Astro2020 White Paper for
State of the Profession Considerations
On
Managing Flagship Missions to Reduce Cost and Schedule

Decadal White Paper

Thematic Area:

Considerations for Improving the Management of NASA's Flagship Missions

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1 Key Issue and Overview of Impact on the Field

1.1 Summary of the Issue

- Flagship missions are highly complex with highly nested systems.
- This level of complexity poses unique management problems as complexity influences risk which, in turn, affects cost and schedule.
- Establishing a strong technical and programmatic leadership team is critical to mission success.
- Developing and using a mission architecture is critical to informing the management organization, product ownership, interface and integration relationships, schedule organization, and integration and test paths.
- In highly nested systems, the mission phasing can be significantly out of sync with product phasing.
- Targeted technology development prior to Phase A is critical to reducing risk.
- Early architecture, concept design, and requirements development is critical to reducing risk.
- Modular design; pathfinders; parallel manufacturing and integration and test paths; and properly handling institutional requirements across interfaces are all management techniques that can be applied to reduce risk.

NASA's large strategic missions, sometimes referred to as flagship missions, are designed to provide answers to some of the most compelling scientific questions being asked.

These types of missions are a series of highly nested subsystems that pose unique management problems[4, 18] when compared to more traditional instrument and spacecraft designs. They typically have an overall architecture that is very complex and nested; they typically require a tremendous amount of technology development; they typically involve many contractors and subcontractors with many associated contracts; and they typically involve staff from all over the world. Successful management of a flagship requires the balance between science requirements, engineering and technology capabilities, and resource constraints.

Mismanaging these flagship missions can and will lead to significant cost and schedule growth[4], both of which are detrimental to NASA's overall reputation which, in turn, is detrimental to the development of future flagship missions.

While many of the same management principles used on smaller instruments and spacecraft are relevant, managing flagship missions requires an evolution of those current best practices to better address the specific needs and additional complexity and vastness of these missions.

This paper explores how to leverage lessons learned from previous flagship missions to better manage flagship missions in the future.

1.2 How it impacts the field of astronomy and astrophysics

Astronomical flagship missions are few and far between. Part of the reason for this is that each one has taken longer to develop and cost more than originally estimated. While this trend is not exclusive to astronomical missions, cost and schedule overruns slow the cadence at which new observatories are launched which reduces the number of instruments available to astronomers and astrophysicists. Better management of these flagship missions should increase the rate at which observatories are launched.

1.3 Why it should be addressed in the Survey

Astro2020 and the community have a stake in the management of NASA's flagship missions as these missions routinely provide awe-inspiring science discoveries. Astro2020 will assess many aspects of the four large, strategic, mission concepts including science imperative, cost, feasibility, and executability. The community needs confidence that lessons – both good and bad – that have been learned on previous flagship missions are being applied to this latest round of mission concepts and will continue to be applied to whatever missions are prioritized.

It is the intent of this White Paper to lay out the arguments as to how to apply lessons learned from a variety of sources, as well as personal experiences on previous flagship missions, to future missions with the intent of reducing the overall cost and schedule of flagship missions.

2 Strategic Plan

2.1 Leadership

"NASA is an Agency with a unique mission that requires leadership, innovation, and creativity to achieve one-of-a-kind, first-of-their-kind technological and scientific advances." (Martin 2012)

Leadership is critical to the development and execution of a flagship mission. This is not just program management leadership. This is science leadership, engineering leadership, and technology development leadership. There needs to be, and there will be, a single individual in charge of a mission, but that person needs to have a senior leadership team that advises him/her in areas of project management, science, engineering, and technology. Those individual leaders would need their own teams to advise them as well. It is only with this strong leadership that a complete, feasible, end to end vision of a mission can be developed.

2.2 The Architecture

It is our position that a well thought out architecture – even at a very high level - can decrease the total mission cost by helping to map out many details of the mission from management organization, product ownership, interface and integration relationships, schedule organization, and integration and test paths, to name a few. Figure 1 shows a notional architecture for a flagship telescope.

