QUESTIONING THE STATUS QUO IN PURSUIT OF LOWERING PLANETARY MISSION COSTS.

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Introduction: The first step in effecting change is admitting that there is a problem. Budgetary challenges have left NASA unable to maintain the mission cadences recommended in the 2013-2023 planetary science decadal survey [1]. This is due in part to a cost-schedule-reliability feedback loop. Small satellites ("smallsats") and methods from NASA's 1990s "Faster, Better, Cheaper" era are a potential solution. However, in order to disrupt the status quo, the planetary science community must first make changes in our culture and assumptions regarding missions.

Reliability ≠ Risk: The distinction between reliability and risk is important for this discussion. Reliability is the dependability of a system or component to function under stated conditions for a set period of time—its odds of success. Risk is a combination of the probability of an undesirable event and its consequences. There are different flavors of consequences: technical, cost, schedule, safety, political. For example, a low-cost mission that is not high-reliability can still be lower in risk than an expensive, high-reliability Flagship mission.

Apollo: For the past 50 years, the Apollo program has provided a blueprint on how to achieve success in the face of incredible complexity. It required weaving together the efforts of 300,000 individuals working for 20,000 contractors and 200 universities in 80 nations [2]. The consequences of failure would have been catastrophic: it was not an option, in effect demanding 100% reliability despite incredible political, financial, and technical risk. To mitigate risk, NASA employed systems management processes from the military. Systems management involves "highly structured, rigid procedures for tracking design changes and wedding them to cost, schedule, and the proper functioning of other subsystems" [3]. Specific practices include functional redundancy and strongly hierarchical project management. It is effective but also expensive: at the peak of the Apollo era, NASA commanded 4.41% of the federal budget [2].

The Space Spiral: The same methodology that brought astronauts to the Moon and back has also enabled the development of high-reliability robotic spacecraft. These spacecraft have traveled all across our solar system, returning data that have provided a deep understanding of planetary formation and evolution.

However, Apollo-era systems management without the political willpower and funding of the Cold War era has left planetary missions susceptible to the "Space Spiral" (**Fig. 1A**), a feedback loop of higher cost, longer schedules/fewer missions, and demand for higher reliability [4]. Because missions are so expensive, their numbers are limited, resulting in a frenzy of scientists trying to collect as much data as possible. High reliability is expected, demanding extensive systems management. This drives up costs and extends schedules, reinforcing the Space Spiral.

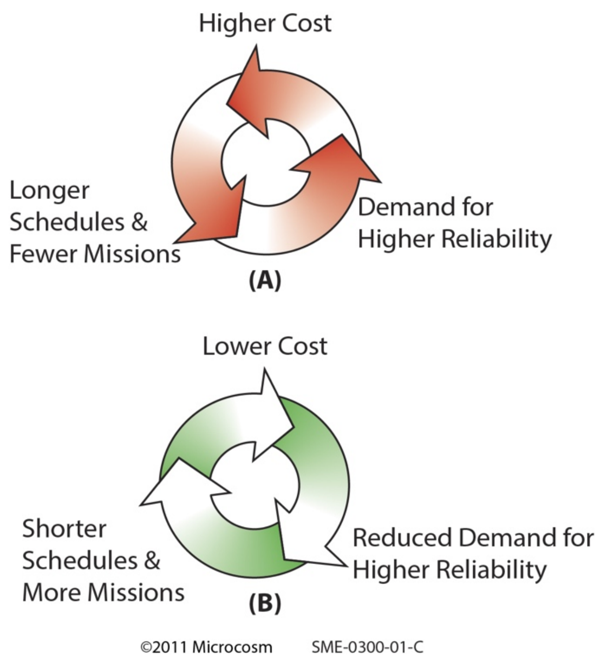

Fig. 1. (A) The Space Spiral and (B) Reverse Space Spiral [4]

Impacts on Science: In spite of cuts to the Planetary Science Division's budget early in the current decadal period, recent missions have resulted in innumerable exciting discoveries. However, the spiraling cost of missions continues to be a programmatic challenge. The midterm review of the last decadal survey found that budgetary and policy decisions limited NASA's ability to achieve the recommended Discovery and New Frontiers cadence and that NASA is unlikely to catch up before the decadal period ends in 2023 [1]. The report also mentioned the descoping of the Mars Astrobiology Explorer-Cacher and Jupiter Europa Orbit to Mars 2020 and Europa Clipper, respectively, due to the unaffordability of the original concepts. As a result of limited funding as well as cost overruns from selected missions, high-priority science objectives from the last decadal survey have not been adequately addressed.

