

Evolving management strategies to improve NASA flagship’s cost and schedule performance: LUVOIR as a case study

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ABSTRACT

The large ultraviolet optical infrared surveyor (LUVOIR) study process has brought to fruition an extremely exciting scientific mission concept. The 3.5 year LUVOIR study duration enabled an unprecedented level of scientific, engineering, and technology thoroughness prior to the Astro2020 Decadal. This detail also shed light on many technical and programmatic challenges for efficiently developing a mission of this scale within the context of NASA’s flagships cost and schedule performances to date. While NASA’s flagships perform exquisitely once on-orbit, there is understandable growing frustration in their development cost and schedule overruns. We felt it incumbent upon ourselves to ask how we could improve on delivering LUVOIR (or any of NASA’s future flagships) on schedule and on budget, not just for the next mission, but for all NASA large strategic missions to come. We researched past and current NASA flagship’s lessons learned publications and other large government projects that pointed to some systemic challenges that will only grow with larger and more complex strategic missions. Our findings pointed us to some ways that could potentially evolve NASA’s current flagship management practices to help improve on their development cost and schedule performance despite their growing complexity. This paper briefly comments on the motivations for NASA’s flagships and on the science motivations for a LUVOIR-like mission. We argue the incentives for improving NASA’s flagships development cost and schedule performance. We review the specific additional challenges of NASA’s flagships to acknowledge their specific issues. We then examine the most repeated systemic challenges we found from previous NASA flagships and other large government projects lessons learned/observed. Lastly, we offer recommendations to tackle these repeated systemic challenges facing NASA’s flagships. The recommendations culminate into a proactive integrated development and funding framework to enable improving the execution of NASA’s future flagship’s cost and schedule performance.

Keywords: LUVOIR, NASA flagship missions, lessons-learned, project management, funding policy

1. INTRODUCTION

1.1 Motivation for NASA’s flagships:

The more we explore and the more the universe reveals, the more questions unfold. A recent study¹ assessed that the exploration and scientific return from NASA’s flagship missions are more than worth the effort and cost to overcome their challenges, and are critical and required for pursuing the most compelling science questions. NASA would be a different agency without the Apollo Program, Voyagers 1 and 2, the Hubble Space Telescope (HST), Chandra, and Cassini, to name a few. Their impact on NASA and humanity are unrivaled compared to any other NASA endeavors and their incentives speak for themselves.

1.2 Science motivations for a large, ultraviolet, optical, near-IR space observatory:

One of the basic, fundamental human questions is “Are we alone in the universe?” We have finally reached a point in our history where we can build a large space observatory that can directly image “pale blue dots” in other solar systems, and spectroscopically characterize the atmospheres of Earth-like planets in the habitable zone around sun-like stars. This will allow us to search for biosignatures – the signs of life – in our solar neighborhood in a statistically meaningful way^{2, 3-14}. Significant technology advancements^{2, 3, 6, 7, 15-29} have occurred over the last two decades that have brought us to this point. The consensus exoEarth yield analysis over the last several years³⁻¹³ indicates that a telescope aperture of 8m or larger is needed to be able to begin to statistically constrain the frequency of life-bearing exoplanets and to make a null-result statistically meaningful. A LUVOIR-like mission will

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also enable surveying and characterizing hundreds of other types, sizes, and atmospheres of exoplanets around other stars that will allow us to begin to put our solar system's planetary characteristics into context with surrounding nearby stars.

In addition to the extraordinary exoplanetary science case, a LUVOIR-like observatory would be able to extend the discoveries of the HST to measure a broad array of general astrophysics questions: tracing ionizing light over cosmic time, constraining dark matter, the cycles of galactic matter, the multiscale assembly of galaxies, stars as the engines of galactic feedback, star and planetary formation, to name a few. Finally, a LUVOIR-like mission would be able to remotely image and spectroscopically characterize with the same resolution what many in-situ planetary spacecraft in our solar system do³. Only, instead of building a series of mission and spacecraft per planetary body, a LUVOIR-like telescope could remotely observe most of the solar system bodies just by repointing. A LUVOIR-like mission could observe small bodies in the solar system, and perform comparisons in planetary atmospheres. A LUVOIR-like mission enables searching for life and telling the story of life in the universe.

1.3 Motivation to improve NASA's flagships development cost and schedule performance:

While NASA's great observatories are world-renowned for their science discoveries^{1,28}, they are also renowned for their cost and schedule overruns during their development^{10, 28-42}. Understandably, the community and all stakeholders are growing weary of NASA's cost and schedule overruns to the point where there are community members wondering if NASA's large strategic missions are worthwhile²⁹. We need to fix this. Taking action now, showing good faith to the community that we recognize this problem and we are willing to do something about it, may enable a future that will keep NASA's flagships discovering answers to known and unknown mysteries³⁰. The alternative may be a decreasing (astrophysics/SMD) budget for the foreseeable future.

1.4 Recognizing and acknowledging the issues:

By their nature and intent, each NASA flagship mission is a unique, system-of-systems built to deliver the broadest, most desired, scientific measurement capability for the most number of stakeholders. With their pursuit of unrivaled science questions, NASA's flagship missions often demand equally unrivaled technologies never attempted before. These technologies help establish the observatory's architecture.

In addition to challenging technologies, NASA's flagships have additional challenges above and beyond smaller, less complex missions. Flagships are one-off, complex, exquisitely precise space observatories that serve an intentional swath of stakeholders because of its tremendous measurement capabilities that cannot be performed with smaller-scale missions. They are complex due to the myriad of unique and evolving science questions they are trying to answer. The science goals necessitate a given-sized aperture^{2, 3, 6-8, 11, 13} and multiple, precision, one-off instruments must operate in coordination with the telescope as a system³. In addition, the flagship's science instruments themselves are, in their own right, complex. This multifaceted, layered complexity is a result of the observatory being a system of systems that has multiple imaging, spectroscopic, and other science capabilities that, often, must work in concert with one another to achieve the desired science observations. The nested nature of the subsystems necessitates hardware development timing scenarios that require multiple things to be developed in parallel. These developments, in turn, drive the schedule of the higher-level integration and test sequences. These multiple, necessarily-parallel developments put a strain on resource demands. If the resources are not available to enable parallel developments, this, itself, will cause the schedule to be lengthened and therefore, will cause cost and schedule overruns. This complexity is warranted in order for a space observatory to provide measurement capabilities to answer the most compelling science questions. **This inherent, intricate complexity requires us to think differently about how to most efficiently and effectively manage and develop flagships.**

For illustration, Figure 1 below shows the LUVOIR mission concept's architecture. Showing it serves two purposes: (1) it demonstrates the complexity of a flagship, and specifically, for a LUVOIR-like mission; (2) it defines nomenclature that will be used throughout this paper that is good to establish up front. The specific nomenclature illustrates the different layers of complexity from the functional decomposition of the hardware starting with the mission, its segments, elements, sub-systems, assemblies, and sub-assemblies. Please note that due to page-space limitation in the figure, only one segment (the observatory segment) was selected that shows both (all) elements (the payload and spacecraft) and their sub-systems. However, only four out of eight sub-systems (the Optical Telescope Assembly (OTA), Payload Articulation System (PAS) and spacecraft bus and sunshade) show their assembly and sub-assembly level hardware for this illustration. There would be similar nested elements for the ground segment

and launch segment, and similarly, there would be assembly and subassembly items for each of the payload instruments (subsystems).

LUVOIR Architecture

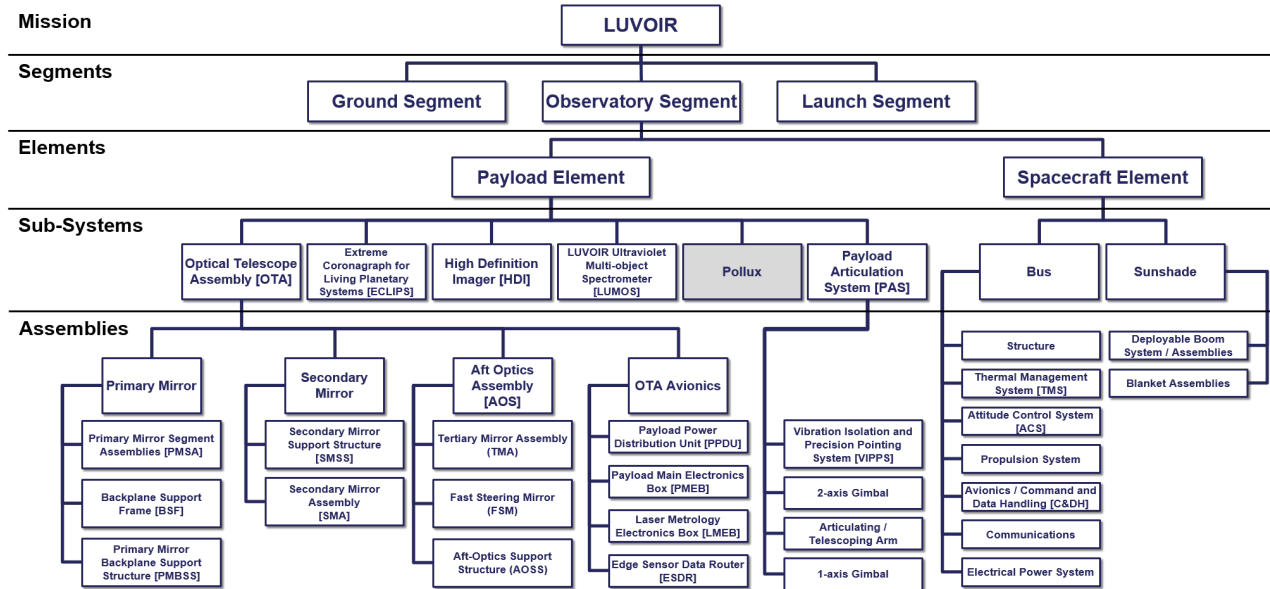


Figure 1: LUVOIR architecture showing the nomenclature of the different hardware layers of LUVOIR’s mission showing the segments and a subset of the elements, subsystems, assemblies, and subassemblies. For the payload element, the subsystems are the OTA, the four instruments and the PAS.

