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AN OVERVIEW OF THE NASA/SCIENCE MISSION DIRECTORATE CUBESAT ACTIVITES

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ABSTRACT

These are amazing times of space and Earth science discovery related to the Earth system, our Sun, the planets, and the universe. The National Aeronautics and Space Administration (NASA) Science Mission Directorate (SMD) provides CubeSats as a component part of the NASA's science and technology programs to conduct important scientific and technology investigations, while also providing crucial hands-on training opportunities for students to participate in research. SMD, working with NASA's Space Technology Mission Directorate (STMD), the Human Exploration Operations Mission Directorate (HEOMD), and its Centers in a coordinated and comprehensive fashion is actively advancing the vision for CubeSats as cost effective and capable tools for research. Recently proposed and selected SMD CubeSat flight projects are showing that CubeSats are working to address essential science goals, and will open up opportunities for researchers in developing and validating cutting-edge space technologies. The use of these small, cost effective and capable research platforms are part of a growing trend in SMD for pursuing space and Earth science. The paper will present the status of current CubeSat activities that SMD is sponsoring and expects to fly in the near future, as well as results studies of CubeSats as platforms for obtaining high priority science data, and platform capabilities that will have a high impact on science and technology return.

1. INTRODUCTION

NASA's Mission Directorates (SMD, STMD, and HEOMD) are leveraging their mutual systems to the benefit of CubeSat activities, and are strategically working together to maximize the capabilities of CubeSats as a new research platform to achieve NASA's goals. The Mission Directorates have clear roles and are implementing a robust but flexible CubeSat program using these "swim lanes."

NASA's SMD mission is to innovate, explore, discover and inspire. SMD's science investigations include fundamental scientific discoveries that have completely transformed our understanding of the Earth, the solar system, and the universe.

SMD is providing science leadership through providing opportunities for CubeSats and other secondary payloads in its research opportunities, through sponsoring Earth and Space science investigations, and through developing precursor instrument technologies for future science measurements. The overall objectives for CubeSat investigations are low cost and frequent access to space in order to:

- Address diverse scientific problems in a wide range of scientific disciplines including heliophysics, astrophysics, planetary, and earth sciences.
- Flight-testing and validation of promising new instrument technologies relatively inexpensively and to reduce the risk of infusion into larger orbital missions.
- Provide science technology engineering and math (STEM) hands-on training for undergraduate and graduate students on time scales consistent with university schedules.

Since 2012, SMD has included CubeSats as a component element of its research program, including orbital spacecraft, aircraft, sounding rockets, scientific balloons, to support scientific, technological, and education investigations.

STMD is providing leadership of small satellite technologies through developing and demonstrating new small spacecraft platform technologies and capabilities for NASA’s future missions in science, exploration and space operations. SMD works closely with STMD to coordinate platform technology needs to enable future science investigations.

SMD Discipline	FY 12	FY 13	FY 14	FY 15	FY 16
Astrophysics	0	0	0	1	0
Planetary Science	0	2	0	2	0
Heliophysics	0	1	4	2	0
Earth Science	0	0	0	0	1
Earth Science Tech	4	4	1	5	0
Student (STEM)	0	0	0	0	3
Year Total	**4**	**7**	**5**	**10**	**4**

HEOMD is providing access to space leadership through the CubeSat Launch Initiative (CSLI),by providing launch opportunities to the U.S. CubeSat Community (academia, government, and non-profits), and through sponsoring CubeSat missions to address strategic knowledge gaps for exploration. Further, HEOMD/Space Communications and Navigation (SCaN) is providing leadership for spectrum licensing and ground segment support of CubeSat investigators for all NASA sponsored missions.

SMD supports the science community through competitively selected science, technology, and education CubeSat investigations, through arranging access to space for its missions through HEOMD/CSLI, and through providing value-added mission management assistance and ground segment services to CubeSat teams.

Figure 1: SMD Discipline CubeSat Rates

SMD’s CubeSat investigations are characterized by the diversity in the number, size, and types of investigations. CubeSat activities have spanned SMD’s four science divisions, and have included Earth science, planetary, heliophysics, astrophysics, and STEM missions.

