The Team Science Challenges of Very Long Duration Spaceflight Missions

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Introduction

Since the dawn of the space age, the duration of spaceflight missions has increased from days to years to decades [1]. Through various mission extensions, Voyager has operated for 43 years to date. Cassini took 7 years to reach the Saturnian system and then orbited for an additional 13 years for a total of 20. The New Horizons mission cruised over 9 years to reach Pluto and has continued into the Kuiper Belt for the past 5 years. The science goals of next-generation heliospheric and planetary missions may demand even longer mission durations. Recent mission concepts to explore the ice giants of Uranus or Neptune all envision complex missions over a multi-decadal span [2,3]. An ongoing Interstellar Probe mission study is exploring a spacecraft required to operate for fifty years to service science goals under discussion [4]. A *very long duration* space science mission calls for not only a spacecraft designed for longevity, but also a team of scientists, engineers, and managers that can support the mission over the very long term.

The problem is that most space science missions—even those operating over decades—were not designed with longevity in mind [5]. In a competitive funding environment, extended missions are never guaranteed. The availability of funding rather than spacecraft health is more often the limiting factor for mission lifetimes. Long-duration mission operations, therefore, have developed incrementally only as-needed or as-funded. Extant practices for operating over the long term are typically improvised or kludged together and highly dependent on select individuals or institutions that are difficult to replicate.

We find little systematic attention has been given to the supporting infrastructures and human organizations needed to sustain space science over the long term, even as potential next-generation missions like the Interstellar Probe or Ice Giants contemplate very long lifetimes. To address this gap, we review 1) past spaceflight missions that have met these challenges, 2) other big science experiments like particle accelerators or ground-based observatories that have operated over long durations, and 3) the emerging literature on the science of team science. We supplemented this information with semi-structured interviews (N = 9) with leading space scientists, science administrators, project managers, and historians of science on the challenges of very long duration science. We hope to build an evolving body of practice that can lead to guidance for a proposed Interstellar Probe mission and other missions that contemplate long durations to achieve their goals.

The Challenges of Very Long Duration Missions

We identify two major problems common to many long-duration science experiments. First, long mission durations can extend past the expected careers (or even lifetimes) of principal investigators and other essential mission personnel. A very long-duration mission must manage *the problem of multi-generational succession* [6]. Multi-generational succession carries specific risks. Much of the necessary know-how for doing science is largely tacit and handed down through apprenticeships or oral traditions [7]. Even in bureaucratized domains with extensive documentation requirements, the cumulative knowledge needed to run a mission can never be entirely written down or reduced to simple rules. If this knowledge is not transferred, personnel turnover can lead to critical omissions, gaps, or silences in institutional knowledge that imperil mission success and spacecraft health—a recognized finding in many NASA accident investigation board reports [8].

Second, the biggest risks for long-term space science missions are rarely technical, but are more often political, especially as spacecraft continue to outperform engineering expectations. To operate over the very long term requires matching commitments from funding agencies or other

resource-granting organizations. Known as the *time inconsistency problem* [9], mission leaders must consider that a commitment from external funders today is no guarantee of a commitment tomorrow. Funding cycles typically require all missions to continually renew or extend their funding on a short-term basis irrespective of their time horizons. Changes in administrations, agencies, or Congress can radically reorient science policy and funding priorities [10]. Analogous to the internal problem of succession, long-duration missions must also sustain the support of successive generations of administrators, politicians, and, ultimately, the public at large to survive.

Managing the Problem of Succession

We found that few missions systematically considered the teaming implications of long-term operations, especially during the planning stage and even into their extended missions. A 2017 NASA senior review of Voyager, for example, was dismayed to find the mission, then entering its 40th year, had no succession plan for its aging workforce [11]. In many instances extended operations depended upon the heroic efforts of a few dedicated individuals whose know-how was difficult, if not impossible, to replace. The untimely exit of any of these people could endanger mission goals like calibrating instrument data or keeping ancient flight hardware and software systems operational. Rather than leave extended operations until later, or worse to luck, future missions should consider long-term operations from the outset. Thinking about succession problems early on can ensure organizational resilience to the exit of mission personnel by onboarding replacements well in advance.

All interviewees agreed that long-term continuity on space science missions also depends on some amount of “overhead.” What this overhead looks like can vary from full-time personnel to a regular 10-20% of a person’s time to a more formal institute akin to the Hubble’s Space Telescope Science Institute [12]. This overhead should serve to capture and make available the knowledge of older members as they exit and pass along this knowledge to new members as they enter. Beyond just archiving more, missions might optimize their work teams for sharing the highly tacit knowledge that forms within organized science [7]. Possible organizational interventions include an informal team culture that prioritizes mentorship and stewardship, overlapping role structures in which team members train their successors and may call upon emeritus members for help or advice, cross-training in different aspects of the mission, the sharing of lessons learned in group forums, recording video oral histories with team members especially as they retire or exit, and networking opportunities for early career team members to facilitate cross-generational interactions.

