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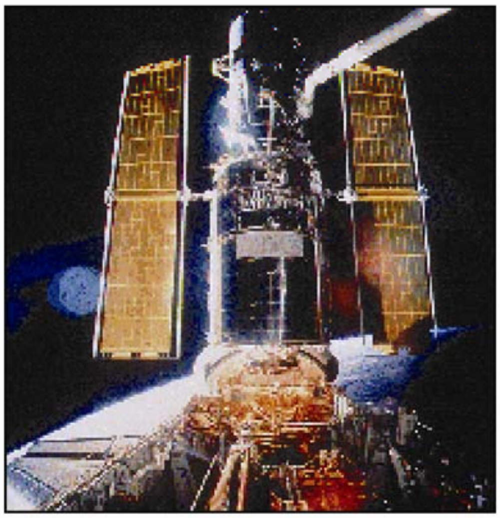
Hubble Space Telescope Systems Engineering Case Study

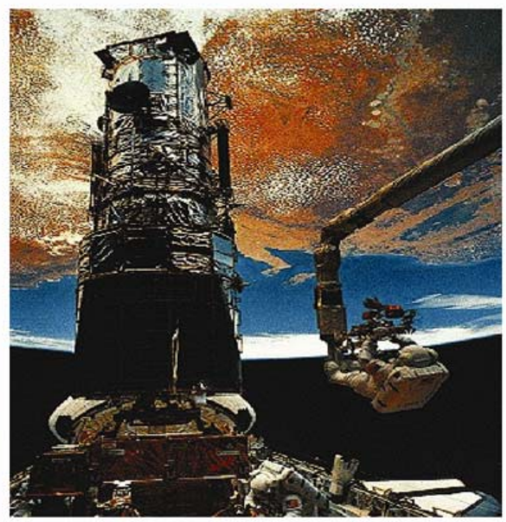
Air Force Center for Systems Engineering

James J. Mattice

HUBBLE SPACE TELESCOPE SYSTEMS ENGINEERING CASE STUDY

By James J. Mattice
SES (Ret.)





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PREFACE

In response to Air Force Secretary James G. Roche's charge to reinvigorate the systems engineering profession, the Air Force Institute of Technology (AFIT) undertook a broad spectrum of initiatives that included creating new and innovative instructional material. The Institute envisioned case studies on past programs as one of these new tools for teaching the principles of systems engineering.

Four case studies, the first set in a planned series, were developed with the oversight of the Subcommittee on Systems Engineering to the Air University Board of Visitors. The Subcommittee includes the following distinguished individuals:

Chairman

Dr. Alex Levis, AF/ST

Members

Brigadier General Tom Sheridan, AFSPC/DR

Dr. Daniel Stewart, AFMC/CD

Dr. George Friedman, University of Southern California

Dr. Andrew Sage, George Mason University

Dr. Elliot Axelband, University of Southern California

Dr. Dennis Buede, Innovative Decisions Inc.

Dr. Dave Evans, Aerospace Institute

Dr. Levis and the Subcommittee on Systems Engineering crafted the idea of publishing these case studies, reviewed several proposals, selected four systems as the initial cases for study, and continued to provide guidance throughout their development. The Subcommittee's leading minds in systems engineering have been a guiding force to charter, review, and approve the work of the authors. The four case studies produced in this series are the C-5 Galaxy, the F-111, the Hubble Space Telescope, and the Theater Battle Management Core System.

FOREWORD

At the direction of the Secretary of the Air Force, Dr. James G. Roche, the Air Force Institute of Technology (AFIT) established a Center for Systems Engineering (CSE) at its Wright-Patterson AFB, OH, campus in 2002. With academic oversight by a Subcommittee on Systems Engineering, chaired by Air Force Chief Scientist Dr. Alex Levis, the CSE was tasked to develop case studies focusing on the application of systems engineering principles within various aerospace programs. At a May 2003 meeting, the Subcommittee reviewed several proposals and selected the Hubble Telescope (space system), Theater Battle Management Core System (complex software development), F-111 fighter (joint program with significant involvement by the Office of the Secretary of Defense), and C-5 cargo airlifter (very large, complex aircraft). The committee drafted an initial case outline and learning objectives, and suggested the use of the Friedman-Sage Framework to guide overall analysis.

The CSE contracted for management support with Universal Technology Corporation (UTC) in July 2003. Principal investigators for the four cases included Mr. John Griffin for the C-5A, Dr. G. Keith Richey for the F-111, Mr. James Mattice for the Hubble Space Telescope, and Mr. Josh Collens from The MITRE Corporation for the Theater Battle Management Core System effort.

The Department of Defense continues to develop and acquire joint complex systems that deliver needed capabilities demanded by our warfighters. Systems engineering is the technical and technical management process that focuses explicitly on delivering and sustaining robust, high-quality, affordable products. The Air Force leadership, from the Secretary of the Air Force, to our Service Acquisition Executive, through the Commander of Air Force Materiel Command, has collectively stated the need to mature a sound systems engineering process throughout the Air Force.

These cases will support academic instruction on systems engineering within military service academies and at both civilian and military graduate schools. Plans exist for future case studies focusing on other areas. Suggestions have included various munitions programs, Joint service programs, logistics-led programs, science and technology/laboratory efforts, additional aircraft programs such as the B-2 bomber, and successful commercial systems.

As we uncovered historical facts and conducted key interviews with program managers and chief engineers, both within the government and those working for the various prime and subcontractors, we concluded that systems programs face similar challenges today. Applicable systems engineering principles and the effects of communication and the environment continue to challenge our ability to provide a balanced technical solution. We look forward to your comments on this case study and the others that follow.

MARK K. WILSON, SES

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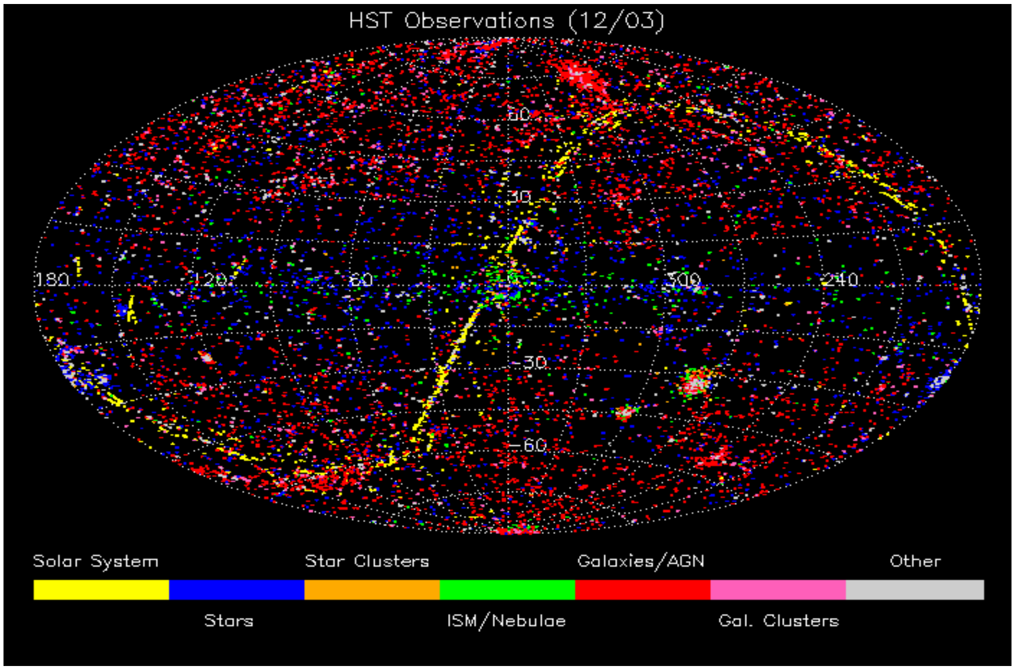
The author wishes to recognize the following contributors: Dr. Kathryn D. Sullivan, President and CEO, Center of Science and Industry, Columbus, OH, a former astronaut and deployment EVA mission specialist, for her personal insights into Hubble on-orbit servicing design adequacy and mission effectiveness; James B. Odom, Senior Vice President, Science Applications International Corporation, Huntsville, AL, Hubble Program Manager, 1981–1986, for his personal insights and research leads; and Jean R. Oliver, Deputy Manager, NASA Chandra X-Ray Observatory, Hubble Chief Engineer, 1974–1988, for his personal insights and critical review of the Hubble Case Study manuscript. The author also wishes to acknowledge the valuable contributions of case study teammates Lt Col John Colombi, AFIT/SYE, Dr. G. Keith Richey (F-111 Case Study author), Mr. John Griffin (C-5A Case Study author), and Dr. Dennis Buede, Stevens Institute of Technology. Finally, of special significance and assistance in dealing with the wealth of HST information available between 1977 and 1987 was the very thorough book [2] *The Space Telescope – A Study of NASA, Science, Technology, and Politics*, by Robert W. Smith of the Smithsonian Institution, with key contributions by many others, including reflections, retrospective essays and interviews.

James J. Mattice

EXECUTIVE SUMMARY

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 scheduled to operate through 2010, 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. A macroscopic, cumulative representation of these observations is shown in the figure below to provide a sense of the enormous volume of astronomical data collected by the HST about our universe, our beginnings, and, consequently, about our future. The telescope is already 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.



The incredible story of the HST program from the early dreams and visions of a space-based telescope in 1946, through extensive, more formal program formulation and developments in the 1970s, tumultuous re-direction in the 1980s (especially due to the impact of the 1986 Challenger disaster), initial launch in 1990, and unplanned major on-orbit repairs in 1993 provides the basis for an exciting case study in all aspects of systems engineering. As we will see, this case represents a program dramatically impacted by a variety of scientific, technical, economic, political, and program management events and factors, many of them unpredictable [2].

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 we will see, it also represents a remarkable systems engineering case study with both contrasts and similarities when compared to large defense systems. 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.

We hope that these differences will illustrate why it is very important for Air Force, as well as other Service and DoD systems engineers at any experience level, to study a case that, on the surface, might seem only remotely relevant to DoD systems management. To the contrary, much can be learned, and perhaps even learned better in terms of systems engineering education, because the reference system is not as easily comprehended by DoD experienced students of the systems engineering process.

A synopsis of some of the most significant HST Learning Principles (LPs) to be explored is as follows:

LP 1, <u>Early and full participation by the customer/user throughout the program is essential to success</u>. 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.

LP 2, <u>The use of Pre-Program Trade Studies ("Phased Studies or "Phased Project Planning" in NASA parlance at the time) 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</u>. 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 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. 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!"

LP 3, <u>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</u>. For HST, the early wedding of the program to the Shuttle, prior NASA (and of course, 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.

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 the 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 becomes 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.

LP 5, For complex programs, the number of players (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.

Table of Contents

PREFACE i

FOREWORD iii

ACKNOWLEDGEMENTS iv

EXECUTIVE SUMMARY v

1.0 SYSTEMS ENGINEERING PRINCIPLES 1

- 1.1 General Systems Engineering Process 1
- 1.2 HST Major Learning Principles 6

2.0 SYSTEM DESCRIPTION 9

3.0 HST SYSTEMS ENGINEERING LEARNING PRINCIPLES 20

- 3.1 Learning Principle 1 – Early Customer/User Participation 20
- 3.2 Learning Principle 2 – Use of Pre-Program Trade Studies 21
- 3.3 Learning Principle 3 – System Integration 23
- 3.4 Learning Principle 4 – Life Cycle Support Planning and Execution 33
- 3.5 Learning Principle 5 – Risk Assessment and Management 37

4.0 SUMMARY 43

5.0 REFERENCES 47

6.0 LIST OF APPENDICES 49

- Appendix 1 - Completed Friedman Sage Matrix for HST 50
- Appendix 2 - Author Biography 52
- Appendix 3 - Documentation, HST Cargo Systems Manual 54
- Appendix 4 - Hubble Space Telescope Level I Requirements For The Operational Phase of The Hubble Space Telescope Program 55

List of Figures

Figure 1-1 The Systems Engineering Process as Presented by the Defense Acquisition University ... 2
Figure 2-1 STS-61 Repair Mission ... 11
Figure 2-2 1990 HST Initial Deployment April 24, 1990 ... 14
Figure 2-3 HST Major System Elements ... 15
Figure 2-4 HST Optical Telescope Assembly ... 18
Figure 3-1 OTA Primary Mirror Assembly ... 25
Figure 3-2 Location of Scientific Instruments in the Optical Telescope Assembly ... 26
Figure 3-3 Encircled Energy vs. Arc-second Radius of Image Produced by HST ... 29
Figure 3-4 Metering Rod Positioning in the Reflective Null Corrector ... 30
Figure 3-5 Displacement of Metering Rod – Design vs. Actual ... 31
Figure 3-6 HST Disposal Mission Requirements Background ... 36
Figure 3-7 HST Disposal Mission Draft Requirements ... 37
Figure 3-8 1977 HST Program/Communications Interfaces ... 39
Figure 3-9 Hubble Space Telescope Responsibilities, 1990 ... 40
Figure 3-10 Marshall SFC HST Responsibilities, 1990 ... 42

List of Tables

Table 1-1 A Framework of Key Systems Engineering Concepts and Responsibilities ... 5
Table 1-2 A Framework for Systems Engineering Concept and Responsibility Domains [2] ... 8
Table 2-1 Time Phase for Program ... 13
Table 3-1 Large Telescope Mirror Size – System Cost Trade (1975) ... 22
Table 3-2 HST Specification ... 23
Table 3-3 HST Specification Weight Status ... 27
Table 3-4 HST Summary Weight Statement ... 28
Table A1-1 The Friedman Sage Matrix for the HST ... 50

1.0 SYSTEMS ENGINEERING PRINCIPLES

1.1 General Systems Engineering Process

1.1.1 Introduction

The Department of Defense continues to develop and acquire joint systems and to deliver needed capabilities to the warfighter. With a constant objective to improve and mature the acquisition process, it continues to pursue new and creative methodologies to purchase these technically complex systems. A sound systems engineering process, focused explicitly on delivering and sustaining robust, high-quality, affordable products that meet the needs of customers and stake holders must continue to evolve and mature. Systems engineering is the technical and technical management process that results in delivered products and systems that exhibit the best balance of cost and performance. The process must operate effectively with desired mission-level capabilities, establish system-level requirements, allocate these down to the lowest level of the design, and ensure validation and verification of performance, meeting cost and schedule constraints. The systems engineering process changes as the program progresses from one phase to the next, as do the tools and procedures. The process also changes over the decades, maturing, expanding, growing, and evolving from the base established during the conduct of past programs. Systems engineering has a long history. Examples can be found demonstrating a systemic application of effective engineering and engineering management, as well as poorly applied, but well defined processes. Throughout the many decades during which systems engineering has emerged as a discipline, many practices, processes, heuristics, and tools have been developed, documented, and applied.

Several core lifecycle stages have surfaced as consistently and continually challenging during any system program development. First, system development must proceed from a well-developed set of requirements. Regardless of overall waterfall or evolutionary acquisition approach, the system requirements must flow down to all subsystems and lower level components. System requirements need to be stable, balanced and must properly reflect all activities in all intended environments.

Next, the system planning and analysis occur with important tradeoffs and a baseline architecture developed. These architectural artifacts can depict any legacy system modifications, introduction of new technologies and overall system-level behavior and performance. Modeling and simulation are generally employed to organize and assess alternatives at this introductory stage. System and subsystem design follows the functional architecture. Either newer object-oriented analysis and design or classic structured analysis using functional decomposition and information flows/ data modeling occurs. Design proceeds logically using key design reviews, tradeoff analysis, and prototyping to reduce any high-risk technology areas.

Important to the efficient decomposition and creation of the functional and physical architectural designs are the management of interfaces and integration of subsystems. This is applied to subsystems within a system, or across large, complex systems of systems. Once a solution is planned, analyzed, designed and constructed, validation and verification take place to ensure satisfaction of requirements. Definition of test criteria, measures of effectiveness (MOEs) and measures of performance (MOPs), established as part of the requirements process well before any component/ subsystem assembly, takes place.

There are several excellent representations of the systems engineering process presented in the literature. These depictions present the current state of the art in the maturity and evolution of the systems engineering process. One can find systems engineering process definitions, guides and handbooks from the International Council on Systems Engineering (INCOSE), European Industrial Association (EIA), Institute of Electrical and Electronics Engineers (IEEE), and various Department of Defense (DoD) agencies and organizations. They show the process as it should be applied by today's experienced practitioner. One of these processes, long used by the Defense Acquisition University (DAU), is depicted by Figure 1-1. It should be noted that this model is not accomplished in a single pass. Alternatively, it is an iterative and nested process that gets repeated at low and lower levels of definition and design.

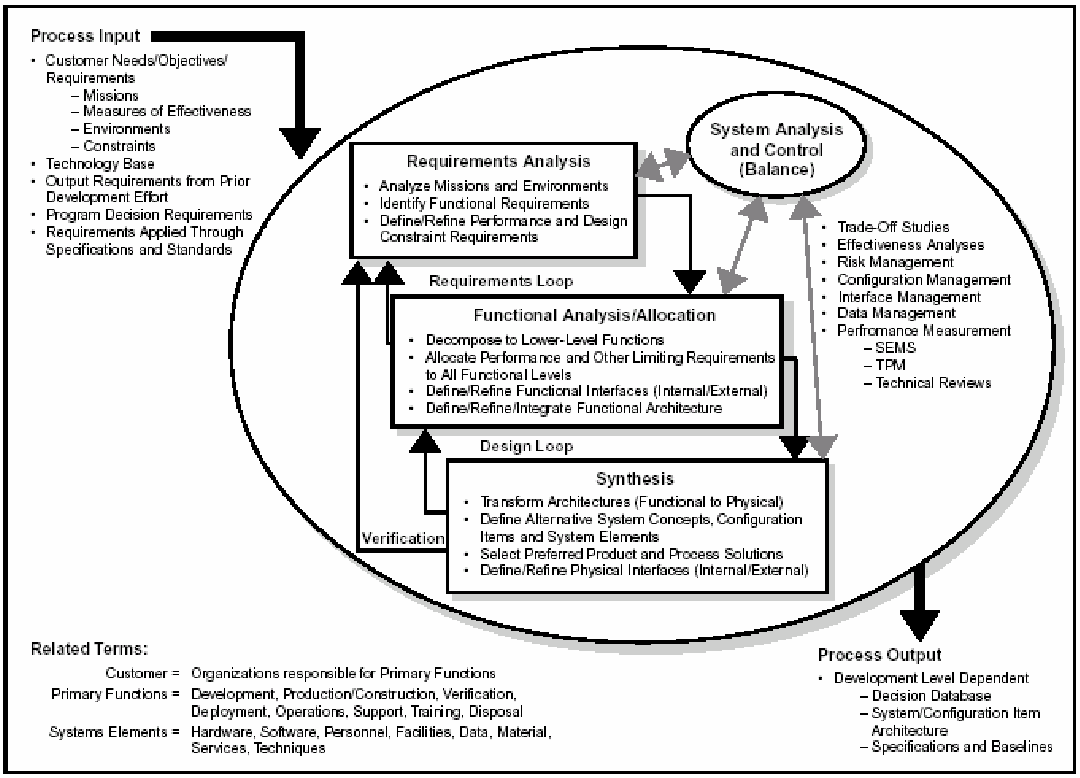


Figure 1-1. The Systems Engineering Process as Presented by the Defense Acquisition University

1.1.2 Evolving Systems Engineering Process

The DAU model, like all others, has been documented in the last two decades, and has expanded and developed to reflect a changing environment. Systems are becoming increasingly complex internally and more interconnected externally. The process used to develop the aircraft and systems of the past was a process effective at the time. It served the needs of the practitioners and resulted in many successful systems in our inventory. Notwithstanding, the cost and schedule performance of the past programs are fraught with examples of some well-managed programs and ones with less stellar execution. As the nation entered the 1980s and 1990s, large DoD and commercial acquisitions were overrunning costs and behind schedule. The aerospace industry and its organizations were becoming larger and were more

geographically and culturally distributed. The systems engineering process, as applied within the confines of a single system and a single company, is no longer the norm.

Today, many factors overshadow new acquisition, including system-of-systems (SoS) context, network centric warfare and operations, and the rapid growth in information technology. These factors have driven a new form of emergent systems engineering, which focuses on certain aspects of our current process. One of these increased areas of focus resides in the architectural definitions used during system analysis. This process will be differentiated by greater reliance on reusable, architectural views describing the system context and concept of operations, interoperability, information and data flows and network service-oriented characteristics. The DoD has recently made these architectural products, described in the DoD Architectural Framework (DoDAF), mandatory to enforce this new architecture-driven systems engineering process throughout the acquisition lifecycle.

