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Briefing Report to the Chairman, Subcommittee on Science, Technology, and Space, Committee on Commerce, Science, and Transportation, U.S. Senate

May 1988

SPACE SCIENCE

Status of the Hubble Space Telescope Program

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National Security and
International Affairs Division

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May 2, 1988

The Honorable Donald W. Riegle, Jr.
Chairman, Subcommittee on Science,
Technology, and Space
Committee on Commerce, Science, and
Transportation
United States Senate

Dear Mr. Chairman:

This report responds to your request for information on the current status of the National Aeronautics and Space Administration's (NASA's) Hubble Space Telescope (HST) program. Specifically, you requested that we address the following questions.

-- What is the current status of the program with respect to cost, schedule, and performance?

-- What is the role of the Space Telescope Science Institute?

-- What are NASA's plans for providing on-orbit maintenance to the space telescope?

On February 19, 1988, we briefed your representatives. The results of that briefing are summarized below and described in more detail in the appendixes. Our objectives, scope, and methodology are discussed in appendix I.

Originally set for December 1983, the HST is now scheduled to be launched aboard the shuttle in June 1989. The delay has been caused by a combination of technical and management difficulties and by a temporary suspension of the shuttle program as a result of the *Challenger* accident. These problems have also caused HST development costs to increase from the original fiscal year 1978 estimate of $435 million to the current estimate of over $1.4 billion. When estimated operations and maintenance and refurbishment costs are added, the total program costs are estimated to be approximately $2.8 billion through fiscal year 1993.

The HST program office has conducted extensive testing to verify that the spacecraft and its components will be able to view objects as far away as 14 billion light years and to could be maintained longer than the currently planned circular orbit. Finally, NASA plans to perform regular servicing and reboost missions at the same time whenever feasible.

As requested, we did not obtain agency comments, and, unless you publicly announce its contents earlier, we plan no further distribution of this report until 5 days from its issue date. At that time, we will send copies of this report to the Chairmen, House and Senate Committees on Appropriations and the House Committee on Science, Space, and Technology; the Administrator, National Aeronautics and Space Administration; and other interested parties upon request.

Should you have any additional questions, please contact me at 275-4268.

Sincerely yours,

Harry R. Finley

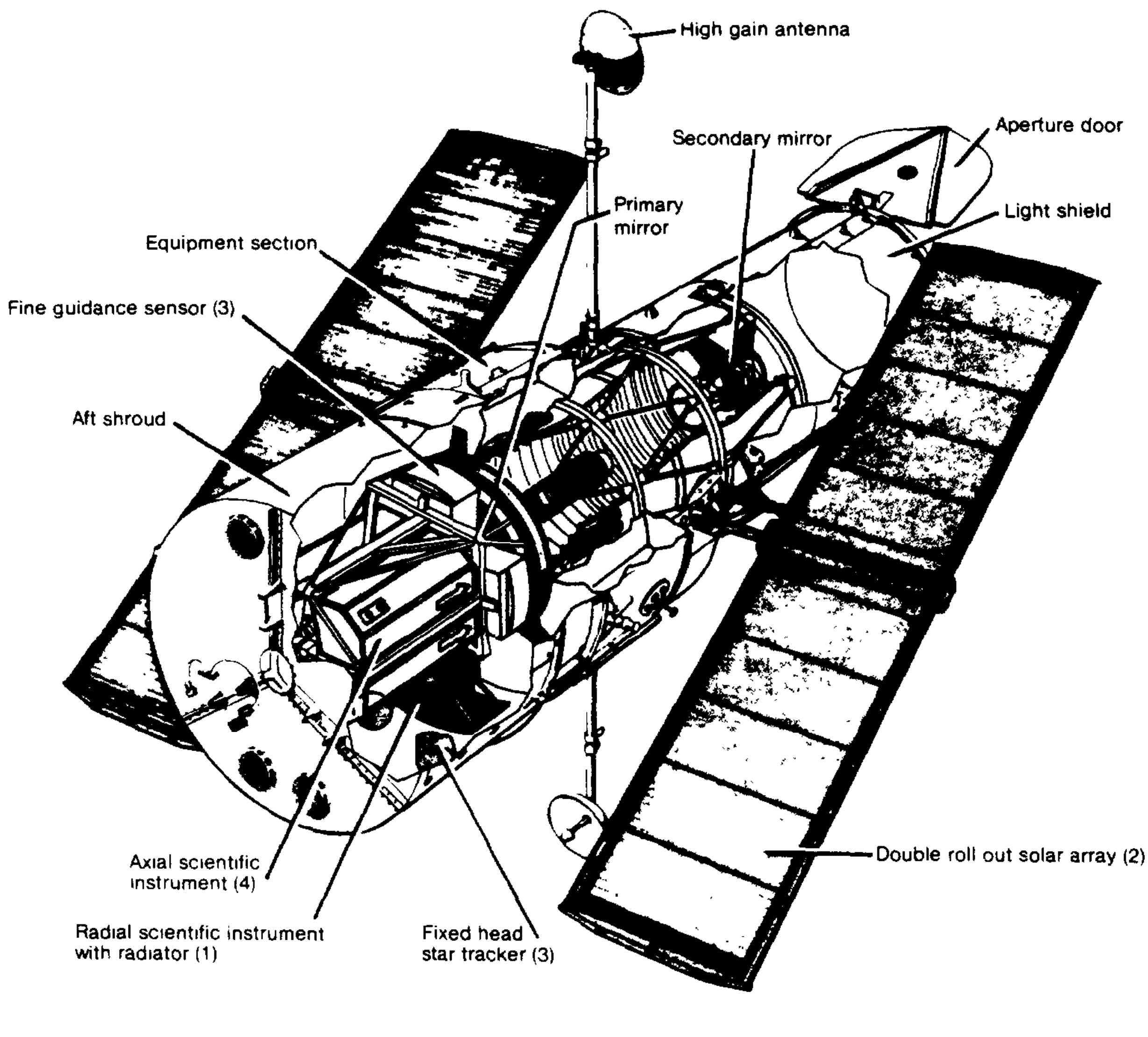
Harry R. Finley
Senior Associate Director

ABBREVIATIONS

ESA	European Space Agency
GSSS	Guide Star Selection System
HST	Hubble Space Telescope
NASA	National Aeronautics and Space Administration
TDRSS	Tracking and Data Relay Satellite System

the pointing and control, and other support functions for the operation of the telescope assembly and the scientific instruments. The five scientific instruments--the wide field/planetary camera, the faint object spectrograph, the high resolution spectrograph, the high speed photometer, and the faint object camera--are located behind the primary mirror at the focal plane. Each of the scientific instruments is a separate module that facilitates on-orbit maintenance, repair, and replacement. The functions of the five scientific instruments are described below.