A critical part of successfully managing any mission, but especially a highly nested mission such as a flagship mission, is a clear definition of roles and responsibilities. Those roles and

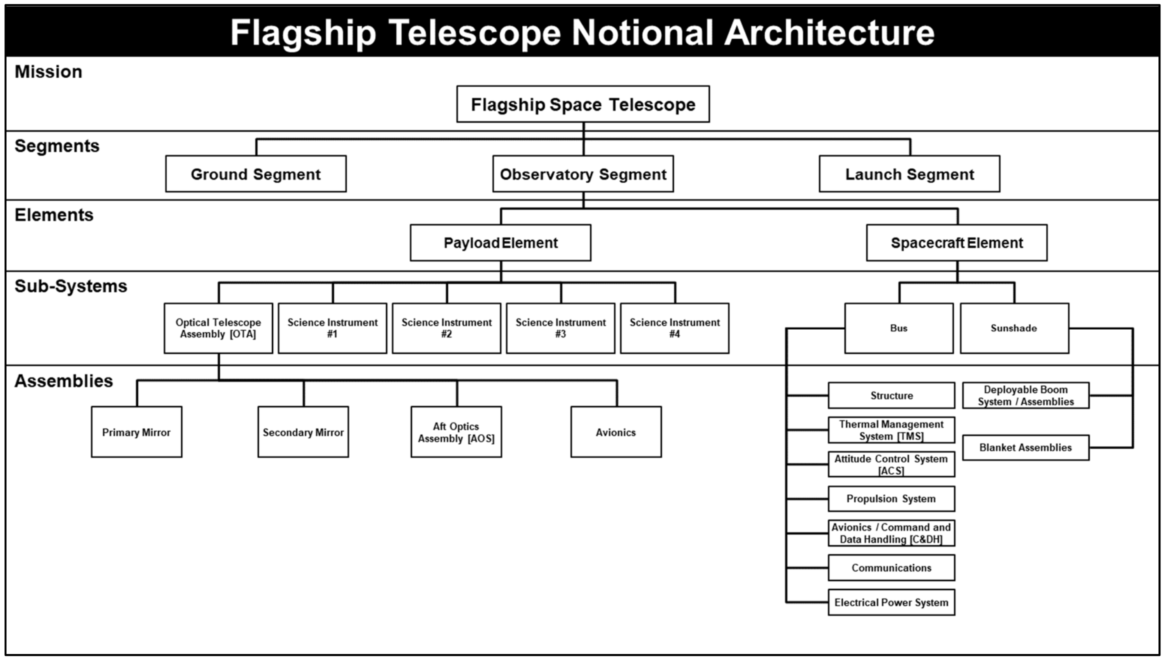

Figure 1 : A Notional Architecture for a Flagship Telescope Mission ("Elements" are only shown for the Observatory for simplicity. They would exist for the Ground and Launch Segments as well. Similarly, "Assemblies" are only shown for a few Sub-Systems. In reality, each sub-system would comprise a set of Assemblies, and each Assembly could be further decomposed into Sub-Assemblies and so on.)

responsibilities should map directly to the architecture. A mission project manager, with the help of a senior leadership team should sit atop the organization. A ground support manager, observatory manager and a launch segment manager would report directly to the project manager while overseeing their respective element managers. While this may seem obvious to the reader, other missions have traditionally used more "flat" organizations with various leads at the same "level" even though that is not representative of the hardware or interface organization and hierarchy. It is our opinion that this leads to inefficiencies.

