ACHIEVING VISIONARY PLANETARY SCIENCE GOALS WITH DEEP SPACE CUBESATS.

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Introduction: Success rates and mission lifetimes for Earth orbiting CubeSats have been improving over the last 5-10 years. Instrument payloads are also becoming more sophisticated, enabling novel science investigations from the CubeSat platform. These developments have been made possible through continued investment from NASA, universities and private industry [1,2]. The growing success of CubeSats in Earth orbit has led to additional investments into the development of deep-space interplanetary CubeSat missions (MarCO, Flashlight, Lunar IceCube, NEA-Scout, LunaH-Map, BioSentinal) by NASA SMD and STMD [3,4,5,6,7,8]. The programs under which these missions were selected are currently funding very important developments in new CubeSat technologies for deep-space exploration, including planetary science instrumentation, and continued investments will enable CubeSats to contribute to deep-space planetary science missions well into the 2050's. As with any new technology, deep-space CubeSat components and instrumentation will become more reliable and more capable with time, and like Earth orbiting CubeSats, success rates will improve with continued in-flight testing through increased launch opportunities. This is crucial for the success of future deep-space CubeSat missions.

There are a variety of challenges unique to planetary science CubeSat missions that will be tested for the first time in the near-future and will enable their use as tools of planetary science and exploration in the 2020's and 2030's. There are currently 8 deep-space interplanetary CubeSats scheduled to launch prior to 2020. These will all provide useful data on communications, propulsion, navigation systems, and radiation tolerance, in addition to achieving their science goals. There is significant interest from the planetary science community in sustained deep-space CubeSat programs, With continued support from NASA Science Mission Directorate there are likely to be opportunities to ride along with upcoming New Frontiers or Discovery class missions in the 2020s, 2030s and beyond. With this in mind, it is important to consider the current environment and the future of deep-space planetary science CubeSats, including cost/risk profiles, form factors, and launch opportunities.

CubeSat Philosophy/Vision for Planetary Science in 2020-2050

Launch Opportunities: The Space Launch System (SLS) Exploration Mission-1 (EM-1) launch vehicle, currently scheduled for launch in 2018, is carrying a deployer capable of launching 13 separate deep-space CubeSat missions after Orion separation. For this trend to continue, other launch vehicles should work to accommodate as many CubeSat payloads (in multiple form factors) as possible. More launch opportunities would enable iteration, improvements, and eventually improved reliability with each mission (successful or unsuccessful).

Cost/Risk: CubeSat low costs are driven in part by size but also by higher risk tolerance. The low cost creates a virtuous cycle: more opportunities, more diverse science portfolios, more access for communities not traditionally involved in planetary science. The CubeSat form factor was originally developed and iterated upon at universities, which enabled a lower cost of development and an acceptance of higher risk mission profiles. Maintainaing a similar low cost, high-risk profile for developing and flying deep-space CubeSats would enable continued innovation in a "learn-as-you-fly" approach. These developments will require a commitment to deep-space CubeSat development from the community and its stakeholders. This process is already underway with the first set of deep-space interplanetary CubeSats. Approximate costs for EM-1 CubeSats range from <$10M to >$20M, less than a typical single instrument on a larger scale planetary science mission. As established suppliers and providers of CubeSat components, subsystems and instrumentation stabilize, development costs can shrink and overall cost estimates will improve such that by the mid-2020s to 2030s estimating costs for deep-space CubeSat missions will be less speculative.

Rideshare: While the Orion capsule is bound for a lunar flyby, the SLS EM-1 CubeSat deployer is currently destined for heliocentric orbit. For lunar- or asteroid-bound CubeSats, this increases the ΔV requirement and imposes significant trajectory, navigation and design challenges in order to execute the mission with small, low thrust propulsion systems.