SMD has completed (flown) four CubeSat missions since 2012, and is currently sponsoring the development of 27 CubeSat missions, comprised of 41 CubeSats, including:

- 11 technology demonstration missions
- 13 science cubesat missions
- 3 STEM cubesat missions

2016	2017	2018	2019
	RainCube		
	MiRaTA	CubeRRT	
	LMPC	CIRiS	
	INSPIRE	CIRAS	
	TBEx	TEMPEST-D	USIP
	CeREs	MarCO	USIP
RAVAN	ELFIN	CuSP	USIP
HARP	Q-PACE	Halo-Sat	CuPID
IceCube	SORTIE	LunaH-Map	TROPICS

Figure 2: Target Launch Dates for SMD CubeSats

The SMD CubeSat portfolio includes a range of sizes between 2U (4 kg) to 6U (8 kg). CubeSats provide a cost-effective way to make *in situ* observations in the altitude regime of 150 - 400 km above the near-earth environment. Flight times are typically 6 months to 1 year in duration. Access to space is achieved on NASA, USAF, and commercial expendable launch vehicles capable of carrying a CubeSat payload from low earth orbit to Earth escape trajectories.

The 27 CubeSat missions involve more than 40 different institutions, in about 30 states. In addition, CubeSats are showing promise as a hands-on learning and applications venue for experimentalists that form the foundation of the NASA space science missions. Undergraduate and Graduate student involvement is at the very core of these investigations.

2. SMD CubeSat Portfolio

Over the past several years SMD’s investment in small satellites and related technologies to support them has steadily increased. SMD implemented the Science CubeSat Integration Panel (SCIP) in 2013 following agreement from each of its research divisions that modest funding be set aside for compelling science investigations using CubeSats. In parallel there were more subtle changes made to the Directorate’s roughly-dozen annual technology solicitations to encourage development of miniaturized science sensors and instruments to increase the usefulness of small satellite platforms for science over the longer term. Studies [1,2] were used to help guide technology investments. In addition, Announcement of Opportunities (AOs) in programs such as Earth Venture and Heliophysics Explorers began encouraging the use of small satellites and CubeSats as viable platforms for obtaining science measurements.

The strategy has paid off over the past two years as new small satellite missions have been selected. Some of the recent science missions chosen include:

- CYGNSS (Earth Science) Christopher Ruf, University of Michigan.
- IceCube (Earth Science) Dong Wu, Goddard Space Flight Center.
- TROPICS (Earth Science) William Blackwell, Massachusetts Institute of Technology.
- LunaH-Map (Planetary Science) Chris Hardgrove, Arizona State University.
- CuSP (Heliophysics) Mihir Desai, Southwest Research Institute.
- HaloSat (Astrophysics) Philip Kaaret, University of Iowa.

Within SMD, technological activities have been expanded to include development of miniaturized science instrument subsystems and detectors. These activities are closely coordinated with STMD, where much of the platform technologies are nurtured. Primary investment areas for STMD include autonomous navigation, hybrid energy systems, space disaggregated network architectures, optical communications, precision pointing propulsion systems, space computing architectures, low-profile antennae, among others. There are a number of SMD CubeSat missions planned for demonstrating new technologies, including:

- The Microwave Accelerometer Technology Acceleration CubeSat (MiRaTA, Earth Science) Kerri Cahoy, Massachusetts Institute of Technology
- The Radiometer Assessment using Vertically Aligned Nanotubes mission (RAVAN, Earth Science) William Swartz, Johns Hopkins Applied Physics Laboratory
- RainCube (Earth Science) Eva Peral, NASA Jet Propulsion Laboratory
- Mars Cube One (MarCO, Planetary Science) Joel Krajewski, NASA Jet Propulsion Laboratory

The SMD CubeSat program informs and is informed by the STMD CubeSat program. Platform technology development is primarily conducted within the STMD program and infused into the SMD program. The notable exception is the SMD Planetary Science MarCO mission; in which reduced SWAP communications were developed for the 2 MarCO fly-by CubeSats to provide an Earth communication link for the InSight Mars lander mission during entry, descent and landing.

The SMD CubeSat portfolio includes approximately 27 missions currently in formulation, development or flight. The SMD CubeSat portfolio is, in essence, the application of a new tool (CubeSats) to the existing efforts to achieve SMD science in the most cost efficient manner. These missions are, in general, lower TRL (Technical Readiness Level) and higher risk investigations of the type previously conducted almost exclusively via sub-orbital flight tests. While the size, weight and power (SWAP) constraints of a CubeSat platform exclude the majority of investigations typically conducted in the suborbital program; those investigations that can utilize this tool gain the tremendous advantages of increased flight duration. To date, the majority of SMD CubeSat missions are selected by and implemented through the previously existing SMD programs for low TRL science and instrument technology development.