A Solution in Smallsats: Smallsats offer a program-level solution to NASA's budgetary challenges. Smallsats, which include CubeSats, are generally classified as spacecraft with a dry (unfueled) mass of <180 kg. Low-mass spacecraft are limited in their capabilities and are therefore less complex, providing fewer opportunities for failure and requiring less testing. Teams are also smaller, relaxing the need for formal processes. These factors shorten schedules, further reducing cost. NASA has already successfully implemented such missions.

Faster, Better, Cheaper. Daniel Goldin was appointed NASA Administrator in 1992 with the directive to cut costs without sacrificing performance. His resulting philosophy was dubbed "Faster, Better Cheaper," (FBC) where "better" was a relative measure of science return per dollar spent. FBC involved two primary methods: (1) technology miniaturization and (2) ensuring spacecraft reliability through small, empowered teams rather than Apollo-style systems management [3]. Defining characteristics of FBC spacecraft included low mass and innovative technical solutions in the face of miniscule budgets.

Mars Pathfinder was one of the first FBC missions. The team was instructed to land a rover on Mars with 1/14 the budget and half the schedule of *Viking*. With only 6 of 19 NASA and Soviet Union missions to Mars succeeding between 1962 and 1996, this was considered impossible: "Mars, it would seem, eats spacecraft" [3]. Despite the odds, *Pathfinder* succeeded, as did 9 of the other 16 FBC missions. However, the failure of 4 in 1999 caused panic and a return to traditional methods.

Venture Program. NASA's Earth Sciences Division provides a more recent template for leveraging the benefits of smallsats. Its Venture class of missions ($100-200M) was born out of recommendations from the 2007 decadal survey for low-cost mission opportunities [6]. The first Venture mission, CYGNSS, launched in 2016 and monitors extreme weather events through a constellation of 8 25-kg spacecraft. Leveraging the Earth Science Division's success, NASA is currently exploring how to smallsats can be used in other Science Mission Directorate divisions.

MarCO. In November 2018, the two *MarCO* 6U-CubeSats successfully operated as communication links for the *InSight* lander at Mars. This marked the first use of a CubeSat in deep space, proving that platform can operate in environments beyond Earth orbit.

Benefits to Science: Despite its tainted legacy, FBC missions produced more publications (a proxy for science return) per dollar spent than traditionally managed missions [5]. This shows that low-cost smallsat missions using FBC methods can be an effective means to maximize mission science return on a programmatic scale. A sub-Discovery-class mission program with a high cadence could provide ancillary benefits:

1. Ample opportunities for scientists and engineers to gain mission experience and carry lessons learned forward to riskier missions
2. Lower-risk platforms to test new, enabling technologies
3. Higher responsivity to unexpected mission opportunities
4. Increasing the number of solar system bodies visited

A Required Change in Mentality: To reverse our unwitting reinforcement of the Space Spiral (**Fig. 1B**), the planetary science community should question our culture and assumptions toward missions and reflect on the most effective ways to maximize finite funds. Specifically, we must:

1. Accept that cost reduction is possible and achievable [3]
2. Recognize that the need to change is not a criticism of prior programs or practices [3]
3. Understand that low cost does not equate to low reliability [3]
4. Resist the urge to turn every spacecraft into a Swiss Army knife of instrumentation
5. Embrace the elegance of missions with focused, well-defined science objectives
6. Be open to novel mission architectures that leverage unique smallsat capabilities
7. Revisit FBC methods in light of recent progress and successes with smallsats

Through analysis groups and decadal surveys, we are empowered to guide decision-making at NASA. The decadal survey midterm review [1] highlighted the need for a clear smallsat strategy, which is now even more urgently needed with *MarCO*'s success. By gathering unified support for innovation in mission cost reduction, we can help address the budgetary challenges that inhibit the progress of our science.

Conclusion: "The largest obstacle to low-cost innovation is the belief that it cannot be done" [3].

References: [1] NRC (2018) *V&V: A Midterm Review*, Nat. Acad. Press. [2] Johnson S. (2002) *The Secret of Apollo*, JHU Press. [3] McCurdy H. (2003) *Faster, Better, Cheaper*, JHU Press. [4] Wertz J. et al. (2011) *Space Mission Eng.*, Microcosm Press. [5] Dillon R.L. and Madsen P.M. (2015) IEEE Trans. Eng. Mgmt. **62**, No. 2. [6] NRC (2007) *Earth Sci. Applications from Space,* Nat. Acad. Press.

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