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# LEAP2 and LCATS industry clusters: A framework for lunar site technology development using global, space-STEM education and global space-industry development networks

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A R T I C L E  I N F O

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A B S T R A C T

Industry clusters, considered the building blocks of modern economies, are an economic concept used to identify and define the geospatial density, growth and network behavior associated with innovation and economic performance. Our program proposes use of cluster analysis related to space-STEM education and space-industry to identify aerospace system-sector industry clusters and factors on a global scale related to lunar site technology development. The goal is to document and encourage space-industry cluster network development, facilitating space-STEM workforce and economic development for communities, based on technologies relevant to particular community areas of interest and aerospace resources. Using a wheel model of unique industrial system-sectors needed for lunar site technology development, analyses and documentation of clusters and factors can assist potential system-sector collaborators in commercial exploration architecture development to cluster network participation and design of space-STEM development. At present, system-sector components for lunar exploration architectures include: satellite communications (Mexico), mission operations (Germany), ISRU and vacuum chamber test environment (Korea), and lunar ecosystem and architectural prototype development (United States). Development of these initial system-sectors are underway through the LCATS and LEAP2 global space-STEM education network project, “Lunar Caves Analog Test Sites (LCATS) for Space-STEM Learning Performance”, featuring a Lunar Ecosystem and Architectural Prototype (LEAP2). To expand the LCATS and LEAP2 initiative, the project seeks to identify, map, and analyze potential collaborating corporate and industry players representing other system-sector components needed for lunar site development from the perspective of evolving a global space-STEM education network beneficial to the local community of the collaborating organization relevant to their expertise in system-sector component development. Additional cluster expertise sought includes mining and energy generation; food and waste processing; water production for fuels; vehicles and equipment systems, and logistics, to name a few. Replication of an LCATS three to four year education and career development program, using actual lunar site technology development is intended to give international student participants the ability to learn about and build a cluster specialization with lunar site outcomes.

*Acronyms/Abbreviations:* ECLSS, Environmental Control and Life Support; GIS, Geographic Information Systems; ISRU, In-situ Resource Utilization; LQ, Location Quotient; LCATS, Lunar Caves Analog Test Sites; LEAP2, Lunar Ecosystem and Architectural Prototype; NAICS, North American Industry Classification System; PREP, Pre-freshman Engineering Program; STEM, Science, Technology, Engineering, and Mathematics; QCM, Quartz Crystal Microbalance; NACE, Statistical Classification of Economic Activities in the European Community; SEP, Student Exchange Program

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## 1. Purpose and background

### 1.1. LEAP2

Lunar Ecosystem and Architectural Prototype (LEAP2), is a commercial lunar site development program being developed by an international consortium of aerospace industry organizations investigating technologies for lunar settlement [1]. LEAP2 addresses space architecture research for a specific lunar site identified as the Marius Hills Skylight, believed to be the opening to a lunar lava tube cave useful for eventual human habitation [2]. The skylight, shown in Fig. 1 is a large pit located in the Marius Hills region of Oceanus Procellarum at 14.2°N, 303.3°E [3]. Surface mining operations in the vicinity of the pit opening are envisioned.

Projects within the LEAP2 program address various technology solutions and missions for achieving multi-generational program goals within a phased exploration approach for development of the site for human settlement. Shown in Fig. 1, and Table 1 are notional time phases of the LEAP2 lunar site development.

The LEAP2 international consortium is loosely organized with industry, academia, and government organizations. LEAP2 example technologies under development include robotic access and sensing technology for scientific measurements, In-situ Resource Utilization (ISRU) technologies such as additive manufacturing for habitat design, regolith simulants research, and manufacturing for planetary construction using polymeric concrete for surface infrastructure. Table 2 illustrates examples of current LEAP2 technology from a sample of consortium members performing individual and collaborative research, including Exploration Architecture Corporation (XArc), USA; Southwest Research Institute (SwRI), USA; Korea Institute of Civil Engineering and Building Technology (KICT), S. Korea; International Space Exploration Research Institute (ISERI), S. Korea.

**Table 1**
Objectives of LEAP2 site development.

| Site Development Phase | Objectives |
|---|---|
| Remote Sensing | Site characterization |
| Robotic Reconnaissance | Scientific measurements |
| Human and Robotic Reconnaissance | Ground truth verification |
| Outpost | Long duration stays; possible surface mining operations |
| Settlement Construction | Infrastructure development |
| Human Settlement | Permanent settlement achieved |

The LEAP2 consortium funds its technology research through individual member's Internal Research and Development (IRAD) budgets. Additionally, collaborative proposals for funding joint technology development are submitted to government agencies of respective member host countries and to other commercial opportunities that may arise. Consortium members also jointly co-author research papers for publication in peer-reviewed journals, conference presentations and symposia. Examples include our scientific investigation into the permeation, adsorption and diffusion of volatiles at the lunar surface [5]; or formation of an ad hoc international working group to promote lunar and Martian putative lava tube exploration and useful exploitation [6] [7].

### 1.2. LEAP2 and STEM education outreach

Cross-disciplinary international collaboration in space exploration is very well recognized. Inspiring the next generation of space explorers with the value of international collaboration is an important aspect of