Figure I.1: Hubble Space Telescope and its Components



The numbers in parentheses refer to the quantity of the item indicated.

Faint object spectrograph

The faint object spectrograph is designed to detect extremely faint astronomical objects in the ultraviolet and visible wavebands. Through examination of the spectrum of light emitted by an object, scientists will gain information concerning the temperature, density, and chemical composition of the object being observed. One of the many uses of the spectrograph will be to obtain information on the physical properties of quasars.

High resolution spectrograph

The high resolution spectrograph is designed to perform much the same way as the faint object spectrograph. However, it will use more light that it will resolve into smaller increments. It is designed to observe only the ultraviolet region of the spectrum and is expected to provide scientists with the most detailed information on the chemical composition of celestial objects ever obtained.

High speed photometer

With no moving parts, the high speed photometer is the simplest of the scientific instruments. It is designed to observe the total light from an object in space and to detect any changes in brightness on a time scale down to microseconds. By measuring the brightness of objects in fine detail, scientists will be able to establish the relation of stars to one another and their distances from earth more precisely than currently possible.

Faint object camera

The European Space Agency (ESA) developed the faint object camera for the HST. This instrument is designed to obtain images of very faint objects in the universe. The camera is expected to be able to detect stars of magnitude 28.[4] The exposure time required to view the faintest objects may be as long as 10 hours. The camera, among other things, will be used to observe supergiant stars outside our galaxy and will examine solar systems with binary or double stars.

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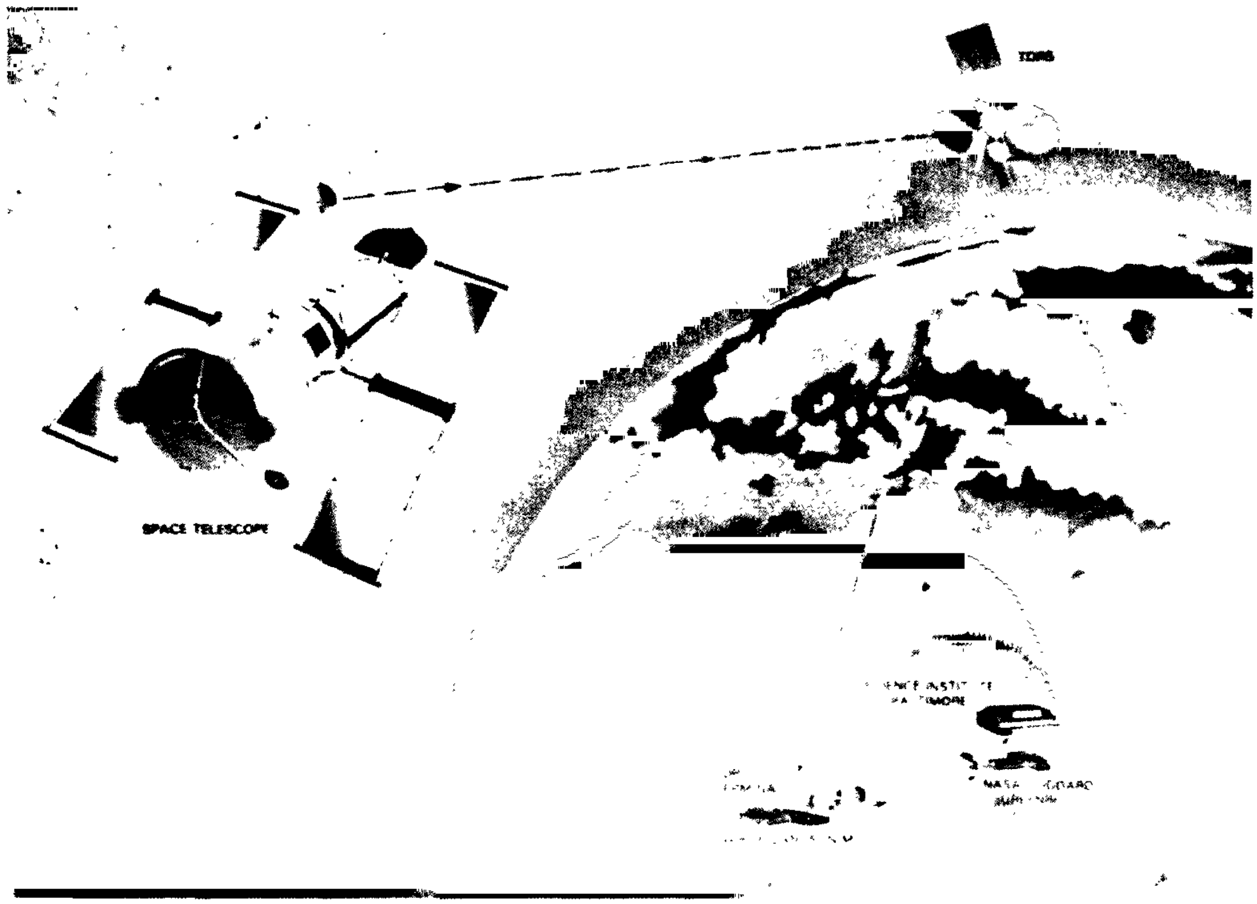
[4]Magnitude is a measure of the brightness of a star, with the brightest stars being magnitude 1. The dimmest stars that ground-based observatories are able to detect are approximately magnitude 24. The HST is expected to detect objects 50 times dimmer than the faintest objects currently detectable.

Figure I.3: Hubble Space Telescope's Use of TDRSS



NASA plans to have three TDRSS satellites in orbit before the HST is operational. The HST will use two of the satellites, with the third satellite serving as a backup. Except for a brief period of time, the two TDRSS satellites will be in continuous communication with the HST, as illustrated in figure I.4. During the short time that the HST is not in direct communication with a TDRSS satellite, it will store its data in an on-board computer for subsequent transmission.

LAUNCH AND DEPLOYMENT

The HST is dependent on the shuttle for launch and deployment. In addition, the shuttle will provide the capability for scheduled on-orbit maintenance and reboost, and, if required, it will retrieve the HST and return it to earth for refurbishment. However, as discussed in appendix IV, NASA currently plans to perform maintenance on-orbit. Figure I.5 illustrates the deployment of the HST from the shuttle.

