

# OpenSpace Annual Progress Report — Year Five

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

**Solicitation: NNH15ZDA004C**

### I. Administrative

<i>Recipient Name and Address</i>	American Museum of Natural History Central Park West at 79th Street New York, NY 10024
<i>Recipient Cooperative Agreement Number</i>	NNX16AB93A
<i>Principal Investigator</i>	Dr. Ro Kinzler
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### II. Accomplishments

The American Museum of Natural History (AMNH) is pleased to submit this fifth annual report on the achievements 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 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 fifth year, AMNH made significant progress toward these objectives through ongoing work on code development, content visualization, and programs for the general public,

youth, and educator audiences. As for all members of the SciAct collective, our planned activities were altered in response to the coronavirus (COVID-19) pandemic. OpenSpace programs were moved from on-site to online, our meetings and conference presentations have all been virtual, and our evaluation has relied on analytics, surveys, and telephone interviews. Our strategies for code developments and project management were largely unchanged, however, since these activities have relied on digital communication and collaboration platforms such as Github, Slack, and our publicly accessible website.

Our Year Five activities are described in greater detail below.

## **Software Development**

The OpenSpace software has continued to grow in Year Five through cooperative development at AMNH, Linköping University and Norrköping Visualization Center C,<sup>1</sup> New York University Tandon School of Engineering, and the University of Utah Scientific Computing and Imaging 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, memory-efficient algorithms to handle data intensive tasks, multi-modal rendering, integration of new data sets, and hardening the software code.

During this period, three significant updates of the OpenSpace software were published: Beta-6 (v0.15.1) was released on February 19, 2020; Beta-7 (v0.15.2) was released on June 30, 2020; and Beta-8 (v0.16.0) was released to the ISI partners on October 16, 2020. 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:

- Presenter Profiles and Profile Editor to enable users to customize and save their favorite settings
- Info button that provides source and rights information about datasets
- C-Troll, an application to jump start OpenSpace on planetariums, hyperwalls, and other multi-channel displays
- Performance enhancements to maintain high frame rate and fast data loading
- Improved support for Linux
- Simplified handling of global map layers to make them selectable in the profile editor
- Automated camera smoothing when changing focus nodes
- Improvements to session recordings enabling more automated playback during live programs

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<sup>1</sup> 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.

Development work in progress includes:

- Initial work connecting OpenSpace to Glue (<https://glueviz.org/>) — an innovative software package for visualizing multiple linked data sets — has begun with two master’s student internships hosted by our development partners at the University of Utah. The work, which will continue in the extension period, was born in collaboration with Dr. Alyssa Goodman, and will provide an excellent basis for collaboration with her new SciAct award, *Cosmic Storytelling with NASA Data: Tools for Exploring Data Science*.

## **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 along with outside scientists and institutions, as detailed below.

### New Scenes

Ongoing content development has brought the number of interactive scenes available in OpenSpace from 17 reported at the end of Year Four to 18 in Year Five.<sup>2</sup>

*Asteroids and Comets:* The trajectories of more than 936,000 asteroids and comets from JPL Horizons Small-Body Database were added to OpenSpace. Object categories include:

- Amor Asteroids: Earth-approaching Near-Earth Asteroids with orbits exterior to Earth’s but interior to Mars’.
- Apollo Asteroids: Earth-crossing Near-Earth Asteroids with semi-major axes larger than Earth’s.
- Aten Asteroids: Earth-crossing Near-Earth Asteroids with semi-major axes smaller than Earth’s.
- Atira Asteroids: Near-Earth Asteroids whose orbits are contained entirely within the orbit of the Earth.
- Centaur Asteroids: Asteroids with either a perihelion or a semi-major axis between those of the four outer planets.
- Chiron-Type Comets: Comets with a Tisserand’s parameter with respect to Jupiter of greater than 3 and a semi-major axis greater than that of Jupiter.
- Encke-Type Comets: Comets with a Tisserand’s parameter with respect to Jupiter of greater than 3 and a semi-major axis less than that of Jupiter.
- Halley-Type Comets: Periodic comets with an orbital period between 20 and 200 years.
- Inner Main Asteroid Belt: Asteroids with a semi-major axis less than 2.0 au and a perihelion distance greater than 1.666 au.

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<sup>2</sup> For a complete list of scenes developed over the course of the grant’s first five years of funding, see Appendix.

- Jupiter Family Comets: Comets with a Tisserand's parameter with respect to Jupiter of between 2 and 3.
- Jupiter Trojan Asteroids: Asteroids trapped in Jupiter's L4/L5 Lagrange points (semimajor axis of between 4.6 and 5.5 au), with an eccentricity of less than 0.3.
- Main Asteroid Belt: Asteroids with a semi-major axis of between 2.0 and 3.2 au, and a perihelion distance greater than 1.666 au.
- Mars Crossing Asteroids: Asteroids that cross the orbit of Mars, with a semi-major axis of less than 3.2 au, and a perihelion distance of between 1.3 and 1.666 au.
- Outer Main Asteroid Belt: Asteroids with a semi-major axis of between 3.2 and 4.6 au.
- Potentially Hazardous Asteroids (PHAs): Asteroids that are deemed potentially hazardous to Earth based on their close approaches. All asteroids with an Earth Minimum Orbit Intersection Distance (MOID) of 0.05 au or less, and with an absolute magnitude (H) of 22.0 or less.
- Trans-Neptunian Asteroids: Any minor or dwarf planets in the solar system that orbit the Sun at a greater average distance than Neptune (semi-major axis of 30.1 AU).

