OpenSpace Annual Progress Report — Year Six

NASA Science Mission Directorate Science Education Cooperative Agreement Notice (CAN)

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I. Administrative

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II. Accomplishments

The American Museum of Natural History (AMNH) is pleased to submit this sixth annual report on the progress to date of *OpenSpace: An Engine for Dynamic Visualization of Earth and Space Science for Informal Education and Beyond*, referred to below as the OpenSpace project. The overarching goal of the OpenSpace project is to build and support the use of a pipeline for transmitting visualized science content from across NASA SMD divisions to Informal Science Institutions (ISIs) and the general public. Central to achieving this goal is the development of open source software, known as OpenSpace, and the promotion of the software's use in informal settings through the establishment of a network of ISI partners.

During the project's sixth year, AMNH made significant progress toward these objectives through ongoing code development, content visualization, and programming for the general public, youth, and educator audiences.

Our Year Six activities are described in greater detail below.

Software Development

The OpenSpace software has continued to grow in Year Six through cooperative development at AMNH, Linköping University and Norrköping Visualization Center C,[1] New York University Tandon School of Engineering, and the University of Utah Scientific Computing and Imaging (SCI) Institute. As in previous years, software engineers and graduate research associates at each of these locations have collaboratively contributed to a workflow that fosters near real-time and efficient algorithms to handle data intensive tasks, multi-modal rendering, integration of new data sets, and improving the resiliency of the overall software codebase.

During this period, three significant updates and two minor updates of OpenSpace software were published: Beta-8 (v0.16.0) was released on December 9, 2020; Beta-9 (v0.16.1) was released on May 7, 2021; Beta-10 (v0.17.0) was released on July 14, 2021; and Beta-10 patches v0.17.1 and v0.17.2 were released on August 9, 2021 and August 27, 2021. Each of these updates improved the software stability and usability, added new visualized content, and responded to feedback from our ISI partners and other OpenSpace users.

Major new features and computational improvements include:

- OpenSpace Launcher and Profile Editor: Using the Launcher, users can select their profile and window configuration when starting OpenSpace. Using the Profile Editor, users can now easily customize their presentations via a GUI.
- Exoplanets: Capability to add all exoplanets identified in the NASA Exoplanet Archive with calculated habitable zone
- Navigate from Web GUI: The Web GUI can be used to fly OpenSpace from a separate device, including touch devices
- C-Troll: An application to launch OpenSpace in immersive environments like planetariums or other multi-channel display systems
- Drag and drop support: Drag and drop images, asset files, and screen recordings in the OpenSpace window to add them into OpenSpace
- Session Recordings: Improvements to increase ease and usefulness of this feature, including simplified video frame export
- 3D models: Improvements to model rendering, including support for more formats and animated models.

Content Development

The creation of new content continues to be driven by the needs of our users and fueled by collaborations with NASA agencies and infrastructure as well as outside scientists and institutions, as detailed below.

[1] The activities at Linköping University are not funded by this grant, but are supported by the Knut & Alice Wallenberg Foundation in Sweden, Swedish e-Science Research Centre, and Stena Foundation.

What we previously referred to as "scenes" we now refer to as "profiles" as the previous nomenclature caused confusion for users. OpenSpace currently has 16 prepackaged profiles.[2] Utilizing the new profile editor feature in the OpenSpace Launcher (see above), users can customize the content included in the profile they select upon launch or create entirely custom profiles if they choose.

Ongoing content development included the addition of one new profile and enhancements to multiple existing profiles.

New Profiles

James Webb Space Telescope: This profile visualizes the NASA-ESA-CAN James Webb Space Telescope, expected to launch in late 2021. The profile includes two visualizations of the Webb trail: One plotted with respect to the Earth-Sun L2, where it will be stationed; and another with respect to the Sun, as we plot the orbits of the planets. A dynamic model of Webb is included with animated deployment sequence and active view frustum.

Bastille Day: This profile visualizes the results of a collaboration with the NASA Goddard Space Flight Center's Community Coordinated Modeling Center[3] and Predictive Science Inc.[4] to visualize the activities of space weather for the 2000 Bastille Day event. This profile shows the time-resolved movement of the magnetic fields close to the Sun and simultaneously shows the impact the space weather has on Earth and Earth's magnetosphere. (Available for download through Github.)

Enhanced Content for Existing Profiles

Default (automatically loaded upon start-up)

- Updated ISS model with increased accuracy
- Improved the visual accuracy of Saturn's ring visualization
- Enhanced Mars coverage, including updated HiRISE and new HRSC MOLA Blended DEM maps
- USGS map layers for Mars moons Phobos and Deimos
- Atmosphere on Titan
- Orion Nebula polygonal model scaled with World Wide Telescope images

OSIRIS-REx

- Added more data from the mission imaging campaign and a new hi-res model of Bennu

[2] For a list and short description of each of the 16 profiles developed over the course of the grant's six years of funding, see Appendix.

[3] The support provided by the Community Coordinated Modeling Center is provided by grants from the NSF external to this project.

[4] The model contributions from Predictive Science Inc. were funded by means external to this project.

Additionally, in April, developers created the OpenSpace Hub (hub.openspaceproject.com) as a place for the community to share new assets, profiles, and session recordings. Among the assets available so far are:

- 3D models and trails of the Hubble and Spitzer telescopes developed by partner California Academy of Sciences,
- 3D models and trails for asteroids 216 Kleopatra and 433 Eros developed by AMNH interns,
- 3D model of buildings in New York City developed by user City College of New York, and
- Trails for the ten closest approach Near Earth Objects of 2021 from JPL Horizons developed by North Carolina Museum of Natural Sciences intern.

Stakeholder Meetings

Throughout the sixth year, key meetings were held among OpenSpace stakeholders.

Phase II Kick-Off Meeting: This "all-hands" meeting on January 5 virtually brought together OpenSpace development partners, the ISI Partner Network, and project management to kick off the second phase of SciAct funding. The goal of the meeting was to support and clarify respective roles across the project and generate shared understandings of major development and programming goals. The group discussed their short-term plans for OpenSpace as well as aspirations for the project in five years. This is the first meeting of this type for the project and the group determined that it would be useful to continue it on an annual basis. The agenda for the 2021 meeting is included in *VIII. Attached Information.*

Developer Meetings: Project developers and managers from AMNH, Linköping University, New York University, and University of Utah met virtually on January 19-22. The meeting was devoted to reflecting on the kick-off meeting, reviewing work-to-date, and finalizing near-term and long-term development goals. The agenda for this meeting is included in *VIII. Attached Information.*

Responding to an identified need to meet more often, this group met virtually on June 28 for a mid-year development check-in to guide the next six months of development.

Informal Science Institution (ISI) Network: Our annual ISI Network and Advisory Board meeting was again held virtually on June 16. Representatives from the six ISI Partner Network institutions along with project evaluators joined the call. This meeting was an opportunity to check-in with the Network and project needs and goals. The agenda for this meeting is included in *VIII. Attached Information.*

Advisory Board Meeting: An Advisory Board meeting is planned for December with new and returning Board members.

OpenSpace Trainings: In Year Six, we have continued the use of telecons for training OpenSpace users. We also shifted our previous weekly virtual "office hours" with our

Software Integration Engineer Micah Acinapura to monthly sessions that are longer and have seen better attendance from our ISI Network Partners. These "Micah Monthlies" have become one of the most successful channels of support for our network partners.

Among the group training webinars held this year, was a webinar for over 50 Solar System Ambassadors, introducing them to OpenSpace and providing basic training in software operation. This training was tailored to the responses received to a pre-training survey sent out by Solar System Ambassador PI Kay Ferrari.

Representatives from AMNH and three ISI Network Partners presented a virtual half day Pre-Conference Intensive at the Association of Science Technology Centers annual conference that was focused on getting new users started with using OpenSpace for space and Earth science programming. This workshop was sponsored by the project to reduce the cost for participants.

In addition to the training sessions highlighted here, developers continued to meet one-on-one and in small groups with new and existing users to address their individual installation and training needs.

