Lunar Surface Innovation Consortium

Johns Hopkins Applied Physics Laboratory

REPORT-OUT FOR LSIC WORKSHOP:

Lunar Mapping for Precision Landing Workshop

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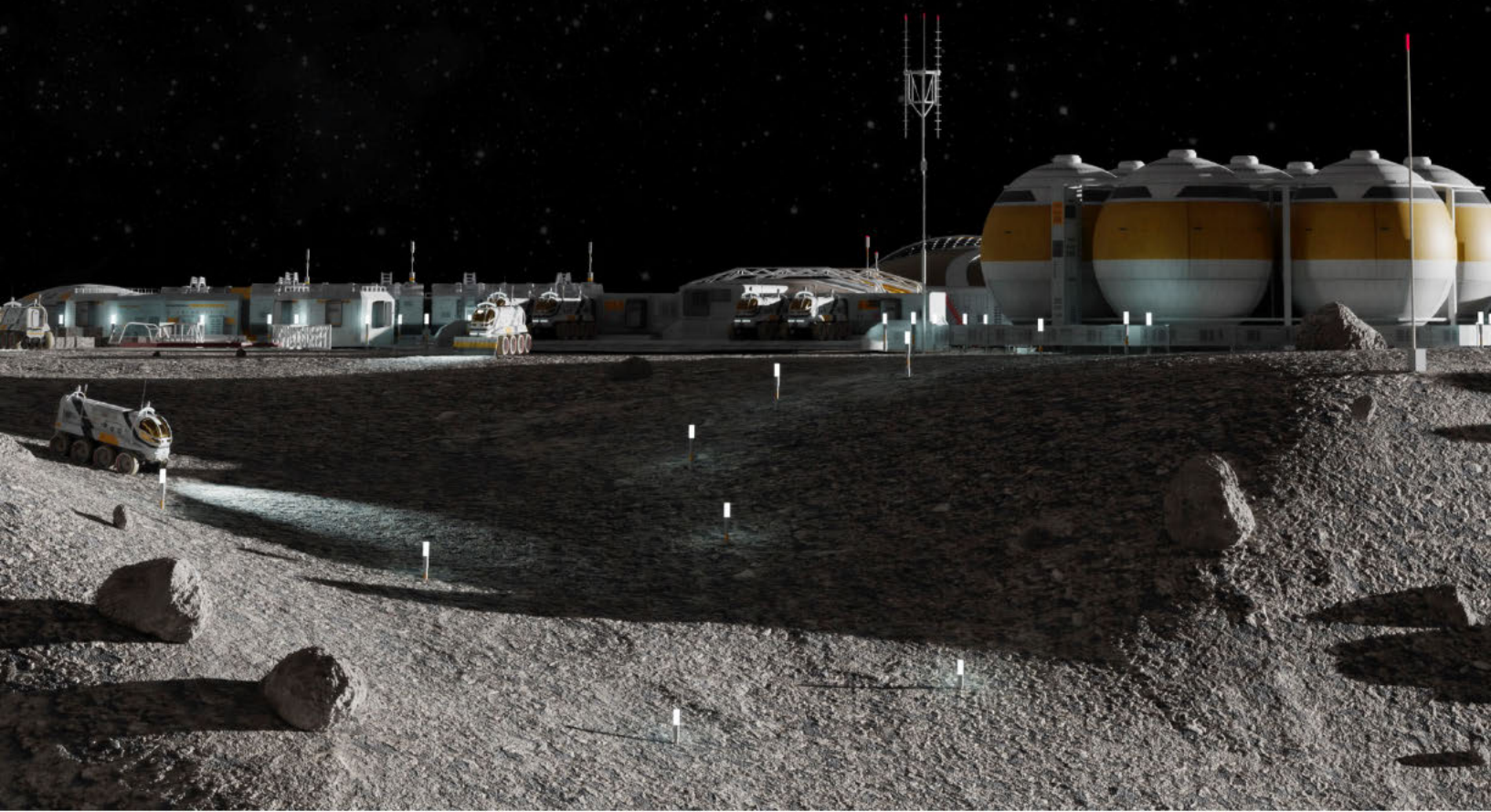


