of volatiles.

PoliMi is currently running a set of preparatory activities to characterize different soil components according to pressure and temperature variations. Politecnico di Milano is also part of the PROSPECT user group of ESA, responsible for the PROSEED - DRILL tool operations. Particular attention is given to modelling and verifying the thermal Energy Exchange process between the icy soil - sampled at lunar pole – and the drilling tool to avoid any sublimation of the icy content the science is interested in.

Politecnico di Milano, ASTRA Team, is also working on Vision-based navigation and Hazard avoidance for Autonomous landing and proximity maneuvering; in particular, the team is still involved in the AIVIONICS ESA study to experimentally assess the effectiveness of Artificial Intelligence techniques when applied to image processing to perform autonomous Navigation during relative dynamics; a strong verification campaign with HIL is included in the study, exploiting the PoliMi in-house GNC experimental laboratory equipped with calibrated lunar surface diorama for landing, and with satellites mockup for proximity maneuvering-- the two scenarios considered in the study.

For several years the Politecnico di Milano, ASTRA Team has been developing GNC techniques for non keplerian trajectories with particular attention to proximity maneuvers in the cis-lunar environment in support of LOP-G related scenarios. In particular, PoliMi has been in charge of supporting the rendezvous docking\undocking guidance definition for the Cis-lunar transfer Vehicle (CLTV), currently under preliminary design under an ESA contract led by TAS-I.

PoliMi-ASTRA is running PhD research in collaboration with ESA's Mission analysis division to assess the benefit of exploiting long-duration missions in the cis-lunar environment over time stable trajectories in order to promptly react to a potentially hazardous Near-Earth object passing on a collision trajectory with Earth , performing a fast flyby or mitigating deviation action for Planetary Defense reactions. Assessment involves all system engineering aspects towards actual feasibility.

Because of the strong expertise in chaotic dynamics in multi-attractor regimes, the ASTRA PoliMi team is also researching distributed\fractionated architectures for both scientific and servicing functionalities exploiting the most beneficial characteristics of non-keplerian orbits in cis-lunar environment: in particular, constellations spread out in the Moon-Earth vacinity are under investigation, to provide NAV-COMM services to operational users in the lunar environment.

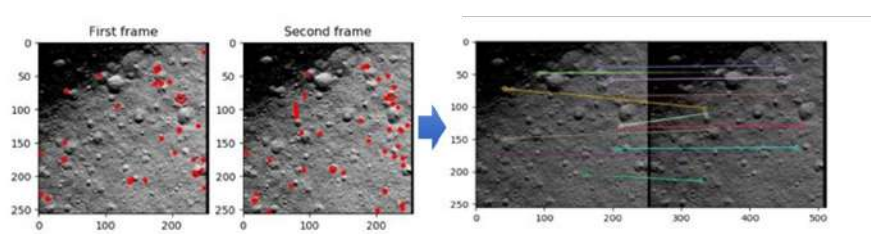
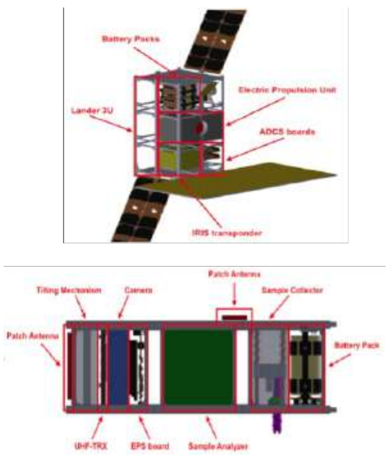


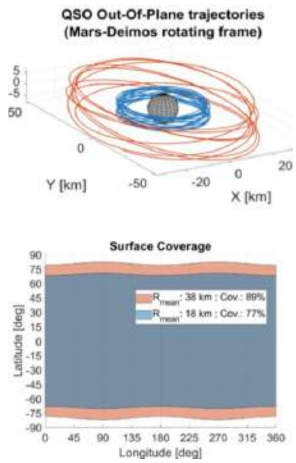
Image processing, features matching for autonomous relative navigation

PoliMi -ASTRA, thanks to its competence in non-keplerian dynamics, is currently investigating how to exploit the multibody Martian moons environment to cleverly design trajectories to build the NAV-COMM constellation to service incoming missions to Mars, under ESA contract, led by TAS-I.