The SMD CubeSat portfolio is being implemented in an exploratory manner in order to determine the true dimensions of CubeSat missions when the metric for success is strictly science return. Issues such as the level of review, the level of management resource reserves, how to deal with variations in launch dates as secondary payloads and the role of extended mission operations are all being actively considered and revised in an attempt to glean as much value from this new tool while still retaining science return as the sole metric of success.

2.1 CubeSat Science

NASA's Science Mission Directorate (SMD) CubeSat science and sensor technology proposals are peer reviewed and competitively selected via NASA Research Announcements (NRA) and NASA Announcements of Opportunity (AOs). The CubeSat mission selection distribution per SMD science disciplines for FY2012 through QTR 1 FY2016 are listed in Table 1.

The CubeSat approach enables several new capabilities for achieving science from space – primarily derived from the lower costs of investigations *employing instrumentation suited to the limited resources of CubeSat accommodations*. These capabilities include:

- Flight of higher risk investigations – new instrumentation or new science
- Flight of investigations to make unique measurements in order to fill in gaps in ongoing science programs

- Increased persistence of observations because of the affordability of suitable investigations.
- Increased coverage of a state observable (temporal or viewpoint) via the use of a constellation of CubeSats (again, for suitable investigations). Variations on this concept include a “string of pearls” approach with multiple spacecraft in the same orbit with different phases and “swarms” of spacecraft providing a dense sampling with daughter spacecraft with command and communication through a mother ship.
- Exploration of variations in program management and quality assurance to evaluate the possibility of new modes of achieving science.

2.2 Platform Technologies

The capability of platform technologies for CubeSats continues to advance at a rapid pace [2]. STMD manages a portfolio of over 30 projects that have direct relevance to SMD science missions, particularly in the areas of high-speed communications, propulsion for precision pointing and station keeping, and power systems.

2.2.1 Advanced Communications

Over the past decade communication systems for CubeSats have largely relied on amateur bands in the UHF. This has proven to be adequate for a number of missions that are education-focused and which do not have challenging data downlink requirements. However nearly all of SMD’s existing and planned Decadal Survey science missions generate voluminous amounts of data and fully burden their downlinks. Future SMD CubeSat science missions — even modest “gap filler” missions designed to complement the larger observatories — will require communication systems far more capable. Current state-of-the-art CubeSat communications capabilities include L, S, and X bands, and planned SMD missions such as the Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment (INSPIRE) will operate in these bands. The MARCO mission will serve as the first interplanetary CubeSat communications relay system, and will provide mission operators with vital entry, descent, and landing performance data during the insertion phase of the Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSIGHT) mission. The high rate link to the Deep Space Network will use, at the very least, an X-band transceiver/transponder.

In addition, STMD has been investing in technologies to push the state-of-the-art in CubeSat communications capabilities in the Ku- and Ka-bands and, more recently, in the area of optical transmission. These investments will be critical for satisfying SMD’s science requirements in the near future. STMD has planned demonstration missions such as the Integrated Solar Array and Reflectarray Antenna (ISARA), which will demonstrate Ka-band communication for possible deep space applications. The Optical Communications and Sensor Demonstration (OCSD) project [3], scheduled for late 2016, is comprised of two 1.5U CubeSats containing a number of technologies for propulsion, pointing, and miniaturization of an advanced laser communications system. The test is designed to demonstrate communication from LEO in excess of 200Mb/s.

In addition to the need for high data rate communications, a significant number of SMD’s future small spacecraft missions will likely consist of multiple platforms, either in the form of constellations or “strings of pearls”. This may require satellite “swarms” to share data between individual platforms and communicate to the ground. Over the past several years STMD has invested in projects such as the Edison Demonstration of Smallest Networks (EDSN) to develop the capability for multiple CubeSats to coordinate observations for conducting goal-oriented research [4]. Although EDSN was lost during a launch failure in December 2015, the technology demonstration objectives were sustained through the Network and Operation Demonstration Satellite (NODES). The NODES mission, comprised of two CubeSats containing radiation-measuring instruments along with crosslink and downlink communications capabilities, was deployed from the International Space Station in May 2016 and is now operational.