As a result of our research on NASA flagship missions²⁷⁻⁶⁰ and several Department of Defense (DoD) large projects⁶¹⁻⁷⁰, this paper focuses on some repeatedly-documented systemic challenges and offers alternative strategies that could lead to NASA significantly improving on cost and schedule performance if implemented. Most of these are within the project manager’s control to implement. We want to acknowledge that some NASA project managers have recognized some of these challenges, and implemented methods to mitigate these challenges on their own initiative on their individual projects. In these cases, there have been individual large missions that have successfully delivered their missions on schedule and on cost. However, some projects follow the current NASA guidance that doesn’t always work out for delivering flagships on cost and schedule. This paper describes nine lessons that can be implemented by the project.

In addition, there is one repeated lesson “observed” that cannot be addressed by the project. This lesson has been repeatedly documented by a vast array of experts and experiences from scientists, engineers, technologists, managers and analysts that have worked directly on NASA’s flagship and other large NASA space flight missions over the decades. This is the issue of cost estimating and funding stability. We discuss where NASA contrasts with other government large projects and even two of NASA’s past missions, and we make recommendations that would provide the project the stable funding it needs to execute an optimized schedule while also giving stakeholders control they want.

1.5 Goal of this paper:

Our goal is to bring to light the current NASA flagship systemic challenges and issues at the project-level and Agency/Congressional-level. We make recommendations on how to mitigate these challenges and remove current barriers with effective and efficient management practices for executing the development of NASA’s flagships. We advocate that these recommendations be considered to build upon and evolve NASA’s current best management practices into what we are calling an ‘integrated development and funding framework’. In doing so, this may significantly improve on NASA’s flagship cost and schedule performance. We want NASA to continue to be known for its flagships and great observatories in the future so that NASA can lead the way in “civilization-class science”³⁰.

This paper offers key strategies that are believed to be critical to efficiently formulate, manage, and implement any NASA flagship, not just LUVOIR.

2. SYSTEMIC-CHALLENGES, FINDINGS, AND RECOMMENDATIONS FOR DEVELOPING NASA’S STRATEGIC “FLAGSHIP” MISSIONS

For reference, Figure 2 below shows NASA’s development lifecycle for all space flight missions as taken from the May 2019 Government Accounting Office (GAO) Report to Congressional Committees on NASA Assessments of Major Projects³¹.

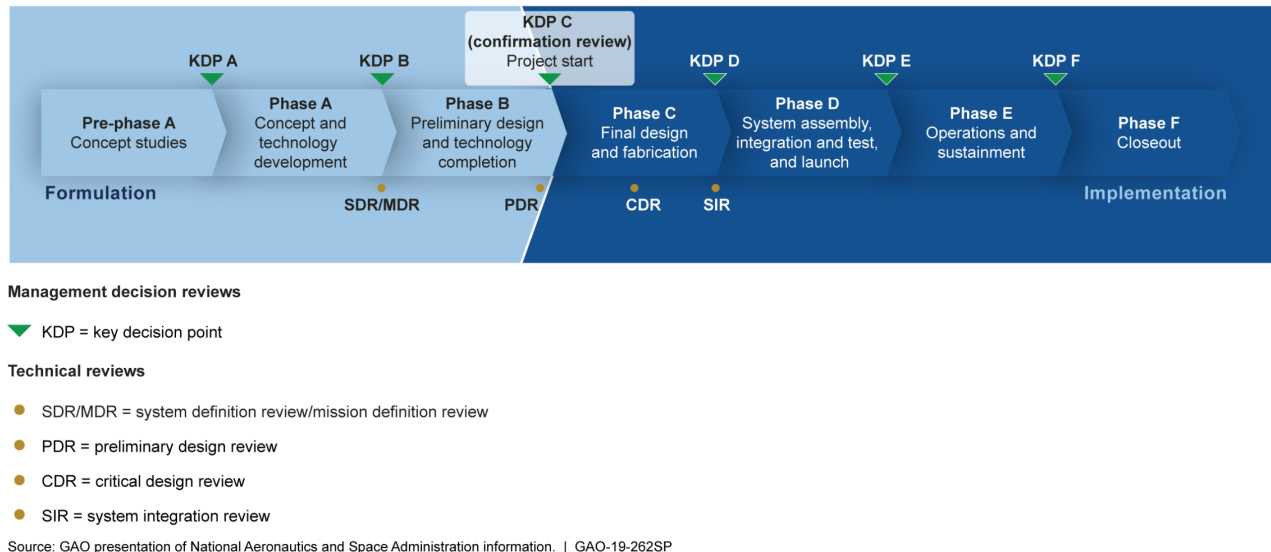


Figure 2: NASA’s development lifecycle for all space flight missions

The mission phasing for NASA’s space flight missions consists of two broad categories: (1) Formulation and (2) Implementation.

- Formulation consists of Pre-Phase A, Phase A and Phase B. Pre-Phase A currently consists of concept studies. The Astro2020 Decadal four large mission concept study teams (HabEx, LUVOIR, Lynx, and OST)⁷¹⁻⁷³ have achieved concept maturity level 4 (CML4)⁷³ as a result of significant investment across NASA, academia, industry, and international contributions to all four studies. Phase A consists of concept design and technology development, and Phase B consists of a preliminary design, requirements completed, and all technology development completed to TRL 6 by the mission’s preliminary design review (PDR).
- Implementation consists of Phases C-F. Under NASA’s current guidelines, Phase C consists of completing the final design and fabrication of all hardware. Within Phase C is the critical design review (CDR) and the system integration review (SIR). Phase D consists of system assembly, integration and test (I&T), launch, and commissioning. Phase E consists of the mission’s on-orbit operations and collection of data. Finally, Phase F is closing out the mission.

2.1 Recommended project-level management strategies for NASA’s flagships

The following nine management strategies can be implemented at the project-level.

2.1.1 Early technology development

NASA flagship technology management challenges: In section 1.4 of this paper, we laid out some of the additional challenges above and beyond what smaller NASA projects encounter. Due to the additional complexity of NASA’s flagships, there are additional challenges these projects face upon trying to execute the mission under

NASA's current space flight mission lifecycle. These challenges are corroborated by the findings from our research on NASA's flagships published lessons learned/observed.

We researched many large NASA flagship lessons learned documents^{1, 27-29, 31-60}. "Late" technology development is repeatedly referred to as a source of cost and schedule overruns. Some past missions knew that waiting to develop technologies through mission PDR was too risky and chose to develop them sooner. Some missions developed their technologies sooner than required, being one of several reasons enabling the mission's successful cost and schedule performance³⁸. Developing technologies earlier than required is not the only contributor to some missions successfully completing their mission's development on cost and on schedule, however, earlier technology development is a big factor for lowering risk as explained below. The fact that NASA allows technologies to develop to TRL6 through mission preliminary design review (PDR) gives the project the discretion to decide when to develop technologies as they see fit within the current NASA rules. For flagship missions in particular or other large projects with multiple instruments, the consequences of this "late" technology development are exacerbated due to the additional complexity and extent of nested and interconnected subsystems and assemblies.

A requirement for getting to mission PDR is that all lower levels of assembly including all segments, elements, and subsystems must hold their PDRs first, as shown in Figure 3. Given this nested nature of flagship observatories, there is a "season of PDRs" that may stretch out over a period of years. Note that all PDRs occurs towards the end of any product's Phase B whether it is at the subsystem-, element-, segment- or mission-level. When subsystem PDRs occur significantly out in front of the mission-level PDR, then it is likely that these subsystems have started to fabricate hardware and even begin integration and testing before the mission-level PDR is held. If there is a technology that is not able to mature by mission PDR in one subsystem, this could throw the project back years in development. Additionally, this may have wasted some hardware developments in both time (labor) and resources. Given some of the interconnections between subsystems, this could also throw other subsystems back years as well.