> As part of an ASI-funded initiative, PoliMI, in collaboration with INAF-OAA, conducted a phase A study for a cubesat-size robotic lander for in-situ sample collection and investigation, targeting the Martian moon Deimos for astrobiology mapping.



Deimos 12U orbiter (up) and 3U lander equipped soil with soil sampler (down)



Non-keplerian orbits and surface coverage on Deimos

The PoliMi ASTRA Team is deeply involved in small bodies related research, too. In particular, different areas can be identified: gravitational models for bodies with non-uniform mass distribution; proximity maneuvering that is satisfactory for scientific requirements, trajectory definition, GNC design with attention to image-based measurements and the long-term dynamic evolution of dust in non-keplerian regimes. In particular, image-based navigation exploiting both visual and infrared data is under development: a tool for thermal and visual image generation has been implemented to support the whole algorithmic chain for on-board autonomous reconstruction of state vectors. HIL and PIL test setups are ongoing to validate the whole chain. ASTRA is currently involved in the ASI-financed LICIA Cube mission to the Didymos binary system to witness the DART spacecraft impact, and is responsible for the cubesat trajectory, GNC, and attitude control from release to end-of-life, to maximize the mission's scientific return.

2. Inter-team/International Collaborations

We started an initiative to prepare a national roadmap for robotic exploration that the Italian Space Agency could implement. In particular, discussions with partners considered opportunities to contribute to the forthcoming season of lunar exploration by European Space Agency Member States, and in the wider frame, NASA as part of the Artemis Accords. A forum for regular communication between NASA and ASI was established to discuss potential Italian contributions to the Artemis mission architectures. In order to stimulate the national industrial community, ASI led a first study of lunar surface assets, elements and relative technologies and analysis of maturity. In order to identify and focus on the most interesting elements (infrastructures, robotic elements, enabling technologies), ASI has fostered engineering studies considering surface and orbital assets to support the Artemis program, with a specific focus on pressurized modules capitalizing on strong ISS-based heritage. The proposed Multipurpose Pressurized Module (MPM) has four Reference Mission Scenarios: Human Lunar Lander, Shelter, Pressurized Rover, and Cargo Lander; the MPM contract oversaw the development of critical breadboards compatible with different scenarios of Lunar surface exploration.

> In terms of robotic missions, several different options were discussed and considered, with a productive interaction with NASA SSERVI that culminated in a joint mini-workshop held September 30th with participation by each Agency and its respective space exploration community.

ASI - NASA SSERVI FIRST MINI-WORKSHOP

on ROBOTIC MOON EXPLORATION

COOPERATION OPPORTUNITIES

Sept 30th 2021

The virtual meeting, organized in the frame of the ASI participation as Associate Agency to SSERVI's International Partnerships Program, is intended to discuss on desirable opportunities for cooperation in Robotic Moon Exploration, presenting current initiatives and new proposals and so promoting joint steps at Agency and Academic levels in the forthcoming challenge of Lunar Exploration.

Agenda

PST time	CET time		
08:00	17:00	Welcome	Barbara Negri (ASI)
08:10	17:10	Introduction to WS topics and agenda	Greg Schmidt (NASA/ SSERVI)
08:30	17:30	ASI: goal of the workshop and ASI initiatives for Robotic Exploration (with focus on Moon)	Gabriele Mascetti (ASI), Simone Pirrotta (ASI)
08:45	17:45	LuGRE payload: an example of ASI/NASA cooperation on CLPS and future opportunities	Mario Musmeci (ASI)
08:50	17:50	Commercial Lunar Payload Services program and partisipation opportunities	Brad Bailey (NASA/HQ)
09:10	18:10	A survey of the Italian Scientific community interests in Robotic Moon Exploration	Francesca Esposito (INAF)
10:10	19:10	Robotic Construction of Radio Telescope Arrays on the Moon	Jack Burns (Univ. Colorado – NASA / SSERVI PI)
10:30	19:30	Discussion and concluding remarks; actions and next meeting date	Kristina Gibbs (NASA/SSERVI) Simone Pirrotta (ASI)
11:00	20:00	End of the event.	