In the future, CubeSat mission designers, launch vehicle providers, and the primary mission stakeholders will need to work together to determine how best to accommodate secondary CubeSats on larger planetary science missions. No spacecraft is launch vehicle independent, but the work currently being done on LunaH-Map, Lunar IceCube, Lunar Flashlight and NEA Scout (all destined for lunar orbit or beyond) may lead to more flexibility from future CubeSats on launch vehicle and destination. The trade-off in this case is increased time spent in deep-space, as these missions require significant time to change their velocity in order to be captured at the Moon or to flyby their target. The launch vehicle/primary mission scenario with the lowest ΔV requirement for a secondary CubeSat mission would be to deliver the CubeSat into the desired orbit at the target planetary body. A CubeSat as a secondary mission, however, would ideally pursue a scientific goal that is significantly different from the primary spacecraft. This can impose significant mission design challenges, and will require a propulsive system to either change orbits, flyby or impact/land on the surface.

Enabling Technologies and Approaches: In addition to the maturation of CubeSat subsystems, the miniaturization of scientific instrumentation has been key for making deep-space CubeSats exciting platforms that enable answering planetary science questions. To date, CubeSat scientific instruments have mostly been either focused development efforts for a particular CubeSat mission or ancillary products of miniaturization for mass-constrained landed instruments. Dedicated focus on instrument miniaturization for CubeSat platforms would accelerate the process of creation of more capable instruments.

New propulsion technologies are available that provide sufficient ΔV for, e.g., insertion into elliptical Mars or lunar orbit, opening up new CubeSat mission possibilities for the next decade. Nevertheless, an ideal case for a planetary CubeSat mission is to be delivered into the desired orbit at the target planetary body by a parent craft. A CubeSat could enable certain measurements by the parent craft, e.g. bistatic radar, transmission spectroscopy. A secondary mission could also pursue a scientific goal that is significantly different from the primary spacecraft. This can impose significant mission design challenges, which must be balanced against the science return.

For future deep-space CubeSat missions, communications may be performed between the CubeSat and Earth via the primary spacecraft. This may impose restrictions on operations, and require CubeSats to be more autonomous than the primary spacecraft. Alternatively, continued investments in novel deployable antenna (and solar panels) will open up bodies further from the Earth as viable targets. If the number of planetary missions increases as the proportion of CubeSats grows, investments in ground networks on Earth to receive the signal may be required.

Form Factor: The current 6U standard is likely to become the smallest deep-space planetary science CubeSat form factor. MarCO, a 6U communications CubeSat that will perform a flyby of Mars, requires a relatively large volume for propulsion and a reflector array for direct to Earth communication, leaving little room for a science payload (MarCO is carrying a small camera). LunaH-Map, a 6U CubeSat launching on SLS, requires ~2U for propulsion, and more than 2U for the science payload in order to maximize the surface area of the detector, a neutron spectrometer. For LunaH-Map, a reflector array is not required since communication at lunar distances is possible with relatively small antennas via the DSN. For both MarCO and LunaH-Map, optical remote sensing is not the primary goal, therefore, large apertures do not need to be accommodated and overall spacecraft volume can be small (6U). Cubesats on the order of 12U in size or greater will be better equipped for carrying optical payloads or larger detector arrays.

Summary: Looking to the future, deep-space CubeSat missions may be best served by sticking to their risk-tolerant roots. If costs are kept low and regular launch opportunities can be maintained, high-quality science with CubeSat missions will be common in 2050. The possibilities for planetary exploration enabled by CubeSats are exciting, and mission designs that implement clever, risky methods for achieving high-quality science are well suited for the platform. CubeSats implementing more risk-tolerant mission strategies can enable high-resolution images, radar, spectral or nuclear remote sensing data that will complement data from the primary spacecraft or from previous missions. Furthermore, instrumented CubeSats that serve as penetrators, or soft-landers, onto planetary surfaces could help provide important constraints on orbital measurements, as well as time-resolved measurements of surface properties. Components for deep-space One of the biggest challenges will be to free deep-space CubeSats from parent craft, by independent management of radiation, power, and telecommunitions. Throughout the 2020's – 2050's, CubeSats will help enrich the scientific return from large planetary science missions by providing high-risk, high-reward complementary data to the primary spacecraft mission.

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