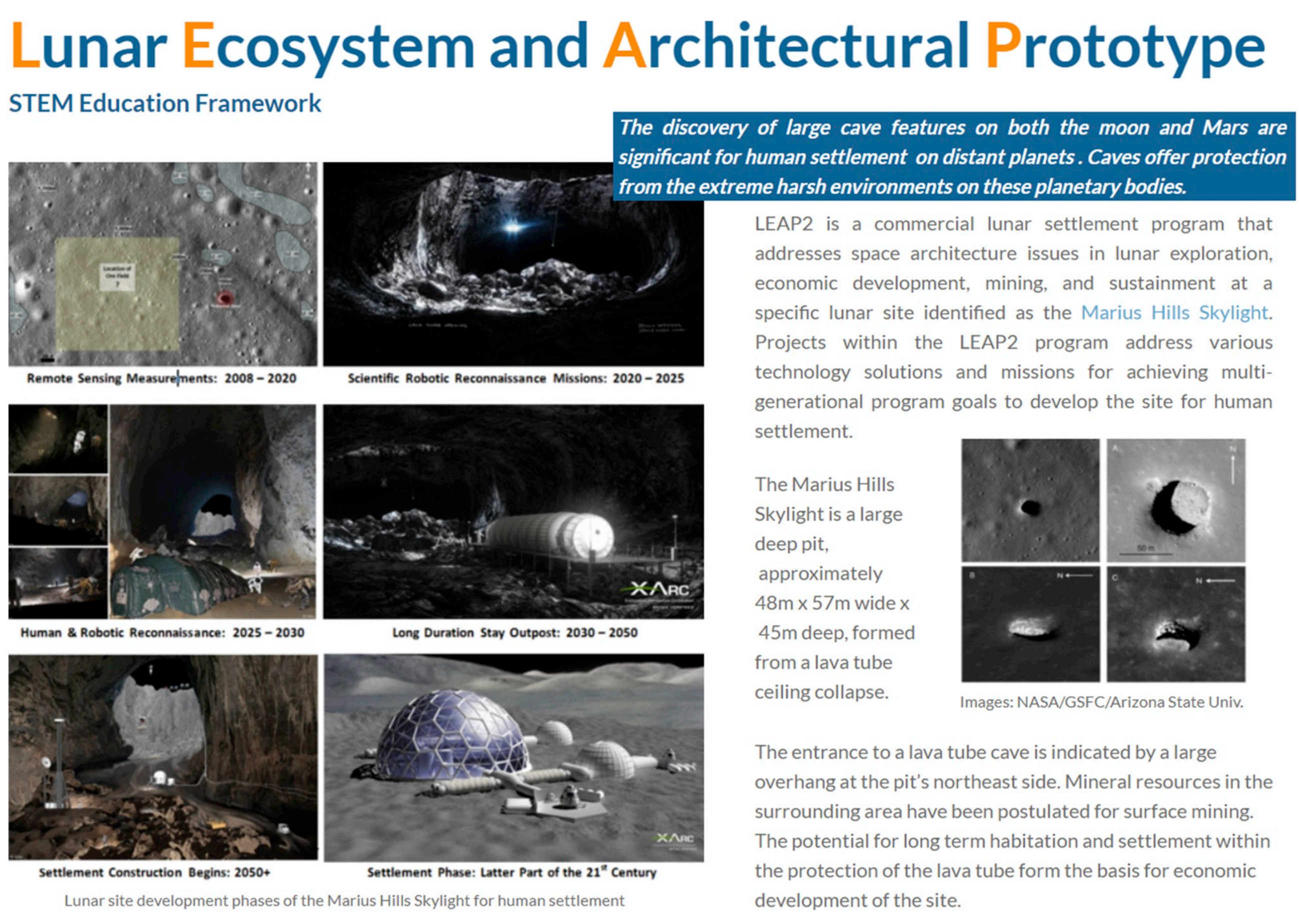
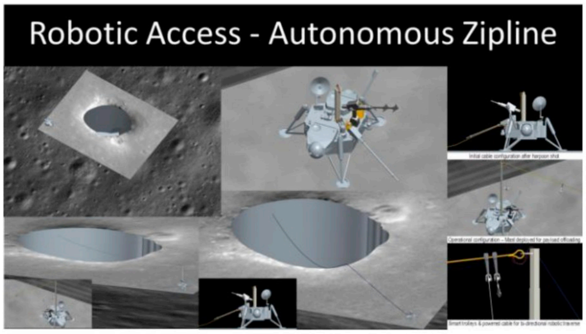


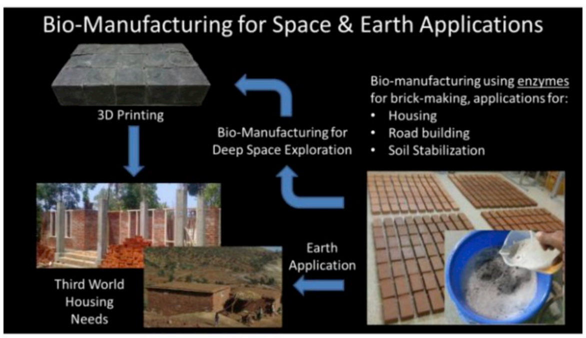

**Fig. 1.** Development phases of the Marius Hills Skylight for human settlement.

**Table 2**
Examples of LEAP2 technology research [4].

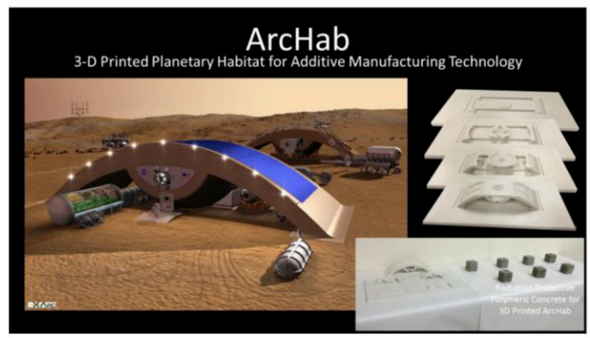


One of the various pit access concepts being investigated

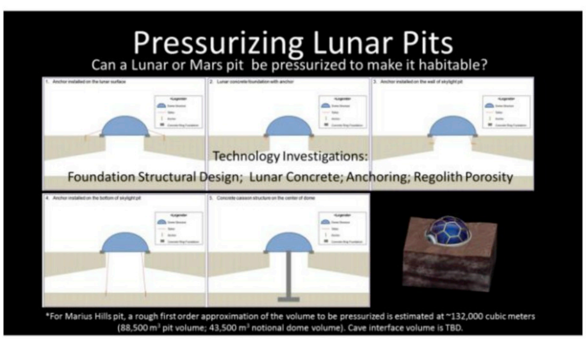
Simulant research; landing pad pavers; ISRU 3D Printer



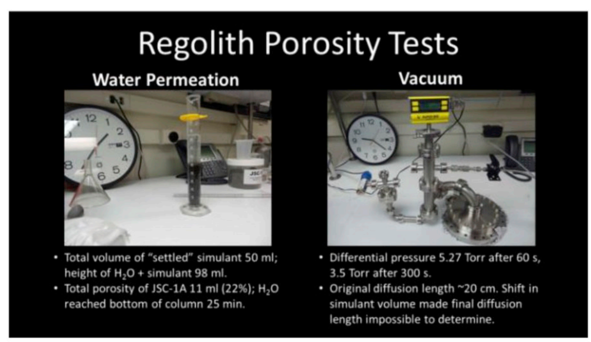
Dual-use technology for terrestrial sustainability



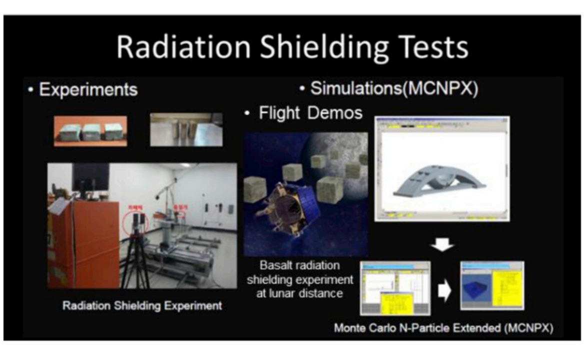
3D printed habitats using in-situ resources for construction



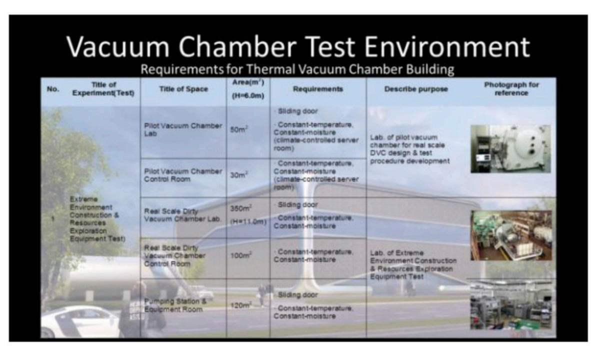
Dome structural foundation and anchoring investigations



Dome pressurization and regolith porosity research [4]



Radiation shielding potential of polymeric concrete



Building facility investment for 50 cu. m. vacuum chamber

the LEAP2 program. The educational outreach component of LEAP2 strives for establishment of an inclusive local community sponsored space program for Science, Technology, Engineering, and Mathematics (STEM) education, community workforce development, and entrepreneurship. Use of terrestrial analogs for testing technology projects and operational processes in a mission context are an equally important aspect of the LEAP2 program, and are used for development of project-based curricula.