Program of the ASI-SSERVI mini-workshop on "Robotic Moon Exploration Cooperation Opportunities"

INFN-LNF Team personnel were involved in the organization of the 2021 NASA Exploration Science Forum & European Lunar Symposium. Also, a topical white paper titled "Next generation lunar laser retroreflectors for fundamental physics and lunar science" was submitted to the Committee on the Biological and Physical Sciences Research in Space 2023-2032 of The National Academies of Sciences of the

USA: its 40 co-authors include all the major stakeholders involved in lunar laser ranging (LLR) science and technology. Moreover, a journal paper titled "Present and Future Lunar Laser Ranging," co-authored with several lunar laser ranging scientists and operators, will be published in 2022. This research will show what the impact of the spread of the reflected laser pulse to Earth will eventually be on the accuracy/precision of the science of interest; with new CCRs deployed on the Moon in 2023, the LLR community is excited to address the improvement/refinement of such cutting-edge measurements.

3. Public Engagement

During 2021, the Fondazione Museo Civico di Rovereto renewed its permanent astronomical and space-themed exhibit and planned a number of outreach events, some of which were unfortunately limited by restrictions resulting from the current pandemic situation.

Several public events were hosted, including the annual "International Observe The Moon Night," with lectures presenting and discussing space research and Solar System exploration initiatives. In particular, one of them was dedicated to the work and innovations of Italian scientist Angioletta Coradin i, who wasparticularly dear to the Museum as she was born in Rovereto town.

During fall 2021, work resumed on a permanent exhibit inside the museum's planetarium. The exhibit was conceived of as a multisensory journey that accompanies the visitor through the human adventure of discovering space beyond our planet as the observation of the Sky and the Exploration of the Solar System are described through models, panels, virtual experiences, sounds, and videos. The journey starts from planet Earth and reaches the farthest frontiers of the observable Universe, while detailing the history of space exploration and its current challenges. Due to the cooperation in place, NASA SSERVI activities are described in a dedicated area of the exhibit. Critical topics like equal opportunities in STEM subjects, awareness of the fragility of our planet and the need to protect and respect it, are highlighted in the renewed exhibition area.

The new permanent exhibition at the Museo Civico di Rovereto

4. Student/Early Career Participation

The entire Italian scientific community foresees an important contribution from students and U.S. researchers.
For INFN-LNF, new team members and/or new roles w.r.t. 2020 are listed hereafter:

Graduate Students

- Giulia Moretti, "Sapienza" University of Rome & INFN-LNF, laboratory testing and space qualifications.

Postdoctoral Fellows

- Laura Rubino, INFN-LNF, space electronics and robotics.
- Lorenza Mauro, INFN-LNF, theoretical gravitational physics and optical simulations.
- Alejandro Remujo-Castro, INFN-LNF, space qualifications and space robotics.

New Faculty Members

- Luca Porcelli, INFN-LNF, Permanent Staff Researcher.
- Lorenzo Salvatori, INFN-LNF, mechanical technician.

INAF has a continuous intake of young researchers entering the technical and scientific activities of the different Italian Observatories.

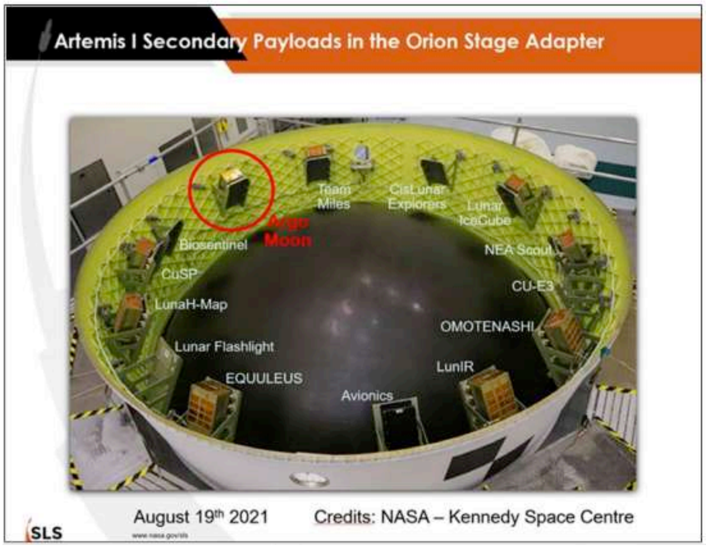
ASTRA Team of PoliMi is composed by 19 members which include full and assistant professors, postdocs, PhD candidates and researchers, regularly involved in dissemination of the team activities, such as the National Researchers' night and the Open Labs events. The team has many collaborations with National and International research centers and industries.