The 25,200-pound telescope spacecraft will be secured in the cargo bay of the shuttle. Once the shuttle achieves the planned 320-nautical mile circular orbit, NASA plans to verify all major functions of the spacecraft before and immediately after it is deployed. In the first 6 months that the spacecraft is deployed, NASA plans to validate the quality and accuracy of the HST scientific and engineering data.

MANAGEMENT

Overall management of the HST program is directed from NASA Headquarters where the HST program office has oversight responsibility. Even though NASA Headquarters has overall management responsibility for the HST, Marshall and Goddard Space Flight Centers and Johnson and Kennedy Space Centers all share in developing and managing the program. Marshall is responsible for directing the building of the spacecraft and for proper integration of all its components. In addition, Marshall is responsible for planning for on-orbit maintenance of the HST and for such maintenance during the first year of HST operations. After this initial period, maintenance of the spacecraft becomes the responsibility of Goddard.

Marshall monitors and manages the contracts with the two prime contractors: Lockheed Missiles and Space Company and Perkin-Elmer Corporation. Lockheed is responsible for the development of the space telescope systems engineering and integration, support systems module design and development, space telescope assembly and verification, and space telescope launch and orbit verification. Perkin-Elmer is responsible for the optical telescope assembly design and development, the focal plane assembly system engineering, and the development of the fine guidance sensors.

Goddard is responsible for developing the science instruments, except for the fine guidance sensors and the faint object camera. Goddard is also responsible for developing the command and data handling subsystem, managing the space telescope mission control center and science operations, and monitoring the activities of the Space Telescope Science Institute, which was established specifically to manage the HST science program.

Johnson is responsible for training the shuttle crew that will deploy the HST and, when necessary, providing on-orbit maintenance. Kennedy will be responsible for launching the HST and for prelaunch testing.

Four months before launch, the HST will be removed from storage at the contractor facility in California and transported to Kennedy aboard a Military Sealift Command transport ship, the Greenwave. The HST will be 1 month in transit by way of the Panama Canal. Once the spacecraft arrives at Kennedy, it will undergo extensive prelaunch testing, and a flight readiness review will be conducted 1 month before launch. The feasibility of the planned transportation route was confirmed by a simulated test.

Other participants

The Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy, a nonprofit consortium of colleges and universities, under a contract with NASA. The Institute is responsible for operating the observer selection program, assisting and providing technical services to the observers, developing and maintaining an archival system for HST data, and disseminating information gleaned from the science program to the public. The Institute's role in the HST program is described in more detail in appendix III.

ESA also participates in the HST program. ESA developed the solar arrays and the faint object camera and agreed to provide 15 full-time staff--10 scientists and 5 computer specialists--to work at the Institute. Also, ESA has established an archiving facility in Munich, West Germany, which will contain all HST data as it is made available to the public. ESA has agreed to handle all requests for HST data from the European community. In addition, ESA will develop the next-generation solar arrays. For its contributions, ESA will be allocated an average of 15 percent of the HST observation time.

OBJECTIVES, SCOPE, AND METHODOLOGY

The Subcommittee on Science, Technology, and Space, Senate Committee on Commerce, Science, and Transportation, asked us to report

-- the current status of the program with respect to cost, schedule, and performance,

-- the role of the Institute, and

-- NASA's plans for providing on-orbit maintenance to the space telescope.

COST, SCHEDULE, AND PERFORMANCE STATUS

COST AND SCHEDULE

The HST program received initial funding in fiscal year 1978. At that time the space telescope was scheduled to be launched in December 1983. In late 1982 serious technical and managerial problems associated with the program became apparent, including insufficient staffing to monitor the program properly and difficulty in maintaining optical quality because of potential contamination. NASA Headquarters established the Space Telescope Development Division to enable the program director to manage the program better. As the NASA Administrator reported in June 1983 hearings before the Subcommittee on Space, Science, and Application, House Committee on Science Technology, many of the problems and subsequent delays in the development of the HST were due to increases in the cost, the size, and the complexity of the program. For example, at least five new technologies essential to the successful operation of the HST had to be developed. By fiscal year 1982 development cost estimates had increased from $435 million to $720 million.

Because of the problems encountered, NASA rescheduled the launch date to the first half of 1985. However, due to unanticipated technical problems with some of the HST components, the launch date was rescheduled again between early 1985 and October 1986. The loss of the *Challenger* in January 1986 again delayed the launching of the HST, and it is now scheduled to be launched in June 1989. Recent test failures with the solid rocket boosters have delayed the return to flight of the shuttle by approximately 2 months. NASA officials said that efforts are being made to minimize the effects of this delay on subsequent shuttle flights and that this delay should not affect the launch of the HST.

The HST program is funded in three accounts: development, operations, and maintenance and refurbishment. The total cost of this funding is estimated to be approximately $2.8 billion through fiscal year 1993.

Development costs

Total development appropriations by fiscal year are shown in table II.1. The development account was used to fund the design and manufacture of the HST and its components. It was not used to fund costs associated with civil service employees, space centers facilities, and launch. The total estimated development cost of the HST based on the October 1986 launch date was $1.2 billion. However, the *Challenger* accident increased the estimated development costs to $1.5 billion through the current

Table II.2: HST Program Operations and Maintenance and Refurbishment Estimated Costs by Fiscal Year

Account	Cumulative to 1987	1988	1989	1990	Estimated through 1993
	-----	-----	(millions)	-----	-----
Operations	$224.5	$50.8	$59.1	$89.2	$712.0
Maintenance and refurbishment	103.5	40.8	52.2	92.2	606.5

Impact of the Challenger accident

The impact of the Challenger accident on appropriations for fiscal years 1987 and 1988 is displayed in table II.3. As indicated, the original development request for fiscal year 1987 was $27.9 million, and NASA did not expect to request development funds after that time because the HST was due to be launched in October 1986. As a result of the Challenger accident, NASA increased the development request to $101.3 million for fiscal year 1987; however, the Congress appropriated $96 million. In addition, the fiscal year 1988 development request was $98.4 million; the Congress actually provided $93.1 million. The development funding request for fiscal year 1989 is $102.2 million. The additional development funding is to cover the cost of (1) storing and maintaining the HST and its components, (2) performance and reliability testing, (3) reassessing safety considerations, and (4) retaining key personnel for pre- and postlaunch support.