### Enhanced Content for Existing Scenes

#### *Default* (automatically loaded upon start-up)

- Fully-textured model of the International Space Station (ISS)
- Constellation illustrations
- Enhanced visualization, including shadowing, of Saturn's rings
- Added asset for C/2019 Q4 "Borisov" interstellar object and C/2019 Y4 (ATLAS) comet
- Improved rendering of orbits and trails including anti-aliasing and fading
- Added a WMS server for the Venus Magellan dataset
- Added an atmosphere to Venus
- Added the ability to display procedurally generated text labels and added labels for planetary bodies in the solar system

#### *Earth Exploration*

- Replaced the L4 G1SST sea surface temperature with the GHRSSST L4 MUR for wider coverage

#### *Lunar Exploration*

- Added alpha channel to Kaguya layer

#### *MESSENGER*

- Added terrain patches created by the MESSENGER Mission

#### *Mars Exploration*

- Model and trajectory of the Mars 2020 Perseverance rover

#### *Voyager*

- Added time range to Voyager rotations

## **Stakeholder Meetings**

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

*Developer Meeting:* Project developers and managers from AMNH, Linköping University, New York University, and University of Utah met at NYU on January 28-29, 2020. The meeting was devoted to reviewing work-to-date, identifying near-term and long-term development goals, with a special focus on integrating other visualization tools such as Glue, identified as a development project for Year Five. The agenda for this meeting is included in *VIII*.

*Attached Information.*

*Informal Science Institution (ISI) Network and Advisory Board Meeting:* Due to the ongoing COVID-19 pandemic we pivoted the annual ISI Network and Advisory Board meeting into a video conference call on June 22, 2020. Representatives from the six ISI Partner Network institutions along with project evaluators joined the call. A training for the recent OpenSpace release (0.15.2) was provided. The agenda for this meeting is included in *VIII*. *Attached Information.* An Advisory Board meeting was not held this year, but plans to meet with an expanded Advisory Board will take place early in Year Six.

*OpenSpace Trainings:* In Year Five, we have continued the use of telecons for training OpenSpace users, and have continued “Micah Mondays,” a weekly opportunity for one-on-one time with AMNH Software Integration Engineer Micah Acinapura. As will be detailed below, we have seen greater interest in such trainings as ISIs across the country pivoted to virtual programming. We also held two webinars with the Museum Alliance for their members and Solar System Ambassadors to introduce new users to OpenSpace and provide basic training in software operation. In addition, The Elumenati, one of our commercial partners, held OpenSpace trainings for the Minnesota GeoDome Network, a group of 15 institutions, and our ISI Network Partner California Academy of Sciences held its own training workshops. Internationally, the Norrköping Visualization Center C organized a self-funded three-day workshop providing training to a growing network of Swedish planetarium users of OpenSpace. PI Ro Kinzler, co-I Emmart, and other AMNH staff presented in a coordinated workshop at the Association of Science and Technology Centers (ASTC) virtual annual meeting in October. The workshop was organized by NISE Network and focused on free NASA tools to build virtual Earth and space programs.

## **Year Five ISI Partner Network Activities**

Each of our ISI Network partners made major shifts in their OpenSpace program offerings early in the year due to the COVID-19 pandemic. All of our partners’ on-site facilities were closed for some portion of the year, and some saw reductions in staff positions and/or time allocations due to the economic effects of the pandemic. Some remain closed as of October 31 to all public visitation, while others have a limited public capacity and have not reopened theaters and

planetariums — arenas where OpenSpace was commonly utilized. Despite these on-site closures, ISI partners were able to connect with their audiences by shifting to virtual programming, reaching over **55,500 people**. Though this is slightly lower than the total reached by in-person events in Year Four, livestreams from these programs have received **278,035 views** to date. 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.

*The Adler Planetarium:* Adler was hit hard by the pandemic, suffering a large number of layoffs and closing their physical space for the foreseeable future. However, they continued their summer internship program remotely, engaging one doctoral level and two teen OpenSpace interns. The doctoral level intern supervised and supported the high-schoolers as they used OpenSpace to learn astronomy content and computer programming, while also gaining professional development and public speaking experience. The two high school interns presented their research during livestream “Mapping a Billion Stars” alongside AMNH astrophysicist Dr. Jackie Faherty (August 13). An additional *Adler Astronomy Live* online program, “Space Ethics,” (October 22) used OpenSpace visualizations. The two programs have been viewed over 1,000 times to-date. The teen interns again presented their research projects in a virtual “Community Bash” to 50 family members and friends.

*American Museum of Natural History (AMNH):* In Year Five, AMNH programs reached **22,065** people, twice the reach of Year Four and six times the reach of Year Three. AMNH held 24 public programs, the vast majority as livestream programs after the Museum closed to on-site visitation, that took audiences on field trips over Earth’s surface, through our Solar System, across our Milky Way galaxy, and out to the edge of the observable Universe.

OpenSpace was also used in a range of educational programs including:

Youth Interns: The Museum continued its relationship with the Bergen Academy for Technology and Computer Science with six high school interns under the direction of co-I Carter Emmart throughout the year. These interns focused on the visualization of NASA missions through spacecraft articulation, preparation of all available mission SPICE kernels and Apollo panorama, and improvement of ISS 3D model. This ISS model was utilized in one of the museum’s livestreams, “Field Trip: Space Flight” (May 27).

In addition, two high school interns in the Museum’s Lang program worked with OpenSpace Project Coordinator Corrie Roe to review and revise the auto-generated captioning on YouTube to increase accessibility of the project’s online programming. The interns were able to review and improve 25-hours of the channel’s videos.

Pre-service teacher preparation: OpenSpace is used as part of an academic class in the Museum’s graduate level teacher preparation program for 15 pre-service teachers

working in high-needs schools in the New York City area as a key tool for learning and teaching about space science concepts in 7th-12th grade classrooms.

Virtual camps for middle school students: In the summer of 2020, OpenSpace was used as a primary tool in an 8-hour virtual camp called “Our Place in Space” for 25 middle school-aged students. The instructors and students used OpenSpace to visualize NASA mission data to explore Martian landscapes, the moons of Jupiter, and much more as they also learned about the specific spacecraft that provided the data and about exciting missions to come. In addition, OpenSpace was featured in two implementations of a 9-hour “Coding Climate Change” virtual camp that engaged 46 middle school-aged students in the intersection of climate science and computer science while helping students develop skills in the popular coding language Python as a means for interpreting NASA Earth Observatory climate data.

