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Deep Space SmallSats: Summary of the Current Thinking, Approaches and Lessons Learned

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Abstract

We are on the threshold of a new era of sustainable exploration and development of Earth's Moon and the solar system at large. Programs such as NASA's Artemis, Commercial Lunar Payload Services, Lunar Gateway, and other commercial lunar landers and orbiters continue to be announced. As a result, rideshare opportunities for CubeSats and other small spacecraft or "smallsats" to reach Cislunar space and other Interplanetary targets will be unprecedented. Already many CubeSat missions to these environments have been manifested, with more and more mission concepts continuing to be proposed. The challenge that is still being addressed by the earliest developers of Interplanetary CubeSats, is how to meet high-priority science and technology demonstration requirements while limited by the resources available to missions constrained by the CubeSat paradigm (low cost-cap, relative compactness, higher risk, with rapid development, lean operations, shared tools and essential measurements or demonstrations for highly focused goals). This paper presents the work of the ASU Deep Space Summit, where representatives from early interplanetary CubeSat developers presented and discussed the specific challenges their missions faced, solutions implemented and the degree of their success to date. The participants also addressed what they viewed as the particular challenges of missions of this type and their degree of impact on development, factors that promote or inhibit mission success and recommendations for dealing with these factors. Following team presentations, extensive conversations on the same subjects were held, providing more detailed information on challenges and general consensus on recommendations for future missions. Further information was gathered from participants in the Summit (representing 11 teams) and all other interplanetary CubeSat missions that are currently Post-Phase-D (or equivalent) in development (5 additional teams) using several different methods, including interviews and a literature review of current interplanetary CubeSat technology. From this information, we make such recommendations in aspects ranging from development and operation approaches, team composition and key role selection, parts selection and qualification, documentation and review, and shared tools and facilities. The aim is that future and ongoing interplanetary CubeSat missions can leverage this knowledge to lower risk and costs. The 16 CubeSats covered by this study represent a mixture of pathfinders, technology demos and science missions.
Keywords: SmallSats, Interplanetary, Deep Space, CubeSat, Lessons Learned

Acronyms/Abbreviations
LEO = Low Earth Orbit
BEO = Beyond Earth Orbit
COTS = Commercial-off-the-shelf

1. Introduction

There is the expectation that by utilizing smallsats and the "cubesat paradigm," the costs for missions to cislunar, deep space and other Beyond Earth Orbit (BEO) targets would be reduced by one order of magnitude or more, as was the case for science and commercial applications in Low Earth Orbit (LEO) [1].

The presumption is that this will pave the way for a new generation of mission concepts, applications, and architectures due to cost savings driven by each spacecraft's aggressive reduction in size and mass. Additionally, advances in miniaturized electronics, high-performance subsystems and science instruments will enable missions with challenging interplanetary/BEO science objectives to potentially reach more destinations (Moon, small bodies, planets) with new, novel, and targeted mission concepts and planetary science investigations [2].

2. Background

It is important to recall that despite the success and growth enabled by smallsats and cubesats, during their initial adoption for LEO missions, longtime space industry stakeholders found that traditional models, architectures, and management processes did not accurately predict or control the costs and risks associated with this new generation of smallsats [3]. Additionally, new spacecraft developers lacked a suitable body of relevant engineering and management knowledge (including engineering practices, architectures, and models) that could be applied to low-cost, high-risk smallsat missions. As a result, many cubesat programs operated with ad-hoc management and design approaches that did not significantly leverage established spacecraft engineering practices. The consequences were low mission success rates and some organizations unable to significantly lower costs [4]. However, the shared body of knowledge to develop smallsat missions reliably and cheaply has made strides in recent years by quantifying the realities of the new types of stakeholders, higher risk profiles, and other distinguishing mission factors [5].

While this new body of knowledge for smallsats has been successfully used to raise the success rate for the latest LEO smallsat missions, mounting evidence shows these new tools may initially prove inadequate and require maturation for the new class of BEO smallsat missions, just as they did for LEO assets [6].

