LMS

Large Mission Study Report

SPONSORED BY THE SCIENCE MISSION DIRECTORATE (SMD)

PREFACE

Conducted from October 2019 to October 2020, this internal NASA study was chartered by the Science Mission Directorate (SMD) as part of its commitment to uphold SMD's core values of leadership, excellence, integrity, teamwork, and safety.

The findings from this internal study will help to inform improvements to decision making, management, and review processes across SMD, with emphasis on establishing and keeping more achievable commitments when large missions are confirmed. This study also may inform Agency-level policies and practices, though that was not its main intent.

TABLE OF CONTENTS:

Executive Summary

EXECUTIVE SUMMARY INTRODUCTION

NASA's Science Mission Directorate (SMD) executes a diverse portfolio of missions across Astrophysics, Biological and Physical Sciences, Earth Science, Heliophysics, and Planetary Science. In this over $7-billion-per-year portfolio[1], the largest and most ambitious strategic missions are often denoted as "flagships" or "large strategic missions."[2]

These missions fulfill the highest-priority objectives for NASA's science enterprise. They are technically complex and technologically aggressive, pushing the boundaries of what is possible in order to meet SMD's mission "to discover the secrets of the universe, search for life elsewhere, and protect and improve life on Earth."[3] They are also essential for maintaining U.S. leadership in space, and for demonstrating the Nation's overall scientific and technical excellence.

Although SMD's large strategic missions have led to tremendous technical and scientific achievements, they have often failed to meet their cost and schedule commitments. These overruns typically have led to the creation of independent review teams, which have generated many useful lessons and recommendations for NASA and SMD. Over the years, NASA and SMD have made positive changes in response to these lessons and recommendations, but clearly there is further room for improvement. As SMD looks into the future, we must position ourselves for success in launching and operating the James Webb Space Telescope (JWST), completing the Nancy Grace Roman Space Telescope and Europa Clipper missions, executing a successful Mars Sample Return (MSR) mission, implementing the 2020 Astrophysics Decadal Survey, and achieving other ambitious goals.

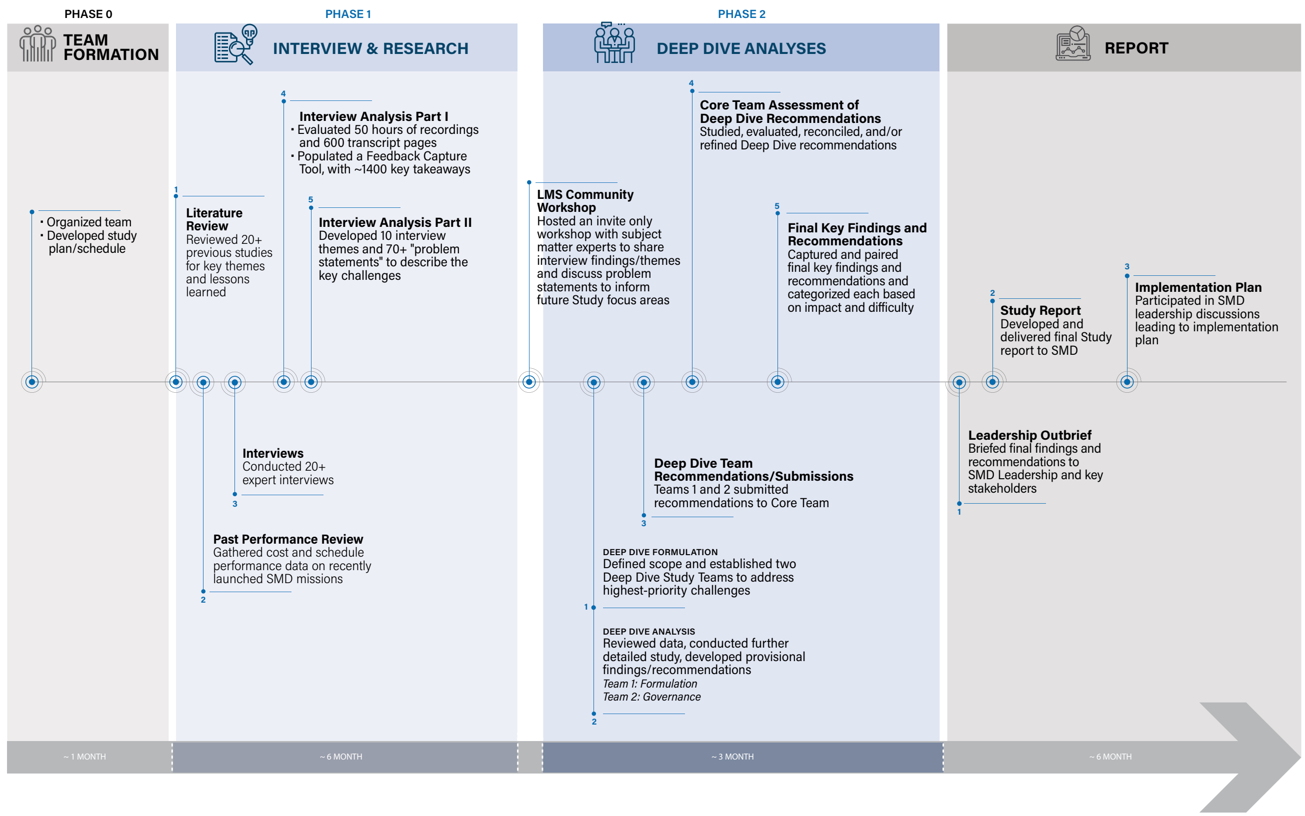
THE CHARTERED STUDY

To ensure that SMD is more successful at ***delivering large strategic missions on time and within budget***, the SMD Associate Administrator (AA) chartered a Large Mission Study (LMS) to examine how NASA makes critical decisions that either impede or support mission and programmatic success. The study process included a review of over 20 previous studies, a series of interviews with a diverse group of subject matter experts, a workshop with splinter discussions, an analysis of recent mission programmatic performance, a pair of focused and independent deep-dive analyses, and the development of final findings and recommendations. The study was conducted from October 2019 to October 2020.

This final report will help inform SMD's leaders to improve decision making, management, and review processes across SMD, with emphasis on establishing and keeping more achievable commitments when large missions are confirmed. It also may inform Agency-level policies, although that was not the main intent of the study.

STUDY PHASES

In Phase 0, the Study Leads and Study Manager assembled the LMS "Core Team," a group of eight NASA civil servant experts responsible for executing the study and developing final findings and recommendations. Each member of the Core Team brought a thorough background in project analysis, management, engineering, and/or science related to large missions. The Core Team was joined by two senior contractor consultants with similar expertise, in addition



[1] *The enacted Fiscal Year 2021 appropriation for the Science Mission Directorate is $7.301 billion.*
[2] *This report uses the term "large strategic missions" to describe the subject of this study. There is no difference between "large strategic missions" and "flagships," but the former term is preferred because it is more descriptive.*
[3] *Science 2020-2024: A Vision for Scientific Excellence, https://science.nasa.gov/science-pink/s3fs-public/atoms/files/2020-2024_Science.pdf, p. 9*

to an ex officio representative from NASA's Agency-level Program Management Improvement Office. The Core Team also received facilitation and organizational support from a contractor consulting team.

In Phase 1, the Core Team gathered data on large missions' performance and lessons learned to identify the broad range of challenges and obstacles in meeting commitments on these missions. After review of over 20 previous studies, they conducted 21 interviews, used the resulting 50 hours of interview recordings to generate 600 pages of transcripts, and populated a Feedback Capture Tool with ~1400 key takeaways from interviewees. They distilled the key takeaways into 74 problem statements across 10 different themes, and then invited over 50 subject matter experts to a workshop to share all the information gathered and to engage in dialogue.

The workshop informed a process by which the Core Team prioritized the problem statements and identified the highest-priority challenges to be addressed during Phase 2 of the Study. These highest-priority challenges were divided into two categories: Formulation and Governance.

In Phase 2, the Core Team chartered two Deep Dive Analysis Groups composed primarily of subject matter experts outside the Core Team. This infusion of new people and ideas was designed to ensure diversity of experience and opinions in the development of findings and recommendations. The goals of the Deep Dive teams were to leverage data gathered by the Core Team, conduct further detailed analysis, and develop specific recommendations to address large strategic mission challenges. The Deep Dive Analysis Teams spent approximately two months on their respective focus areas, then delivered their results to the LMS Core Team. The Core Team reconciled the Deep Dive Teams' results against one another and against their own findings. After an iterative phase of further evaluation, study, and prioritization, the Core Team developed the final set of findings and recommendations provided in this report.

LESSONS LEARNED

The final findings and recommendations span a wide range of processes in the creation, execution, and oversight of large strategic missions. They reflect the following lessons that emerged during the study:

- Large strategic missions require greater priority, resources, and attention during the pre-formulation period, during which key architecture decisions are made.
- Whereas practices and processes for Phases A through F are well-defined in existing Agency/SMD documentation, there is comparatively little guidance to govern the pre-formulation period.
- The sheer complexity of large missions stresses existing engineering and project management tools and capabilities.
- Technologies for large strategic missions, as elements of highly complex systems, must often be matured earlier in the project life cycle than technologies for smaller missions.
- Particularly in the early phases, SMD must be honest and clear with stakeholders about the limits of our understanding of how to develop technically challenging and/or unprecedented systems. This applies both to the inherent immaturity of early technical solutions and the inherent inaccuracy of early cost models.
- SMD's current instrument selection process, which is designed to maximize procurement integrity, often does not adequately account for payload-level accommodation risks.
- SMD's internal management and analysis capabilities must be strengthened to ensure it is able to carry out its oversight role effectively for large strategic missions.
- SMD must collaborate with its Centers and other institutions on long-term strategic capability management in order to ensure those institutions are ready to execute large missions.
- Missions are better able to identify and resolve problems when there is a team culture of open communication, truth-telling, and accountability that is led, modeled, and promoted from the top down.

FINDINGS & RECOMMENDATIONS

The study yielded ten sets of findings and recommendations:

I. *Pre-Phase A Team Composition*
II. *Pre-Phase A Architecture Trades and Descope Options*
III. *System Maturity Assessment*
IV. *Technology Integration into Complex Systems*
V. *Analytical Tools*
VI. *Cost & Schedule Estimation to External Stakeholders*
VII. *Standing Review Boards*
VIII. *Instrument Selection Process*
IX. *SMD Capabilities*
X. *Center Capabilities*

Please see a full review of key points associated with each in the **"Key Findings and Recommendations"** section of the report.

Introduction

STUDY BACKGROUND

The Study adapted its definition of large strategic missions from the one developed by the National Academies of Sciences, Engineering and Medicine in *Powering Science: NASA's Large Strategic Science Missions (National Academies Press, 2017)*. For the purpose of the Study, large strategic missions are defined as missions with the characteristics below:

- Lifecycle cost greater than $1 billion[4]
- Responsive to a high priority identified by the National Academies
- Directed to a specific institution for development
- Technically challenging and scientifically groundbreaking

The following are some examples of large strategic missions recently or currently in development:

- Mars Science Laboratory (MSL) / Mars Curiosity Rover
- Eugene Parker Solar Probe (PSP)
- James Webb Space Telescope (JWST)
- Mars Sample Return (including the Mars 2020/ Perseverance mission)
- Europa Clipper
- Nancy Grace Roman Space Telescope

LARGE MISSION STUDY GUIDELINES

The study was governed by the following questions and principles:

Questions (from LMS Terms of Reference, Appendix D):

- What are the characteristics/attributes of large missions that lead to optimal project cost, schedule, and technical performance?
- What are the characteristics/attributes of large missions that lead to poor project cost, schedule, and technical performance?
- Are technical and management processes (risk management, cost estimation, technology management, engineering peer reviews, etc.) being applied effectively to large missions?
    - If not, why not?
    - If these processes are being applied properly, but without the intended results, then should these processes be modified?
- Do NASA's internal policy, oversight, and communication processes support informed and timely decision making? If not, why not?
- How can NASA improve its communication and coordination with external stakeholders (e.g., other USG entities, partners, Congress, scientific community) to preserve stakeholder support and facilitate mission success?
- Are there specific or generic capability issues with Centers, industry, or international partners that negatively impact the establishment of realistic commitments at Key Decision Point-C (KDP-C)* and successful implementation within those commitments?

This report does not explicitly answer each of these six questions individually; rather, the questions were the basis for the interviews conducted during Phase 1. Nevertheless, the final LMS findings and recommendations span the full domain of these questions.

Study Principles:

- Don't try to solve every problem
- Don't attempt to change things that cannot be changed
- Seek input from the diverse spaceflight community
- Direct recommendations specifically to SMD leadership
- Ensure recommendations are limited, specific, actionable, and impactful
- Share final findings and recommendations broadly and openly

OVERVIEW OF PREVIOUS STUDIES

Laura Delgado Lopez, a Policy Analyst in the NASA SMD Policy Branch, led an assessment of previous Large Mission-related reviews, studies, papers, and conference presentations. Conducted during Phase 1 of the Study, Delgado Lopez's assessment integrated the findings of previous relevant studies, constructed a history of related policy changes and recommendations, and identified how policies might overlap across LMS study themes.

Delgado Lopez drew upon 22 documents from the time period of 2005 through 2020. Some of the analyses and reports focused on single missions, while others studied multiple missions. Most of the missions covered by the documents were large strategic missions managed by SMD, but some were not. All of the documents focused in some way on technical, scientific, management, or governance challenges that NASA had faced in the past, or that NASA would likely face in the future.

In the 1990s, cost growth in NASA missions was identified as a "long-standing issue" and became the focus of several targeted studies between 1992 and 2012. These studies considered both robotic and crewed systems. During this period, external stakeholders sought to understand why costs had grown on large missions, identify mitigation strategies, and quantify any signs of improvement. Internal stakeholders were focused primarily on capturing lessons learned, incorporating best practices, and making any necessary policy and process improvements. Key developments include the 2005 NASA Authorization Act, that established cost and schedule growth thresholds that trigger Congressional notification and reporting requirements. In 2009, House Appropriaitons Committee report language triggered the Government Accountability Office (GAO) to execute an annual assessment of major NASA projects (defined as costing > $250M). Two years later, NASA chartered the 2011 Explanation of Change Study and the 2012 Flagship Programmatic Assessment.