Like the management team, systems engineering teams and various mission boards such as configuration control boards and risk boards can be set up as "boxes" around various branches of the architecture. Mission Systems Engineering encompasses the Ground, Observatory, and Launch Segments and their lower levels. The details of those lower levels can be delegated. There can be an Observatory Systems Engineer that oversees the Payload and the Spacecraft and subsequently, there can be a Payload Systems Engineer and a Spacecraft Systems Engineer that oversee the subsystems below each of those Elements. That can continue to expand depending on how nested the system is. This allows people to manage reasonable chunks of responsibilities.

Figure 2 shows how the architecture can be used to highlight critical interfaces that are defined by interface control documents (ICDs). Again, while the Figure 2 may seem obvious, experience suggests that executing interface control is easier said than done. Interface agreements tend to become a series of documents that are less clearly defined and lead to ambiguity.

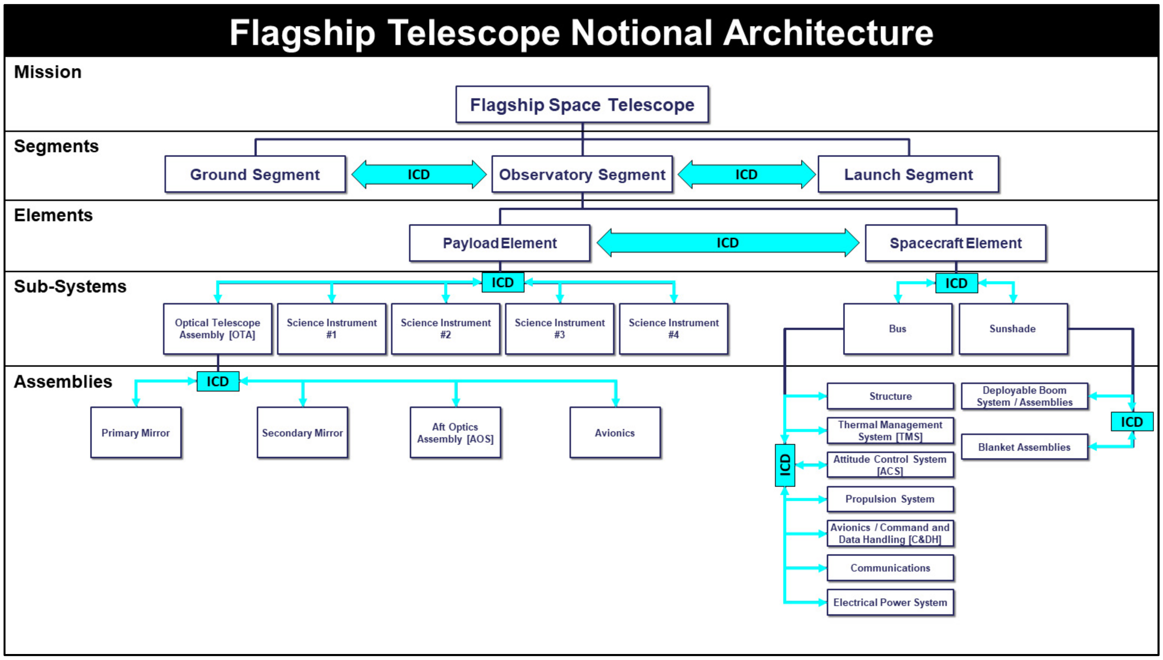

Figure 2 : A Notional Architecture for a Flagship Telescope Mission with Interface Control Document Interfaces Highlighted

Finally, this same architecture can be used to inform the decision making process as to how to sequence the integration and test flow, as illustrated in Figure 3.