3. Missions Overview

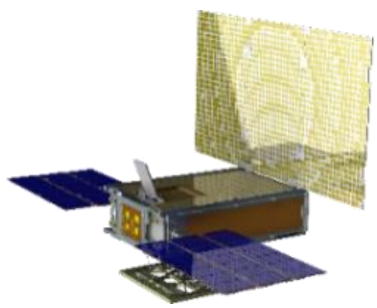

Fig. 1: MarCO was a set of two cubesats that were the first to leave Earth orbit on a Mars flyby [22]

The "Reference missions" in the paper cover all space missions whose spacecraft fit the typical definition of a smallsat, have a BEO destination, were built after 2015 and are past phase D (or equivalent) in development. These represent a diverse collection of cubesat missions, performing an array of science investigations and technology demonstrations developed by various government, academic and commercial organizations.

The core of missions covered by the paper is the secondary payloads on the first flight of NASA's SLS Rocket on the Artemis-1 (formally EM-1) Mission [7]. Three of these cubesats (Cislunar Explorers [8], CU-E3 [9], and Team Miles [10]) are the winners of the CubeQuest Challenge, part of NASA's Space Technology Mission Directorate (STMD) Centennial Challenge Program [11]. The other missions include three (NEA Scout [12], BioSentinel [13], and Lunar Flashlight [14], through the Human Exploration and Operations Mission Directorate, two (CuSP [15] and LunaH-Map [16]) through the Science Mission Directorate, two through NASA's NextSTEP program (Lunar IceCube [17] and LunIR [18]) and three (ArgoMoon [19], EQUULEUS [20], OMOTENASHI [21]) from submissions by NASA's international partners.

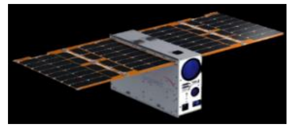

Fig. 2: LICIACube, is a spacecraft hosted payload on the NASA Dart mission. [23]

The three missions covered that were not part of the Artemis-1 mission were the MarCO [22], LICIACube [23] and CAPSTONE [24] missions.

Three missions covered did not make their planned delivery to Artemis-1.

4. Spacecraft Design and Development Approaches

For the development of the various subsystems of the reference missions, it was recommended that one of two approaches be taken: 1) The use of high-reliability COTS if available (and operational limits acceptable for deep space) or 2) Design for Reliability if no acceptable COTS exists within constraints. Note that both these approaches are constrained by cost and schedule and are meant to fit within cubesat standards (minimal volume and mass). This allowed teams to minimize testing by proving designs were resilient analytically.

Much greater than typical engineering margins should be taken to ensure meeting cubesat constraints. Discussions between teams suggested going as far as leaving at least 33% of power and 25% of mass and volume available as a margin for design changes and dealing with unexpected challenges. Early preparations for mass and power drawdown plans might be warranted as many reference designs required significant mass reductions and power re-budgeting.

The spacecraft should have a finite set of well-defined features (with assured margin), including baseline and threshold designs, coming out of PDR that are fiercely defended against change. The addition of more features, even during the beginning of the design process, should be resolutely fought against. Many missions suffered from requirements creep, causing redesigns and delays.

The reference mission developers noted that designing a mission around performing a flyby vs. an orbital capture significantly lowers the engineering challenges (and associated costs) and overall represents much lower risk approaches to missions. A flyby is a path a spacecraft follows past a celestial body to get information about it. In a flyby, the spacecraft passes close but isn't "captured" into an orbit by gravity. During a flyby, a spacecraft must use its instruments to observe the target as it passes, changing the aim of the instruments as it passes. While spacecraft in a flyby

Fig. 3: CAPSTONE – First CubeSat Mission to attempt achieve a Lunar Orbit [24]

Fig. 4: From left, Cislunar Explorers [8], CU-E3 [9], and Team Miles [10]. Cislunar Explorers and CU-E3) had been assembled and completed final structural verification through a fit-check. However, they experienced late-stage hardware failures that required extensive disassembly to diagnose and repair, causing them to miss their deadline for delivery to Artemis-1.

has a limited opportunity to gather information, the reference missions show that advanced science and mission support capabilities with smallsats is still possible. The scope and challenge of many engineering tasks are lowered by the more lower performance requirements of propulsion (with LunIR being able to complete its science mission without a propulsion system) and shorter mission life. Early interplanetary smallsat missions should thus include flyby or probe architectures when these are based on viable science goals, especially when teamed with architectures that rely on swarms of smallsats performing many single or double flybys over long periods. However, it should be noted that these missions should not replace or shift focus away from the unique science and cost savings of having longer-term cubesat missions with the far greater operational capabilities enabled by using propulsion and achieving gravitational capture.