The benefit of project-based educational programs is quite established [8] [9]. "The capacity to think critically, solve problems, communicate effectively, and work in teams are some of the life skills highly valued by employers, but these skills are not addressed effectively in most formal educational curricula", (International Youth Foundation, 2012) [10]. Project-based learning, a teaching methodology that utilizes student-centered projects to facilitate student learning, is touted as superior to traditional teaching methods in improving problem solving and thinking skills, and engaging students in their learning [11] [12]. A number of international space education programs employing project-based curriculum currently exist, including: the International Space University (ISU) summer sessions held in alternating host countries; various programs of the U.S. Space & Rocket Center, Space Camp; the Stuttgart summer workshops of the Institute of Space Systems at the University of Stuttgart; or the Space Development Theory and Practice (SDTP) International Workshop of the Youth Space Center of Bauman Moscow State Technical University - to name a few. With a few notable exceptions, international student participation is for the most part geared toward university level education. These programs typically present a broad stroke approach to the application of space technologies in curriculum or program venues which can vary from year to year.

The differentiator with the LEAP2 education initiative is the specificity of its technology research and development projects. For project-based learning, all consortium sponsored curricula initiatives are focused on their application to advancing the body of knowledge for site development of planetary pits and lava tubes, in particular, development of the Marius Hills Skylight as a commercial prototype for understanding how to use these planetary features to the benefit of human settlement on distant planets.

### *1.3. LCATS*

With $1.24 M in grant funding from NASA, a "Lunar Caves Analog Test Sites (LCATS) for Space-STEM Learning Performance" program is being developed by the non-profit WEX Foundation of San Antonio, Texas [13]. LCATS provides real-world context for students to assist aerospace professionals with solving actual space exploration technology development challenges of the LEAP2 program. LCATS provides Space-STEM learning experiences in space exploration using project-based curricula to work within the LEAP2 framework.

Attaching the LCATS program to actual technology, engineering and science investigation challenges throughout the various LEAP2 site development growth phases aligns the student learning experience with mission priorities for planetary surface systems engineering and mission operations, science experiments and science instrumentation, and allows students to freely advance ideas for technology concept investigations. Local Texas caves in the area and region are utilized as analog environments for fielding student experiments and technology challenges through simulated mission operations, Fig. 2.

The LCATS program works with host schools in lower-income and high-needs communities to recruit math and science students to change their education and career trajectories. A particular focus is placed on improving Space-STEM teaching and student comprehension for students who have been traditionally underserved and underrepresented in institutions of higher education. LCATS goals include preparing and encouraging underrepresented minorities, female and economically disadvantaged students to pursue higher education and careers in human space exploration.


**Fig. 2.** LCATS is a NASA-funded, science-based academic enrichment program.

The LCATS program environment, shown in Fig. 3, engages a pipeline of motivated middle and high school students to assist aerospace professionals solve real-world space exploration technology development challenges through investigations of science experiments, space exploration mission operations, technology development, and habitability system architectures for Space-STEM learning performance. Intensive "hacker" workshops employing collaborative knowledge, critical thinking, and problem solving are conducted for student teams led by educators and undergraduate/graduate interns acting as team mentors/team leaders and supported by professional subject matter experts to guide students in development of innovative hands-on applications that provide practical solutions for the LEAP2 lunar mission architecture challenges.

The LCATS program allows students to form student consulting teams for a potential three to four year experience of cohorts addressing space architecture technology challenges for an actual commercial lunar exploration, mining, and human settlement project as applied to the various growth phases of the LEAP2 site development program. As previously shown in Table 1, the LEAP2 site development phases begin with remote sensing and satellite missions (LCATS Year 1 mission), then site characterization and reconnaissance mission scenarios of robotic and crewed missions (LCATS Year 2 mission), and culminate with space architecture designs for eventual habitation and human settlement (LCATS Year 3 mission). Students are challenged with project-based, mission oriented, field tested student learning experiences. Students are required to maintain engineering notebooks for each annual mission phase. In their fourth year of the program, student cohorts memorialize their 3-year experience in the form of a comic book with super hero action characters which they create and produce for public distribution.

The theme of our Year 1, Remote Sensing Phase project is *"When the Dust Settles"*, in which students learn about issues of lunar dust and measurement techniques. Cohorts of competitively selected students attend out-of-school laboratory workshops throughout the academic year, two Saturdays per month. The technology showcase for the program's first year curriculum has focused on development of Quartz Crystal Microbalance (QCM) technology for dust particle measurements. The student project progresses through a series of analog test environments for science instrument testing, starting with a cave environment and culminates in launch of the student designed QCM dust measurement instrument on a high altitude balloon for upper atmospheric dust particle measurements. A successful balloon launch with the breadboard QCM design was completed in June 2018 [14]. The curriculum elements are shown in Fig. 4.

The LCATS Year 2 robotic reconnaissance and LCATS Year 3 space architecture/habitat design mission scenarios and curricula for student projects are still in development.

Employing undergrad/graduate level student interns as class mentors for the middle and high school students provides an additional benefit of student engagement at the university level for parallel development of technology investigations. An example of how the various student educational levels interact with professionals and mentorship roles for a LEAP2 technology challenge is shown in Fig. 5. Illustrated is the sequence of QCM technology utilization of the student project investigation for learning measurements of dust particles in various test environments. Graduate/Undergrad interns (identified as UTSA Advanced Robotics in Fig. 5) obtain familiarity with the QCM technology through the different test environments while also working in parallel on the QCM flight hardware development for a LEAP2 commercial


**Fig. 3.** The LEAP2 Lunar Caves Analog Test Sites (LCATS) student experience.

lunar payload to the lunar surface.

The intent of the LCATS student experience is to create a sustainable testing environment where students are encouraged to discover, learn, explore and achieve through an informal experiential space exploration research experience. At the same time, students are acquainted with professional opportunities in space-STEM through sustained research, field experiences, and mentorship.

The LCATS program operates with an international network of support partners comprised of the LEAP2 consortium principals plus additional organizations shown in Table 3 which have a participatory role relevant to certain project learning activities.

#### *1.3.1. LCATS economic premise*

On an economic level, the purpose of our LCATS ***evidence-based*** project is to demonstrate how any community can have its own space program and use that program to drive a pipeline for nurturing an entrepreneurial and STEM workforce for the community. Our overarching aim is to show how a community space program can act as a catalyst when used as an informal educational framework for STEM workforce development and economic growth [15].