To highlight this point, Figure 3 below shows the offset nature of different levels of PDRs for nested products for LUVUOIR. Consider the OTA for example. In this schedule, the OTA PDR occurs ~3 years before the mission-level PDR. If projects are allowed to develop hardware to TRL6 up until mission PDR, some subsystems, assemblies, and subassemblies may have already been fabricated, integrated, aligned, and tested well before mission PDR occurs. If a subsystem's technology doesn't develop and a different solution/technology needs to be swapped in and used (currently allowed through mission PDR), there are serious risks to having to potentially restart considerable portions of the design cycle all over again sending the project back years in its development lifecycle. It is also important to recognize that the skilled-personnel ("marching army") increases deliberately and substantively between Phase A to Phase B.

DoD large project technology management issues

Interestingly, NASA is not unique to cost and schedule overruns due to infusing undeveloped technologies into incomplete designs and then finding out the consequences when they don't develop as expected. The Department of Defense large projects have also encountered similar lessons learned/observed, regarding "late" technology development^{69, 70}. In 2018, the U.S. Navy's development of the USS Gerald R. Ford (CVN-78) nuclear-powered aircraft carrier, was originally capped to cost \$10.5B (FY07) and breached \$13.027B. The Navy fully attributed these cost overruns to immature technologies and an incomplete design. "*CVN 78 began construction with immature technologies and an incomplete design, leading to cost and schedule growth,*" the U.S. Government Accountability Office noted in an April report.⁶⁹

NASA flagship technology management recommendations: As a result of the compounding and cascading effects of cost and schedule growth if there are any "late" technology developments on a complex, nested NASA flagship, we recommend that flagships mature all technologies to TRL6 before starting Phase A, and not by mission PDR.

2.1.2 Managing flagship complexity with earlier requirements definition

Flagship requirements management challenge: Findings from our research cite that any changes^{28, 31-40, 42} to science requirements after a baseline cost and schedule have been assessed, cause an increase in the development schedule. These changes force the new requirements to be flowed down to all aspects of the mission that are impacted. These changes may place additional requirements on hardware that was already defined in the baseline.

This hardware may need changes made to their design in order to meet the new requirements. This is in addition to the potential need to build and test any new hardware or even take hardware away. Any of these aspects of requirements changes after a baseline has been established adds additional time to the mission. Adding time while there is a marching army will increase the cost and schedule of any mission. In the meantime, some community members are holding the mission accountable to the Decadal timeframe cost estimate which did not account for changes to the requirements.

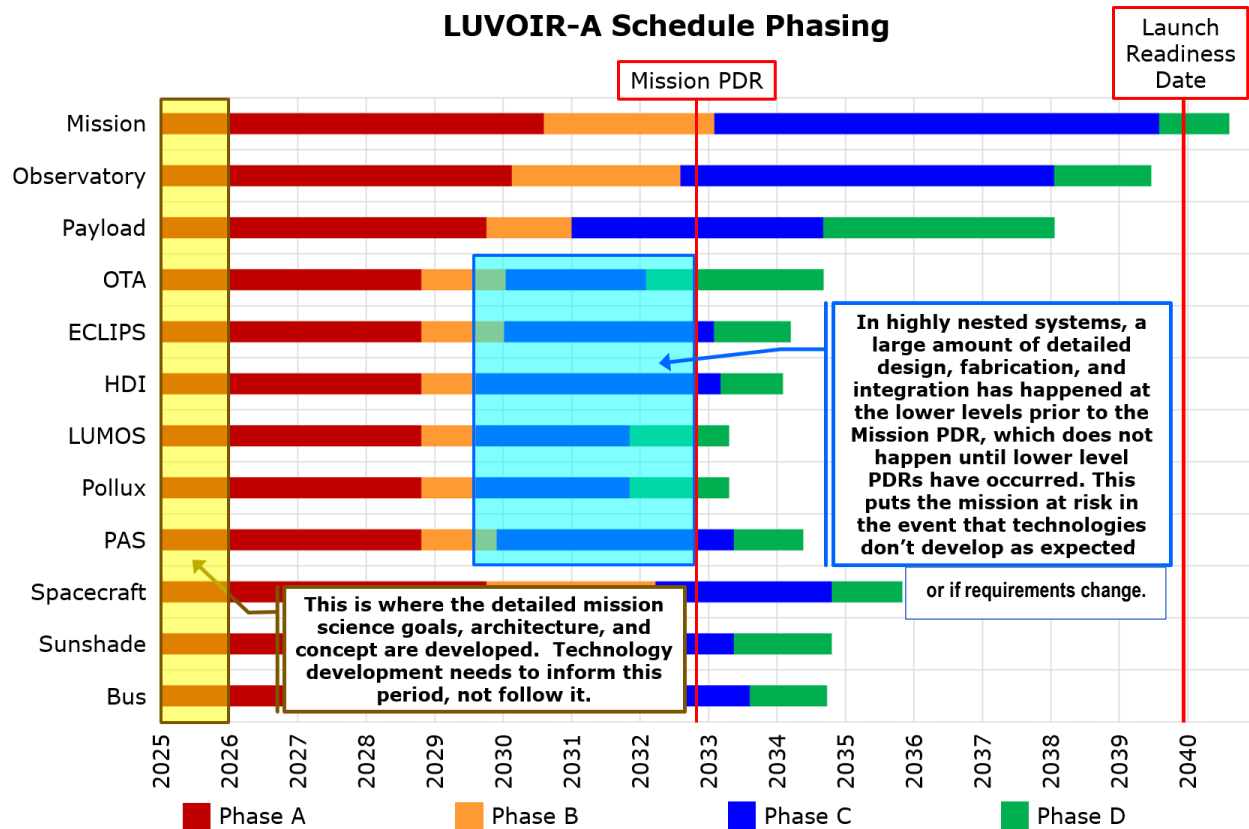


Figure 3: The LUVOIR-A Schedule Phasing shows where the mission PDR is relative to lower level sub-assembly phasing. This demonstrates the offset and nested nature of lower-level (subsystem) product PDRs that feed into higher-levels of assembly.

Additionally, allowing multiple assembly- or subsystem- level requirements to stay open in the form of “to be reviewed” (TBRs) and “to be determined” (TBDs) through a flagship’s segment or mission PDR can have the same effect as a technology not maturing as expected. Alternately, completing the design of an assembly before the design of its parent subsystem may place unwelcome constraints on the higher levels of assembly. These types of late design completions or changes will lengthen the project’s development schedule, and hence, force cost and schedule overruns^{35, 42, 69}.

Furthermore, when partners are onboard with contracts in place (industry, academia) there are at least two types of issues with late requirements definition or late requirements changes: (1) a mission with incomplete interface control requirements with TBRs and TBDs can increase the cost and schedule of those products due to late completion of requirements or late modifications; and (2) late changes to designs already under contract can force changes on other subsystems, thus increasing the cost and schedule of other contracts as well. These are all examples of the negative consequences that late completion of a mission’s requirements or late changes to a mission’s requirements can cause cost and schedule overruns in multiple manifested ways.

Flagship’s requirements management recommendation: As a result of the compounding and cascading effects due to late completion of requirements or late changes to requirements on a complex, nested, flagship mission, we recommend that flagships can help manage this complexity by developing and defining all requirements down to the

subsystem level early in Phase A so that requests for procurement (RFPs) can be released at the subsystem level (see Sections 2.1.6; 2.1.7; 2.1.8; and 4 of this paper).

As part of the release of the subsystem RFPs in Phase A, requirements need to include clear interface requirements, complete performance requirements, acceptance testing requirements, and expected institutional rules to be followed (See Section 2.1.8) upon delivery to the next higher level of integration for integration and testing (I&T). This enables partners to develop and follow their own internal processes. Partners would be expected and required to flow down, define, and establish all requirements within their subsystem down to the assembly, sub-assembly and component level also in Phase A.

After all requirements have been established and defined in Phase A, all efforts should be made to prevent mission creep and scope changes^{28, 34, 35, 42} (See Section 4.3.1 of this paper).

2.1.3 Managing flagship complexity with pathfinders

Flagship first-of-a-kind, one-off management challenges: Findings from our research as well as personal experiences on flagship space flight project hardware developments indicate that, in all cases where engineering breadboards, pathfinders, engineering development units (EDUs), and engineering test units (ETUs) were used, multiple issues were discovered, some of which would not have been discovered until the higher-level of assembly^{35, 41, 57, 59}. The time and resources invested to develop and learn about these in the early years saved significant time and resources than if they had been discovered during I&T on the critical path on the flight unit. Different types of practice units enabled, and ultimately, saved on their mission's cost and schedule performance^{28, 32-60}. These units allowed the team to catch early what would have been disasters if caught late during system-level I&T. Successful units were used on the JWST OTA Pathfinder⁴¹, Cassini engineering breadboards and ETUs⁵²⁻⁵⁹, and Chandra³⁵. In all cases, they help inform designs and realistic tolerances, find design flaws, help layout test procedures and sequences, and help train and provide rehearsals for personnel.