The NASA Systems Engineering Process. The recent NASA systems engineering process is probably best described in the "NASA Systems Engineering Handbook" [25] published in 1995. The announced NASA position regarding this document is that it does not represent the current process or all current best practices but is useful mainly as an educational tool for developing systems engineers. This handbook evolved over time, beginning in 1989 with an extensive effort resulting in an initial draft in September 1992 and subsequent improvements captured in the latest (1995) version. Interestingly, the forward makes a strong statement that the handbook is primarily for those taking engineering courses, with working professionals who require a guidebook to NASA systems engineering representing a secondary audience. The reason for this appears to be that the handbook, although substantive (in excess of 150 pages), is not intended to hold sway over individual field center systems engineering handbooks, NASA Management Instructions, other NASA handbooks, field center systems engineering briefings on systems engineering processes, and the three independent systems engineering courses being taught to NASA audiences.

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.

1.1.3 Case Studies

The systems engineering process to be used in today's complex system-of-systems projects is a process matured and founded on the principles of systems developed in the past. The examples of systems engineering used on other programs, both past and present, provide a wealth of lessons to be used in applying and understanding today's process. It was this thinking that led to the construction of the four case studies released in this series.

The purpose of developing detailed case studies is to support the teaching of systems engineering principles. They will facilitate learning by emphasizing to the student the long-term

consequences of the systems engineering and programmatic decisions on program success. The systems engineering case studies will assist in discussion of both successful and unsuccessful methodologies, processes, principles, tools, and decision material to assess the outcome of alternatives at the program/system level. In addition, the importance of using skills from multiple professions and engineering disciplines and collecting, assessing, and integrating varied functional data will be emphasized. When they are taken together, the student is provided real-world, detailed examples of how the process attempts to balance cost, schedule and performance.

The utilization and mis-utilization of systems engineering learning principles will be highlighted, with special emphasis on the conditions that foster and impede good systems engineering practice. Case studies should be used to illustrate both good and bad examples of acquisition management and learning principles, to include whether:

- Every system provides a balanced and optimized product to a customer
- Effective Requirements analysis was applied
- Consistent and rigorous application of systems engineering Management standards was applied
- Effective Test planning was accomplished
- There were effective major Technical program reviews
- Continuous Risk assessments and management was implemented
- There were reliable Cost estimates and policies
- They used disciplined application of Configuration Management
- A well defined System boundary was defined
- They used disciplined methodologies for complex systems
- Problem solving incorporated understanding of the System within bigger environment (customer's customer)

The systems engineering process transforms an operational need into a set of system elements. These system elements are allocated and translated by the systems engineering process into detailed requirements. The systems engineering process, from the identification of the need to the development and utilization of the product, must continuously integrate and balance the requirements, cost, and schedule to provide an operationally effective system throughout its life cycle. Case studies should also highlight the various interfaces and communications to achieve this optimization, which include:

- The program manager/systems engineering interface essential between the operational user and developer (acquirer) to translate the needs into the performance requirements for the system and subsystems.
- The government/contractor interface essential for the practice of systems engineering to translate and allocate the performance requirements into detailed requirements.
- The developer (acquirer)/User interface within the project, essential for the systems engineering practice of integration and balance.

The systems engineering process must manage risk, both known and unknown, as well as internal and external. This objective will specifically capture those external factors and the impact of these uncontrollable influences, such as actions of Congress, changes in funding, new instructions/policies, changing stakeholders or user requirements or contractor and government staffing levels.

Lastly, the systems engineering process must respond to “Mega-Trends” in the systems engineering discipline itself, as the nature of systems engineering and related practices do vary with time.

1.1.4 Framework for Analysis

The case studies will be presented in a format that follows the learning principles specifically derived for the program, but will utilize the Friedman-Sage framework to organize the assessment of the application of the systems engineering process. The framework and the derived matrix can play an important role in developing case studies in systems engineering and systems management, especially case studies that involve systems acquisition. The framework presents a nine row by three column matrix shown in Table 1-1.

Table 1-1. A Framework of Key Systems Engineering Concepts and Responsibilities

Concept Domain	Responsibility Domain		
	1. Contractor Responsibility	2. Shared Responsibility	3. Government Responsibility
A. Requirements Definition and Management			
B. Systems Architecting and Conceptual Design			
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration			
E. Validation and Verification			
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment and Management			
I. System and Program Management			

Six of the nine concept domain areas in Table 1-1 represent phases in the systems engineering lifecycle:

A. Requirements Definition and Management

B. Systems Architecting and Conceptual Design

C. Detailed System and Subsystem Design and Implementation

D. Systems and Interface Integration

E. Validation and Verification

F. System Deployment and Post Deployment

Three of the nine concept areas represent necessary process and systems management support:

G. Life Cycle Support

H. Risk management

I. System and Program Management

While other concepts could be have been identified, the Framework suggests these nine are the most relevant to systems engineering in that they cover the essential life cycle processes

in systems acquisition and the systems management support in the conduct of the process. Most other concept areas that were identified during the development of the matrix appear to be subsets of one of these. The three columns of this two-dimensional framework represent the responsibilities and perspectives of government and contractor, and the shared responsibilities between the government and the contractor.

The important feature of the Friedman-Sage framework is the matrix. The systems engineering case studies published by AFIT employ the Friedman-Sage construct and matrix as the baseline assessment tools to evaluate the conduct of the systems engineering process for the topic program. The Friedman Sage matrix is not a unique systems engineering applications tool per se, but rather a disciplined approach to evaluate the systems engineering process, tools, and procedures as applied to a program.

The Friedman-Sage matrix is based on two major premises as the founding objectives:

- In teaching systems engineering, case studies can be instructive in that they relate aspects of the real world to the student to provide valuable program experience and professional practice to academic theory.

In teaching systems engineering in DoD, there has previously been a little distinction between duties and responsibilities of the government and industry activities. More often than not, the government role in systems engineering is the role as the requirements developer.

1.2 HST Major Learning Principles

For this case study, a learning principle is a discussion of the key points relevant to the appropriate concept domain in Table 1-2. In this sense, a learning principle is really a systems engineering "lesson learned" for the HST. HST major learning principles are:

LP 1, <u>Early and full participation by the customer/user throughout the program is essential to program success</u>. In the early stages of the HST program the mechanism was not well defined and the user community was initially polarized and not effectively engaged in program definition and advocacy. This ultimately changed for the better, even if 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 program requirements and requirements management. Over time, the effectiveness of "The Institute" led to equally effective user involvement in the operational aspects of system (deployment and operations) as well.

LP 2, <u>The use of Pre-Program Trade Studies ("Phased Studies or "Phased Project Planning" in NASA parlance at the time) 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</u>. These activities cover a range of feasibility, conceptual, alternative and preliminary design trades with cost initially a minor, then later a major, factor as the process proceeds. For HST, several Headquarters and Center organizations funded these studies and sponsored technical workshops for HST concepts. This 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. 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!"

LP 3, Provision for 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 from early on (part of the program baseline). For HST, the early wedding of the program to the Shuttle, prior NASA (and of course, NASA contractors) 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 SE 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.

LP 4, Life Cycle Support Planning and Execution must be integral from day one (including concept and design phases) and 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 unplanned, unforeseen events (even usage in unanticipated missions). HST likely represents the benchmark for building-in system sustainment (reliability, maintainability, provision for technology upgrade, built-in redundancy, etc.), all with provision for operational 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, becomes quite evident. Had this not been the case, it is not likely that the unanticipated, unplanned mirror repair could have even been attempted, let alone be totally successful.

LP 5, For complex programs, the number of players (government and contractor) demands that the program be structured to cope with high risk factors in many management and technical areas simultaneously. For HST, there was heavy reliance on the contractors (especially Lockheed (LMSC) and Perkin-Elmer (P-E)) and they each “owned” very significant and unique program risk areas. In the critical optical system area, and with LM as the overall integrator, there was too much reliance on LM 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 QA function throughout. While most other risk areas were no doubt managed effectively, lapses here led directly to the primary mirror defect going to orbit undetected in spite of substantial evidence that could have been used to prevent this occurrence.

1.2.1 HST Friedman Sage Matrix

Table 1-2 shows the Friedman Sage matrix for the HST and seven entrees in the matrix most representative of the five learning principles.

HST Learning Principle 1, Early Customer/User Involvement, is represented by the first row of the concept domain, Requirements Definition and Management. The case study will follow the systems engineering process used in the definition and documentation of the requirements in the system specification, along with the contractor and government processes to translate functional requirements into design requirements. For HST, while the bulk of the responsibility lay with the customer (the world telescope science community) early in the process, the unique roles of NASA as a program broker and industry co-advocate was also a vital part of the process.

HST Learning Principle 2, Use of Pre-Program Trade Studies, is represented by the second row of the concept domain and is considered a strength of the NASA process involving a phased approach which attempts to sort out major conceptual and design technical issues early with out cost as an initial driving force. A system of the multi-dimensional complexity (electrical/optical/mechanical) in all operational phases (ground build/test, launch mated to Shuttle, on-orbit deployment/maintenance) demanded a high degree of systems architecting as a shared responsibility. While not focused upon as a learning principle, the impact of good HST architecting and conceptual design had a profound impact on all aspects of System and Subsystem Detailed Design and Implementation, especially on the part of the contractors and the NASA launch/operations organizations.

HST Learning Principle 3, Systems Integration, captures the enormous area of systems engineering activity spanning from the total system design concept domain through the actual build and test validation/verification domain. It is here that the system engineering process and discipline must prevail to literally make all of the pieces come together at every level successfully. The responsibility here is shared with the contractor more in the “do it" role and the government ensuring adherence to systems engineering discipline and sufficiency of process and resources.

HST Learning Principle 4, Life Cycle Support, covers two broad concept domains for HST – Deployment and Post Deployment, and Life Cycle Support. Design for sustainment and supportability, HST team shared responsibility for these domains had to be design drivers with the deployment phase largely automated and the maintenance phases largely planned and implemented for Astronaut implementation through servicing missions.

HST Learning Principle 5, Risk and Systems Engineering Management, necessarily transcends the concept domains of Risk Assessment/Management and System/Program Management. Ownership and implementation of technical risk management for HST was unusually complex, shared and often indistinguishable from system/program management functions. The very structure and processes for each were intertwined, shared but often blurred with respect to accountability when things did not work as planned.

Table 1-2. A Framework for Systems Engineering Concept and Responsibility Domains [2]

Concept Domain	Responsibility Domain		
	1. SE Contractor Responsibility	2. Shared Responsibility	3. Government Responsibility
A. Requirements Definition and Management			LP 1 Early customer/user involvement
B. Systems Architecting and Conceptual Design		LP 2 Use of pre-program trade studies	
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration		LP 3 Systems integration	
E. Validation and Verification			
F. Deployment and Post Deployment		LP 4 Life cycle support	
G. Life Cycle Support		LP 4 Life cycle support	
H. Risk Assessment and Management		LP 5 Risk and systems engineering management	
I. System and Program Management			LP 5 Risk and systems engineering management

2.0 SYSTEM DESCRIPTION

Historical Context

For decades astronomers dreamed of placing a telescope in space well above the Earth's atmosphere, a complex filter that poses inherent limitations to optical investigation and observation of celestial bodies. A 1923 concept of an observatory in space was suggested by the German scientist Hermann Oberth (who first inspired Dr. Wernher von Braun to study space travel). In 1962, and later in 1965 and 1969, studies at the National Academy of Sciences formally recommended the development of a large space telescope as a long-range goal of the emerging U.S. space program. Two Orbiting Astronomical Observatories, designed for observing the stars, were successfully launched by NASA in 1968 and in 1972. These generated impressive scientific results and stimulated both public and institutional support for a bigger and more powerful optical space telescope.

With the approval of the Space Shuttle program and with the Shuttle's inherent capacity for man-rated flight, large payloads, and on-orbit servicing, stability, and control, the concept of a large telescope in space was seen as practical (albeit at significant expense and with major technical and systems engineering challenges). In 1973 NASA selected a team of scientists to establish the basic telescope and instrumentation design and Congress provided initial funding. In 1977 an expanded group of 60 scientists from 38 institutions began to refine the earlier recommendations, concepts, and preliminary designs.

NASA formally assigned systems responsibility for design, development, and fabrication of the telescope to the Marshall Space Flight Center in Huntsville, Alabama. Marshall subsequently conducted a formal competition and selected two parallel prime contractors in 1977 to build what became known as the HST. P-E in Danbury, Connecticut, was chosen to develop the optical system and guidance sensors, and LMSC of Sunnyvale, California, was selected to produce the protective outer shroud and the support systems for the telescope, as well as to integrate and assemble the final product.

The design and development of scientific instrumentation payloads and the ground control mission were assigned to Goddard Space Flight Center in Greenbelt, Maryland. Goddard scientists were selected to develop one instrument, and three of the others became the responsibility of scientists at major universities. The European Space Agency agreed to furnish the solar arrays and one of the scientific instruments.

The Space Telescope Science Institute (STScI), on the campus of Johns Hopkins University in Baltimore, Maryland, performs planning of scientific experiments for the HST. The STScI, dedicated in 1983, is operated by the Association of Universities for Research in Astronomy (AURA) and directed by Goddard. Institute scientists generate the telescope's research agenda, select observation proposals from astronomers around the world, coordinate on-going research, and disseminate results. They also archive and distribute results of the investigations. In 1985 the STOCC, located at Goddard, was established as the ground control, health monitoring and safety oversight facility for the telescope. The STOCC converts the observation agenda from the STScI into digital commands and relays them to the telescope. In turn, the STOCC receives observation data and the STScI translates it into a customer-usable format.

Development, fabrication, integration, and assembly of the HST was a daunting, almost 10-year process. The precision-ground mirror was completed in 1981. Science instrument packages were delivered for testing in 1983. The full-up optical assembly was delivered for integration into the satellite in 1984, and assembly of the entire spacecraft was completed in 1985.

Launch of the HST, originally scheduled for 1986, was delayed during the Space Shuttle return-to-flight redesign and recertification program that followed the Challenger accident. Systems engineers used the interim period to significant program advantage for extensive testing and evaluation to ensure high system reliability and ready feasibility of planned on-orbit servicing maintenance functions.

The HST was transported from the Lockheed site in California to the Kennedy Space Center, Florida, in 1989. It was prepared for launch and carried aloft aboard the STS-31 mission of the Space Shuttle Discovery on April 24, 1990.

The HST, with anticipated resolution power some 10 times better than any telescopic device on Earth, was on the verge of introducing a whole new dimension of astronomical research and education. However, soon after initial experiments began to show mixed results, a major performance problem was traced to a microscopic flaw in the main mirror that significantly reduced the ability of the telescope to focus properly for demanding (and most valuable) experiments. The focusing defect was found to result from an optical distortion due to an incorrectly shaped/machined/polished mirror. The mirror was too flat near a small area of one edge by about 1/50th of the width of a human hair. This caused an "optical aberration" that prevented focusing of light into a sharp point. Instead, the light collected was spread over a larger area, creating a fuzzy, halo-like, blurred image, especially for faintly lighted or weakly radiating objects.

Nonetheless, relatively bright objects could still be seen to a degree far superior to the capabilities of ground telescopes. A plan was devised to utilize the telescope's capabilities and instruments less affected by the aberration for such tasks as ultraviolet and spectrographic observations. As a result, the HST provided significant new insights and discovery about the universe. Exciting images of Supernova 1987A, a black hole fueled by a disk of cold gas, and other images proved a mark of project success to many. However, for many others, this was not good enough from an overall scientific, technical, return-on-investment, and political perspective.

Since the mirror could not practicably be returned to earth or physically repaired on orbit, the decision was made to develop and install corrective optics for HST instruments. The idea parallels putting on prescription eyeglasses or contact lenses to correct a person's vision. This approach proved feasible, even if physically and technically challenging, because the program managers and systems engineers had designed the system specifically for on-orbit servicing to upgrade instruments and change out degradable components. Instruments were designed to be installed in standard dresser-drawer fashion for ease of removal and replacement.

On 2 December 1993 the STS-61 crew launched on Space Shuttle Endeavor for an 11-day mission with a record five spacewalks planned. Watched by millions worldwide on live television, the astronauts endured long hours of challenging spacewalks to install instruments containing the corrective optics and replaced the telescope's solar arrays, gyroscopes, and other electronic components (Figure 2-1). They installed WF/PC-2 and replaced the High Speed

Photometer with the COSTAR instrument. They also installed a new computer co-processor to upgrade the telescope's computer memory and processing speed, the Solar Array Drive Electronics unit, and the Goddard High Resolution Spectrograph Redundancy Kit. After five weeks of engineering check-out, optical alignment, and instrument calibration, the confirmation of success came as the first images from the space telescope were received on the ground.

Source: NASA photo no. 94-H-16

Figure 2-1. STS-61 Repair Mission

Figure 2-1 shows Astronaut F. Story Musgrave, anchored on the end of the Remote Manipulator System (RMS) arm, as he prepares to be elevated to the top of the towering HST to install protective covers on magnetometers. Astronaut Jeffrey A. Hoffman (bottom of frame) assisted Musgrave with final servicing tasks on the telescope, wrapping up five days of space walks.

Procurement and Development

Since the HST would be built largely by industry, and as part of its attempts to control program costs and foster competition, NASA stimulated its contractor base to develop competing designs and contracting strategies to achieve an optimum acquisition strategy. Various prime, sub, and associate contract approaches were considered, with heavy input from the potential contractor teams. All of this implied a complex program management structure within and among industry players and also within NASA. Earlier competitive approaches were considered by both Marshall and Goddard, even when they were still vying for the lead NASA role during the Phase A process, and seemed both to favor an associate prime contractor relationship for the major elements of the program, even if it would be more complex managerially.

Contract Award

After the protracted phased studies, Marshall ultimately selected two prime (associate) contractors to build the HST. P-E was chosen over Itek and Kodak to develop the optical system and guidance sensors. Interestingly, Kodak was later contracted by P-E to provide a backup main mirror, which is still in storage at Kodak's facility in Rochester, N.Y. LMSC was selected over Martin Marietta and Boeing to produce the protective outer shroud and the support systems

module (basic spacecraft) for the telescope, as well as to assemble and integrate the finished product.

ESA agreed to furnish the spacecraft solar arrays, one of the scientific instruments, and manpower to support the STScI in exchange for 15% of the observing time and access to the data from the other instruments. Goddard scientists were selected to develop one instrument, and scientists at the California Institute of Technology, the University of California at San Diego, and the University of Wisconsin were selected to develop three other instruments.

The Goddard Space Flight Center normally exercises mission control of unmanned satellites in Earth orbit. Because the HST is so unique and complex, two new facilities were established under the direction of Goddard, dedicated exclusively to scientific and engineering operation of the telescope: the STOCC and the STScI.

Impact of External Influences

Many consequences of history involving national security, economics, politics, "big science" project special interests, and NASA's then-recent successes set the stage for the creation and implementation of the HST program. The election of John F. Kennedy to the White House, and the bold new vision he announced of a man on the moon by 1970 (which became project Apollo), set the stage for an extraordinary initiative by the world astronomy community to successfully advocate, market, and lobby for appropriations for a large space telescope in lieu of more Apollo- or Voyager-like projects.

Overall NASA budgets had risen sharply. Kennedy had inspired big thinking and Nixon's 1972 approval of the Shuttle as the manned spacecraft for the immediate future all played to the HST's ultimate advantage and needs (in spite of still-austere 1970s budgets for big space science projects). The astronomers' success in reconciling their and others' competitive interests in funding for large ground-based vs. space-based telescopes was also a factor. Their ability to gain significant control of the to-be HST research agenda by working with NASA and with academic and political factions to establish the STScI (which became affectionately known as "The Institute"), provided a unique user/customer relationship with the program. By issuing the "Hornig Report" [3] in 1977, the Space Science Board of the National Academy of Sciences provided the final impetus to overcoming reservations about the proposed Institute approach within and external to NASA.

The political and technical influence of contractors (Grumman, Lockheed, McDonnell Douglas, TRW, their teams and others) who had been investigating concepts and feasibility for a large space telescope also began to be felt, but in ways that were more traditional for programs of this type. The mere fact that these industry players were also significantly involved in a growing military space intelligence and operations programs is noteworthy. There are more than hints that HST's potential for military utility was explored. It would not be far fetched to assume that these attributes were one factor among several in the eventual success of program advocacy.

Clearly, the HST program was dramatically influenced by a myriad of external factors before, during, and after the formal launch of the program in a collectively unique fashion over time, as Table 2-1 shows.