This process begins by partnering with the community education system to develop curricula at multiple levels and internship programs that focus on the courses needed to gain the STEM knowledge applicable to a very specific community vision, which gets students excited about learning and being part of something that is a grand adventure. Actually being a participant in the community's efforts to explore space can entice a new generation of students into the STEM fields. With a local space program, e.g., a community goal to go to the moon (or even go into low earth orbit by developing its own satellite, or its own space station module) the community can enable and inspire students who in turn become scientists and engineers, as well as the entrepreneurs who start companies, facilitating local job growth. In the case of LEAP2, we are essentially using a commercial lunar base development program to demonstrate how such a program could impact economic development for the regional community.

Our aspiration is to replicate and scale the LCATS STEM education model by expanding it into a global network of specialist LEAP2 space-STEM communities. Our approach is to identify aerospace industry clusters which can contribute to capacity-building of an international space workforce.

## 2. Global space industry clusters

### *2.1. Cluster analysis*

Industry clusters are considered as building blocks of modern economies. The economic concept of identifying industry clusters is used to define the geospatial density, growth and network behavior associated with innovation and economic performance. Economic cluster analysis is a subset of industrial development theory called economies of agglomeration, first studied in the late 1800's [16,17].

Cluster analysis outputs include identification of regional geographic density of specific industry supply, value, and production chains. The analysis uses economic activity and geographic information systems (GIS) data to measure and document the dynamic behavior of knowledge flows, labor, and production networks. Location quotients (LQ)[1] and density models are used to show regional concentration use patterns of industry productivity, and regions which can be

[1] (Ratios for quantifying how concentrated a particular industry, cluster, occupation, or demographic group is in a region as compared to the nation. It can reveal what makes a particular region "unique" in comparison to the national average.).

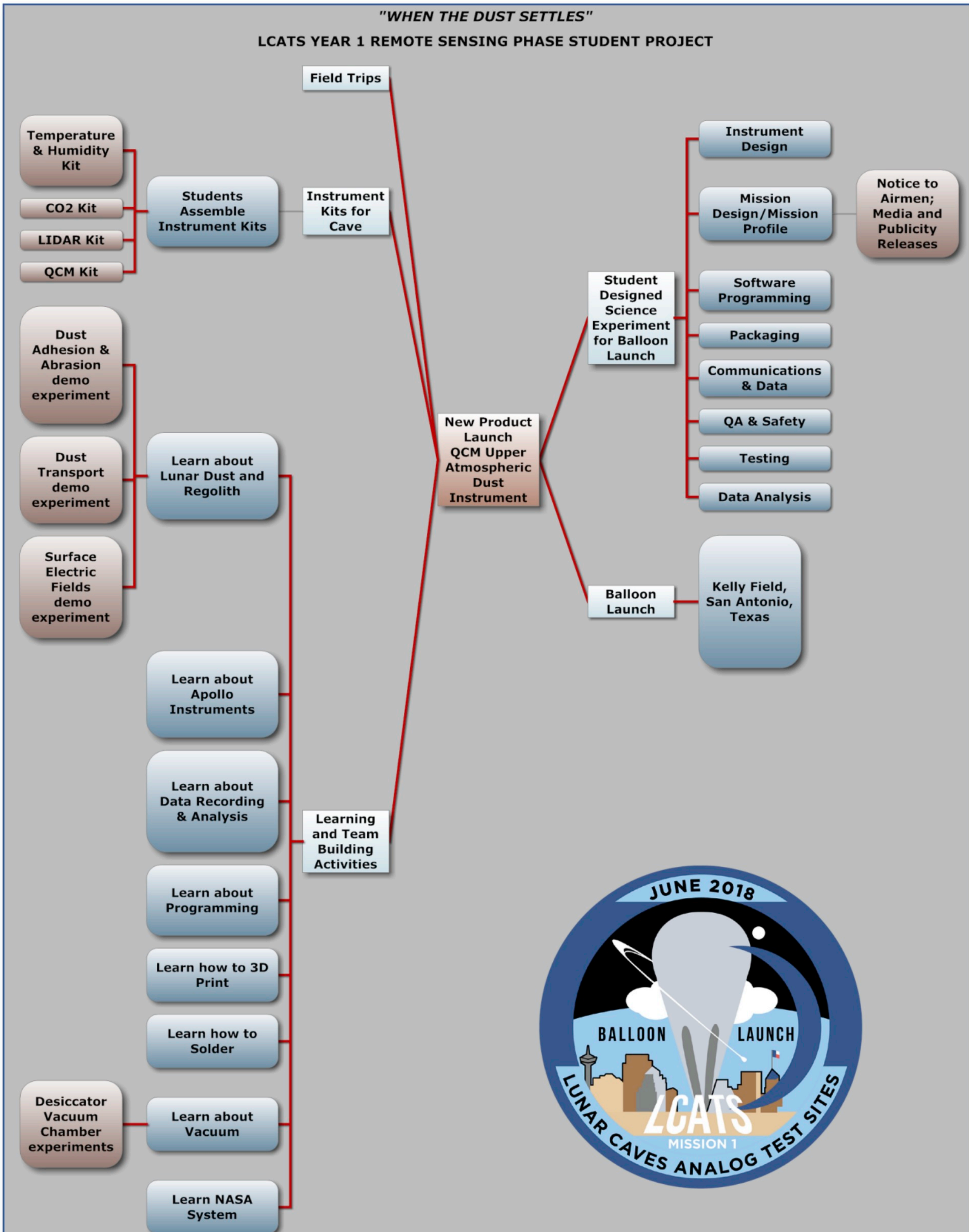



**Fig. 4.** LCATS year 1 remote sensing student project ends with successful high altitude balloon launch.

benchmarked to discover sector-group efficiencies and linkages. Factors considered include the various types of resources that may be unique for particular industry sector development.

The objective is to document and encourage space-industry cluster network development based on technologies and specialties beneficial to the LEAP2 framework and relevant to the particular community areas of interest and available aerospace industry resources. Our proposed methodologies for obtaining, validating, and reporting information to achieve the objectives are provided in Appendix A.