Flagship first-of-a-kind, one-off management recommendations: During Pre-Phase A, the team should judiciously and strategically identify and plan out which types of practice units are needed on which pieces of critical hardware. Some will be used to inform the designs, (i.e., error budget alignment allocation reality checks), while others will be used to inform test procedures, handling, integration, alignment, and even cleaning procedures. Others will be used to check out ground support equipment (GSE) and eventually, some will be high-fidelity units (ETUs) used to simulate the function of the eventual flight hardware to validate the designs, requirements, and interfaces. Judicious selection and development of engineering breadboards, pathfinders, EDUs and ETUs are critical for effectively managing complex flagships.

2.1.4 Managing flagship complexity with modular design

Flagship complexity management challenges: Past published NASA lessons learned⁴¹ have indicated that there are two challenges associated with flagships where modularity would have helped:

1. Flagships have additional challenges during I&T in terms of hardware accessibility. Embedded components, subassemblies, assemblies, and subsystems can be difficult to access if hardware anomalies occur. If hardware needs to be accessed and tested, or worse, swapped out with flight spares, without a modular design, this can add unnecessary time during peak marching army levels while the development is on the critical path⁴¹. In addition to being difficult to access, trying to reach hardware that was not meant to be accessed can place nearby hardware at risk of being bumped (misaligned) or damaged. Although it may take additional time on the front end, designing a mission to be modular upfront can lower schedule and hardware risk during I&T.
2. A 2010 public law [Public Law 111-267-Oct. 11, 2010 124 Stat. 2833] has strong language about future observatory-class scientific spacecraft to be serviceable. It is stated here for ease to the reader:

“SEC. 804. IN-SPACE SERVICING.

The Administrator shall continue to take all necessary steps to ensure that provisions are made for in-space or human servicing and repair of all future observatory-class scientific spacecraft intended to be deployed in Earth-orbit or at a Lagrangian point to the extent practicable and appropriate. The Administrator should ensure that agency investments and future capabilities for space technology,

robotics, and human space flight take the ability to service and repair these spacecraft into account, where appropriate, and incorporate such capabilities into design and operational plans.

SEC. 805. DECADAL RESULTS.

NASA shall take into account the current decadal surveys from the National Academies' Space Studies Board when submitting the President's budget request to the Congress."

Hubble was designed to be serviceable, and it did incorporate a modular design^{32, 36, 37, 39, 47}. This design aspect was critical to enabling the five servicing missions on HST that replaced instruments, gyros, and many other hardware to give HST its successful longevity and increasing science performance each time it was serviced and upgraded. Ambitiously, astronauts even replaced circuit boards within the Space Telescope Imaging Spectrograph (STIS) instrument. In order to access inside the instrument, the astronauts had to unscrew 111 screws to open the instrument cover of the STIS instrument⁴⁷.

A third benefit to designing a mission to be modular is designing in robust interfaces such that for a large observatory such as LUVOIR, being able to detach certain grouped hardware can ease transportation issues to I&T facilities or to the launch site. If designed to be modular from the start, proper interface requirements and performance requirements can be specified to enable repeated disassembly and reassembly at certain interfaces. A pathfinder could demonstrate the alignment repeatability of such interfaces. One example of this would be designing the OTA wing folds³ to be repeatably assembled, disassembled, then reassembled. Making each instrument modular and independently accessible is another example. Other examples would be making the spacecraft with orbital replacement units (ORUs) for the various spacecraft hardware functions³.

Flagship complexity management recommendations: Although designing a mission to be modular is not required to achieve the science goals, doing so lowers risk on the critical path during I&T by making hardware more readily accessible, lowers risk to nearby hardware, it can ease transportation requirements, and it can enable science beyond the prime mission by making instruments and other levels of assembly serviceable. During Pre-Phase A, the team should design the mission to be modular and assess the degree of modularity that would be optimal for different aspects of the mission. These trades should occur in Pre-Phase A.

2.1.5 Managing the duration of a flagship's development schedule by enabling parallel manufacturing, integration, & I&T

Flagship development schedule management challenges: With a large mission like LUVOIR where there are multiples of tens of things (for instance, the number of primary mirror segment assemblies (PMSAs) – ranging between 55 to 120 for the two currently envisioned LUVOIR optical telescope assembly (OTA) point designs)³, fabricating, assembling, integrating, and testing them serially would stretch out the schedule to an unacceptable degree. Developing the payload serially and then the spacecraft serially would also stretch out the schedule, thus forcing cost and schedule overruns. Developing subsystems in parallel enables the shortest possible schedule for the development of the mission when it has peak marching army numbers. Of course, the funding recommendations outlined in Section 4.3 of this paper are necessary to enable these parallel element and subsystem developments. The IMS carefully plans out the timing of when to start and finish each product so that they all shows up when needed for each level of I&T.

Flagship development schedule management recommendations: In order to optimize the schedule and make it as efficient and effective as possible which also lowers the overall cost of the development of the mission^{3, 42, 74, 75}, many aspects of the mission need to be executed in parallel^{3, 10, 28, 42, 74, 75}. Enabling parallel processes (such as with the PMSAs) has other benefits as well (See Section 2.1.9 of this paper). Time should be spent in Pre-Phase A to map out the IMS and identify which things need to be developed in parallel and how many identical operations should take place at any given time. This will also provide other important long-term planning aspects such as parallel integration, I&T, and the types of facilities that need to have multiple-of's, such as mirror fabrication facilities, polishing and coating facilities, etc. In addition, a cost-benefit-risk analysis should be done on the overall cost of performing different aspects of the mission in parallel vs. serially.

2.1.6 Managing flagships with acquisition and partner strategies

Flagship acquisition and partner strategy management challenges: With large, one-off, complex NASA flagships there are several issues with competing the entire management of the mission development to a single prime contractor. Rather than state all of the challenges, we state the recommendations and benefits for enabling the government to act as the “prime”.

Flagship acquisition and partner strategy management recommendations: We recommend that the government act as the “prime contractor” (or “prime”) on large flagship missions. There are many benefits:

- a. NASA sets and keeps control of the requirements early in Phase A, including coordinating any changes to requirements across multiple interfaces and across many partners.
- b. Earlier requirements definition enables the government setting the interface requirements at the procurement level including setting the acceptance performance metrics, delivery schedules, and institutional rules that will be followed at the next higher level of assembly.
- c. With NASA acting as the prime and with earlier requirements definition, this allows bringing multiple partners onboard earlier via smaller contracts that align directly with each partner’s area of expertise. They can focus on areas where they excel.
- d. NASA is able to select the “best in class” provider at the subsystem level.
- e. NASA retains expertise by being the systems integrator. This is critical for growing and maintaining systems engineering which is one of NASA’s core competencies.
- f. Negotiating international roles is an inherently governmental role. As with all past flagship missions, international partners will continue to want to invest and contribute to them.

Earlier partner involvement can occur in two ways: (1) In Pre-Phase A, multiple partners can be funded through broad agency announcements (BAAs) to leverage external expertise in technology developments; (2) In early Phase A, after the government has defined all requirements and interfaces to the subsystem level, multiple, Requests for Procurement (RFPs) can be openly competed for those subsystems since those requirements have been clearly defined. After partners have been awarded the development of subsystems, partners can then develop and follow their own internal processes. Partners would then be required to flow down, define, and establish all requirements within their subsystem down to the assembly, sub-assembly and component level also in Phase A. Establishing requirements early and bringing partners onboard earlier enables broader and earlier buy-in.

2.1.7 Managing flagships with institutional requirements

Flagship institutional requirements management challenges: With multiple partners come multiple unique institutions with perfectly valid internal processes and institutional rules and requirements to follow. This scenario, however, does inherently and potentially create conundrums as to which institutional rules should be followed during I&T for handling, I&T procedures, etc. at each successive level of integration and testing at different institutions.

Flagship institutional requirements management recommendations: We recommend that rules be established upfront as part of the RFP. The call for proposals should define all performance requirements, interface requirements, test requirements, and expected rules to be followed at each higher level of integration. The development and flow down of the requirements and interface definitions to the subsystems should occur in early Phase A.

2.1.8 Managing flagships with an integrated, ‘one-team’ environment

Flagship integrated, ‘one-team’ environment management challenges: With the need for broad and multiple partners on flagships, partners can be rightfully stove-piped developments. However, when there are anomalies, the project would benefit from having expertise from across the team help solve anomalies. Fresh perspectives can help solve issues, but only if they know about them in time to be effective.

Flagship integrated, ‘one-team’ environment management recommendations: It is beneficial to the execution and efficiency of the project to allow cross-fertilization of expertise to help address issues when they arise. The government needs to figure out a way to protect the intellectual property rights of partners and federal regulations

governing International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR) while also rewarding individuals and entities for helping to solve issues when they arise.