Furthermore, because of the Challenger accident, the operations and maintenance and refurbishment appropriations requests decreased. The decreases were partly due to the fact that the required verification testing was stretched out because of the additional time available. In addition, the development of second- generation science instruments (which are funded through the maintenance and refurbishment account) and the Data Archiving and Distribution System (which is funded through the operations account) was deferred to help offset the increases in the development account.

reverberations from the orbiter engines. The impedance test subjected the spacecraft to a series of shocks or jolts that are normally experienced during launch to verify that the spacecraft would remain secured by the flight support system during launch.

According to HST officials, the environmental tests were successfully completed. However, during the thermal vacuum test some electrical circuitry erosion was identified. The erosion was attributed to the length of time that the spacecraft had been in storage. Marshall officials do not anticipate repeating the thermal vacuum test before the June 1989 launch. However, if the launch is delayed beyond the scheduled date, a decision will be made at that time on whether to repeat the test.

Other problems were also identified during testing. For example, a sag was detected in the insulation of the optical telescope assembly radial bay. In addition, several of the thermostats that control the temperature of the HST were found to contain excessive moisture. According to HST officials, these problems have been corrected. However, a component of the wide field/ planetary camera, which affects its ability to digitize pictures, is currently being repaired at the contractor facility. Officials stated that this problem would have limited the use of this instrument had the HST been launched. In addition, several governmentwide alerts have been issued that have necessitated corrective actions, including retesting and/or replacing any defective items.

Functional tests

Many of the functional tests of the ground support systems have been completed. However, because enhancements to the systems are being developed, additional functional tests will be required to verify that the ground systems and spacecraft meet performance requirements. According to HST officials, an end-to-end test that verified that the existing ground support systems can communicate with and control the spacecraft and scientific instruments under simulated orbit conditions was successfully completed. Additional end-to-end tests are planned as the ground support systems are enhanced and verified. The last of these functional tests is scheduled to be conducted at Kennedy just before launch. This final test is intended to verify communications with TDRSS as well as the flight readiness of the entire system.

Failure modes and effects analysis, critical items list, and hazard analysis

As required by NASA regulations, program officials performed a failure modes and effects analysis to identify hardware items

SPACE TELESCOPE SCIENCE INSTITUTE

The Space Telescope Science Institute, located at Johns Hopkins University, is operated by the Association of Universities for Research in Astronomy, under contract with NASA. Generally, NASA seeks input and guidance from the scientific community in its space programs. However, due to the size and complexity of the HST program, NASA decided that the scientific community should have greater involvement in the HST planning and operation than in past programs. Therefore, when NASA selected the Association in 1981 to operate the space telescope science program, the Institute became the first non-NASA organization with major science operational responsibility for a NASA observatory program. The Institute's total funding through fiscal year 1986 was $58.2 million, and it is estimated to be $189.1 million through fiscal year 1992. The estimated annual operating costs for the Institute after the HST is launched will be approximately $25 million.

Although NASA maintains overall management oversight of the Institute to ensure that the scientific objectives of the program are being achieved, the Director of the Institute reports directly to the Space Telescope Institute Council, a standing committee of the Association's Board of Directors. Goddard monitors the operations of the Institute through informal periodic visits, annual contractor reviews, and reports received from the Institute on observational proposals. In addition, the Institute Visiting Committee, an independent assessment group composed largely of scientists, annually assesses the Institute's operations.

The Institute is responsible for soliciting and selecting observational proposals from astronomers; collecting, reducing, disseminating, and archiving the telescope data; and developing and assisting in the development of various software programs related to HST operations. In addition, the Institute will maintain contact with the worldwide scientific community through a monthly newsletter, seminars, and articles in professional journals.

CALL FOR PROPOSALS

The Institute issues a call for observational proposals on an annual basis to the worldwide scientific community. The Institute operates two programs for observers: the Guaranteed-Time Observer Program and the General Observer Program. The Guaranteed-Time Observer Program awards a portion of observing time during the first 34 months that the HST is in orbit to those scientists who were instrumental in developing the HST,

ARCHIVING AND DISTRIBUTING HST DATA

A prime function of the Institute is to collect and distribute the telescope data. The Institute will provide research facilities and assistance to the observers, who will analyze their own data as they become available. During the first year that the data are available, the principal observer will have proprietary rights to this information. After the first year, all data will be made available to those who are interested.

The Institute will use the Data Archiving Distribution System, which NASA developed, for storing the telescope data at Johns Hopkins University. At the conclusion of the 1-year proprietary period, the data will be available to the worldwide public from the Institute or ESA. Under the terms of the NASA/ESA memorandum of agreement, all HST data will be transmitted to the ESA facility in Munich. NASA is currently negotiating with at least two other countries--Canada and Japan--to establish similar facilities that would minimize the large number of requests for information that the Institute is expecting to receive.

INTERNATIONAL PARTICIPATION

The HST will be available to scientists from every country in the world. NASA expects to receive approximately 2,000 observation proposals in the first year of HST operation; however, only about 300, or 15 percent, can be accommodated. American scientists from academia, government and private industry as well as certain foreign nationals employed by American institutions or companies will be eligible to apply to the Institute for NASA research grants if their proposals are selected by the Institute.

Although most foreign scientists are not eligible for NASA research funds, NASA will provide use of the HST at no cost. NASA's policy of providing research opportunities to foreign and American scientists without charge is consistent with NASA's enacting legislation and conforms with the policy stated in 42 U.S.C. 6601, et. seq. Furthermore, a NASA official stated that to charge a user fee would adversely affect those scientists in countries where there is no government support for space research. According to this NASA official, the advantage of judging all proposals on merit without regard to ability to pay is that it provides greater assurance of receiving quality scientific information.

DESIGN PHILOSOPHY

Because the HST was designed to be maintained on-orbit, consideration was given to reducing the complexity of maintenance tasks. Early in the design phase some of the major components identified as needing the most frequent servicing or replacing were designed as modular orbital replacement units. Most of these units are self-contained boxes that are mounted with fasteners or connectors in the equipment bays that surround the spacecraft. They include the solar arrays, the batteries, the computers, and the five scientific instruments, as well as electronic and mechanical control units, the low-gain antenna, and the reaction wheel assembly. Large equipment bay doors provide easy access for removing and replacing the units by the shuttle crew.

To facilitate on-orbit maintenance further, the exterior of the spacecraft is equipped with handrails, foot restraint sockets, and tether attachments, which provide easy access to the components for on-orbit maintenance. In addition, standardization of many common elements, such as bolts and connectors, reduces the number of required tools for maintenance and simplifies astronaut maintenance training.