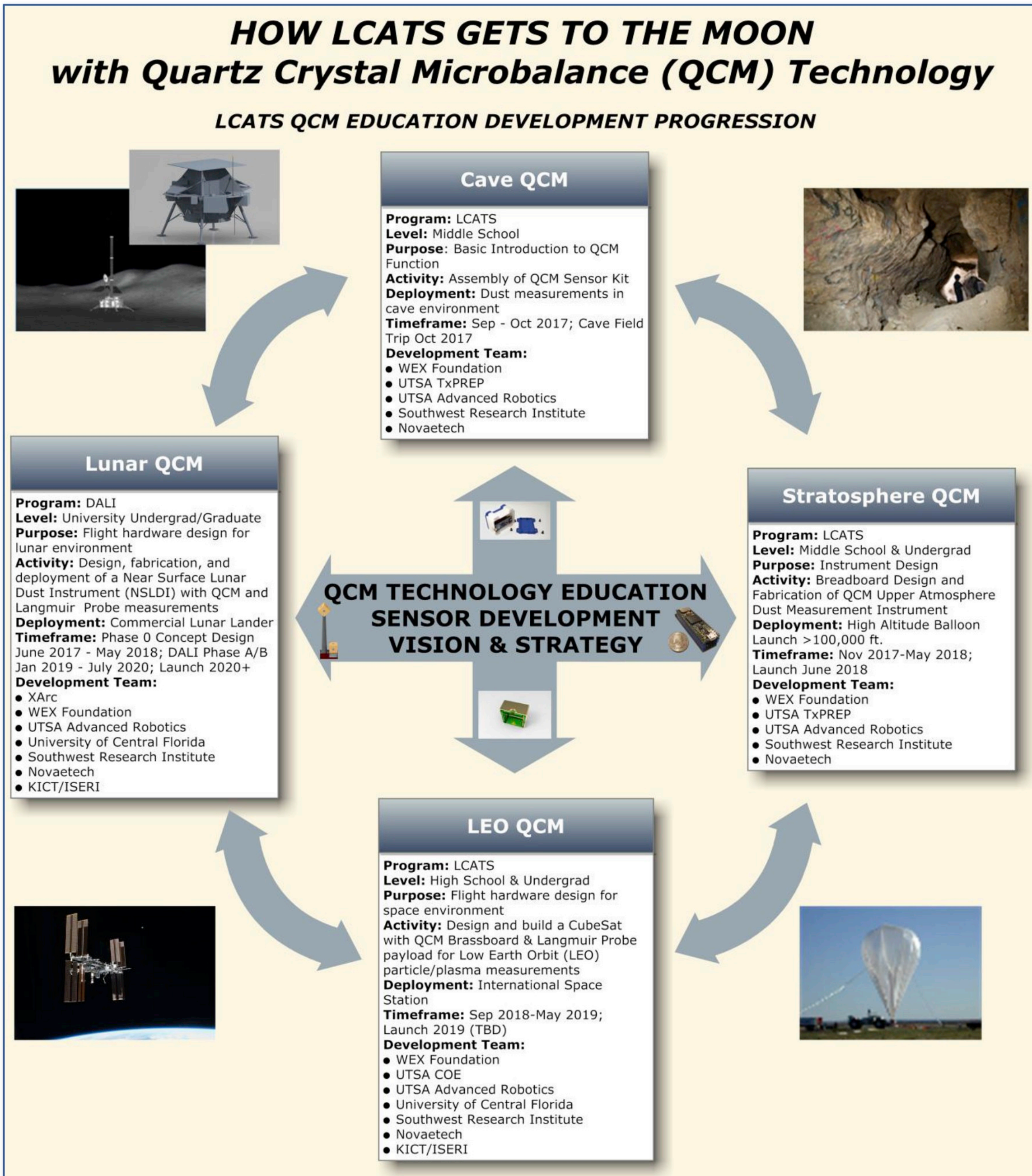



**Fig. 5.** LEAP2/LCATS QCM education development programs.

### 2.2. LEAP2 and LCATS space industry clusters

To expand the LCATS and LEAP2 initiative, our research seeks to identify, map, and analyze additional potential collaborating corporate, industry and governmental agency players representing other space architecture components needed for lunar site technology development. Aspects examined include local, regional, and international factors from the perspective of evolving a global space-STEM education network beneficial to the local community of the collaborating organization relevant to their expertise for the LEAP2 development effort. Expansion of LEAP2 technology research to additional aerospace industry system-sectors widens the framework for LCATS curriculum development for Space-STEM education projects. Additional system architecture elements expertise sought includes mining and energy generation; food and waste processing; Environmental Control and Life Support Systems (ECLSS); water production for fuels; vehicles and equipment systems; and logistics, to name a few.

Fig. 6 shows a lunar site technology development wheel model for identifying global industry clusters. On a global scale, potential collaborators that are identified through cluster and statistical analyses may be added to the LEAP2 framework as participants in expanding the LEAP2/LCATS program. The aerospace system-sector industry clusters identified for this research will provide the basis of a global STEM education, collaboration and employment opportunity network.

### 2.3. LCATS-SEP

Shown in Fig. 7 is a practical implementation for internationalizing the LCATS student experience. A pilot program is in development called Lunar Caves Analog Test Sites-Student Exchange Program (LCATS-SEP).

**Table 3**
LCATS support partners.

| LCATS PARTNER | DESCRIPTION |
|---|---|
| WEX Foundation | Principal Investigator: Prime institution administering the program |
| University of Texas at San Antonio (UTSA) Prefreshman Engineering Program (TxPREP) | Institutional Co-Principal Investigator: Curriculum development, research, coordination, student recruitment/ retention, and instructors |
| Southwest Research Institute (SwRI) | Co-Investigator: Science & engineering subject matter experts |
| Steuck & Associates (S&A) | Co-Investigator: Program external evaluator |
| Texas Alliance for Minorities in Engineering (TAME) | Collaborator: TAME affiliated club participation |
| San Antonio Challenger Center, Scobee Education Center | Collaborator: Mission control operations center for LCATS missions |
| SPS Digital | Consultant: Social media outreach, website, and online marketing |
| UTSA Advance Robotics (AR) | Collaborator: Undergraduate and graduate student robotics club develops prototypes of science instrument kits for LCATS curriculum, and provides mentoring to high school students |
| Korea Institute of Civil Engineering and Building Construction (KICT) (S. Korea) | Collaborator: International collaboration and access to civil engineering facilities for planetary construction |
| Hanyang University, International Space Exploration Research Institute (ISERI) (S. Korea) | Collaborator: Testing excavation methods and 3D printed habitat technologies, robotics, and drilling; student exchange program and curriculum development |
| Novaetech S.r.l. (Italy) | Collaborator: Science instrumentation and QCM sensor expertise through spin-off from National Institute for Astrophysics (INAF) |