Table 2-1. Time Phase for Program

Year	Event
1962	The first official mention of an optical space telescope, just four years after NASA was established, when a National Academy of Sciences study group recommended the development of a large space telescope as a logical extension of the U.S. space program.
1965	This recommendation repeated by another study group. Shortly afterwards the National Academy of Sciences established a committee, headed by Lyman Spitzer, to define the scientific objectives for a proposed Large Space Telescope with a primary mirror of about 3 meters or 120 inches.
1968	The first such astronomical observatory – the Orbiting Astronomical Observatory-1 – launched successfully and provided important new information about the galaxy with its ultraviolet spectrographic instrument.
1969	The Spitzer group issued its report, but very little attention was paid to it by the astronomy community. At that time, quasars, pulsars, and other exotic cosmic phenomena were being discovered and many astronomers felt that time spent working towards a space telescope would be less productive than their existing time in ground-based observatories.
1972	A National Academy of Sciences study reviewed the needs and priorities in astronomy for the remainder of that decade and again recommended a large orbiting optical telescope as a realistic and desirable goal. At the same time, NASA convened a small group of astronomers to provide scientific guidance for several teams at the Goddard and Marshall Space Flight Centers who were doing feasibility studies for space telescopes.
1972	NASA named the Marshall Center as lead center for a space telescope program.
1973	NASA established a small scientific and engineering steering committee to determine which scientific objectives would be feasible for a proposed space telescope. The science team was headed by Dr. C. Robert O'Dell, University of Chicago, who viewed the project as a chance to establish not just another spacecraft but a permanent orbiting observatory.
1975	ESA became involved with the project. The O'Dell group continued their work through 1977, when NASA selected a larger group of 60 scientists from 38 institutions to participate in the design and development of the proposed space telescope
1978	Congress appropriated funds for the development of the space telescope. NASA assigned responsibility for design, development, and construction of the space telescope to the Marshall Space Flight Center in Huntsville, AL. Goddard Space Flight Center, Greenbelt, MD, was chosen to lead the development of the scientific instruments and the ground control center.
1981	Construction and assembly of the space telescope was a painstaking process that spanned almost a decade. The precision-ground mirror was completed; casting and cooling of the blank by Corning Glass took nearly a year.
1983	The STScI was dedicated in a new facility near the Astronomy and Physics Departments of Johns Hopkins University and tasked to perform the science planning for the telescope. The Institute is operated under contract to NASA by AURA to ensure academic independence. It operates under the administrative direction of the Goddard Center.
1983	The science instruments were delivered for testing at the Goddard Center.
1984	The optical assembly (primary and secondary mirrors, optical truss and fine guidance system) was delivered for integration into the satellite.
1985	The STOCC is established at Goddard as the ground control facility for the telescope. The STOCC also maintains a constant watch over the health and safety of the satellite.
1985	Assembly of the entire spacecraft at the Lockheed Sunnyvale facility was completed.
1986	The HST was originally scheduled for launch in this year. It was delayed during the Space Shuttle redesign that followed the Challenger accident. Engineers used the interim period to subject the telescope to conduct intensive testing and evaluation, ensuring the greatest possible reliability. An exhaustive series of end-to-end tests involving the STScI, Goddard, the TDRS, and the spacecraft were performed during this time, resulting in overall improvements in system reliability.
1989	The telescope was shipped by Air Force C-5A from LMSC, Sunnyvale, to the Kennedy Space Center in October.

Table 2-1. Time Phase for Program (Cont'd)

Year	Event
1990	HST was launched on April 24 (see initial deployment picture below) by the Space Shuttle STS-31 crew onboard Discovery and soon began its two decades of astronomical observations and remarkable discoveries. Initial "trial run" images were exciting compared to those from ground-based telescopes.
1990	A major mirror problem was detected. The system was inherently out of focus and uncorrectable to acceptable limits. Root cause – too much material removed in mirror manufacture, making it too flat by 2.2 μm (1/50th the width of a human hair); critical light gathering reduced from 70% to 15%. Error determined to be caused by improper assembly of a "reflective null corrector" test device used to control mirror material processing (removal and polishing).
1990–1993	NASA undertook a detailed failure analysis and characterization of the flaw, designed effective corrective optics to be inserted into the telescope during the first servicing mission, and provided effective interim modeling-based corrective solutions to enable productive use of HST prior to the mirror repair servicing mission.
1993	Space Shuttle Endeavor (STS-61) carried the first servicing crew of astronauts to orbit. In a highly demanding, 5-day extravehicular activity (EVA), corrective optics and other servicing functions (new solar arrays to correct jitter, new gyros, computer upgrade, etc.) were installed on HST. Essentially full design function of HST was restored, to the delight of most.

Figure 2-2. 1990 HST Initial Deployment April 24, 1990

HST System Design

HST is a 2.4-meter reflecting telescope that was deployed in low-Earth orbit (600 kilometers) by the crew of the Space Shuttle Discovery (STS-31) on 25 April 1990 (see Figure 2-3). Since its inception, HST was destined to perform a different type of mission for NASA: to serve as a permanent space-based observatory. To accomplish this goal and protect the spacecraft against instrument and equipment failures, NASA had always planned on regular servicing missions. Therefore, Hubble has special grapple fixtures, 76 handholds, and is stabilized in all three axes.

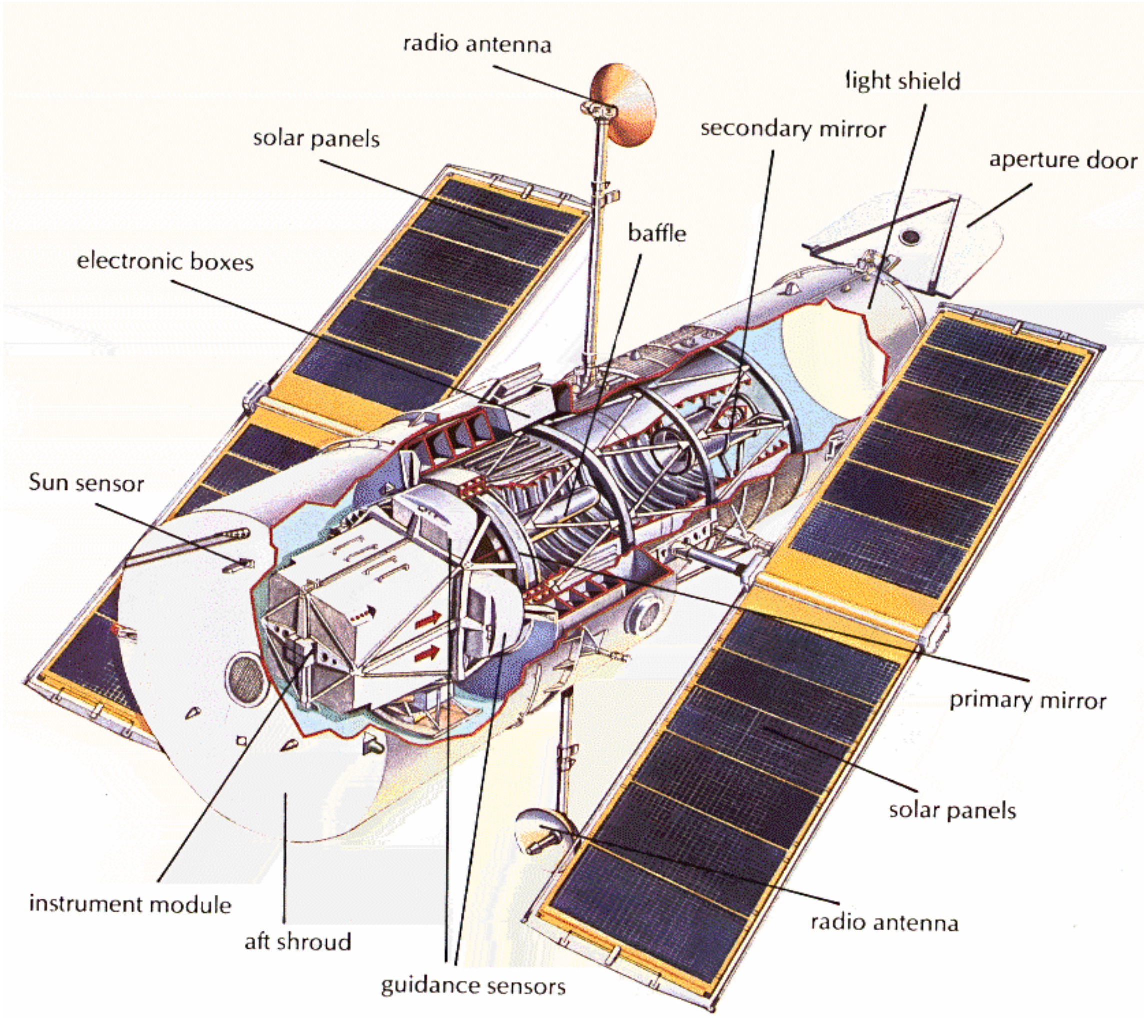


Figure 2-3. HST Major System Elements

HST's current complement of science instruments includes two cameras, two spectrographs, and fine guidance sensors (primarily used for astrometric observations). Because of HST's location above the Earth's atmosphere, these science instruments can produce high-resolution images of astronomical objects. Ground-based telescopes can seldom provide resolution better than 1.0 arc-second, except momentarily under the very best observing conditions. HST's resolution is about 10 times better, or 0.1 arc-seconds.

When originally planned in 1979, the Large Space Telescope program called for return to Earth, refurbishment, and re-launch every 5 years, with on-orbit servicing every 2.5 years. Hardware lifetime and reliability requirements were based on that 2.5-year interval between servicing missions. In 1985, contamination and structural loading concerns associated with return to Earth aboard the Shuttle eliminated the concept of ground return from the program. NASA decided that on-orbit servicing might be adequate to maintain HST for its 15-year design life. A 3-year cycle of on-orbit servicing was adopted. The first HST servicing mission in December 1993 was an enormous success. Additional servicing missions were accomplished in February 1997, December 1999, and March 2002.

Contingency flights could conceivably still be added to the Shuttle manifest to perform specific tasks that cannot wait for the next regularly scheduled servicing mission and/or required tasks that were not completed on a given servicing mission. This is not now likely with the present NASA and Administration vision for the national "Moon, Mars and Beyond" space exploration initiative. However, the *Washington Post* reported on 5 October 2004 that NASA has awarded a $330 million contract to Lockheed Martin to build a robot spaceship to carry replacement parts to the HST. NASA stated that it must start work on a robotic servicing mission this fall because Hubble's batteries are expected to give out in 2007. NASA also awarded a preliminary $144 million contract to MD Robotics, which will build an arm that will help the unmanned spaceship dock with the telescope.

The early years after the launch of HST in 1990 were momentous, with the discovery of the spherical aberration flaw in the primary mirror and the search for a practical solution. The STS-61 (Endeavor) mission of December 1993 obviated the effects of spherical aberration and fully restored the functionality of HST.

Because of the complexity of the HST as a system of systems, a brief description of the major components of the spacecraft and its payloads is provided as context for the systems engineering challenges and learning from the case study.

Science Instruments

The following subsections present a representative, not all-inclusive, list of the science instruments aboard the HST.

Wide Field/Planetary Camera 2 (WF/PC2)

The original Wide Field/Planetary Camera (WF/PC, pronounced "wiff-pik") was changed out and displaced by WF/PC2 during the STS-61 Shuttle mission in December 1993. WF/PC2 was a spare instrument developed in 1985 by the Jet Propulsion Laboratory. It is actually four cameras. The relay mirrors in WF/PC2 are spherically aberrated to correct for the spherically aberrated primary mirror of the observatory (HST's primary mirror is 2 microns too flat at the edge, so the corrective optics within WF/PC2 are made too high by that same amount).

Corrective Optics Space Telescope Axial Replacement (COSTAR)

Although COSTAR is not a science instrument per se, it is a corrective optics package that replaced the High Speed Photometer during the first servicing mission to HST. COSTAR (built by Ball Aerospace) is designed to optically correct the effects of the primary mirror's aberration on the three remaining scientific instruments: Faint Object Camera (FOC), Faint Object Spectrograph (FOS), and Goddard High Resolution Spectrograph (HRS).

Faint Object Camera (FOC)

The FOC was built by the European Space Agency (ESA). It is the only instrument to utilize the full spatial resolution power of HST. Two complete detector systems comprise the FOC. Each uses an image intensifier tube to produce an image on a phosphor screen that is 100,000 times brighter than the light received. This phosphor image is then scanned by a sensitive electron-bombarded silicon (EBS) television camera. This system is so sensitive that objects brighter than 21st magnitude must be dimmed by the camera's filter systems to avoid saturating the detectors. Even with a broadband filter, the brightest object that can be accurately measured is 20th magnitude.

Faint Object Spectrograph (FOS)

A spectrograph spreads out the light gathered by a telescope so that it can be analyzed to determine such properties of celestial objects as chemical composition and concentration, temperature, radial velocity, rotational velocity, and magnetic fields. The FOS (built by Martin-Marietta Corporation) examines fainter objects than the HRS (see Section 2.1.5 below), and can study these objects across a much wider spectral range – from the ultraviolet (UV – 1150 angstroms) through the visible red and the near-infrared (IR – 8000 angstroms).

The FOS uses two 512-element Digicon sensors (light intensifiers) to detect light. The "blue" tube is sensitive from 1150 to 5500 angstroms (UV to yellow). The "red" tube is sensitive from 1800 to 8000 angstroms (longer UV through red). Light can enter the FOS through any of 11 different apertures from 0.1 to about 1.0 arc-second in diameter. There are also two occulting devices to block out light from the center of an object while allowing the light from just outside the center to pass through. This allows analysis of the shells of gas around red giant stars in the faint galaxies surrounding a quasar.

The FOS has two modes of operation, low resolution and high resolution. At low resolution it can reach 26th magnitude in one hour with a resolving power of 250. At high resolution the FOS can reach only 22nd magnitude in an hour (before the signal/noise ratio becomes a problem), but the resolving power is increased to 1300.

Goddard High Resolution Spectrograph (HRS)

The Goddard HRS also separates incoming light into its spectral components so that the composition, temperature, motion, and other chemical and physical properties of objects can be analyzed. The HRS contrasts with the FOS in that it concentrates entirely on UV spectroscopy and trades the ability to detect extremely faint objects for the ability to analyze very fine spectral detail. Like the FOS, the HRS uses two 512-channel Digicon electronic light detectors, but the detectors of the HRS are deliberately blind to visible light. One tube is sensitive from 1050 to 1700 angstroms; while the other is sensitive from 1150 to 3200 angstroms.

The HRS also has three resolution modes: low, medium, and high. "Low resolution" for the HRS is 2000 – higher than the best resolution available on the FOS. Examining a feature at 1200 angstroms, the HRS can resolve detail of 0.6 angstroms and can examine objects down to 19th magnitude. At medium resolution of 20,000 that same spectral feature at 1200 angstroms can be seen in detail down to 0.06 angstroms, but the object must be brighter than 16th magnitude to be studied. High resolution for the HRS is 100,000, allowing a spectral line at 1200 angstroms to be resolved down to 0.012 angstroms. However, "high resolution" can be applied only to objects of 14th magnitude or brighter. The HRS can also discriminate between variations in light from objects as rapid as 100 milliseconds apart.

Optical Telescope Assembly (OTA)

The heart of the HST is the OTA represented in Figure 2-4. It consists of the 2.4-meter Ritchey-Chretien Cassegrain telescope, attachments for the scientific instruments, support structures, stray light reducing baffles, and the fine guidance system. P-E, as an associate contractor, was responsible for the design, development, fabrication, assembly, and verification of the OTA, as well as support of HST development, integration, and operations.

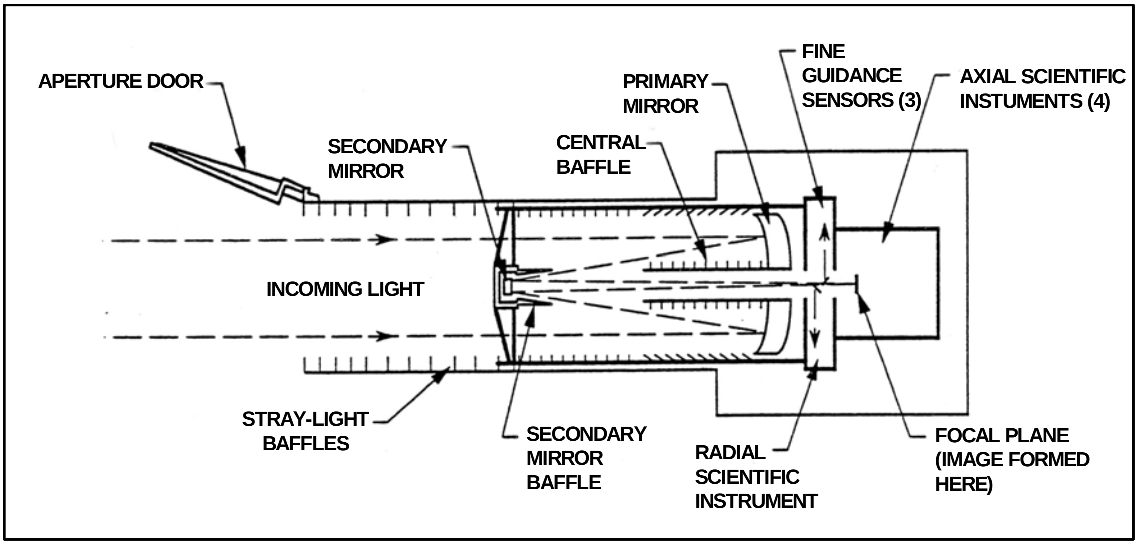


Figure 2-4. HST Optical Telescope Assembly

The OTA provides high-quality images to the focal plane, which sends sub-images to the various instruments via "pick-off" mirrors. Among the many subcomponents the most critical are the primary mirror assembly, the metering truss structure, and the focal plane structure. These are of special interest here because they posed the most significant technical challenges in terms of sheer size, extreme tolerances, and application of advanced materials, designs, and manufacturing processes.

Support System Module (SSM)

The SSM provides the support structure for all HST hardware, including physical attachments, thermal control, pointing control for the telescope, solar array electrical power, communications, and data handling links. LMSC was the associate contractor for SSM design, development, fabrication, assembly, and verification, as well as for integration of overall systems engineering and analysis for the overall HST program. LMSC also supported NASA in planning and conducting HST ground, flight, and orbital operations.

Structurally, the SSM consists of the aperture door attached to a light shield and the forward shell surrounding part of the OTA, a ten-bay equipment section, and the aft shroud/aft bulkhead. The forward shell is the main attachment point for the solar array "wings," high-gain antennas, magnetic torque generators, remote manipulator for deployment/retrieval, and two forward trunnions for latching the spacecraft in the Shuttle orbiter payload bay. Most of the equipment housed in the equipment section is made in the form of orbital replacement units (ORUs), a modified Spacelab "pallet" designed with hinged access doors or removable panels so as to be easily (relatively speaking) replaced by astronauts wearing cumbersome space suits. ORU pallets can carry needed combinations of scientific instruments, fine guidance sensors, ORUs, tools, and miscellaneous support equipment (tether attachments, working lights, etc.).

Mission Operations

Although HST operates around the clock, not all of its time is spent observing. Each orbit lasts about 95 minutes, with time allocated for housekeeping functions and for observations. "Housekeeping" functions include turning the telescope to acquire a new target or

avoid the sun or moon, switching communications antennas and data transmission modes, receiving command loads and downlinking data, calibrating, and similar activities.

When the Space Telescope Science Institute (STScI; see Section 3) completes its master observing plan, the schedule is forwarded to Goddard's Space Telescope Operations Control Center (STOCC), where the science and housekeeping plans are merged into a detailed operations schedule. Each event is translated into a series of commands to be sent to the onboard computers. Computer loads are uplinked several times a day to keep the telescope operating efficiently.

When possible, two scientific instruments are used simultaneously to observe adjacent target regions of the sky. For example, while a spectrograph is focused on a chosen star or nebula, the WF/PC can image a sky region offset slightly from the main viewing target. During observations the Fine Guidance Sensors (FGS) track their respective guide stars to keep the telescope pointed steadily at the right target. Engineering and scientific data from HST, as well as uplinked operational commands, are transmitted through the Tracking Data Relay Satellite (TDRS) system and its companion ground station at White Sands, New Mexico.

Up to 24 hours of commands can be stored in the onboard computers. Data can be broadcast from HST to the ground stations immediately or stored on tape and downlinked later. The observer on the ground can examine the "raw" images and other data within a few minutes for a quick-look analysis. Within 24 hours, Goddard Space Flight Center formats the data for delivery to the STScI, which is responsible for data processing (calibration, editing, distribution, and maintenance of the data) for the scientific community.

3.0 HST SYSTEMS ENGINEERING LEARNING PRINCIPLES

There were five primary systems engineering principles which impacted the Hubble Space Telescope development, production, and deployment. These will be discussed in detail in the following sections. Other systems engineering principles and learnings are shown in the complete Friedman Sage Matrix (Appendix 1). These were also in play to various degrees and at various times throughout the program life cycle spanning from 1962 to 1993 (Table 2-1), the focus of this case study, and even to the present (2005).

3.1 Learning Principle 1 – Early Customer/User Participation

Early and full participation by the customer/user throughout the program is essential to program success.

Requirements Definition and System Specification

The main purpose of the HST – to provide astronomers with the capability to conduct research in their scientific discipline – is in apparently sharp contrast to DoD's goal of providing warfighters with superior military capabilities. What is similar is that both science and warfighting are largely human endeavors, as is systems engineering. Thus, we should not be surprised to discover more similarities than differences in what can be learned from these two very different types of programs from a systems engineering perspective.