---

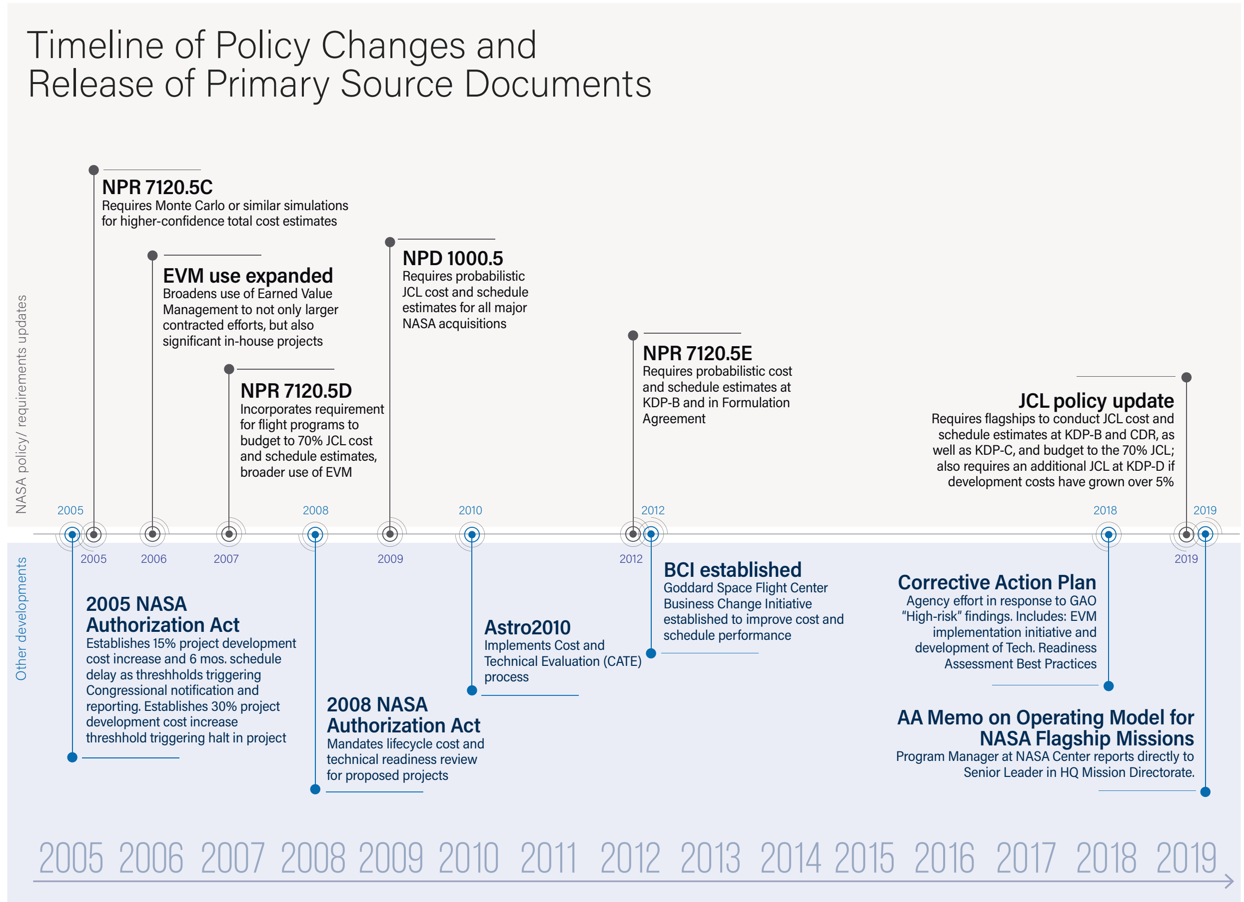
[4] Note: Not every large or $1 billion or greater cost mission is a large strategic mission. Some Principal Investigator-led missions (e.g. New Frontiers missions) exceed $1 billion in lifecycle cost but, because they do not meet the other characteristics for a large strategic mission, they do not fit the category of missions that were the focus of this study.

** For more information about KDP-C please see NPR 7120.5E: https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E*

Previous studies recognized that NASA and its stakeholders had faced significant turning points in the 2010s. A 2012 NASA Office of Inspector General (OIG) report, for example, described a challenging fiscal environment and the Agency experiencing a "crossroad for future direction" at the end of the Shuttle era. The Astrophysics community has built toward the long-awaited launch of JWST while processing the lessons learned from its cost and schedule overruns and also preparing for the 2020 Astrophysics Decadal Survey. One view into this discussion was provided at a session on mission costing at the 2019 USRA Symposium, "The Space Astrophysics Landscape for the 2020s and Beyond."

Overall, the assessment found that NASA had made a series of improvements to its cost and program management practices based on lessons learned on previous large strategic missions. Some process improvements were captured in NASA Procedural Requirement (NPR) 7120.5E, while others were prescribed in "how to" documents such as the NASA Space Flight Project and Program Management Handbook and the NASA Cost Estimating Handbook.

However, the assessment also uncovered a set of remaining challenges very consistent with those that had emerged from the LMS interview phase. These challenges have both technical and cultural roots. Among many others, they include the difficulty of effecting cultural change across different organizations, the "uniqueness" of large missions, and the ways in which optimism is valued and rewarded within NASA.



Developed as part of the assessment of previous studies, this timeline captures a subset of key updates to NASA policy and requirement documents, as well as external developments tied to cost and programmatic performance, in 2005 - 2020.

SMD COST AND SCHEDULE PERFORMANCE

Independent consultant Gary Rawitscher conducted an assessment of SMD missions' cost and schedule performance over the last 20 years. The assessment covered missions of all sizes, from Explorer-class projects to large missions, that had closed books on their development costs. This background not only provided important context, but allowed for enhanced and informed discussion among the Core Team and participants during the LMS Workshop.

The two data sets reviewed in the assessment include:

- SMD Resource Management Division data on Phase C/D cost/schedule performance vs. KDP-C[5] commitments since the 70% JCL rule[6] was established in March 2006 and codified in NPR 7120.5D in 2007
- An Aerospace-Corporation-collected data set on Phase B/C/D cost/schedule performance vs. KDP-A and KDP-B estimates for missions launched since 2000, with comparisons of performance before and after the new JCL rules came into effect

A review of these data sets produced the following top-level **conclusions**:

- Cost overruns for launched missions have not gotten worse recently.
- Cost overages vs. KDP-C commitments have been somewhat smaller for missions launched in the past few years vs. the early post-70%-CL/7120.5D period.
- Cost overruns of formulation estimates have diminished for projects that have launched under the new policies implemented in 2006.
- While formulation phase growth rates have been lower since the new rules were implemented, project

[5] Refer to NPR 7120.5, which defines the mission phases and key decision points.
[6] Joint Cost and Schedule Confidence Level (JCL) analysis is an integrated uncertainty analysis of cost and schedule. It can be used to estimate the level of confidence that a project will meet both its cost and schedule commitments. In 2006 the Agency implemented a policy of budgeting to a 70% level of confidence based on JCL analysis.

costs are still growing, and average growth of 20% or more vs. both KDP-A estimates and KDP-B estimates is still substantial. Formulation growth is particularly striking compared to post-new-rules growth of only 2.9% vs. the Agency Baseline Commitment during implementation. Thus, it is clear that SMD needs to focus on improvements during formulation if we are to make significant future progress in reducing overages/slips.

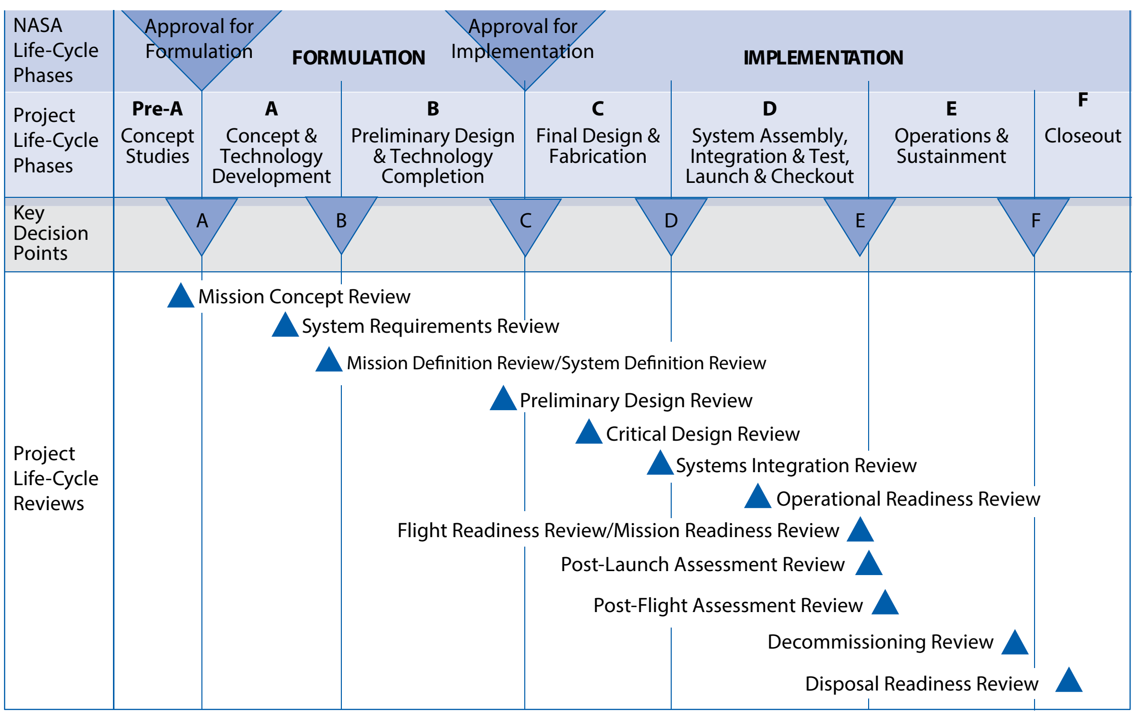
- Project size alone is not a predictor of the size of a project's percentage overrun.
- There's no significant trend of an increase in the number of missions slipping.

Mars Science Laboratory (MSL) / Curiosity Rover and Parker Solar Probe (PSP) were SMD's only large strategic missions that had been developed under the 70% JCL rule and had completed development at the time of the study. Of these two, MSL experienced a significant overrun after missing its initial launch window, whereas PSP actually underran its Agency budget commitment. Although, as indicated above, "Project size alone is not a predictor of the size of a project's percentage overrun," it is obvious that an overrun on a large mission is more expensive than an equal percentage overrun on a smaller mission. Typically, the main consequence of a large strategic mission overrun is to delay the next large strategic mission in that Division's queue. This delays the implementation of the Nation's highest science priorities and keeps large segments of the community in a holding pattern, often for several years.

STUDY MANAGEMENT

The LMS Core Team commenced work in October 2019, and presented its findings and recommendations to the SMD Leadership Team in October - November 2020. After the study was complete, the SMD Associate Administrator directed the SMD Deputy Associate Administrator for Programs to develop the implementation plan in response to the study. That implementation plan, approved by SMD, is provided within the Appendix.

SIMPLIFIED PROJECT LIFE CYCLE



The LMS Core Team (members and consultants) consisted of the following personnel:

LMS TEAM MEMBERS AND CONSULTANTS
Sandra Connelly (Sponsor) Deputy Associate Administrator, SMD
John Gagosian (Chair) Deputy Director, SMD Joint Agency Satellite Division
Peg Luce (Deputy Chair) Deputy Director, SMD Heliophysics Division
Mike Henry (Study Manager) Policy Analyst, SMD Policy Branch
Mike Blythe (Ex Officio) NASA Program Management Improvement Office
Richard Cook Associate Director, JPL
Jeanette Edelstein Interview Transcription, SMD Contractor
Laura Delgado Lopez Policy Analyst, SMD Policy Branch
Rachel Morrow Facilitator/ SMD Consultant, Booz Allen Hamilton
Curt Niebur Program Scientist, SMD Planetary Science Division
Joe Pellicciotti Deputy Chief Engineer, NASA
Gary Rawitscher SMD Consultant
Aki Roberge Research Astrophysicist, GSFC Astrophysics Division
Rich Ryan Program Business Manager, Mars Sample Return
Steve Shinn Acting Chief Financial Officer, NASA
Britney Smith Facilitator/ SMD Consultant, Booz Allen Hamilton

Additional contract support was required to provide subject matter expertise in study facilitation, workshop planning, transcription, and technical writing.

Study Phases

Study Process:
Phase 0 – Phase 1 – Phase 2

The following sections provide an in-depth review of the phased approach executed by the LMS Leads, Study Manager, and Core Team.

- **Phase 0:** Establish Core Team and Study Plan
- **Phase 1:** Conduct research and interviews to identify specific problems to be solved
- **Phase 2:** Develop findings and recommendations focusing on the highest-priority problems

STUDY PHASE 0:

Core Team members were recruited by Study Leads based on the recommendations of leaders within SMD, GSFC, and JPL. As seen in the "**Study Management**" section of this report, the team included experts across various disciplines and NASA organizations, and collectively had decades of experience in management, support, research, and engineering of large missions. The team was diverse across demographics, institutional affiliation, and expertise.

STUDY PHASE 1:

Literature Review:

As the Study commenced, the Core Team received access to an extensive collection of source documents. These materials ranged from independent assessments of individual large projects to more general investigations of NASA processes. Core Team members studied these documents in preparation for the interviews described below and requested the support of an SMD Senior Policy Analyst to review, analyze, and summarize the source documents for future discussion.

This literature review yielded a wide set of both explicit and implicit findings and recommendations from the source material. These outputs were organized into themes to facilitate further discussion and the highlights of the analysis are captured above in "**Overview of Previous Studies.**" As stated, not all recommendations were specific to large missions, but the analysis established a very useful baseline of information as Core Team members proceeded in planning and executing their interviews and analysis.

Interviews:

The Core Team collaboratively assembled a diverse list of subject matter experts to interview. The team's diversity criteria included space sector (civil, commercial, defense), competency area (science, program management, engineering, etc.), institutional affiliation (NASA HQ, NASA Center, Federal Agency, Federal Lab, Private Company, University), career stage, science theme, mission affiliation, and other demographic factors. The Core Team ultimately agreed on a slate of 21 interviewees.