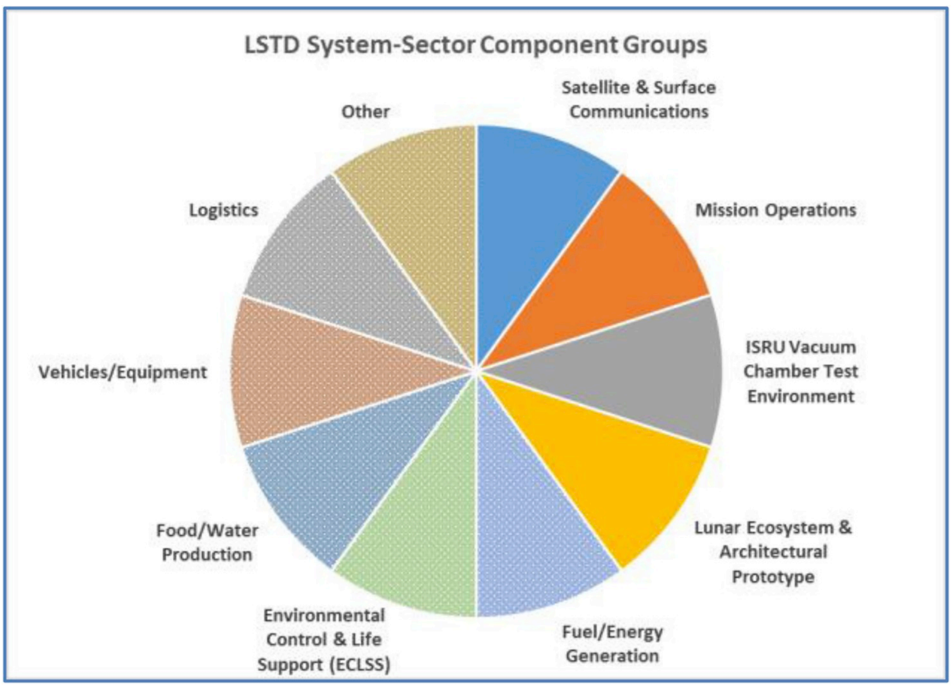



**Fig. 6.** Lunar site technology development (LTSD) space system-sectors for global industry clusters.

Note that the host country program participants shown were not identified through a cluster analysis assessment, but are an outgrowth of discussions underway through current collaborations between the LEAP2 system-sector program participants. The LCATS-SEP pilot program will utilize the following system-sector specializations of the host countries identified in Fig. 7:

- Satellite communications (Mexico)
- Mission operations and training performance (Germany and Italy respectively)
- ISRU construction and ISRU vacuum chamber test environment (S. Korea)

LCATS-SEP will be an augmentation of our current LCATS program. The current LCATS program is a local academic year program, while LCATS-SEP is intended as a three-week summer student exchange program between the international system-sector collaborators. The pilot program depicted in Fig. 7, envisions a phased-in growth model for system-sector program participants over three years. By the third year, cross-cultural student exchanges are occurring between all four system-sector program participants. Anticipated types of program experiences for student exchanges include:

**Year 1**: Our current LCATS partners, South Korea's International Space Exploration Research Institute (ISERI) of Hanyang University, and the Korean government-sponsored research institute, Korea Institute for Civil Engineering and Building Technology (KICT), utilize their expertise in ISRU technology for lunar infrastructure construction and ISRU "dirty" thermal vacuum chambers. These chambers are available to simulate the lunar environment with simulated regolith within the vacuum chambers for LEAP2 technology research applications. LCATS-SEP students would experience:

*Student summer program in South Korea for In-Situ Resource Utilization (ISRU), testing excavation methods and 3D printed habitat technologies, robotics, and drilling.*

**Year 2**: Our current collaborative education partnership with the City of Darmstadt, Germany offers another example of cluster specialization. Darmstadt is often called "Europe's gateway to space" because

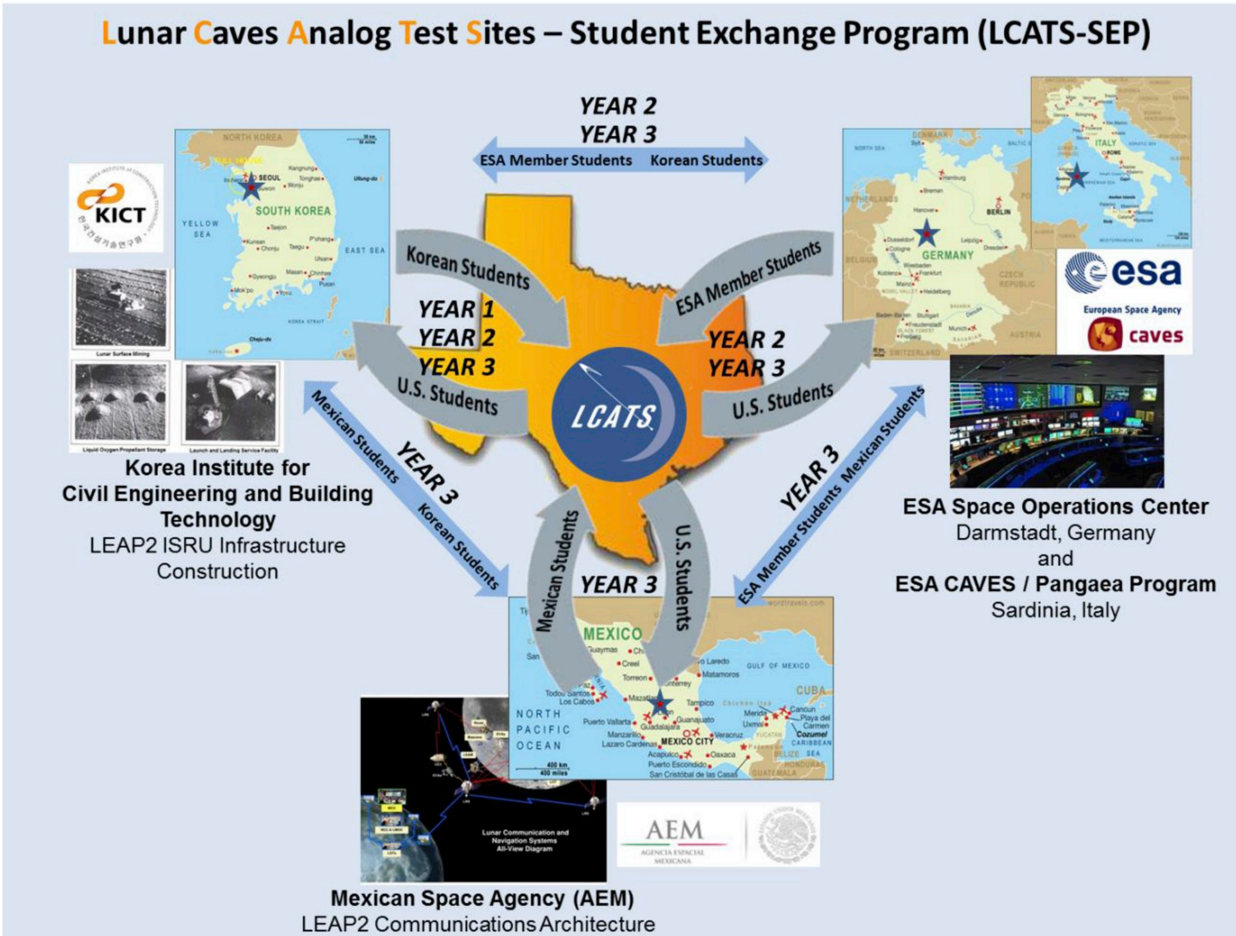



**Fig. 7.** Phased growth model of the LCATS-SEP pilot program.

of the location of the European Space Agency (ESA) Space Operations Centre (ESOC). Development of projects and curriculum for LEAP2 mission control operations is the cluster expertise for this LCATS network node. In addition, the European Space Research and Technology Centre (ESA/ESTEC), and the International Lunar Exploration Working Group (ILEWG) & Vrije University at Amsterdam, under the guidance of Dr. Bernard Foing (paper co-author), will look specifically at European and international aspects of education and industry networks. For example, the cluster expertise of the ESA program CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills) would be used for preparing students to work safely and effectively in multicultural teams in an a cave environment where safety is critical.

