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NASA's Small Spacecraft Systems Virtual Institute and Small Spacecraft Enterprise

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Abstract

In January of 2017, NASA's Space Technology and Science Mission Directorates established the Small Spacecraft Systems Virtual Institute (S3VI). The mission of the agency-wide institute is to advance the field of small spacecraft systems to expand the capabilities and utility of small spacecraft to perform high-value science by promoting innovation, exploring new concepts, identifying emerging technology opportunities, and establishing effective conduits for the collaboration and the dissemination of research results relevant to small spacecraft systems and subsystems. To achieve this, the S3VI serves as the common portal for NASA-related small spacecraft activities, hosts the Small Spacecraft Body of Knowledge as an online resource for the annual Small Spacecraft Technology State of the Art report, including a components and subsystems database, and also collects and organizes related knowledge such as small spacecraft reliability processes and best practices. The S3VI also serves as the front door for other governmental, non-governmental, and external agencies that wish to collaborate or interact with NASA small spacecraft organizations.

NASA also presently has a growing number of small spacecraft related programs, projects, and efforts underway to advance the utility of small spacecraft instruments, technologies, and missions to support NASA to achieve its exploration and science goals. These various activities will be outlined and described to include small spacecraft applications and supporting technologies for cis-lunar and deep space missions.

Keywords: small spacecraft, technology, cis-lunar, deep space

Acronyms/Abbreviations

Ames Research Center (ARC), Community of Practice (CoP), Goddard Space Flight Center (GSFC), Human Exploration and Operations Mission Directorate (HEOMD), in situ resource utilization (ISRU), Jet Propulsion Laboratory (JPL), Marshall Space Flight Center (MSFC), Other Government Agency (OGA), Small Spacecraft Body of Knowledge (SSBoK), Small Spacecraft Systems Virtual Institute (S3VI), Small Business Innovative Research (SBIR), Science Mission Directorate (SMD), Subject Matter Expert (SME), SmallSat Parts On Orbit Now (SPOON), Small Satellite Reliability Initiative (SSRI), Small Spacecraft Technology (SST) program, Space Technology Mission Directorate (STMD), Small Business Technology Transfer (STTR), Technology Readiness Level (TRL).

1. Introduction

The breadth of NASA's Small Spacecraft Systems Virtual Institute (S3VI) spans several elements that associate directly to developing, accessing, sharing, and integrating both NASA internal and external community content related to small spacecraft. The agency began to seriously invest in small spacecraft technologies more than a decade ago with its first investment in the bionanosatellite, GeneSat-1, developed and operated by NASA Ames Research Center and local universities. This first small satellite project, and still the majority of NASA small satellite investments focus on CubeSats and related form factors. In addition, the creation of the CubeSat deployer standards, even if self-imposed, helped to ignite a larger trend in the aerospace industries. Small

spacecraft are beginning to be adopted within missions for which they previously have not been considered, as their technological sophistication and capabilities are rapidly advancing to enable their utility for cis-lunar and deep space applications (see Figure 1). Small spacecraft afford an increasingly capable platform to precede and accompany human explorers to the moon, Mars, and other destinations to scout terrain, characterize the environment, identify risks, and prospect for resources. Distributed systems of small spacecraft can responsively provide cost effective communications, monitoring, and inspection infrastructure for human exploration missions and cis-lunar commercial activity. Similarly, small spacecraft projects are compatible with small, flexible, innovative teams including those in the civil science and exploration communities. A growing number of NASA-funded programs now allow and solicit the use of small spacecraft to achieve their mission goals.

Over the course of the past decade as the growth in both capability and usage of small spacecraft within NASA accelerated, it became clear that from at least an awareness point of view, that a central information and knowledge-based function was needed to assist various NASA organizations embracing small spacecraft in their program and project portfolios. In January 2017 NASA created the S3VI to serve the agency as this coordination support function, which ultimately provides a knowledge platform for the small spacecraft community at large.