EXECUTIVE SUMMARY

Precision landing and hazard avoidance systems are necessary to enable access across the lunar surface. Communication between lunar data providers and data users is necessary and, to date, has been inefficient. Thus, the high-level goal of the workshop was to share knowledge between lunar geologists, data scientists, and navigation engineers that work on Terrain Relative Navigation (TRN) Systems for lunar missions. Expected outcomes were to initiate new conversations about TRN for lunar missions, to provide participants with an overview of the available lunar orbital imagery data, to highlight the lunar Digital Elevation Models (DEMs) currently available, to pose the necessary considerations for using the data in the development and testing of TRN systems, and to collect community input about needs for developing robust TRN systems for lunar landed missions.

Pre-registrations for the workshop included 425 attendees from over 138 institutions. There were 288 attendees on Day 1 of the meeting, 229 attendees on Day 2 of the meeting, and 210 attendees on Day 3 of the meeting. Over the course of the workshop, there were 367 unique attendees, including 12% non-profit, 19% academia, 34% industry, and 35% government.

High priority challenges and needs identified:

- Terrain Relative Navigation (TRN) systems need lunar maps with unique characteristics (e.g., format, resolution, metadata).
- Industrial partners and navigation engineers need more informational resources and conversations with mission teams to enable them to fully utilize existing lunar data.
- Standard data sets and controlled maps would be beneficial for testing algorithms.
- Current flight-qualified processor capability may be insufficient for advanced TRN algorithms and map processing.
- Targeted new missions and instrumentation would fill gaps in data needed for TRN systems.
- Standardized rendering tools, data verification and validations (V&V) metrics, and metadata are desired by the community.

WORKSHOP OVERVIEW

The Lunar Surface Innovation Consortium (LSIC) Workshop on Lunar Mapping for Precision Landing was held virtually March 2-4, 2021. The workshop included invited plenary speakers each day, breakout sessions to gather community input, and a poster session. The program and agenda were jointly planned with the LunaMaps team (POC: Carolina Restrepo, GSFC) from NASA Space Technology Mission Directorate's Game Changing Development program. The three workshop days were broken into general themes: Day 1 focused on Terrain Relative Navigation (TRN) definitions and an introduction to Digital Elevation Maps (DEMs), Day 2 focused on DEM building and tools, and Day 3 focused on modeling and rendering the lunar surface.

Recordings of the workshop and associated information can be accessed at the event website: http://lsic.jhuapl.edu/News-and-Events/Agenda/index.php?id=120

Workshop Goals

The high-level goal of the workshop was to bring together lunar geologists, data scientists, and navigation engineers that work on Terrain Relative Navigation (TRN) Systems for lunar missions to initiate conversations and to provide participants with an overview of the available lunar orbital imagery data, a description of the lunar Digital Elevation Maps (DEMs) currently available, and the considerations for using the data in the development and testing of TRN systems. The specific workshop objectives included:

1. to increase awareness of existing lunar data sets, where they are located, and best practices for use;
2. to communicate the map requirements needed to achieve navigation solutions for lunar TRN to lunar scientists and data scientists;
3. to provide navigation engineers with a deeper insight into the map data and the map building processes that produce the maps used to calculate spacecraft positions during flight; and
4. to obtain feedback from the LSIC community, including data scientists and data users, on how the community can help NASA catalog existing tools, methods and approaches for building DEMs, for accurate rendering of the lunar surface, and for validation and verification of TRN systems that can fill technology gaps for future lunar landing missions.

Workshop Attendance

Pre-registrations for the workshop included 425 attendees from over 138 institutions. There were 293 attendees on Day 1 of the meeting, 232 attendees on Day 2 of the meeting, and 216 attendees on Day 3 of the meeting. Over the course of the workshop, there were 367 unique attendees, with a breakdown of: 35% Government, 34% industry 12% non-profit, and 19% academia. For a full attendance breakdown, see Appendix A.