Year Six ISI Partner Network Activities

All of ISI Network partners operated with some changes due to the ongoing COVID-19 pandemic. Most had on-site visitation limits for some portion of the year, and one of our partners remained closed for all on-site visitors. As in Year Five, our partners continued their engaging online and socially distanced programming, impactful remote internships, and innovative installations using OpenSpace. In Year Six, the six ISI Network partners reached over **149,300 people on-site** and **358,400 people online**.[5] The scope, style, and frequency of each partner's programs varied, as detailed below, showcasing the versatility of OpenSpace as a tool for online presentations.

Adler Planetarium: In Year Six, the Adler Planetarium, while still closed to the public, reached their audience through virtual programming. In February, the Adler hosted a two-hour livestream, "Mars-di Gras: Mars Rover Landing Watch Party," which had over 650 peak live viewers. OpenSpace was used to contextualize the rover's journey and landing. The Adler also made use of OpenSpace in digital outreach events such as the "Wow Signal" online video series, one of which occurred during the reporting period. The recording of the Perseverance livestream and other videos using OpenSpace reached over **17,300 people online** in Year Six.

The Adler continued to host impactful internships. This year, two high school student interns were tasked with creating a 5-minute planetarium show, from concept development through presentation, that included research, producing visuals in OpenSpace, and providing a final

[5] This represents a significant part but not the total OpenSpace reach in Year Six (see Additional Year Six Activity below for more).

narration. They learned the capabilities of the OpenSpace software, how to vet and assess reputable data sources, video editing and frame sequencing, and guidance on strengthening their communication and presentation skills. The content developed by the interns was presented to an audience including other Adler interns and staff members. This content will continue to be useful for future programs both online and when the Adler re-opens its exhibitions to the public.

American Museum of Natural History (AMNH): In Year Six, OpenSpace was utilized in a variety of ways that reached over **246,900 people online**.

AMNH continued its two main series of virtual public programming, "Astronomy Online" and "Frontiers Lectures," with a few other special programs. Recordings of the 11 Astronomy Online programs this year have received over 150,700 views to date.

"Astronomy Online" programs use OpenSpace to explore a variety of Earth and space science topics — from Mars 2020 to climate change to space weather forecasting — designed for middle and high school-aged learners and their families. This series of programming was awarded a 2021 Media & Technology MUSE Award from the American Alliance of Museums in the "2020 Response" category, which recognizes, "In the face of the unique social, political, environmental, health, and economic challenges of 2020, any digital or technology innovation or leadership that has embraced disruption, dramatically improved digital literacy or pivoted for the new normal."

"Frontiers Lectures" are evening programs that host experts from STScI, Johns Hopkins, NASA GSFC CCMC, and beyond to dive deeply into a subject, such as new understandings from New Horizons data, the risks of solar weather, and interstellar interlopers. Most of these programs used OpenSpace to provide context, and some were conducted almost entirely in OpenSpace.

Among the special programs were event-based livestreams organized by the AMNH OpenSpace team, including a livestream with NASA astronauts Mary Cleave, Paul Richards, and Alvin Drew to celebrate the Perseverance landing, and a pair of live programs in October ahead of the James Webb Space Telescope launch. Future programs about Webb are planned as AMNH was selected as aWebb Space Telescope Community Events site.

In addition to virtual programs, OpenSpace was used in internships, online learning activities, and pre-service teacher preparation.

Youth Interns and Volunteers: The Museum continued its relationship with the Bergen Academy for Technology and Computer Science with three high school interns under the direction of co-I Carter Emmart during the academic year. These interns contributed to improving and expanding visualizations in the software through lunar terrain processing, refining Mars Reconnaissance Orbiter data, and creating an Apollo mission lunar surface panorama. Co-I Emmart also worked with a former Bergen Academy student, now college freshman, to visualize the Lucy mission trail and two high school students in the

Museum's Lang program to add landing site insignias for Earth's Moon, Mars, Venus, and Titan.

In addition, two high school interns in the Museum's Lang program, one high school student completing their senior work experience, and one Scout volunteer worked with OpenSpace Project Coordinator Corrie Roe on web projects. This included reviewing and revising the auto-generated captioning on YouTube to increase accessibility of the project's online programming, and researching and summarizing information about upcoming missions to write content for the project's social media. The interns increased accessibility on over 10 hours of video content and contributed to social media posts that reached over 10,000 people online.

Online learning: Late in Year Five, the Museum's National Center for Science Literacy, Education and Technology created quizzes on Kahoot! and the Museum's Ology website using OpenSpace images and clips. The quizzes can be used as stand-alone educational games, or to supplement the Museum's Astronomy Online programs, as the quizzes use clips and screenshots from the Astronomy Online programs about space flight, the Moon, Earth, and Mars. In Year Six, these quizzes have been played 64,200 times to date.

Pre-service teacher preparation: OpenSpace is used in the Museum's Masters of Arts in Teaching Earth Science Residency (MAT-ESRP) program for 15 pre-service teachers working in high-needs schools in the New York City area as a tool for learning and teaching about space science concepts in 7th-12th grade classrooms.

In addition, the OpenSpace pilot for six of the Astronomy Online and Frontiers Lecture programs described above was Deon Desir, a graduate from the Museum's MAT-ESRP who is also in his fourth year of teaching science at Eagle Academy for Young Men, a public high school in Brooklyn, NY.

Finally, project staff and the growing group of OpenSpace pilots at AMNH organized nine training sessions, demonstrations, and conference presentations, which are further detailed below.

California Academy of Sciences (Cal Academy): In Year Six, California Academy of Sciences used OpenSpace in a variety of on-site and online programs.

In April, the Morrison Planetarium reopened to on-site visitors and resumed its daily live program flown entirely in OpenSpace, "Tour of the Universe." The "Tour of the Universe" was also incorporated into Cal Academy's weekly NightLife program, which began on-site in August. Over 193 shows, these programs reached over **17,700 visitors on-site**.

For its virtual programming, Cal Academy had two main series: "Cosmic Conversations" and "Tour of Space/the Universe." This year, "Cosmic Conversations," which are approachable dialogues with a STEM expert, featured former astronauts, mission engineers, early career planetary geologists, astrobiologists, among others. "Tour of Space/the Universe" were held weekly for the entire year. Beginning in April, this program was a simulcast of Cal

Academy's in-person planetarium program. Additional special virtual programs included a Benjamin Dean lecture and program about Webb. These livestreams were broadcast on the Morrison Planetarium Facebook page, OpenSpace YouTube, and, new this year, on the Cal Academy YouTube and Facebook. In all since November 1, 2020, Cal Academy held an incredible 70 virtual programs, reaching approximately 4,400 people live. In total, Cal Academy reached a total of **93,300 people online** in Year Six.

Denver Museum of Nature and Science (DMNS): In Year Six, Denver Museum of Nature & Science (DMNS) had two series of Earth science virtual programming using OpenSpace: Digital Earth and Digital Earth Academy. Digital Earth runs 4-6 times a year, and has been a popular live program appearing in DMNS' Gates Planetarium since 2008. The original Digital Earth program used non-OpenSpace planetarium visualization software for its after-hours shows, but with the start of the pandemic, it switched to an online version that relies almost completely on OpenSpace. During the first year of streaming, Digital Earth had a considerably larger audience than the original planetarium version.

This greater exposure resulted in an anonymous $20,000 donation to DMNS in September 2020 expressly for supporting Digital Earth programming. After discussions with DMNS' education division, co-I Ka Chun Yu decided to use this money in part to fund the development of a new Digital Earth Academy series, targeting elementary and middle school students with a new monthly show during the academic year, consisting of two hour-long broadcasts during school hours for each show.

Digital Earth Academy is based on DMNS' successful Scientists In Action model, which consists of free, live broadcasts hosted by scientists, who interact with students globally on a broad range of scientific topics and disciplines during a day's worth of programming. The new Digital Earth Academy took this broadcast model, but retained a focus on Earth sciences. The production team also used OpenSpace to create videos that students could watch before the broadcast, which introduced the broad idea of exploring Earth from space and science concepts important for understanding the main broadcast. The show topics in this inaugural year included titles like "Oceans," "Ice," "Climate Change," "Weather," "From Stonehenge to Skyscrapers" (on human-structures visible from space), and "Extremes" (about the zeniths and nadirs of Earth environmental variables, such as temperature, elevation, acidity, and salinity).