Finally project staff and our growing cadre of OpenSpace pilots at AMNH held an additional 18 training sessions, demonstrations, and conference presentations, which are further detailed below.

*California Academy of Sciences (CAS):* Cal Academy reached **16,356** individuals with OpenSpace programming — more than double their reach in Year Four, and 30 times their reach in Year Three! The enormous jump in reach is in part due to a daily show CAS launched in September of last year, which was attended by 15,069 visitors since November 1, 2019 and before closing to the public in March 2020. But not entirely, as the CAS team has to-date streamed 25 weekly live “Tours of Outer Space,” and an additional 8 “Cosmic Conversations” — approachable dialogues with a STEM expert — using OpenSpace. These livestreamed programs reached 1,237 viewers live and have seen 13,709 total views to date. The team also led OpenSpace tutorial workshops at two virtual conferences, Dome Dialogues e-Conference and Great Lakes Planetarium Association (GLPA), the recordings of which are publicly available and have been viewed 278 times.

*Denver Museum of Nature and Science (DMNS):* Early in 2020, Software Integration Engineer Micah Acinapura traveled to DMNS to install OpenSpace in their planetarium, which had been recently updated.

DMNS held four live online programs during Year Five in a series called *Digital Earth*. Featuring Co-I Kachun Yu and Geologist Bob Raynolds, these programs reached **1,701** viewers during the stream (almost twice DMNS’ reach in Year Four) and have seen an additional 665 views since being posted publicly. These were ticketed events that were free to members. DMNS’s internship program was cancelled due to COVID-19.

*Houston Museum of Natural Sciences (HMNS):* HMNS doubled their reach to **30,868** members of the public who encountered OpenSpace content. OpenSpace visualizations were used in a new exhibit that paired a physical Mars globe with flyovers of the Martian surface, and in

several on-site and online student presentations. OpenSpace was used by 15 interns who engaged the public in HMNS's Burke Baker Planetarium and Discovery Dish outreach program, studied scenarios for farming on Mars, and rendered video content for the Mars globe exhibition.

*North Carolina Museum of Natural Science (NCMNS):* NCMNS staff led five on-site and three virtual OpenSpace programs this year, which reached a total of **14,837** people. As in years past, OpenSpace is also on permanent display in the museum's Astronomy and Astrophysics Lab in the form of curated, looping visualizations. The success of the content has led their partner institution, Museum of Life and Science in Durham NC, to incorporate recorded OpenSpace visualizations in their Launch Lab. In total, **140,986** visitors had the opportunity to view these videos across the two settings.

NCMNS also held student internships focused on OpenSpace in Year Five. Four undergraduates helped develop OpenSpace programming and content at the museum, led OpenSpace demos in the Astronomy and Astrophysics Lab, and created user guides for the software and an astrobiology content guide that will be shared on the OpenSpace website.

### **Additional Year Five Community, Academic, and ISI Activities**

We saw exciting growth in the number and types of institutions and individuals that have adopted OpenSpace this year. Many of these new users learned of the software through their professional networks or by attending an OpenSpace event, and began using it without any contact with the project team. This was indeed our goal for the final year of the project: To see OpenSpace take on a life of its own, activated by people well beyond the funded network and close associates of the project team.

While live reach numbers for most of these programs are not available, some institutions were able to collect and share their audience numbers with us. In those cases, we find that OpenSpace reached an additional **8,165** people live through in-person or streaming programs in Year Five, and saw over 134,000 views of published videos (including the recorded livestreams). Below are some of the most notable and exciting examples of OpenSpace implementation amongst this broader community, featuring new adopters and new uses by previous users. Additional OpenSpace users are also listed below.

*Amateur Astronomers Association of New York (New York, NY):* While the Amateur Astronomer's Association public observing nights were on hold, AAA President Irene Pease held weekly live-streamed virtual tours of the night sky, paired with tours into the universe with OpenSpace. These programs reached over 400 people live, and have totaled over **5,700** views since being published.

*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” and “Star Formation.” Fellow App State professor Dan Canton, Director of App State’s Dark Sky Observatory (DSO), has also adopted OpenSpace in his own coursework, at DSO open houses, and for DSO’s monthly virtual programming during the pandemic. In all, OpenSpace was experienced by at least 150 people at App State.

*City College of New York Planetarium (New York, NY):* CCNY Planetarium Director James Hedberg has been enormously active in the development and spread of OpenSpace this year. In addition to regularly helping community users in our Slack workspace, Dr. Hedberg has contributed new content that was featured in several OpenSpace programs this year, including 80 digital artworks of IAU constellations and a 3D model of NYC that was key to the success of AMNH’s Manhattanhenge program. Dr. Hedberg also answered questions live in the chat of the AMNH’s Field Trip: Constellation program (September 18) and regularly shares OpenSpace videos on social media channels, racking up more than 700 video views.

*Fiske Planetarium, University of Colorado Boulder (Boulder, CO):* Our Software Integration Engineer had multiple live installation sessions with Fiske Planetarium staff to install OpenSpace on their new Sky-Skan system in October.

*Michigan Science Center (Detroit, MI):* The Michigan Science Center, a new user, has featured OpenSpace in seven of its online “ECHO Live!” programs. The recordings of these livestreams total over 8,600 views to-date.

*Museum of Science, Boston (Boston, MA):* The Museum of Science, Boston adopted OpenSpace in May with its switch to virtual programming. One planetarium staff wrote in an email that, “OpenSpace has made us feel right at home considering how similar it can be to our normal planetarium software. We are very grateful that we’re able to continue educating during the pandemic.” OpenSpace was used in 14 of the museum’s *Exploring Space* videos, which occurred on a nearly weekly basis during the summer. The first month of these programs reached 2,473 live viewers. Since being posted, the programs have been viewed over 27,900 times.