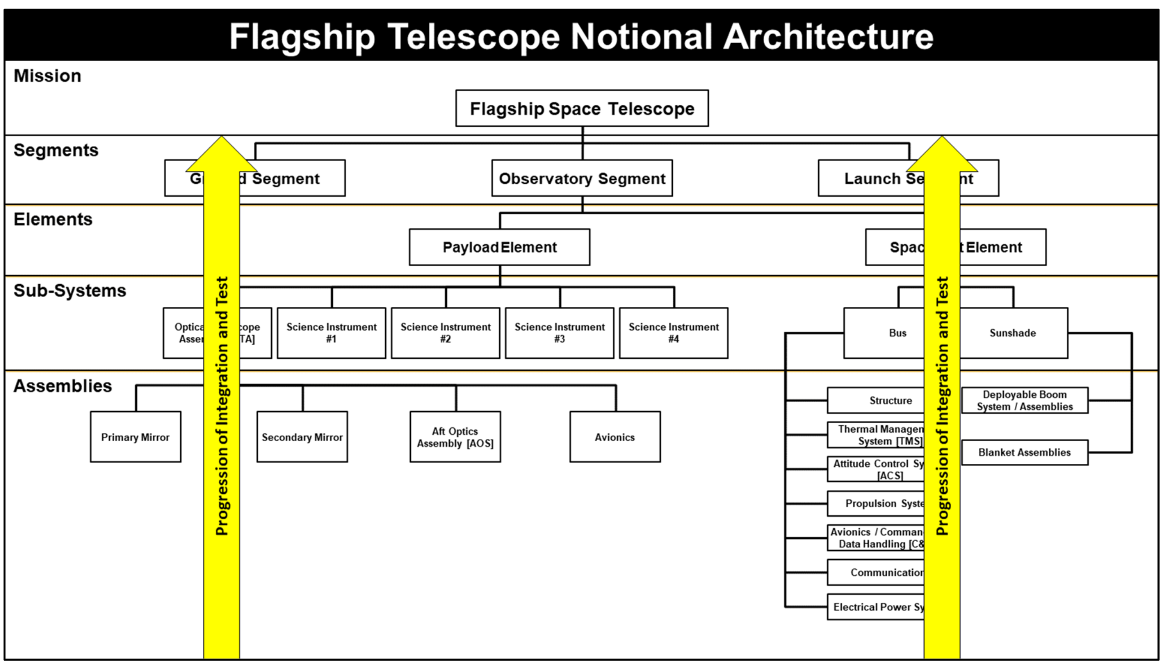

Figure 3 : A Notional Architecture for a Flagship Telescope Mission Showing the Path of Integration and Test

2.3 Mission Phasing

2.3.1 Mission vs Product Phasing

All NASA Missions are developed following NASA Procedural Requirement 7120.5, *NASA Space Flight Program and Project Management Requirements* along with the complementary *NASA/SP-2014-3705, NASA Space Flight Program and Project Management Handbook* as well as *NASA/SP-2017-6105, NASA Systems Engineering Handbook.* These documents describe the various "phases" that a project is split into.

As projects become more and more complex and nested with lower level products - the segments, elements, sub-systems and so on - there becomes a greater disconnect between the phases of the mission or the project and the products that make up the mission. Phases are structured around reviews and mission level reviews can't be completed until all lower level product reviews are completed. So, the more levels there are, the more out of sync a project and its products can become. This becomes problematic in two critical areas that can influence cost and schedule:

- Technology development, and
- Requirements development

It is imperative for a project of this magnitude to minimize changes that have a ripple effect across the entire architecture.