All interviewees agreed to be recorded so that the Core Team could review their statements later. However, all statements made by the interviewees were and are considered NASA internal pre-decisional data. The LMS Core Team assured the interviewees that any material generated from the interviews would remain non-attributional.

Each interviewee received interview questions in advance, though the interviews were not limited to those questions. Each interview lasted two to three hours and was conducted either in-person or using a virtual conference-based platform because of travel limitations.

Participation was limited to Study Leadership, Core Team members, a transcriptionist, and additional contractor support. A full list of questions can be found in **Appendix (B)**. To the right is a list of interviewees and their affiliations at the time of the Study.

Interview Transcript Analysis:

At the conclusion of the interviews, over 50 hours of recordings and 600 transcript pages were submitted to the Core Team for further evaluation. From this effort the Core Team's objective was to then identify common themes, conclusions, and recommendations from the set of interviews. The Core Team's analysis of the transcripts utilized a feedback-capture tool that captured over 1400 takeaways (i.e., statements of fact, opinions, and/or recommendations) from the interviews.

The 1400 takeaways were classified into 10 general themes. Then, similar takeaways were grouped and combined to yield 74 unique "problem statements" describing the key challenges

LARGE MISSION STUDY

Interviewees + Affiliation

PRIVATE SECTOR

- Jim Crocker — Lockheed Martin (Retired)
- Jim Oschmann — Ball (Retired)
- Tom Young — NASA, Lockheed Martin (Retired)

ACADEMIA

- Phil Christensen — Arizona State University
- Marcia Rieke — University of Arizona
- Maria Zuber, — Massachusetts Insitute of Technology (MIT)

GOVERNMENT

- John Durning — NASA GSFC
- Orlando Figueroa — NASA (Retired)
- Jo Gunderson — NASA (Retired)
- Jason Hylan — NASA GSFC
- Mike Menzel — NASA GSFC
- Paul Shawcross — U.S. Office of Management and Budget
- Eleanor Silverman — National Reconnaissance Office (NRO), former NASA
- Ed Weiler — NASA (Retired)
- Jeremy Weirich — former U.S. Senate Appropriations Committee
- Geoff Yoder — NASA (Retired)

FFRDCS & UARCS

- Bob Bitten — Aerospace Corporation
- Barry Goldstein — Jet Propulsion Laboratory (JPL) (Retired)
- Mike Ryschkewitsch — NASA (Retired), Johns Hopkins Applied Physics Lab
- Pete Theisinger — Jet Propulsion Laboratory (JPL)
- Valerie Thomas — Jet Propulsion Laboratory (JPL)

LEGEND: PRIVATE SECTOR; ACADEMIA; GOVERNMENT; FEDERALLY FUNDED RESEARCH AND DEVELOPMENT CENTERS (FFRDCS) AND UNIVERSITY AFFILIATED RESEARCH CENTERS (UARCS)

EXCERPTS FROM LMS INTERVIEWEES

> “Design problems are baked into the cake at the start, and not uncovered until you have eaten half the cake.

> “Flagships can meet all the PDR success criteria but still not be ready for implementation.

> “Humans are bad at accurately assessing complexity.

> “The sponsor is always going to ask, ‘Well, what new is required to accommodate this payload?’ And you don’t know that list… There’s a whole bunch of things that you don’t know yet, that will come up later and will cost you resources and time. So you’ll be compensated, but you will not be made whole. And the design problems will remain.

involved in executing large strategic missions. These problem statements and the 10 themes provided context for moderated breakout sessions during the workshop event that initiated Phase 2 of the study. A full list of the themes can be seen below, and full definitions can be found in **Appendix C: Themes and Definitions**.

10 LMS Study Interview Themes:

1. Governance
2. Culture, Sociology, and Psychology
3. Cost Estimation and Project Funding
4. Project Planning and Control
5. Reviews
6. External Stakeholder Relations
7. Capabilities: Workforce and Infrastructure
8. Contracting and Acquisitions
9. Technical Risk Mitigation
10. Technical Management and Systems Engineering

LMS WORKSHOP

The conclusion of Phase 1 offered an opportunity to receive input from the wider community of experts who had not participated in that phase.

Study leadership engaged a contractor team to provide tailored planning, facilitation, and execution for what was originally planned to be an in-person multi-day interactive workshop. However, the team quickly pivoted their planning efforts to a remote format in the wake of the COVID-19 pandemic. This shift towards a virtual solution resulted in a half-day workshop utilizing a WebEx training platform.

Workshop Preparation + Execution

Following the LMS interviews, the LMS Team, in coordination with contract support, planned and executed an LMS virtual workshop on June 24, 2020. The purpose of the workshop was to discuss the Phase 1 findings with key subject matter experts and stakeholders, in order to inform the focus of the reminder of the study.

All Phase 1 assessments, including the distilled interview takeaways, the SMD cost and schedule performance assessment, and the analysis of previous studies, were shared with participants; and each session included a question and answer and discussion component.

Following the general presentations, the Core Team members led breakout groups, which were held in separate virtual WebEx rooms with external secretaries to capture feedback and discussion. Each breakout group covered two of the LMS 10 interview takeaway themes; their primary task was to review the relevant problem statements and provide an opportunity for feedback, edits, and discussion on the statements. Breakout groups were organized by the following themes:

	BREAKOUT GROUP THEMES (TWO THEMES PER GROUP)
G1	A. Governance B. Culture, Sociology, & Psychology
G2	A. Cost Estimation & Project Funding B. Project Planning and Control
G3	A. Review B. External Stakeholder Relations
G4	A. Capabilities: Workforce & Infrastructure B. Contracting & Acquisition
G5	A. Technical Risk Mitigation B. Technical Management & Systems Engineering

The workshop was highly effective, based both on Core Team feedback and responses from participants to a post-workshop satisfaction survey. The insights, questions, and comments gained from the approximately 50 attendees were instrumental in shaping Phase 2.

STUDY PHASE 2

Deep Dive Team Formulation

Following the workshop, and based partly on the discussion there, the Core Team prioritized the problem statements to identify those with the greatest impact on the successful execution of large strategic missions. The highest-priority problem statements were then grouped into two categories: Formulation and Governance. These two sets of problem statements then served as the basis for two Deep Dive Analyses that were conducted over the following two months.

The Formulation Deep Dive Analysis focused on problems encountered during the pre-formulation and formulation phases of projects, such as architecture trades, technology development, requirements definition, cost modeling, etc. The Formulation Analysis was led by Mark Clampin (Director of the GSFC Exploration Science Directorate) and Jeanne Davis (SMD Astrophysics Division Associate Director for Flight). The Governance Deep Dive Analysis focused on cultural, organizational, and political issues, many of them above the project level. The Governance Analysis was led by Orlando Figueroa and Mark Saunders (both NASA Retired). The Deep Dive Analysis Leads were responsible for assembling their own teams, but each Deep Dive team utilized a study manager from the Core Team to ensure alignment between the Deep Dives and the end goals of the Large Mission Study. Aki Roberge managed the Formulation Analysis and Mike Henry managed the Governance Analysis.

The Deep Dive teams had access to the entire Phase 1 data set assembled by the Core Team. The Deep Dive Leads conducted periodic meetings with the LMS Study Lead in order to clarify scope and requirements, eliminate roadblocks, and ensure progress toward delivery of the final Deep Dive Analysis reports. The two Deep Dive teams used different methodologies to study the material and develop findings, but both provided extremely useful reports to the Core Team. Each Deep Dive Analysis Report contained specific recommendations that the Core Team considered in formulating the overall LMS recommendations.

Key Findings + Recommendations

DEVELOPING FINDINGS & RECOMMENDATIONS

After receiving the Deep Dive Analysis reports, the Core Team conducted detailed discussions with the Deep Dive Leads to explore the rationale for the Deep Dive conclusions. These discussions provided an open and healthy dialogue regarding potential solutions to the problems under study. In some cases, there was overlap or disagreement between the two Deep Dive Teams' conclusions, and the Core Team had to reconcile them. Ultimately, the Core Team considered the combined output of the Deep Dive Analyses, applied its own judgment and experience, reviewed the complete data set acquired over the one-year LMS study period, and developed a final integrated set of 10 findings and recommendations.

The Core Team's findings and recommendations are not prioritized. Each pairing of findings and recommendations should be reviewed, assessed, and evaluated in tandem to ensure that the intent is accurately interpreted. The recommendations are as follows:

I PRE-PHASE A TEAM COMPOSITION

FINDING: The Pre-Phase-A period, in which Decadal Survey Recommendations are turned into decisions on mission architectures, preliminary requirements, and budget estimates, is absolutely critical to project success. But because the missions are not yet "projects," the teams doing Pre-Phase-A work do not receive enough priority or visibility, and they do not have the right competencies to do this critical work.

RECOMMENDATION:

Formulate Pre-Phase-A teams with the following characteristics:

- They are populated through a nationwide leadership search. Balance the need to "promote from within" against the mandate to find the very best talent available for missions of National importance and the value of new and diverse ideas. Don't just look at the pool of project managers who are "available" at a center.
- They contain experts on manufacturing, integration & test, verification & validation, and operations. This will ensure architecture trades are fully informed.
- They are streamlined to facilitate collaboration and rapid decision-making.
- They are composed with succession planning in mind, i.e., to ensure continuity over the 15 – 30 years between Decadal Survey and launch.

II PRE-PHASE A ARCHITECTURE TRADES AND DESCOPE OPTIONS

FINDING: During the Pre-Phase-A period, requirements development and architecture trades are often over-constrained, driving the mission unnecessarily toward very expensive solutions. For example, for years the Europa mission was focused on a very expensive orbiter rather than the current multiple-flyby architecture. Likewise, Spitzer also carried a very expensive architecture for years before being forced to reconceptualize. But once expectations are set at KDP-A, it will be too late to make any changes without serious political risks.

RECOMMENDATION:

- Don't just accept the mission concept from the Decadal Survey. Conduct requirements analyses and architecture trades during pre-phase-A that quantify science vs. cost, thereby preventing unnecessary adoption of very expensive solutions. Explore a range of solutions that are faithful to the prioritized science goals, but which may incur lower risk. Maintain dialogue with Academy committees during this process to ensure the intent of the Decadal Survey is honored.
- Develop and document realistic descope options during Pre-Phase A, thereby giving SMD the tools it needs to ensure the KDP-A concept is executable.

III SYSTEM MATURITY ASSESSMENT

FINDING: Large missions are inherently complex, and the impact of that complexity on technology transition, manufacturing, integration & test, and operations is often woefully underestimated. During formulation NASA does not perform a sufficiently structured evaluation of how these complexities will affect each stage of the project lifecycle.

RECOMMENDATION: Establish SMD-specific criteria for Concept Maturity Level (CML)[7] and Manufacturing Readiness Level (MRL)[8] to complement the existing system of Technology Readiness Levels (TRLs). Use and periodically assess progress against these standards during pre-formulation and formulation. Utilize these standards at Key Decision Points (KDPs) to ensure projects do not proceed through 7120.5 milestones before key issues have been addressed.

SMD Deputy Associate Administrator for Programs (DAA/P) and SMD Chief Engineer should evaluate/tailor current CML and MRL standards for adoption by SMD

IV TECHNOLOGY INTEGRATION INTO COMPLEX SYSTEMS

FINDING: The current NASA standard for technology maturity, i.e., TRL-6 by PDR, is much too lenient for large missions. By the time a large mission gets to PDR, much flight hardware is already being built (e.g., mirror segments, detectors, and other long-lead items). Thus, there is significant risk of major cost impacts if technology problems necessitate redesigns to other elements of the system. In addition, even if we demonstrate that the individual technologies have reached TRL-6, there is no indication that the full suite of technologies, linked together in a complex mission system, will operate as designed.

---

[7] R. Wessen (JPL), C. Borden (JPL), J. Ziemer (JPL), J. Kwok (JPL), Space Mission Concept Development Using Concept Maturity Levels, AIAA SPACE 2013 Conference and Exposition
[8] Department of Defense, Manufacturing Readiness Level (MRL) Deskbook, 2018, http://www.dodm

RECOMMENDATION:

Move the current NASA TRL standard to the left for large missions

- *Technologies must achieve TRL-6 by MDR rather than current standard of PDR*

Establish a new system-level engineering demonstration standard for PDR for very missions

- *Technologies must be integrated into a system-level demonstration in a relevant environment by PDR*

Examples:

- *New detectors should be tested in an instrument ETU in a high-fidelity optical testbed*
- *Large deployable mechanisms should be tested at relevant scale with offloading and metrology*
- *The sampling system for a planetary lander/rover should be tested end-to-end*

V ANALYTICAL TOOLS

FINDING: Large and complex systems rely on smart management of performance margins and the use of modeling to verify system performance. But the integration of mechanical, thermal, and optical models has not been seamless, leading to long modeling cycles. And incorrectly defined performance margins can lead to expensive over-design (if margins are too large) or expensive re-design (if margins are too small)

RECOMMENDATION:

- Use new or existing SMD strategic technology program lines to fund the development of turnkey, anchored integrated modeling systems and other engineering tools to reduce analysis timelines.
- When systems utilize multiple partners/providers, specify the margin and risk philosophy as early as possible in the life cycle, to ensure the integrity of performance budgets.

VI COST AND SCHEDULE ESTIMATION

FINDING: Current methods of estimating cost & schedule rely on models that are not capable of fully predicting the cost & schedule uncertainty for unprecedented systems, especially when designs are preliminary. Early estimates often show a high degree of precision but have poor accuracy. This creates a false sense of confidence in early numbers and timelines, leading stakeholders to latch onto these inaccurate preliminary estimates, which can unrealistically constrain the project in later phases.

RECOMMENDATION:

Lifecycle cost estimates for large missions at MCR should be communicated outside of NASA in terms of categories or broad bins, not as overly precise point estimates with error bars.