The anonymous donation has allowed for further development of OpenSpace's visualization capacity, beyond what was originally envisioned in the NASA proposal. Co-I Yu worked with developers at The Elumenati to create a software connection (a Spout feed) between OpenSpace and Elumenati's Worldviewer2 visualization tool. This allows for global maps and animated geospatial data layers to be superimposed on top of OpenSpace's digital globe model, as well as allowing other media assets like photos and regular videos to be blended, layered, and controlled by the presenter. The open source nature of OpenSpace made it possible for a private company to integrate the software into their platform.

With all of these programs, DMNS reached approximately 5,500 people live. In addition, recordings of the programs have been viewed over 2,500 times on the museum's YouTube and Facebook to date. In total, DMNS reached over **8,000 people online**. Co-I Yu acknowledges that although many of this past year's online program and software development were possible because of the anonymous donation, the donation itself was made possible by OpenSpace: "There is no doubt in my mind that the terrific OpenSpace visuals, the engaging style of storytelling we've built up over the years, and the increased audience reach allowed this amazing gift to happen."

Houston Museum of Natural Sciences (HMNS): HMNS continued to utilize OpenSpace in its internship, public, and school programs in Year Six, and added an installation on its exhibit floor. In all, approximately **18,200 people on-site** and **100 people online** experienced OpenSpace at HMNS.

HMNS had 18 high school interns as part of its internship program in Year Six. Interns worked on-site, creating OpenSpace visuals for display and giving presentations to visitors, including school groups. In the Expedition Center, interns simulated flight paths on Mars to illustrate missions to Mars and for an activity about classifying Martian rocks. The interns operated a Discovery Dish for programs using OpenSpace for T. Rex Week in July and for outreach presentations at local summer camps and schools.

In addition to the intern presentations, a planetarium program, "Death of the Dinosaurs," created by the Astronomy Department for T. Rex Week, included OpenSpace flights to various fossil quarries around Earth and continues to be shown daily due to its popularity.

In August, a kiosk with OpenSpace was installed in the Burke Baker Planetarium lobby. Visitors can use a touch screen to fly to different places in OpenSpace. This is among the first instances of an interactive OpenSpace exhibit.

North Carolina Museum of Natural Science (NCMNS): In Year Six, NCMNS staff led seven virtual OpenSpace public programs, multiple conference and school presentations, and continued to innovate new ways to utilize OpenSpace. In all, NCMNS reached over **126,600 people on-site** at NCMNS and its partner institutions, Museum of Life and Science and A Time for Science, and **4,400 online**.

Like all of the museum's public programming, the annual Astronomy Days was held virtually. The weekend of programming included three OpenSpace presentations: "The Terrestrial Planets" presented by Co-I Dr. Rachel Smith, "The Giant Planets in OpenSpace" presented by a NCMNS intern, and "Seeing the Whole Universe" presented by AMNH Co-I Emmart. The museum also used OpenSpace in its Perseverance landing livestream, "Starry Night" virtual public program, and virtual Science Café "From Dust to Planets: Clues from Meteorites" with AMNH curator Dr. Denton Ebel.

OpenSpace continues to be on permanent display in the museum's Astronomy and Astrophysics Lab in the form of curated, looping visualizations. An additional video display was installed to accompany a new exhibit about the museum's Apollo lunar sample.

NCMNS also held student internships focused on OpenSpace. Four undergraduates and one high school student worked to develop OpenSpace programming and content, led OpenSpace demos in the Astronomy and Astrophysics Lab, and created content guides for OpenSpace that were published on the OpenSpace website.

Dr. Smith is a strong advocate for OpenSpace, and has supported its adoption at multiple institutions. Additional uses of OpenSpace in formal education settings and conference presentations, and the use of OpenSpace by partner institutions, Museum of Life and Science and A Time for Science, are described in the sections below.

Additional Year Six Community, Academic, and ISI Activities

We saw exciting growth in the number and types of institutions and individuals beyond our ISI Partner Network that have adopted or expanded their use of OpenSpace this year. In Year Six, we connected with and supported 12 new users, a greater increase than in previous years.

As an open source software, OpenSpace is freely available to anyone, anywhere. As such, it is likely that OpenSpace is utilized by many more institutions and individuals than we could track. Below, we identify 28 known users, detailing the most notable and exciting examples of OpenSpace implementation amongst this broader community, including new adopters (indicated with an *asterik) and new uses by previous users, in alphabetical order.

While live reach numbers for most of these programs are not available, some institutions were able to collect and share their on-site audience numbers with us, and we are able to tally video views of livestreams and recorded content. With this information, we learned that OpenSpace reached an additional **200 people on-site** and **6.6 million people online**.

Amateur Astronomers Association of New York (New York, NY): The Amateaur Astronomers Association resumed some of its in-person programming this year but continued to hold a semi-monthly livestreamed series focused on moons around the Solar System called “Moon-topia,” hosted by former AAA President and current AMNH Hayden Associate Irene Pease. Pease also hosted regular virtual programs on her science communication channels, Friendly Neighborhood Astronomer, using OpenSpace. Recording of these livestreams reached over 9,700 people in Year Six.

Appalachian State University (Boone, NC)*:* NCMNS Co-I Smith has continued to use OpenSpace in her Appalachian State University coursework, integrating it into undergraduate courses “Astrobiology: Searching for Life in the Universe.” Fellow App State professor Dr. Dan Canton also used OpenSpace in his fall introductory astronomy course and in monthly virtual public programming in his capacity as director of the Dark Sky Observatory. Undergraduate students act as the OpenSpace pilots for these programs. In all, OpenSpace was experienced by approximately 300 people online at App State.

*Arizona State University (Tempe, AZ): Through a ROSES-21 proposal that ultimately was not funded, we connected with the ASU Marston Exploration Theater director who is

interested in using OpenSpace. Our Software Integration Engineer has installed OpenSpace and provides training support for the director and student presenters. This is also a great connection for the NASA missions that are based at the university.

*B612 Foundation (Mill Valley, CA): Partner Cal Academy hosted former NASA astronaut Dr. Ed Lu as a guest on "Cosmic Conversations" in February. Dr. Lu is the Executive Director of the B612 Foundation, an organization that works towards protecting the Earth from asteroid impacts and informing and forwarding world-wide decision-making on planetary defense issues. Through this connection, Dr. Lu and his team became interested in using OpenSpace to visualize asteroids. In July, a few developers joined our Slack workspace and have been working on the visualizations with our team.

City College of New York Planetarium (New York, NY): CCNY Planetarium Director James Hedberg has continued to be a "superuser" of and contributor to OpenSpace. In Year Six, Dr. Hedberg continued to make short educational videos using OpenSpace to illustrate concepts, from changes in the night sky to the Moon's wobble. These videos took off this year, gaining 5.26 million views to date. Dr. Hedberg also live-streamed a program from the planetarium, presented as part of Cal Academy's "Cosmic Conversation" series, and spoke about OpenSpace in his plenary talk at IAU's virtual Communicating Astronomy to the Public conference.

*Fernbank Science Center (Atlanta, GA): The Fernbank Science Center has been using OpenSpace since April 2020, when in-person programs were forced to stop due to the pandemic, but was not previously on our known user list. By January 2021, the Fernbank hosted three to four live virtual planetarium programs each week, with about half using OpenSpace. With new content and guest presenters, each show is unique and reaches up to 10,000 live viewers.

*Fleischmann Planetarium, University of Nevada (Reno, NV): In July, our Software Integration Engineer installed OpenSpace in the Fleischmann Planetarium when he was in the area on personal travel. The planetarium is one of only two in Nevada.

Michigan Science Center (Detroit, MI): Staff at Michigan Science Center, a new user in Year Five, has throughout the year regularly met with our Software Integration Engineer for training to use OpenSpace in public programming. The primary OpenSpace user at MiSci is the Director of Theaters and Science, and a great ambassador for OpenSpace in her roles as a Solar System Ambassador and in the Great Lakes Planetarium Association (GLPA). OpenSpace was used in public programs virtually and in-person at an exhibit grand opening.

*Minnesota State University — Moorhead Planetarium (Moorhead, MN): In June, the MSUM planetarium, a member of the planetarium vendor Elumenati's GeoDome Network, reached out with questions about using OpenSpace in their dome. The staff, which includes some undergraduate students, has met regularly with our developers for training as they create public programs and produce a planetarium show.