5. Mission Involvement

2021 was a crucial year for ASI Solar System Exploration missions, mainly the cubesat-based ArgoMoon and LICIACube, to be implemented in cooperation with NASA but relevant as the first national space systems operating in a deep space environment, which has progressed close to the operational phase.

"Argomoon" is a 6U cubesat, being selected in 2016 by NASA HQ Exploration Systems Mission Directorate (ESMD) as a Secondary Payload for the Artemis 1 mission of the Space Launch System (SLS)-- the heavy-lift launch vehicle designed to allow space exploration beyond Low-Earth Orbit. The first part of the ArgoMoon mission will aim to take significant photographs of the launcher, while in the following six months, the satellite will orbit around the Earth with an apogee close to lunar orbit, to collect pictures of the lunar surface.

During spring and summer 2021, the ArgoMoon ProtoFlight Model was integrated, tested, and accepted by ASI form the contractor Argotec and then delivered to NASA for integration into the Orion Stage Adapter of the first SLS flight. The beginning of the Artemis 1 mission is now planned for the summer of 2022.



Artemis 1 Secondary Payloads in the Orion Stage Adapter of the Space Launch System

Light Italian Cubesat for Imaging of Asteroids (LICIACube) is a 6U cubesat that will participate in the NASA "Double Asteroid Redirection Test (DART) mission, whose purpose is to impact the secondary asteroid of the binary system Didymos in order to test orbit deflection methods for Planetary Defense purposes. LICIACube will be released from the dispenser hosted as a piggyback payload on DART in proximity of the target and will perform an autonomous fly-by of the binary Didymos system just before and after the impact, collecting pictures of the asteroid surface and of the generated ejecta plume.

The integration of LICIACube Flight Model was completed during the first months of 2021; it was tested and accepted by ASI for shipment and delivery to the Applied Physics Laboratory (APL) team. NASA selected APL to develop the DART mission flight model and manage the interface with the Italian payload. The cubesat and its dispenser has been integrated on DART's external surface and was transported to the launch site during summer 2021.

The launch of DART and LICIACube occurred on 24th of November from the Vandenberg air force base onboard a SpaceX Falcon 9 launcher. Both spacecraft are currently in cruise towards the target; mission operations will start in late September 2022.

LICIACube team members at the APL facility, in Baltimore, for the integration of the cubesat on DART

LICIACube team members at Vandenberg air force base; the Falcon9 rocket carrying the DART and LICIACube spacecraft can be seen in the background

Moreover, the NASA Commercial Lunar Payload Services (CLPS) program has been identified as a potential and promising source of opportunities for the national community, in order to allow robotic missions to access the lunar surface for scientific investigations and technology testing and validation.

Already, the ASI experiment Italian Lunar GNSS Receiver Experiment (LuGRE) has been identified as one of the payloads of the CLPS 19-D mission, planned to land in the "Mare Crisium" basin of the Moon in 2024 to characterize and demonstrate the use of GNSS signals in cislunar space, including at the lunar surface and in the near-lunar environment. The LuGRE GNSS receiver will gather data throughout the mission and send to ground IQ samples and GNSS raw measurements for GPS and Galileo. This data will then be post-processed for collective science purposes to determine the satellite visibility during different phases of the mission and the quality of the received signal. In addition, to demonstrate the feasibility of on-board real-time positioning and navigation, the receiver will exploit different navigation techniques: during MTO, the receiver will compute Position, Velocity and Time (PVT) and Precise Orbit Determination (POD) solutions, and once on the surface of the Moon a filtered lunar surface positioning study will be performed. These scientific data are therefore of substantial relevance for the next lunar missions (e.g., Orion, Gateway, Artemis programs) as they will foster the use of GNSS for future lunar technologies.

The INFN-LNF team is working to benefit from commercial flight opportunities to the lunar surface, which were also offered by ESA to Member States research groups: the first NGLR (with fixed pointing) will be launched with a NASA-CLPS mission dubbed Ghost Blue on the Firefly lander; launch is scheduled for Q4 2023 and the landing site will be the Mare Crisium. Also, the first MoonLIGHT (equipped with MPAc and the robotic dust cover) will be launched the NASA-CLPS/PRISM1A (CP-11) mission on the Intuitive Machines lander; launch is scheduled for Q1 2024 and the landing site will be the Reiner Gamma swirl region.

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