- The lifecycle cost bins would be established in addition to the recently established categories for large missions ("Directorate" and "Agency")[1], to further distinguish missions in each large mission category.
- Potential lifecycle cost bins expressed in FY20$ might be the following (SMD should modify bins as appropriate):

  $1B – $3B
  $3B – $6B
  $6B – $10B
  >$10B

While ***lifecycle costs*** early in the project should only be broadly estimated, ***pre-formulation and formulation phase work content*** must be planned with as much detail and precision as possible, to enable accurate cost estimates of this early content and thus allow sufficient budgets to be allocated to complete these early phases.

At each milestone prior to KDP-B (assuming the more robust formulation process recommended by this study), the multiple independent lifecycle cost estimates commissioned by the Agency/SMD should focus only on achieving sufficient accuracy/precision to place the mission in a bin.

- Those estimated to be close to the top boundary of a bin should be either:
  - *Directed to reduce their scope or at least develop easily executable future descopes to ensure they stay in that bin, or*
  - *Placed in a higher bin.*

VII STANDING REVIEW BOARDS (SRBS)

FINDING: Standing Review Boards (SRBs) historically have been formed too late in the project life cycle to influence key early decisions. Also, the emphasis on filling every column in the table of expertise leads to SRBs with a large number of specialists and too few members who can focus on big-picture issues.

RECOMMENDATION:

SRBs for large missions should contain more scientists, project managers, and systems engineers--and fewer technical specialists--than they do currently.

- The big issues on large missions often center how all the complex parts fit together
- Rely on Center-chartered review teams to capture detailed technical issues at the subsystem or instrument level
- Continue to invite SRB members to Center-led reviews in order to maintain insight
- If detailed technical knowledge is required on the SRB, get that knowledge via consultants rather than full SRB members
- The membership of the SRB should evolve as the mission proceeds through the life cycle:
  - *To sustain the SRB independence through the long life cycle*
  - *To ensure the right skills are represented for different phases*

Note: The newly-established SMD policy of convening large strategic mission SRBs prior to MCR addresses the first part of the finding, i.e. that SRBs "are typically formed too late in the project life cycle."

[1] *Connolly, "SMD Flagship Implementation," presentation to NASA Agency Program Management Council, August 13, 2020.*

VIII INSTRUMENT SELECTION PROCESS

FINDING: Instrument selection for large missions relies on an AO process that is largely independent of the project and which often underestimates accommodation risks, based on (1) the immaturity of the technical baseline at the time of the competition and (2) the inherent limitations of the proposal evaluation process, in which the risk of each instrument is evaluated individually. After the selection is made, it may be a year or more before the project can fully quantify the technical, schedule, and cost impacts of the actual selected payload suite. In short, the purity of the selection process inhibits the effectiveness of the systems engineering.

RECOMMENDATION:

Reassess the instrument selection process for each large strategic mission. Tailor the process so that accommodation issues are balanced against science return and are appreciated before selection.

Identify ways for the project to become involved in the proposal evaluation and accommodation study processes as early as possible.

- *This will require the DAAR to consider changes to the competition model with nontrivial regulatory and policy implications that balance cost and procurement risk.*

Enable direct interaction during pre-phase A between potential instrument providers and the pre-project to evolve interfaces and accommodation on both sides.

- *This will require changes to the SDT model and resolution of any legal issues.*

IX SMD CAPABILITIES

FINDING: For large strategic missions, the Agency Operating Model specifies that Center-based project managers shall report programmatically and organizationally to program directors at NASA Headquarters. Center management is not part of the programmatic authority chain and therefore is not responsible for project performance against commitments. NASA has reassessed its Operating Model as recently as 2019 but has decided firmly against making any significant changes. This places a huge responsibility on the HQ-based program offices to provide oversight, direction, and independent assessment of projects. These HQ-based offices are small, and they depend on specific skills that are not adequately represented at HQ. This increases the risk that HQ's program function will not be done effectively, and that problems will lead to explosive cost and/or schedule growth before they are identified.

RECOMMENDATION:

The capabilities of the HQ-based program offices must be strengthened.

- A cadre of experienced programmatic analysis experts must be built and maintained in-house. Some of these can be found at the Centers. Others can be developed over time from the very best Program Analysts (PAs). Each HQ Program Office should have a Deputy Program Manager for Business with a staff of expert analysts.
- Draw from the entire NASA workforce when filling the Program Executive (PE) position on large missions. In other words, don't just pick the best available PE in the home division within SMD, but recruit from the whole Agency community of experts.
- Consider establishment of SL positions if necessary, to attract the best Program Scientist (PS) and PE candidates.

X CENTER CAPABILITIES

FINDING: It has never been more difficult to operate a Field Center. NASA's budget outlook is very dynamic. NASA's competition model leads Centers to focus disproportionately on winning and executing smaller missions, which diverts attention and resources from large mission success. The labor market is extremely competitive, with non-civil-space industries paying more to get the top talent. Facilities are decaying. Workforce demographics by age/experience are not healthy, with a huge retirement wave likely in the near future. Agency-level reorganization (i.e., MAP) has resulted in the Centers having less direct investment capability. And COVID-19 has presented serious employee safety challenges while affecting productivity in many areas. It is not surprising that Center Directors are unable to focus more on project performance. Although SMD is not directly responsible for maintaining the health of the Centers, SMD must collaborate with Centers to ensure that key capabilities exist there.

RECOMMENDATION:

SMD AA and Institutional Leadership (i.e., Center Directors, JPL Director, partner agency directors) must work closely together to identify and solve problems on large missions.

- *Initiate quarterly leadership meetings early in the project life cycle, i.e., during Pre-Phase-A.*
- *Quarterly leadership meetings should include SMD and all participating institutions, with partner agencies included as appropriate.*

SMD AA, Center Directors, and JPL Director must collaborate to assess and develop Institutional capability (e.g., workforce, expertise, facilities and infrastructure, etc.) necessary to accomplish current and future work.

- *Require analysis of Center and JPL workforce forecasts for use in the Pre-ASM and ASM processes.*
- *Jointly advocate for funding to maintain and develop core capabilities.*
- *Maintain/update the Tiers documents on a regular basis to reflect strategic priorities & desired future capabilities.*

Conclusion

The final Large Mission Study findings and recommendations are focused on addressing the most compelling problems that limit SMD's ability to set achievable commitments on its largest and most ambitious missions, and to meet those commitments. We hope they will help our project teams, leaders, and stakeholders to establish sound practices that increase our chances of success. However, of course, there is no "bullet-proof" process. Our success will always depend on strong decision-making that is based on careful analysis, honest dialogue, independent review, awareness of what we do not know, and the active encouragement of diverse voices and viewpoints.

As SMD continues to pursue an ambitious and inspirational series of large strategic missions, we must embrace their extreme challenges without shying away. But we must also be honest about the magnitude of the challenges. At NASA, optimism is one of our greatest strengths, but also the trait that frustrates our stakeholders the most. Our project managers are brilliant, but we cannot ask them to work miracles, and we should never give them requirements that far outstrip their resources.

We carry out large strategic missions because they lead to quantum leaps in human knowledge, and they perform technical feats that seem nearly impossible. Even more, they inspire future generations to push beyond the status quo. The reaction to the recent landing of Perseverance is just the latest example of our power to inspire. Let us continue to value and honor our privilege to do such things.

Acknowledgements

The SMD Large Mission Study could not have come to fruition without key contributions by literally dozens of people in the science and aerospace communities.

Aside from the Core Team, the heaviest lifting was done by the Deep Dive Analysis teams, whose insight during the second phase of the study provided much rich and thoughtful material from which the final LMS recommendations were derived. These were truly "all-star" lineups: The Formulation Deep Dive included Co-Leads Mark Clampin and Jeanne Davis in addition to Bob Bitten, Helen Cole, Jessica Gaskin, Patrick Hill, Jason Hylan, Aki Roberge, Rich Ryan, Elizabeth Turtle, and Charles Whetsel. The Governance Deep Dive included Co-Leads Orlando Figueroa and Mark Saunders in addition to Waleed Abdalati, William Craig, James Crocker, Tony Freeman, Barry Goldstein, Virginia Hall, Heidi Hammel, Mike Henry, Mark Jacobs, Trish Pengra, Louise Prockter, Steve Thibault, Nicholas White, Richard Cook, Mike Ryschkewitsch, Gary Rawitscher, and Ellen Stigberg.

Special thanks are also due to all the Phase 1 interviewees (identified above) who provided an immense treasure trove of insights to the Core Team during the first phase of the study. These wide-ranging, frank, stimulating, predominantly serious (but sometimes humorous) conversations were the "highlight of the week" for most members of the Core Team. We cannot thank the interviewees enough for their time, candor, enthusiasm, and positive intent. Thanks also to the dozens of experts whose thoughtful contributions during the June 2020 workshop were instrumental in interpreting the interview takeaways and focusing the scope of the second phase of the study.

Britney Smith, assisted by Rachel Morrow, provided expert insight and leadership in facilitating the workshop, the scoping of the Phase 2 effort, the finalization of recommendations, and the writing of this report. Nathan Trail kept the workshop running smoothly. Sean Robins provided database tools to analyze the interview takeaways. Frances Adiele and BeBe Ragsdale provided excellent writing and graphic design during the creation of this report. Special thanks to the SMD Heliophysics Division and Director Nicky Fox for funding this support from Britney and the entire Booz Allen Hamilton team.

Jeanette Edelstein's transcription, which involved hundreds of hours of in-person and post-interview listening and writing, was a monumental effort. She provided us with a data record that proved invaluable in Phase 2 of the study. And thanks to all the other transcribers from Angela Clark-Williams' team at Electrosoft who provided a definitive record of the workshop in June 2020.

Key early advice came from Rob Woods, who helped to conceptualize the study at the very beginning, and Mike Blythe, who provided excellent perspective from his current Agency role and his past leadership of the 2012 Flagship Assessment Team.

SMD Deputy Associate Administrator for Programs Wanda Peters led a very collaborative and open conversation to develop the implementation plan that is included as an appendix to this report. She led a diverse set of experts from across the Agency, including members of the LMS Core Team, in the development of practical steps to put the LMS recommendations into practice.

The idea for this study originated from SMD Deputy Associate Administrator Sandra Connelly. She was an early and consistent champion of the study, and she provided sustained guidance that ensured that it stayed on target. However, despite her keen interest in the study and its results, she provided the Core Team with complete autonomy to execute the study and to develop final recommendations. Her support and trust were key factors enabling the team to discuss very difficult issues, many of which ventured into the cultural and political arenas. No topic was off-limits. Sandra and SMD Associate Administrator Thomas Zurbuchen have built an organization that values learning and truth-telling, and it is only within such a framework that this study could achieve any real value. For this we are most grateful.

Appendices

Implementation Plan
Interview Questions
10 Themes + Definitions
Recommendation Matrix
Cost and Schedule Assessment graphics
Literature Review Timeline
Terms of Reference (ToR)


National Aeronautics and
Space Administration
NASA
EXPLORE
SCIENCE
SMD Large Missions Study Implementation Plan
Dr. Wanda C. Peters
Deputy Associate Administrator for Program, Science Mission Directorate
April 2021

SMD Large Mission Study Implementation Plan Team

- **Purpose**: To evaluate the findings from the Science Missions Directorate (SMD) Large Mission Study (LMS) for implementation, which will be used to make SMD more successful at delivering large strategic missions on time and within budget

LMS Implementation Team Members			
Wanda Peters (Chair)	SMD Deputy AA for Programs	**Mayra Montrose**	SMD Asst. Deputy AA for Programs
Mike Blythe	Office of NASA AA	**Michael New**	SMD Deputy AA for Research
Jeanne Davis	SMD Astrophysics Associate Director	**James Ortiz**	Office of NASA AA
John Gagosian	HQ Joint Agency Deputy Dir./LMS Chair	**Gregory Robinson**	SMD JWST Program Director
Jeffrey Gramling	SMD MSR Program Director	**Richard Ryan**	SMD MSR Program Business Manager
Marc Greenberg	OCFO/Strategic Investments Division	**Joan Salute**	SMD Planetary Associate Director
Garth Henning	OCFO/Strategic Investments Division	**Magdiel Santana**	OCFO/Strategic Investments Division
Nicholas Jedrich	OCE/SMD Chief Engineer	**Joseph Smith**	SMD Heliophysics Program Executive
Peg Luce	SMD Heliophysics Deputy Director		
Center Representatives			
Dennis Andrucyk	GSFC Center Director	**Michael Watkins**	JPL Center Director
Anne Kinney	GSFC Deputy Center Director	**Leslie Livesay**	JPL Associate Director

2


SMD Large Mission Study
Implementation Principles
• Focus implementation on most important problems/issues
• Don’t attempt to change things that cannot be changed
• Seek input from the diverse spaceflight community
• Direct recommendations specifically to SMD leadership
• Ensure recommendations are limited, specific, actionable, and impactful
• Share final findings and recommendations broadly and openly
3

SMD Large Missions Study Implementation Plan

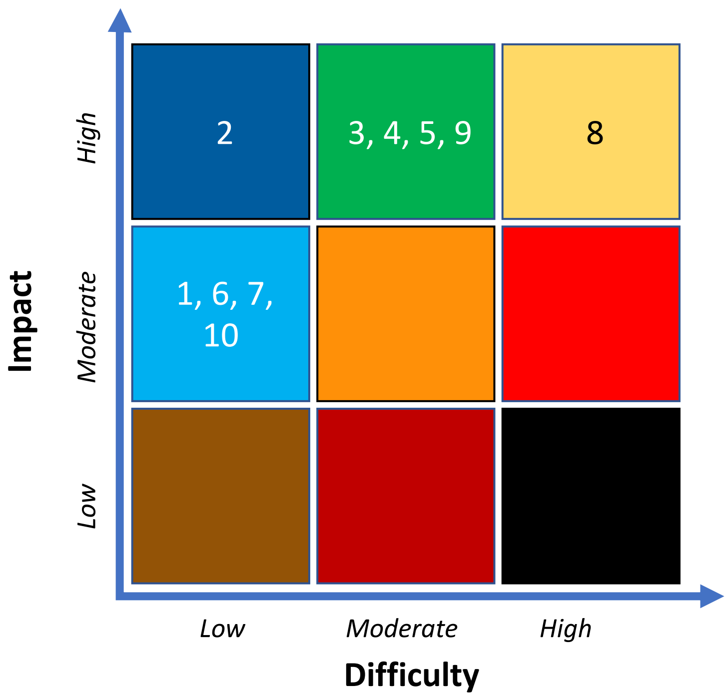
- The LMS implementation plan is intended for ***Large "Strategic" Missions*** in the Science Mission Directorate. Determination of applicability to a given mission will be made during mission pre-formulation

- NASA has defined ***Large "Strategic" Missions*** as having several of the following characteristics:
  - ✓ Responsive to a high priority identified by the National Academies (typically through a decadal survey)
  - ✓ Defines our Nation's scientific, technological, and industrial leadership on the world stage
  - ✓ Are strategic Agency priorities with high visibility and a demonstration of leadership (Large stakeholder interest)
  - ✓ High complexity (interfaces, deployments, new technologies, many contributing partners/organizations) requiring SMD AA engagement
  - ✓ Requires Agency-wide prioritization to enable focused execution
  - ✓ Technically challenging and scientifically groundbreaking,
  - ✓ Represents entirely new architectures that have not been flown before
  - ✓ Directed to a specific institution for development
  - ✓ Life Cycle Cost greater than $2 billion (*as defined in NPR 7120.5F*)

- SMD LMS Implementation team's approach
  - ✓ Utilized the principles established by the LMS team
  - ✓ Discussed primary lessons learned from prior and current large strategic missions in the development of this implementation plan

In this plan, all mandatory actions (i.e., requirements) are denoted by statements containing the term "shall." The terms "may" or "can" denote discretionary privilege or permission; "should" denotes a good practice and is recommended but not required; "will" denotes expected outcome; and "are/is" denotes descriptive material.