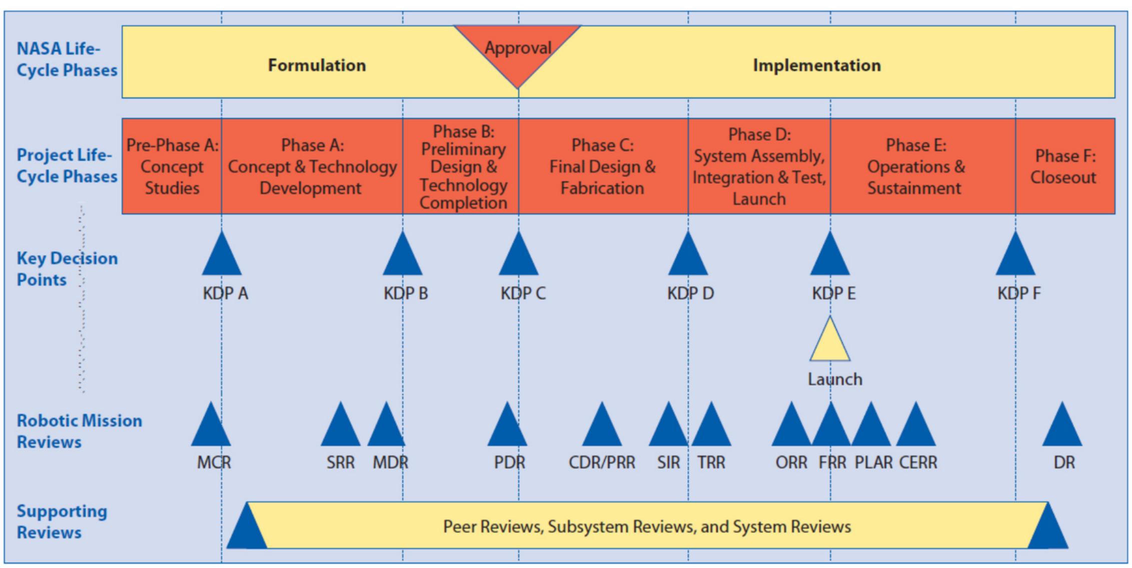

Figure 4 : Typical NASA Mission Phases, from *NASA/SP-2017-6105 NASA Systems Engineering Handbook*.

2.3.2 Early Technology Maturation

As is illustrated in Figure 4, NASA allows for a project to mature technologies to Technology Readiness Level (TRL) 6 up through Mission Preliminary Design Review (PDR) and the Government Accountability Office (GAO) reports failing to do so increases mission costs[7-10, 12].

However, due to the nested nature of flagship missions as illustrated in Figure 5, it is inadequate to allow the development of technologies through Mission PDR. By that time, nested entities such as assemblies and sub-systems could be through design, fabrication, integration, and test. Should a technology fail to mature as expected, it could alter the overall architecture and subsequently alter the conceptual and detailed designs. In either case, the size of the development team grows rapidly from Phase A to Phase B.

On flagship missions, we believe that ***enabling*** technologies – technologies that drive the mission architecture and for which the mission cannot accomplish the required science goals - should achieve a TRL 6 before the start of Phase A. Maturing technologies in this timeframe allows there to be interaction between technology development and the architecture and conceptual designs[13], as shown in Figure 6.