The S3VI is jointly funded by NASA's Science Mission Directorate (SMD) and Space Technology Mission Directorate (STMD). The Human Exploration and Operations Mission Directorate (HEOMD), as well as a number of other small spacecraft-related NASA organizations, engage in some activities hosted by the S3VI. The S3VI is physically located at NASA Ames Research Center, but has affiliates and participation from the NASA spaceflight centers, as well as relationships with other government agencies (OGAs) that have similar small spacecraft programs.

The charter of the S3VI specifically directs the institute to advance clear communication, coordination and consistent guidance regarding NASA's small spacecraft activities across all of NASA. This is primarily achieved through enhanced internal integration across the NASA mission directorates via knowledge exchange in the form of seminars, focus groups, and broad-based communications that typically extend from the S3VI's webportal.

Over the course of an almost two-year existence, the S3VI has continued to build its presence as the central point of contact for small spacecraft information dissemination for the agency. It accomplishes this by means of a number of methods. The institute serves as a repository for streamlined development approaches and

processes that are unique to small spacecraft best practices and it hosts a number of small spacecraft parts databases to support mission design. In all, the S3VI supports its charter by providing the national small spacecraft research and development community (industry and academia) with access to mission enabling information and data.

There are three main tenants of the S3VI approach to fulfilling its charter. The first is to engage with the small spacecraft community, NASA stakeholders and OGAs. This is done through participation in working

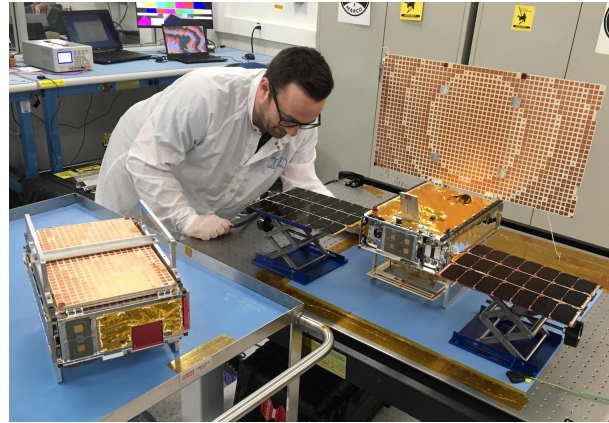


Figure 1. Mars Cube One, or MarCO, will head to deep space to test a first-of-its-kind technology demonstration: near-real-time communication between Earth and Mars using CubeSats. Image credit: NASA/Jet Propulsion Laboratory-Caltech

groups, conferences, and related activities. The second pillar is to create and maintain the Small Spacecraft Body of Knowledge (SSBoK), hosted within the S3VI web portal < <https://www.nasa.gov/smallsat-institute> >, which taken together is a collection of programmatic, technical and related data, information, and knowledge for use by the larger small spacecraft community. Particular content includes small spacecraft parts and systems databases, studies, lessons learned experiences from various missions, and access to other online resources. The final approach relies on broadcasting solicitations, launch opportunities, and other networking opportunities that directly or indirectly support the community.

2. Small Spacecraft Body of Knowledge

Over the past several years, significant investments have been made in small spacecraft technology, science payload instruments, launch systems, and related efforts to include workforce development to support and cultivate emerging disciplines and applications created as a result of the platform's continued success. The S3VI is chartered to work with the community to capture and share the knowledge gained through these efforts and continue to build upon not only the

technological capabilities enabled by the products of our efforts but also to learn from our lessons along the way.

A key feature of the S3VI web portal is the SSBok, an online resource to host NASA's community supported Small Spacecraft Technology State of the Art Report; lessons learned collected from small spacecraft missions, system and subsystem development, and related activities; testing and reliability data, and other content important in providing the U.S. small spacecraft research community with access to mission enabling information in one location. The SSBok has several subelements.

1.1 Database Federation and Common Search

The S3VI works with its stakeholders and members of the community to identify the scope of the databases existing and needed to provide information effective in supporting streamlined development approaches and processes for small spacecraft. The first databases in this collection are listed below.