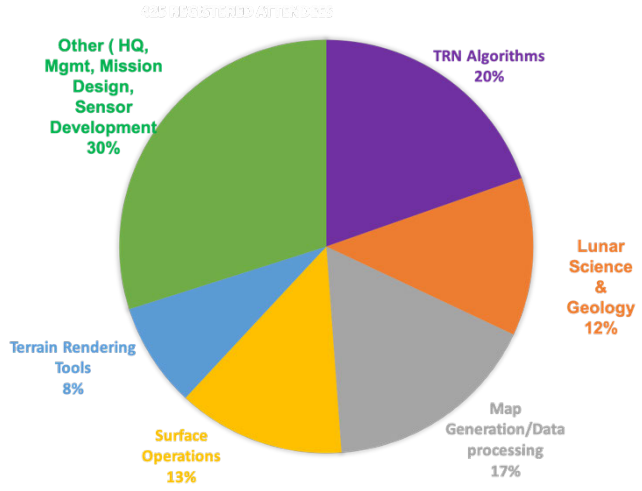


Figure 1. Demographic breakdown for the Lunar Maps for Precision Landing Workshop. The attendees were composed of 20% TRN Algorithm developers, 12% lunar scientists, 17% map and data producers, 13% surface operations specialists, 8% TRN rendering tools developers and 30% other specialties. Participants selected one category at registration.

WORKSHOP PROGRAM AND DISCUSSIONS

Plenary Sessions

The workshop included plenary sessions each day with presentations by invited speakers that fit into the day's theme. The full program, including speakers, is included in Appendix B. Presentation files and recordings are available at the event website: http://lsic.jhuapl.edu/News-and-Events/Agenda/index.php?id=120

The program on Day 1 was designed to introduce the larger community to available data products and uses and provide them with information about how to access the data, points of contact, and expected uncertainties and best practices as well as specific TRN challenges for lunar applications. Day 1 (TRN definitions) began with framing talks by conference organizers and Michelle Munk from NASA HQ. Next there were presentations covering TRN and Orbital Imagery source basics. Afterwards, the presentations introduced relevant lunar data sources, including the Lunar Reconnaissance Orbiter (LRO) Lunar Orbital Laser Altimeter (LOLA), the LRO Camera Narrow Angle Camera (NAC) instrument, and the Kaguya Terrain Camera. These instrument presentations were given by members of the instrument teams in order to provide information about the instrument capabilities, data products created by the team, and expected uncertainties or limitations when used in TRN applications. A panel discussed best practices for map data usage for lunar applications. The plenary session finished with three additional talks with relevant TRN examples, including the Mars 2020 Lander Vision System, the OSIRIS-Rex natural feature tracking system, and a description of specific challenges for lunar TRN.

The Day 2 agenda was designed to highlight DEMs and associated tools by showcasing specific lunar data sets, describing ways that maps relevant for TRN algorithms were created, and reviewing the uses and limitations of the data and validation and verification efforts. Plenary presentations included descriptions of lunar DEM products and how they are created, including a discussion of LOLA DEMs, the Ames Stereo Pipeline, Stereophotoclinometry, and the United States Geological Survey (USGS) SOCET Set. Specific examples of TRN product generation products for the Mars 2020 landing were shown. The plenary session ended with a discussion of map validation and verification efforts and needs.

Day 3 focused on tools for modeling and rendering the lunar terrain. The plenary presentations included a presentation from the LRO Project Scientist, Dr. Noah Petro, about lunar geology and the availability and uses of LRO data sets. The other plenary talks described modeling lunar surface features, particularly for the case of rovers on the surface, and also needs for lunar terrain rendering. The day also included a panel that discussed specific terrain rendering tools. These presentations showcased the state of the art in rendering tools and how they match to what we know about the surface.

Breakout Sessions

SUMMARY OF SESSION TOPICS

Breakout sessions were held each day of the workshop. The attendees were assigned to 5 separate groups each day to ensure small enough numbers to enable robust communication. The breakouts were themed to tie into the conversations of the day.

