

Hubble Space Telescope

Product Systems Engineering > Decision Management > Special:UserLogin
> Hubble Space Telescope

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This article describes a remarkable engineering feat with vast scientific benefits and implications. The topic may be of particular interest to those facing formidable systems engineering challenges where one might thrive on a thoughtful blend of humility and optimism. For additional information, refer to the links provided in Section V: Lessons Learned below.



Contents

Background
Purpose
Challenges
Systems Engineering Practices
Lessons Learned
References
 Works Cited
 Primary References
 Additional References

Background

The Hubble Space Telescope (HST) Case Study was developed by the United States Air Force Center for Systems Engineering (AF CSE) located at the Air Force Institute of Technology (AFIT). The AF CSE was tasked to develop case studies focusing on the application of

systems engineering principles within various aerospace programs. The HST study (Mattice 2005) is one of four initial case studies selected by AFIT for development in support of systems engineering graduate school instruction. The cases are structured using the Friedman-Sage framework (Friedman and Sage 2003; Friedman and Sage 2004, 84-96), which decomposes a case into contractor, government, and shared responsibilities in the following nine concept areas: STOPPED HERE

1. Requirements Definition and Management
2. Systems Architecture Development
3. System/Subsystem Design
4. Verification/Validation
5. Risk Management
6. Systems Integration and Interfaces
7. Life Cycle Support
8. Deployment and Post Deployment
9. System and Program Management

The case study provides a useful example of the rising cost of defect correction through successive life cycle phases, demonstrating how an error (in test fixture specification) that could have been fixed for \$1,000 at the design stage, or detected and fixed with a \$10 million investment in an end-to-end test of the telescope on the ground, ended up costing \$1 billion to fix when the system was in service.

Purpose

The Hubble Space Telescope (HST) is an orbiting astronomical observatory operating in the spectrum from the near-infrared into the ultraviolet. Launched in 1990 and still operational, HST carries and has carried a wide variety of instruments producing imaging, spectrographic, astrometric, and photometric data through both pointed and parallel observing programs. Over 100,000 observations of more than 20,000 targets have been produced for retrieval. The telescope is well known as a marvel of science. This case study hopes to represent the facet of the HST that is a marvel of systems engineering, which, in fact, generated the scientific research and observation capabilities now appreciated worldwide.

Viewed with the clarity that only time and hindsight provide, the HST program certainly represents one of

the most successful modern human endeavors on any scale of international scope and complexity. As a systems engineering project the HST had to respond to requirements from the diverse international scientific community at a time when NASA was implementing a different research-development-acquisition philosophy and process than what was predominately being used in most major government acquisition programs. As with most other large programs, powerful influences outside the systems engineering process itself became issues that HST systems engineers in effect had to acknowledge as integral to their overall system/program/engineering management responsibility.

Challenges

The story of how this remarkable capability came to be is a story of the complicated interactions of a systems engineering process, which we like to believe we understand, with equally demanding political, budgetary, and institutional processes we often fail to understand or comprehend at the time they occur. In the final analysis, these processes are inseparable and integral to attaining program success. The challenge to modern systems engineers is to fully embrace the discipline of the systems engineering process while at the same time learning how to continue to practice it in spite of inevitable external influences and instabilities that often cannot be anticipated.

Major differences revolved around the nature and needs of a very different HST “customer” or user from most DoD systems. The HST had to respond to requirements from the diverse international scientific community instead of from DoD’s combatant commands. In addition, at the time, NASA implemented a different research-development-acquisition philosophy and process than the DoD Acquisition Management Framework described in the DoD 5000 series acquisition reforms. As with most other large programs, powerful influences outside the systems engineering process itself became issues that HST systems engineers in effect had to acknowledge as integral to their overall system/program/engineering management responsibility.

Systems Engineering Practices

During the critical systems engineering phase for the HST program (1970s concept studies thru 1990 launch) there appears to have been no NASA systems engineering master process. Rather, field center

processes were operative and possibly even in competition, as centers (especially Marshall and Goddard for HST) were in keen competition for lead management roles and responsibilities. We will see the systems engineering and program management impacts of this competition as it played out for HST, with the science mission objectives and instrumentation payloads being the motivation for Goddard vs. the vehicle/payload access to space motivation of Marshall. In the final analysis, the roles of the major contractors in engineering the system with uneven NASA participation over the system life cycle had a telling effect.