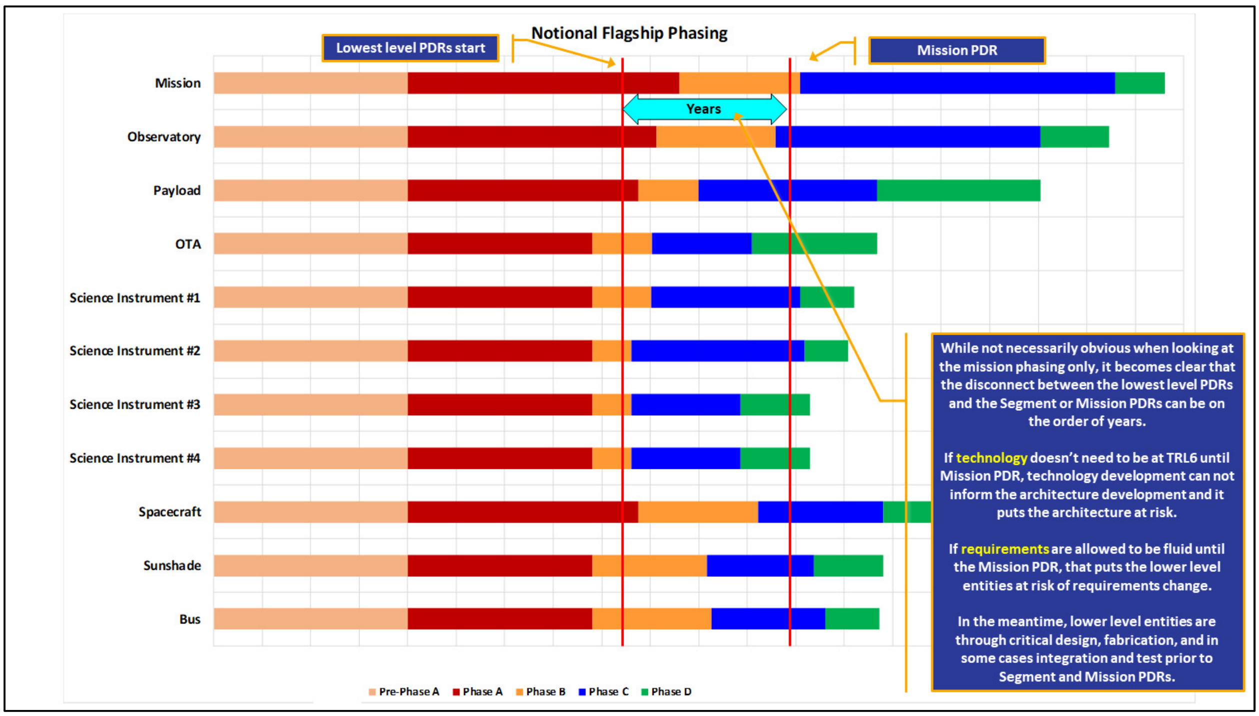

Figure 5 : A Notional Flagship Mission Phasing to illustrate that a significant amount of the conceptual design, detailed design, and even some integration and test at the lower levels is complete by the time a Segment or the Mission gets to PDR.

Enhancing technologies which are not required and could be replaced with alternative, existing technologies, wouldn't need to be developed as early so long as the alternative can replace it at any time with minimal impact to existing designs and interfaces.

2.3.3 Requirements

While true with any mission, complex, highly integrated flagship-level missions can reduce complexity and increase efficiency by requiring complete requirements definitions prior to