Day 1 breakouts focused on discussions of "roadblocks for Lunar TRN development". Attendees were randomly assigned to 1 of 5 separate zoom rooms. Using the online collaboration tool Miro, attendees were guided through a discussion of their TRN needs, what roadblocks, if any, exist for developing robust lunar TRN systems, and what sorts of help might be useful in overcoming said roadblocks. The full boards from Day 1 can be seen in Appendix B.

Day 2 breakouts were focused on discussions of map validation and verification efforts. Attendees were randomly assigned into 5 separate groups. In each Zoom room, an APL LSIC facilitator conducted an informational interview of a lunar scientist, data producer, or map expert. The participants commented and added discussion on the Miro boards. The full boards from Day 2 can be seen in Appendix C.

Day 3 breakouts were designed to collect feedback on benchmark data sets needed for TRN algorithm development and testing and landing missions at specific target sites. The attendees were assigned to 1 of 5 Zoom rooms based on their affiliation and organizational type. For participants from industry, breakout discussions focused on what types of data and/or meta data would be of use in a benchmark data set for TRN algorithm development. For participants from more academic institutions, breakout session discussions focused on specific regions of the Moon that are high-interest for landed missions that would benefit from well-characterized maps for landing site selection and TRN systems.

BREAKOUT SESSION DISCUSSION THEMES

The Day 1 breakout sessions focused on roadblocks to developing robust TRN systems and potential solutions. The volume and quality of lunar data that is already available was discussed during the plenaries and in the breakout sessions. Lunar data from missions such as LRO are publicly available on the Planetary Data System (PDS) and other similar websites (e.g., LunaServe, Quickmap). However, there was a disconnect between many commercial companies (e.g., map users and algorithm developers) about the availability of these data and how to access them. Presentations from the LRO Project Scientist and LRO instrument teams provided descriptions of the data, how to access them, and their limitations. There was general mutual appreciation of connecting data producers and the data users. Future follow-on discussions on the LSIC Extreme Access TRN subgroup will continue to provide avenues for this discussion.

Several additional themes emerged about roadblocks to developing high-fidelity TRN systems for the Moon, including:

1) The limitations of current spaceflight hardware for TRN algorithms that are compute-resource heavy. Every group recognized the need for increased investment and development in more-powerful space-rated high performance computing systems. It was unclear if more powerful flight processors were potentially under development and how capable they are for image processing.
2) The lunar poles present a challenging environment for TRN with low-incidence lighting and resultant long shadows. There was interest in developing new systems that utilize data in wavelengths outside the optical range, including radar, thermal infrared, and high-resolution lidar. The challenges of data and sensor fusion were discussed for this approach, as well as the lack of sufficient high-resolution data in these wavelengths at the poles. The availability of methods for generating combined data products with sufficient understanding of the uncertainty would be important. The high cost of space-rated instruments, currently,

was also discussed. Whether investment could be made to increase the availability of COTS instruments that could be flown on smaller, dedicated satellites is a question for discussion.

3) There was general agreement about the need for open-source/standardized tools and validation data. Each group discussed, to some degree, the need for common representative data sets and/or trajectories to allow for testing of TRN algorithms and development of new methods.
4) The community needs open-source tools that can interface with the variety of lunar data sets. TRN algorithm developers are not map or data experts and many discussions centered around inefficiencies of data wrangling. Having tools and common data standards more readily available would enable developers to concentrate on developing systems. It would be beneficial for data to have standardized formats for TRN algorithm testing and development that are easier to use than what is available in the PDS with standard meta-data and error products associated with them.
5) There is a need for requirements-based, standard V&V procedures. It was recognized that there is not necessarily a one-size-fits all TRN solution because different missions have different requirements for map validation and testing. However, it was not clear that all maps had been validated to the same degree.
6) There remains a need for higher-resolution and/or ground-truth data. With multiple landings planned on the lunar surface in the coming years, some discussions centered on making the landing images available to the public so they could be used for further development and V&V. There was a desire for NASA to have some requirements levied to make descent image data from CLPS landers public when they are carrying NASA payloads.
7) A useful product that could be generated for the community would be a data set including 2-3 lunar mission trajectories of interest with truth states, synthetic imagery, and actual imagery. This set would include an easy-to-use interface to evaluate performance and compare to competing algorithms.