NASA's decision to establish a unique (for purposes of a major program development) STScI had major implications for virtually all system, subsystem and component processes and decisions. The Institute was intended as, and became, a vital link between NASA and the astronomy community. It was designed to ensure that the astronomer-scientist customer did indeed have a direct say in what the HST would actually be able to do: what observations would be made when and by whom. It would become a direct, if not the controlling, external input to HST operations and NASA decisions regarding initial requirements, design, development, and on-orbit operations and maintenance.

How the Institute came to be is, in itself, a case study in institutional and agency politics. It arose out of the classical dilemma of whom – scientists or bureaucrats – should control the identification of requirements and manage the scientific content of a major science-focused program involving a huge commitment of taxpayer dollars. For HST, as well as for prior NASA legacy programs, this issue was the subject of assessment by numerous agencies, Congress, the executive branch, and scientific interest groups. The result was to form an Institute that would define location, the research agenda, and scientific instrument requirements, and play a key role in HST ground and space operations. A competition among the several groups interested in large telescopes, both space and ground based, was held to select the organization that would manage the institute. Of the five finalists the two dominant ones (although even they had many misgivings and internal conflicts about bidding) were AURA and AUI (Associated Universities Incorporated), both of which had extensive experience in operating national ground observatories and national laboratories/institutes. After an extensive, formal source selection (generally judged as being free of politics although it was an election year), the AURA/Johns Hopkins University team won the contract, with Johns Hopkins the selected site for what would become the HST-linked Institute.

The real challenge for the Institute would become how to wrest control over HST scientific operations from NASA. The answer involved reaching a successful compromise between the requirements of its academic clientele with those of its funding sponsor, NASA. This represented a classic clash of academic vs. bureaucratic values affecting major program technical requirements, and thus the systems engineering process, from early on. As a result of its victory, the fledgling AURA team had the difficult challenge of negotiating a contract with NASA to establish and implement the Institute (to ultimately define the scientific/technical baseline mission of the HST program) in an environment of fierce vested interests and, coincidently, critically short funding and time for program development and execution.

3.2 Learning Principle 2 – Use of Pre-Program Trade Studies

The use of pre-program trade studies to broadly explore technical concepts and alternatives is essential and provides for a healthy variety of inputs from a variety of contractors and government (in this case NASA) centers.

Pre-Proposal Competitive Phase

As with the other cases in this series, the HST program featured numerous positive, and in practice, some questionable examples of creative and effective systems engineering applications used throughout its long and complex concept exploration and development phases. For the HST some of these were:

- Phased (A, B, C, D) in-house and contractor project/engineering studies addressing critical feasibility and requirements issues. These included NASA's then-current "Phased Program" approach:
    - **Phase A** – addressed the question: Can we build such a large space telescope, assuming a national decision to do so (where cost is not yet a driving consideration)?
    - **Phase B** – included conceptual design refinement with cost a factor and requirements for Phases C and D better defined.
    - **Phases C/D** – involved detailed design, development, and construction, marking the transition from concept to implementation.
- NASA and contractor team processes for managing risk, cost, schedule, and configuration.
- Use of independent review and payload specification groups.
- Use (and in some cases, non-use) of simulation, laboratory, and ground testing prior to initial flight and on-orbit repair.
- Definition of relative roles and contributions of prime and subcontractors, NASA in-house (multiple center), and customer program management/systems engineering perspectives.

Systems Architecture and Conceptual Design

"Tumult" probably best describes the early years of the design and development of the HST. The literature points to early and continuing underfunding and understaffing, especially in the systems engineering area. Technical challenges were formidable in spite of some impressive

advances made in optical telescopes as a result of highly classified reconnaissance programs and Air Force adaptive optics advances in ground-based space surveillance technology. It was generally felt that the telescope designers could achieve the right optical designs for the operational environment. The Phase B and C/D studies described earlier had narrowed many of the physical design issues, and identified many of the material tolerances, guidance and stability requirements, methods, and risks.

Operational Mission Analysis

Once the decision was made to design, develop, build, launch, host, and maintain the HST in a union with the Shuttle, certain design requirements followed. Early studies had postulated that a 3-meter aperture telescope, if feasible, would meet the demanding astronomy observation challenges. Enormous challenges to the very practicality were recognized and debated. There were even major questions raised earlier as to whether or not a leap to a large telescope, without several incremental steps to build confidence and experience, was the best approach. Cost trade studies in 1975 [4], summarized in Table 3-1, showed that reducing the primary mirror size (the main system design driver) below 2.4 meters yielded diminishing returns. Beyond this point the cost for precision pointing, support equipment, and most other subsystems would remain the same.

Table 3-1. Large Telescope Mirror Size – System Cost Trade (1975)

Mirror Size, Diameter, Meters	Est. System Cost, $M
3	334
2.4	273
1.8	259

The 1975 NASA trade studies led to the decision to reduce the mirror size to 2.4 meters (7.9 feet), primarily as a cost containment measure. The reduced size, while still very large, would presumably simplify anticipated complex manufacturing, test, and assembly while still permitting the telescope and its support structure to fit in the Shuttle payload bay and perform required light gathering, optical accuracy, pointing, and stability control functions. However, analysis showed that the reduction from 3 meters would come at the “expense” of telescope light collecting capability (reduced by a third), imaging exposure of objects (longer time required), restricted capability (some distant or weak objects would not be viewable), and resolving power (reduced to 0.1 second of arc). On the positive side, the telescope weight was forecast to be reduced from about 25,000 to 17,000 pounds (not counting the scientific instruments). The final specification for the system is shown in Table 3-2.

Table 3-2. HST Specification

Parameter	Dimension
Stowed configuration Length Diameter	 43 ft 6 in. 14 ft 0 in.
Deployed configuration Length (aperture door opened) Diameter (SA and HGA deployed)	 53 ft 10 in. 41 ft 10 in.
Weight	24,973 lb
Orbit altitude Orbit inclination	320 ±5 n. mi. 28.4°
Propulsion	None
Attitude control Slew rate Settling time Pointing stability	Reaction wheels Magnetic torquers 6 deg/min 2 min 0.007 arc second
Solar array (two) Length Width Power	 39 ft 9 in. 9 ft 6 in. 4400 W
High-gain antenna (two) (+V3, -V3) Dish diameter (effective) Boom length (from HST centerline) LHC polarization	 4 ft 2 in. 19 ft 4 in.
Low-gain antenna (two) (fwd, aft) Small spiral cone LHC polarization	
Science data storage	1×10^9 bits
Data rate (baseband modulation) Science data (HGA-to-TDRSS) Engineering data	 1 Mbps (3.072 Mbps encoded) 500 bps (LGA-to-TDRSS) 4, 32 kbps, 1 Mbps Rec DR (HGA-to-TDRSS or LGA-to-GSTDN)
Transmitter frequency S-band multiaccess (2) S-band single access (2)	 2287.5 MHz 2255.5 MHz
Receiver frequency S-band MA (low-gain antenna) Command receive rate	 2106.4 MHz 1 kbps, 125 bps

The studies had also exercised various concepts of operation for launch, deployment, and servicing (including on-orbit vs. return to earth) with cost tradeoffs a major consideration – perhaps too much so in contrast to the needed depth of systems engineering in the critical early stages. The bottom line is that the final HST system architecture was, in the final analysis, to be determined more by external factors described earlier (the role of the science customer, wedding to the Shuttle, decision to provide for on-orbit servicing, optimism about the ability to build an extraordinary optical design, etc.). These decisions would be traded off initially against overly optimistic cost projections and expectations. It would take the experience of time and program maturation, as well as the unanticipated Challenger-imposed delay, to implement the architecture successfully.

3.3 Learning Principle 3 – System Integration

Provision for 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.

System/Subsystem Detailed Design and Implementation

The decision to reduce the primary mirror from 3 meters to 2.4 had profound effects on the design of other major components. The SSM had been redesigned to envelop the telescope optics and this affected other components (shield, shroud, and equipment section). This gave rise to new problems in linking the SSM to the OTA in such a fashion that large thermal gradient deformations arising from continuous day-night orbital changes would not be allowed to distort critical optical functions, such as focusing. This problem was generic to multiple components of the system and was finally overcome by the successful design and development of a set of "kinematic" joints that, in effect, dynamically isolated the components from each other.

The OTA provided additional systems engineering challenges. It was to be built by P-E, which had built many large observatory and balloon telescopes and some space telescopes and mirrors (more than 50 from the 1930s to the start of HST fabrication in 1977). It was common knowledge that the OTA –in particular, precision machining of the large primary mirror to phenomenal tolerances – would be the biggest challenge for P-E and the "long pole" for the entire program. The situation was seen as so critical that a backup mirror was funded and built by Eastman Kodak (EK). Intentionally, EK would finish its mirror by more conventional, yet high-precision polishing techniques, and P-E would use a radically new, computer-controlled polishing system.

P-E's use of aggressive new approaches extended to its use of special mounts to simulate zero gravity during test and thus obtain the most accurate finish and compensate for gravity-generated dimensional changes. The size of the mirror required a support system consisting of 138 rods on the back surface of the mirror, with each rod uniquely countering a different fraction of the gravitational force to be dealt with. The sum and distribution of the rod upward forces were to counter exactly the weight and weight distribution of the mirror, thus creating a precise zero gravity condition for finishing and testing the mirror.

It was the primary mirror manufacturing, especially its precision manufacturing and subsequent test procedure, that led to the major on-orbit performance failure shortly after the 1990 launch. The unique systems engineering implications of this failure are covered in more detail in the Validation and Verification discussion below.

There were other major subsystem and significant component systems engineering issues, including the very precise primary mirror assembly (see Figure 3-1). The mirror is of special interest as it contains the primary mirror/lens itself, made from a blank of Corning ultra low-expansion glass, with thin front and rear face plates fused to an egg crate construction inner core. In addition to the special grinding, polishing, and fitting to an incredibly precise shape, it is vacuum-coated with aluminum and magnesium fluoride to enhance ultraviolet reflectivity.

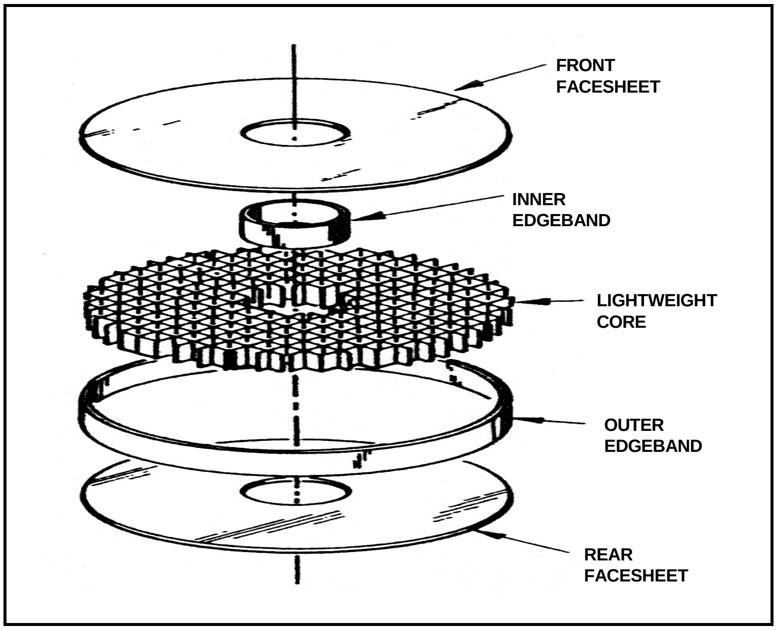


Figure 3-1. OTA Primary Mirror Assembly

The fine guidance sensors are the final representative illustration of the HST subsystem engineering story, although many other components could merit discussion. These sensors were critical because they enable the telescope to be properly pointed and controlled. The minutely faint (in many cases) signal of objects that HST must image in deep space requires that the telescope point in precisely the right direction for long periods of time to collect enough image energy to record the object. Exposure periods of up to 24 hours are not uncommon. These sensors were deemed so critical that Marshall commissioned an alternative design at the Jet Propulsion Laboratory (JPL). However, in 1979, Marshall forecast that the JPL study would not lead to a functional sensor by the anticipated 1983 launch date. The program thus became dependent on the P-E sensors.

The sensors also served as a separate scientific instrument by working in twos and threes to lock on multiple targets, maintain reference positioning to guide stars, and measure angular differences between stars. In recognition of this dependence and multi-functionality, a special customer Astronomy Science Team for fine guidance sensors was convened and successfully ensured that engineering changes to the sensors did not exert a negative impact on critical performance.

Systems and Interface Integration

System integration challenges for the HST span a broad array of physical, structural, electrical, optical, electronic, thermal control, power, and operational software/hardware domains (all uniquely different for pre-ascent, ascent, and on-orbit phases of the mission). One representative example is the function and placement of the scientific instruments within the confines of the OTA, shown in Figure 3-2. Each instrument has specific requirements for packaging, power, thermal control, and orientation with respect to the primary mirror. Usually these and other functional requirements flow down to the component and device levels within each instrument. The complete set is, in turn, constrained by the OTA and Shuttle bay geometry and functional interfaces. Most functions are simultaneously monitored, and in some cases

separately controlled, on the ground (at the launch control and STScI locations) and in the Shuttle when the system is deployed to orbit. The nature of system integration work here is clearly one of discipline, documentation, and communication, human as well as machine. Extend this to the full HST system for typical tasks (such as manned deployment, manned on-orbit servicing, or unmanned autonomous operations) and the crucial importance of effective, systems engineering- based system integration becomes readily apparent.

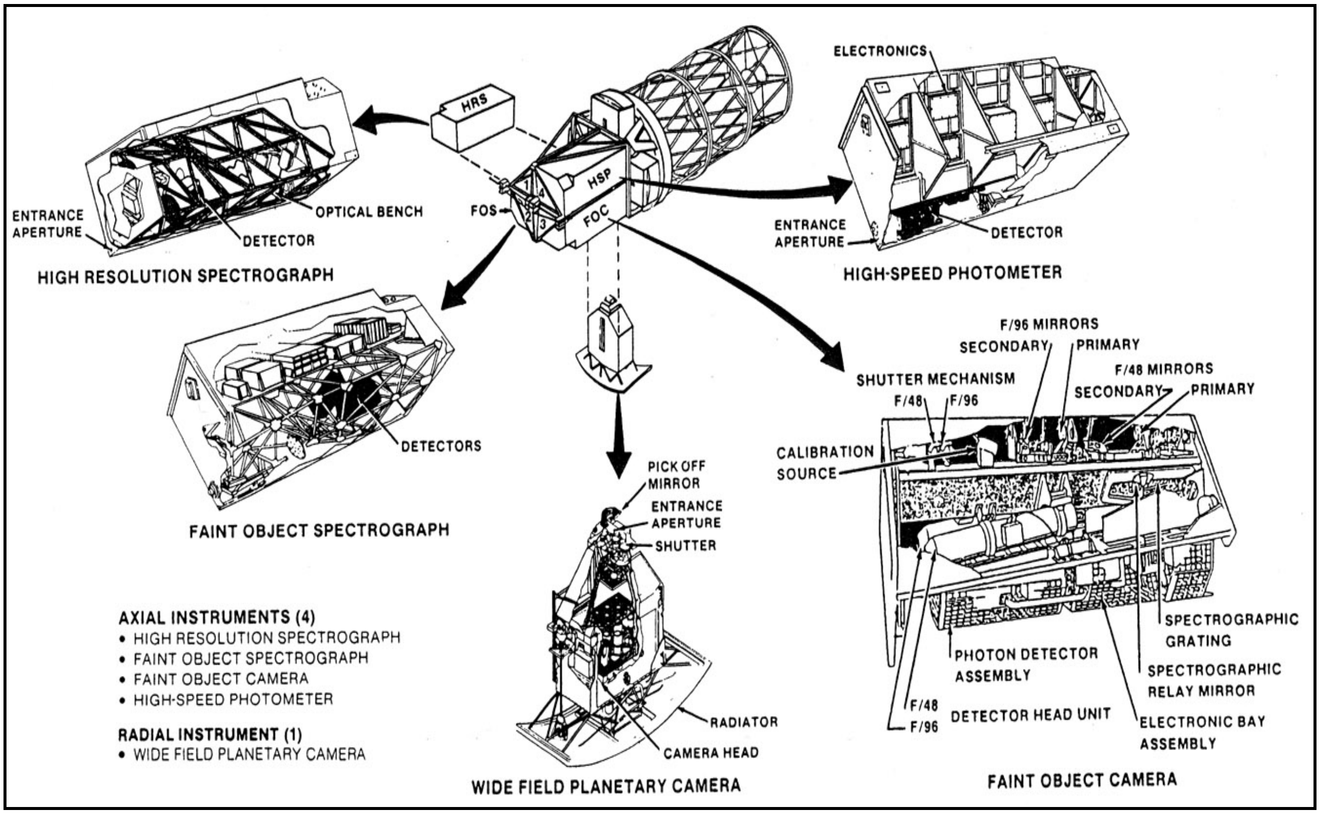


Figure 3-2. Location of Scientific Instruments in the Optical Telescope Assembly

Weight Allocation and Management

Another major systems integration issue, as with most aeronautical and space systems, is weight allocation and management. This is especially true for a system that will be placed on orbit. Tables 3-3 and 3-4 below illustrate two levels of HST's tracking its weight status at two different points in time (thus, comparing the two common components will not necessarily match). Table 3-3 represents the aggregate weight status at the major subsystem level and illustrates top-level tracking and planning for the launch, and in this case, maintenance mission elements. Note the references to extensive weight reference plans, standards, and documentation that are critical to successfully managing weight and maintaining flexibility and reserve for contingencies throughout the development, fabrication, integration, deployment, and maintenance phases of the system life cycle.

Table 3-3. HST Specification Weight Status

Description	Original CEI Weight (lb)	GFE and Spec.Wt. Changes (lb)	Approved Revised CEI Weight (lb)	Current Weight (lb)	Current Margin (lb)
SSM	9,200	+1,921	11,121	10,594	+527
OTA	6,300	+3,338	9,638	9,033	+605
Axial SI	2,800	-92	2,708	2,660	+48
Radial SI	500	+100	600	569	+31
SIC&DH	75	+62	137	136	+1
SA	770	+27	797	735	+62
Total	19,645	5,345	25,001	23,727	+1,274
NASA reserve - HST			499	0	+499
HST limit weight (1)			25,500	23,727	+1,773
Launch mission					
HST			25,500	23,727	+1,773
Space support equipment	1,800		1 ,800	300	+1,500
NASA reserve - mission			400	0	+400
Mission limit weight (2)			27,700	24,027	+3,673
Maintenance mission					
Space support equipment	TBD		TBD	TBD	
Spares - ORU's	TBD		TBD	2,605	
Total HST-provided equipment - maintenance			TBD	TBD	

(1) STS/HST Payload Integration Plan, NSTS 14009 Rev. B, October 1985.

(2) Space Telescope Level II IRD, Space Telescope to Shuttle Orbiter Interface STR-04B, September 14, 1979.

Table 3-4 shows one additional example of flow-down of weight management one level lower to include tracking of many functional support subsystems and the scientific instruments. The weight dimension illustrates only one dimension of the systems integration work for these and many other components. This is why systems integration is a special branch of modern systems engineering and must be approached with the utmost human and technical discipline. The HST program represents an example where this was ultimately accomplished with great success, a tribute to all of the government, contractor, and customer (designers, developers, science users, astronauts and mission control) personnel involved over decades of activity.

Table 3-4. HST Summary Weight Statement

Description	Wt-last report (lb)	Current-wt incl/cont (lb)	Changes-last to current (lb)	Weight class (percent)				Note no. (refer to section 3.0)
				Est	Calc	Act	Spec	
Structure	5,263.8	5,292.5	+28.7	1	23	75	1	1
Mechanisms	541.6	541.8	+0.2	11	67	15	7	2
Thermal control	618.3	603.4	-14.9	5	56	39	-	3
Electrical power	2,055.7	2,043.8	-11.9	4	6	90	-	4
Communication and instrumentation	234.9	236.9	+2.0	11	33	55	1	5
Data management	380.5	375.7	-4.8	1	-	99	-	6
Pointing control	1,151.3	1,153.7	+2.4	-	12	88	-	7
Crew systems	373.4	364.1	-9.3	3	69	28	-	8
Manufacturing variation	-18.0	-18.0	-	-	-	100	-	8
Support systems module	10,601.5	10,593.9	-7.6	3	24	72	1	
Optical telescope assembly	9,116.7	9,033.4	-83.3	-	6	94	-	10
Solar cell array	164.5	164.5	-					
SSM-provided equipment	42.5	42.5	-					
Deployment mechanisms/drives	460.6	460.6	-					
Electronic control/miscellaneous	65.1	67.8	+2.7					
Solar array	732.7	735.4	+2.7	-	4	96	-	11
Faint object camera	706.0	706.0	-	-	-	100	-	
Faint object spectrograph	682.1	682.1	-	-	-	100	-	
High resolution spectrograph	684.7	684.7	-	-	-	100	-	-
High speed photometer	586.8	586.8	-	-	-	100	-	
Wide field and planetary camera	568.6	568.6	-	-	-	100	-	
SIC&DH	135.9	135.9	-	-	-	100	-	
					-			
Scientific instruments complement	3,364.1	3,364.1	-					
Total HST on orbit	23,815.0	23,726.8	-88.2	1	13	86	-	

Validation and Verification

Perhaps the most stunning example of an HST validation/verification test is the one pertaining to the undetected primary mirror manufacturing defect. The methodical determination of the root cause, how it happened, why it was not detected prior to the 1990 launch, and systems engineering lessons learned are well documented [17]. The critical defect was recognized after users noted that both of the high-resolution imaging cameras (wide field/planetary and faint object) demonstrated the same spherical aberration. This was caused by the mirror's having been made ever so slightly in the wrong shape (too flat in a small region relative to the mirror's center). As tiny as it was (1/50th the diameter of a human hair) the mirror error was ten times greater than the design tolerance. The impact on the mirror's performance is shown in Figure 3-3. The mirror as fabricated was simply not capable of achieving the required focusing power to operate acceptably for many imaging tasks.