Norrköping Visualization Center C (Linköping, Sweden): The Visualization Center C re-opened to a reduced capacity earlier in 2021 and has been showing the previously rendered OpenSpace show, "OpenSpace 3D" regularly. Additionally, the occurrence of high-profile visitors, such as Marcus Wallenberg, Peter Wallenberg, Jr., and Prince Carl Philip of Sweden, during the year speaks to the national importance of utilizing OpenSpace for public outreach and fundraising.

In addition to the live shows, the Visualization Center has created a new production "VAST" that premiered on October 30. This movie is part of the WISDOME effort funded by the Knut and Alice Wallenberg foundation that will expand the use of OpenSpace to four additional dome planetariums in Umeå, Stockholm, Gothenburg, and Malmö, Sweden. The developer team created a museum exhibition piece accompanying the movie that enables visitors to visit planets, missions, and extragalactic datasets interactively. This exhibition piece will be shared with interested partners of this grant.

*Paulucci Space Theatre, Hibbing Community College (Hibbing, MN): The Paulucci Space Theatre received a major upgrade during the pandemic and reopened in June with OpenSpace installed in its planetarium. This is largely due to SMSU Planetarium director Ken Murphy (see below), who provided key assistance. Murphy explained: "[Paulucci's Director and I have] been talking for over a year about how to move forward. He drove to my place to see what I had. I was more there to encourage and offer advice on what modern planetariums do these days. I showed up to do an OpenSpace presentation to the donors and college administrators, and trained [the Paulucci Space Theatre Director] and his assistant on how to use and present with OpenSpace." As one of two planetariums in the north of Minnesota, this is an exciting installation. The Paulucci received news coverage with its reopening that highlighted OpenSpace.

Southwest Minnesota State University Planetarium (Marshall, MN): The SMSU Planetarium, which last year emerged as a "super user" of OpenSpace, resumed some on-site programming in Year Six. SMSU Planetarium director Ken Murphy has been a great ambassador for OpenSpace as well, presenting about OpenSpace in regional astronomy clubs and assisting other Minnesota planetariums install and learn OpenSpace.

*Springfield Science Museum (Springfield, MA): In November, we connected with the Springfield Science Museum's planetarium manager after he reached out for help with OpenSpace on our public Slack. The museum hosted some virtual programs and is interested in having OpenSpace as a key component of the planetarium's future upgrade.

*Suffolk County Vanderbilt Museum & Planetarium (Centerport, NY): In June, OpenSpace was installed in the Charles and Helen Reichert Planetarium through a remote installation session between planetarium vendor SSIA Technologies with our developers. This was exciting as Vanderbilt has long been interested in using OpenSpace in their planetarium, but due to technical constraints, were not able to install it successfully until now. In addition to live and

recorded planetarium programming, the planetarium serves as the meeting location for the Astronomical Society of Long Island.

*A Time for Science (Greenville, NC): A Time for Science, a partner institution with NCMNS and new user, opened an interactive OpenSpace exhibit in Year Six. The installation uses arcade-style buttons that allows visitors to fly around in OpenSpace. The museum also used OpenSpace for its middle school field trips to explore the Moon-Earth system. Students were asked to make models representing the relative size and distance of the Earth and Moon and then compared these to the data in OpenSpace. In just two months since its reopening in September, A Time for Science has reached 1,600 visitors on-site with OpenSpace.

US Space & Rocket Center (Huntsville, AL): While closed to the public in 2020, the Rocket Center utilized OpenSpace for planetarium-style tours live-streamed to Facebook. Now that the Rocket Center has reopened, it is using OpenSpace for live programs on a video wall in its Saturn V Hall, with plans to install the latest version of OpenSpace in its 250-seat, 8K laser planetarium in the winter. Planetarium Director David Weigel also presented with Co-I Emmart for the annual meeting of the regional planetarium organization, the Southeastern Planetarium Association (SEPA).

*Versant Power Astronomy Center, University of Maine (Orono, ME): In June, OpenSpace was installed on the Astronomy Center's two-channel dome in a remote installation session between planetarium vendor SSIA Technologies with our developers. The planetarium is one of the four permanent planetariums in Maine, and received an update in 2020. It is open to the public, a resource for students of the University of Maine, and host to programs for area students of all ages.

These 8 additional users either continued with the same activities as in previous years, had limited engagement with OpenSpace due to the pandemic, or are just getting started with using OpenSpace:

- Edward R. Murrow High School (Brooklyn, NY)
- Fiske Planetarium, University of Colorado Boulder (Boulder, CO)
- Iziko Planetarium and Digital Dome (Cape Town, South Africa)
- Ho Tung Visualization Laboratory (Hamilton, NY)
- Lower Eastside Girls Club (New York, NY)
- *Masten Space Systems (Mojave, CA)
- Museum of Life and Science (Durham, NC)
- New York University (New York, NY)
- *New Zealand Astrobiology Network (Wellington, New Zealand)
- University of Utah (Salt Lake City, UT)

Finally, OpenSpace has received interest or started installation conversations with 11 institutions in Year Six, that we will pursue into Year Seven:

- Bell Museum, University of Minnesota (St. Paul, MN)
- Cheyney University Of Pennsylvania (Cheyney, PA)

- Cincinnati Museum Center (Cincinnati, OH)
- Fayetteville State University (Fayetteville, NC)
- Kitt Peak National Observatory (Tucson, AZ)
- Liberty Science Center (Jersey City, NJ)
- Oregon Museum of Science and Industry (Portland, OR)
- Pisgah Astronomical Research Institute (Rosman, NC)
- Planetarium Hamburg (Hamburg, Germany)
- Raritan Valley Community College (Branchburg, NJ)
- University of the Free State (Bloemfontein, South Africa)

Planetarium vendors
As institutions welcome back on-site visitors and in increasing numbers, planetarium vendors have increasingly reached out to discuss OpenSpace integration with their systems.

Elumenati has maintained their active adoption of OpenSpace as a core feature of their system. We partnered with Elumenati on a virtual booth and demonstration for LPSC in March. In September, we partnered with Elumenati to utilize their Worldviewer software for an AMNH livestream about climate change and wildfires. The Elumenati's GeoDome Network remains a strong presence among OpenSpace users.

SSIA Technologies was a new vendor this year, that stepped in to service some of the former North and South American customers of Sky-Skan, which filed for bankruptcy in Year Five. As mentioned above, SSIA was responsible for connecting us with a few new installations of OpenSpace. We will continue to provide training for SSIA so they can install and support new instances of OpenSpace.

We continue to be in conversation with other planetarium vendors ePlanetarium, Evans & Sutherland, Front Pictures, Fulldome Pro, Seiler Instrument, Vioso, and ZEISS as the need arises.

III. Status, Changes, Issues

Personnel Changes
Dr. Mark SubbaRao, previously co-I at the ISI Network partner Adler Planetarium, left his role to lead NASA's Science Visualization Studio. This led to some restructuring of the subaward budget and scope to reflect institutional capacity.

We're pleased to share that Dr. James Hedberg has joined the OpenSpace Advisory Board. As mentioned above, Dr. Hedberg, the Director of the City College of New York Planetarium, is an innovative contributor and strong advocate for OpenSpace. We look forward to his contributions in this new role.

IV. Dissemination Activities, Collaborators, and Cross-Collaboration Agreement Activities

Online Presence

In Year Six, in addition to the dozens of streaming programs and resulting videos, we have continued to develop digital channels to support our users and further increase awareness and participation in OpenSpace activities. We continued to see our online reach and engagement grow, building on the great increases we saw in Year Five.

Website (www.openspaceproject.com)

The OpenSpace website remains the entry point for potential new users, offering an overview of the project, introduction to the team, opportunities for participation, and a link to download the software. From the website, visitors can connect with our community workspaces and social media platforms. This year, we have added more user guides and tutorials, program guides, and resources to aid the adaptation and implementation of OpenSpace.