5. Technical Challenges

The requirements and technical challenges of interplanetary missions drive systems toward larger volumes and surface areas than traditional cubesats have attempted. This can lead to misalignment of resources when developing the spacecraft's different subsystems. To avoid this misalignment for future missions, the reference developers made the following observations on general types of challenges faced by missions of this type.

Complexity-Related: Complexity by any measurement is significantly greater for this class of mission than for LEO smallsats. In many cases, the design of certain subsystems became more difficult as the limited volume and mass made the subsystems more complex to meet minimum requirements. Many of the reference missions also employed or were testing technologies to compensate for the smallsat's lack of resources or ground support. Simply integrating and testing such systems represented work outside the scope of a "typical" smallsat mission. An increase in the complexity of deep space cubesat missions can be anticipated in the next generations as the proportion of science user requirements driven increases.

Payload-Related: Thermal control and susceptibility to contamination are significant concerns to systems with optics and biological components. Many science payloads also found meeting the mass and volume constraints of a 6U cubesat challenging. Higher-performance instruments, like those on missions such as Lunar IceCube and LunaH-Map were challenged by the limited bandwidth available from Earth-based Deep Space Network (DSN)). To utilize many next-generation instruments on cubesat communication systems, expanding BEO communication assets will be required.

Target- Related: Lifetime issues are target-dependent, particularly related to longer-term radiation exposure in deep space, because these missions require many months to reach the Moon or the asteroid via low energy trajectories. These trajectories take significant effort to design and are outside the scope typical LEO smallsat developers have previously done [22]. These efforts had to be repeated every time the launch date was changed. Software that can map low energy trajectories simply and quickly will be vital for future BEO smallsat missions. The limited availability of uplink time for communications and position correction makes command and control a particular problem for missions of greater operational complexity.

Propulsion-Related: propulsion, more than any other subsystem, caused the greatest number of unforeseen difficulties for most reference missions. Nearly all missions with high-performance or low TRL propulsion systems reported development issues that caused unforeseen increased costs and schedules. Development issues related to propulsion systems would cause several missions to initially fail PDRs and CDRs. Three reference missions would end up switching their selected propulsion systems past their PDR. CU-E3, which had no propulsion system, reported that their original mission goals were changed due to the lack of propulsion systems that could meet their requirements in a small enough form factor. The LunIR team purposefully designed its mission to achieve its objectives without its propulsion system

Thermal-Related: Both the extreme colds and heat experienced (and the length of time systems are subjected to those extremes) by interplanetary smallsats during pre-deployment and during flight far beyond those experienced by LEO smallsats. Thermal control became a major issue for many reference missions as they:

Contend with basic physics of having large power systems in small volumes, where there is limited mass for absorbing heat without significant temperature changes and limited surface area for radiating heat away from the spacecraft.

Host sensitive science instruments (such as spectrometers and lasers) and high-performance subsystems (such as radios and population) have specific and, in some cases, relatively narrow operational temperature ranges.

Conflicting thermal control requirements for instruments vs. other subsystems (Example: cold instruments vs. moderate batteries vs. hot propulsion systems)

6. Organizational Lessons Learned

In some cases, organizational-related issues can be mitigated by the involvement of members who have experience with larger missions with mutual benefit. Some general observations made by the reference missions on what made successful teams were:

Special attention should be given to solving this issue for critical leads in small package/payload systems engineering, mission operations and ground data systems managers, and thermal design engineering.

Developers agreed that it is critical to have a spacecraft or systems engineer, who is guaranteed to be part of the team for a long period, has strong system engineering and development cycle knowledge and has strong expertise to work with multiple subsystems.