2.1.9 Managing flagships with team, experience, and depth

Flagship team, experience, and depth management challenges: Findings from our research as well as personal experiences cite that project managers that have never built space flight hardware do not have the necessary experience to anticipate, and therefore, head off known challenges and risks.

Separately, in order to enable parallel processes as described in section 2.1.5 of this paper, it is too risky to have a single subject matter expert (SME) for developing products.

Flagship team, experience, and depth management recommendations: Findings from our research as well as personal experience necessitates that critical project leadership roles be filled with individuals with relevant space flight hardware development experience. There is no substitute for experience.

To enable parallel developments, there needs to be a minimum of two SMEs for the development of parallel processes where either could lead the development of that product. This could be a more experienced individual and a less experienced individual that gets mentored by the more experienced individual.

3.0 COST ESTIMATION AND FUNDING CHALLENGES

There are two funding issues that present challenges to efficiently and effectively managing NASA's flagships discussed in this section: (3.1) Cost estimating challenges, i.e., knowing how much funding a given flagship needs, and (3.2) challenges related to disbursing the funds to the flagship project.

3.1 Cost estimating challenges for managing flagships

Historically, NASA has struggled with estimating the final cost and schedule duration of its flagship missions. Given that NASA's science flagship missions are prioritized by the National Academy of Sciences Decadal process ("Decadal") cost estimates are a significant part of the consideration when priorities are established. Cost estimates near a mission's Decadal have been used historically as their bench mark cost. Mission concepts are immature at the time of the Decadal. They are immature because their science requirements are not settled, their technologies have not been developed, and their architecture and design are not well-defined. Immature concepts beget immature cost estimates.

3.2 Funding disbursement challenges for managing flagships

Congress appropriates NASA's and NASA's flagship budgets on an annual basis. Funding issues are manifested in two ways: funding profile and stable funding.

1. Historically, the way NASA's next, newly prioritized flagship is funded occurs in correlation with the previous-prioritized flagship mission's development. When the previous flagship nears launch, a "budget wedge" opens up. Each year, the budget wedge may gradually increase depending on the success of the previous flagship's development. Assuming it is successful, in any given annual appropriation, the budget wedge for the new flagship is usually based on what budget is available rather than on what the project needs. It's like an allowance. Meanwhile, the management of NASA's flagships initially optimize their mission's development schedule into an integrated master schedule (IMS) by intending and planning to develop the necessary products in parallel for the most efficient schedule, and hence, the lowest cost overall. The IMS is a well-thought out management plan used to designate the total time needed to develop (design, procure, fabricate, integrate, align, and test) each level of assembly from components through systems (including funded schedule reserve) for each product development. Given the nested nature of flagships, the IMS also plans out the timing of when lower levels of assemblies need to be delivered to be integrated into the next higher level of assembly. The timing of the completion and arrival of each product for the next level of integration is critical to control cost and schedule overruns. If a lower level assembly is not ready when required for integration into the higher level assembly, the higher-level assembly must wait for the lower-level assembly to be completed, delivered, and go through acceptance testing. An IMS is optimized to minimize the total duration of the development lifecycle

when the marching army has peaked in numbers. Minimizing the total duration with a well-timed and executed IMS (development plan) helps save on the total mission cost. If the funding profile (total amount of money in a given annually appropriated year) disbursed to a flagship's project is less than needed to execute the multiple parallel developments as planned in the project's IMS, then the project must defer work^{28, 41, 42, 74-75}. Deferring work has cascading and compounding consequences on a complex flagship's development. It lengthens the overall schedule while there is a marching army. The work still must be completed. Thus, as long as any necessarily-parallel product developments are forced to be deferred due to funding issues, NASA flagships will continue to incur cost and schedule overruns under this scenario. This has been cited as one of the biggest systemic challenges to managing flagships^{3, 28, 34, 41, 42, 61-68, 74-75}.

2. Again, NASA and NASA's flagships receive annual appropriations from Congress. Continuing resolutions (CRs) force a status quo budget level equal to the previous year's budget. Hence, even planned increases in a flagship's budget are prohibited until a budget is passed by Congress. Congress has passed a NASA budget on-time only 7 times in the history of NASA²⁸. Continuing resolutions are the norm and can be expected. CRs are yet another manifestation of forcing a project to defer.

There is precedence with two of NASA's historical programs/projects that were *fully-funded** by Congress^{28, 42}. These were the Apollo program and the 'Return to Flight' development of the space shuttle Endeavour after the Challenger space shuttle disaster. Congress also has a variety of full-funding mechanisms for other branches of the government (See Section 4.0 of this paper). It appears that with proper motivation, Congress and NASA recognize the significance and positive impact of a *full-funding** policy. (*See Section 4.1 for a description of a full-funding policy).

4.0 RECOMMENDED FUTURE NASA FLAGSHIP FUNDING STRATEGY

Before addressing the recommendations, some awareness and context is needed. In this section, we see the array of full-funding mechanisms that have been available to the Department of Defense for their large projects since the 1950s and continue today.

4.1 DoD large project lessons for NASA: DoD's full-funding policy

Full-Funding Definition: All funds are appropriated up front or on an incremental basis that enables a project to execute their Integrated Master Schedule (IMS). In other words, all funding is received when it is needed.

The Department of Defense (DoD) has benefited from Congress' full funding policy for many of its large DoD projects such as aircraft carriers, fighter jets, helicopters, and submarines, etc. since the 1950s. Also since the 1950s, the DoD, for the majority of time, has not had to develop their large flagships with Congressional annual appropriations. Therefore, they typically don't have to worry about funding stability. The DoD's large projects continue to benefit from a variety of full-funding policy mechanisms today. The branch of Congress that funds the DoD understands that incrementally funding their projects annually could cause severe cost and schedule overrun impacts to these national assets. The only lessons learned they argue about openly in documentation is which full-funding policy is best⁶¹⁻⁶⁸. The range of full-funding policy methods afforded to large DoD projects include (1) No-year funding, (2) Incremental Funding, (3) Multiyear Procurement, (4) Block Buy Contracting, (5) Economic Order Quantity, and (6) Advanced Procurement to name some of them. Congress has recognized for ~70 years the merit of fully-funding these national assets because they also understand the consequences if they don't^{3, 28, 42, 61-70, 74, 75}.

Full Funding Policy Methods/Options Available to DoD Large Projects⁶¹⁻⁶⁸

Brief definitions are provided for each full-funding method below:

- **No-year (Zero-year) Funding⁶¹⁻⁶⁸:** All funding for building/developing DoD large projects is appropriated all at once in a single lump sum before starting the development.
- **Incremental Funding⁶¹⁻⁶⁸:** The funding for building DoD large projects is appropriated in 2 or more year increments, typically ~2-5 years, and in amounts that do not limit long-lead items being purchased or does not limit the development of anything due to lack of funding in a given year. In other words, this is still front-loaded funding. However, each year requires an appropriation bill to be passed by Congress.

- **Multiyear Procurement (MYP), Block Buy Contracting (BBC), and Economic Order Quantity Authority**⁶⁵:

Multiyear procurement (MYP) and Block Buy Contracting (BBC) are contract funding mechanisms that allow a certain percentage of savings, sometimes less than 5% to sometimes greater than 15%, over the traditional contracts that require annual renewal by Congress by allowing a single contract to be valid for several years' worth of funding without having to renew the contract each year. This is allowed on a limited number of defense acquisition programs.

- **Multiyear Procurement (MYP)**⁶⁵

Under a MYP contract, a single contract requires congressional approval in the first year that enables stable funding for two to five years' worth of procurement without requiring Congressional annual renewal in the following years. MYPs must be approved in both a DoD appropriations act and a non-DoD appropriations act. However, to qualify for an MYP contract, a program must meet legal criteria according to statute, 10 U.S.C. 2306b.

- **Block Buy Contracting (BBC)**⁶⁵

BBC also requires congressional approval for a single contract in the first year for several years' worth of procurement, however, it is more flexible for several reasons, namely:

- a) There's no permanent statute governing the use of BBC.
- b) BBC only needs to be approved in a single appropriations act.
- c) There are no legal criteria required to qualify for a BBC (because there is no statute governing its use).
- d) A BBC can cover more than five years of planned procurement.
- e) BBCs are less likely to include cancellation penalties.

- **Economic Order Quantity (EOQ) Authority**⁶⁵

This provides the authority to allow a few select "long-lead" items to be procured in the first or second year usually for "batch items".

- **Advance Procurement (AP) Funding**⁶⁵⁻⁶⁷

This provides the authority to disburse funds one or two years prior to the procurement of the entire system usually for long lead items for that system. The amount disbursed in an AP is subtracted from the full system procurement appropriation. It is similar to EOQ acquisitions.

4.2 Differences between DoD's large projects and NASA's flagships

Fully-funding NASA flagships with a no-year funding policy would be ideal, however, it is not realistic.