The current maintenance plan for the HST does not include use of the planned space station for maintenance or repairs. However, the HST hardware has been designed to be compatible with the space station and the orbital maneuvering vehicle should NASA alter its current plans. This vehicle, sometimes referred to as the space tug, is expected to be available in the 1990s. It will be more maneuverable than the shuttle and will perform a variety of missions for which the shuttle is not well suited, including delivering, retrieving, and reboosting payloads on-orbit.

The orbital replacement units will be transported in the shuttle in specially designed carriers configured to accommodate different combinations of elements for different servicing missions. There are eight different configurations that provide an environment similar to the interior of the HST and are designed to protect the units in transit from shocks and temperature variations. However, only two of these carriers are scheduled to be delivered by the 1989 launch date. The remaining six carriers are in various stages of design and development. Program officials stated that the availability of only two carriers will not adversely affect their maintenance plans, since the remaining six unit carriers will not be needed during the first 2 to 3 years of HST operation.

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TECHNICAL MANAGEMENT INFORMATION SYSTEM

From the inception of the HST program, NASA has archived technical and engineering data in the Technical Management Information System. This system captures and stores data, which can be selectively accessed, on optical laser disks. The data consist of information on hardware maintenance, spacecraft operation, maintenance mission planning, and spacecraft upgrade. This system provides a historical record of HST technical and engineering design to technicians or engineers who will maintain the HST in the future.

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MAINTENANCE AND REFURBISHMENT

The HST was designed to have a minimum operational life of 15 years. NASA originally planned to retrieve the HST and return it to earth every 5 years for major maintenance and refurbishment. However, because of the cost of maintaining a ground-based maintenance facility and the possibility of damaging the sensitive telescope during the return flight, NASA now intends to do all maintenance and refurbishment to the HST on-orbit. In addition, NASA now believes the HST will have a useful life far beyond the 15-year period and plans to leave the HST on-orbit indefinitely.

MAINTENANCE PLANS

NASA plans to conduct maintenance missions for the following purposes.

1. Regular servicing. Once every 3 years the HST will require service to replace batteries, inspect and replace parts, and exchange science instruments.

2. Unscheduled/fast reaction missions. In the event of system failures that jeopardize the continued operations of the HST, a repair mission would be scheduled based on the criticality of the malfunction. For catastrophic malfunctions, missions would be launched as soon as possible. For serious, but not catastrophic, failures, repairs would be scheduled within a 6- to 9-month period. Repairs for all other failures would be scheduled to coincide with regular servicing.

3. Reboost missions. These missions will be required periodically to return the HST to its original orbit. Aerodynamic drag on the HST will cause it to loose altitude over a period of time.

NASA plans to minimize the number of maintenance missions by performing repairs and reboosts concurrently whenever feasible. NASA is also currently studying the feasibility of placing the HST in an elliptical orbit of 320 by 360 nautical miles, which would reduce the frequency of reboost missions. To minimize the number of required maintenance missions further, NASA is planning to replace the HST's nickel cadmium batteries, which are expected to last approximately 3 years, with nickel hydrogen batteries, which are expected to last 2 years longer. According to the Program Scientist for the HST, the nickel hydrogen batteries will be available in time for the 1989 launch.

especially its scientific instruments. The proportion of time guaranteed to these observers declines steadily during the 34-month period.

The General Observer Program is for all other potential observers. To be selected to become an observer in this program, one must submit an observational proposal. The proposals go through a two-tier review process. The primary criteria for selection of the proposals are scientific merit and technical feasibility. Initially, the proposals will be reviewed in detail and ranked by one of approximately six panels, each representing a different subdiscipline in astronomy. Then, the Institute Telescope Allocation Committee will prepare the final recommended observing program from the ranked lists provided by the subdiscipline review panels. If two or more similar proposals are received, the Institute will determine whether the two general observers should collaborate or whether one proposal is superior to the other. If a proposal that is submitted within the General Observer Program duplicates a proposal in the Guaranteed-Time Observer Program, the guaranteed observer's proposal will take precedence.

GUIDE STAR SELECTION SYSTEM

In addition to assisting in the development of several software programs for the science operations ground systems,[8] the Institute has responsibility for developing the Guide Star Selection System (GSSS). The GSSS is vital to HST pointing and control. For the HST to focus on a target, the fine guidance sensors must lock onto at least two stars, called guide stars. Only a limited number of stars meet the criteria for guide stars. The GSSS consists of photographs of the northern and southern skies, which contain most of the guide stars. These stars have been identified, mapped, and stored on optical laser disks. The GSSS was developed at a total cost of $6 million. Although it was designed primarily for use with the HST, it is also of significant value to ground-based observatories. Because of the number of requests already received for use of the GSSS by ground-based observatories, NASA may decide to charge for the information.

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[8]The science operations ground systems is a set of software packages that schedule observational proposals, produce spacecraft command data, and format and calibrate HST science data.

that are critical to the performance and safety of the HST. The analysis also included identifying any potential hardware failures between the HST and the orbiter shuttle that could endanger the mission. This analysis was used to prepare the critical items list of components that, if they failed, could cause the loss of the HST or the orbiter.

A hazard analysis was then performed to determine potential dangers that could develop while operating the system hardware and software. The hazard analysis identified both the hazards and their status of resolution and then categorized the hazards as controlled or as accepted risks. In addition, the hazard analysis identified other potential risks caused by the environment and mission activities, such as space debris[7] or thermal variations.

The failure modes and effects analysis, the critical items list, and the hazard analysis, which began in November 1986, identified and evaluated all but a small number of shuttle-critical items involved in potential failures of the HST. Actions to address the few remaining items were in progress as of Aprilc 1988.

Through governmentwide alerts, HST officials identified several components of the HST that had experienced high failures rates and/or had not met original design specifications. For example, the bolts that hold the optical telescope assembly to the HST housing experienced high failure rates during testing by another government agency. At the time of our audit work, NASA was testing these bolts and other components to determine what actions should be taken.

NASA officials maintained that none of the component failures or the problems that have been identified will cause a delay in the scheduled launch of the HST.

[7]Contamination of the HST from space debris was considered in NASA's hazard analysis; however, officials do not believe that it will pose a threat because of the altitude at which the HST will orbit.

Table II.3: Impact of the Challenger Accident on the HST Appropriations by Fiscal Year

Account	Pre-Challenger 1987	Pre-Challenger 1988	Post-Challenger 1987	Post-Challenger 1988
	(millions)			
Development	$27.9	$ 0	$96	$93.1
Operations	68.5	75.8	47	51.6
Maintenance and refurbishment	69.1	76.1	45	42.1

PERFORMANCE TESTING

HST program officials have conducted extensive testing to verify that the spacecraft and its components will function as designed. During the more than 2-year delay due to the Challenger accident, the HST program office has undertaken several activities aimed at correcting deficiencies identified during required testing of the telescope and its support and ground systems and at modifying systems to enhance performance.