For the Artemis-1 missions, having a dedicated Safety Team or Safety Engineer was important in managing requirements verification documentation as well as maintaining communication with the launch vehicle and integrating organizations, which was beyond the original scope for many missions. For many of the reference missions, the Program Manager or Principal Investigator filled this role, and it was found to be an oversize drain on their time and focus to the detriment of the missions. In the future, such requirements should be consistent with the cubesat mission class, thus eliminating the concern.

Flight Software requires someone with expertise to lead and plan development. This is especially a difficult thing for Academic missions where the traditional computer engineering curriculum does not cover the specialized knowledge needed for developing flight software for space missions. Many Reference developers also reported a lack of understanding of the scale of the software engineering tasks as well as having difficulty capturing all the software requirements at the beginning of development. The development of and training on open-source and shared software tools, already underway, must be encouraged and expanded.

Efforts to design and maintain the correct trajectory do not scale to the smaller size. Even small satellites require a trajectory design and navigation team(s) with a similar or even greater scope of work to larger exploration missions. Missions still must have a full flight dynamics team for trajectory design, exactly as for a much bigger spacecraft

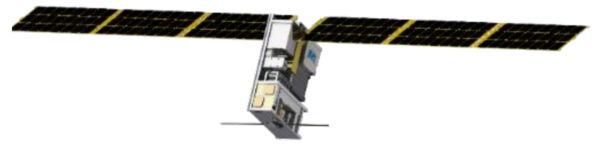

Fig. 5: The Lunar IceCube Mission contains many high-performance COTS and custom systems including a cryocooled infrared spectrometer, 120W solar array, and Busek BIT-3 RF Ion engine [22]

7. Lessons Learned

The representatives attending the Deep Space Summit were in general agreement about the programmatic and project planning challenges faced by the teams and proposed several solutions for future Deep Space and Interplanetary cubesat missions. Many were discussed throughout this paper, but the critical fifteen findings are summarized here:

7.1. Need for system and discipline engineers experienced with small-scope space missions

It is acknowledged that, for the most part, the reference developers are part of the creation of a first-generation small-scope interplanetary smallsat mission cadre and that, in many cases, their efforts are creating opportunities for training next-generation deep space mission developers. However, there is no clear path for future missions to leverage the expertise held by those who contributed to these reference missions for their own success.

It is recommended that NASA build on the already developing core of engineers and managers/mentors and established processes at proposing institutions ranging from NASA centers to small start-ups and universities and use them simultaneously on future projects of this nature. This approach will help to alleviate turnover induced at government or corporate organizations by experienced personnel being subsumed in larger projects or at academic institutions by time constraints of student availability. This issue can also be mitigated by the involvement of members of larger missions with mutual benefit in some cases. Special attention should be given to solving this issue for critical leads in small package/payload systems engineering, mission operations and ground data systems managers, and thermal design engineering.

7.2. Enhance Interplanetary Mission development culture to support small scope, cost-capped opportunities

NASA has recently recognized the programmatic need for a greater number of cost-capped, small package opportunities along with the availability of technologies needed to support these opportunities, but the development of approaches most suitable for these opportunities are still in the experimental stage or non-existent.

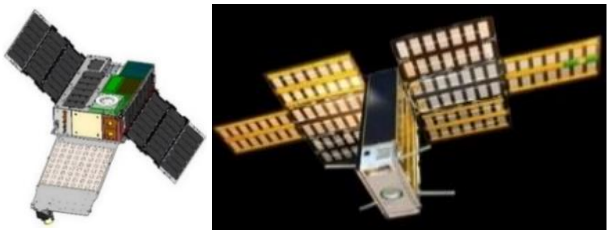

Fig. 6: CuSP [15] and LunaH-Map [16]

It is recommended that agencies create a lower cost, higher risk, 'small scope mission' line of business operating in parallel with conventional one-of-a-kind missions. This option would incorporate shared toolkits and facilities, streamlined, automated documentation and review processes and risk assessment (analogous to JPL airborne or GSFC/WFF suborbital/balloon programs). Institutions utilizing this option would need to identify, support as infrastructure, and facilitate the reuse of facilities for calibration and environmental testing of standard packages for several payload types.