*New York University (New York, NY):* This year, our developers at NYU were able to install OpenSpace on a multi-channel hyperwall in the Tandon School of Engineering, where it was used to demonstrate OpenSpace to visitors before closing because of the pandemic.

*Norrköping Visualization Center C (Linköping, Sweden):* Linköping University’s Visualization Center C reopened its planetarium to public visitors in July with a 45-minute rendered OpenSpace show, “OpenSpace 3D: Planets, Moons, Stars, Galaxies.” The program takes viewers from Earth to the edge of the known universe, with stops at the Apollo landing sites and Mars. Showing three or four times per week, it has been consistently sold to capacity, reaching over 1,400 people. Before the end of the calendar year, the Visualization Center C

will host Victoria, Crown Princess of Sweden, for a private demonstration, and participate in the Norrköping Light Festival.

As the primary international contributor to OpenSpace, the Norrköping Visualization Center C and Linköping University provide three full-time developer positions through funding from the Swedish e-Science Research Centre and the Stena Foundation. In addition, the Visualization Center C is leading the WISDOME effort, funded by the Knut & Alice Wallenberg Foundation, to increase outreach and improve scientific literacy, for which OpenSpace has been selected as one of the flagship projects.

*Southwest Minnesota State University Planetarium (Marshall, MN):* The SMSU Planetarium has become an emerging “super-user” of OpenSpace, developing their own configurations and assets. The software was installed in SMSU’s planetarium in Year Four, and was used in their Apollo anniversary show series, which was covered by local press.

*University of Utah (Salt Lake City, UT):* The Scientific Computing and Imaging Institute, one of our development partners, typically uses its multi-screen array to demonstrate OpenSpace to visiting researchers and other guests. This was unable to happen beyond March of this year, but OpenSpace demonstrations did occur for University courses such as for a 30-student software development graduate course.

*US Space & Rocket Center (Huntsville, AL):* Director of the US Space & Rocket Center’s INTUITIVE Planetarium David Weigel is enthusiastic about seeing OpenSpace in their 250-seat, 8K laser planetarium. While the Center was closed due to the pandemic, he instead put on three livestreamed programs on the Center’s Facebook. The programs — tours of Mars, Earth’s Moon, and beyond the Milky Way — saw 300 live viewers and have since been viewed over 10,000 times. With the Center re-opened to the public, we have resumed installation conversations.

Additional users, some of whom had limited engagement with OpenSpace due to the pandemic, include:

- Edward R. Murrow High School (Brooklyn, NY)
- Lower Eastside Girls Club (New York, NY)
- Ho Tung Visualization Laboratory (Hamilton, NY)
- Iziko Planetarium and Digital Dome (Cape Town, South Africa)
- Museum of Life and Science (Durham, NC)
- University of Chicago (Chicago, IL)

OpenSpace has received interest or started installation conversations with 17 institutions in Year Five, that we will pursue into Year Six:

- A Time for Science (Greenville, NC)
- Bell Museum, University of Minnesota (St. Paul, MN)

- Carnegie Science Observatory (Pasadena, CA)
- Connecticut Science Center (Hartford, CT)
- Denison University (Granville, OH)
- ExplorationWorks (Helena, MT)
- Exploratorium (San Francisco, CA)
- Fels Planetarium, Franklin Institute (Philadelphia, PA)
- Kitt Peak National Observatory (Tucson, AZ)
- National Museum of Science and Technology (Stockholm, Sweden)
- Los Alamos National Laboratory (Los Alamos, NM)
- Smithsonian National Air and Space Museum (Washington, D.C.)
- Oregon Museum of Science and Industry (Portland, OR)
- Peoria RiverFront Museum (Peoria, IL)
- Planetarium Hamburg (Hamburg, Germany)
- Raritan Valley Community College (Branchburg, NJ)
- University of Nebraska — Lincoln, Ralph Mueller Planetarium (Lincoln, NE)

### **Planetarium vendors**

Though much of our work with vendors this year was interrupted by the pandemic, Elumenati has maintained their active adoption of OpenSpace as a core feature of their system. They held virtual OpenSpace training sessions in May and June for the Minnesota Geodome Network. Two members of this network are now actively in conversation with us to install OpenSpace on their systems.

## **III. Status, Changes, Issues**

### **From On-Site, to At-Home**

As described above, our OpenSpace project plans were significantly impacted by the institutional closings brought on by COVID-19. Rather than slow down our work, however, the crisis inspired our team to double down, working with laser focus to optimize the software for high performance streaming on a range of popular social media platforms including YouTube and Facebook, as well as the video conference platform Zoom. Content was enhanced specifically to appeal to broad audiences and to be effective on small screens. Keeping an agile design mentality we were able to develop new programming models that allowed for multiple presenters, engaging hosts, and deep interaction with youth and adults via simultaneous chats and onscreen Q&A. As well as having subject matter experts as presenters we engaged additional SMEs to answer questions in real time in the chat during the livestreams, exposing participants to multiple and diverse subject matter experts during each program. With this heightened focus on reaching audiences at home, the number of public-facing live events AMNH

produced increased from 13 in Year Four to 24 in Year Five, and across the ISI Partner Network, from 45 to 59.<sup>3</sup>

To deepen the impact of these programs for young learners, the AMNH team developed online quizzes that individuals or whole classes could take after watching a livestream, or as standalone experiences that leveraged the videos in a new format. These quizzes were posted on AMNH's Ology site and Kahoot!.

While this shift in effort did impact the number of visualized Scenes we had planned, lowering our five-year total from 20 to 18, it has not impacted our software release schedule or planned features.

Our evaluation strategy required extensive redesign, which is described below.