Since November 2020 to present, openspaceproject.com has received over 77,000 total visits (a 50% increase from Year Five). Of these visits, United States IP addresses again led in geography, accounting for nearly 35,000 (44.9%) visitors. This was followed by seven countries with over 1,000 visits: U.K., India, Germany, Canada, Netherlands, Sweden, and Australia. An additional 50 countries had at least 100 visitors each. Our geographical spread has continued to grow.

About 35% of visits originate through search engines like Google, DuckDuckGo, and Bing, but almost the same amount (36%) are direct, meaning visitors do not search for or click on a link, but type in the website address.

Support and Community Channels

Wiki (wiki.openspaceproject.com): We have continued to populate this public wiki-style website for users, content creators, and developers. This space has the most detailed documentation for each of these audiences. This year, basic tutorials with short videos were added, which we hope will serve as a model for future tutorials.

GitHub (https://github.com/OpenSpace/): GitHub is the public source code repository for OpenSpace. Users and developers can also report technical problems with the software, offer bug fixes, and make contributions to the code.

Reddit (https://www.reddit.com/r/OpenSpaceProject/): In November, the team created an OpenSpace Reddit as an additional support channel and place to share uses of the software. Though the numbers have remained small so far, the platform has enabled us to reach and support a new audience of potential users.

Slack (openspacesupport.slack.com; team-openspace.slack.com): In addition to supporting work across the project team, these messaging and file sharing spaces also act as a community-driven forum for collaboration. In Year Six, we continued to create private

channels for institutions to connect directly with software developers, and saw more community contributions and conversation on our public support workspace.

Newsletter (example: https://mailchi.mp/amnh/thisweekinopenspacefeb16): Our newsletter has had a steady audience of over 360 subscribers, including ISI professionals, SMEs, and members of the public. There are two newsletters available: A weekly events roundup and a quarterly update. This year, the newsletter was opened over 4,300 times with an average of 4.4% direct engagement.

OpenSpace Social Media Platforms

In addition to followers, a common analytic used on social media platforms are "impressions" and "reach." While each platform calculates these differently, they can be thought of as how many people saw the content. Another useful indicator on these platforms is "engagement" — this measures if people interact with the content, such as through clicks and views. An "engagement rate" is the percentage of viewers who interact with the content.

Instagram (@openspaceproj): The OpenSpace Instagram account, which was previously our most nascent, saw great growth in Year Six. In Year Six, we more than tripled our followers to 648, tripled interactions to nearly 1,500, and quintupled our impressions to over 40,000. We previously only posted a few videos that received 600 views, but this year the 10 content-focused and 1 announcement videos we posted have been viewed a total of 29,813 times to date.

YouTube (www.youtube.com/c/OpenSpaceSoftware): This year, the OpenSpace YouTube channel saw over 472,000 impressions, 36,000 views, and 2,500 watch hours. This was an increase of about 40% in each of these categories compared to Year Five, and does not include the AMNH flagship or other partner YouTube channels, which are described below. Our total subscribers, 2,721, is a 45% increase from our previous total. The top geography of our viewers at 30% had US IP addresses. The top 10 videos by views included two live-streams, four OpenSpace tutorial videos, and four short visualizations.

Facebook (@OpenSpaceVisualization): The OpenSpace Facebook page continued on its upward trend. Our reach, which in Year Five was estimated to be over 505,000, more than doubled to over 1,178,000. Engagement is also up, tripling to over 81,300. Followers increased by 55% to 889.

Twitter (@openspaceproj): This year, the OpenSpace Twitter account maintained its reach, which saw a dramatic increase in Year Five. We saw the greatest increase in profile visits, which increased by five times (from 1,831 to 10,320). Our followers also grew to 789, up by 30% from last year. The account's 179,160 impressions and 256 mentions were modest increases from Year Five.

Additional Online Reach

In addition to the OpenSpace platforms, content using OpenSpace is hosted on the websites and social media platforms of our ISI Network partners, other users, conferences, and beyond. While not all analytics are available, the number of times videos are watched is generally public information. This allowed us to determine videos using OpenSpace gained approximately 6.6 million views in Year Six.

A large part of that total is from the OpenSpace-based educational content posted to the CCNY Planetarium Instagram account, which saw a huge growth this year. Whereas previous content totaled a few thousand views with followers totalling around 300, in Year Six, the account gained 5.26 million views and its follower count increased to over 14,900. The most popular video (https://www.instagram.com/reel/CQTMeJMnAaL/) used OpenSpace to create an analemma of the Sun from New York City. This video alone accounts for 2.4 million views and received 85,000 likes! With over 100 innovative videos and approximately 3.8% engagement, this is a very exciting use of OpenSpace that can communicate basic astronomy concepts in compelling new ways.

Press Coverage

OpenSpace visualizations were included with press materials for two scientific publications: A paper in *Nature* by Dr. Jackie Faherty (AMNH) and Dr. Lisa Kaltenegger (Carl Sagan Institute, Cornell University) about Earth as a transiting exoplanet, and a paper in *The Astrophysical Journal Letters* by Harvard's Center for Astrophysics about new understandings of how stars form (see *Academic Publications* below for full citation). These papers were covered by many news outlets around the world, including CNN (US), The Guardian (UK), Tencent (China), and News18 (India). In the case of the *Nature* paper, the authors were able to determine the paper was reported in 1,200 online articles and videos. Coverage that used OpenSpace images or videos received over 350 million hits!

OpenSpace was also utilized by local news to talk about public programs, space events, and planetarium openings. For example, New York City's CBS2 showed a clip of an upcoming eclipse visualized in OpenSpace[6] and WDIO ABC in Minnesota mentions OpenSpace by name for the reopening of the Paulucci Space Theatre.[7]

Conferences, Colloquia, and Symposium

While some conferences and colloquia were postponed or cancelled again due to the pandemic, others continued in a virtual format or resumed in-person meetings.

[6] Lonnie Quinn, "'Ring Of Fire' Solar Eclipse Set For Sunrise Thursday; Experts Looking Forward To 'A Show In The Sky,'" CBS2 (June 9, 2021). https://newyork.cbslocal.com/2021/06/09/ring-of-fire-solar-eclipse-sunrise-thursday/

[7] WDIO, "Paulucci Space Theatre preparing to reopen" (June 10, 2021). https://www.wdio.com/news/paulucci-planetarium-space-theatre-upgrades-space/6134214/?cat=10335

Glue-con, NYC (January 27): OpenSpace was one of four software packages invited to attend this mini-conference regarding interconnection of visualization software to ease their use by scientists. This conference is directly related to future thesis project work.

Lunar and Planetary Sciences Conference (March 15-20): An educational poster, "OpenSpace: Interactive Public Outreach in a Virtual World" (Abstract #2206), was presented at the virtual LPSC conference. We also partnered with planetarium vendor Elumenati on a virtual booth, livestreaming demonstrations of OpenSpace throughout the conference.

American Astronomical Society's 52nd Annual Meeting of the Division for Dynamical Astronomy (AAS DDA 52) (May 17-21): Dr. Jackie Faherty, 2020 Vera Rubin Early Career Prize winner, was one of two featured speakers at this year's virtual DDA meeting. OpenSpace visualization of the Gaia DR2 sample of stars were featured on the DDA meeting website and included as part of Dr. Faherty's presentation.

British Computer Society Open Source Specialist Group: Open Source in Space (May 20): Lead OpenSpace Developer Dr. Alexander Bock provided a presentation about OpenSpace as part of a virtual panel about open source space technologies. The talk was a brief introduction into the software framework, its origins, and the design principles behind it. The recording of the presentation has been viewed over 100 times.

SIGGRAPH (June 25): Lead Developer Dr. Alexander Bock and former developer Jonathas Costa co-presented previous year's work on accurate real-time atmosphere models to the prestigious SIGGRAPH conference as an invited talk.

5th Planetary Data Workshop (June 28-July 2): Co-I Emmart and Software Integration Engineer Micah Acinapura attended the virtual meeting. As in previous years, this was a great opportunity to connect with others doing or interested in similar visualization work.

Goldschmidt Conference (July 4-9): Goldschmidt, organized by the European Association of Geochemistry and the Geochemical Society, is the foremost annual, international conference on geochemistry and related subjects. NCMNS Co-I Dr. Rachel Smith presented a virtual paper, "Observations of Variability in Young Stellar Objects and Implications for Protoplanetary Carbon Reservoirs" to approximately 50 attendees online.