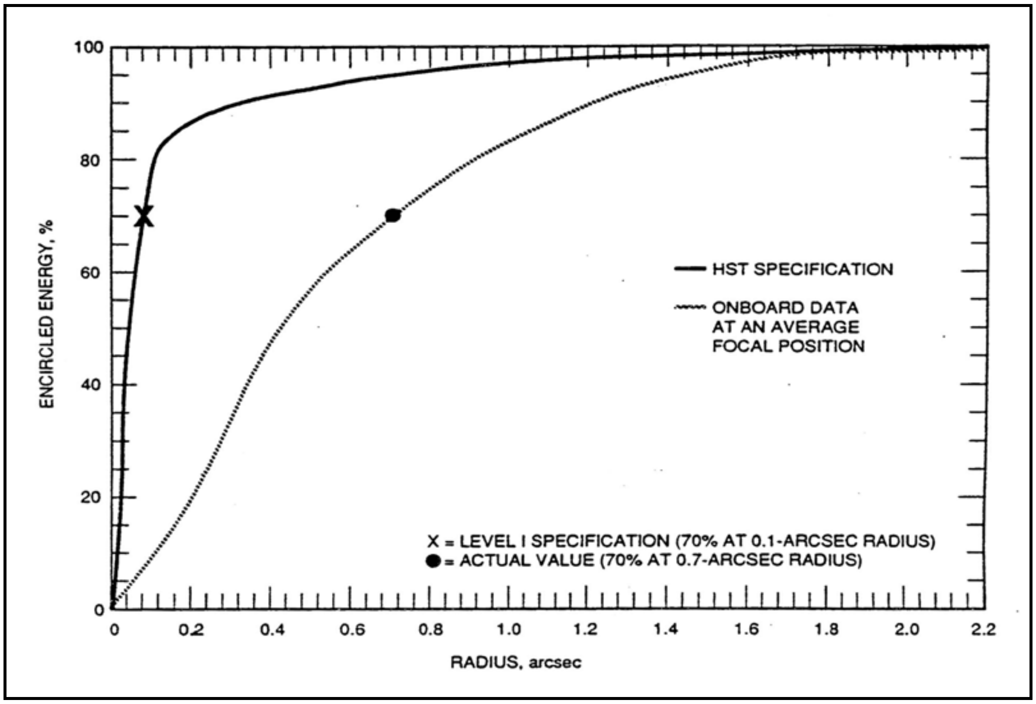


Figure 3-3. Encircled Energy vs. Arc-second Radius of Image Produced by HST

How could this happen with all of the attention given to producing and testing this critical component? The answer, to quote the Investigation Board [17], is that: "The error in the HST mirror occurred because the optical test used in this process was not set up properly; thus the mirror was polished to the wrong shape." The root cause was found to reside in the setup of the optics – the reflective null corrector (RNC) used as a template to shape the mirror. Figure 3-4 illustrates the position of metering rods used to space optical elements in the RNC.

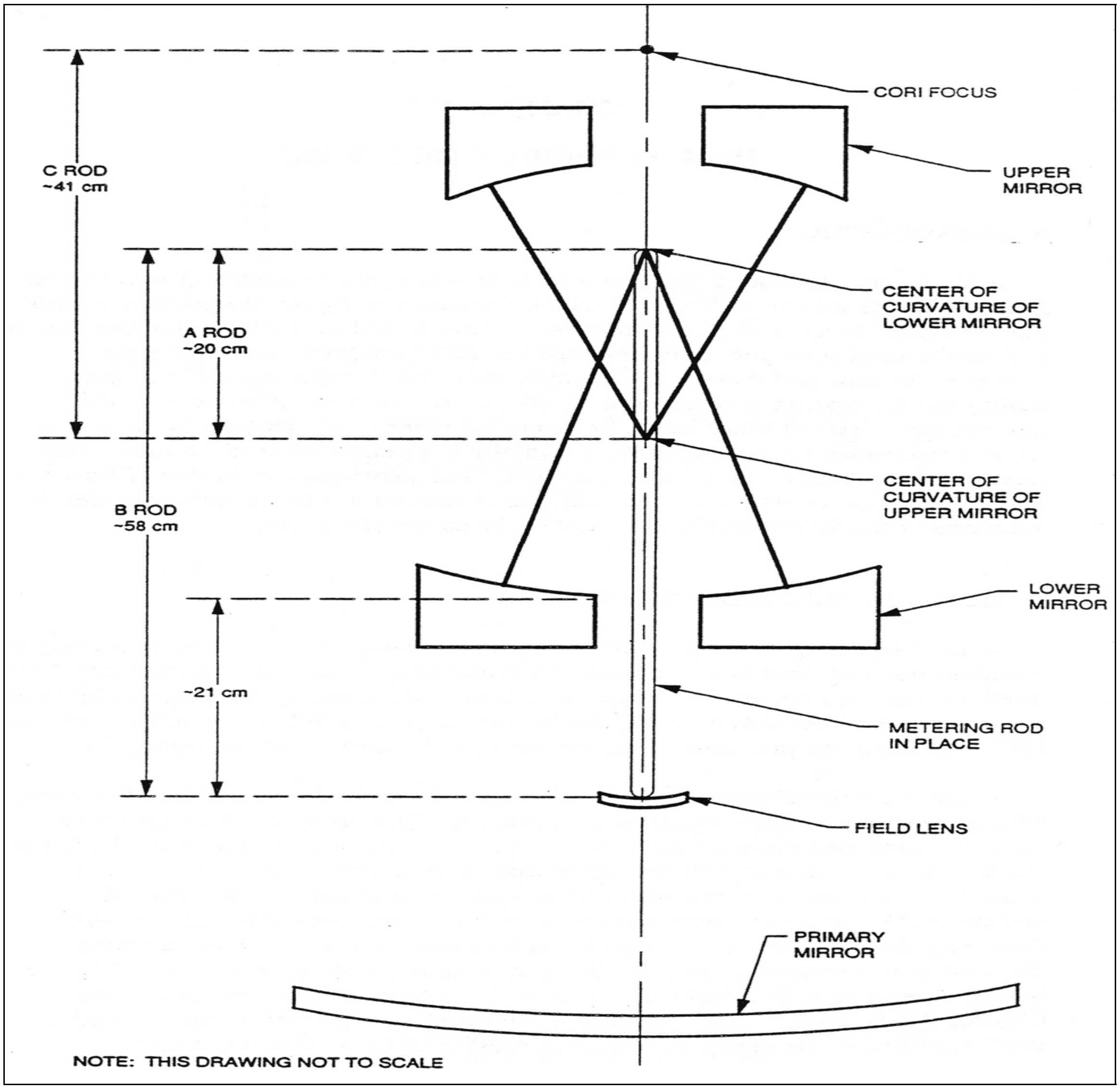


Figure 3-4. Metering Rod Positioning in the Reflective Null Corrector

The RNC consists of two mirrors and a lens. The lens proved to be improperly positioned between the mirrors by an amount that exactly generates the observed error. Figure 3-5 illustrates the undesirable displacement due to the interferometer focusing on the field cap instead of on the metering rod.

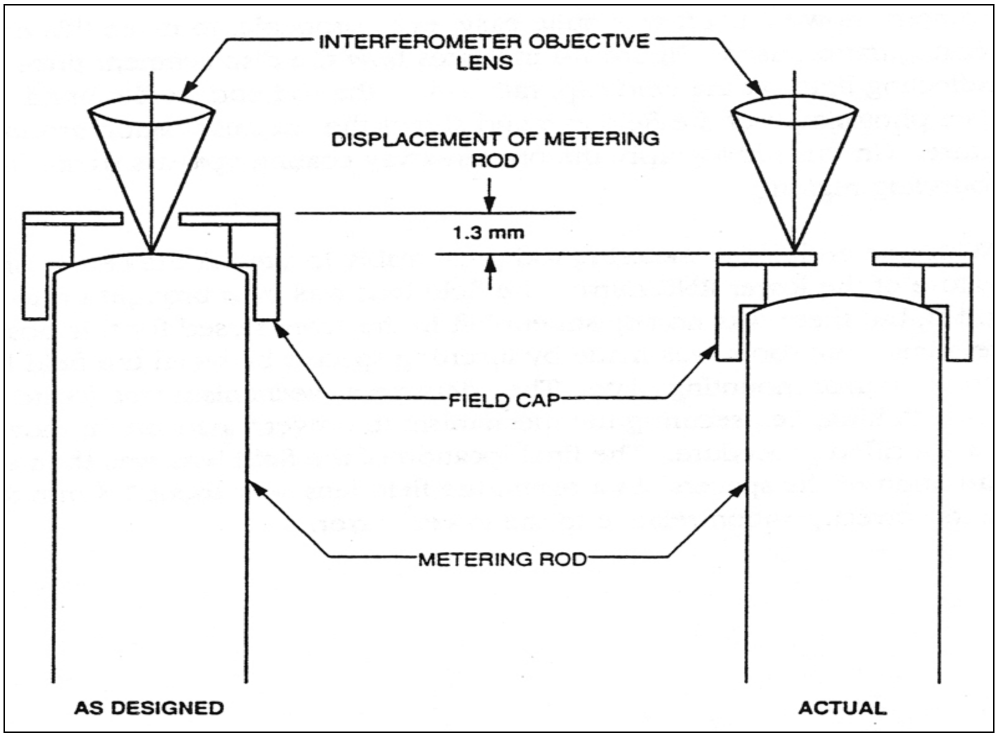


Figure 3-5. Displacement of Metering Rod – Design vs. Actual

The exact cause of the spacing error is a matter of conjecture, since the records necessary to reproduce what actually happened could not be found – another breakdown in technical discipline. A simulated scenario using what could be gleaned about the laboratory procedures from interviews and other documentation determined that, in all likelihood, optical readings used to determine critical spacing and location arose from erroneous reflection from the field cap over one metering rod rather than from the rod end itself. Further assessment showed that no verification of the RNC dimensions were carried out after assembly of the test setup, even though there were indications of a problem from at least two auxiliary null corrector tests used to align the test apparatus and check the vertex radius of the primary mirror. Both results were discounted as being flawed in their own right, since P-E had placed total reliance on the RNC for both manufacturing quality and finished mirror precision.

P-E and NASA both understood and accepted this approach despite a lack of independent measurements to confirm the reliability of the primary test. The failure was not one of system engineering design, but rather one of manufacturing system design and process/quality control. This event occurred at a time when there was also great concern about cost and schedule, possibly overshadowing the obvious need for independent verification testing, or attention to the apparently anomalous RNC data suggesting that something might have been wrong.

The failure report goes on to identify lessons learned that bear repeating here as they are entirely applicable to any system engineering task, and the cause of many that fail:

- **Identify and mitigate risk** – Neither contractor nor government knowledge and acceptance of a critical single point test failure possibility should be accepted without rigorous technical analysis. Adherence to simple fault tree analysis would have driven all parties to a different implementation of the selected approach. Direct test

comparison of the properties of the P-E mirror with the backup EK mirror, which met all specifications, would have indicated the presence of a problem.

- **Maintain good communication within the project** – Normally desirable delegation of authority and responsibility and problem resolution at the lowest possible level, in this case permitted P-E to deal with all mirror issues internally, with little outside communication or accountability. Internal concerns and communication among P-E designers, testers, and fabricators were discounted, disconnected, and discouraged.
- **Understand accuracy of critical measurements** – Key test methods were accepted or rejected on the basis of whether they were believed to be "certified" or not. The RNC was alleged to be certified (although there was no audit trail to this effect) and therefore was accepted as correct, in spite of the possibility of a flawed setup procedure. Other tests indicating a problem were not believed to be certified and were discounted, even if they indicated a problem. Accuracy (capability) and precision (outcome) are not the same things.
- **Ensure clear assignment of responsibility** – Project management, quality assurance, and engineering must work together, but with clear, separate functions known and respected. In this case, unclear roles, incomplete documentation, over-reliance on internal experts, lack of outside independent verification, and lack of understanding of the possible impact of a single flawed process proved catastrophic.
- **Remember the mission during crisis** – Cost and schedule problems in many aspects of the program preoccupied program management and caused the lack of focus on a critical issue. At the conclusion of the mirror polishing task management abandoned the review of all data for the final report and reassigned the team as a cost-cutting measure.
- **Maintain rigorous documentation** – Rigorous documentation, especially for high-precision requirements and operations, is the forcing function for the ability to ascertain whether adequate results are being obtained. Continuity of critical documentation throughout the design, development, fabrication, and test cycle is vital and was not followed for the mirror build.

The second example of HST validation and verification involves total system test. Since HST would actually operate in space and success could not be known with certainty until space performance was observed, the program struggled with ground vs. space approaches, incremental vs. all-up, and the associated cost and risk implications. DoD and NASA had been successful with all-up testing of the large and complex Titan II and Saturn missile systems in the 1960s, achieving the attendant reductions in numbers of test flights and big cost savings.

However, HST was seen as a higher risk program with respect to optical concepts employed and on-orbit and manned operations for deployment and servicing. This was particularly true with regard to the issue of whether or not to conduct a high-fidelity, total system vacuum thermal test in a large chamber. Advocacy and cost estimates for the program during the selling phase did not provide for this type of test. Initially a modular approach was considered. Here, major subsystems or components (SSM, OTA, and individual instruments) would be tested separately (and by different contractors) but not the whole system in the all-up mode in a realistic vacuum thermal environment. LMSC did not propose such a test in its bid but soon came to

realize its importance and pressed for it as a contract modification to avoid long-term costs (reasoning that an untested HST would experience earlier and more frequent maintenance needs; thus requiring more Shuttle flights). This argument finally prevailed.

Later, the cost and tempo of the assembly/test program would become a major issue as schedules were in jeopardy. LMSC was directed and funded to accelerate to a 24-hour work day to meet the anticipated launch schedule. While some time was recovered it was insufficient and by 1985 the stress on key staff was enormous. Searching for answers as to why acceleration did not lead to desired recovery, LMSC suggested that it was because the HST was being built on the "protoflight" principle – meaning that the complex instrument being designed, built, and tested was the one that would fly. This was in contrast to much of LMSC's earlier experience with incremental approaches that involved a design-build-test-fix repetitive cycle. In the final analysis considerable schedule was recovered, but the planned launch schedule still was delayed.

By 1986, the program was moving rapidly and being readied for the crucial vacuum-thermal test (30 days or more of rapid cycling and functional checks). In spite of the Challenger accident NASA decided to proceed at full speed, with the all-up testing running from May 6 to July 1, 1986. It was generally seen as successful, but there were doubts as to the feasibility of making necessary fixes in time to meet schedule had not the Challenger event happened. The main correctable deficiencies involved premature solar array degradation and loss of battery efficiency, as well as other areas. Separate lack of maturation of the ground system and its testing was an additional risk.

An up-and-running aggressive test program also proved to be a motivation for NASA and the contractors to engage in a meaningful post-Challenger systems engineering effort until return-to-flight timing could be better defined. Additional motivations were retention of the skilled workforce to be sure the system was ready to launch and the $7 million cost for delay because of the level of effort underway. The telescope "safing" system that keeps the solar arrays properly pointed for power continuity was found to be unreliable. Scientific instruments, each in its own right a technology challenge, needed considerable work, as did the ground command and control system. There was so much to be done that the possibility of a second vacuum-thermal test arose and was finally rejected. Total cost now approached $2 billion, including planned future on-orbit refurbishments, an order of magnitude more than the original estimates.

3.4 Learning Principle 4 – Life Cycle Support Planning and Execution

Life Cycle Support planning and execution must be integral from day one, including concept and design phases.

Deployment and Post Deployment

The payload configuration for the HST was stowed in the Shuttle Orbiter payload bay using payload latch retention assemblies and an active keel fitting. Complex electrical interfaces, interface power control, and connecting/disconnecting umbilicals were provided and set up for remote operation from the Orbiter flight deck. Other berthing aids and closed-circuit TV were also provided.

Prelaunch Operations

HST was configured for flight at the launch pad at the completion of prelaunch testing. The essential electrical bus, heaters, and key shutters were all powered-up as part of this process. The bus was powered continuously by the Orbiter from prelaunch through deployment and monitored by the Orbiter computer system to allow ground crews to detect any automatic "failover" of the essential bus to internal (battery) power.

Mission Operations

The complicated set of deployment operations is best described sequentially by most significant deployment event [19]:

- Direct insertion ascent to operational orbit.
- Payload bay door opening.
- Ku-band antenna deployment.
- Cabin depressurization to 10.2 lb per in^2 absolute.
- Post-ascent condition inspection of the HST in the payload bay.
- Activation of HST external main bus power (after a minimum of 3 hours to allow for out-gassing of communications equipment); power application to communications equipment.
- Transmissions begin with Orbiter, TDRS.
- Star trackers tested; ground-based data processing checked out.
- Crew prepare for EVA (should one become necessary).
- Maneuver for HST deployment.
- HST grappled, unlatched, and placed on internal battery.
- Orbiter power removed; umbilical disconnected.
- HST maneuvered for deployment by the remote manipulator.
- Deployment of solar array, followed by blankets that are then electrically connected to the HST to begin battery charging.
- High-gain antennas unlatched and deployed, and aperture door unlatched.
- HST placed in its release attitude with respect to the sun.
- HST pointing control system activated; software placed in drift mode until release.
- HST released just after orbital noon of the release orbit.
- Ground operations control center begins communications via relay satellite.
- Orbiter separates to a distance of 45 nmi.

Clearly, the engineering design (conceptual, preliminary and detailed) of this complex array of mechanical, electrical, electro-optical, and human components, all operating in an earth-to-orbit dynamic environment, would have posed an enormous challenge even if the project had enjoyed ideal circumstances (unlimited resources, time, and talent). Of course, this was not the

case. The undeniable fact that "the darn thing worked," notwithstanding the separate primary mirror failure, is a real validation of the systems engineering excellence that resulted from the industry-government-university project team.

Life Cycle Support

Programs structured with real life cycle performance as a design driver will perform better, and will be capable of dealing with unplanned, unforeseen events (even usage in unanticipated missions). A requirement for on-orbit maintenance and repair was part of the HST architecture, acquisition strategy, and program plan from day one. A baseline list of orbital replacement items had been developed. The architecture described a set of Orbital Replacement Units, tool sets, tool carriage, storage, thermal protection, astronaut access limitations, access boxes, cradles, etc. As one small example (representative of many mundane items included), to support on-orbit servicing some uniformity of repair/change-out attachment items (i.e. 7/16" hex bolts) was part of the design baseline, with some variations of head height, surface finish, etc., to accommodate component access limitations. As an architecture, these functions and components were conceptual and in a preliminary design stage of definition. There were some preliminary specifications, loads, and dynamic interface descriptions (for example, a "Flight Support Equipment, Pallets" document had been written, along with some others). Guidance on how to implement the design requirements per the architecture at that time did not exist and would require a dedicated activity comprising systems engineering, human factors, and detailed, iterative functional design and practice.

An interview with Kathy Sullivan [20], then an astronaut and a key HST deployment mission EVA specialist, indicated that overall astronaut user/contractor/program office interfaces and interactions were good for the support missions. The Challenger-imposed five-year delay provided needed time to look deeper into servicing mission details and to take advantage of other contingencies that might develop. While the primary mirror repair was not one of these, all of the provisions for the others enabled the mirror fix to be accomplished more expeditiously than might have otherwise been the case.

For the repair/replace mission, the guiding document was the *Shuttle Flight Operations Manual*, Annex for EVA [18]. For payloads such as the HST, the *Cargo Systems Manuals* [19] applied and contained EVA Annexes for specific cargos. An Annex 11 had to be written for the specific HST repair/replace mission. The specific purpose of the documentation was to inform future mission designers and planners of system/subsystem design and functional requirements (especially the relationships among them) and to provide detailed technical and functional checklists for future mission specialists. Systems engineering inputs and even control of these documents are crucial and must include both physical and functional design criteria that have been thoroughly tested; in this case, in mechanical, electrical/electronic, and credible (from the astronauts' perspective) human dimensions.