Day 2 breakouts were dominated by interviews with lunar data experts. Some general themes emerged:

1) Map-makers need specific requirements from the community and spacecraft providers to produce useful products from the existing data sets. In order to generate products that will be of most use to TRN system developers, lunar data experts and map makers need accuracy requirements, both for absolute accuracy relative to the lunar (LRO) reference frame and within-image distortion. The required landing accuracy for different systems and missions would also be useful. This can be related to the camera field of view (FOV) and the altitude of data collection. The sooner this information can be provided in development, the better. It might be useful for STMD to put out a Request For Information (RFI) to CLPS and other industry providers to generate this information.
2) Space-qualified LIDARs are currently expensive, which limits their availability to be used in validating image and current map data. It would be beneficial to invest in development of cheaper LIDAR systems that could be purchased by lander providers or to identify new ways to validate image and map data.
3) Definition of requirements for TRN-systems would reduce some of the churn in development efforts that results from lack of clarity of the problem. Aspects of the problems that are not clearly defined include the resolution needed for robust TRN systems and whether that varies depending on whether the mission is crewed or robotic. Defining this will illuminate whether the existing data is of sufficient resolution and will inform a plan for obtaining it if not. References to a "LRO2" were made across all three days of breakout sessions, however, defining requirements would ensure that any follow-on mission is scoped to provide the necessary data.
4) Standard, rigorous, requirements-based V&V procedures would be beneficial.

Day 3 focused on benchmarking data sets and the needs for two specific communities: spacecraft providers who need specific data to test algorithms, and scientists and engineers who want data on specific regions on the Moon for mission design and planning.

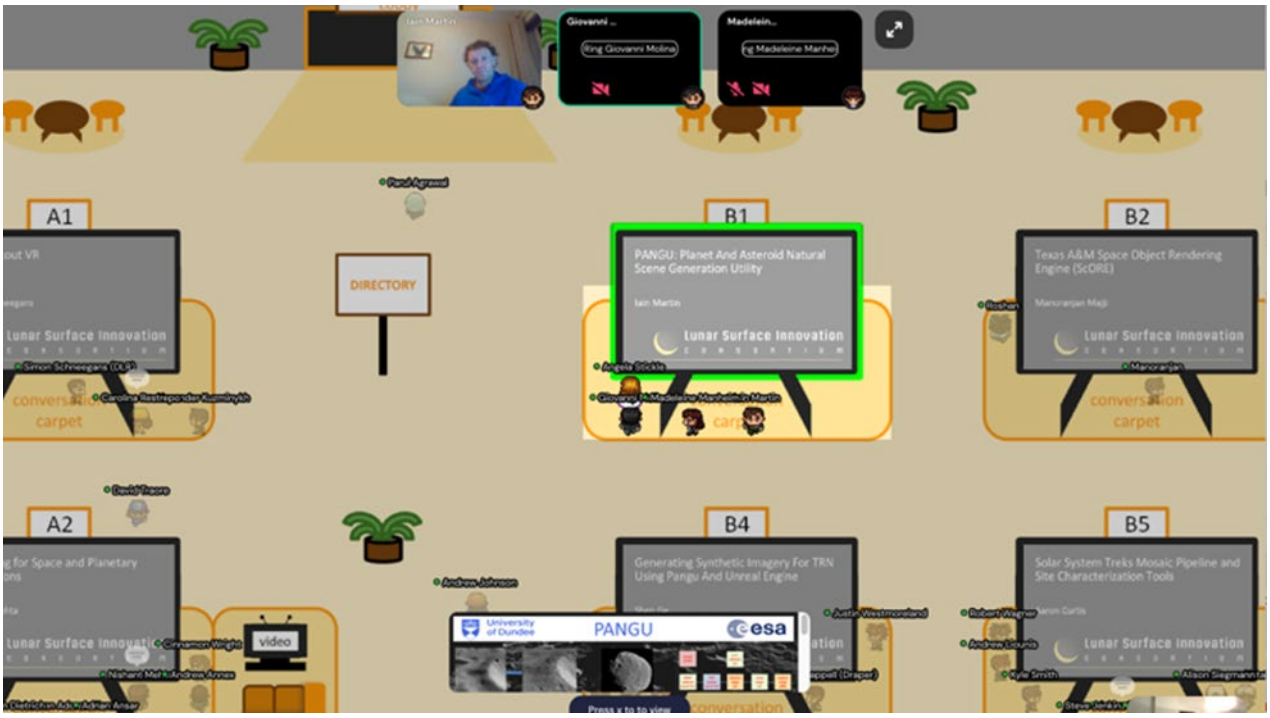
1) In general, there was a desire for validated benchmark data sets that could be used for testing and validating new TRN algorithms. There was not a consensus, however, about what would be most useful to include in this data set with respect to geologic features, lighting, or resolution of data. The overall theme was that a