Southeastern Planetarium Association (SEPA) annual meeting (July 30-31): Co-I Emmart partnered with US Space & Rocket Center's planetarium director to share the latest from OpenSpace and WorldWide Telescope, including upcoming WWT-OpenSpace integration, to about 40 planetarium professionals online.

84th Annual Meeting of the Meteoritical Society (MetSoc) (August 15): NCMNS Co-I Dr. Rachel Smith presented a science talk, "Variability in Gas-phase Co Reservoirs in Massive Young Stellar Cores and Binaries," at the MetSoc meeting in Chicago, IL, to about 75 attendees on-site and others on Zoom. Dr. Smith and AMNH scientists Dr. Denton Ebel and Marina Gemma also boothed a table demonstrating OpenSpace to interested attendees.

Live, Interactive Planetarium Symposium (LIPS) (September 23): The annual LIPS, originally planned to be in-person in Pittsburgh, PA, was shifted back to virtual (and free of change) in August. We had planned to be a sponsor and were still able to present as such, for no cost, at the eLIPS.

Association of Science Technology Centers (ASTC) Annual Conference (September 30): "Explore a Universe of Programming with OpenSpace" was a preconference half-day intensive workshop led by OpenSpace PI, Rosamand Kinzler, along with developers and representatives from four of the ISI Network partners. The virtual workshop was attended by five new users and included an OpenSpace demo and tutorial before attendees created lightning presentations piloted by an experienced OpenSpace user.

Space Apps NYC (October 1-3): In addition to presenting about OpenSpace as part of the Space Apps NYC virtual symposium, OpenSpace was named a sponsor of the symposium and hackathon for donating our Zoom account. The team also supplied suggestions for symposium speakers.

Vetenskapsdagen (October 11-14): Lead Developer Dr. Alexander Bock presented OpenSpace to a Sweden national event celebrating educational science and STEM research called Vetenskapsdagen (the days of research/science). This specific subevent was aimed at future physics teachers and providing them with the ability to utilize OpenSpace in classrooms.

CROSS Sixth Annual Research Symposium (October 11-14): Lead Developer Dr. Alexander Bock presented the OpenSpace project for the University of California in Santa Cruz's CROSS (Center for Research in Open Source Software) Sixth Annual Research Symposium.

UCLA Earth, Planetary & Space Sciences Fall Colloquium (October 19): NCMNS Co-I Dr. Rachel Smith was invited to give a colloquium for the Department of Earth, Planetary and Space Sciences (EPSS) at UCLA. The talk, "Connecting the Public with Science: Lessons from a Major Public Museum," prominently featured OpenSpace and was attended by 78 people on-site.

IEEE VIS 2021 (October 24-29): Co-I Prof. Anders Ynnerman, Lead Developer Dr. Alexander Bock, and Dr. Mark Subbarao co-organized an Application Spotlight called "Challenges for Visualization in Immersive Planetarium Domes" designed to engage the wider visualization community and which featured OpenSpace one of the prominent examples of the success of this collaboration.

Academic Publications

M.E. Gemma, C. Roe, M. Acinapura, C. Emmart, D.S. Ebel, R. Kinzler, V. Trakinski, B. Abbott, and R.L. Smith (2021), *OpenSpace: Interactive Public Outreach in a Virtual World* [Virtual poster session], Lunar and Planetary Sciences Conference 2021. Abstract #2206.

F. Lan, M. Young, L. Anderson, A. Ynnerman, A. Bock, M. Borkin, A. Forbes, J. Kollmeier, B. wang (2021), *Visualization in Astrophysics: Developing New Methods, Discovering Our Universe, and Educating the Earth*. Computer Graphics Forum 40:3. https://arxiv.org/abs/2106.00152

In addition, OpenSpace visualizations were utilized in the press releases accompanying the following publications:

- Kaltenegger, L., Faherty, J.K. *Past, present and future stars that can see Earth as a transiting exoplanet*. Nature 594, 505–507 (2021). https://doi.org/10.1038/s41586-021-03596-y
- Bialy, S., et al. *The Per-Tau Shell: A Giant Star-forming Spherical Shell Revealed by 3D Dust Observations*. The Astrophysical Journal Letters 919: 1 (2021). https://doi.org/10.3847/2041-8213/ac1f95

Graduate Theses

OpenSpace has continued to be a focus of master student work at Linköping University; NASA Community Coordinated Modeling Center, Goddard Space Flight Center; New York University; and University of Utah. The following theses were submitted in Year Six:

- Selling, Y., and Lindgren, E. *Interactive Visualizations of Astronomy Images* (Master's Thesis, Linköping University, Linköping, Sweden). 2021.
- Paulsson, J., and Andersson, A. *Interactive Visualization of Air Traffic in OpenSpace* (Master's Thesis, Linköping University, Linköping, Sweden). 2021.

SMD Collaborators, Cross-CAN Awardee, and NASA Infrastructure Collaboration Activities

We have had ongoing conversations, development activities, and public programming in collaboration with NASA Subject Matter Experts and other awardees. We were also a collaborator on four ROSES SciAct Appendix Collaboration proposals.

<u>Cross-Collaboration with Science Activation Awards</u>

In addition to these formal cross-collaboration agreements, we collaborated with various SciAct projects this year around SMEs and OpenSpace presentations. Members of the AMNH OpenSpace team also participated in the Visualization Affinity Group, Social Media Action Group, and Slack planning group.

Projects preceded by an *asterisk had not previously collaborated with OpenSpace.

**Cosmic Data Stories:* We are excited to have the CosmicDS project join SciAct this year. We have previously collaborated with PI Dr. Alyssa Goodman around the Glue visualization software. This year, our developers worked on the WorldWide Telescope integration, which was identified as of interest by the CosmicDS team. We will continue to work on the Glue and WWT integration in Year Seven, and look forward to hosting SMEs in public programs using these tools.

NASA@ My Library: Continuing our collaboration, we worked with the NASA@ My Library team on two successful livestreamed programs, distributed to their library network, which organized a mix of in-person watch parties and virtual watch-alongs. Our two livestreamed programs, focused on Webb, presented by Co-I Emmart, AMNH Software Integration Engineer Micah Acinapura, and Dr. Jacqueline Faherty, AMNH astrophysicist with multiple Webb GO research projects. These programs occurred in mid-October and have since gained a few hundred views on the OpenSpace YouTube and STAR Net Library Facebook page.

Smoky Mountain STEM Collaborative: We met with SMSC throughout the year and are in touch on our Slack to provide training and support to integrate OpenSpace into their public outreach programs including International Observe the Moon Night in October. We are looking forward to a discussion with SMSC about the potential use of OpenSpace by community college instructors and students.

Cross-Collaboration with NASA Infrastructure Projects

Projects preceded by an *asterisk had not previously collaborated with OpenSpace.

JPL Eyes: We continue to collaborate with Eyes personnel to exchange data, resources, and strategies for covering upcoming mission milestones. We also utilized the Eyes' visualization of the Perseverance landing in a livestream and Jason Craig, Manager of Visualization, Technology, and Development, is a member of our Advisory Board.

NASA HEAT: This Year, HEAT invited OpenSpace to present a community webinar open to all at GSFC. The July 22 webinar was attended by about 30 people and the recording was posted as an internal GSFC resource.

Solar System Treks: Our software engineers continue to exchange relevant data with Treks for use in our respective software. This year, OpenSpace added Treks as a resource on its website.

JPL Museum and Informal Education Alliance: After consultation with the MIE Alliance, we have scheduled a webinar about using OpenSpace to showcase Webb in February 2022.

Solar System Ambassadors: After meeting with Kay Ferrari at the 2.0 kick-off meeting in January, we have considered how we can facilitate more Solar System Ambassadors' use of OpenSpace. This year, we held a webinar on July 15 for over 50 Solar System Ambassadors to introduce them to OpenSpace and provide basic training in software operation. This training was tailored to the responses received to a pre-training survey sent out by Solar System Ambassador PI Kay Ferrari.

NASA-Funded SMEs in Year Six

In Year Six, 25 NASA-funded Subject Matter Experts contributed to and/or used OpenSpace, 11 of whom are new to the project (indicated with an *asterisk). This brings the total number of

unique SMEs to 82.[8] We have grouped this year's SMEs based on their relationship to OpenSpace; in some instances, SMEs are counted in more than one use category, so the total will exceed 25.