Classification of Recommendations from the Large Missions Study



No.	Recommendation Title
1	*Pre-Phase A Team Composition*
2	*Pre-Phase A Architecture Trades and Descope Options*
3	*System Maturity Assessment*
4	*Technology Integration into Complex Systems*
5	*Analytical Tools*
6	*Cost and Schedule Estimation*
7	*Standing Review Boards (SRBs)*
8	*Instrument Selection Process*
9	*SMD Capabilities*
10	*Center Capabilities*

5

Bottom Line Up Front – SMD Large Missions Study Implementation Plan

No.	Large Missions Study Recommendation	Disposition	Large Missions Study Implementation Plan
1	*Pre-Phase A Team Composition*	Accept	Staffing will be based on needed skill sets and expertise (not based on availability of personnel). An Agency-wide search shall be conducted, followed by a nationwide search, if needed
2	*Pre-Phase A Architecture Trades and Descope Options*	Accept	Program Office will conduct independent assessment of Pre-Phase A architecture trades and descope options for evaluation at KDP-A. Implementation effective immediately.
3	*System Maturity Assessment*	Accept w/Follow-Up	Further action is required. A team, sponsored by the SMD DAA/P and led by the SMD Chief Engineer, will be formed for further investigation.
4	*Technology Integration into Complex Systems*	Partially Accept	Mandate increased scrutiny of technology maturity at reviews and KDPs. Implementation effective immediately. Further action is required - A strategic approach will be developed by the SMD Chief Technologist to identify technology needs and funding sources for technology development.
5	*Analytical Tools*	Partially Accept	Large strategic missions will incorporate common tool sets, when possible, and establish an agreed margin and risk philosophy with partners and providers early in the life cycle.
6	*Cost and Schedule Estimation*	Accept	Life cycle cost estimates shall be communicated in terms of bins for Pre-Phase A and ranges for Phases A and B to set external expectations. Implementation effective immediately.
7	*Standing Review Boards (SRBs)*	Accept	The SMD policy of convening the SRBs prior to MCR, and when required, convening of the Independent Review Boards (IRBs), has already been implemented. Initiating SRB kickoff meetings.
8	*Instrument Selection Process*	Partially Accept w/Follow-Up	Further action is required. A team led by the SMD Deputy AA for Research will be established. Modification of SMD policy may be required.
9	*SMD Capabilities*	Accept	Program Offices of large missions will be adequately staffed early in pre-formulation in order to perform programmatic assessments and oversight. Implementation effective immediately.
10	*Center Capabilities*	Accept	SMD and Centers have ownership and accountability of large strategic missions and will work closely to identify and solve problems. Implementation effective immediately.

The SMD Large Missions Implementation Plan will require an intentional shift in how we approach the development of our missions

6

1. Pre-Phase A Team Composition

Finding from LM Study	Recommendation from LM Study	Implementation Plan – Accept
The Pre-Phase-A period, in which Decadal Survey Recommendations are turned into decisions on mission architectures, preliminary requirements, and budget estimates, is absolutely critical to project success. But because the missions are not yet "projects," the teams doing Pre-Phase-A work do not receive enough priority or visibility, and they do not have the right competencies to do this critical work.	Formulate Pre-Phase-A teams with the following characteristics: 1. They are populated through a nationwide leadership search. Balance the need to "promote from within" against the mandate find the very best talent available for missions of National importance and the value of new and diverse ideas. Don't just look at the pool of project managers who are "available" at a center. 2. They contain experts on manufacturing, integration & test, verification & validation, and operations. This will ensure architecture trades are fully informed. 3. They are streamlined to facilitate collaboration and rapid decision-making. 4. They are composed with succession planning in mind, i.e., to ensure continuity over 15 – 30 years between Decadal Survey and launch.	**Pre-Phase A (Project Team):** • Formulation team shall be established based on skill sets and expertise required for the formulation and implementation of complex mission architecture/design • Selection of project leadership teams will be based on expertise in designing, managing and developing a complex mission architecture/design (not based on the availability of personnel). An Agency-wide search shall be conducted, followed by a nationwide search, if needed • Succession planning will be utilized when composing the team to ensure continuity of knowledge over the mission's life span • The Project Manager, who will be responsible for execution of the mission, shall be selected and leading the team by KDP-A **Pre-Phase A (Program Office):** • SMD large strategic missions will have a dedicated Program Director and Program Office that resides at NASA Headquarters • Program Offices will provide oversight, direction, and independent programmatic assessment of the mission throughout the life cycle. • Program Offices should be adequately staffed (e.g., Program Director, Deputy Program Directors for Technical & Business, and Program Executive(s)/Mission Manager(s))

7

2. Pre-Phase A Architecture Trades and Descope Options

Finding from LM Study	Recommendation from LM Study	Implementation Plan – Accept
During the Pre-Phase-A period, requirements development and architecture trades are often over-constrained, driving the mission unnecessarily toward very expensive solutions. For example, for years the Europa mission was focused on a very expensive orbiter rather than the current multiple-flyby architecture. Likewise, Spitzer also carried a very expensive architecture for years before being forced to reconceptualize. But once expectations are set at KDP-A it will be too late to make any changes without serious political risks.	1. Don't just accept the mission concept from the Decadal Survey. Conduct requirements analyses and architecture trades during pre-phase-A that quantify science vs. cost, thereby preventing unnecessary adoption of very expensive solutions. Explore a range of solutions that are faithful to the prioritized science goals, but which may incur lower risk. Maintain dialogue with Academy committees during this process to ensure the intent of the Decadal Survey is honored. 2. Develop and document realistic descope options during Pre-Phase A, thereby giving SMD the tools it needs to ensure the KDP-A concept is executable.	**During Pre-Phase A** • Requirement analyses and architecture trades will be conducted to quantify science in comparison to cost (clearly identifying mission requirements) • Descope options will be developed and documented during Pre-Phase A and evaluated at KDP-A to determine realism and feasibility of options • Program Office will ensure that independent assessments of architecture trades and descope options are conducted **At KDP-A** • Pre-Phase A architecture trades and descope options will be evaluated at KDP-A for assessment of mission concept maturity, technology maturity, risks, cost and schedule realism, and project maturity, to enable the making of early decisions and programmatic adjustments

Descope options need to be continually evaluated, not just at KDP-A, because situations, such as cost exceedance, schedule exceedance, or technical issues driving cost or schedule exceedances, require the enacting of the option(s)

8

3. System Maturity Assessment

Finding from LM Study	Recommendation from LM Study	Implementation Plan – **Accept w/Follow-up**
Very large missions are inherently complex, and the impact of that complexity on technology transition, manufacturing, integration & test, and operations is often woefully underestimated. During formulation NASA does not perform a sufficiently structured evaluation of how these complexities will affect each stage of the project life cycle.	Establish SMD-specific criteria for Concept Maturity Level (CML)* and Manufacturing Readiness Level (MRL)** to complement the existing system of Technology Readiness Levels (TRLs). Use and periodically assess progress against these standards during pre-formulation and formulation. Utilize these standards at Key Decision Points (KDPs) to ensure projects do not proceed through 7120.5 milestones before key issues have been addressed. • SMD DAA/P and SMD Chief Engineer should evaluate/tailor current CML and MRL standards for adoption by SMD *R. Wessen (JPL), C. Borden (JPL), J. Ziemer (JPL), J. Kwok (JPL), *Space Mission Concept Development Using Concept Maturity Levels*, AIAA SPACE 2013 Conference and Exposition **Department of Defense, *Manufacturing Readiness Level (MRL) Deskbook*, 2018, http://www.dodmrl.com	• Requires additional investigation by a team that is sponsored by the SMD DAA/P and led by the SMD Chief Engineer in collaboration with Center Engineering Directors and Chief Engineers to determine engineering readiness and system maturity at different phases of the project life cycle • Implementation will require creation or modification of NASA policies and practices • The SRBs and Agency/Industry consultants or subject matter experts will be engaged to assess the maturity of engineering and manufacturing readiness • **ACTIONS REQUIRED**: 1. Investigation of feasibility (e.g., subjective interpretation of maturity and readiness levels, consistency of application) 2. Determine return on investment (e.g., reduction of risk, improved accuracy of system maturity assessment) 3. Evaluate and tailor current CML and MRL standards for adoption by SMD 4. Clarify maturity and readiness expectations for the projects and the SRBs

9

4. Technology Integration into Complex Systems

Finding from LM Study	Recommendation from LM Study	Implementation Plan – Partially Accept
The current NASA standard for technology maturity, i.e., TRL-6 by PDR, is much too lenient for very large missions. By the time a very large mission gets to PDR, much flight hardware is already being built (e.g., mirror segments, detectors, and other long-lead items). Thus, there is significant risk of major cost impacts if technology problems necessitate redesigns to other elements of the system. In addition, even if we demonstrate that the individual technologies have reached TRL-6, there is no indication that the full suite of technologies, linked together in a complex mission system, will operate as designed.	1. Move the current NASA TRL standard to the left for very large missions • Technologies must achieve TRL-6 by **MDR** rather than current standard of **PDR** 2. Establish a new **system-level** engineering demonstration standard for PDR for very large missions • Technologies must be integrated into a system-level demonstration in a relevant environment by PDR • Examples: a) New detectors should be tested in an instrument ETU in a high-fidelity optical testbed b) Large deployable mechanisms should be tested at relevant scale with offloading and metrology c) The sampling system for a planetary lander/rover should be tested end-to-end	Maturity of technologies for large strategic missions should be achieved as early as possible in the life cycle of the mission, requiring significant investments in Pre-Phase A • Adequate funding and sufficient phasing of funding for technology development and technology maturity are required early in the project life cycle • *LMS Recommendation #1* – Not Accepted – Moving the current NASA TRL standard to the left (e.g., MDR) for very large missions. Technology maturity by MDR should be established as a goal, not a requirement • *LMS Recommendation #2* – Accepted – Increased scrutiny of technology maturity will be required at reviews and shall be enforced at KDPs • Focus shall be placed on ensuring TRL-6 is achieved by instrument or payload level PDR, prior to mission-level PDR, and will be strictly enforced for large strategic missions as an entrance criteria for the mission PDR • **ACTION REQUIRED**: The SMD Chief Technologist shall develop a strategic approach for identifying technology needs for large strategic missions as reflected in the Decadal Survey, communicating current investments (if any) in the identified technology areas, and, if no investments currently exist, shall include needed technologies as part of SMD's investment priorities

10

5. Analytical Tools

Finding from LM Study	Recommendation from LM Study	Implementation Plan – Partially Accept
Very large and complex systems rely on smart management of performance margins and the use of modeling to verify system performance. But the integration of mechanical, thermal, and optical models has not been seamless, leading to long modeling cycles. And incorrectly-defined performance margins can lead to expensive over-design (if margins are too large) or expensive re-design (if margins are too small).	1. Use new or existing SMD strategic technology program lines to fund the development of turnkey, anchored integrated modeling systems and other engineering tools to reduce analysis timelines. 2. When systems utilize multiple partners/providers, specify the margin and risk philosophy as early as possible in the life cycle, to ensure the integrity of performance budgets.	Maturing of integrated modeling systems, other engineering tools and programmatic tools is needed. Selection of tool sets should be made with emphasis placed on the ability to collaborate among large mission partners and team members • *LMS Recommendation #1* – Not Accepted – The types of engineering tools envisioned by this recommendation have broad applicability across all of NASA's mission directorates (SMD, HEOMD, STMD, ARMD). Therefore, SMD is engaging with NASA's Office of Chief Engineer about ways to implement an Agency-wide solution to address the need for these tools. Because we have not yet explored all options for partnering with other NASA organizations, it is not prudent for SMD, at this time, to divert resources from existing technology investments toward tools development. • *LMS Recommendation #2* – Accepted – A margin and risk philosophy is needed as early as possible in the life cycle to ensure the integrity of performance budgets. However, a standardized margin and risk philosophy is not recommended. Large missions should incorporate a common tool set, when possible, and establish an agreed margin and risk philosophy with partners and providers early in the life cycle There are multiple layers to the finding that are outside the control of SMD. Aspects of this recommendation are being worked on multiple fronts (e.g., by Centers, Digital Transformation Efforts, OCE – Model Based Engineering, OCFO). SMD will monitor the activities associated with the integration of analytical tools for impacts to SMD missions