- **Small Spacecraft Parts On Orbit Now (SPOON).** The S3VI collaborates with the Air Force Research Laboratory (AFRL) and Space Dynamics Laboratory (SDL) on the development of a small spacecraft parts database called SPOON. This database is intended to capture information on publicly available small spacecraft (mass <180 kg) components, parts and technologies developed by commercial vendors, universities, and government organizations that have achieved technology readiness level (TRL) 5 or greater. These parts are categorized under the following major satellite subsystems: Power, Propulsion, Thermal Design, Guidance, Navigation and Control (GNC), Command and Data Handling (C&DH), Communications, Structures, Materials and Mechanisms, Integration, Launch and Deployment, and Deorbit Devices. Over the course of 2018-2019, The Aerospace Corporation will collaborate with the S3VI team on a data exchange task to import their small satellite parts database into SPOON. The enhanced data management tool resulting from this collaboration will make accessible verified space segment information on satellites, programs, organizations, launch vehicles, deployment mechanisms, ground segment, products, and parts comprising or flown on satellites, along with their relationships to each other.
- **Small Spacecraft Technology State of the Art Report.** The S3VI is currently collecting information regarding the state of the art for technology, components, and systems relevant to small spacecraft for Earth and interplanetary mission design. The community is invited to contribute content via the

SPOON database. In 2018-2019 the S3VI will initiate conversion of its Small Spacecraft Technology State of the Art report to a rolling submission and review. The report will be published directly as an online report.

- **NASA TechPort.** The Technology Portfolio System, TechPort, is NASA's first comprehensive resource for locating information about NASA-funded technology development activities. This system enables the public to explore NASA's technology portfolio and learn about technology programs and projects, as NASA works to mature technologies for aeronautics, space exploration, and scientific discovery missions.
- **Small Business Innovation Research (SBIR)/ Small Business Technology Transfer (STTR).** This database will be federated over the course of 2019. The SBIR/STTR database offers users the ability to search research and technology development projects in small spacecraft as well as other topic areas funded by SBIR/STTR.
- **NASA Electronic Parts and Packaging (NEPP) Program.** The NEPP program generates technical knowledge and recommendations about electrical, electronic, electromechanical (EEE) part performance, applications, failure modes, test methods, reliability and supply chain quality within the context of NASA space flight missions and hardware. Both parts and related radiation papers comprise this database set.

This past year, the S3VI developed and implemented a common search capability that allows the public to search its federated small spacecraft databases for parts and technologies. Search results are displayed as direct links to particular databases related to their search inputs. As new databases are federated they will be searchable directly, or as part of the common search feature on the S3VI webportal.

The SSBok also provides access to study reports, manuscripts and presentations from workshops and conferences focused on various topics associated with small spacecraft.

1.2 Small Spacecraft Community of Practice

The NASA Office of the Chief Engineer hosts a collection of NASA-internal Communities of Practice (CoP) centered on engineering disciplines. Each is comprised of a distributed, peer-driven network of individuals, engaged in a specific discipline, who come together to share their collective knowledge and to learn from one another. The Small Spacecraft CoP provides information, resources, access to peer expertise, and

opportunities for knowledge sharing and collaboration in sound management, engineering, manufacturing, and verification practices for development of small spacecraft projects including but not limited to scientific research, aerospace research, and technology development for space activities. The CoP serves as a forum for representatives from many different areas supporting small spacecraft to share challenges, approaches, and lessons learned for development of small spacecraft projects, including the implementation of safety, mission assurance, design, and test guidelines. The S3VI supports and coordinates the CoP and hosts NASA internal seminars on various topics of interest to the community. In 2019 the S3VI plans to open the CoP to the external small spacecraft community inviting both participants as well as speakers to the series.

3. Small Spacecraft Technology State of the Art Report

The Small Spacecraft Technology State of the Art report provides an overview of the current state of the art of small spacecraft technologies in each of the major spacecraft subsystems. It was first commissioned by NASA's Small Spacecraft Technology (SST) program in mid-2013 in response to the rapid growth in interest in using small spacecraft for many types of missions in Earth orbit and beyond, and further revised in mid-2015. In the 2013 and 2015 versions of this report, information was collected primarily through desk research. In 2016 the decision was taken to migrate to an online report with the intention to further expand the collaboration with other government agencies and the aerospace industry to present current information on spacecraft technology. Since the last publication in 2015, this report was acquired by the S3VI.