Finally, we're pleased to report that Dr. Jaqueline (Jackie) Faherty is joining our advisory board. Dr. Faherty has been recently recognized with the Vera Ruben prize for Dynamical Astronomy from the AAS for her scientific accomplishments, as well as for her engagement with the public using visualization tools including OpenSpace. Jackie has been an OpenSpace advocate and "super-user" for two years now, spearheading the integration of the Gaia data set into OpenSpace, featuring the software in multiple conference and science talks, and regularly presenting to the public in the Hayden Planetarium and more recently online. Jackie will bring her dual perspective as a scientist and educator to bear in her role as an OpenSpace advisor.

## **IV. Dissemination Activities**

### **Online Presence**

In Year Five, 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. As online environments became the only means to connect with the public, we aimed to engage audiences by sharing more content in more formats on more platforms than ever before. Our online reach and engagement grew, as we saw more people using and sharing OpenSpace during this time.

Website ([www.openspaceproject.com](http://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

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<sup>3</sup> Cal Academy, as mentioned above, held daily live planetarium shows until its closing in March due to the pandemic. The total of 62 programs across the ISI Partner Network counts these programs as 1. If each daily show between November 1, 2019 and the Academy's closing March 12, 2020 were counted, this number would total 143.

media platforms. This year, we have added additional user guides and tutorials, program guides, and resources to aid the adaptation and implementation of OpenSpace. These guides were developed by AMNH, CAS, DMNS, and NCMNS.

To accommodate the enormous increase in video content, we have reorganized the video page on the OpenSpace website to include curated lists of highlighted videos, weekly OpenSpace tours, tutorials, and conference presentations.

Since November 2019 to present, openspaceproject.com has been visited by 53,519 unique visitors (double the same period last year) and 51,520 total visits (2.7 times the same period last year). Of these visits, United States IP addresses again led in geography, accounting for nearly 25,000 (47.8%) visitors. This was followed by six countries with between 1,000 and 3,500 visits: India, United Kingdom, Canada, Sweden, Germany, and Netherlands. An additional 40 countries had at least 100 visitors each. This is wider geographical spread than in previous years: We are seeing more visits from more countries than ever.

About 40% of visits continue to 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](https://wiki.openspaceproject.com)): We have continued to populate this public wiki-style website for users, content creators, and developers. This space currently has the most detailed documentation for each of these audiences. The wiki's appearance and search functionality were upgraded this year.

*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 contributions to the code.

*Slack* ([openspacesupport.slack.com](https://openspacesupport.slack.com); [team-openspace.slack.com](https://team-openspace.slack.com)): These messaging and file sharing spaces also act as a community-driven forum for collaboration. In Year Five, 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/18d536b22e78/thisweekinopenspaceseptember28>): Our newsletter has grown to over 300 subscribers, including ISI professionals, SMEs, and members of the public. We created a new weekly programming newsletter in May, when we began to see three to six livestreamed OpenSpace programs per week, and shifted to send our monthly newsletter on a quarterly basis, when warranted by updates.

### OpenSpace Social Media Platforms

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.

*YouTube* ([www.youtube.com/c/OpenSpaceSoftware](http://www.youtube.com/c/OpenSpaceSoftware)): This year, the OpenSpace YouTube channel saw 320,060 impressions, 25,990 views, 1,800 watch hours, and 514 new subscribers. The top geography of our viewers at 27% had US IP addresses. We also made an effort to improve the auto-generated captions, which are used by about 10% of viewers. In our top 10 videos by views, three are OpenSpace tutorial videos, four are livestreams from this year, one is a previous livestream, and two are visualization recordings under 5-minutes in length.

*Twitter* ([@openspaceproj](https://twitter.com/openspaceproj)): This year, the OpenSpace Twitter account continued to regularly share content and programs, and received more mentions and retweets, driving total impressions to 176,489, or 3.7 times last year’s impressions. We saw a great increase in engagement and reach since the pandemic began in April: In the last six months, we received 80% of our engagement and two-thirds of our total impressions. Our followers also grew to 605, an increase of over 200 from last year.

*Facebook* ([@OpenSpaceVisualization](https://www.facebook.com/OpenSpaceVisualization)): The OpenSpace Facebook page, which had steady but stagnant support in previous years, saw a huge increase in interest this year, nearly doubling our followers to 569 and exponentially increasing our reach. In Year Four, our reach was estimated to be 1,500; in Year Five, our reach estimate is 505,128.

*Instagram* ([@openspaceproj](https://www.instagram.com/openspaceproj)): The OpenSpace Instagram account remains our most nascent, started in April 2019. In Year Five, we doubled our followers to 158, tripled our reach to over 3,700, and saw 1.5 times interactions on posts and stories.

### Other Social Media Platforms

In addition to OpenSpace’s social media platforms, this year we find it particularly useful to examine the project’s impact on the social media accounts of the partner institutions. We again do not have detailed analytics for all of these accounts, but highlight three instances here:

*Video views*: In addition to being hosted on the OpenSpace social media channels, recorded livestreams and other OpenSpace videos can be found on the social media platforms of our ISI Network partners, other users, conferences, and beyond. These videos gained 1,286,063 views in Year Five.

*AMNH:* For the first time since the live Pluto flyby in 2016, AMNH hosted OpenSpace livestreams directly on the Museum’s YouTube channel. During streaming on the AMNH platform (which has 270,000 subscribers and visibility through press coverage), we reached a total of 16,277 viewers, who interacted through the chat feature 17,973 times. Through these programs, the museum gained 1,694 new subscribers and 142,997 views to date. 72% of these views were from non-subscribers. An average of 31% of these views are from New York or New Jersey, an additional 33% are from the rest of the US, and 36% are international.

*NCMNS:* NCMNS shared select analytics for its two April livestreams. Streaming on both Facebook and YouTube, the live reach of these programs totaled over 14,000, and watch time totaled over 580 hours. On the museum’s Twitter, Instagram, and Facebook accounts, promotional posts were seen by over 15,700 and had an average engagement rate of 5%.

### **Conferences and Colloquia**

While some conferences and colloquia were cancelled due to the pandemic, others shifted to a virtual format with reduced attendance costs, reaching larger and more diverse audiences than ever before.