*Student summer program in Europe; combination of mission control operations in Darmstadt, Germany, and mission simulation and performance skills in* cave *environment in Sardinia, Italy.*

**Year 3**: Our collaboration with the Mexican Space Agency (AEM) to establish a pilot LCATS program with a focus on satellite communications would identify a Mexican aerospace industry cluster within a city, region, or community in Mexico where satellite communications expertise resides. With the local community resources and professional and industry expertise in satellite communications, a LEAP2 lunar communications architecture could potentially be the framework for developing LCATS student projects and curricula focused on space communications technology:

*Student summer program in Mexico learning about satellite communications and lunar communication architectures.*

**Years 1–3:** International students from partner international organizations join US students in San Antonio, Texas for summer program to build CubeSat satellites with LEAP2 relevant payloads for launch from the International Space Station, or on sub-orbital flights.

*Student summer program constructing CubeSats with specialized and varying payloads which address relevant science investigations contributing to the LEAP2 lunar site development knowledge base.*

### 2.4. LCATS-SEP exchange matrix modelling tool

The number of student participants on an annual basis for the pilot program will depend on budgeting considerations. Much logistical detail such as student age constraints, education level, transportation and housing, liability, funding responsibilities between host countries and visiting country, and host country specific curriculum is in development. Fig. 8 shows a segment of our student exchange matrix modelling tool developed for determining distribution of exchange students between system-sector program participants, and for calculating budgeting estimates at cost per student.

## 3. Expanding LCATS and LCATS-SEP to space industry clusters in developing countries

A global resurgence in space related activities is contributing to a growing space economy with projections that the space industry could reach $1.1 trillion by 2040 [18]. Many African, Asian and Latin American countries are enhancing their space programs, notably in the areas of remote sensing, communication, and navigation with capacity

| YEAR3 | | US | Korea | ESA | Mexico | |
|---|---|---|---|---|---|---|
| | Total Class Size (in host | 20 | 15 | 15 | 15 | |
| | | | | | | |
| | Student Exchanget Allo | 16 | 12 | 12 | 12 | |
| | | | | | | |
| US Cubesat-3 Worksho | | | 3 | 4 | 3 | |
| Korean ISRU-3 Worksh | Distribution of | 4 | | 4 | 3 | |
| ESA CAVES-2 Worksho | exchange students per | 4 | 3 | | 3 | |
| ESA ESOC-2 Workshop | workshop | 4 | 3 | | 3 | |
| AEM SpaceComm-1 W | | 4 | 3 | 4 | | |
| | allocation total check | 16 | 12 | 12 | 12 | |
| | | | | | | |
| | Workshops International Mix | | | | | Class Siz |
| San Antonio, TX | US Cubesat-3 Worksho | 10 | 3 | 4 | 3 | 20 |
| Seoul, Korea | Korean ISRU-3 Worksh | 4 | 4 | 4 | 3 | 15 |
| Sardinia, Italy | ESA CAVES-2 Worksho | 4 | 3 | 5 | 3 | 15 |
| Darmstadt, Germany | ESA ESOC-2 Workshop | 4 | 3 | 5 | 3 | 15 |
| Mexico City , Mexico | AEM SpaceComm-1 Wc | 4 | 3 | 4 | 4 | 15 |

**Fig. 8.** LCATS-SEP exchange matrix modelling tool.

building in space hardware, ground hardware, education & research, and organization and regulatory structure [19]. Although capacity building in developing countries is not at the moment focused on human space flight, we believe there is opportunity for these countries to contribute to the number of competently prepared students who will ultimately pursue space-STEM postsecondary studies and careers with interests in human space exploration. Our goal to expand the LCATS model into a LEAP2/LCATS Global space-STEM education network of communities includes outreach to developing countries with burgeoning space industry or agency capabilities. Implementing the LEAP2/LCATS model for space-STEM education with a pipeline of motivated students contributes to capacity building of a space sector workforce in the developing country.

Following a successful outcome of the LCATS-SEP pilot program, we propose scaling the LCATS-SEP by first identifying candidate host countries through the space industry cluster assessment methodologies discussed in Appendix A. The cluster analysis research uses a combination of data collection and analysis based on types, sources, topics and visualization to conduct a global cluster and statistical analysis, resulting in the discovery of regional space-industry clusters and potential collaborators for lunar site technology development. With both data sets and maps, it results in an information resource that can be used by communities that seek information on partners with which they would like to network for community space development. Such data also becomes a useful contribution for a global space capacity index, such as that being developed by the United Nations Office of Outer Space Affairs (UNOOSA) [20].

## 4. Conclusions

We have presented how LEAP2 consortium objectives for developing technologies, science investigations, and mission architectures specific to site development and utilization of planetary pits and lava tubes for eventual human settlement can provide a framework for space-STEM education initiatives. Using the LEAP2 framework, our nascent LCATS education program has successfully completed its first year project phase with an initial student cohort investigating a critical LEAP2 technology for lunar dust characterization. The breadboard development and flight test of this technology using a mentor chain of professional scientists/engineers with graduate/undergraduate students guiding a student cohort of middle and entry level high schoolers demonstrates our contention that technology projects of the STEM program can be in the critical path for technology demonstrations of the commercial LEAP2 venture.

We have also presented a model for evolving a global space-STEM education network of LEAP2/LCATS system-sector specializations, which can give students opportunities to collaborate on an international scale. With aerospace industry cluster analysis this model can be scaled to include developing countries with space-industry clusters as additional potential collaborators for lunar site technology development.

Space exploration and space science are typically international endeavours often involving multiple countries and international space agencies. Anticipated project goals, objectives, and intended outcomes for a LEAP2/LCATS network are to demonstrate to our students the value of international collaboration which is so prevalent in our industry for many space exploration missions. The understanding of space is a global concern, requiring multi-level international collaborations for optimal success. Through project-based learning experiences we can help build a robust, multi-generational, international space workforce for the future. Collaboration between communities with international exchange programs can change students' lives by opening their eyes to different methods of achieving their goals, and that the friendships students make abroad promote the cause of international cooperation and world peace.

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## Appendix A. LEAP2/LCATS cluster analysis methodology for identifying space industry clusters

Related to LEAP2 and LCATS, assessments perform specific space-industry cluster analyses tasks of:

1. Collecting potential global space industry and corporation data based on:
   a. industry sector codes (such as NAICS and NACE) related to space commercialization sectors, and identify space capabilities in a country (using tools such as UNOOSA's pilot project for Space Development Profiles and Space Solutions Compendium);
   b. current research requests and allocations for NASA, ESA, and other space organizations;
   c. space-industry/education/workforce participation and development, and;
   d. factors of local, regional, and international expertise, interests, and space economic development policy.
2. Conducting location quotient (LQ) analyses and statistical comparisons based on current and potential industry space system-sector cluster associations and factors.
3. Mapping potential space exploration architecture system-sector collaborators by geospatial clusters and by factors.