11

6. Cost & Schedule Estimation to External Stakeholders

Finding from LM Study	Recommendation from LM Study	Implementation Plan – Accept
Current methods of estimating cost & schedule rely on models that are not capable of fully predicting the cost & schedule uncertainty for unprecedented systems, especially when designs are preliminary. Early estimates often show a high degree of precision but have poor accuracy. This creates a false sense of confidence in early numbers and timelines, leading stakeholders to latch onto these inaccurate preliminary estimates, which can unrealistically constrain the project in later phases.	1. Lifecycle cost estimates for large missions at MCR should be communicated outside of NASA in terms of categories or broad bins, not as overly precise point estimates with error bars. a) The lifecycle cost bins would be established in addition to the recently established categories for large missions ("Directorate" and "Agency"), to further distinguish missions in each large mission category b) Potential lifecycle cost bins expressed in FY20$ category might be the following (SMD should modify bins as appropriate): • $1B – $3B; $3B – $6B; $6B – $10B; >$10B c) While ***lifecycle costs*** early in the project should only be broadly estimated, ***pre-formulation and formulation phase work content*** must be planned with as much detail and precision as possible, to enable accurate cost estimates of this early content and thus allow sufficient budgets to be allocated to complete these early phases d) At each milestone prior to KDP-B (assuming the more robust formulation process recommended by this study), the multiple independent lifecycle cost estimates commissioned by the Agency/SMD should focus only on achieving sufficient accuracy/precision to place the mission in a bin. • Those estimated to be close to the top boundary of a bin should be either: 1. Directed to reduce their scope or at least develop easily executable future descopes to ensure they stay in that bin 2. Placed in a higher bin	Focus is placed on how early life cycle cost (LCC) estimates are communicated to external stakeholders. Pre-formulation and formulation phase work content must be planned with as much detail and precision as possible, to enable accurate cost estimates of early mission content. Cost estimates shall include realistic and supportable levels of uncertainty, which reflects mission complexity and risk postures **During Pre-Phase A (Pre-Formulation)** • Cost estimates shall be communicated to external entities in broad terms such as life cycle *cost bins* – Cost bins will reflect estimates' levels of uncertainty, and will be modified or adjusted, as appropriate **During Phases A & B (Formulation)** • LCC estimates shall be communicated to external stakeholders as *target cost ranges* (in Phase A) & *probabilistic cost estimates* (in Phase B), each informed by the project's cost estimate and one or more independent cost estimates (e.g., SRB) – A SMD large mission with an estimated Phase B LCC greater than or equal to $2 billion shall develop a joint cost and schedule confidence level (JCL) and provide ranges for cost and schedule based on the corresponding 70% JCL values or as approved by the Decision Authority (per NPR 7120.5F)

This implementation plan applies to missions with a LCC >$2B (Category 1 missions as defined in NPR 7120.5F). Bins and ranges also applies to early schedule estimates

12

7. Standing Review Boards

Finding from LM Study	Recommendation from LM Study	Implementation Plan – Accept
Standing Review Boards (SRBs) historically have been formed too late in the project life cycle to influence key early decisions. Also, the emphasis on filling every column in the table of expertise leads to SRBs with a large number of specialists and too few members who can focus on big-picture issues.	1. SRBs for large missions should contain more scientists, project managers, and systems engineers--and fewer technical specialists--than they do currently. • The big issues on large missions often center how all the complex parts fit together • Rely on Center-chartered review teams to capture detailed technical issues at the subsystem or instrument level • Continue to invite SRB members to Center-led reviews in order to maintain insight • If detailed technical knowledge is required on the SRB, get that knowledge via consultants rather than full SRB members • The membership of the SRB should evolve as the mission proceeds through the life cycle: ✓ To sustain the SRB independence through the long-life cycle ✓ To ensure the right skills are represented for different phases	**Large Mission Review Boards** • SMD shall continue to utilize and engage SRBs, emphasizing board formation early in the life cycle of large strategic missions to ensure influence of key early decisions and expansion of SRB scope to include Independent Review Board (IRB) expectations/scope, when appropriate • SMD, with concurrence from other convening authorities, will improve SRB composition and identified needed skill sets for the board, with a focus on diversity of experience in the required competencies • With large strategic missions, there is a natural turnover of SRB member. Membership will be monitored by SMD (DAA/P) to determine if intentional changes in membership are needed **During Pre-Phase A (Pre-Formulation)** • SRB Chair and Deputy Chair shall be identified early in the pre-formulation process, focusing on leadership skills for the chair and succession planning for selection of the deputy chair • Specialized technical subject matter experts (SMEs) will be engaged primarily as consultants to the SRB. However, when needed, Technical SMEs will serve as full SRB members • Kickoff meetings shall be held with SRB membership and SMD leadership (e.g., AA, DAA, or DAA/P) to set expectations

Note: The newly-established SMD policy of convening the SRB prior to MCR addresses the first part of the finding, i.e., that SRBs "are typically formed too late in the project life cycle." SMD will continue to utilize Independent Review Boards (IRBs) when appropriate.

13

8. Instrument Selection Process

Finding from LM Study	Recommendation from LM Study	Implementation Plan – Partially Accept w/Follow-up

Instrument selection for large missions relies on an AO process that is largely independent of the project and which often underestimates accommodation risks, based on (1) the immaturity of the technical baseline at the time of the competition and (2) the inherent limitations of the proposal evaluation process, in which the risk of each instrument is evaluated individually. After the selection is made, it may be a year or more before the project can fully quantify the technical, schedule, and cost impacts of the actual selected payload suite. In short, the purity of the selection process inhibits the effectiveness of the systems engineering.	1. Reassess the instrument selection process for each flagship mission. Tailor the process so that accommodation issues are balanced against science return and are appreciated before selection.
	2. Identify ways for the project to become involved in the proposal evaluation and accommodation study processes as early as possible.
	• This will require the DAA/R to consider changes to the competition model with nontrivial legal and policy implications that balance cost and procurement risk
	3. Enable direct interaction during pre-phase A between potential instrument providers and the pre-project to evolve interfaces and accommodation on both sides
	• This will require changes to the SDT model and resolution of any legal issues
		The SMD instrument selection process is very fair. However, it may not adequately accommodate systems engineering needs. Further action is required for addressing this recommendation. A team led by the SMD Deputy AA for Research should be formed for further investigation
		For Pre-Phase A (Pre-Formulation)
		• Strict firewalls shall be set-up and maintained early in the pre-formulation process, when possible. Firewalls must address organizational conflict of interest and potential legal or procurement issues. This is required for the pre-project team to be involved in the proposal evaluation and accommodation study processes
		• Systems Engineers should be required as members of the pre-project team during Pre-Phase A to define accommodations and interfaces
		Areas for Further Consideration
		• Investigate how pre-project offices can be closely involved in instruments proposal evaluation:
		  • Where strong firewalls can be structured, allow others within the home institution to propose instruments to the projects
		  • Where credible firewalls cannot be structured, prohibit home institutions from competing for instrument with the possibility of directing one or more instrument(s) to the home institution
		• Evaluation of instrument selection approaches for large strategic missions (e.g., instrument first versus spacecraft first; establishment of standard interface definitions)
		• Establishment of viable descope approach or process

14

9. SMD Capabilities

Finding from LM Study	Recommendation from LM Study	Implementation Plan – **Accept**
For large missions, the Agency Operating Model specifies that Center-based project managers shall report programmatically and organizationally to program directors at NASA Headquarters. Center management is not part of the programmatic authority chain and therefore is not responsible for project performance against commitments. This places a huge responsibility on the HQ-based program offices to provide oversight, direction, and independent assessment of projects… These HQ-based offices are small, and they depend on specific skills that are not adequately represented at HQ. This increases the risk that HQ's program function will not be done effectively, and that problems will lead to explosive cost and/or schedule growth before they are identified.	1. The capabilities of the HQ-based program offices must be strengthened • A cadre of experienced programmatic analysis experts must be built and maintained in-house. Some of these can be found at the Centers. Others can be developed over time from the very best Program Analysts (PAs). Each HQ Program Office should have a Deputy Program Manager for Business with a staff of expert analysts. • Draw from the entire NASA workforce when filling the Program Executive (PE) position on large missions. In other words, don't just pick the best available PE in the home division within SMD; recruit from the whole Agency community of experts. • Consider establishment of SL positions if necessary, to attract the best Program Scientist (PS) and PE candidates	• Although Center-based project managers report programmatically and organizationally to program directors at NASA Headquarters, center management still have programmatic responsibilities for ensuring projects meet their performance commitments • Program Offices of large strategic missions should be adequately staffed in order to perform programmatic assessments and oversight • Each Program Office should have a Deputy Program Manager for Business • The need for and phasing of expert analysts will be determined by the Deputy Program Manager for Business and the analysts will be matrixed from RMD, OCFO, or contracted via the PP&C contract • If needed, an Agency-wide recruitment for the PE positions may be conducted, focusing on individuals with experience working complex, large missions • Consideration for the establishment of SL positions for PEs or PSs shall be based on mission specific needs, not as a recruitment tool, and requires Agency (NASA AA) level approval

Adequate funding, especially with appropriate phasing in Pre-Phase A, Phase A and Phase B, is critical for large strategic missions

15

10. Center Capabilities

Finding from LM Study	Recommendation from LM Study	Implementation Plan - Accept
It has never been more difficult to operate a Field Center. NASA's budget outlook is very dynamic. NASA's competition model leads Centers to focus disproportionately on winning and executing smaller missions, which diverts attention and resources from large mission success. The labor market is extremely competitive… Facilities are decaying. Agency-level reorganization (i.e., MAP) has resulted in the Centers having less direct investment capability. It is not surprising that Center Directors are unable to focus more on project performance. Although SMD is not directly responsible for maintaining the health of the Centers, SMD must collaborate with Centers to ensure that key capabilities exist there.	1. SMD AA and Institutional Leadership (i.e., Center Directors, JPL Director, partner agency directors) must work closely together to identify and solve problems on large missions • Initiate quarterly leadership meetings early in the project life cycle (i.e., during Pre-Phase-A) • Quarterly leadership meetings should include SMD and all participating institutions, with partner agencies included as appropriate 2. SMD AA, Center Directors, and JPL Director must collaborate to assess and develop Institutional capability (e.g., workforce, expertise, facilities and infrastructure, etc.) necessary to accomplish current and future work • Require analysis of Center and JPL workforce forecasts for use in the Pre-ASM and ASM processes • Jointly advocate for funding to maintain and develop core capabilities • Maintain/update the Tiers documents on a regular basis to reflect strategic priorities & desired future capabilities	• Both SMD and Centers have ownership and accountability for the large strategic missions • The SMD AA and Center Directors will continue to work closely to identify and solve problems • SMD, Center, and Project leaderships will work together to balance science objectives against available resources • SMD's investment in Centers' capabilities will align with Tiers documents, reflecting the balance between strategic priorities and the desired capabilities necessary to accomplish current and future work for large missions • Senior Executive Dialogues and Senior Executive Quarterlies will be established early in the project life cycle, especially once prime contractors are under contract • Center workload capacity will be a major factor in assessing project performance as part of the acquisition strategy, particularly when multiple large missions are in development at the Center • Stakeholders must ensure projects receive an adequate and stable funding profile, particularly in the early stages of the project life cycle to enable the establishment of good architectures and the initiation of other preliminary work

Requires an intentional shift in culture that promotes the sharing of information in an open and inclusive manner

16


Thank you!
EXPLORE
with us

LARGE MISSION STUDY

Interview Questions

1. What has NASA done well in managing large strategic missions? Please give examples from specific missions.

2. What has NASA not done well in managing large strategic missions? Please give examples from specific missions.

3. How well does the current NASA project management process (i.e. NPR 7120.5) enable effective management of large missions? What changes would you recommend, if any?

4. What can be done during formulation to improve execution of the implementation phase?

5. What can be done to enable more efficient execution to minimize cost of large missions?

6. What can be done to prevent the over-optimism and/or political pressure that has historically led to unrealistic cost and schedule baselines?

7. How well do current independent review processes enable effective management of large missions? What changes to review processes would you recommend, if any?

8. (If not covered above) Do we have the right approach to:
    a. technology management?
    b. risk management?
    c. cost estimation?

9. Are there capability issues with Centers, industry, or international partners that negatively impact our ability to establish and meet commitments? If so, what is the nature of the capability issues?

10. What are the top three things that NASA HQ could do to facilitate the success of large strategic missions?

11. What are the top three things that NASA Centers could do to facilitate the success of large strategic missions?

12. What are the top three things that political actors and policymakers like Congress and the Executive Branch could do to facilitate the success of large strategic missions?

13. What recommendations do you have for better structuring NASA projects in terms of acquisition strategy and contract management?

14. What are the best incentives, if any, to improve performance of contractors and/or Centers?

15. How can NASA facilitate collaboration between NASA, contractors, and partners to improve performance?

16. What recommendations do you have for better structuring NASA interagency or international agreements to improve performance?

17. What recommendations do you have for improving communications and coordination within NASA to improve performance?

18. What recommendations do you have for improving communications and coordination with external stakeholders to sustain support for our programs and projects?

19. How well has NASA implemented the recommendations from past assessments and reports? What has improved? What has stayed the same (or gotten worse)?