For HST, the most significant correct decision for servicing missions was the agreement that the program would use the physical assets and added time available while the system was still on the ground to rigorously work the on-orbit issues. This may seem obvious, but the telescope "owners" are the science community, which understandably (and normally for good reason) does not want anyone to "mess" with their delicate instruments. A questionable decision was to detach the technical development of servicing (assigned to Goddard) from overall system design and development for launch (assigned to Marshall). The unique and different design

approaches of the two organizations were very evident to all. This caused many reworkings of the "game plan for servicing" and eventually resulted in the need to evolve a new team midcourse in the program. This was especially true with respect to getting Goddard to work on servicing (vs. technical issues related to the science instruments) as top priority. Ultimately it was successful, though difficult and strained.

With the current Administration's decision to cancel Servicing Mission #4, NASA has been forced to consider an earlier-than-planned mission to dispose safely of the HST, likely through a controlled de-orbit process initiated by an "add-on" propulsion de-orbit system launched on an ELV [22]. This could take place as early as 2008. Safety (minimum risk to humans on earth) is the primary design driver. Figures 3-6 and 3-7 below are the top-level draft requirements summary as advertised in August 2004 on the NASA Website (http://hubble.gsfc.nasa.gov) for potential contractors who might be interested in responding to an evolving acquisition strategy and procurement process. Ironically, HST's fate continues to be closely linked to generally unrelated external events (in this case, the new "Moon, Mars and Beyond" Space Exploration Presidential initiative and safety concerns with continued Shuttle and International Space Station operations).

HST Disposal Mission (Background & Preliminary Requirements)

Background

- **NASA HQ Code S has formally tasked the HST Program to implement a mission to safely dispose of HST**
  - Reliably dispose of HST via add-on propulsion system launched on an ELV
  - Mission execution readiness date of April 2010 with potential of being moved up to 2008
  - Capable of mission execution independent of the operational state of HST
- **Rapid development activities are in work:**
  - Requirements Definition
    - Flow requirements from Level I to Program Level II and end-item Level III
  - Engineering responsible for mission design, systems and discipline engineering and key technologies
    - Feasibility studies
      - Modeling & simulations of mission concepts
      - Autonomous rendezvous and capture sensor demonstrations
  - Project organization in place
    - Staffing requirements identified
    - Acquisition strategies are being worked with procurement
    - Potential partners have been identified (NASA, DARPA, NRL, Industry)
- **Data Set to Support HST End of Mission Alternatives Sources Sought is available at http://*hubble.gsfc.nasa.gov***

Figure 3-6. HST Disposal Mission Requirements Background

Draft Requirements

Level I

1) The method of disposal must ensure that the risk of casualty to humans on the ground meets the 10,000:1 NASA Standard (reference NSS 1740.14)
2) Earth return via the Space Shuttle retrieval is not permissible

Level II

1a) A de-orbit stage shall be capable of de-orbiting HST from a 300 nm circular orbit and reliably steer HST into a pre-determined, uninhabited region of the planet in accordance with NASA Orbital Debris Mitigation Guidelines (NSS 1740.14).

1b) A disposal orbit stage shall be capable of raising HST to a 2500 km orbit in accordance with NASA Orbital Debris Mitigation Guidelines (NSS 1740.14).

2) The maximum allowable acceleration during propulsive burns is .1 g
3) The maximum allowable load at any of the three berthing pins is 1000 lbf.
4) All subsystems other than the propulsion subsystem shall be redundant. No single failure in any subsystem shall require a switch to the redundant side of another subsystem.
5) The de-orbit stage shall be attached to existing hard points on the HST structure.
6) The capability of the de-orbit stage to perform rendezvous, capture/docking and de-orbit of the HST spacecraft shall be irrespective and independent of the health and configuration of the HST. See DRM Note Below
7) The functional reliability of the propellant and propulsion subsystems shall be at least 0.99 at 1 year (TBR) after stage attachment.

Design Reference Mission: 1) Preliminary analysis results in a worst case unpowered drifting HST having body rates of +/- 0.22 deg/sec on all three axes simultaneously. All powered operational states of HST are also possible

2) HST physical configuration is the current post SM3B configuration, see data set.

Figure 3-7. HST Disposal Mission Draft Requirements

3.5 Learning Principle 5 - Risk Assessment and Management

For complex programs, the number of players (government and contractor) demands that the program be structured to cope with high risk factors in many management and technical areas simultaneously. The HST is a classic example of a venture with inherently high technical and program management risks by any measure. Significant risk elements had to be dealt with by employing a variety of different systems engineering and management tools and processes. Many aspects have already been described, some initially in terms other than risk (such as validation, verification, and test). Some more notable risk elements, management, and mitigation measures of the HST program throughout its life cycle phases include:

- **Requirements definition** – early studies involving the feasibility of autonomous or human-assisted approaches; special consideration of the needs of the astronomy/ scientific customer; trade studies to examine basic sizing (example: mirror size-performance-cost trades).
- **Systems architecture** – use of “phased” (A/B/C/D) studies involving all of the academic, government, and industry players to build a national technical and political consensus on preferred concepts of operation; decision to tie the HST architecture to the Shuttle.
- **System/subsystem design** – partitioning of the design, development, and eventual fabrication of the major functional elements of the system (instruments, SSM, OTA, etc.); employment of innovative techniques to overcome unique environmental

problems; kinematic joints for dynamic isolation of sensitive components and zero-gravity support system for assembly and test; decision to build a backup primary mirror from a second source with different fabrication and polishing methods; unsuccessful attempt to develop an alternative approach to fine guidance sensors; special teams, such as the Astronomy Science Team, to provide independent outside assessment and validation of scientific and engineering approaches. There are many other examples of both successful and unsuccessful design approaches.

- **Systems integration** – system-of-systems-level integration issues; unique environmental risk elements (physical, electronic, and optical interactions in assembly, packaging for launch, deployment, operations, and servicing).
- **Validation and verification** – successful all-up functional test and vacuum-thermal systems test; failed primary mirror test process implementation; use (and in some cases non-use) of independent review and technical audit groups; failure to employ decision tree failure prevention analysis in mirror case; aggressive use of Challenger-imposed down time to maintain technical competence and implement an aggressive test and deficiency correction program.
- **Deployment and life cycle support –** implementation of on-orbit servicing strategy; effective use of Challenger-imposed down time to master on-orbit astronaut human and mechanical tasks and provisioning; relentless astronaut ground practice and test using actual hardware in development and under test.
- **System and program management** (see Section 3.4.5.4) **–** the impacts of sustained lean (sometimes deficient, particularly early on) systems engineering manpower; acquisition strategy (associate contractors, Marshall-Goddard relationships); partitioning of technical roles and responsibilities between industry and NASA program management functions; use of Program Evaluation and Review Technique (PERT) milestone and critical path management; technical vs. cost risk factors and tradeoffs between the two; use of NASA-contractor working groups to resolve design, fabrication, and assembly issues

Communications

Communications must be considered the most significant human challenge to all aspects and phases of the HST program throughout its lifetime, even to the present. For purposes of this case study, we will deal with some 16 years of communications issues (roughly from the issuance of the RFP in 1977 through completion of the first servicing mission in 1993, including the repair/correction of the primary mirror defect). We will consider a few of the most representative communications processes and challenges within and across several program interfaces that had a significant bearing on HST systems engineering, including:

- Between and among affected NASA Headquarters and field program management and support centers (Marshall and Goddard primarily; Johnson and Kennedy secondarily) responsible for requirements consolidation, systems engineering, source selection, contracting, program management, and operations oversight.
- LMSC and P-E, the primary associate contractors.
- Major subcontractors (some 25), who worked on approximately 70 major subcontracts.

- ESA, provider of solar arrays, the faint object camera, and science operations personnel.
- Technical requirements definition teams (for astronomy, telescope, data, operations, and scientific instruments areas).
- Ground system (command, data flow, and operations), which dealt with all of the components of a national, on-orbit research facility (STScI at Johns Hopkins, STOCC at Goddard, among others).

Some indication of the nature of the program relationships among many of these players is generically represented in Figure 3-8. An organizational structure of this type, with parallel government and industry associates, plus parallel management, engineering, and scientific prime functions, posed an enormous technical, management, communications, and control challenge. The impacts on the ability of systems engineers and program managers to execute all facets of the HST program were certainly of first order.

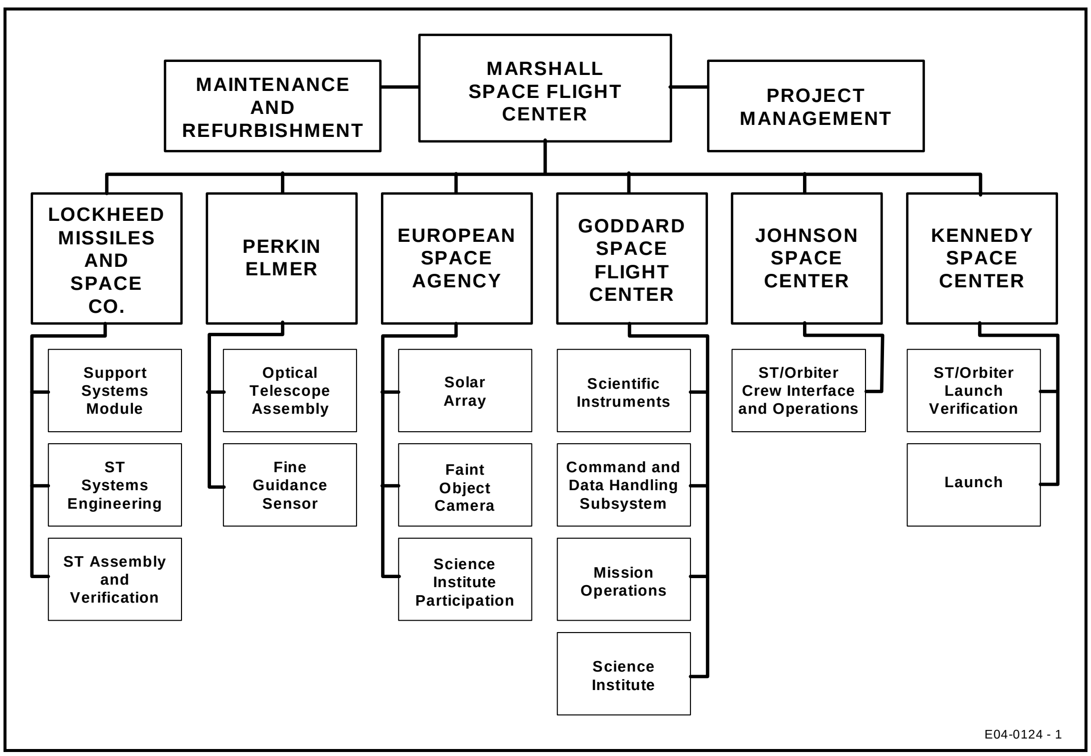


Figure 3-8. 1977 HST Program/Communications Interfaces

System and Program Management

In retrospect, with Marshall ultimately chosen for the lead NASA role, it was clear that Marshall saw advantages in terms of cost and lead roles if it awarded contracts to associates that it could control and acted as integration manager for the overall effort. By contrast, Marshall believed that only a large aerospace prime (a Lockheed, Boeing, Grumman, etc.) would have the capability to design, build, and manage both the telescope and support system module. Because of the special optical requirements of the telescope, Marshall knew that a large optical company (Itek and P-E had both indicated interest) would be needed and that each might be expected to

align itself with one of the primes. This would lead to a robust, if not limited, competition, with a less favorable impact on total system cost. In the final analysis, Marshall elected to pursue the associate contractor approach, rather than working exclusively through a prime, believing it could more effectively and affordably manage the major elements of the program vs. the full-up assembly as a whole, all with better control, leverage, and management effectiveness.

The 1977 organization for the HST program illustrated above had matured through the 1980s. Figure 3-9 illustrates a 1990 representation. In 1977 the Goddard-Marshall relationship was generally seen as poor and as a continuing struggle over how to divide responsibilities, with the roles and relationships of the centers and headquarters a major issue. This came to a head in 1983 (after the JPL had been considered for an associate role and dropped on the basis of cost) with the signing of an MOA by Goddard. Goddard's role, while subordinate in the management sense, was nonetheless very sizable, significant, and clear.

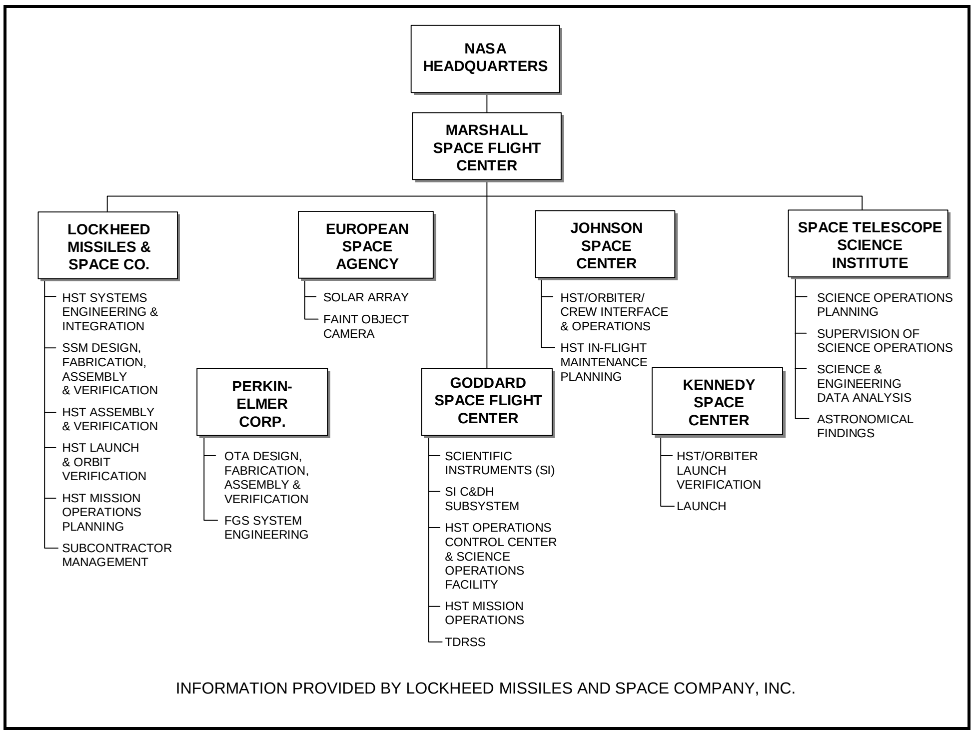


Figure 3-9. Hubble Space Telescope Responsibilities, 1990

Total manpower was also a critical factor, especially impacting NASA-Marshall systems engineering talent available to penetrate and oversee the contractors' technical activities. Total Marshall staffing in the first year (1977) was only 72 and was to grow to only 116 by FY 1981 when program activities were forecast to peak. DoD was seen as an influence here because of NASA-DoD agreements to limit the numbers of project personnel with access and thus minimize unwanted adverse technology transfer. This was reinforced by the separate desire of NASA Headquarters to minimize interference with contractor performance of program tasks and to keep HST a "low-cost" program.

The manpower issue would have a profound impact on how systems engineering would play out over the course of the program. The normal functions of moving from requirements to design specifications, selection and use of mathematical models and tools, engineering of the

manufacture, test, and verification of system elements, quality assurance, and technical audit functions, all to support program milestones and decisions, had to be thought through in a severely manpower-limited situation. As if this were not enough, it became increasingly evident that HST posed a major system-of-systems engineering challenge. This was because all of the optical, electronic, and mechanical components of major subsystems, often designed and built by others, were, in fact, critically interconnected. In a very direct fashion, changes or inadequacies of any one part would change the performance, if not the function, of the others. NASA project managers considered their systems engineering management options:

- Give the management function to the prime contractor.
- Give it to a separate support contractor, like an Aerospace Corporation.
- Do it with civil service manpower.

By a process of elimination (civil service was not really a practical option due to insufficient numbers and alleged bad experience with the separate support contractor approach), the project managers was left with the prime contractor, with the exception of the OTA focal plane structure, which was assigned to P-E.

By 1990, while most of the players remained the same, several key differences in management and systems engineering responsibility and relationships became evident:

- LMSC's roles in systems engineering and integration, mission operations planning, and subcontractor management were more explicitly defined through program maturation.
- Goddard's relationship with the STScI was more distanced, with the Institute functions in scientific activity planning, oversight of science operations, science and engineering data analysis, and astronomical findings placed more directly under the oversight of Marshall.

In addition, Marshall project management responsibilities became more specifically defined as shown in Figure 3-10. The HST program was "projectized" with specific offices formed for management and oversight of the OTA, SSM, and Maintenance and Refurbishment components of the program. Notably, separate parallel offices are evident for systems engineering, program planning, and control and operations, as well as the Project Chief Engineer (separate from the systems engineering function) and the Project (Chief) Scientist. Not evident from the chart is the conscious decision to keep engineering (and management) presence at the contractors' sites and parallel engineering at Marshall to a minimum.

To make the organization work, project management created a number of NASA-contractor working groups (chaired by contractor representatives) intended to serve as the forum for resolution of design and manufacturing issues. Chairing these groups compelled the contractor into a visible leadership role, which, in turn, forced a greatly improved understanding of all the critical interfaces and produced close human contact between and among the key players on all sides. To track all of the working groups' technical activities throughout the program, NASA used a modified version of the PERT that was created in the 1950s for the Navy Polaris program and later adapted successfully for the Apollo program. NASA also implemented a well-disciplined system for technical document generation and configuration control to support technical management of both hardware and software (again no doubt based upon earlier manned space flight experience).

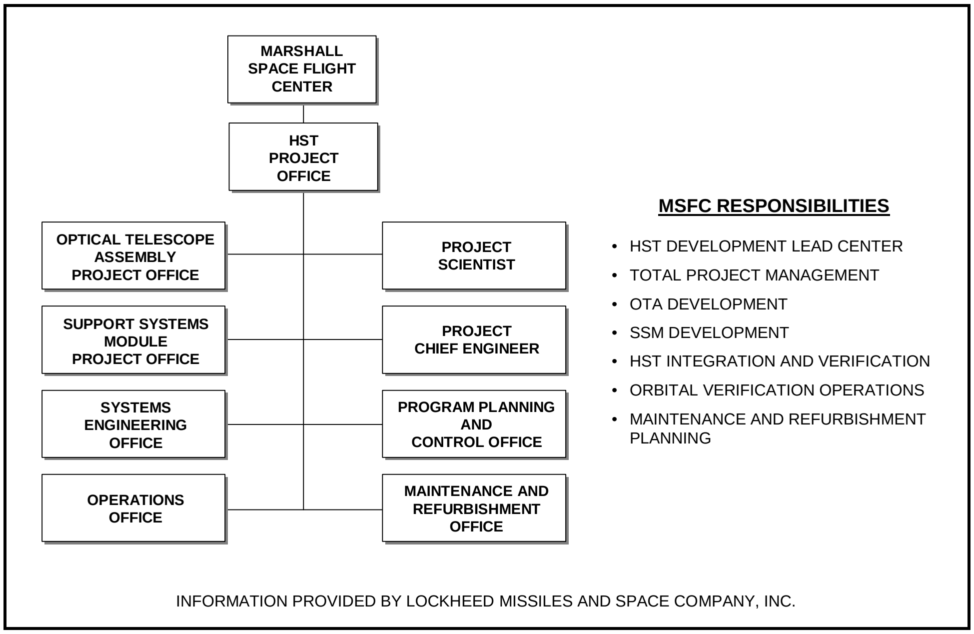


Figure 3-10. Marshall SFC HST Responsibilities, 1990

As the program progressed, NASA's technical management strategy (streamlined staffing and technical oversight, minimum in-house engineering, few support contractors at Marshall, a small NASA presence at LMSC and P-E, and frequent reviews and rigorous change control management) would fall far short of the mark. As already discussed in Sections 3.2, 3.3, and 3.4 above, NASA drastically underestimated what it would take to design, build, and test a system of HST's complexity.

Nonetheless, by 1990, after several organizational shifts and major infusions of funding and engineering talent, the program seemed to be running reasonably smoothly, having survived and recovered from major cost, systems engineering, manpower, management, and organizational challenges, as well as the Challenger tragedy.

4.0 SUMMARY

HST and its servicing missions have been key to implementation of NASA's national science goals for space exploration and discovery of our physical origins. HST has yielded unprecedented information crucial to understanding the structure of our universe, testing physical theories, and revealing new phenomena throughout the universe, especially through the investigation of extreme environments. HST helps scientists understand how both dark and luminous matter determine the geometry and fate of the universe. HST instruments have helped us understand the dynamic and chemical evolution of galaxies and stars and the exchange of matter and energy among stars and the interstellar medium. HST has expanded our knowledge of how stars and planetary systems form together and has provided detailed images that assist us in understanding the nature and history of our solar system and what makes Earth similar to and different from its planetary neighbors. A better sense of the scope and magnitude of HST scientific discovery and achievement can be gained by reviewing Reference 23.

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.