7.3. Further "standardization" needs to evolve to support 'beyond first generation' interplanetary cubesats

Widespread standardization was not realizable in this 'first generation' of interplanetary smallsats. Only the ArgoMoon and LICIACube reference missions shared a common bus design (shown in Figure 1), with the major difference between the two spacecraft designs being the instruments they carry. The reference developers had expressed different views as to what degree of standardization is or could ever be appropriate. While a consensus was not reached, the teams acknowledge that different payloads imply different subsystem requirements or at least different configurations of subsystems. The question at hand was: How to embrace the 'diversity' of payloads while encouraging the use of COTS and standardization? Developing a single common bus that could meet as many mission requirements and configurations as possible most likely takes significant penalties in mass and volume as the subsystems will need to be designed to be available to the largest number of payloads and instrument types. However, if several bus designs are targeted for specific target environments and/or hosted payload types, that can be developed that might enable the greatest diversity of missions of this type and potentially lower costs as well.

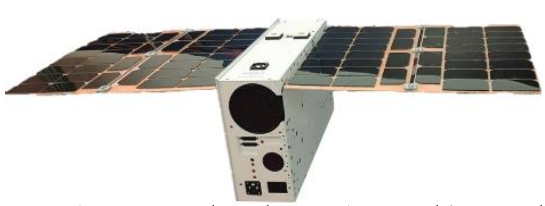

Fig. 1: ArgoMoon based on ArgoTech's Hawk-6 Platform [19]

The ability to "mix and match" COTS subsystems and payloads that have common interfaces and open software architectures may be the best compromise. The industry (encouraged by NASA and its partners) should aim to develop several reliable deep space-proven COTS subsystems with hardware lines and software tools matched with the most frequently visited targets and different payload types (e.g., particle analyzer, spectrometer, field detectors) with adequately standardized external constraints (volume, mass, power) to accommodate a range of payloads can be reached. To enable more standardization for early missions, larger form factors (12U was identified as possibly to be sufficient) may be required.

7.4. Use shared tools tailored for cost-capped missions to overcome non-scalable systems of comparable or greater complexity than conventionally sized exploration missions or typical LEO CubeSat missions

The development of new technology or even the adaptation of LEO technology for BEO missions required significantly more time and money than many of the reference mission developers expected. While direct hardware costs were still inexpensive and scalable/comparable to traditional cubesat missions, engineering needs are far greater. Cost, effort, and time to complete program management, systems engineering, flight software development and systems integration tasks, are not comparable to typical LEO CubeSats, nor do they scale down linearly from larger exploration missions.

NASA should continue to encourage the use of shared software tools (for modeling, testing, and data production), shared build and test facilities, several reliable deep space subsystem choices (computer and operating systems, communication, power, and active control systems) and to use incentives, including funding opportunities, to facilitate the creation of such tools and approaches. It must be acknowledged that many of these tools will differ from tools already developed for LEO smallsats and will be dedicated and designed to serve smallsat missions that also leave Earth's orbit.

7.5. Expand from 6U to 12U for the standard volume for BEO missions

Fundamental physics dictates the need for high-performance subsystems when operating beyond Earth orbit, Making operating around other planetary bodies especially challenging targets for 6U spacecraft. The result was that the reference spacecraft had as much as twice the density of conventional cubesats with the same limited external area. Thus, the reference missions had far greater challenges when designing for heat dissipation, subsystem configuration and unhindered field of view of instruments. In particular, the reference missions that required cold imaging sensors or very stable payload conditions had difficulty with the limited surface area and volume of the 6U form factor.

Future innovations may relieve some of these problems, but they will remain fundamental design issues, as discussed in [25]. It was suggested that for missions that have extreme thermal control requirements, the 12U form factor, even without increasing the launch mass of the spacecraft, would alleviate much of the difficulty by providing additional surface area for radiators. Furthermore, expanding the 'standard' 6U deep space cubesat size used by most of the reference missions to 12U would have an even greater impact, alleviating greater packing density and thus the removal of waste heat from power-hungry propulsion and communication systems. In addition, more surface area and less restricted field of view would be available for power, communication, thermal control, and uncontaminated fields of view for subsystem and payload optics.