The DoD has the benefit of having a better understanding of the costs to build and develop their large projects, because they typically build "multiple-of-things" for each thing (aircraft carriers, submarines, fighter jets, etc.) and they have been building them (or similar ones with technology upgrades or other relatively small variations) for ~ 70 years. Therefore, not only do they have a much better understanding of how much it costs to build each thing, they have lots of historical data on the actual ranges of costs, how much the costs vary, and the impacts of introducing new technologies for each thing.

On the other hand, NASA's flagships are one-off, state-of-the-art, precision space observatories. Accurate final cost and schedule estimates are not possible at the time of NASA science decadal, because for any newly prioritized flagship, it has never been built before. Therefore, there is not a database of historical costs for one just like it even if there may be some similarities. Additionally, it has low TRL technologies, the requirements are changing, and they are bound to change some more before the final decision on the final design.

4.3 Recommended funding strategy:

We recommend a NASA-DoD "hybrid incremental full-funding" policy that reconciles the need for a NASA flagship to develop multiple products in parallel in order to minimize the overall cost and schedule, while also allowing stakeholders to keep control of the potential for runaway costs and provide pre-established "smaller" amounts of funding that span several years. Importantly, the funding would not be on an annual basis. Specifically, we propose that NASA's flagship projects be incrementally, fully-funded and executed in discrete blocks of work

that align with the project’s development product milestones and schedule. Each funding block is defined by a gate, called a Funding Decision Point (FDP), where the decision is made to fund the next block of work. These are separate from NASA’s Key Decision Points (KDPs) that align with the mission phases. For each funding block, the project receives all of the necessary funding - only for that funding block – before that block of work is initiated.

At each FDP, four things occur:

1. The project must demonstrate that the current funding block has been completed and has successfully achieved all of its milestones.
2. At the end of each successfully completed funding block, new cost, risk, and schedule estimates are performed by an independent cost and risk estimating entity for (A) the remainder of the mission’s development, and (B) the amount of funding needed for the next funding block only.
3. The project generates a high-fidelity budget request for the next block of work to be completed, and the independent cost estimating entity independently validates it. As the project’s design matures and converges through formulation, the cost and schedule estimates will become more accurate.
4. NASA decides to commit to funding *only the next block of work*, based on the budget request, updated cost estimate, and project success.

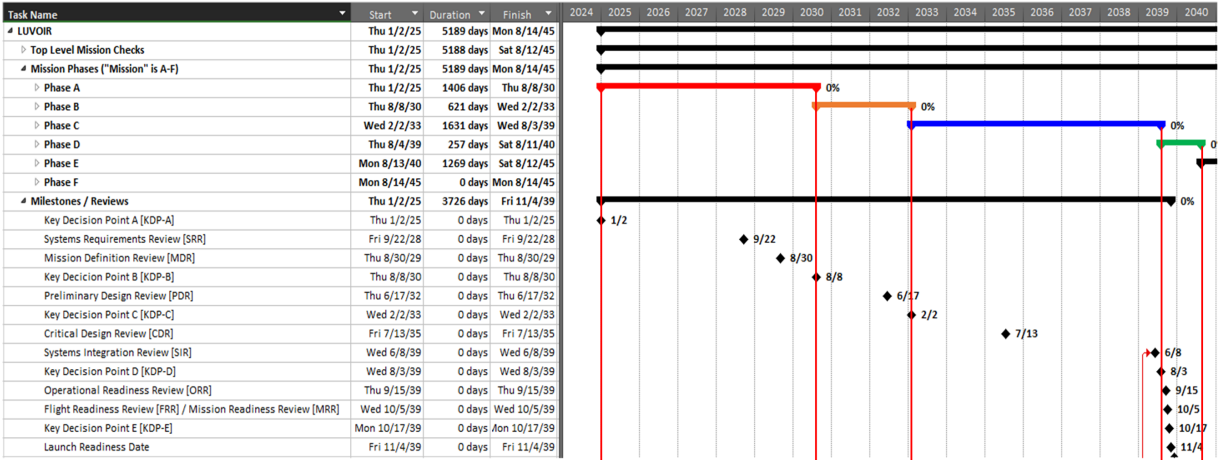
We recommend six distinct funding blocks for a project’s lifecycle where each block is fully funded one at a time. Five of these funding blocks occur within a NASA flight project’s development formulation period (Pre-Phase A through Phase B). In Figure 4 below, the right-hand column, “Decision Point Criteria”, states the criteria for being approved to enter that row’s funding block. So, for instance, to pass into Funding Block 1, Start of Pre-Phase A, the mission must be prioritized by the Decadal. To get into Funding Block 2, the start of Phase A, all technologies must be demonstrated to TRL 6 at the system level, and so on.

Funding Block	Funding Decision Point	Decision Point Criteria
1	Start of Pre-Phase A	Decadal Prioritization. Agency decision to proceed with mission Pre-Phase A study.
2	Start of Phase A	All technologies demonstrated at system-level to TRL 6.
3	Issue Requests for Proposals (RFPs)	Requirements developed to sub-system level. Ready to issue RFPs for all industry, academic, and international partners.
4	Mission System Requirements Review (SRR)	All requirements developed to lowest level. Project successfully passes Mission SRR.
5	Key Decision Point (KDP) - B	Mission satisfies all criteria for completing Phase A.
6	KDP - C	Mission completes Preliminary Design Review and satisfies all criteria for completing Phase B.

Figure 4: Funding blocks and funding decision points (FDPs) and their criteria.

Figure 5 below shows the funding blocks in the context of LUVOR-A’s development schedule. Each funding block covers the work and products needed to be fully funded to implement the optimized IMS. For LUVOR, the funding blocks line up as shown in Figure 5 below:

Top Level LUVOIR A Schedule for Reference



Potential Funding "Blocks"

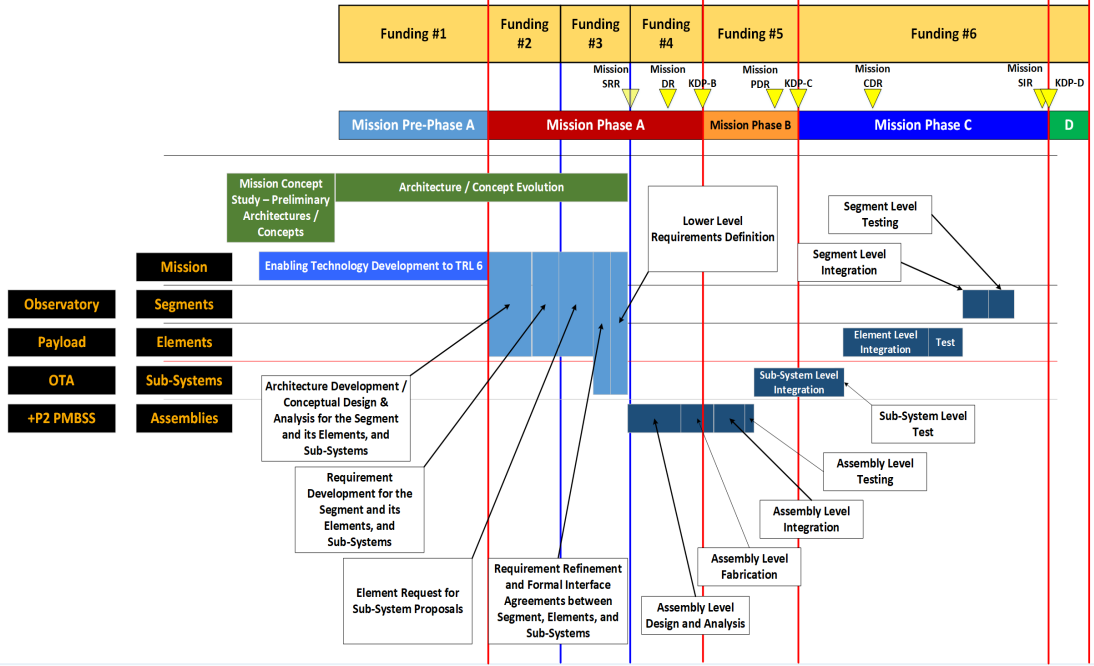


Figure 5: This shows funding blocks in the context of LUVOIR-A's development schedule. Each funding block covers the work and products needed to be fully funded to implement the optimized IMS.