Global data on space industry sectors and occupations are collected by industry classification codes and run through various analyses, including location quotients, geographic cluster analysis, and Geographic Information System (GIS) analytics. Local, regional, and international factor data is also collected and compared statistically using SAS software. Information and listings from major space agencies, and other space agency organizations are used. Where possible, publicly available data is used, and when necessary, triangulated and compiled across data sources to assure accuracy of the units of measurement and appropriate usage for analyses. Reporting includes narrative, statistic, technical, and data visualization reporting, with discussion and mapping of system-sectors, as well as potential industry and corporate participants. Potential programs for lunar site

| HOST COUNTRY A<br>LCATS/LEAP2<br>Cluster Analyses | TASK 1 | | | TASK | | Task 3 |
|---|---|---|---|---|---|---|
| | Background Research | | | Cluster | | Reporting |
| | Month1 | Month2 | Month3 | Month4 | Month5 | Month6 |
| | DATA TYPE, SOURCE | DATA COLLECTION | DATA MANAGEMENT | CLUSTER ANALYSES | ANALYSES | REPORT |
| Secondary Data: Industry, Agencies | INDUSTRY SECTOR CODES | INDUSTRY DATA | INDUSTRY | LQ, SYSTEM-SECTOR | STATISTICAL SUMMARY | TECHNICAL |
| | SPACE AGENCIES, PATENTS | AGENCY, PATENT DATA | PROGRAMS, PATENTS | TABLES, NARRATIVES | PROGRAM SUMMARY | DATA VISUALIZATION |
| Secondary Data: Factors, STEM | ECONOMIC FACTORS | FACTOR DATA | FACTORS | CA, BACKGROUND | DATA SUMMARY | NARRATIVE |
| | SPACE-STEM PROGRAMS | PARTICIPATION DATA | ACTIVITIES | LCATS/LEAP2 POTENTIALS | LUNAR SITE TECH DEVELOPMENT FRAMEWORK | LCATS/LEAP2 NETWORK |
| GIS Mapping and Data Visualization | SHAPEFILES | GEOCODING INDUSTRY, PROGRAMS | GEOCODING ALL DATA | GEOCODING LQ, LCATS/LEAP2 | GEOCODING ANALYSES | GIS REPORT |
| Data Management Platform | | | | | | REPORT AND DATA |

**Fig. 9.** Typical Cluster Analysis Research Task Calendar.

technology development with space-STEM programming network connections to LEAP2/LCATS are identified, along with potential in-country sources of funding, venues and education partners for implementing community space-STEM curricula.

In order to facilitate the documentation of current and potential space-industry cluster network development, workforce building, economic development and space-STEM programming applicable to the LEAP2/LCATS framework, interested foreign collaborators are asked what factors they consider to have positive and negative impacts on community space industry development, and what areas they see as most promising for space industry commercialization.

*Organization of research activities*

The research is accomplished through three main task activities, typically over a six month research period as shown in Fig. 9:

**Task 1, Background Research:** includes (a) assessment of data types relevant to data topics and sources from which the data will be collected; (b) collection of the data; and (c) compilation and cleaning of the data
**Task 2, Cluster Analyses:** includes (a) running cluster, location quotient, and statistical comparative analyses on the data; and (b) summarizing and visualizing data analyses and results
**Task 3, Report:** includes a final report compiled from section reports that include statistics and technical, data visualization, space system-sector cluster analyses, global LEAP2/LCATS network, GIS maps, findings and data sets.

At the end of each month, progress reports from each research topic area are completed for compilation into the final report. Table 4 identifies how each task is broken down into research topics, which reflect a section for the final report: A) space industry system-sector, based on industrial codes; B) space agency and organizations, programs and patents; C) economic development factors, cluster development factors; D) LEAP2/LCATS activities and frameworks for potential collaborators; and E) GIS geocoding, mapping and geospatial analyses.

Table 4
Breakdown of Tasks and Research Topics

| TASK | DESCRIPTION |
|---|---|
| Task1 Month1 | In order to identify global industry clusters and potential collaborators for Lunar Site Technology Development (LSTD) and LEAP2/LCATS programs, the study creates a wheel of space system-sector groups that each represents a main contribution to LSDT, such as those identified in Fig. 6. Additional system-sectors pie slice groups that reflect needed expertise are documented. Industrial classification (IC) code bridging tables are created from NAICS, NACE and other IC global systems, to be used in assessing the system sector groups, organizing data, and in performing searches. Information on organizations that currently conduct space exploration and development, as well as associated programs and patents are searched, to build portfolios for analysis. Economic factors pertaining to industrial cluster development are identified through a literature review, and compiled and identified in cluster models for use in cluster analyses and statistical comparisons. Space-industry participation and activity types related to education, workforce and industry development are identified in order to collect program design types and performance numbers. Available shapefiles and sources of GIS data, as well as their platforms (python, HTML, etc.) are located so that GIS materials created during the course of the research will translate across users. A progress report records industry, organization, factor, framework, and GIS information located, and data inventories are created for each data type and source. |
| Task1 Month2 | Using data inventories created in the previous month, data is pulled, stored in its original format, and compiled into topical sets of spreadsheets. Gaps in data and additional queries for requested data are followed up, where needed. A progress report records data inventory status, state of the data and basic data characteristics, along with usability projections. |

(*continued on next page*)

Table 4 (*continued*)

| TASK | DESCRIPTION |
|---|---|
| Task1 Month3 | Data that has been collected is compiled and cleaned, moved into working sheets and sorted according to usability. Usable data is organized into analysis-ready spreadsheets, sorted as to units of measure and intended analysis method, geocoded, and formatted with a standard column structure. Sheets are tested with GIS and data visualization software to identify any problems or formatting needs. A progress report summarizes the state of the data and its general structure going into analyses. |
| Task2 Month4 | Analyses begin with location quotients (LQ) of the space system-sector industry data to identify performance density and to assist with identifying weak, moderate and strong system-sectors that may be included in the LSTD wheel. Cluster analyses are performed to further assess industry support networks for potential company and organization LSTD system-sector collaborator regions. Agency, patents, and potential collaborator data is visualized through tables, and narratives created. Geocoding of LQ and other variables are done and GIS analytics are run to look for relationships. A progress report records analysis activities and summarizes results, data use and preliminary findings. |
| Task2 Month5 | Descriptive statistics, as well as statistical comparisons of factors, programs, and activities are run. Summaries of the findings and results, data visualization, GIS, and potential framework collaborator assignments are completed for the LSTD network. A progress report includes take-aways, analyses discussions, limitations and issues, and possible recommendations. |
| Task3 Month6 | A final report is compiled from section reports. It includes: an executive summary, background, statistics and technical report, data visualization and narrative, cluster analysis, LEAP2/LCATS network, and GIS, findings and results discussion, as well as data sets, and addendum materials, as needed. Other publications and presentations from this study may be posted on the web, distributed in print or digital form, or shared as expertise. |

## Appendix B. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.actaastro.2018.08.006.

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