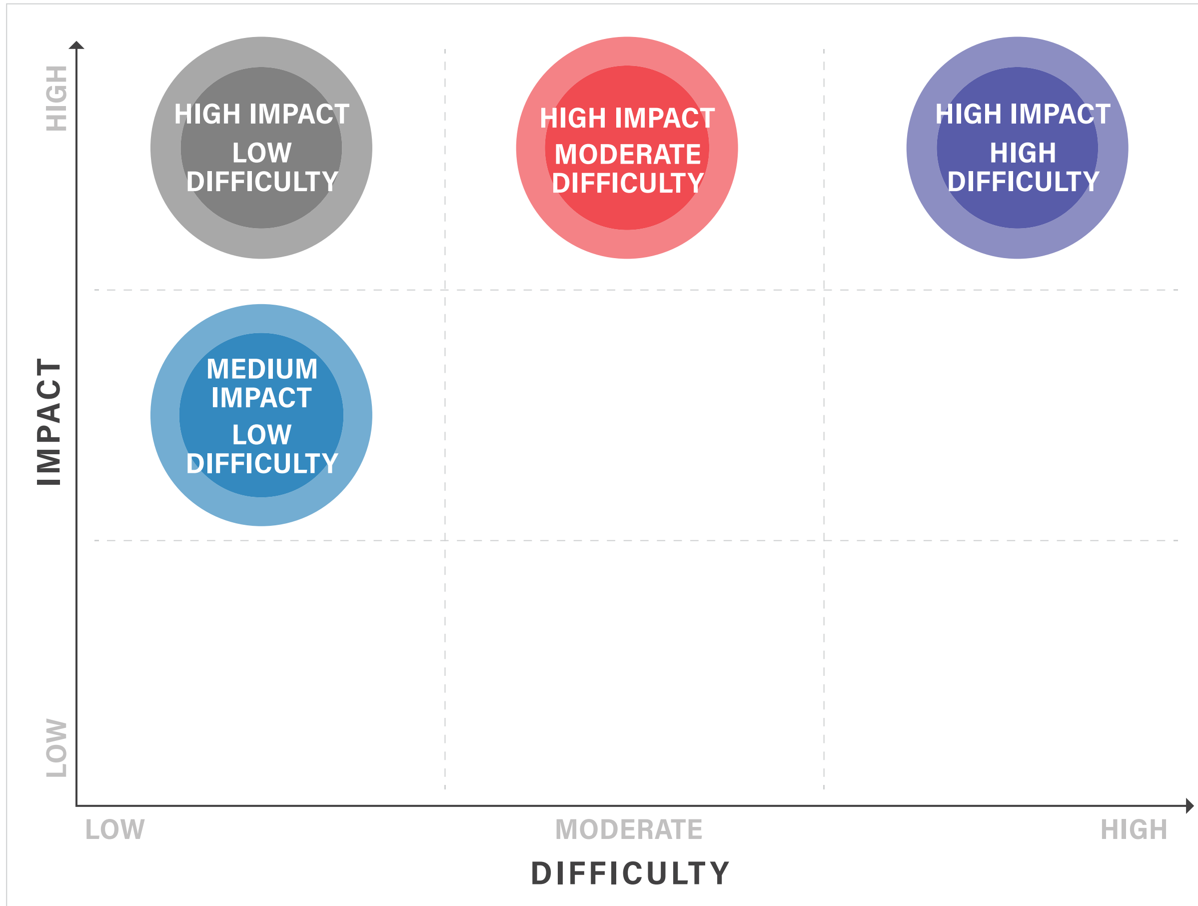
APPENDIX C: THEMES + DEFINITIONS

Theme	Definition and/or Examples
Governance	The structure within which Centers, Program Offices, Mission Directorates, and Agency leadership make key decisions, provide direction and oversight to projects, and implement a system of organizational checks and balances. Includes the specific authorities, responsibilities, and relationships of each entity in this process.
Culture, Sociology, and Psychology	Real-world "human factors" and behaviors of organizations (and the people in them) that have a direct impact on management effectiveness and project performance. Includes strategies to facilitate communication, collaboration, and rational decision-making.
Cost Estimation and Project Funding	The process by which funding (NOA) requirements and cost are (1) estimated by the project, program, and independent organizations; (2) documented for reviews and KDPs; and (3) used in the generation of annual budgets during PPBE. Applies to the entire period starting with pre-decadal studies and culminating at project closeout.
Project Planning and Control	The process by which project work is planned, and performance against that plan is monitored and assessed. These functions include Scheduling, EVM, Contractor Insight and Oversight.
Reviews	The process by which the project and decision authorities gain insight and make decisions (including KDPs) through the use of independent review teams. Includes Center-chartered teams (such as engineering peer reviews and IRTs), SRBs, and special ad-hoc review teams (such as WIETR, ICRP, etc.).
External Stakeholder Relations	The process by which NASA engages with each of its key external stakeholders to understand and manage their expectations and then to deliver the project to meet or exceed these "managed expectations." Includes engagement with external stakeholders such as OMB, Congress, the National Academies, advisory committees, the science community, and others.

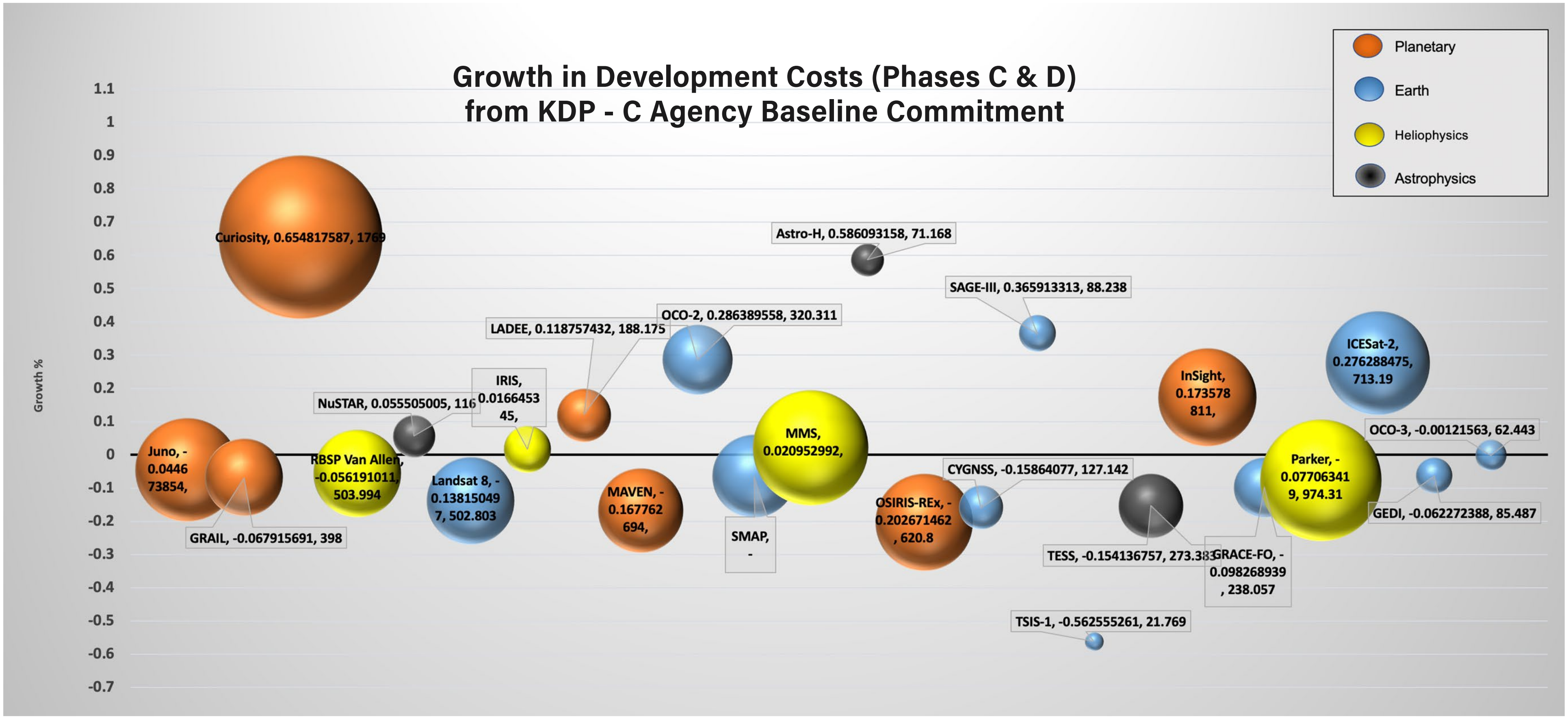
Theme	Definition and/or Examples
Capabilities: Workforce and Infrastructure	Technical capabilities of the Government, academic, and contractor communities, particularly as applied to specialized disciplines and facilities critical to success of large missions. Includes the way technical experts collaborate to find innovative solutions, as well as their ability to implement those solutions via available tools, processes, skillsets, and expertise. Also includes the facilities and infrastructure available to the Government, academic, and contractor communities, and investments in long-term sustainment. Also includes the way "knowledge capture" and "lessons learned" processes are applied to ensure the success of future projects.
Contracting and Acquisitions	The process by which acquisition strategy is defined, solicitations are created, selections are made, and contractors are incentivized. Includes the specific roles of the Project, Program, Center, Mission Directorate, and Agency.
Technical Risk Mitigation	The processes by which technical risk is managed, whether that risk is driven by technology or by complex engineering developments. This includes the process by which technologies are matured, adopted into a mission design, developed into producible flight designs, and qualified. It also includes analytical and laboratory methods for demonstrating the successful operation of complex systems, even when those systems don't include "technology" items. Further includes development of new manufacturing capabilities.
Technical Management and Systems Engineering	Management of System Performance Budgets, Requirements Management, Configuration Management, Data Management, Probabilistic Risk Assessment, etc.

RECOMMENDATIONS

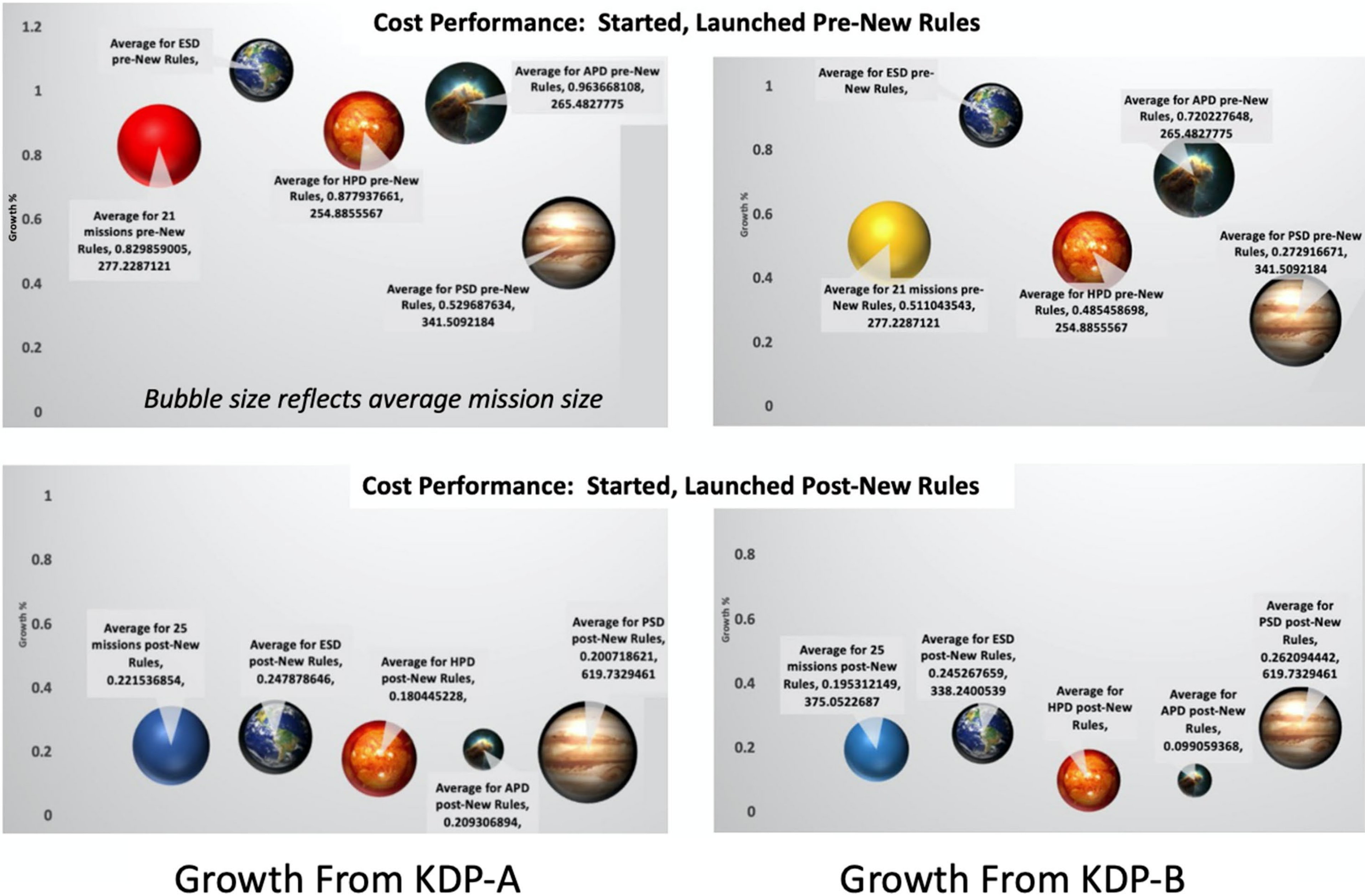
- Pre-Phase A Architecture Trades and Descope Options
- System Maturity Assessment
- Technology Integration into Complex Systems
- Analytical Tools
- SMD Capabilities
- Pre-Phase A Team Composition
- Cost and Schedule Estimation
- Standing Review Boards (SRBs)
- Center Capabilities
- Instrumental Selection Process



The key findings and recommendations presented to Senior SMD Leadership were categorized using a matrix: IMPACT (Low, Moderate, High) on the y axis and DIFFICULTY (Low, Moderate, High) on the x axis. Note: the classification of the recommendations in the matrix was a tool to inform future in-depth conversations regarding potential implementation, and not a reflection of prioritization or urgency. The categorizations of impact vs. difficulty are subjective and based on the expertise and opinions of the Core Team and Leads. Please see a full review of the themes and categories in the Recommendation section of the report.