4.4 Discrete Funding Block Advantages:

There are several advantages to this funding block approach outlined above compared to the current method NASA's flagships are funded and executed:

1. As the mission progresses through mission formulation (Pre-Phase A through Phase B), the mission design develops, matures, and becomes more detailed and complete. By assessing the mission cost and risk at each funding decision point (FDP), the accuracy of each succeeding cost estimate becomes more accurate. The independent costing entity can signal runaway cost growth outside the error bars of the previous FDP.
2. Congress and NASA need only commit to funding the next block of work; not the full mission. Each FDP provides the opportunity to delay, augment or deny the next block of funding in response to inadequate project development performance, unacceptable cost growth or adjustments to science scope

3. Fully-funding each block of work up front, enables the project to execute all of the required parallel developments and not have to defer any work due to the funding profile. An equal and additional benefit to fully-funding each block of work allows the project to use reserves for their intended purpose: unavoidable and inevitable unknown unknowns that will be revealed as the development progresses and not to try to use reserves to execute pieces of deferred work while there is a marching army waiting for a product to show up.
4. This funding method lowers the risk of cost overruns on the flagship mission. It also lowers the risk of potential flagship overruns negatively impacting other projects and priorities. While cost overruns within astrophysics don't generally impact smaller projects, this would help insure to the community (perception or potential reality) that this would not happen since the funding block is fully-funded upfront and kept in a different "effective silo". Since each funding block is discrete with "shorter-term" milestones and goals, there is less likelihood that the project would experience cost overruns compared to today's NASA flagship funding method. Again, since the Agency would be committing to fund only one funding block at a time, this would provide stakeholders the opportunity at any FDP to delay, cancel, or make any other adjustments.

4.5 Individual funding block's milestones and exit criteria:

Each funding block's milestones and exit criteria are described below. Within each funding block, proactive management strategies are incorporated to address and overcome the systemic-challenges described in Section 2 of this paper.

4.5.1 Funding Block 1: Pre-Phase A milestones and exit criteria:

We recommend a strong Pre-Phase A project office be established to address many of the systemic-challenges facing previous NASA flagships as described in Section 2 of this paper, namely, earlier technology development, earlier establishment of science objectives and requirements, an architecture that coalesces around the science requirements and technologies, and long-term planning for facilities, the verification and validation approach, I&T, etc.⁷⁸

There are several advantages to executing these activities in Pre-Phase A:

1. A substantially smaller "marching army" is needed in Pre-Phase A to develop and define the science objectives and requirements, develop the technologies and the architecture while strategically planning out the verification and validation approach, I&T approach and requirements, and other long-term considerations³. Doing this in Pre-Phase A reduces overall cost and schedule risk to the entire development of the mission.
2. The "right-sized army" is utilized for each block of work making the resources more effective and efficiently used.
3. Developing technologies to TRL6 in Pre-Phase A reduces cost and schedule risk for all later development phases:
 - a. Reduces risk that the architecture will change.
 - b. Reduces risk that the design will change.
 - c. Reduces risk that the science requirements will change.
 - d. Reduces risk that requirements will change and minimizes the number of TBRs and TBDs
 - e. Reduces risk that interface requirements will change, thus, minimizing changes to contracts.
4. Maturing technologies off the critical path when there isn't a large marching army waiting, is worth it by itself. The labor grows deliberately and substantively from Phase A to B and through D.
5. Concurrently developing technologies consistent with a specific architecture ensures that hardware does not have to be re-engineered, reaffirming early technology development.

There are three main Pre-Phase A exit criteria (A through C) activities described below.

- A. **Technology Development:** A small technology team will work with NASA HQ to release Broad Agency Announcements (BAAs) so that NASA, industry, and academia can work together (or independently) to advance (competing) technologies. In either case, involving all expertise will help get to a developed and successful mission sooner. The exit criteria for Pre-Phase A is to develop all technologies to TRL 6 at the

component, subsystem, and system level. This needs to include subscale system demonstrations where there are two types, namely:

- a. Those where the size of the demonstration is smaller in scale (some smaller ratio of the size of the system-level technology to demonstrate the function and its performance (an example for LUVOIR might be a smaller sunshade deployment demonstration).
 - b. Those where the technology is full-size (full-scale), however, fewer items are used in the demonstration (an example for LUVOIR might be the use of three, four, or five full-sized primary mirror segment assemblies (PMSAs)³, to enable a system demonstration.
- B. **Science Definition:** Establish a funded science steering committee (SSC) led by community members to be maintained throughout the project's lifecycle. The SSC will be responsible for interpreting the Decadal recommendations and defining the science objectives for the mission. Throughout Pre-Phase A, the SSC will:
- a. Work with the engineering team to decompose science objectives into requirements to guide the architecture, concept design, and technology development.
 - b. Perform the necessary science analyses to validate an architecture's and concept design's given performance with the developing technologies.
 - c. Establish a process by which new science objectives are proposed, reviewed, evaluated, and dispositioned (accepted or rejected) by the project. The evaluation would necessarily need to consult the other Pre-Phase A project office areas of engineering, technology, and architecture to determine its impact(s) if implemented (science value, cost, and risk) on the overall mission. As noted earlier, attempting to establish the value of any changes needs to be weighed in the context of knowing that changes in later parts of the flagship's development can ripple through and cause cost and schedule overruns. Therefore, another responsibility of the SSC will be to protect the science requirements from external pressures to change the mission scope once they have been established by the end of Phase A.
 - d. Support the engineers in resolving all TBDs and TBRs for the engineering requirements which will be enabled by establishing science requirements earlier and holding to them, to minimize science creep.
- C. **Architecture, Concept Development, and Long-term Planning:** A group of discipline engineers led by the Project Systems Engineer ("Lead Systems Engineer"), will be responsible for maturing the architecture and studying concept designs commensurate with the science objectives and developing technologies.

In addition, the architecture team will perform trades relevant to the architecture and designs. The trades will be weighed against science, execution feasibility, cost, risk, as well as the demands each architecture trade places on the ground verification and validation and I&T process including systems engineering integrated modeling tools, facilities, ground transportation, ground support equipment (GSE) (optical, electrical, thermal, and mechanical GSE), contamination control requirements, meeting launch vehicle survival vibration and load requirements, and ease of access to subsystems and subassemblies during I&T via a modular design which also enables serviceability. These and more need to be considered when designing a flagship mission^{3, 78}.

All missions that have used engineering breadboard units, pathfinders, engineering development units (EDUs), and engineering test units (ETUs), recount that the time and resources invested during the formulation period (Phases A and B) to develop and learn from them were vastly smaller than the time and resources that would be encountered and expended if they were learned during I&T on the critical path on the flight unit. Different types of practice units enabled and ultimately, saved on their mission's cost and schedule performance^{3, 33-44, 52-60, 74, 75}. These units allowed the team to catch early what would have been disasters if caught late during system-level I&T on the critical path on the flight unit. The architecture team should plan out which types of practice units are needed on which pieces of critical hardware. Judicious selection and development of engineering breadboards, pathfinders, engineering development units (EDUs) and engineering test units (ETUs) to simulate the function of the eventual flight hardware helps validate designs and requirements and helps inform integration and test procedures.

The goal of the Pre-Phase A project office is to mature the most known risk drivers of the mission concept to the point where most, if not all known risks are mitigated to the most extent possible. This will position and enable the execution of Phases A through D to address the known challenges with less risk. Executing these activities in Pre-Phase A will enable the remainder of the formulation and implementation phases to only have to deal with unknown risks. Figure 6 below pictorially depicts the goal of Pre-Phase A.

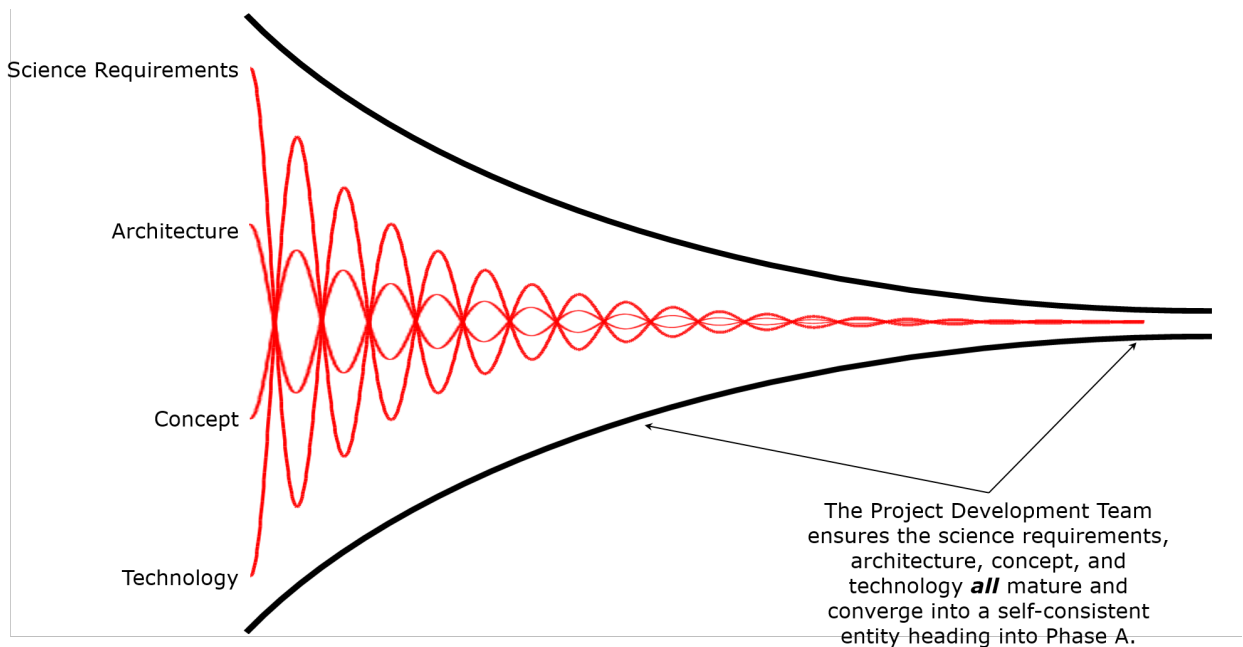


Figure 6: This shows how the science, architecture, concept design, and technology converge prior to entering Phase A, increasing the likelihood of a successful Phase A.