variety of resolutions and lighting conditions would be beneficial for polar locations, and well-validated non-polar sites (e.g., Apollo landing sites) would be of use. Further, there was wide-spread interest in using international data sets, especially Kaguya and Chang'E data. Meta-data should include specific information about how the data was gathered, expected uncertainties, camera models, and examples of potential pitfalls to avoid in using the data.

2) Overall, there were several obstacles identified for landing site selection, including poor lighting at the poles, lack of NAC-scale Digital Terrain Models (DTMs), validated maps, and surface hazard databases (e.g., boulders and craters). For specific missions, a variety of landing sites of interest were identified, including: lunar poles, permanently shadowed regions (PSRs), Reiner-gamma and other swirls, Schrodinger basin, Amundsen crater, lunar pits, farside locations, pyroclastic deposits, Orientale basin, Schiller-Shickard, and Tycho crater and central peak.

Poster Session

Day 3 included a poster session from received abstracts. The goal of the poster session was to provide information about the state of the art in Terrain Rendering Tools. Community members were invited to showcase their tools developed for lunar (and other planetary body) terrain rendering. To provide an environment that would enable networking and discussions, we used a tool called Gather Town for the poster session. Within Gather Town, a virtual environment was set up in which users each had an avatar that could move through the environment to view posters, booths, or videos and to chat with those around them. An example of the setup is shown in Figure 2. The workshop showcased 11 submitted poster presentations.