7.6. Commit to a reasonable schedule to avoid severely impacting mission development

As secondary payloads, smallsat missions tend to have launch dates or initial trajectories that are not controlled by the mission developers (as was the case for the Artemis-1 reference missions). The reference development teams found the uncertainty in the schedule of their launch vehicle was highly disruptive for planning and even affected the design of their spacecraft. Additionally, the teams reported that many tasks, such as navigation and operational planning, had to be repeated or augmented as launch windows slipped, conditions changed, and scope increased. Uncertainty in the schedule (both pandemic and development delay driven) was incredibly disruptive for planning for all the teams. As time dragged out, the availability of personnel became more limited, and task completion slipped.

Commitment to specific launch dates with allowable slips agreed upon far in advance is advisable for future opportunities. In that case, launch service alternatives could be made available in a service comparable to that offered by NASA's CubeSat Launch Initiative. This would standardize rideshare and delivery to target opportunities. Also, greater communication between the primary mission and secondary payloads to where several launch windows are committed to. The other solution is to have high design margins where the spacecraft can survive the most extreme environmental conditions, and fuel and other key resources are designed to account for worst-case scenarios. Long term, the reference teams believed this would limit future missions' ability to lower costs. Missions must also design their spacecraft to be prepared for significant time stored by a spacecraft integrator or launch service provider on a host spacecraft or storage facility in an uncontrolled environment before launch.

7.7. Provide assets to avoid severe navigation and tracking constraints during and post-deployment.

The lack of availability of navigation and tracking assets, especially for multiple secondary or multi-manifest deployments in a short period of time, greatly increases the risk of mission loss for BEO secondary payloads. This aggravates the constraint imposed by the lack of onboard resources for trajectory correction, data processing and storage on BEO cubesats. In addition, trajectory constraints and the requirements to be powered-off during launch dictate that all the reference mission spacecraft wake up lost in space and lost in time, not knowing where they are relative to Earth or Sun. Compounding these issues, most small satellite typically tumbles right after deployment. It is anticipated that most future missions will also have these constraints.

Missions must be designed to tolerate large pointing errors and not knowing the position of itself or of Earth after powering on. Designing the power system and communications system (near Omni-directional antenna pattern, baud rate scaling) to be operational in most potential tumble orientations greatly increases survivability in off-nominal cases. The ability to orient at the beginning of the mission itself without intervention is important to minimize risk.

The reference developers acknowledged that few options are available in the short term other than the enhancement of cislunar communication assets, many already planned, should be implemented as soon as possible to reduce this 'bottleneck.' This includes upgrades to the NASA DSN and commercial ground stations.

7.8. Expand the use of trade space studies to assess and address risk for small-scope, cost-capped missions

The trade space for selecting and configuring features for small, cost-capped, limited-scope spacecraft is complex. BEO missions are driven technically by mission objectives, power, telecommunications, and propulsion requirements. Understanding and having clear and specific requirements for these performance metrics going into a project is key to its success. Given that interplanetary cubesats aim to be high-risk and low-cost when full implementation of traditional space-focused systems engineering processes (such as those found in NASA/SP-6105 NASA Systems Engineering Handbook) was attempted (or attempted in part) by some of the reference missions it was found that in many cases there were specific determinants maintaining low costs and staying on schedule. On the other hand, many of the reference missions did suffer predictable consequences from the omission of standard systems engineering processes such as risk management, configuration management, and quality assurance. Many of the reference missions managed at academic institutions lacked experienced systems engineering personnel. This forced the PI to fulfill this role for many of the missions, splitting their focus.

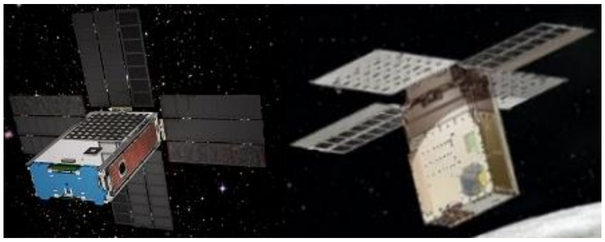

Fig. 2:From left BioSentinel [13] and Lunar Flashlight [14].