Lessons Learned

Five learning principles (LPs) were derived that address the more broadly applicable areas of systems engineering knowledge. These five LPs inform the areas of the SEBoK that are most strongly related to the case study. The five areas are:

- stakeholder requirements definition (LP1);
- planning (pre-program trade studies) (LP2);
- system integration (LP3);
- life cycle model management (LP4); and
- risk management (LP5).

A synopsis of the HST Learning Principles (LPs) are as follows:

Stakeholder Requirements Definition LP1: Early and full participation by the customer/user throughout the program is essential to success. In the early stages of the HST program, the mechanism for involving the customer was not well defined. The user community was initially polarized and not effectively engaged in program definition and advocacy. This eventually changed for the better, albeit driven heavily by external political and related national program initiatives. Ultimately, institutionalization of the user's process for involvement ensured powerful representation and a fundamental stake and role in both establishing and managing program requirements. Over time, the effectiveness of "The Institute" led to equally effective user involvement in the deployment and on-orbit operations of the system as well.

Planning LP 2: The use of Pre-Program Trade Studies (e.g. "Phased Studies" or "Phased Project Planning") to broadly explore technical concepts and alternatives is

essential and provides for a healthy variety of inputs from a variety of contractors and government (NASA) centers. These activities cover a range of feasibility, conceptual, alternative and preliminary design trades, with cost initially a minor (later a major) factor. In the case of HST, several NASA Headquarters and Center organizations funded these studies and sponsored technical workshops for HST concepts. This approach can promote healthy or unhealthy competition, especially when roles and responsibilities within and between the participating management centers have not yet been decided and competing external organizations use these studies to further both technical and political agendas. NASA Center roles and missions can also be at stake depending on political and or budgetary realities. The systems engineering challenge at this stage is to “keep it technical, stupid!”

Systems Integration LP 3: A high degree of systems integration to assemble, test, deploy, and operate the system is essential to success and must be identified as a fundamental program resource need as part of the program baseline. For HST, the early wedding of the program to the Shuttle, prior NASA and NASA contractor experience with similarly complex programs, such as Apollo, and the early requirement for manned, on-orbit servicing made it hard not to recognize this was a big systems engineering integration challenge. Nonetheless, collaboration between government engineers, contractor engineers, as well as customers, must be well defined and exercised early on to overcome inevitable integration challenges and unforeseen events.

Life Cycle Models LP 4: Life Cycle Support planning and execution must be integral from day one, including concept and design phases. The results will speak for themselves. Programs structured with real life cycle performance as a design driver will be capable of performing in-service better, and will be capable of dealing with unforeseen events (even usage in unanticipated missions). HST probably represents a benchmark for building in system sustainment (reliability, maintainability, provision for technology upgrade, built-in redundancy, etc.), while providing for human execution of functions (planned and unplanned) critical to servicing missions. With four successful service missions complete, including one initially not planned (the primary mirror repair), the benefits of design-for-sustainment, or life cycle support, throughout all phases of the program become quite evident. Without this design approach, it is unlikely that the unanticipated, unplanned mirror repair could even have

been attempted, let alone been totally successful.

Risk Management LP 5: For complex programs, the number of stakeholders (government and contractor) demands that the program be structured to cope with high risk factors in many management and technical areas simultaneously. The HST program relied heavily on the contractors (especially Lockheed Missiles and Space Company (LMSC) and Perkin-Elmer (P-E)), each of which “owned” very significant and unique program risk areas. In the critical area of optical systems, NASA depended on LMSC as the overall integrator to manage risk in an area where P-E was clearly the technical expert. Accordingly, NASA relied on LMSC and LMSC relied on P-E with insufficient checks, oversight, and independence of the quality assurance function throughout. While most other risk areas were no doubt managed effectively, lapses here led directly to the HST’s going to orbit with the primary mirror defect undetected, in spite of substantial evidence that could have been used to prevent this.

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Primary References

None.

Additional References

None.

[< Previous Article](#) | [Parent Article](#) | [Next Article >](#)

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