*235th Meeting of the American Astronomical Society (January 4-8):* AMNH’s Dr. Jackie Faherty used and spoke about OpenSpace in her plenary lecture for AAS, “Visualizing a Billion Stars for Science and Education.”

*Glue-con, NYC (February 27-28):* Dr. Alyssa Goodman spearheaded a two-day hackathon at the Simons foundation-funded Center for Computational Astrophysics (CCA) with approximately 25 invited hackers to work on projects related to the scientific data visualization software Glue. The OpenSpace team worked on getting Glue to interact more fluidly with OpenSpace, which would enable researchers to easily visualize their data in the context of the Digital Universe Atlas and in immersive settings for public presentation.

*Appalachian State University Physics & Astronomy Colloquium: Investigating Protoplanetary Chemistry with Ground-based Astronomy, Interstellar Analogues, and Meteorites (March 27):* Co-I Rachel Smith used OpenSpace to describe research results from her sabbatical semester in Fall 2019 and described how the software can be used in teaching to 30 attendees.

*Dome Dialogues e-Conference #11 (May 6):* Cal Academy Manager of Planetarium Engineering Dan Tell gave a detailed walkthrough of OpenSpace basics to 95 planetarium professionals.

*Eurographics & Eurovis 2020, Mapping the Stars: From Drawings to Virtual Flights of the Cosmos (May 26):* In her keynote presentation to 217 live viewers, Dr. Jackie Faherty used OpenSpace to illustrate her thesis that Astronomical research depends upon our ability to

make precise and accessible maps of the cosmos. This video has since been viewed over 900 times.

*236th Meeting of the American Astronomical Society* (June 1-3): Dr. Jackie Faherty presented a poster, “Visualizing a Billion Stars for Science and Education,” featuring OpenSpace content.

*Lunar and Small Bodies Graduate Forum* (July 1): Columbia University PhD candidate and AMNH planetary scientist Marina Gemma presented the capabilities and content of OpenSpace to 49 space science graduate students.

*Live, Interactive Planetarium Symposium 2020: Keeping Virtual Content Interactive* (July 14): Museum of Science, Boston’s Educator and Solar System Ambassador Caity Sullivan, demonstrated to 87 attendees how she and her colleagues have used OpenSpace to create interactive programs online.

*International Planetarium Society (IPS)* (August 17): Co-I Carter Emmart led a virtual workshop “OpenSpace: Frontier of Open Source Planetarium Software,” with other project team members in attendance, showcasing the latest improvements in OpenSpace. The workshop had high visibility, with 229 attendees, and was recorded for future use. Throughout the conference, a recorded demonstration of OpenSpace was also included within planetarium vendor Sky-Skan’s sponsorship video.

*International Virtual Observatory Alliance Educational Interest Group First Virtual Meeting* (August 31): OpenSpace’s Project Coordinator Corrie Roe described resources and best practices for online astronomy programming in a presentation titled “Virtual and Remote Planetarium Programming: Case Studies and Resources,” which included several case studies featuring OpenSpace.

*Association of Science Technology Centers annual conference* (October 16-21): A Pre-Conference Intensive, “Tools and Training for Starting a Successful Space and Earth Science Virtual Public Program,” brought together NASA-funded informal education projects with museum professionals looking to establish online space and Earth science programs for the public. The OpenSpace project team joined the NISE Network, NASA’s Universe of Learning, and NASA Museum Alliance to hold a workshop for 24 ISI professionals. OpenSpace team members also attended sessions throughout the conference.

*23rd Annual International Mars Society Convention* (October 15-18): Co-I Carter Emmart demonstrated OpenSpace visualizations of Mars during the Virtual Banquet to over 2,000 live viewers.

*IEEE VIS 2020: Visualization in Astrophysics: Developing New Methods, Discovering Our Universe, Educating the Earth* (October 26): Alex Bock, Lead Developer of OpenSpace, gave a keynote address, “Bridging the Gap: Bringing Expert Tools into Planetariums and Living Rooms.” The talk described the use of OpenSpace for research and outreach with a

particular focus on the importance and promise of developing interoperability with other scientific visualization tools such as Glue to enable the visualization of varied data in a single scene.

*IEEE VIS 2020: Visualization in Astrophysics: Developing New Methods, Discovering Our Universe, Educating the Earth* (October 26): In her invited talk, “Visualizing the Dynamic Milky Way for Science and Education,” Jackie Faherty used OpenSpace to illustrate the importance of interactive three-dimensional visualization to enable research and discovery in astrophysics.

### **Publications, Posters, and Conference Papers**

J. Costa, A. Bock, C. Emmart, C. Hansen, A. Ynnerman, C. Silva (2020, October 25-30), *Interactive Visualization of Atmospheric Effects for Celestial Bodies*, IEEE VIS 2020.

M.E. Gemma, C. Roe, C. Emmart, V. Trakinski, R.L. Smith, M. Acinapura, B. Abbott, D.S. Ebel, and R. Kinzler (2020), *Data Exploration Using OpenSpace* [Virtual poster session], Lunar and Planetary Sciences Conference 2020, The Woodlands, TX, United States. Abstract #2392.

### **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 Five:

- Broman, E. & Rossing, I. (2020). *A System for Procedural Camera Movements for Navigation in Astrographics* (Master’s Thesis, Linköping University, Linköping, Sweden).
- Ejdbo, M. & Elmquist, E. (2020). *Interactive Sonification in OpenSpace*. (Master’s Thesis, Linköping University, Linköping, Sweden). Retrieved from: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-170250>.

## **V. Evaluation, Collaborators, and Cross-Collaboration Agreements Activities**

### **Evaluation and Assessment 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 Five, 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.

### **Top-Level Metric Projections**

The top-level metric for OpenSpace in the first phase of funding was the number of interactive scenes of NASA data available within the software. A scene consists of the full astrophysical context plus multiple visualized assets required to support rich narrative programming about NASA missions and science results.