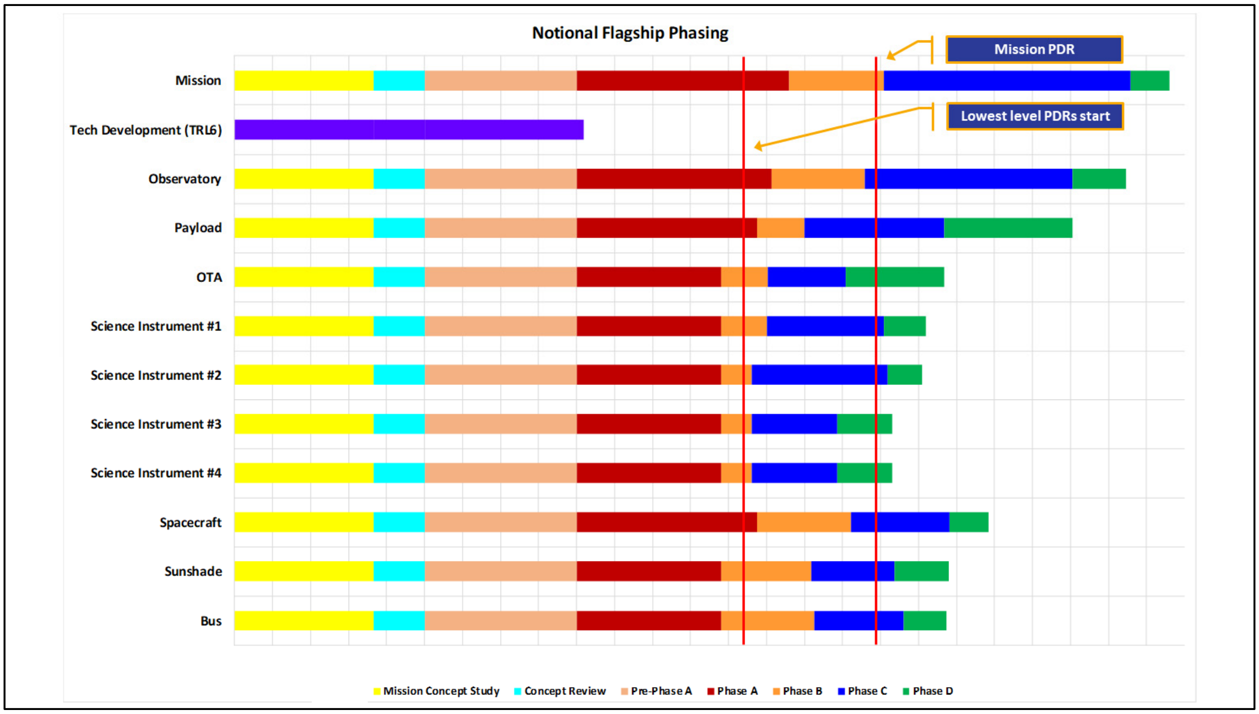

Figure 6 : A Notional Flagship Phasing to illustrate that if technology is developed to TRL-6 prior to the start of Phase A, it can better inform the early Phase A work and reduce the risk that the Mission would need to reset as late as PDR because of a failed technology development.

standing up a full design team. Smaller design teams will still be necessary to evaluate the feasibility of requirement allocations early on. While requirements are always subject to be reviewed, modified, or waived during the design process, ***minimizing*** the number of open, incomplete requirements and the length of time they are open through the detailed design phase will reduce risks to the schedule and cost. As illustrated in Figure 5, if requirements are allowed to stay open until a Segment or Mission PDR, the lower level entities are at risk of redesign due to evolving requirements rippling through sub-systems and assemblies. Alternatively, the lower level entities, as nearly finished products, may become unexpected constraints on the design of other parts of the evolving system.

Directed technology development before Phase A and directed early Phase A engineering test units and pathfinders can be used to converge on requirements that are difficult to close.

Despite the complexity of the system and the nested nature of a large flagship mission, flagship missions should define requirements using a strong systems engineering discipline that enables each of the part of the mission architecture to develop as independent as possible. It is understood that all of these systems interact, and that interaction will come with product requirements evolution that is inevitable. However, the more that each can exist in its own design space, the easier it is for designs to progress in parallel which is critical for making the schedule as efficient as possible.

2.4 Techniques for Managing Complexity

2.4.1 Modular Design

Using the mission architecture as a roadmap, flagship missions can manage complexity by making some aspects of the design modular. That is, design the system so that specific entities can be readily integrated and de-integrated at any time with minimal impact to schedule. Modules can be an entire sub-system such as a science instrument, or it can be a much smaller part of a sub-system such as a detector assembly which might need to be replaced late in the development cycle.

With a large, complex observatory, modular designs may add complexity up front during the concept and design phase, but, if strategically applied, should save time during later phases such as integration and test.

Modular design can enable flexibly during integration. For example, if all of the science instruments are modular which implies each is accessible without impacting the others, this can provide multiple integration paths allowing the project to compensate for non-nominal deliveries.

2.4.2 Pathfinders

One of the major lessons learned during other large flagship missions such as Chandra[2] and JWST[6, 11], is the need for engineering pathfinder tests. Pathfinder are used to flesh out design details, integration procedures and processes, and test flows and execution. Pathfinders should be used off the critical schedule path to help mature and optimize designs, plans, procedures, test setups, and integration sequences as much as possible for a "one-of-a-kind design" such as a flagship telescope.