Used OpenSpace in public programming: 16

- Dr. Kimberly Arcand (Director of Visualization, Chandra X-ray Observatory)
- *Dr. Candice C. Bedford (Postdoctoral researcher, JSC)
- *Dr. Jen Blank (Senior Scientist, Ames)
- *Dr. Mary Cleave (Astronaut, Atlantis Shuttle)
- *B. Alvin Drew (Astronaut, STS-118)
- Dr. Denton Ebel (NASA Emerging Worlds Grant; AMNH)
- Dr. Jackie Faherty (Co-PI, ROSES ADAP)
- Marina Gemma (NASA Emerging Worlds Grant; PhD Candidate, Columbia University)
- *Dr. Sarah M. Hörst (PI, NASA Cassini Data Analysis Program)
- Dr. Germán Martínez (Staff scientist, LPI)
- Dr. Cathy Olkin (Deputy Project Scientist, New Horizons; Deputy PI, Lucy)
- *Paul Richards (Astronaut, STS-102 Discovery)
- *Dr. Svetlana Shkolyar (Postdoctoral fellow, GSFC)
- Dr. Rachel Smith (PI, NASA Emerging Worlds Research Program, Astrobiology)
- *Dr. Suzanne Smrekar (Deputy PI, InSight)
- *Dr. John Spencer (Science team, New Horizons; CIRS, Cassini)

Used OpenSpace in formal education setting: 2

- Dr. Jackie Faherty (Co-PI, ROSES ADAP)
- Dr. Rachel Smith (PI, NASA Emerging Worlds Research Program, Astrobiology)

Used OpenSpace in research capacity: 1

- Dr. Jackie Faherty (Co-PI, ROSES ADAP)

Collaborated on new or improved data or functionality: 10

- Dr. Alyssa Goodman (Harvard University)
- Dr. Cathy Olkin (Deputy Project Scientist, New Horizons; Deputy PI, Lucy)
- Dr. Jennifer Heldmann (Research Scientist, Ames)
- Dr. Masha M. Kuznetsova (Director, CCMC, GSFC)
- Dr. Jon Linker (Co-I, SECCHI and IMPACT, STEREO)
- Dr. Leila Mays (Deputy Director, CCMC, GSFC)
- Jeff Nee (Education Specialist, JPL)
- *Dr. Anastasia Romanou (Research Scientist, GISS)
- Dr. Mark SubbaRao (Lead, SVS, GSFC)

[8] In reports for Years One, Two, and Three, the total number of NASA-funded SMEs was generated by adding the cumulative number by year. This meant some individuals were counted more than once if involved with OpenSpace across multiple years. We feel the new metric of unique SMEs, adopted in Year Four, better reflects the longevity of our relationships with SMEs.

- *Dr. Konstantinos Tsigaridis (Research Scientist, GISS)

Other SMEs in Year Six

An additional (non-NASA) 13 SMEs also used OpenSpace as a tool for exploring and communicating space science data for a broad audience, including 7 new SMEs (indicated with an *asterisk). This brings the total of unique (non-NASA) SMEs to 32. As above, we have grouped based on their relationship to OpenSpace; in some instances, SMEs are counted in more than one use category, so the total will exceed 13.

Used OpenSpace in public programming: 12

- Dr. Dan Canton (Dark Sky Observatory, Appalachian State University)
- Dr. James Hedberg (City College of New York)
- *Dr. Robert Hurt (Senior Scientist, IPAC-Caltech)
- *Dr. Steven Jaret (Planetary geologist, AMNH)
- Dr. Juna Kollmeier (Director, SDSS)
- *Dr. Laura Kreidberg (Director, Atmospheric Physics of Exoplanets, Max Planck Institute for Astronomy)
- Dr. Ed Lu (Executive Director, B612 Foundation)
- *Dr. Amaya Moro-Martin (Science Mission Office, STSCI)
- Irene Pease (CUNY)
- Dr. Bob Raynolds (DMNS)
- *Dr. JD Skok (SETI)
- *Dr. Natasha Stavros (Director, Earth Lab Analytics Hub, University of Colorado Boulder)

Used OpenSpace in formal education setting: 2

- Dr. Dan Canton (Dark Sky Observatory, Appalachian State University)
- Irene Pease (CUNY)

Used OpenSpace in research capacity: 1

- *Dr. Lisa Kaltenegger (Director, Carl Sagan Institute, Cornell University)

Collaborated on new or improved data or functionality: 2

- Dr. James Hedberg (CCNY)
- Dr. Ed Lu (Executive Director, B612 Foundation)

V. Evaluation

Evaluation by HG&Co

The OpenSpace project's external evaluator is HG&Co (507 Dartmouth Ave, Silver Spring MD; 301-655-1925; kate@hgandco.com). In Year Six, HG&Co worked with the AMNH team to conduct three strands of evaluation activity: a survey administered to participants in OpenSpace programs across the OpenSpace ISI Network; an in-depth qualitative evaluation of the high

school through graduate school internship programs implemented over the course of the year; and a survey-based evaluation to assess the health of the OpenSpace ISI Network. The results are detailed in the attached Evaluator Report.

In addition to their evaluation activities, HG&Co also chaired the SciAct Evaluator Group this year, providing the Zoom and notes for the monthly meetings.

Top-Level Metric Projections

The top-level metric for OpenSpace in the first phase of funding was the number of interactive "scenes," now "profiles", of NASA data available within the software. In our extension application, we identified a metric to represent the growth of the project in Phase II, the number of OpenSpace users, with the goal to reach 100 users by the end of Year 10. At the end of Year Six, we have 33 active users of OpenSpace.

SciAct Alignment

The OpenSpace PIs and evaluator worked together to ensure the project is appropriately engaged with the SciAct portfolio-level activities led by PRE, including aligning with mid-level objectives and determining which specific program indicators track back to those objectives.

OpenSpace is currently aligned with SciAct MLOs 1b, 1c, and 3c:

1b) Provide opportunities for participants to engage with the disciplinary content related to NASA science and engineering.

1c) Increased number of and frequency with which NASA SMD assets are used by learners across the US.

3c) Engage participants in learning experiences that promote development of skills for STEM careers.

(1b, 1c) As noted elsewhere in this report, OpenSpace focuses on increasing public engagement in NASA science and engineering via ISI programs for public audiences of all ages. In Year Six, 206 programs and 4 exhibits utilized OpenSpace to communicate science and engineering concepts. Year Six activity brings the total number of OpenSpace ISI Partner Network programs to 390. On-site programs and exhibits reached 149,500 people this year, bringing the total on-site reach to 1.1 million.

(1b, 1c) Another method of engagement that we have seen grow this year is online reach, which includes views of online programs, recordings of these programs, and produced videos. In Year Six, OpenSpace reached approximately 6.91 million people online, more than doubling online reach to 11.96 million. Additional online reach — through the OpenSpace website, OpenSpace social media platforms, and OpenSpace content on Kahoot and Ology — this year totaled over 2 million, bringing the total online reach of OpenSpace content to over 5 million. (This does not include the estimated 350 million hits to news articles using OpenSpace visuals.)

(1b, 1c, 3c) The ISI Partner Network hosted 31 interns ranging from high school to graduate level in a variety of multi-week, semester, and year-long internships and mentored experiences with data visualization and code development. Cumulatively, OpenSpace has been the focus of 190 internships. One of the main evaluation activities is an in-depth qualitative evaluation of the internship programs with internship journals and post-internship interviews.

Total Activity, Years 1-6

	NASA SMEs	Public institutions	Public programs	On-site reach[3]	Online reach[4]	Other online reach[5]
Y6	25[1]	33[2]	206	149,500	6,917,400	2,015,000
Y1-6 Total	**82**	**33**	**384**	**1,106,900**	**11,955,400**	**5,044,000**

1 Eleven of the NASA-affiliated SMEs are new to the project in Year Six.
2 Twelve of the public institutions are new to the project in Year Six.
3 On-site reach includes programs and exhibition experiences on-site at ISIs and other public institutions.
4 Online reach includes views of online programs, recordings of these programs, and produced videos.
5 Other online reach includes visits to the OpenSpace website, the reach of OpenSpace social media, and views of OpenSpace content on Kahoot and OLogy.