The OpenSpace target goal is to increase the number of scenes within OpenSpace from 0 in 2015 to 20 by the end of Year Five. In Year Five, we increased from last year's 17 scenes to 18 scenes, two shy of the projected. As described above, we shifted some resources from the creation of new scenes to enhancing existing scenes in response to requests from ISI partners (e.g. the addition of the constellation artwork and the ISS to the default scene), to support timely programming related to the launch of Mars 2020 (the addition of Mars 2020 content to the Mars scene), and to optimize performance on streaming platforms.

### **SciAct Alignment**

The OpenSpace PIs and evaluator worked together to ensure the project is aligned with the SciAct goals and determine which specific program indicators track back to those goals.

OpenSpace is currently aligned with SciAct goals 1, 2, and 4:

#### *1. Enabling STEM Education in 50 States*

OpenSpace enables STEM education in 50 states through our ISI Network. Each of the six institutional partners, located across the United States, promote science learning through public programming, and support STEM-focused internships and mentored experiences.

Our Network partners hosted 41 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 159 internships.

#### *2. CoSTEM goal, #2: Increasing public engagement in STEM via ISI programs for public audiences of all ages (including youth and educators)*

As noted elsewhere in this report, OpenSpace focuses on increasing public engagement in STEM via ISI programs for public audiences of all ages.

In Year Five, 178 programs utilized OpenSpace to communicate science and engineering concepts to an estimated 62,499 people. Year Five activity brings the total number of OpenSpace ISI Partner Network programs to 258, beyond our projected 225 programs

projected by the end of Year Five. In addition to the reach through online programs, 171,046 visitors saw OpenSpace in an in-person museum exhibit in Year Five, bringing OpenSpace's live reach over 1,102,00.

Another method of engagement that we have seen grow this year is through videos produced in part or entirely from OpenSpace visualizations. In Year Five, there were 1,312,053 views of OpenSpace videos, bringing total video views to 5,037,968. Additional online reach through the OpenSpace website and social media this year totaled 1,056,897, bringing the total online reach of OpenSpace content to 3,029,268.

#### *4. Leverage through partnerships*

All content visualized in OpenSpace is developed through partnerships with NASA and other SMEs as well as programmers and computer science experts scattered across several universities and research institutions. We strive to increase the number of users and commercial vendors who are key to the broad distribution and adoption of OpenSpace.

### **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.

#### Cross-Collaboration with Science Activation Awards

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

*\*GLOBE:* The GLOBE team helped us identify and connect with a NASA SME for our October 15 Earth Science Week livestream, produced in partnership with NASA@ My Library. This led to a conversation about a potential future program using OpenSpace and GLOBE experts and data.

*GSFC/NSSEC:* Dr. Masha Kuznetsova co-supervises master's students' development of new heliophysics models and simulations in OpenSpace. Additionally, NSSEC representatives and collaborators presented the work in two streaming programs (October 2020).

*Gulf of Maine Research Institute:* We have continued to regularly share educational best practices with the Gulf of Maine team and have engaged them to help us develop strategies for leveraging OpenSpace as a platform for citizen science activities. OpenSpace team members attended the NASA Citizen Science workshop series this summer and fall, which offered great insight and connections to citizen science projects.

*NASA@ My Library:* Continuing our collaboration, we worked with the NASA@ My Library team on three successful livestreamed events, distributed to their library network. While previously we saw libraries holding in-person watch parties for these livestreams, during the pandemic, the goal has been to engage their patrons at home. Our three

livestreamed programs, all featuring NASA-funded SMEs, have been viewed over 3,800 times to date on YouTube and Facebook, including over 500 live viewers.

*NISE Network:* This year, we collaborated with the NISE Net team to provide an OpenSpace video resource to distribute with an upcoming toolkit. We also proposed and presented in the ASTC Pre-Conference Intensive organized by NISE Net with other SciAct projects.

*\*Smoky Mountain STEM Initiative:* This year, we were able to connect ISI Network Partner NCMNS with the Smoky Mountain STEM team, with the goal to collaborate on use of OpenSpace and a presentation for a future meeting of the North Carolina Section of the American Association of Physics Teachers.

*STSci/Universe of Learning:* We were asked to present OpenSpace at the January AAS splinter session *Visualization of Research Data for the Public*, organized by Universe of Learning. Additionally, our Software Integration Engineer worked with STSci scientist Dr. Kimberly Arcand to add her 3D models into OpenSpace for a virtual public program sponsored by Columbia University.

*University of Colorado, Boulder:* OpenSpace was installed in Fiske Planetarium at the end of Year Four, and our team continued to support its implementation in its upgraded planetarium in Year Five. Due to the pandemic, we were unable to continue our conversations about utilizing Colorado's 360-degree videos in pop-up showcases in our Hall of the Universe.

*WGBH:* Early in the year, we consulted with WGBH on a potential use case of OpenSpace in classrooms, which will inform future development. Members of the OpenSpace team also attended the five UDL and accessibility webinars organized by WGBH. Following these webinars, we benefited from a one-on-one accessibility consultation focused on maximizing the accessibility of our user interface.

### NASA Infrastructure Projects

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

*\*Astronomy Picture of the Day:* After discussions with the APOD team at the annual meeting, we had the goal to add the APOD to our OpenSpace startup. With some development hours, our engineers ultimately identified this as a more intensive project that would require redeveloping the entire software startup process.

*JPL Eyes:* We are in continuous contact with Eyes personnel, sharing resources and knowledge, and strategies for covering upcoming mission milestones. NASA Eyes is now listed on the OpenSpace Web site's Content Resource page. Additionally, Jason Craig, Manager of Visualization, Technology, and Development, is a member of our Advisory Board.

*Solar System Treks:* Our software engineers continue to exchange relevant data with Treks for use in our respective softwares.