The Pre-Phase A project office may look similar to the one depicted in Figure 7:

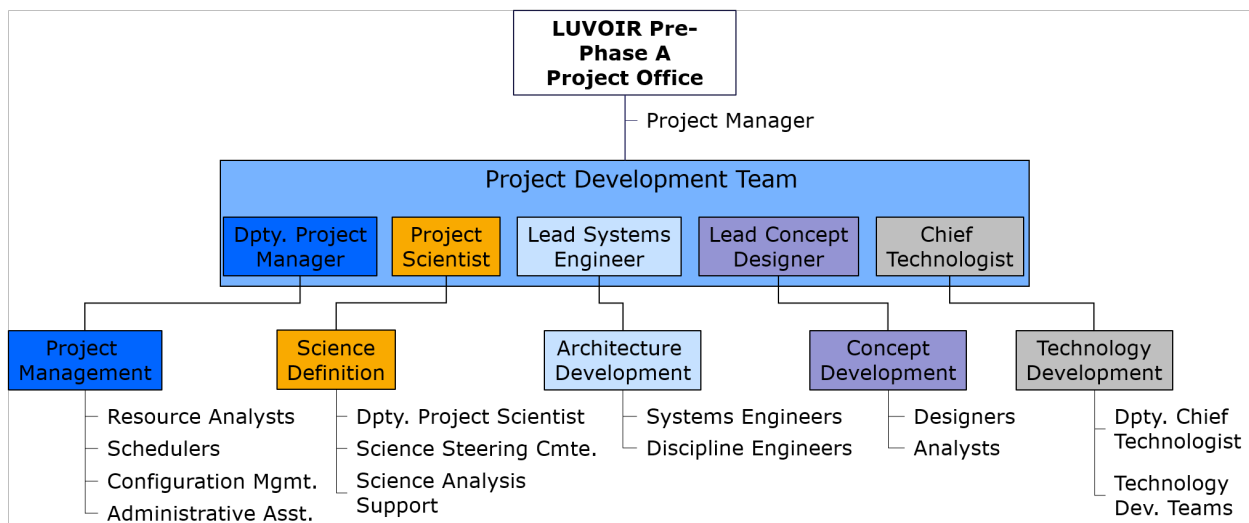


Figure 7: While this is labeled for LUVUOIR, establishing a Pre-Phase A project office for any NASA flagship is recommended. The project office coordinates all of the activities to develop each area and coordinates across each area given their dependence on one another.

Two independent cost estimates are performed: (1) the mission to obtain a more accurate mission cost; (2) the next block of funding. A review is held before the mission can pass into the next funding block.

4.5.2 Funding Block 2: Phase A – (Part 1 of 3) milestones and exit criteria:

Phase A is split up into three separate funding blocks for funding different products and milestones. At the beginning of Funding Block 2, all technologies have been demonstrated to TRL6 including subscale system demonstrations, the science objectives are defined, and the architecture and concept designs have been demonstrated at the system-level. During Funding Block 2, the science requirements are flowed down to engineering and mission

requirements to the subsystem level (See Figure 1 in this paper). The subsystem level requirements must establish and define performance requirements, acceptance testing requirements, interface requirements, and rules that will be followed during the next higher level of integration to name a few. These subsystem requirements definitions must be part of the selection criteria in the RFP call documentation. As discussed in Section 2.1.6, the LUVOIR Team envisions the government as the prime to establish all requirements as early as possible. The government can then issue RFPs to leverage industry, academia, and international partners in their areas of expertise as early as possible. The RFPs are issued competitively at the subsystem level. The actual RFPs would not be released until the start of Funding Block 3. The exit criteria for Funding Block 2 is for NASA to be ready to release the RFPs. "Ready for release" means all requirements mentioned above are clear, complete, and have been reviewed and approved by stakeholders.

At the end of funding block 2, two independent cost estimates are performed: (1) the mission cost; (2) the next block of funding. At this point, the mission cost estimate should be more accurate. A review is held before the mission can pass into the next funding block.

4.5.3 Funding Block 3: Phase A – (Part 2 of 3) milestones and exit criteria:

Funding Block 3 begins with releasing all RFPs. During funding block 3 (FB3), the requirements are refined and formal interface agreements between segments, elements, and subsystems are made. In the latter half of funding block 3, the subsystem proposals are received, evaluated, and awarded. Given the acquisition is at the subsystem level, once the partners are onboard, they define all lower-level requirements within their subsystems.

The required exit criteria for Funding Block 3 are: (1) ensure the release of the subsystem RFPs at the beginning of FB3; (2) refine all requirements and formalize all interface agreements between all segments, elements, and subsystems; (3) evaluate and make award selections for all subsystems from the received proposals; (4) all partners are required to flow all subsystem-level requirements down to their assemblies, sub-assemblies and components. By the end of funding block 3, all requirements at all hardware and software levels must be established and defined; and (5) The mission successfully passes its Systems Requirements Review (SRR)

At the end of funding block 3, two independent cost estimates are performed: (1) the mission cost; (2) the next block of funding. A review is held before the mission can pass into the next funding block.

4.5.4 Funding Block 4: Phase A – (Part 3 of 3) milestones and exit criteria:

Funding Block 4 is the third and last funding block within Phase A. Funding block 4 begins and completes assembly-level design and analysis. Assembly-level fabrication is well underway.

The required exit criteria for Funding Block 4 includes meeting the normal NASA Key Decision Point-B (KDP-B) entrance criteria following the standards as defined in NASA Procedural Requirements document on NASA Space Flight Program and Project Management Requirements, NPR 7120.5E.

At the end of funding block 4, two independent cost estimates are performed: (1) the mission cost; (2) the next block of funding. A review is held before the mission can pass into the next funding block.

4.5.5 Funding Block 5: Phase B milestones and exit criteria:

Funding Block 5 funds all of Phase B. Assembly-level fabrication and integration and testing is completed. Sub-system-level integration is well underway. The mission must pass the mission Preliminary Design Review (PDR). This is the final funding block during NASA's formulation period. The mission prepares for NASA's Key Decision Point-C (KDP-C).

The required exit criteria for Funding Block 5 (Phase B) is to pass PDR and meet all of the normal KDP-C entrance criteria following the standards as defined in NASA Procedural Requirements document on NASA Space Flight Program and Project Management Requirements, NPR 7120.5E.

At the end of funding block 5, the final two independent cost estimates are performed: (1) the mission cost; (2) the next block of funding. A review is held before the mission can pass into this final funding block.

4.5.6 Funding Block 6: Phases C and D milestones and exit criteria:

The final funding Block (Funding Block 6) is the final funding block to fully fund Phases C and D, NASA's Implementation Period. This will allow the full funding necessary for the project to follow the optimized IMS. This will enable the project to deliver a launch ready observatory, launch, and complete mission commissioning by the end of Phase D.

Following the steps outlined in this integrated development and funding framework would enable significant improvements for NASA's flagships to deliver on cost and schedule.

5.0 CONCLUSION

This paper has recounted the marvel and incredibly enlightening surprises that NASA's flagship missions discover and their impact on NASA and humanity. NASA's flagships are arguably, equal to, if not more profoundly significant national-assets given they are each one-offs and given their world-renowned popularity and enthusiasm in all corners of the Earth. We would like to see NASA's flagships be recognized as on par in difficulty, complexity, and value compared to other government agency national assets. Due to NASA's flagship scientific discovery potential, they all receive significant international contributions, thus, they are also peaceful manifestation of positive international cooperation. We would like to see NASA continue to pursue audaciously bold queries into: how the universe began; where its headed; how the universe operates; how planets form; whether or not Earth, the only pale blue dot we've ever known in our vast universe, is alone; contextually, how similar or different is our solar system from other nearby ones; and be able to remotely monitor our solar system planetary bodies with imaging capabilities equal to in-situ spacecraft³.

This paper has also recounted in detail the repeatedly-documented, lessons-learned/-observed systemic-challenges for NASA's flagship missions. By implementing the proactive, integrated development and funding framework described herein, we believe that NASA's flagships can be developed with significantly better cost and schedule performance. In turn, this may engender trust from its stakeholders and allow NASA's flagships to be revitalized with enthusiasm from the community.

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