For example, NASA conducted functional and environmental tests that verified the performance of the spacecraft, the science instruments, and the ground support systems under simulated orbit conditions. According to HST officials, the results of these tests indicated that the flight components of the system will meet or exceed the scientific performance objectives. In addition, the ground support systems have been changed to increase HST's on-orbit efficiency. Due to the delay, developing and testing of the ground support system components have been rescheduled over a longer period of time than originally planned so that the new enhancements and how they will interface with the completed system can be validated. Furthermore, in compliance with NASA's Space Transportation System requirements, the HST program participated in a failure modes and effects analysis and the critical items list review.

Environmental tests

The environmental tests conducted on the spacecraft and the scientific instruments included a thermal vacuum test, an acoustics test, and an impedance test. The thermal vacuum test simulated the environment in which the HST will operate to measure the performance of the thermal systems and the electrical circuitry. The acoustics test simulated the conditions of launch to evaluate whether the spacecraft could withstand the launch date of June 1989.[6] According to program officials, the development account will expire 1 month after the HST is launched.

Table II.1: HST Program Development Appropriations by Fiscal Year

Fiscal year	Appropriation	Cumulative appropriation
	(millions)	
1978	$ 36.0	$ 36.0
1979	79.2	115.2
1980	112.7	227.9
1981	119.3	347.2
1982	121.5	468.7
1983	182.5	651.2
1984	195.6	846.8
1985	195.0	1,041.8
1986	125.8	1,167.6
1987	96.0	1,263.6
1988	93.1	1,356.7
1989	102.2[a]	1,458.9

[a]Amount requested.

Operations and maintenance and refurbishment costs

The operations account is being used to fund activities such as missions operations and science program implementation. Initial operations funding began in fiscal year 1981. Operations costs through 1989 will be $334.4 million, with costs through fiscal year 1993 estimated at $712 million. Maintenance and refurbishment costs are $196.5 million through fiscal year 1989 and are estimated to total approximately $606.5 million through fiscal year 1993. The maintenance and refurbishment account is used to fund such items as support service equipment, replacement units, ground maintenance, and storage. Initial funding began in fiscal year 1983. Both of these estimated costs are summarized in table II.2.

[6]HST officials indicated that they currently plan a June 1989 launch, but they have budgeted for an August 1989 launch in the event of a further launch delay.

We developed the information in this report through an examination of technical and budget documents and discussions with NASA officials at NASA Headquarters, Washington, D.C.; Marshall Space Flight Center, Huntsville, Alabama; and Goddard Space Flight Center, Greenbelt, Maryland. In addition, we met with officials of the Space Telescope Science Institute at Johns Hopkins University, Baltimore, Maryland, to discuss the management and operation of the HST science program. We discussed this report with HST program officials and they concurred with the information presented. Technical or editorial comments they had were incorporated into the report as appropriate. We did not obtain formal agency comments.

Our work was performed from August 1987 to February 1988 in accordance with generally accepted government auditing standards.

APPENDIX I

Figure I.5: Hubble Space Telescope Deployment

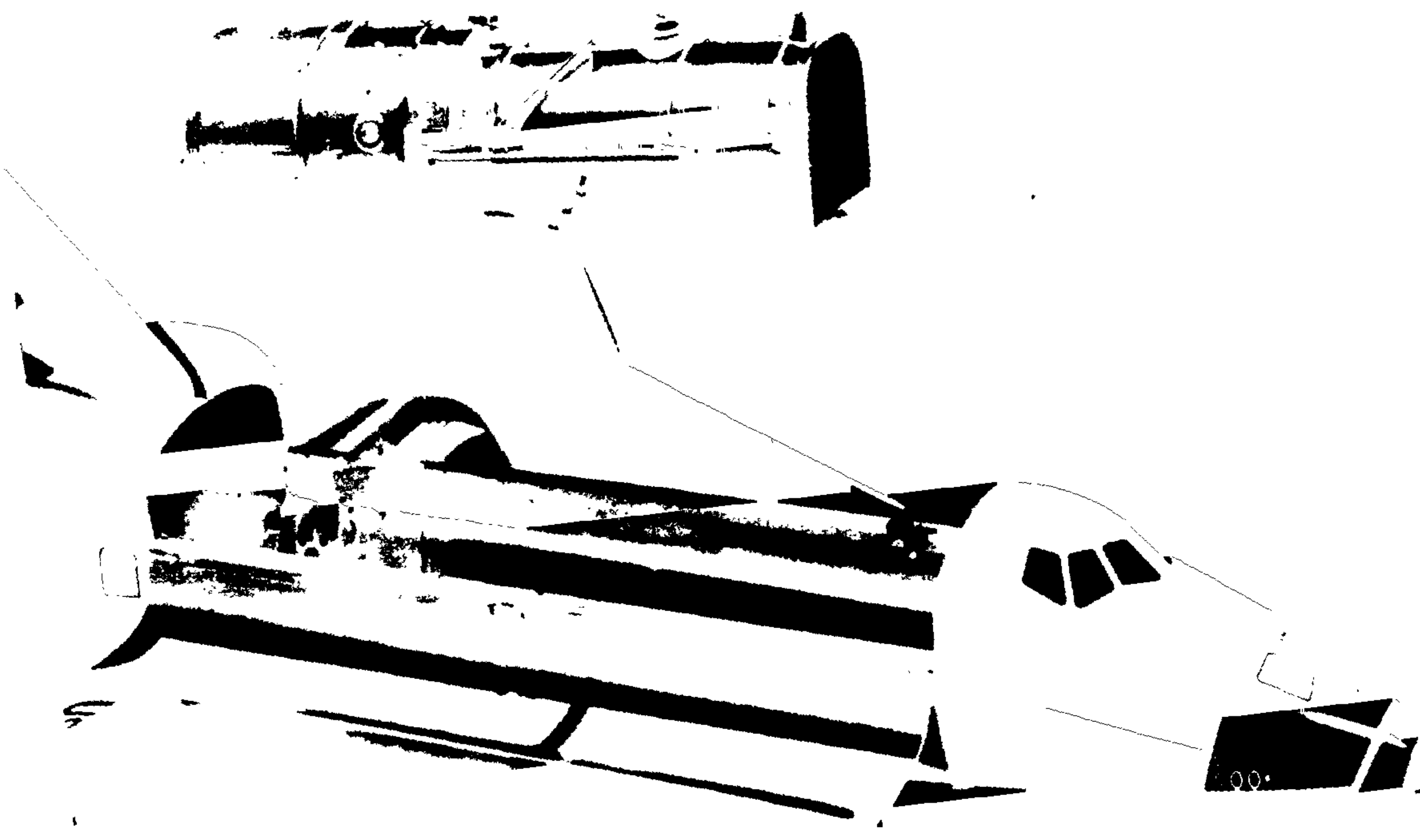
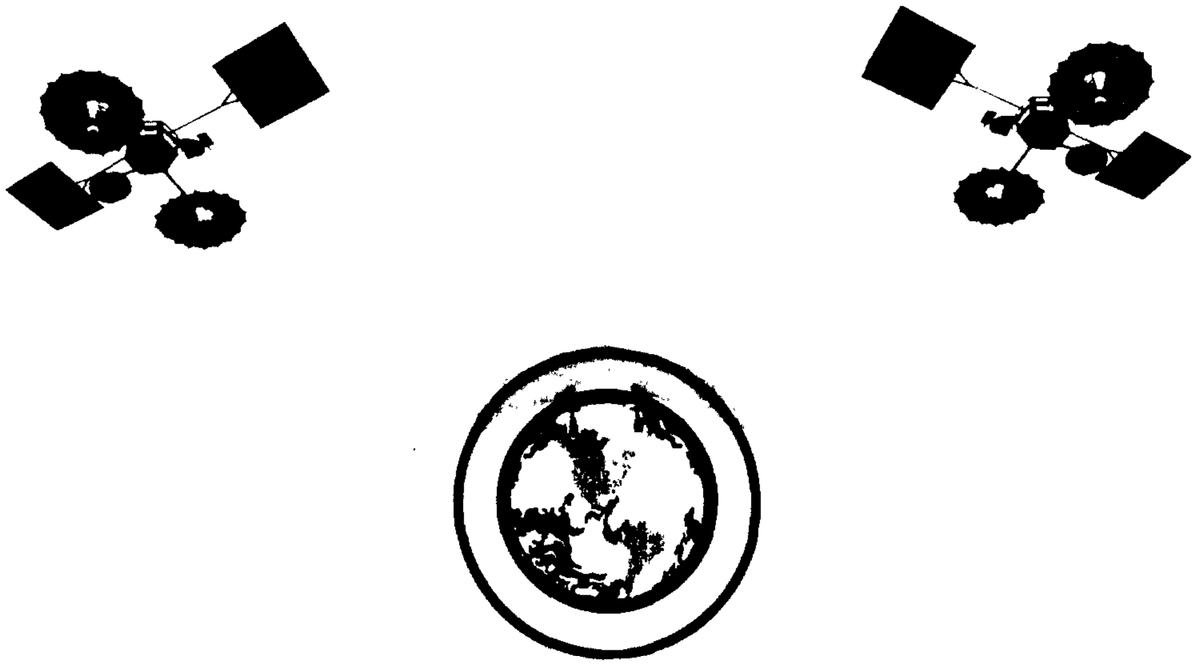