Stepping back from the remarkably successful scientific and educational outcomes of the program from the perspective of the customer and the taxpayer, we must ask: Was the HST, as a total program, a true systems engineering success and what lessons were learned? We can gain some appreciation for the answers, which represent a complex mix of responses, by further asking the question as a function of each of the Friedman-Sage concept domains.

- ***Was an effective Requirements Definition and Management process evident?*** From the perspective of the ultimate user, the answer would have to be, in general, "yes." There was full participation by this customer/user throughout the program. However, in the early stages the mechanism was not well defined and the user community was initially polarized and not effectively engaged in program definition and advocacy. This changed for the better, albeit driven heavily by external political and related national program initiatives. Ultimately, institutionalizing the user's process for involvement ensured powerful representation and a fundamental stake and role in both program requirements and requirements management. Over time the effectiveness of "The Institute" led to equally effective user involvement in system deployment and operations.
- ***Were Systems Architecting and Conceptual Design conducted effectively from a systems engineering perspective?*** Here the answers are both "yes" and "no," depending on the time frame and specific related activity under discussion. The use of Phased Studies to explore concepts and alternatives appears to have provided for a healthy variety of inputs from a variety of contractors and NASA centers. Thus, competition was evident, but it is not clear that it was always productive, especially the dimension going on within and between the centers. Center roles and missions

were clearly at stake to a greater or lesser degree depending on the year or administration. Many references and documented interviews indicate that the program was starved for both quality and quantity of systems engineering talent during this and some subsequent program phases, especially within NASA, and external to NASA to the extent that contracts lacked funding for systems engineering vs. conceptual content.

- ***Was the System/Subsystem Detailed Design and Implementation executed effectively?*** Weighing the enormity of the challenge against the resources available and the outcomes, again final the answer would have to be "yes," on balance. However, this phase was lengthy, complicated, and controversial. Clearly there were many pros and cons. If success were measured by initially estimated vs. actual cost (almost an order of magnitude cost growth), one would have to raise serious questions. On closer inspection, it appears that initial estimates were simply wrong and lacking in quality systems engineering input, let alone realism. On the other hand, the growth was not atypical of many, if not most, major NASA, defense or even public works (rapid transit, highways, nuclear power, etc.) projects of the era. From a schedule standpoint, substantial delays were routine, and often attributable to management, political, and funding instability, as well as dearth of government systems engineering talent, especially at critical times early in the program. In spite of the turbulence, often caused by external factors, enthusiasm and support for the program by the faithful customer and developer communities endured and ultimately paid off.
- ***Was System and Interface Integration conducted and managed effectively?*** All indications are that this was one of the strengths of the program. Was it because this was simply a "must" or was there more to it? Clearly, provision for a high degree of integration to assemble, test, deploy, and operate HST was identified as a fundamental need from early on. Early wedding of the program to the Shuttle, prior NASA (and of course, 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 that HST was a big systems engineering integration challenge. Here collaboration between NASA engineers and the contractors, as well as the science customers, seemed to peak. Program failures seemed to be less traceable to failures in system integration (functional definition, design, and execution of multiple critical functional interfaces) than to "weak links" that could be worked around, poor risk management, or improper test implementation.
- ***Were System Validation and Verification planned, conducted and executed effectively?*** In retrospect, and negating initially the contributions of such external events as the Challenger-imposed delay, we would have to respond with an overall "no." System and subsystem validation and verification occurred at many levels and literally across hundreds of activities. Many, if not most, tests were no doubt planned and conducted effectively if not efficiently. However, the two critical examples discussed earlier – the total system vacuum-thermal test (ultimately conducted after considerable debate) and the landmark lack of rigor in the optical system (primary mirror) test are of sufficient magnitude and importance to outweigh most others. One occurred before Challenger and the other after. Clearly, the time made available by

the Challenger delay proved vital and the decision to invest significant additional resources, including systems engineering talent, was both wise and necessary. This decision stands to NASA's credit, as NASA could have easily justified further delay in applying new resources while awaiting the outcome of the Challenger investigation and return-to-flight program plan. The prudent use of the time and additional resources also leveraged improved outcomes for other program life cycle phases.

- ***Were System Deployment and Post-Deployment planned and executed effectively?*** As these functions were finally executed after dramatically shifted schedules and with the support of significant additional resources, the answer would have to be a resounding "yes." This is of added significance because HST first-time deployment was also first-time full system validation and verification in the often surprising, demanding, and unforgiving operational environment of space. This impressive result, notwithstanding the deployment-unrelated failure of the primary mirror, is real testimony to the collaborative approach and dedication of literally hundreds of contractor, government, and scientific community participants to make a complex program, system engineering, and management process work the first time.
- ***Was the Life Cycle Support dimension of the program effectively planned and executed?*** This dimension was integral from day one (concept and design phases) and the results speak for themselves. HST probably represents the benchmark for building in system sustainment (reliability, maintainability, provision for technology upgrade, built-in redundancy, etc.), all with provision for human execution of functions critical to servicing missions. With four successful service missions complete, including one initially not planned for the primary mirror repair, the benefits of design-for-sustainment, or life cycle support, throughout all phases of the program becomes quite evident. Had this not been the case, it is not likely that the unanticipated, unplanned mirror repair could have even been attempted, let alone been totally successful.
- ***Were Risk Assessment and Management effectively planned and implemented?*** Closely linked to most other life cycle phases, especially validation and verification, the results here are mixed. The complexity of the program and the number of players – government, university, and contractor – demanded that the program be structured to cope with high risk in many management and technical areas. Here there was heavy reliance on the contractors (especially LMSC and P-E), each of which "owned" very significant and unique program technical risk areas. In the critical optical system area, and with LMSC as the overall integrator, NASA seemed to place too much reliance on LMSC to manage risk in an area where P-E was clearly the more expert technically. 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 occurrence. On the positive side, as with validation and verification, the Challenger delay was used to good advantage to attack and reduce risk in many other areas. An excellent example is the way the HST program addressed the risks to astronauts in further understanding and practicing on-orbit servicing functions using time and

assets that were "available" (with creative requisitioning) from system fabrication and test work-in-progress during the delay period.

- ***Was System and Program Management organized and implemented effectively?*** This could well be the most arguable facet of the case in terms of criticality to the success/failure track record of the program. Students of program management theory and practice argue passionately that the organizational structure evolved for the HST program was a design for difficult program management, if not for failure. Others indicate it was a structure designed for maximum involvement of all players. Still others say that if the program was ultimately successful, as it was and is, then the program was effectively managed by definition. Clearly the program management structure was complex and diverse, and reflected a realization of many technical, organizational, political, and institutional factors.

  Could the program have been organized differently and still have succeeded? Of course – and probably with equally positive results, but it would most likely still not have avoided many, if not all, of the pitfalls. Most programs can be managed with virtually any proven, rational management approach that allows the uninhibited participation of all key contributors, especially systems engineers. *How* the organizational arrangement is used by leaders and managers is vastly more important than *what* it represents on paper. Minimum conditions for success must be met, such as establishing open and effective communications within and across government, contractor, and customer lines. Other requisites for success include rigorous systems engineering discipline enabled by the program management structure, interface and configuration control, risk management, and other well-known attributes. HST program management organization and execution either had or evolved many of these characteristics. Where and when these were lacking or not focused upon, problems arose that were more attributable to human action or inaction than to the organizational structure. Organization and management structure is always necessary but never sufficient to get the job done. This is an important learning point given management's propensity to try to reorganize its way out of problems, rather than deal with root causes (usually human interaction and systems engineering process rigor issues) directly.

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6.0 LIST OF APPENDICES

Appendix 1 - Completed Friedman Sage Matrix for HST

Appendix 2 - Author Biography

Appendix 3 - Documentation, HST Cargo Systems Manual

Appendix 4 - Hubble Space Telescope Level I Requirements For The Operational Phase of The Hubble Space Telescope Program

Appendix 1

Completed Friedman Sage Matrix for HST

Table A1-1. The Friedman Sage Matrix for the HST

Concept Domain	Responsibility Domain		
	1. SE Contractor Responsibility	**2. Shared Responsibility**	**3. Government Responsibility**
A. Requirements Definition and Management	Contractors involved the scientific user community in system requirement studies for sizing the telescope, defining the instrument suite, and determining concept of operation.	Contractors and NASA centers worked collaboratively, if not competitively, on requirements definition and analysis.	Government was responsible for finding the right mechanisms to bring science users into the requirements process.
B. Systems Architecting and Conceptual Design	Multiple competing contractors were funded over several years for phased concept and architecture development approaches to the mission.	Concepts and architectures were iterated and reviewed jointly; scientific community customers participated; early example of "system-of-systems" approach.	Multiple NASA centers participated with in-house studies and concept exploration program management. Phased approach was mandated by NASA.
C. System and Subsystem Detailed Design and Implementation	Contractor (LMSC) responsible for overall system design, telescope assembly, support system module and subsystem/ instrument functional interface definition; P-E for optical system and guidance sensors; STScI for most instruments.	Considerable data exchange and sharing; convening of review and oversight groups; and joint program reviews.	ESA responsible for solar arrays; Goddard for some instruments.
D. Systems and Interface Integration	LMSC responsible overall; P-E responsible for optical system with LMSC oversight.	Jointly monitored but largely contractor dominated in execution. Extensive joint integration planning, documentation and configuration management by all participants, including users.	Marshall Center responsible overall for NASA. Goddard led for instrument package integration oversight.
E. Validation and Verification	Total system vacuum thermal test (LMSC) and rigorous optical system V&V (P-E) a contract requirement; (primary mirror test failure led to system failure).	Contractor team and government team shared responsibility for V&V result review, approval and/or rework.	NASA responsible for final review and approval. Direction for V&V acceleration only partially successful; Challenger delay used to advantage.
F. Deployment and Post Deployment (post launch)	Deployment supported by contractor team (system/subsystem functionality, operations support, problem analysis, etc.).	Joint oversight of all operations, especially early on and through the primary mirror failure root cause analysis.	Goddard responsible for mission control; two operations support facilities established (STOCC and STScI).

Table A1-1. The Friedman Sage Matrix for the HST

Concept Domain	Responsibility Domain		
G. Life Cycle Support	Program designed for life cycle support (on-orbit servicing); ORU equipment integral to all contractors SE and PM activities. Accelerated disposal mission requirements and program development initiated in February 2004.	ORU functional design and performance jointly defined. Program office, contractor, and user communications and interfaces were good; payoff evident in coping with unplanned need to correct primary optics on orbit (mirror failure).	Experienced astronauts represented the mission astronauts to validate service mission details. Flight operations manuals and EVA annexes well prepared in advance.
H. Risk Assessment and Management	Contractor integral to all phases of program risk assessment and mitigation; evident from requirements through development and test; primary risk management OPR.	Generally, joint involvement in risk management, assessment and mitigation activities; usually worked well; major benefits from Challenger delay; suffered early on for lack of adequate SE manpower because of cost concerns.	NASA clearly in an oversight role; heavy dependence on contractor risk management and judgment; used special review groups to work problems and provide independent inputs.
I. System and Program Management	LMSC, P-E associate contractors with LMSC responsible for overall SE and integration; elected as the best approach for optimum NASA control and leverage.	Contractor and NASA elements organized under a project CONOPS (OTA, SSM, Maintenance and Refurbishment components); shared responsibility for management, problem solving and cost-schedule-performance monitoring.	Marshall lead with Goddard essentially an associate for the mission operations and scientific payload management; separate parallel center offices for SE, program planning and program control functions.

Appendix 2

Author Biography

MR. JAMES J. MATTICE

Jim Mattice is Director of Management / Organizational Development at the Universal Technology Corporation, Dayton, Ohio. He provides corporate leadership in the areas of strategic planning and new business development. He also supports on-going government and commercial activities in the areas of research, development, technology advocacy, technology transition, executive development and training. In previous positions Jim served as:

- Air Force Executive-in-Residence at the Federal Executive Institute, Charlottesville, Virginia
- Deputy Assistant Secretary of the Air Force for Research and Engineering, Office of the Secretary of the Air Force, the Pentagon
- Executive Director in the office of the Commander, Aeronautical Systems Center (ASC)
- Director, Development Planning, ASC
- Director, AF Manufacturing Technology Program
- Other senior management positions in Air Force Laboratories and multilateral international defense fora (NATO TTCP, AGARD/RTO, etc.).

Current/recent activities include:

- Strategic Planning support to the Air Force Manufacturing Technology Program and the DOD Joint Defense Manufacturing Technology Panel (JDMTP)
- Member, National Academy of Engineering Board on Manufacturing and Engineering Design (BMED)
- Chairman, NASA Next Generation Launch Technology (NGLT) Executive Program Review Team (ExPRT)
- Member, NASA Kennedy Space Center University-Affiliated Space Technology Development Center (USTDC) Senior Advisory Board
- Author, *Hubble Space Telescope Systems Engineering Case Study* for the Air Force Institute of Technology (AFIT) Systems Engineering Institute, May 2004
- Member, National Academy of Engineering Committee for Owner-Enabled Handgun Technology Readiness Assessment
- Leader, AFRL BRAC 2005 Strategic Planning Red Team
- Member, National Research Council Committee on Integration of Commercial and Military Manufacturing
- Member, US Army Future Combat Systems Critical Manufacturing Technologies Independent Assessment Panel
- Member, DOD Technology Area and Assessment Review Panel for the Materials and Processes

- Member, DOD Technology Area and Assessment Review Panel for Manufacturing Technology
- Study Director, AF Manufacturing Technology 2015 Strategic Planning Study
- Facilitator, AF Research Laboratory Nanotechnology Strategic Planning Team
- Lead Facilitator, NATO/RTO Counter-Terrorism Workshop
- Member, Defense Science Board 2005 Task Force on the DoD Manufacturing Technology Program

Appendix 3

Documentation, HST Cargo Systems Manual

1. *HST Systems Description Handbook*. ST/SE-02, LMSC/D974197B, May 1985.
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Appendix 4

HUBBLE SPACE TELESCOPE

LEVEL I REQUIREMENTS

FOR THE OPERATIONAL PHASE

OF THE HUBBLE SPACE TELESCOPE PROGRAM

(Extracted in part from http://hstsci.gsfc.nasa.gov/dowloads/level1.pdf)

> This Level 1 requirements document for the Hubble Space Telescope is a merging of requirements as defined in the approved 1983-85 and the 1989 Level 1 Requirements documents, as amended by approved waivers and Critical Decision Items (CDI's). The intent of this formal release is to present the complete Level 1 requirements in a single integrated document. As such, it supersedes and replaces all previous Level 1 requirements

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BASELINE ISSUE

February 29, 1996

Office of Space Science
Astrophysics Division

National Aeronautics and Space Administration
NASA Headquarters
Washington, DC

February 29, 1996

HUBBLE SPACE TELESCOPE

LEVEL I REQUIREMENTS
FOR THE OPERATIONAL PHASE
OF THE HUBBLE SPACE TELESCOPE PROGRAM

CONCURRENCE APPROVAL
National Aeronautics and Space Administration
NASA Headquarters
Washington, DC

February 29, 1996

CONTENTS

1. SCOPE
1.1 Control
2. OVERALL PROGRAM REQUIREMENTS
2.1 Operational Life
2.2 Servicing Mission Authorization
2.3 Scientific Capabilities
2.4 Space Transportation
2.5 Communications
2.6 Mission Termination
3. OBSERVATORY PERFORMANCE
3.1 Image Quality
3.1.1 Image Stability
3.1.2 Target Positioning
3.1.3 Guide Star Acquisition and Tracking
3.1.4 Solar System Object Tracking
3.1.5 Stray Light Performance
3.2 Science Observational Capabilities
3.2.1 Core Capabilities
3.2.2 Additional Observational Capabilities
3.3 Spacecraft Subsystems Performance
3.3.1 Power
3.3.2 On-board Data Storage
3.3.3 Data Quality
3.3.4 Time/Frequency
3.3.5 Data Management
4. GROUND SYSTEM REQUIREMENTS
4.1 General Functional Capabilities
4.2 Observatory Operations
4.2.1 On-Line Operations
4.2.2 Planning and Scheduling
4.2.3 Maintenance Mission Planning
4.2.4 Simulation and Test
4.3 Data Acquisition,
4.3.1 Data Rates
4.3.2 Data Volume
4.3.3 Data Storage
4.3.4 Data Dissemination
4.4 Science Operations
4.4.1 Research Management
4.4.2 Observing Support
4.4.3 Science Data Processing and Products
4.4.4 Data Archive
5. SERVICING SUPPORT REQUIREMENTS
5.1 Initiation Criteria
5.2 Planning Support

5.3 Orbital Replaceable Unit Requirements
5.4 Orbital Replacement Instrument Requirements
5.5 Space Support Equipment
5.6 Technical Information Management
6. SAFETY AND EQUIPMENT RELIABILITY
6.1 Crew Safety
6.2 Equipment Reliability

HUBBLE SPACE TELESCOPE
LEVEL I REQUIREMENTS
FOR THE OPERATIONAL PHASE

1. SCOPE

This document combines and updates the original Hubble Space Telescope (HST) Level I Requirements document dated December 23,1983, the amendment dated October 29,1985, and the Level 1 Requirements operational phase augmentation document dated May 17, 1989. Approved waivers and approved Critical Decision Items (CDI's) have been incorporated as required. The requirements herein cover the operational phase of the HST program. The performance requirements provided in this document represents the minimum performance levels to be used in assessing the need for on-orbit servicing or upgrade and for ground system modifications.

The mission of the HST Project is to provide a space observatory for use by the international astronomy community to increase the sensitivity and resolving power and extend the spectral range of astronomical observations decisively beyond those achievable from earth observatories.

The normal operations and condition of the HST will be maintained by NASA, including the command, Control and communications system. Within broad policy generated by NASA, the HST science program will be managed by the Space Telescope Science Institute (STScI) to maximize the scientific usefulness of the observatory and to bring the user community into direct contact with and control of the science that is done.

The European Space Agency (ESA) has provided two sets of solar arrays and one scientific instrument (the Faint Object Camera) for the Hubble Space Telescope and personnel for the STScI. In return, scientists from ESA member nations are guaranteed at least 15 percent of the HST observing time on the average through May 2001. ESA participation is defined in a Memorandum of Understanding.

1.1 Control

This document shall be controlled at Level I by NASA Headquarters, Office of Space Science (OSS), which carries the primary responsibility for fulfillment of these requirements.

2. OVERALL PROGRAM REQUIREMENTS

The goal of the HST program during the operational phase is to maximize the scientific productivity of the Observatory. To meet this goal, NASA shall operate, maintain and enhance the HST spacecraft and supporting ground systems while the Space Telescope Science Institute (STScI), in accordance with NASA policy guidance and oversight, shall conduct the HST science program.

2.1 Operational Life[1]

A high level of scientific productivity, using acquisition methods and strategies in conjunction with instrumentation selected through peer review, shall be maintained to the extent

[1] Per CDI-049.

possible, and/or practical, for 15 years, or longer[2]. The measures to be taken to achieve this will include:

a. operational work-arounds such as procedural and software changes,

b. orbital replacement of malfunctioning spacecraft equipment,

c. orbital replacement of scientific instruments,

d. orbital replacement of limited-life equipments or units, at the appropriate mission life points,

e. development of Space Support Equipment (SSE) to support maintenance missions,

f. maintenance and upgrade of the supporting ground system, and

g. reboost as required to maintain a satisfactory orbital altitude.

2.2 Servicing Mission Authorization

The execution of all servicing missions requires approval by the NASA Administrator.

2.3 Scientific Capabilities

A scientific measurement capability is provided through a complement of up to four axial scientific instruments, one radial scientific instrument, and three Fine Guidance Sensor[3]. This capability shall be maintained and enhanced through the acquisition and on-orbit installation of replacement scientific instruments and Fine Guidance Sensors, and the maintenance and modification of the supporting ground system. The HST shall be able to accommodate a cryogenically-cooled infrared SI, including provision for the removal of evaporated cryogen from the aft shroud.

2.4 Space Transportation

The Space Shuttle shall provide the basic transportation for all phases of the HST program including deployment, on-orbit servicing, and reboost or return to earth.

2.5 Communications

All normal forward and return link data transmission shall be via the NASA Communications Network (NASCOM) and the Space Network (SN). In situations where there is an outage of the normal communication service, the remaining or replacement elements of the Deep Space Network (DSN) 26 meter subnet or the Goddard Space Flight Tracking and Data Network (GSTDN) shall provide tracking, command, and engineering telemetry for health and safety communications support.

2.6 Mission Termination

At the completion of the useful operational life of the HST, as determined by NASA Headquarters, the HST shall be either placed in a long-term stable orbit or safely deorbited.

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[2] Per CDI 054.

[3] GSFC Waiver #11 points out that the first servicing mission installation of the corrective optics package COSTAR left HST one short of the five SI's called for in the original wording. The wording of this sentence has been modified to make it more flexible in terms of instrument complement.