2.4.3 Enable Parallel Manufacturing, Integration and Test Operations

The more things that can be done in parallel as opposed to serially, the more efficient the schedule can be. Successfully initiating parallel operations requires significant upfront planning. There needs to be a master plan and vision – a storyboard – with all of the parallel paths mapped out rigorously in an integrated master schedule. This will be iterated multiple times as the architecture and the concept designs evolve.

Parallel operations require significant training because pseudo-independent teams of people will be required to execute identical operations at the same time. This does not allow for having a single expert become a bottleneck anywhere. While an expert will be required to initiate a given plan, training of and delegation of authority to multiple teams will be required.

2.4.4 Managing Institutional Requirements

For flagship missions, we assume that a single NASA Center will be responsible for managing the mission and formally delivering the segment level products. Other NASA Centers, industry partners, international partners, and academia will also be involved with the engineering and development of the lower-level products.

With this breadth of development comes the challenge that each entity has their own set of rules governing the design, manufacturing, integration and test of products. While all NASA requirements stem from Agency level requirements, they are all tailored and optimized for each Center's work and experiences. Likewise, each industry, international, and academic partner has their own set of rules.

Having multiple rules doesn't necessarily present any problems during the development of individual products. However, it can become problematic during integration and test at higher levels of assembly. Past projects have seen anomalies that need to be addressed when multiple products from multiple Centers or industry partners are in place. These anomalies create inefficient scenarios when there is debate as to which rules are going to be followed – the ones under which a product was developed or the ones under which that product is being integrated into the larger system.

Any flagship team will need to address and communicate which rules will be in place at various levels of assembly so that any issues or conflicts can be addressed, and ideally, resolved prior to hardware deliveries. This would need to happen during the early Phase A work when the detailed mission science goals, architecture, and concept are developed.

This does not preclude agreements that allow partners to use their own internal rules for design, development, and testing of products. It does acknowledge that different entities do things differently and ultimately those products are going to be handled at a higher level of assembly at a Center that may impose rules that conflict with those from a lower level. The intent is to minimize compatibility issues that will inevitably present themselves during integration and test at various levels.

2.5 Team, experience, and depth

A significant factor in project success is having an experienced leadership team with hands-on relevant space flight mission development experience[16]. There is no substitute for end-to-end project lifecycle experience. That being said, any flagship will extend for many years and the project needs to be multiple people deep in critical positions in anticipation that not everyone will decide to finish the project.

Consider the architecture shown in Figure 1, and pick any product block. There should be at least two people who are subject matter experts (SMEs) that are cognizant of the product and can step in and lead should the other not be available. In this context, it is completely acceptable that one of those two people be a more junior person who is being mentored by the more experienced, senior person. In that way, both the flagship mission and the Agency benefit from training on the job.

Product Development Leads (PDLs) or Subsystem Leads need to be given the full authority to make decisions along with the responsibility to deliver a product consistent with requirements.

Those same PDLs need to understand, and work within, the project's decision making "command" structure which follows the mission architecture.

2.6 Funding

In order to implement these management strategies, which are expected to lead to cost and schedule savings, funding strategies and approaches need to be changed. Crooke et al. explores this in the Astro2020 APC whitepaper entitled "Funding Strategy Impacts and Alternative Funding Approaches for NASA's Future Flagship Mission Developments."[5]

3 Summary

Flagship missions present unique management challenges. The way flagship missions are managed directly impacts the cost and schedule of the mission. Lessons learned from previous flagship missions provide guidance on how to evolve management strategies so as to minimize the cost and schedule for delivering these grand, but imperative, undertakings. Early architecture development and organization is critical to ensuring that technology is developed in a usable manner. Likewise, technology development must be done early enough to intelligently inform iterations on the architecture and science operations strategies, all of which optimize the development of requirements and preliminary designs. Early pathfinding activities can inform designs, procedures, and processes while parallel fabrication, integration, and testing can shorten development schedules. An early and holistic approach to addressing the development of the entire mission, from architecture development to design to planning for integration and test methodologies, needs to be planned upfront.

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