*JPL Museum Alliance:* This year, we offered two one-hour live OpenSpace tutorials for Museum Alliance members that were recorded and archived as a resource. These tutorials were attended by 210 informal science educators, including Solar System Ambassadors and planetarium and museum staff. In addition, OpenSpace Production Coordinator Corrie Roe was asked to present in another Museum Alliance webinar, “Remote Outreach Best Practices: Livestreaming” in May, to speak to the resources and best practices we employed for livestreaming. We also utilized the Museum Alliance calendar and Ryver chat forum to share upcoming events and connect with other informal science educators.

*NASA Astrobiology Institute:* We consulted with NAI on a use case example of incarcerated people experiencing OpenSpace through formal education, bringing specific parameters of this use case into our Developer Meeting.

*Solar System Ambassadors:* After meeting with Kay Ferrari at the annual meeting in 2019, we have considered how we can together facilitate more Solar System Ambassadors’ use of OpenSpace. This year, we were able to introduce OpenSpace to more Solar System Ambassadors as a key audience of the Museum Alliance tutorial webinars.

### NASA-Funded SMEs in Year Five

Thirty-two NASA-funded Subject Matter Experts contributed to and/or used OpenSpace in Year Five, 22 of whom are new to the project (indicated with an \*asterisk). This brings the total number of unique SMEs to 65.<sup>4</sup> 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 31.

### ***Used OpenSpace in public programming: 21***

- \*Dr. Kimberly Arcand (Director of Visualization, Chandra X-ray Observatory)
- Dr. Harold C. Connolly, Jr. (Mission Sample Scientist, OSIRIS-REx, GSFC)
- Dr. Brian Day (SSERVI; Ames)
- Dr. Denton Ebel (NASA Emerging Worlds Grant; AMNH)
- \*Dr. Bethany L. Ehlmann (Research Scientist, JPL)
- Dr. Jackie Faherty (Co-PI, ROSES ADAP)
- Marina Gemma (NASA Emerging Worlds Grant; PhD Candidate, Columbia University)
- \*Dr. Martha Gilmore (PI, Venus Flagship Mission Study)
- \*Dr. Victoria Hamilton (Mission Scientist, OSIRIS-REx, GSFC)

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<sup>4</sup> In reports for Years 1-3, 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 this new metric of unique SMEs, adopted in Year Four, better reflects the diversity of relationships across NASA.

- Dr. Masha M. Kuznetsova (Director, CCMC, GSFC)
- \*Dr. Allegra N. LeGrande (Physical Research Scientist, GISS)
- Dr. Jon Linker (Co-I, SECCHI and IMPACT, STEREO)
- \*Dr. Kennda Lynch (LPI)
- Dr. Mordecai-Mark Mac Low (ROSES ATP)
- \*Dr. Germán Martínez (LPI)
- Dr. Leila Mays (Deputy Director, CCMC, GSFC)
- Dr. John F. Mustard (Mars 2020; Deputy PI of CRISM on MRO 2001-2016)
- \*Dr. Phil Quinn (JSC SRAG)
- \*Dr. Elizabeth Rampe (Exploration Mission Scientist, JSC)
- Dr. Rachel Smith (PI, NASA Emerging Worlds Research Program, Astrobiology)
- \*Dr. Kathryn Whitman (JSC SRAG)

***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: 15***

- \*Clayton Allison (JSC SRAG)
- \*Dr. Janet Barzilla (JSC SRAG)
- \*Michael Cook (JSC SRAG)
- Ryan Boller (Data Systems Assistant, GSFC)
- \*Ben Feist (Data Visualization Software Engineer, ARES, JSC)
- \*Dr. Alyssa Goodman (Harvard University)
- Dr. Jennifer Heldmann (Research Scientist, Ames)
- Dr. Masha M. Kuznetsova (Director, CCMC, GSFC)
- Dr. Jon Linker (Co-I, SECCHI and IMPACT, STEREO)
- \*Dr. Peter Macneice (Solar Scientist, CCMC, GSFC)
- Dr. Leila Mays (Deputy Director, CCMC, GSFC)
- \*Dr. Matthew J. Miller (Exploration Research Engineer, JACOBS/JETS; Advanced Exploration Group, JSC)
- \*Dr. Lutz Rastaetter (Geospace Scientist, CCMC, GSFC)
- \*Dr. John Wilkin (Ocean Surface Topography Science Team, JPL; Carbon Monitoring System, GSFC)

### Other SMEs in Year Five

An additional 11 SMEs also used OpenSpace as a tool for exploring and communicating space science data for a broad audience, bringing the total of unique individuals across Years One to Five to 25. 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 11.

#### ***Used OpenSpace in public programming: 11***

- Dr. Dan Canton (Dark Sky Observatory, Appalachian State University)
- \*Dr. Adrienne Cool (San Francisco State University Planetarium & Observatory)
- Dr. Jana Grcevich (Columbia University)
- Dr. James Hedberg (City College of New York)
- \*Dr. Pascal Lee (Mars Institute, SETI)
- \*Dr. Michael Nayak (AFRL)
- Irene Pease (CUNY)
- \*Dr. Bob Reynolds (DMNS)
- Emily Rice (AMNH)
- \*Dr. Daniel Wolf Savin (Columbia Astrophysics Laboratory)
- Dr. Mark SubbaRao (Adler Planetarium, University of Chicago, IPS)

#### ***Used OpenSpace in formal education setting: 3***

- Dr. Dan Canton (Dark Sky Observatory, Appalachian State University)
- \*Dr. M. Scott Harris (College of Charleston)
- Irene Pease (CUNY)

#### ***Collaborated on new or improved data or functionality: 1***

- Dr. James Hedberg (CCNY)

## **VII. Appendix: OpenSpace Scenes Developed in Years 1-5**

*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.

*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 scene 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 occulting 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.

*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 scene 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 Five Triangle

OpenSpace Year Five Evaluation Report

OpenSpace Developer Meeting Agenda

OpenSpace ISI Network and Advisory Board Meeting Agenda