It is recommended that early risk assessment through trade studies of approach cost, schedule, physical resources, and impact of modification to meet threshold and baseline requirements be conducted. The "Small Spacecraft Technology Program Guidebook for Technology Development Projects" was created to provide recommended practices for the research and technology development projects sponsored by NASA's Space Technology Mission Directorate's (STMD) Small Spacecraft Technology Program [26]. While not published in time to help shape the development of the reference missions (August 2021), many of the developers acknowledge it as offering superior guidance for efficiency, best practices, and improved success of smallsat missions. Many of the recommended practices derive from lessons learned by small spacecraft developers over the course of many past projects.

7.9. Need to incorporate state-of-the-art technologies along with reasonable COTS to realize the potential of cubesat class missions fully

The cubesat paradigm, while relying on COTS for supporting subsystems to reduce costs and to preclude 'reinventing the wheel,' should be well suited for technology demonstration missions due to more acceptable risk and will therefore be able to push forward state-of-the-art, offer improved measurement capability, and improve benefit to cost ratio for any missions. However, several reference missions experienced significant issues with COTS providers, leading to unexpected costs and delays. Including COTS components that subject to discontinuation or change without warning and inconsistent pricing

Many reference missions reported that although they used COTS subsystems developed for space, many required some modifications to meet mission needs. Many of these modifications had to be done by the supplier. Only a few commercial smallsat COTS vendors were willing to do custom products and services, and when they did, it came with high non-recurring engineering costs that were, for the most part, shouldered by the development teams.

It is recommended that future opportunities that allow R&D project flexibility to push state-of-the-art forward while also acknowledging that state of art components (rather than preexisting >10-year-old spares) for critical (payload) subsystem can lower costs in the long run. To avoid the issues of dealing with 'black boxes' from commercial vendors, it is recommended that NASA require ICDs and transparency from vendors (and continuation of the NASA Electronic Parts Program) to allow the team to plan for and mitigate any impact on the payload. In addition, it is recommended that NASA develop and test models for 'batch' parts selection and testing and payload calibration to supply to future missions.

7.10. Need for expansion of infrastructure providing resources to many small missions operating BEO

External resources, such as communication, navigation and tracking services which must serve many missions (such as NASA's DSN), are an issue for many missions and will continue to be an issue with current architectures.

It is recommended that NASA facilitate the utilization of architectures that make the cubesat paradigm useful beyond single 'pathfinders' missions, which made up the bulk of the reference missions. Potential solutions include the development of BEO communication and navigation infrastructures that aim to enable these activities with lower resource needs from the individual spacecraft. Additionally, the paradigm where a spacecraft would deliver multiple smallsat platforms to their target trajectory or target environment would relax the need for internal resources for propulsion, communication, navigation, and tracking.

7.11. Further development needs on the first-generation miniaturized deep space radio systems

The RF communication systems used by the reference missions proved to have significantly greater drains on power, volume, and thermal rescores than expected. Even with flight heritage, the systems used exceeded the estimates for the resources they required. In addition, the options for communication and ranging systems that were compatible with the DSN were limited; as such, only 6 of the 16-reference missions did NOT use the IRIS system for their main radio. The Iris radio is a small form factor (<1U) software-defined radio developed by the Jet Propulsion Laboratory (JPL) and manufactured at Space Dynamics Laboratory [28].

More development is needed for these systems, with customer support needed to make them viable COTS solutions for large numbers of future missions. Designing, integrating and debugging small high-performance RF comms systems require specialized knowledge. Additional support for developing competing systems would enable more flexibility for future missions.

7.12. Eliminate uncertainties in requirements scope by providing predefined and set launch service conditions

The Artemis-1 rideshare reference missions reported that there were significant and unexpected design, testing and verification burdens imposed due to

NASA Human Rated (Class A+) driven health and safety requirements. These requirements were generally considered out of scope, not just compared with LEO secondary payload/rideshare requirements, but with the expectations communicated when the flight opportunity was announced. Additionally, safety requirements were poorly defined initially and changed throughout the process. Requiring a significant increase in time and costs to the teams.