Figure I.4: Planned TDRSS Satellite Communications Coverage of Earth



The "halo" surrounding the earth indicates the altitude at which orbiting satellites are in continuous communication with TDRSS.

Presently, there is one TDRSS satellite in a 22,500-nautical mile geosynchronous orbit above White Sands, New Mexico. NASA officials stated that although they are planning to have three satellites in orbit before June 1989,[5] the HST could operate at almost 100 percent capacity with only one satellite. However, if none of the TDRSS satellites are functional, the HST would not transmit any scientific data. Because the HST can only communicate with ground-based stations for short periods of time during each orbit, only vital engineering data for monitoring the spacecraft would be relayed.

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[5]The second TDRSS is scheduled to be deployed on the first post-Challenger shuttle flight. The third TDRSS is scheduled to be deployed on the third post-Challenger shuttle flight.

Other components

Sometimes referred to as the sixth scientific instrument because of their ability to locate stars accurately, the fine guidance sensors are intended to provide the extremely high pointing stability required because of the very high spatial resolution of the space telescope. Two of the sensors are required to locate and lock onto an object, leaving the third sensor to be used to view and measure the positions of other stars in the vicinity. The fine guidance sensors are expected to produce measurements at least 10 times more accurate than those that can be obtained from ground-based observatories.

The support systems module consists of four main sections: the light shield, the forward shell, the equipment section, and the aft shroud. The light shield protects the scientific instruments from damaging light from the sun, the earth, and the moon. The equipment section contains 10 compartments that house the electronic and control modules, such as the batteries and the gyroscopes. The forward shell and aft shroud protect the telescope and scientific instruments from environmental hazards.