2.2.2 Propulsion

To accommodate CubeSat station keeping and orbital control maneuvers as well as for supporting swarm capabilities, STMD has made a number of investments in propulsion systems over the past few years, consistent with an growing trend in the private sector. The relatively large amount of attention in this area is attributable to the difficultly of miniaturizing existing propulsion systems for CubeSats, although significant progress has been noted recently in chemical and electrical propulsion systems. STMD’s most recent investment is the Busek BET-100 miniature CubeSat electrospray system that will produce thrust in the micronewton range. The thrusters will enable precision pointing that may be necessary for future science missions involving a significant number of coordinated assets. Other investments include ion thruster development that makes use of various gases, including Xenon and Iodine, and hydrazine systems that allow for constellation deployment and orbit maintenance. Demonstration missions will occur as the technology readiness levels of the various investments increase. A relatively near-term demonstration is now being formulated by NASA Marshall Space Flight Center, NASA Glenn Research Center, and Busek, Inc. to validate the ability of a small Hall Effect Thruster to achieve high ΔV in a 12U CubeSat.

For the deep space environment solar electric propulsion will be necessary for future SMD missions in planetary science and heliophysics. A recent SBIR award to ExoTerra Resource, LLC will develop the capability to provide ΔV in excess of 1km/s through the use of high power, high efficiency solar arrays coupled with a highly efficient Hall thruster.

2.2.3 Power

The majority of CubeSat missions rely on photovoltaic cells for obtaining needed power for the spacecraft and science instruments [2]. Although existing technology has satisfied the needs of current missions and manufacturing costs are low, the performance of existing solar cells is generally no better than 20%. For near-Earth missions NASA generally relies on industry for advancements in photovoltaic cell performance. For SMD planetary missions that are beyond 4AU different designs are needed to accommodate the low light intensities, low temperatures, and high levels of radiation. STMD currently has several active projects in this area which could push the state of the art to nearly 50% beginning-of-life efficiency as far away as 5AU, given advancements in structures and pointing mechanisms. In addition to solar cells, NASA's SBIR program has awarded Nanohmics, Inc. to develop an advanced solar thermoelectric generator and coatings to optimize emissivity.

For on-board energy storage most CubeSat missions rely on lithium polymer or lithium ion for rechargeable secondary batteries. STMD has one active project in this area and a demonstration mission is planned for December 2016. The California State University Northridge / Jet Propulsion Laboratory CSUNSat1 mission will demonstrate a new type of low-temperature (238K) lithium-ion battery / super capacitor energy storage system. For missions in LEO as well as in deep space this capability could reduce the need for battery heaters and will optimize the mass and volume for the CubeSat form factor. Additionally, STMD has invested in a lower-TRL approach through an SBIR award to MicroLink Devices, Inc. in which performance enhancements to tritium-powered beta voltaic batteries will be developed.

2.3 Education and Work Force Training

SMD continues to offer unique educational space flight opportunities for universities through the Undergraduate Student Instrument Project. The USIP undergraduate university program has provided flight opportunities in 2013, and now offers CubeSats in 2015. Overall, NASA made 22 CubeSat selections during USIP, including 3 SMD missions, and 19 Office of Education missions.
These missions provide authentic hands-on experiences.

2.4 CubeSat Management Implementation

SMD offers CubeSats as research tools in its Earth and space science research announcements. The NASA SMD CubeSats investigations are a mission element of its overall science program portfolio. During 2016, SMD is implementing:

- 99 spacecraft missions (using 84 spacecraft)
- 18 sounding rocket and balloon missions
- 26 CubeSat missions (science, technology and education)
- 25 airborne science missions.

As an element of the SMD science portfolio, CubeSats offer a low-cost orbital option for enabling scientific discovery, technology, training and education goals aligned to SMD.

SMD, working with NASA's Space Technology Mission Directorate (STMD), the Human Exploration Operations Mission Directorate (HEOMD), and its Centers in a coordinated and comprehensive fashion, is actively advancing the vision for CubeSats as cost effective and capable tools for research.

Consistent with its leadership role in the SMD Suborbital Research Program, SMD is leveraging its investments and expertise in suborbital research, personnel, expertise, tools and facilities at across the nation to enable SMD CubeSat missions through providing light touch project management oversight, and value-added engineering services in support of CubeSat investigations.

SMD appropriately tailors its risk posture and mission assurance approach, commensurate with the size, cost, and complexity of mission. Further, SMD assists its mission teams throughout the implementation process, and provides assistance by NASA experts as requested by the PI team.