VI. Known Future Plans

In Year Seven, we will continue to identify and address points of friction that slow down or prevent adoption of the software by a broad range of users as well as adding new data sets for expanded programming.

Software and Content Development Goals
Software and content development activities planned for Year Seven include:

- New features, including:
    - Automated camera path
    - Simplified GUI
    - Integration of WorldWide Telescope window
    - Improving the interconnectivity of OpenSpace with other scientific tools
- New content to be explored for potential development include:
    - Dynamic Earth data
    - Earth climate modeling
    - Astrophysical modeling
    - Upcoming missions, including Psyche and Artemis
- Continue to build out OpenSpace Community Hub
- Ancillary materials
    - Documentation
    - Program guides

    - Training videos

ISI Partner Network Goals

ISI Network programs planned for Year Seven include:

- *Frontiers Lecture with Dr. Sasha Hinkley* (November 2021, AMNH)
- *Astronomy Online: James Webb Space Telescope* (December 2021, AMNH)
- *Astronomy Days* (January 2020, NCMNS)
- Additional programs around Webb early science results (spring 2022)

Additional goals for the ISI Partner Network include:

- Consulting accessibility and Universal Design for Learning (UDL) experts to improve public programs
- Develop program guide template for sharing presentation outlines across the network

Dissemination and Adoption Goals

To support existing users and encourage further adoption of the software, we are planning the following dissemination activities for Year Seven:

- Develop and distribute additional online resources for users, developers, and scientists, including tutorial videos, program guides, and training materials
- Hold training session at a NASA Center
- Hold training webinar for MIE Alliance (February 2022)
- Attend Great Lakes Planetarium Association (GLPA) conference (November 2021)
- Attend and present at AGU (December 2021) in "ED11A: Amazing Technologies and Capabilities That Contribute to STEAM" session
- Attend and present at AAS (January 2021) in "Interactive Digital Research, Education, and Science Communication with AAS WorldWide Telescope" special session
- Attend and/or submit abstracts to additional identified conferences:
    - LPSC (March 2022)
    - AAS (June 2022)
    - IPS (August 2022)
    - LIPS (September 2022)
    - ASTC (September 2022)

VII. Appendix: OpenSpace Profiles

Apollo 8: Models and trajectories for the Apollo 8 mission, allowing real-time playback of the complete mission, including the moment when the iconic "Earthrise" image was taken.

Apollo 11 and 17: A model and trajectory for Apollo 11 and the landing sites of the Apollo 11 and 17 missions, including photogrammetry of boulders from Apollo 17 station sites, allowing real-time playback of Apollo 11 from launch to lunar landing.

Asteroids and Comets: More than 936,000 asteroids and comets from JPL Horizons Small-Body Database, including: Amor Asteroids, Apollo Asteroids, Aten Asteroids, Atira Asteroids, Centaur Asteroids, Chiron-Type Comets, Encke-Type Comets, Halley-Type Comets, Inner Main Asteroid Belt, Jupiter Family Comets, Jupiter Trojan Asteroids, Main Asteroid Belt, Mars Crossing Asteroids, Outer Main Asteroid Belt, Potentially Hazardous Asteroids, and Trans-Neptunian Asteroids.

Bastille Day: This profile visualizes the results of a collaboration with the NASA Goddard Space Flight Center's Community Coordinated Modeling Center and Predictive Science Inc. to visualize the activities of space weather for the 2000 Bastille Day event. This profile shows the time-resolved movement of the magnetic fields close to the Sun and simultaneously shows the impact the space weather has on Earth and Earth's magnetosphere. (Available for download through Github.)

Earth Exploration: Daily updates of NASA GIBS global, temporal, multispectral, and multi-platform data gathered by NASA's Earth Observing System (EOS), including the True Color and Suomi National Polar-Orbiting Visible Infrared Imaging Radiometer Suite (NPP VIIRS) global mosaics, the latest of which loads on default. The profile is also supported by ESRI global elevation modeling.

Exoplanets: The locations of exoplanets are a native part of the Digital Universe and can be viewed in OpenSpace. Both dynamical and stellar occluding discoveries by the NASA Kepler mission are included.

Gaia: Data from ESA's Gaia Data Release 2 (DR2) are available in OpenSpace using a new and experimental out-of-core, octree-based renderer. The dataset that is automatically synchronized at startup contains the 7.224 million stars in the release for which radial velocity is available.

InSight Lander: A model of the InSight lander, its trajectory towards Mars, entry into the Martian atmosphere, and subsequent descent and landing on November 26, 2018. This content was created in collaboration with NASA JPL Eyes, which provided the data and models.

James Webb Space Telescope: This profile visualizes the NASA-ESA-CAN James Webb Space Telescope, expected to launch in late 2021. The profile includes two visualizations of the Webb trail: One plotted with respect to the Earth-Sun L2, where it will be stationed; and another with respect to the Sun, as we plot the orbits of the planets. A dynamic model of Webb is included with animated deployment sequence and active view frustum.

Juno: The approach of the NASA Juno space probe to the Jupiter system and its initial orbits around the planet.

Rosetta: The orbital trajectory and projected imaging onto a 3D model of Comet 67P/ Churyumov-Gerasimenko, the orbit from which the Philae lander was dropped, and observed comet outgassing during its post-perihelion phase in September 2015.

Lunar Exploration: Exciting new data, including compelling levels of detail in resolution, surface composition, and gravity measurements, acquired from mission sources and through collaboration with other NASA colleagues, including JPL's Moon Trek. All Apollo landing sites can be viewed in OpenSpace at 50-cm spatial resolution and one-meter height resolution, including Apollo 15 and 16 Metric Camera and 16 orbital track mosaics. Global gravitational free-air anomaly mapping by the Japanese Selenological and Engineering Explorer (Kaguya) mission is also included.

Mars Exploration: Global image, color, and elevation data are combined in an array of choices from multi-resolution imaging campaigns. 100-meter, Thermal Emission Imaging System (THEMIS) infrared, six-meter CTX, and local HiRISE data are currently available as layers in OpenSpace.

Mars 2020 Mission: As deliberations over the best landing site for the Mars 2020 life science investigation and sample collection mission occurred, these landing sites were developed to be explored in OpenSpace with a combination of HiRISE and CTX imaging and derived stereo elevation modeling, with mineralogical coloration by the Compact Reconnaissance Imaging Spectrometer (CRISM) experiment onboard NASA's Mars Reconnaissance Orbiter (MRO).

MESSENGER: Spacecraft model, trajectories, global, multispectral image maps and elevation, local closeups, and a static volumetric magnetosphere model.

New Horizons: NASA's New Horizons flyby of Pluto served as the OpenSpace project's mission visualization proof of concept. During the grant period, the New Horizons mission was updated with refined data and newly released maps from the spacecraft's Long Range Reconnaissance Imager (LORRI) camera, including the "stereo mosaic," which provides stereo coverage from multiple angles enabling the visualization of a height map.

OSIRIS-REx: Demonstration of the entire mission of NASA's OSIRIS-REx spacecraft on its way to the asteroid Bennu and its subsequent journey back to Earth, including orbital trajectory and anticipated timings for instrument deployment. This profile is continuously being updated as new discoveries are made during this spacecraft's ongoing operations.

Space Weather: AMNH continues to collaborate with NASA GSFC's Community Coordinated Modeling Center (CCMC) to visualize heliospheric observation and modeling combined with space weather modeling of Earth's magnetosphere. Solar modeling based on observations of the Sun's magnetic field and events are propagated through interplanetary space. The visualization of Earth's magnetosphere is simulated by CCMC's Bats-R-US code, and the ENLIL real-time solar wind application is used as a volumetric dynamic simulation visualization.

Voyager: The Voyager mission has been reconstructed into NASA's current digital mission description of SPICE, so that we can view the journeys of both spacecraft to the outer planets within OpenSpace.

VIII. Attached Information

OpenSpace Year Six Evaluation Report
OpenSpace Phase 2 Kick-Off Agenda
OpenSpace Developer Meeting Agenda
OpenSpace ISI Network Meeting Agenda