3. OBSERVATORY PERFORMANCE

The purpose of this section is to define the minimum acceptable performance capabilities for the Observatory. These shall serve as criteria for planning and initiating orbital servicing activities. It is expected that some flight subsystems will degrade with time, e.g., the HST exterior thermal coatings, which cannot be refurbished or replaced and whose degradation cannot be circumvented by ground system work-arounds.

3.1 Image Quality

The optical system shall consist of a f /24 Ritchey-Chretien telescope with a 2.4-meter diameter primary mirror and corrective optics. The optical image, including effects of optical-wave front error, pointing stability, and scientific instrument to OTA alignment, should satisfy the following on-axis requirements at 6328 Angstroms and be a design goal at ultraviolet wavelengths: 70%[4] of the total energy of a stellar image must be contained within a radius of 0.10 seconds of arc; the resolution of the image using the Rayleigh criterion for contrast shall be at least 0.10 seconds of arc; and the full-width half-intensity diameter of the image shall be no more than 0.10 seconds of arc. After correction for astigmatism, these specifications shall apply to the image quality over the entire usable HST field.

The HST shall be capable of collecting and imaging radiant energy in a broad spectral band from 1216 Angstroms to 10 micrometers. Specifically, the OTA optical throughput, which includes the combined reflectivity of both the primary and secondary mirrors and the central obscuration effect, shall be no less than 38 percent at 1216 Angstroms and 55 percent at 6328 Angstroms[5].

The overall system must be capable of measuring unresolved objects appreciably fainter than those accessible from the ground; i.e., at least 27 mv with a signal-to-noise ratio of 10 in 4 hours of observing time[6].

The overall system must be capable of measuring extended sources of surface brightness 25 mv per square seconds of arc with a signal-to-noise ratio of 10 in 10 hours, with a resolution of at least 0.25 seconds of arc[7].

3.1.1 Image Stability

The image jitter due to all causes shall be less than 0.012 arcsec R.M.S. over a period of 24 hours. The optical image quality, as defined in 3.1. shall be simultaneously maintained at the

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[4] GSFC Waiver #2 requested the 70% figure to be changed to 60% at 6328A and 35% at 1216 However, the original Level I requirement was met or exceeded following 1993 servicing mission, so the requirement has not been modified.

[5] GSFC Waiver #19 requested waiver based on reduced throughput that would result with incorporation of COSTAR. However, the original Level 1 requirement was met or exceeded following 1993 servicing mission, so the requirement has not been modified.

[6] GSFC Waiver #3 wanted to reduce this requirement. The original Level I requirement was met or exceeded following 1993 servicing mission, so the requirement has not been modified.

[7] GSFC Waiver #4 requested a 10% reduction in the requirement for extended object sensitivity. The original Level I requirement was met or exceeded following 1993 servicing mission, so the requirement has not been modified.

apertures of up to four axial scientific instruments[8], one radial scientific instrument, and three Fine Guidance Sensors for elapsed periods of 24 hours allowing up to 4 hours for thermal stabilization after thermally worst-case slews.

3.1.2 Target Positioning[9]

The HST shall contribute an error no greater than 0.03 arc seconds during the acquisition and positioning of a fixed or moving target within any instrument aperture.

3.1.3 Guide Star Acquisition & Tracking[10]

The HST must be able to acquire and track on guide stars in at least 75% of randomly selected targets located at the galactic poles when using the stellar statistics of "Guide Star Probabilities," NASA Contractor Report 3374, January 1981.

3.1.4 Solar System Object Tracking[11]

Tracking errors for moving targets shall remain less than 0.03 arcsec. r.m.s., for tracking rates less than 0.02 arcsec/sec, and less than 0.04 arcsec, r.m.s., for tracking rates between 0.02 and 0.20arcsec/sec, over 3 arcmin apparent displacement.

3.1.5 Stray Light Performance

The scattered light surface brightness must be less than 23 mv per square seconds of arc except within 50 degrees of arc of the sun or 30 degrees of arc of the moon or 90 degrees of arc of the bright earth limb[12].

3.2 Scientific Observational Capabilities

The scientific productivity of the HST requires that certain core observational capabilities be maintained throughout its operational lifetime. Loss of any of these capabilities shall justify instrument replacement at the earliest planned servicing mission.

3.2.1 Core observational Capabilities

Allocation of time and details of observing programs are based on scientific merit. In the long term, a stable observational capability shall be provided to enable the following:

a. Visible photometric imaging at high spatial resolution for science and target acquisition support.

b. Ultraviolet spectrophotometry at medium to high spectral and spatial resolution.

c. Near infrared spectrophotometry (> 1 micron) and imaging with high resolution. This capability is to be available for at least five years of HST lifetime, and should be instituted as soon as possible after launch[13].

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[8] GSFC Waiver #11 points out that the first servicing mission installation of the corrective optics package COSTAR left HST one short of the five SI's called for in the original wording. The wording of this sentence has been modified to make it more flexible in terms of instrument complement.

[9] Per CDI-057.

[10] Per CDI-058.

[11] CDI-063 waived this requirement for launch, but required implementation by March 1991. In 1993, GSFC requested a further waiver, which was denied.

[12] Revised from 80 degrees to 90 degrees per CDI-055.

[13] Per CDI-066.

High spatial resolution is intended to mean roughly 2 samples per cycle at a 50% value of the Optical Telescope modulation transfer function. Medium and high spectral resolutions are intended to mean 1000 and 30,000, respectively. The minimum fields of view for the UV/visible and IR imaging shall be approximately 90 and 10 arcsec, respectively. Performance degradation below any of the levels stipulated - but not total loss - does not constitute justification for immediate instrument replacement, but shall be a factor in prioritizing replacement in service mission planning. The capability of conducting parallel observations, i.e., concurrent operation of any two science instruments on a noninterference basis, is a general core capability.

3.2.2 Additional Observational Capabilities

In addition to the core capabilities, a versatile observational capability shall be maintained to support, at any time, at least several of the following:

a Wide field of view (approx. 2 arcmin) visible imaging

b. Imaging at UV wavelengths

c. Faint object (approx. mv = 20.5) visible spectroscopy at high spatial resolution

d Faint object UV spectroscopy

e. Very high resolution (approx. 10^5) UV spectroscopy

f. High speed (approx. 20 microsec) photometry.

3.3 Spacecraft Subsystems Performance

In general, unacceptable subsystem performance is that which compromises the observational capabilities specified in Section 3.2 or results in operational impacts which degrade science productivity. Specific requirements, which are particularly relevant to the maintenance of adequate support for science mission operations, follow.

3.3.1 Power[14]

The electrical power system shall provide adequate energy to maintain the scientific operational capabilities stated in paragraphs 3.2 and 3.2.1. In addition, the batteries shall maintain sufficient storage capability to enter safemode or gravity gradient mode (164 amp-hours). A servicing mission will be required prior to the time that the battery storage capability is projected to be less than 164 amp-hours or the solar array capability is projected to be less than that required to maintain scientific operational capabilities in paragraphs 3.2 and 3.2.1.

3.3.2 On-Board Data Storage

The flight system shall provide at least 100 Mbytes of science and engineering data storage.

3.3.3 Data Quality

The system shall provide a bit error rate not worse than 2.5×10^{-5} without Reed - Solomon encoding for all telemetry and 1×10^{-7} for end-to-end data flow for all data processed by the SI C&DH with Reed-Solomon encoding.

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[14] Per CDI-053

3.3.4 Time/Frequency

The system shall provide a clock signal to the science instruments with a 1 microsecond resolution relatable to Universal Time Code (UTC) to within 10 milliseconds. Frequency stability of the on-board frequency signal shall be at least $1X10^{-9}$ over 24 hours.

3.3.5 Data Management

The on-board system shall manage and communicate a long term average of 300 Mbytes of science data per day. It shall be capable of supporting approximately a twofold growth in this average data volume due to advanced instrument requirements.

4. GROUND SYSTEM REQUIREMENTS

The ground system required to support the HST program shall support Observatory and science management, the former performed by the Goddard Space Flight Center (GSFC) and the latter, under contract to GSFC, by the Space Telescope Science Institute (STSCI).

4.1 General Functional Capabilities

The ground system shall provide the following general routine functional capabilities in support of mission operations:

a. Spacecraft and scientific instrument command and control.

b. Performance monitoring and engineering trend analysis.

c. Science and mission planning and scheduling, including parallel science data acquisition and parallel event scheduling.

d. Capture and processing of engineering and science data.

e. Science data analysis and general observer selection and support.

f. Archiving and distribution of science data and archival research support.

g. Support for spacecraft subsystem and science instrument maintenance, replacement and refurbishment.

h. Orbit and attitude data collection and processing.

4.2 Observatory Operations

The ground system shall be capable of supporting HST operations on a continuous basis. Availability for all mission critical facilities shall be at least 99.8% with a mean time to repair of less than 1 hour. The availability for off-line support systems shall be greater than 97.5% with a mean time-to repair of 8 hours. Routine maintenance shall be performed without disruption of flight operations support. The observatory operations project organization shall ensure that sufficient and appropriate hardware equipments and software programmers-developers and key hardware and software maintenance skills are available to support expected life-cycle activities, including the incorporation of efficiency and capabilities enhancements and upgrades and problems resolution.

4.2.1 On Line Operations

The following on-line operational capabilities, normally used to support real time transactions, shall be provided[15]:

a. Generation, uplink, and logging of command loads and real-time commands.

b. Monitoring of all flight systems and science instruments in order to assure their health, safety, and data quality.

c. Generation and uplink of commands to adjust pointing and maintain tracking.

d. Attitude determination and sensor calibration in support of pointing control.

e. Monitoring and recording of the performance, runtime, and any anomalies in the flight and ground systems.

4.2.2 Planning and Scheduling

The ground system shall provide the following capabilities:

a. Planning and scheduling, accounting for all constraints, in order to maximize efficient use of the Observatory. The goal is to achieve an annual average of 35% on-target time (OTT). OTT is defined to be the period which begins with the initiation of the Fine Guidance Sensor (FGS) acquisition process and ends with the release of the telescope pointing control each orbit (e.g., the HST is released to slew to the next target). In achieving this 35% goal, the intent is to minimize the amount of “on target’ time spent for acquisition while maximizing the actual amount of target exposure time. If an observation can be accomplished on gyro control only, then OTT begins with commencement of science data collection or with any instrument-peculiar target acquisition procedures (e.g., shutter open) and ends with release of spacecraft pointing control each orbit.

b. Planning maneuvers and housekeeping activities to maintain the amount of dark time available for scientific observing at or above 20 minutes per orbit averaged over the precession cycle.

c. Timeline re-planning and scheduling for observing targets of opportunity within 24 hours of authorization.

d. Concurrent operation of two scientific instruments (parallel science) plus the use of a Fine Guidance Sensor for astrometry[16].

e. Preparation of schedules and command loads for 24 clock-time hours of HST operation, including scheduling of parallel activities, in less than 12 working hours as a goal, and including the ability to reschedule 5% of these activities in response to mission needs[17].

f. Maintaining reference materials and procedures to enable acquisition, tracking and observation of moving targets as per Section 3.1.4.

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[15] Interactive selection and execution of alternative preplanned mission sequences (referred to as branching) for up to 20% of the total activity” was formally waived via CDI-062 and GSFC Waiver #16.

[16] Per CDI-059, waived for launch but to be implemented by March ’91.

[17] Per CDI-061-Rl.

4.2.3 Servicing Mission Planning

The ground system, to support planning for servicing missions, shall provide reliability forecasting, mission simulations, mission operations and post-mission data processing and analysis.

4.2.4 Simulation and Test

The capability shall be provided to simulate the operation of the HST to support building or modifying hardware and software over the full life cycle of HST, test operational procedures and commands, assist in fault diagnostics, verify compliance of new subsystems against interfaces, and train new operators. The system shall be capable of testing new or revised flight software before installation without undue disturbance of ongoing normal orbital operations.

4.3 Data Acquisition

The ground system shall maintain and upgrade its data capture and processing throughput capability commensurate with advanced science instrument requirements.

4.3.1 Data Rates

The ground system shall be capable of simultaneously receiving data at rates of 1.024 Mbps and 32 or 4 or 0.5 Kbps.

4.3.2 Data Volume

The ground system shall be capable of capturing a peak maximum data volume of 900 Mbytes in a 24 hour period and of processing, on a long term average, 300 Mbytes daily for transmission to the STScI within 24 hours after receipt.

4.3.3 Data Storage

The ground system shall provide a minimum of 30 days of fail-safe storage of captured (unedited) data.

4.3.4 Data Dissemination

After a one year proprietary period, HST data shall be made accessible to the general scientific community. Archived data shall be periodically transferred to the HST European Coordination Facility and other facilities as authorized by the Associate Administrator, Office of Space Science.

4.4 Science Operations

The STScI has been established for the purpose of conducting and managing the science operations of the HST program. Its primary functions include:

a. Establishment of science program guidelines.

b. Selection of HST general observers and archival researchers, providing them technical assistance with their research programs, and managing grants to selected U.S. general observers.

c. Developing operational procedures and science observing schedules, including parallel science and parallel events scheduling.

d. Providing applications utilities and calibration data for analysis of HST data.

e. Processing, archiving and publicizing HST science data and results.

f. Evaluating Observatory and scientific instrument performance.

g. Maintaining the Guide Star Selection System.

4.4.1 Research Management

The ground system shall provide for the management and selection of research proposals, tracking associated resource requirements, and maintaining resulting products of the research throughout the life of the program.

4.4.2 Observing Support[18]

The ground system shall have the capability to support two general observers concurrently in the conduct of their observing programs involving such functional areas as target acquisition, acquisition verification, and quick-look data analysis.

4.4.3 Science Data Processing and Products

Calibrated standard data products shall be available to observers within five days of their acquisition. Uncalibrated data in SOGS format[19] shall be available to observers 24 hours after receipt by the STScI Calibration algorithms, tables, and files shall be made available to authorized observers within thirty days of the request. Transportable versions of the data analysis software shall be maintained for use by observers who have access to compatible computers.

4.4.4 Data Archive

The capability shall be provided to archive, search and retrieve all the edited and calibrated science and related engineering data. The system shall support the access and distribution needs of up to 1000 archival researchers per year. A minimum of 3 years of current data shall be maintained on-line to facilitate automatic real-time interactive access. The remainder shall be permanently archived and retrievable, within a reasonable time, on request ("reasonable" defined as seconds to minutes if requested by an online user, and 1-2 weeks if by mail). The system shall accommodate both local and remote users via electronic access, restrict access to only authorized users, and prevent against inadvertent loss or destruction of data, accidental or malicious.

5. SERVICING SUPPORT REQUIREMENTS

Over the operational lifetime of the HST, a capability must be maintained for on orbit servicing in order to restore, wherever possible, original levels of performance and to enhance the science capability. Assuring this involves the timely development of replacement scientific instruments; Space Shuttle Program support; servicing mission planning; timely availability of Orbital Replaceable Units (ORUs); the development and maintenance of supporting test equipment, ORU delivery systems, spare components, and the Space Support Equipment (SSE); and a ground logistics system. Two classes of missions may be needed: Planned Service Missions (PSM) and Contingency Service Missions (CSM). Although both types require planning, the CSM launch preparation is triggered by a critical event, whereas the PSM occurs

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[18] GSFC Waiver #18 eliminated branching as a requirement.

[19] Per CDI-064.

on a schedule related to forecasted maintenance need. A PSM is used to restore or upgrade the Observatory and scientific instrument performance (cf. Section 3.0). It is also used to reboost the spacecraft. The CSM corrects a failure which leaves a single point failure mode in a mission critical subsystem. A CSM may also be utilized to reboost the Observatory.

The program infrastructure shall maintain the capability to return the HST from orbit. The capability to return the HST from orbit shall not be maintained for every HST servicing mission, but instead will be provided only if so specified in the mission call-up instructions. That is, the hardware, software, procedures, etc., necessary for returning the HST from orbit shall be developed, verified, etc., on a schedule that permits the recovery of the HST by the Space Shuttle from orbit on any mission so desired, provided that recovery capability is specifically ordered up prior to mission initiation. Specific hardware capability does not, however, have to be planned for nor carried on every servicing mission, thus optimizing the use of the Space Shuttle lift capability to better support HST servicing missions where there is no identified imminent need for returning the HST.

5.1 Initiation Criteria

The decision to perform a servicing mission will be made by the Administrator in response to an Office of Space Science request. The request for a CSM will be initiated as soon as a justifying condition or pending condition is established. The need and requirements for a PSM shall be reviewed at least every six months and, under normal circumstances, confirmed at least 18 months prior to the scheduled launch.

A CSM will be requested whenever there is a loss of an ORV(s) which leaves the HST with a potential single point mission failure. A mission failure condition is one in which the Observatory is no longer in communication with the ground or commandable, cannot be safely retrieved for servicing or reboost, is unable to support any science operations, or has lost the scientific payload. Potential failure of any one of the five major subsystems - power, thermal, pointing control, command and data handling, communications - is justification for initiating the CSM process.

The criteria considered in planning and requesting a PSM are the forecast of:

a. Orbital decay to an altitude such that science operations become constrained or mission duration is imperiled.

b. Loss of core observational capability as specified in Section 3.2.1

c. Subsystem performance degradation below levels specified in Section 3.

d. Availability of advanced instruments.

Activities supporting conduct of a CSM ‘will require major mobilization of effort across NASA in order to effect rapid repair of the HST. The basic purpose or such a call-up will of course be to repair the HST before it sustains further failure which could then result in irreversible damage to or loss of the Observatory. For planning purposes, the maximum allowable Space Shuttle response time – that is, time from call-up of the CSM by the Administrator to achieving launch readiness status – is assumed to be no greater than 12 months.

If resources and the situation allow, routine servicing activities and/or replacement of scientific instruments may be accomplished during a CSM.

5.2 Planning Support

The servicing support system shall:

a Maintain a long term schedule of servicing missions including best estimate of launch dates, the most likely complements of subsystems and scientific instruments, and associated procurement schedules and activities.

b. Provide a reliability model of the HST, updated periodically with flight data, for use in decision support and logistics management.

c. Account for all ORUs through a logistics data system covering reliability parameters, inventory status, and EVA timeline activities and tool requirements.

d. Maintain trend analyses on sub-system performance, orbital decay and relevant geophysical models.

5.3 ORU Requirements

An inventory of critical Orbital Replaceable Units (ORUs) shall be provisioned and maintained to ensure support of a CSM call-up at any time. The inventory shall also include those ORUs which need to be replaced on PSMs based on current forecasts of need dates. To the extent the budget permits, an inventory of desirable ORU changeouts, i.e., those which will result in enhancements, shall also be supported.

5.4 Orbital Replacement Instrument Requirements

In order to meet the scientific performance requirements established in Section 3.2 or to upgrade FIST science return, additional scientific instruments will be acquired for installation on PSMs. These Orbital Replacement Instruments (ORIs) shall:

a. Be fully compatible with the flight and ground data management and communication systems, as they currently exist or are expected to be upgraded.

b. Meet operational phase thermal, mechanical and electrical interface specifications.

c. Have as a design goal an operational lifetime of at least 5 years.

d. Use, to the maximum extent practicable, on-orbit replaceable subsystems. Algorithms shall be provided along with the ORIs to permit on- orbit support and instrument-unique ground data processing.

5.5 Space Support Equipment

A baseline set of reconfigurable Space Support Equipment (SSE) shall be maintained to support servicing missions. This baseline includes:

a. The Flight Support System (FSS) to provide the mechanical and electrical interface between HST and the Space Shuttle.

b. Orbital Replacement Unit Carrier(s) to provide mounting, power, environmental protection and load isolation for the ORUs and ORIs.

c. EVA crew aids and tools.

On a single mission, the capability shall exist to carry into orbit a full set of replacement batteries, a set of solar arrays, at least one radial and one axial module, and multiple ORUs as required. The actual servicing mission equipment mix for a given mission will be determined by

Observatory performance and trend analyses, space support equipment considerations, available EVA capability, Space Shuttle performance capabilities, and other considerations determined relevant at the time.

5.6 Technical Information Management

An automated information management system shall be maintained which provides:

a. Management and resource control data.

b. Technical design and test data.

6. SAFETY AND EQUIPMENT RELIABILITY

6.1 Crew Safety

The design of the SSE, ORUs and ORIs shall assure that the Space Shuttle Orbiter or crew safety shall not be compromised at any time under either normal or contingency modes of operation. These modes include all phases of mission activity, i.e., rendezvous, capture, on-orbit maintenance, redeployment, reboost and earth return.

6.2 Equipment Reliability

The HST and SSE shall meet the requirement that no single failure or operator error result in damage to the Space Shuttle. Any deployment or extension which could prevent payload bay door closure must be controlled by independent primary and backup methods, and the combination must be two-failure tolerant. Payload equipment which could interfere with the closing of the payload bay doors shall be jettisonable without EVA.

The HST shall have no single point failure that will jeopardize recovery of the HST or affect Space Shuttle crew safety. Nor shall a single point failure within the HST subsystems cause a permanent loss of command capability, engineering telemetry, or scientific data. HST structures shall be designed with adequate factors of safety to meet these requirements.