The State of the Art report will be updated to identify and provide an overview of the following: current technologies that were inadvertently missed in previous editions of this report, newly developed technology, and emerging technologies with matured technology readiness level (TRL) values. The update process will encompass parts that were submitted to the SPOON database throughout the year, as well as research compiled from other sources. The online version will be updated throughout the year to capture ongoing technology available to small spacecraft missions. TRL 9 technology identified in previous editions of the report will be removed only if there is a new 'best in class' TRL 9 component, thereby informing the public of the currently available innovative, space proven small spacecraft technology.

3.1 Subject Matter Experts

Subject matter experts (SME) are technical professionals cognizant of a particular technical

discipline. They have been identified as an expert in their field by NASA management. These experts are frequently used by NASA to perform deeper technical review on projects, but are also used to provide peer review of technical papers, and other technical documents, such as engineering analyses.

For the SPOON database, the S3VI identified a set of SME's to review information provided to SPOON, and selected for the NASA Small Spacecraft Technology State of the Art report. The experts' primary activity is to insure completeness and consistency with NASA standards provided in the information such as TRL.

3.2 Advantages

The State of the Art report benefits different users within the small spacecraft community where small spacecraft mission design is performed and researched. Within government organizations, this report is used as a vital resource for possible subsystem component selection for small spacecraft mission proposals. In academia, students and teachers utilize this report for inexpensive space mission design. For industry, contents of this report encourage competition, maintaining the forefront of small spacecraft innovation.

4. Active and Planned Working Groups

The S3VI supports and coordinates working groups on small spacecraft topics of interest. In 2017, the Small Satellite Reliability Initiative (SSRI) was established. The S3VI also supported a number of activities related to small spacecraft rideshare during the year.

4.1 Small Satellite Reliability Initiative – A Public-Private Collaboration

At present, CubeSat components and buses are generally not appropriate for missions where significant risk of failure, or the inability to quantify risk or confidence, is acceptable. However, in the future, we anticipate that CubeSats will be used for continuity missions requiring known reliability for Earth observation, astrophysics, planetary and heliophysics missions. In addition, small spacecraft could be developed using CubeSat components and subsystems but will not have the CubeSat form factor. Both CubeSats and small spacecraft could then be used where their attributes could otherwise enable or enhance mission objectives or provide other meaningful benefits—e.g. lower cost, increased coverage (spatial, temporal, spectral), agility, and resiliency. Historically, it was understood and accepted that "high risk" and "CubeSat" were largely synonymous; expectations were set accordingly. However, their growing potential utility is driving an interagency effort to improve and

quantify CubeSat reliability, and more generally, small satellite mission risk.

The SSRI—an activity with broad collaborative participation from civil, Department of Defense, and commercial space systems providers and stakeholders—targets this challenge. The initiative seeks to define implementable and broadly accepted approaches to achieve reliability and acceptable risk postures associated with several small spacecraft mission risk classes—from “do no harm” missions, to those associated with missions whose failure would result in loss or delay of key national objectives. These approaches will maintain, to the extent practical, cost efficiencies associated with small satellite missions and consider constraints associated with supply chain elements, as appropriate.

The SSRI addresses this challenge from two architectural scopes—the mission- and system-level, and the component- and subsystem-level. The mission- and system-level scope targets assessment approaches that are efficient and effective, and mitigation strategies that facilitate resiliency to mission or system anomalies while the component- and subsystem-level scope addresses the challenge at lower architectural levels. The initiative is not limiting recommended strategies and approaches to proven and traditional methodologies, but is focused on fomenting thought on novel and innovative solutions.

The SSRI membership publishes the presentations and results of each technical interchange on the S3VI webportal <<https://www.nasa.gov/smallspacecraft-institute/reliability-initiative>>. The forth SSRI technical interchange meeting is planned for Fall 2018.