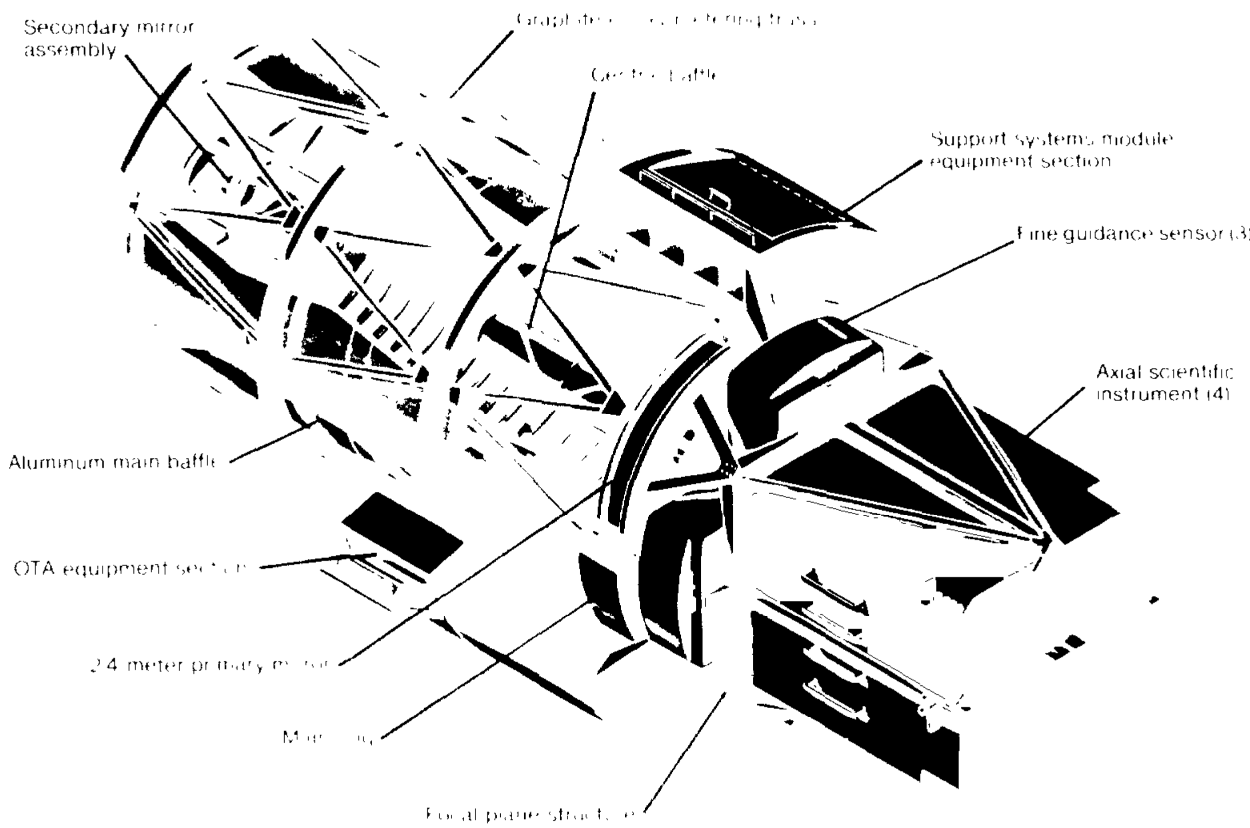
Flight support system

The flight support system consists of equipment that will secure the spacecraft in the shuttle cargo bay. This equipment will also be used for docking with the HST during maintenance and repair missions and for holding the HST during orbit reboost operations.

Tracking and Data Relay Satellite System

The Tracking and Data Relay Satellite System (TDRSS) will be used to transmit HST scientific and engineering data to earth. As figure I.3 illustrates, the HST will transmit data to TDRSS, which, in turn, will relay the data to the White Sands, New Mexico, ground-based station. The data will be transmitted from the White Sands facility to Goddard Space Flight Center in Greenbelt, Maryland, where the scientific data will be checked for errors in transmission and then transmitted to the Space Telescope Science Institute at Johns Hopkins University in Baltimore, Maryland. Goddard will maintain the engineering data and use it to ensure that all HST systems are operating properly.

Figure I.2 Optical Telescope Assembly



The numbers in parentheses refer to the quantity of the item indicated.

Scientific instruments

Wide field/planetary camera

The wide field/planetary camera is designed to examine large areas of space, thus enabling plotting of spatial relationships of distant objects such as galaxies and quasars.[3] The fine resolution of this camera is expected to be better than ground-based observatories by at least a factor of 10.

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[3]Quasars, first discovered in 1963, are celestial bodies from 4 to 10 billion light years distant that are powerful sources of radio energy.

BACKGROUND

For centuries ground-based observatories were the primary source of astronomical information about our galaxy. With the advent of space flight, satellites were used on planetary flyby missions to photograph specific celestial bodies in space. In the early 1960s interest developed in creating an observatory that could be maintained in orbit for an extended period of time. When the National Aeronautics and Space Administration (NASA) was established in 1958, one of its primary objectives was to develop a spaceborne observatory; however, it was not until 1977 that NASA obtained the funding to begin developing a permanent observatory in space.

The Hubble Space Telescope (HST) is one of four[1] planned space observatories that will be placed in low earth orbit by NASA. Because the HST will be operated above the atmospheric veil surrounding the earth, it will make a major contribution to understanding the stars and galaxies, the nature and behavior of the gas and dust between them, and the broad question of the origin and scale of the universe.

STRUCTURE OF HST

The unique value of the HST to the scientific community will be its ability to see farther into the universe than ground-based observatories. The viewing limit of ground-based observatories is approximately 2 billion light years;[2] the human eye can see only about 600,000 light years away. The HST is expected to look at objects 14 billion light years away.

The HST is composed of the optical telescope assembly, the scientific instruments, and the support systems module. The HST is illustrated in figure I.1, and figure I.2 shows its optical telescope assembly, which contains the primary and secondary mirrors, light baffles, and a graphite epoxy support structure. The support systems module provides the power, the communications,

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[1]The other three observatories are the Gamma Ray Observatory, the Advanced X-ray Astrophysics Facility, and the Space Infrared Telescope Facility. These observatories are planned to be deployed in the future.

[2]A light year is the distance traversed by light in one mean solar year--about 5.880 trillion miles--and is used as a unit of measuring stellar distances.

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transmit imagery of unprecedented clarity. NASA is continuing to conduct performance tests of the various components of the HST system. Because the HST is designed to operate outside the earth's atmosphere, some of the tests have been simulations. Other tests have been conducted on the communications and ground systems interface with the HST. Based on the results of all tests conducted so far, program officials believe that the HST can meet its performance requirements. Testing will continue up to and immediately after launch.

The Space Telescope Science Institute is a research institute operated by the Association of Universities for Research in Astronomy, a nonprofit consortium of colleges and universities, under contract with NASA. When NASA contracted with the Association for the operation of the HST science program, the Institute became the first non-NASA organization with major science operational responsibility for a NASA observatory program. The Institute is primarily responsible for soliciting and selecting the observational proposals from astronomers as well as collecting, archiving, and distributing HST data. Under a memorandum of agreement with NASA, the European Space Agency (ESA) has agreed to provide 15 full-time staff to the Institute. In addition, ESA will assist the Institute in handling requests for HST data by disseminating the data to the European community. For its involvement in the program, ESA will receive an average of 15 percent of the HST viewing time.

NASA will provide funds to the Institute for allocation to American scientists and certain foreign nationals employed by American companies and institutions whose observational proposals are accepted and who request financial assistance in conducting their research. Although most foreign scientists will not be eligible to receive NASA research funds, they will be able to use the telescope and Institute facilities at no cost.

The HST was designed to be maintained and refurbished on-orbit. Maintenance missions will provide regular servicing every 3 years, reboost the HST when required, and respond to system failures that jeopardize the continued operations of the HST. NASA is currently studying ways to reduce the number of maintenance missions. For example, it is testing a nickel hydrogen battery that will require less frequent replacement than the current nickel cadmium batteries. In addition, to reduce the number of reboost missions, NASA is considering placing the HST in an elliptical orbit that