Combined with its partnership with other NASA Mission Directorates (STMD, HEOMD, OSMA) and external organizations (NSF), SMD is working foster CubeSats as an important research tool.

3.0 CubeSat Assessments and Plans

NASA sponsored studies related to CubeSats to better understand the science potential of the new platforms. A study conducted by the NASA Ames Research Center (ARC) Working Group Study, Dr. Neil Murphy, JPL et al, developed a strategy to exploit the growing capabilities of small satellites to address Living with a Star (LWS) system science goals, to identify knowledge gaps, and relevant technologies.

The ARC LWS Working Group's findings include:

- Capabilities of nano and small spacecraft are developing rapidly, driven in a large part by the frequent access to space.
- CubeSats are now capable of sophisticated measurements, with architectures capable of significant data volumes. Further, small spacecraft buses (e.g. those compatible with EELV Secondary Payload Adaptors) are becoming more capable and affordable.
- The extension of the International Space Station (ISS) to 2024 has opened a reliable, cost effective platform for achieving new science (or "taking new measurements.")
- These new, cost effective platforms have the potential to provide new tools to address significant science goals, particularly when such goals are best addressed using distributed measurements.
- LWS system science has a critical need to use cubesat / smallsat technologies and launch opportunities to enable essential multi-point (and often multi-orbit) in-situ and remote-sensing measurements in key regions in the Sun-Earth domain.

A study conducted by the National Academies of Sciences, Engineering, and Medicine, Dr. Thomas Zurbuchen, University of Michigan, et al, reviewed the current state of the scientific potential and technological promise of CubeSats, and the potential of CubeSats as platforms for obtaining high-priority science data.

The NAS/SSB's study's findings and observations include:

- CubeSats have already produced high-value science as demonstrated by peer-reviewed publications that address decadal survey science goals.
- CubeSats are useful as instruments of targeted investigations to augment the capabilities of large missions and ground-based facilities, they are enabling new kinds of measurements, and they may have the potential to mitigate gaps in measurements where continuity is critical.
- Educational and training roles are important for all programs and science disciplines.
- Attributes (small size and standardized form factor and interfaces) ensure that CubeSats can be put in a "plug and play" format in rocket fairings, lowering the cost of integration with launch vehicles.
- The resulting reduced cost of development per CubeSat allows for the conduct of higher risk activities.
- CubeSats enable creation of entirely new architectures not feasible with traditional, larger, and more expensive platforms - a principal example of this is constellations of a large number of smaller spacecraft.
- Once entirely new architectures are opened up, the potential for transformative science using CubeSats jumps exponentially.

3.1 SMD Perspectives on CubeSats

Constrained size is driving innovation. While not appropriate for all scenarios, SmallSats have some distinct advantages:

- Demonstrating precursor technologies, while also reducing the risk and cost of infusion into larger NASA flight projects;
- Valuable as a platform for component flight testing and proof-of-concept demonstrations
- Utilizing constellations or swarms of small spacecraft. Enabling affordable distributed systems to achieve broader observational coverage;
- Conducting stand-alone single small spacecraft missions. Dedicate a given spacecraft to a single observational objective – thereby enabling persistence of observations;
- Providing critical complementary measurements to existing missions.
- Changing the traditional flight project mission assurance model.

- CubeSats used as an educational and training tool will enable spaceflight experience for more people, earlier, and more often.

The SMD CubeSat initiative is expected to maintain and expand its role as a tool as part of the SMD science, technology, and STEM program. Today SMD is sponsoring many CubeSat science, technology and STEM-related missions in various stages of development. New technologies and improvements in CubeSat platform capabilities will make investigations more reliable, efficient and will allow for greater science to be conducted without the need for an increase in flights.

4.0 Conclusions

The current and emerging capabilities of CubeSats show great promise in furthering space-based exploration and scientific discovery, in serving as platforms for technology maturation and in providing opportunities for hands-on student flight research.

Smallsats have the potential to reduce both the cost of development as well as the cost of deployment (via a wide array of access to space), and thereby increase progress toward NASA goals.

Through leveraging existing capabilities to the benefit of these low-cost platforms, NASA is fostering innovation that helps the United States remain a leader in scientific discovery, while also maturing technologies for the Nation's space missions, and training young scientists and engineers.

5.0 Acknowledgments

The success of this most recent phase of CubeSats…

6.0 References

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