4.2 Rideshare and Access to Space

In June 2018, the S3VI partnered with the Small Payload Ride Share Association (www.sprsa.org) to co-sponsor and host the 20th Annual Small Payload Rideshare Symposium. This symposium featured plenary and panel discussions on topics to include:

- Space traffic management
- Rideshare user’s perspectives
- Development of operationally responsive spacecraft
- Hosted payload opportunities
- Small launcher systems
- Swarms and constellations launch and operations

The symposium focuses on concepts and technologies to enable the small payload community to meet future launch needs and test new capabilities in a cost-effective manner.

4.3 Planned Working Groups

Under consideration for 2019 are working groups or workshops to cover topics on small spacecraft swarms for science and exploration as well as high volume manufacturing of small spacecraft.

5. NASA Small Spacecraft Missions

Small spacecraft provide a responsive platform to address strategic knowledge gaps and test technologies that will permit sustainable human presence and exploration beyond Earth. Current lunar, cis-lunar and deep space missions include seven NASA and NASA sponsored CubeSats launching aboard Exploration Mission-1 (EM-1).

Among these missions, the Lunar Flashlight and Lunar IceCube spacecraft will prospect for water in lunar polar craters and across the lunar surface. The presence and abundance of accessible water will inform future exploration mission planning and help lay the groundwork for the in-situ resource utilization (ISRU) that will enable long term human presence and commercial activities on the moon. Launching alongside these missions is the BioSentinel CubeSat that will help better quantify the radiation hazard facing astronauts on missions beyond Earth. Additional exploration precursor CubeSats on EM-1 include the Near Earth Asteroid (NEA) Scout and LunIR which will perform reconnaissance flybys of an asteroid and the lunar surface, respectively.

The S3VI plans for 2018-2019 include the development of an architecture and process for capturing and hosting a complete NASA small spacecraft mission database comprised of upcoming missions such as those on EM-1, as well as missions currently on orbit, and those from the recent past.

6. Small Launchers

The global space industry is experiencing a robust growth period as evidenced by approximately \$1B in space investments just during the first quarter of 2018 [1]. Included in this wave are emerging small launchers. Approximately 30 active systems are currently in development or quickly becoming operational [2]. Taken together with existing rideshare providers and associated rideshare mission aggregators the US is experiencing increasing domestic launch capacity. In addition, international providers are also available to the small spacecraft community, increasing global capacity further.

The S3VI is working to develop aides for mission designers to increase awareness of these launch service providers and related opportunities, as well as to provide tools and information supporting mission/launch development. This capability is planned for initial roll out starting in 2019.