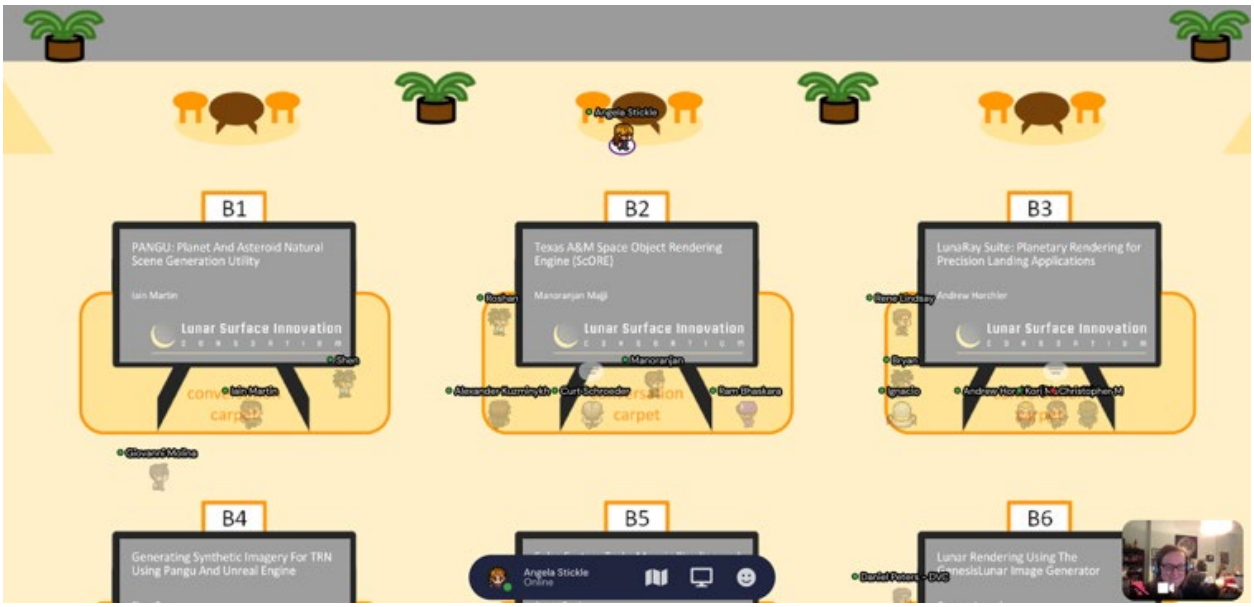


Figure 2. Screenshots from the GatherTown poster session during the workshop. (top) Example of discussion with poster presenter. When a user was near the poster, a copy of the poster was shown on the screen and video feeds were initiated between nearby users, simulating standing next to a poster at a live event. (bottom) The submitted posters were arranged in a poster hall that users could use their virtual avatars to walk around in and interact with presenters and other attendees. The poster locations were included in directories placed around the venue.

KEY TAKEAWAYS FROM THE WORKSHOP

Throughout the workshop, the webinar client worked well and no major technical issues occurred during presentations. From discussions in plenary sessions and breakouts, we identified several high priority challenges and needs:

- Terrain Relative Navigation (TRN) systems need lunar maps with unique characteristics (e.g., format, resolution, metadata). These are often different than requirements from scientists, for which many of the maps were previously generated. More details from the map-users are needed to ensure adequate products are generated in the future, and support should be made available to map producers if new products are necessary.
- It was widely recognized that a better connection between data providers and data users (e.g., algorithm developers, testers, etc) would be beneficial. One of the objectives for the Extreme Access Focus Group going forward is to address this disconnect through continued conversation and collaboration in our TRN subgroup.
- The standard data and maps produced by the LRO team are optimized for science, and may not be in the preferred format or include all the relevant information for TRN system developers to use for algorithm development and testing. The data providers are open to generating new publicly available products for use in TRN systems, however, the LRO project is not currently explicitly funded to do so. Specific new data products, with requirements defined by the TRN development community, could be provided but would require additional funding outside the nominal LRO science mission.
- There is interest in a central location to access lunar maps relevant to TRN system development. This repository should also include descriptions of the data, potential pitfalls in using specific maps (e.g., known uncertainties, data gores and averaging, artifacts, etc). This repository would allow easy access to relevant LRO, Chang'E and Kaguya data.
- All three days of breakout sessions also included some discussions of the need for standardized data-sets and tools for benchmarking and validating TRN algorithms and channelizing development so that new providers can leverage previous work. Open-source tools to interface with lunar data would improve efficiency by enabling

developers to focus efforts on algorithm development rather than interfacing with the data. Another suggestion was to provide incentives or requirements for data sharing for upcoming landed missions to obtain "ground-truth" and higher-resolution data that could be used by the community for testing algorithms.

- Standardized rendering tools, data verification and validations metrics, and metadata are desired by the community.
- Current flight-qualified processor capability is insufficient for advanced TRN algorithms and map processing.
- Targeted new missions and instrumentation would fill gaps in data needed for TRN systems, but better definition of the requirements would help to hone such a mission.