It is recommended that well-defined interplanetary rideshare ICDs be provided with opportunity announcements. Additionally, programs should model their ICDs on the simplified and less stringent safety and interface requirements used on other human space missions that have proven effective. For example, the reference developers point to programs launching cubesats from the International Space Station (ISS) as a possible reference for more reasonable requirements when incorporating cost-capped cubesat Missions on human-rated facilities for future BEO smallsats [28].

7.13. Develop more reasonable environmental requirements more typical of secondary payloads

An issue encountered by the reference developers on the Artemis-1 mission was shifting environmental requirements (e.g., the environment the cubesats were kept in before deployment). The cubesat missions' requirements (driven by science and technology goals) were not regarded in developing the environmental requirements of the launch environment. In the case of the SLS, due to the evolving development of the second stage where the cubesats are stowed, these requirements would shift through the program's life.

The developers recommend maintaining a 'payload bay' with active environmental controls in future missions where multiple secondaries are deployed. This will be critical for limiting both the costs of the secondary payload but also in limiting the risks to the primary mission payloads in the future

7.14. Further streamlining of licensing and certifications by the US government and international agencies is needed

The reference developers found that the regulations and policy compliance process for BEO missions were far more extensive than they had experienced in the past and were expecting. Multiple government agencies, who often don't communicate with each other, are involved in getting final launch approval. Items like Planetary Protection, Orbital Debris Mitigation., Range Safety requirements for launch and transport requirements for an overseas launch are beyond the scope that most development teams had done in the past and require significant oversight and guidance.

Additionally, Frequency approval for Cislunar and other BEO missions is often an unexpected labyrinth of requirements and approvals that require extensive attention to detailed requirements and time to receive full approval. Getting a license or approval to use a frequency through either the FCC or other agencies might hinge on successfully completing the ITU's coordination process takes months to years (there is a case of one reference mission taking 4 years to get approval), so missions should start working on the application and submittal as early as possible.

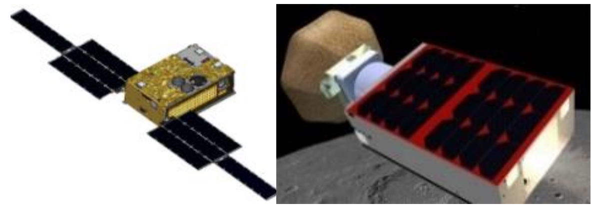

Fig. 7: On the left, EQUilibriUm, Lunar Earth point 6 U Spacecraft (EQUULEUS)'s main objectives are to demonstrate trajectory control techniques to reach an Earth–Moon libration orbit and image Earth's plasmasphere to study the radiation environment around Earth [20]. On the right is the Outstanding MOon exploration TEchnologies demonstrated by Nano Semi-Hard Impactor (OMOTENASHI) which contains the smallest lunar lander to date and instruments to observe the Lunar radiation environment [21].

7.15. Develop alternate build, test, and integration to minimize the impact of large-scale shutdowns

It is important to note that the COVID-19 pandemic presented significant issues to the development of every reference mission surveyed. From 2019 onward, many teams had to operate on a limited and remote basis (in some cases, teams were locked out of their facilities entirely for months) during the extended shutdowns. Additionally, pandemic-related issues would lead to part supplier/vendor issues, cost overruns, schedule delays, team turnover and other problems. In many cases, this was during critical integration and testing periods. This paper attempts to separate the effect of the pandemic from the lessons learned that are discussed.

While acknowledging the unprecedented nature of the pandemic, a possible solution to a similar situation in the future, in the case of future shutdowns, would be for teams to plan to have their facilities that have policies in place that would allow for continued use with personal protection plans (such as Personal Protection Equipment, Social distancing, etc.) in the event of a public health crisis or plan to have a back-up. Another solution would be for NASA to agree to provide supplementary support for the use of alternative facilities and personnel in the event of a shutdown of partner facilities. Additionally, teams found that setting up remote access to test hardware for software development proved to be incredibly important. Especially with covid lockdown and academic holidays, having remote access to development hardware allowed for software development and testing to continue uninterrupted.

8. Conclusions

The white paper for the ASU Deep Space Summit covers the topics discussed in this paper in further detail and expands on many other areas not covered in this paper. The white paper can be found on the summit website here: https://www.asudeepspacesummit.org/

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