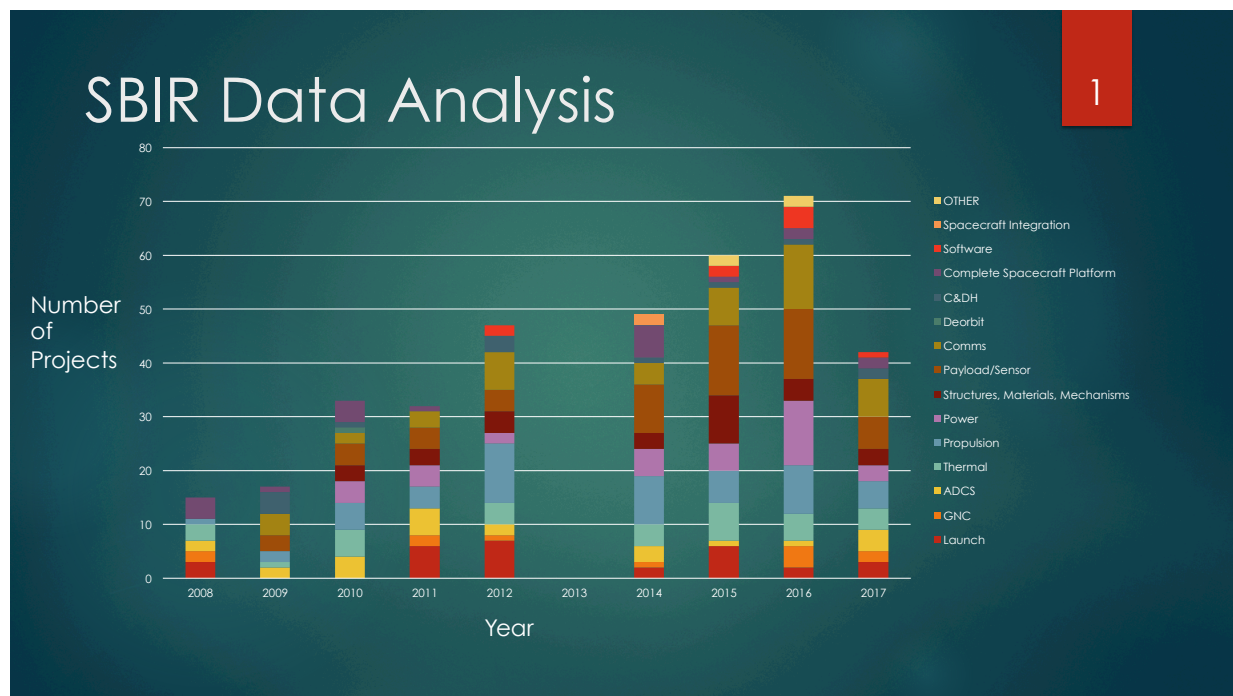


Figure 2: SBIR-funded small spacecraft projects

NASA's HEOMD also sponsors the CubeSat Launch Initiative (CSLI) <https://www.nasa.gov/directorates/heo/home/CubeSats_initiative>, which provides free launch services to qualified CubeSat developers. Developers are typically educational or university led; industrial-led missions are not supported. Selected teams are mapped to an upcoming launch opportunity. The teams then begin to work with the mission integration team to prepare their CubeSat for launch.

7. Small Business Innovative Research

Another significant source of funding and support for small spacecraft is the SBIR program. A large fraction of current small spacecraft related companies can trace their early beginnings to the SBIR program, and we are now starting to see some consolidation and investment into these small companies. Figure 2 shows a summary of the types of SBIR small spacecraft projects funded by technical area or subsystem over time. [Note, 2017 is only a partial listing of awards.]

8. Closing Technology Gaps

NASA investments in small spacecraft support and leverage the growing capabilities in U.S. industry and academia. NASA enters public-private partnerships with industry, purchases commercial spaceflight hardware, contracts with commercial and academic institutions for mission operations, and makes targeted investments in advanced technology to close critical gaps for small spacecraft exploration missions.

Examination of small spacecraft deep space mission concepts highlighted the need for more capable propulsion systems for volume-constrained spacecraft. Additional advancement in small spacecraft avionics is also required to expand the reach of small spacecraft to new destinations and allow them to operate in challenging new environments. There is joint interest with other U.S. Government entities in low cost radiation tolerant systems and the ability to navigate accurately without Earth-centric aids (such as GPS) for small spacecraft. There is also joint interest in distributed spacecraft mission capabilities and autonomous collaboration between space systems.

There is clear and growing investment by the public and private sector in small spacecraft. This affords NASA the ability to target specific gaps that market forces will not otherwise fill. Achieving NASA strategic goals in novel and more affordable ways will require pushing technology boundaries beyond the capabilities currently sought by commercial and other U.S. Government agency applications.

9. Conclusion

All of NASA's space flight Mission Directorates (SMD, STMD, HEOMD) have significant, active programs in small spacecraft. Investments initially envisioned to help enable rapid and lower cost planetary science missions are directly applicable to the successful operation of small spacecraft in cis-lunar space. However, there are areas that still need to be addressed and improved such as mission reliability and

small spacecraft launch that will continue to attract the attention of program managers and scientists.

To that and related goals, the S3VI will continue to support the development and growth of small spacecraft capabilities and adoption through the creation and exchange of information and studies among the various small spacecraft and launch stakeholder communities. Particular plans continuing into 2019 include the continued expansion of information available in the SSBoK, along with S3VI-hosted workshops and technical exchanges that foster new and existing relationships with other government agencies, universities, and industry to promote collaboration and information sharing. The S3VI will continue to provide information on such topics as security, information assurance, and orbital debris, along with reliability and access to space for small spacecraft.

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