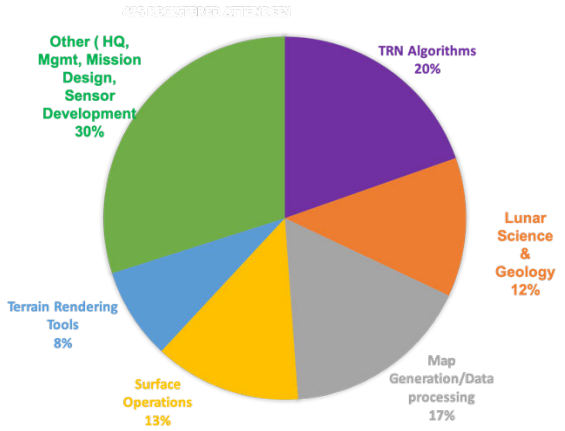
ACTION ITEMS AND FOLLOW-UP

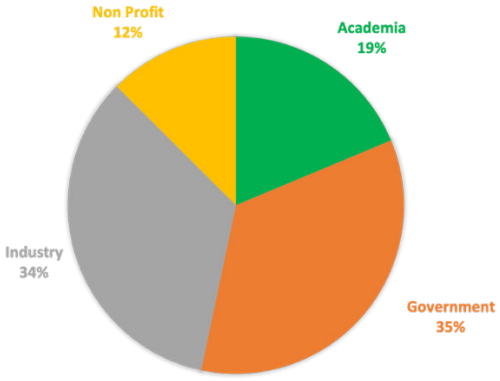
The LSIC Extreme Access Focus Group is performing follow-on activities as a result of the TRN workshop discussions:

1. Formation of a TRN subgroup dedicated to continuing discussion between map-makers, map users, and algorithm developers to overcome obstacles to TRN-system development, discuss the formation of benchmark data sets and V&V requirements.
2. Generate a resource guide, to be posted on the LSIC confluence site, for where and how to access lunar data.
3. Participate in discussions about open-source development efforts for TRN software.

Appendix A. Attendance Breakdown

Pre-registered attendee breakdown





Some institution types inferred

During the workshop, 367 unique attendees participated from 30 states and 16 different countries. Daily attendee numbers are shown in Table A.1

Table A.1 Attendee statistics for the LSIC Workshop on Precision Landing

Overall Unique Attendees	**367**
Day 1 Attendees	293
Day 2 Attendees	232
Day 3 Attendees	216

Appendix B. Day 1 Breakout Session Miro Boards

Theme: TRN Roadblocks

Questions:

- What were you most surprised about from today's workshop?
- What have you recently learned about other TRN community needs?
- What are specific roadblocks to developing adequate TRN systems (categories: Hardware, Software, Data/Maps, Other)?
- What might help you overcome specific roadblocks (categories: Hardware, Software, Data/Maps, Other)?
- How can we create a community consensus for a standard "test set"?
- What does your group currently use as a "test set" or reference?
- What community "best practices" do you want put into place?
- What data is missing to develop accurate TRN systems?
- What has been your favorite TRN project?

Appendix C. Day 2 Breakout Session Miro Boards

Theme: Data/Map V&V

Following a NASA-led presentation on examples of known efforts for validation, verification, or landing site certification efforts, attendees had the opportunity to raise their issues or questions related to map V&V. We wanted to learn what errors maps have, what people need, how they go about correcting them, what can NASA provide to help?

APL facilitator	Interviewee	Room
Wes Fuhrman	Noah Petro (GSFC)	V&V 1
Ben Greenhagen	Trent Hare (USGS)	V&V 2
Michael Nord	Robin Fergason (USGS)	V&V 3
Sarah Withee	Yang Chen (JPL)	V&V 4
Angela Stickle + Reeve Heinis	Andrew Johnson (JPL)	V&V 5

Appendix D. Day 3 Breakout Session Miro boards

Theme: Benchmark data set needs

Questions:

- What would you like to see in a benchmark data set?
- What data would be of most use?
- What types of meta-data are useful?
- What geometric/photometric fidelity do you need?
- What are the most important altitudes to operate in?
- What is the best way to encourage community discussion?

- What locations are you most interested in exploring/landing at?
- What obstacles exist for landing site selection?
- What benchmark data sets are valuable?
- What would you like to see in a benchmark data set (polar and non-polar sites)?