However, no amount of long-term thinking or organizational overhead can ensure the success of a long-term mission unless the project can also provide adequate career opportunities for its team members over the life course. These include not only opportunities for advancement, training, or doing exciting science, but also recognition of the need for career flexibility and sustainability as team members transition between different critical life points [13]. Minus these opportunities or if these opportunities are disproportionately hoarded, potential team members in the pipeline may be unwilling to join the project. Compounding these issues is the nature of scientific work on long-duration space science missions. From a staffing perspective, there are real challenges in attracting people to a mission in which expected payoffs are uncertain, emerge slowly, or require enormous sacrifices. Funding realities likely preclude substantial numbers of full-time employees dedicated to a single mission over long periods. In all likelihood, long-lived spaceflight missions will not be the primary focus for most investigators or engineers for much of their careers. As such, assembling a viable career will depend on the wider set of opportunities in

space science that may be adjacent or complementary to long-duration missions. Very long-duration missions should think about broader capabilities, bodies of expertise, or disciplinary orientations relevant to their science or engineering goals and encourage their support within the space science community. Simultaneously, rather than force human careers to adapt to the cadence of robotic space exploration, project leaders might rethink careers through the lens of the life course. A wide body of research, for example, demonstrates that STEM jobs are notoriously difficult to combine with family life and that these difficulties are exacerbated as one goes up the hierarchy of skill and authority in science teams [14]. Retaining a diverse and competent scientific workforce over the long term likely requires corresponding flexibility to the life transitions all team members experience as they age [15].

Managing the Time Inconsistency Problem

Long-lived space science missions tend to stay alive through a confluence of factors: a) the spacecraft is healthy, b) the mission continues to produce good science and/or operate in unexplored areas, c) science teams, internally-speaking, seem to work well together, and d) continued operations are relatively inexpensive compared to the cost of a new start [11]. Put another way, the longevity of a spaceflight mission is tied to its performance. Very long-duration missions should consider clear performance expectations and devise ways of communicating performance measures to relevant stakeholders to generate perceptions of productivity.

At the same time, sustaining long-term science takes a group effort. A mission must engage with other external audiences like the wider space science community or the public, who offer their support and therefore bestow legitimacy upon the project. Acquiring such legitimacy—that of a generalized perception that an entity's actions are desirable, proper, or appropriate—can be essential to survival during times of organizational failure, miscues, or reversals [16]. A strong endorsement from the Space Science Board might avoid cancellation. Arresting images of Jupiter taken by an on-board camera can sustain public interest in an otherwise complex and inaccessible science mission [17]. Acquiring external legitimacy demands not only extensive engagement with these audiences (e.g., active participation in the decadal survey) but also demonstrations that internal organizational practices conform to outside expectations (e.g., matching the demographics of the mission to the demographics of an increasingly diverse society). Framing the mission's goals in terms that both the science community and the public can understand with milestones that both communities can use to measure success is essential in mission planning.

Finally, funding space science is historically an uncertain endeavor given downward budget pressure and precarious support that challenges long-lived commitments [18]. Three sources of funding stability are commonplace in big science projects. First, funding agencies can extend time horizons and review cycles to match the tempo of scientific activity. The NSF's Long-Term Ecological Research Network funds investigators on renewable six-year grants (the NSF's longest such funding duration) and reviews the entire research network only once a decade [19]. A slower funding pace, therefore, avoids disrupting long-term scientific operations needed to collect data over extended temporal and spatial scales [20]. Second, projects can seek diversified funding sources to prevent an over-reliance on a sole funding source. For example, in the world of high-energy particle accelerators, international participation and public-private partnerships are now the norm to get new projects off the ground [21]. Third, projects can seek to secure a legal mandate that insulates their support from future reprioritization. The US's desire to maintain scientific diplomatic ties and honor international agreements with its European partners helped save Cassini after the CRAF cancellation in the early 1990s [22]. Relatedly, the funding of the upcoming Europa

flagship mission was written into previous NASA appropriations bills, providing stability to the project [23].

Conclusion

History has shown that long-duration missions approaching 50 years are possible, but only if missions give equal weight to the human challenges of extended operations as they do engineering ones. With proper planning and an organizational structure, missions can turn “luck” into “good fortune” over the long term.

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