SMD Missions since 7120.5D, arranged by Launch Date (earliest to the left, to most recent to the right)


Cost Performance: Started, Launched Pre-New Rules
1.2
1
0.8
0.6
0.4
0.2
0
Growth %
Average for ESD pre-New Rules,
Average for APD pre-New Rules, 0.963668108, 265.4827775
Average for HPD pre-New Rules, 0.877937661, 254.8855567
Average for 21 missions pre-New Rules, 0.829859005, 277.2287121
Average for PSD pre-New Rules, 0.529687634, 341.5092184
Bubble size reflects average mission size
Average for ESD pre-New Rules,
Average for APD pre-New Rules, 0.720227648, 265.4827775
Average for PSD pre-New Rules, 0.272916671, 341.5092184
Average for 21 missions pre-New Rules, 0.511043543, 277.2287121
Average for HPD pre-New Rules, 0.485458698, 254.8855567
Cost Performance: Started, Launched Post-New Rules
0.8
Average for 25 missions post-New Rules, 0.221536854,
Average for ESD post-New Rules, 0.247878646,
Average for HPD post-New Rules, 0.180445228,
Average for PSD post-New Rules, 0.200718621, 619.7329461
Average for APD post-New Rules, 0.209306894,
Average for 25 missions post-New Rules, 0.195312149, 375.0522687
Average for ESD post-New Rules, 0.245267659, 338.2400539
Average for HPD post-New Rules,
Average for APD post-New Rules, 0.099059368,
Average for PSD post-New Rules, 0.262094442, 619.7329461
Growth From KDP-A
Growth From KDP-B

APPENDIX F: LITERATURE REVIEW TIMELINE SOURCE DOCUMENTS

2010

Controlling Cost Growth of NASA Earth and Space Science Missions
National Research Council; July 2010

James Webb Space Telescope (JWST) Independent Comprehensive Review Panel
Webb ICRP; October 2010

2011

Project Tracking and Reporting Team (PTRT) Study
NASA; October 2011

2012

Programmatic Assessment of Selected Flagship Projects – Preliminary Results
NASA, Aerospace Corporation; March 2012

NASA's Challenges to Meeting Cost, Schedule, and Performance Goals
NASA Office of Inspector General; September 2012

2013

Cost and Schedule Growth in NASA Missions: Finding and Recommendations from the Explanation of Change Study and Flagship Mission Assessment
NASA, Aerospace Corporation; January 2013

Mars Science Laboratory: Lessons Learned Study
NASA; October 2013

2017

WIETR Individual Member Independent Report
Rawitscher; September 2017

WFIRST Independent External Technical/Management/Cost Review (WIETR)
WIETR; October 2017

2018

Breaking the cost curve: applying lessons learned from the James Webb Space Telescope development to built more cost-effective large space telescopes in the future
Feinberg et al, GSFC and contractors; 2018

Agency Program Management Council: JWST Replan with Independent Review Board briefing
June 2018)

Explanation of Change Study Update to Examine the Cost, Schedule, and Technical Changes to NASA Projects
GSFC and Aerospace Corporation; 2018

2019

Space Astrophysics Landscape for the 2020s and Beyond – Universities Space Research Association
Presentations by Figueroa (NASA, ret.), Storrie-Lombardi (NASA JPL), Dressler (Cargenie Observatories), Mountain (AURA, Inc.); April 2019

NASA: Assessment of Major Projects 2019
Government Accountability Office (GAO); May 2019

[Clipper] Planetary Instruments Cost Study: Post-PDR Update
NASA; May 2019

The LUVOIR Final Report - Chapter 12: Management and Systems Engineering August 2019

Challenges and Potential Solutions to Develop and Fund NASA Flagship Missions
Bitten et al, GSFC and Aerospace Corporation; 2019

2020

JWST Technical Challenges Have Caused Schedule Strain and May Increase Costs
GAO; January 2020

NASA: Assessment of Major Projects 2020
GAO; April 2020

Terms of Reference (TOR)

SMD Large Mission Study (LMS)

Submitted by:

7/31/19

John Gagosian
Deputy Director (Acting), Joint Agency Satellite Division
Science Mission Directorate
NASA Headquarters

Date

Approved by:

7/31/19

Thomas H. Zurbuchen
Associate Administrator
Science Mission Directorate
NASA Headquarters

Date

Terms of Reference (TOR)

SMD Large Mission Study (LMS)

1. Background

SMD's approach to program and project management is multifaceted and based upon continuous evaluation and improvement. Some recent large strategic missions have failed to meet their cost, schedule, and/or technical performance commitments. These cases highlight the many challenges involved in establishing realistic and achievable commitments for large strategic missions and in implementing within those commitments.

NASA and SMD have recently chartered a number of studies and assessments of large strategic missions, many of them specifically focused on individual missions. The studies have yielded important findings and recommendations, but further effort is required to develop general findings and recommendations that will help SMD establish more reliable commitments at KDP-C and keep those commitments in the future. All activities related to project conception and execution should be considered, including the decadal survey process, strategic technology investments, and science community engagement.

For the purposes of this study, large strategic missions are defined as missions with the characteristics listed below. These characteristics are similar to those outlined by the National Academies in *Powering Science: NASA's Large Strategic Science Missions* (National Academies Press, 2017). See Appendix B.

- Lifecycle cost greater than $1 billion;
- Responsive to a high priority identified by the National Academies (typically through a decadal survey);
- Directed to a specific institution for development;
- Technically challenging and scientifically groundbreaking.

The following are some examples of large strategic missions recently or currently in development:

- Mars Science Laboratory (MSL) / Mars Curiosity rover;
- Parker Solar Probe (PSP);
- James Webb Space Telescope (JWST);

3

- Mars 2020;
- Europa Clipper; and
- Wide Field Infrared Survey Telescope (WFIRST).

The findings and recommendations of this study will improve decision, management, and review processes across SMD.

2. Team and Management

The SMD Large Mission Study (LMS) Team, commissioned by the Associate Administrator for the Science Mission Directorate (SMD AA), will steer and support the LMS, carry out its activities, and decide on findings and recommendations. The Team will be led by an SMD Deputy Division Director with support from SMD, OCE, OCFO, GSFC, and JPL.

Team members will include, but are not limited to, the following:

- Team Lead / SMD Deputy Division Director
- Study Manager/Coordinator from SMD Policy Branch
- SMD Front Office Representative
- SMD Senior Scientist
- Senior Program Manager
- GSFC Senior Representative
- JPL Senior Representative
- Office of the Chief Engineer Representative
- Senior Consultant and Subject Matter Expert (SME)

The SMD Deputy AA for Programs (DAAP) will oversee the study, as needed, and final study findings and recommendations will be presented to the SMD AA and DAAP. SMD senior staff and Center leadership will maintain insight into study activities as described in Section 7. The results are also expected to be shared outside SMD after delivery to the SMD AA.

The Team's findings and recommendations will be determined by consensus of the members of the LMS team, relying significantly on inputs from tiger teams as described in Section 4.

The confidentiality of the sources for all inputs to the study will be protected as much as feasible throughout the study, and each member of the Team will agree to respect and enforce such confidentiality.

3. Purpose

The purpose of this study is to make and implement selected recommendations to ensure that SMD is more successful at delivering large strategic missions on time and within budget. The study will examine how NASA makes critical decisions during pre-formulation and formulation (Pre-Phase-A through Phase B) that either enable or prevent mission success. And it will examine how NASA addresses problems during implementation (Phases C through F), when solution space is limited and delays are expensive.

The study is intended to answer the following questions:

1. What are the characteristics/attributes of large strategic missions that lead to optimal project cost, schedule, and technical performance?
2. What are the characteristics/attributes of large strategic missions that lead to poor project cost, schedule, and technical performance?
3. Are technical and management processes (risk management, cost estimation, technology management, engineering peer reviews, etc.) being applied effectively to large strategic missions?
   a. If not, why not?
   b. If these processes are being applied properly, but without the intended results, then should these processes be modified?
4. Do NASA's internal policy, oversight, and communication processes support informed and timely decision making? If not, why not?
5. How can NASA improve its communication and coordination with external stakeholders (e.g., other USG entities, partners, Congress, scientific community) to preserve stakeholder support and facilitate mission success?
6. Are there specific or generic capability issues with Centers, industry, or international partners that negatively impact the establishment of realistic commitments at KDP-C and successful implementation within those commitments?

4. Scope of Work / Study Approach

The Team is open to examine all NASA activities on large strategic missions including initial concept studies, early formulation documents, acquisition strategy and make-buy decisions, technology selection and development approaches, design stability and maturation, key decision point (KDP) documents, interactions with Standing Review Boards, the KDP-C process, programmatic oversight (including the use of Earned Value Management), government/contractor interactions at the working and executive levels, risk management, etc. The Team will begin by reviewing previous studies, reviewing relevant project and Agency documents, and performing interviews with approximately 10 to 15 very senior project management experts with NASA experience. These interviews will inform a workshop with panel discussion(s) to provide maximum input and identify items for further investigation. Focus areas for further and more in-depth investigation will be assigned to "tiger teams" drawn from the Team and/or other SMD, Center, and external personnel. The number of tiger teams is expected to be five or fewer. The end product of the study will be a set of findings and recommendations to be presented to the SMD AA, senior SMD leadership, and Center leadership. *The goal of the findings and recommendations is not to cover every aspect of executing large strategic missions, but rather to recommend a limited number of actions that will have the greatest impact on NASA's future performance on these projects.* After the findings and recommendations are accepted by the SMD AA, the Team will provide outbriefs to other HQ and Center staff.

5. Top-Level Schedule

Six-month study duration:

- **Phase 0: Form the LMS Team** (1 month)
- **Phase 1: Interviews-** Current and recent project stakeholders (Internal, DOD/IC, Industry (Old and New Space)). Results of interviews will determine workshop content (2 months)
- **Phase 2: Workshop and Tiger Teams-** Panel discussion(s) of representative current and former large-scale missions, with PEs of flagship missions invited to explore topics from the interviews. Tiger teams will be formed to conduct further study on items identified during the workshop. (2 months)
- **Phase 3: Report-** Capture findings and recommendations in written and verbal briefings to leadership and broader stakeholder community. (1 month)

6. Resources Required

Contractor support may be required to provide subject matter expertise, study facilitation, interview transcription, and technical writing. Travel will also be required for interviews.

7. Deliverables

The Team's final report will consist of findings and recommendations related to each tiger team focus area. The findings and recommendations will contain sufficient depth to stand alone and to facilitate specific forward actions by SMD. Interview materials and results, as well as workshop content, will be provided as appendices to ensure clarity and depth of understanding for future readers. The content of the final report will be summarized and presented at DD, Program Manager, and PE forums.

6

During the course of the study, the Team Lead will provide written status reports to the SMD DAAP on a biweekly basis. The Team Lead will also conduct status telecons with SMD and Center senior staff to facilitate insight into study activities and to coordinate support and feedback as needed.

Appendix A:

Top-level actions:

1. Identify Team members, form the Team, and hold kick-off meeting
2. Coordinate Team review of previous applicable reports and assessments
3. Identify interviewees, formulate interview questions, and set interview format and schedule
4. Perform interviews and gather and assess results
5. Organize and conduct workshop with panel discussion(s)
6. Gather and assess workshop results and actions
7. Form tiger teams to further investigate selected focus areas
8. Coordinate tiger team investigations
9. Formulate findings and recommendations
10. Write final report with key deliverables

Appendix B:

Definition of Large Strategic Missions, according to *Powering Science: NASA's Large Strategic Science Missions,* National Academies Press, 2017:

NASA's Science Mission Directorate (SMD) operates dozens of spacecraft performing many different missions. The most high profile of these are the large strategic space science missions often referred to as "flagship" missions. These include missions such as the Hubble Space Telescope and the Chandra X-Ray Observatory, Curiosity rover, Magnetospheric MultiScale (MMS), and Terra Earth observation satellite. These missions typically are billion-dollar class missions, the most costly, the most complex, but also the most capable of the fleet of scientific spacecraft developed by NASA. They produce tremendous science returns and are a foundation of the global reputation of NASA and the U.S. space program. Large strategic missions are essential to maintaining the global leadership of the United States in space exploration and in science because only the United States has the budget, technology, and trained personnel in multiple scientific fields to conduct missions that attract a range of international partners. A large strategic mission can be a single spacecraft, or coordinated constellation, designed to achieve a set of science goals. All large missions are by definition strategic, but not all strategic missions are large. Large strategic missions are critical for the conduct of space science in each of NASA's four divisions (astrophysics, Earth science, heliophysics, and planetary science) and are required for the pursuit of the most compelling scientific questions.

Large strategic missions are directed by NASA to a specific institution to develop, although their instruments and subsystems are often competed. Large strategic missions tend to

7

- *Focus on reconnaissance and on conducting a broad suite of objectives;*
- *Have longer lifetimes and sustained attention to details regarding consistency of operations and calibration;*
- *Operate with an evolving science program that responds to what has been learned as the mission proceeds, as opposed to a more-fixed science program;*
- *Travel to hard-to-reach destinations or challenging environments; and*
- *Carry a large number of larger and heavier scientific instruments.*

In contrast, smaller missions generally

- *Focus on a single objective or on a small number of tightly related objectives;*
- *Travel to easier-to-reach destinations or to more benign environments; and*
- *Carry fewer and smaller instruments.*

These characteristics for large strategic and medium and small missions are not exclusive. For example, medium-size missions such as NASA's New Horizons spacecraft have traveled to hard-to-reach locations such as the edge of the Solar System. In addition, some medium and small spacecraft have had long lifetimes. But capabilities and lifetimes generally scale with the size and cost of a mission.

CHANGE LOG

Date	Event	Change	SMD Signature
7/31/19	Initial Release		[signature]

GRAPHICS

Graphic Name/Description	Section and Page Number
Phases and Timeline Overview	Executive Summary, page 2
Overview of Previous Studies Timeline Caption: Developed as part of the assessment of previous studies, this timeline captures a subset of key updates to NASA policy and requirement documents, as well as external developments tied to cost and programmatic performance, in 2005 - 2020.	Executive Summary, page 4
Mission Lifecycle	Executive Summary, page 5
Table of LMS Team Members and Consultants	Introduction, page 6
Table of Interviewees and Affiliation	Study Process, page 7
10 Study Themes	Study Process, page 8
Breakout Group Themes	Study Process, page 8
Recommendations – Impact vs. Difficulty Matrix	Key Findings and Recommendations, page 9

HYPERLINKS

Name/Description	Section and Page Number	Hyperlink
Recommendation Titles: Pre-Phase A Team Composition, Pre-Phase A Architecture Trades and Descope Options, System Maturity Assessment, Technology Integration into Complex Systems, Analytical Tools, Cost & Schedule Estimation to External Stakeholders, Standing Review Boards, Instrument Selection Process, SMD Capabilities, and Center Capabilities	Executive Summary, page 2	Hyperlink to Report "Recommendations"
7120.5	Executive Summary, page 5	Hyperlink to 7120.5: https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E
Study Management	Study Process, phase zero, page 7	Hyperlink to Report "Study Management"
Overview of Previous Studies	Study Process, phase one, page 7	Hyperlink to Report "Overview of Previous Studies"
Powering Science: NASA's Large Strategic Science Missions (National Academies Press, 2017)		Hyperlink to https://www.nap.edu/catalog/24857/powering-science-nasas-large-strategic-science-missions


NASA