Chapter XII

The Hubble Space Telescope

The Hubble Space Telescope was the most costly and challenging science technology project managed by the Marshall Space Flight Center (MSFC). Because of Hubble's $2 billion expense, Marshall became a leading member of a complex coalition that moved Congress to continue support. Because of the project's complexity, Marshall constantly struggled to balance scientific and technical requirements with financial resources. Whenever the project fell out of equilibrium, the Center worked with the coalition to find a new alignment. Like any middle manager, Marshall often got more blame for problems than it got credit for achievements. But the Center's efforts to overcome management and engineering troubles helped ensure that the Space Telescope became a scientific success.

Conception and Coordination

Scientists and space pioneers had long recognized that a telescope in space would escape many conditions distorting observations from the ground. Some of these early conceptions had a Marshall connection. Wernher von Braun, in *Collier's* in 1952, had envisioned space observatories tended by a Space Station. In 1965 and 1967, Marshall had let contracts for studies of Space Telescopes.[1]

Professional astronomers associated with universities and research institutes, however, first lobbied for the Large Space Telescope (LST), which eventually became the Hubble Space Telescope. Most prominent among them was Lyman Spitzer at Princeton. In the late 1960s Spitzer and other astronomers urged NASA Headquarters to support an optical telescope with a three-meter primary mirror. Headquarters responded by sponsoring a scientific and engineering conference for the telescope organized by the Marshall Center in Huntsville in the spring of 1969. Later that year some Headquarters officials in the Office of

Advanced Research and Technology and in the Office of Space Science and Applications (OSSA) began urging von Braun and Marshall to push the project. The most active and determined promoter of this effort was Jesse Mitchell, director of physics and astronomy programs at OSSA.[2]

In an era of budget cuts and personnel reductions, Marshall needed new work. Von Braun told one member of the space telescope coalition, "That's the project I would like to see Marshall do." Ernst Stuhlinger, the Center's leading scientist, noted that the project was gaining support just when the Center was phasing out of the Saturn project, and argued that "We can hardly afford not to consider it as a very promising future MSFC project." He believed that "the LST Project would utilize many of the skills existing at MSFC, including technical, scientific, test, quality assurance, and project management types. It would help us retain and even strengthen our in-house capabilities." While von Braun had not wished to initiate a major new project until the Saturn project ended, his successor as Center Director, Eberhard Rees, decided to submit a formal proposal for a space telescope. Accordingly, late in 1970 when Headquarters approved preliminary management and engineering studies, Marshall established a telescope team within the Program Development Directorate.[3]

The team, with James A. Downey III as manager and with Jean Olivier as chief engineer, followed Program Development's entrepreneurial routines. Downey, who, as a member of the Space Sciences Lab, had also helped bring the High Energy Astronomy Observatories (HEAO) project to Marshall, guided planning studies for the space telescope. Later he recalled that the space telescope team followed formal procedures while HEAO had been "catch-as-catch-can." The telescope team had regular channels for working with Center laboratories and communicating with outside groups. Downey recollected that "within Program Development it was certainly the major scientific activity, far and away the major scientific activity we were studying." Team members drew ideas and information from scientists like Spitzer, Herbert Friedman, Robert O'Dell, and Riccardo Giacconi. Also useful were previous studies by Langley Research Center (LaRC) that suggested including a space telescope in plans for a Space Station. Indeed some of Marshall's early plans for the telescope were similar to the design of the *Skylab*-Apollo Telescope Mount; like *Skylab* the telescope would be joined to a Space Station or a Research and Applications Module (later called Spacelab) and would record data on photographic film that astronauts would regularly change. Costs, and lack of support for a Space Station, quickly drove the team toward an untended satellite concept.[4]

Marshall faced competition from Goddard Space Flight Center (GSFC) for management of the project. A strong rival, Goddard had numerous professional astronomers and superior experience with astronomy satellites. In contrast Marshall had less experience in optics and astronomy, and no astronomers with doctoral degrees. Moreover some officials in the Headquarters Office of Space Science and Applications preferred working with Goddard, a Center they had worked with frequently. This preference showed in November 1970 when OSSA personnel described the assets of both Centers in a management meeting at Headquarters. Some present wondered whether Marshall was up to the task of managing such an ambitious science project. Dale Myers, associate administrator for Manned Space Flight, was blunt, saying that "MSFC could not do the large space telescope program."[5]

Nevertheless Marshall had advantages. Goddard had too many commitments and too few people and so its director did not support the new project. Marshall, in contrast, had too many people and too few commitments; a Center manpower study argued that "MSFC could accept and successfully pursue the lead role assignment for the LST and our assigned Shuttle responsibilities, in addition to continuing with our on-going and other anticipated programs." Moreover, Marshall leadership had become enthusiastic about the Space Telescope. Before one planning conference, Stuhlinger urged Program Development to show Headquarters' officials that Marshall was "willing to put its full strength behind the LST project." Whenever NASA had a telescope meeting in Huntsville, recalled one astronomer, Marshall practically welcomed the visitors with "a brass band and red carpet." Beyond the style, the substance of Marshall's plans was often impressive; in January 1971 Jesse Mitchell, NASA director for physics and astronomy programs, praised the Center's Program Development team for giving an "excellent" presentation.[6]

Behind the scenes, some NASA officials, like Administrator James Fletcher, feared that Marshall's personnel surpluses could lead the Office of Management and Budget to close the Center. Fletcher told his successor that Marshall had to be kept open to preserve its expertise for the Shuttle program. These circumstances led Hubble historian Robert Smith to the charge that "the manpower argument" was "decisive" in determining the assignment of Lead Center and that Marshall became the manager for reasons other than technical competence.[7] This contention seemed doubtful to Downey. Looking back years later, he thought that Headquarters officials had worried more about the success of the large Space Telescope than about the needs of Marshall; "they will go to the Center where they think it [a project] can best be done."[8]

Headquarters recognized Marshall's technical and managerial strengths. The Center had experience with previous scientific satellites and was Lead Center for *Skylab* and its experiments. Marshall's early designs included a pressurized cabin to facilitate repairs in space, and Goddard could not match the proficiency on manned projects that Marshall had accumulated on *Skylab*. Most importantly, Marshall had far more expertise than Goddard did in managing big engineering projects, coordinating numerous organizations, and integrating diverse hardware. William Lucas remembered that "those people [at Headquarters] who saw or grasped the significance of the systems engineering involved saw it as a Marshall program."[9]

Even so, as early as mid-1971 Headquarters proposed a division of labor between Huntsville and Greenbelt. Jesse Mitchell, the key Headquarters official who promoted the telescope, expressed his conviction that Marshall was better prepared to do the project than Goddard, but he insisted that the two Centers cooperate. He said Washington expected Marshall to answer the question, "How can MSFC work with GSFC in a gainful way?" Marshall suggested that Goddard provide scientific specifications for the spacecraft, direct development of the scientific instruments, and manage orbital operations; Marshall could develop the overall spacecraft and the optical apparatus. By early 1972 Marshall's plans called for a large Space Telescope with three hardware modules, with the optical telescope assembly (OTA) and the support systems module (SSM) for itself, and the scientific instrument package (SIP) for Goddard. Under this scheme "the Scientific Instrument Package [would] be 'sub-contracted' to GSFC for development along with the Flight Operations." Under these terms, the Agency made Marshall Lead Center for the LST in April 1972.[10]

Although this plan would use the strengths of both Centers, it left many questions unanswered. Could the Centers work out a clear division of labor on a complex project that lacked clear borders between science, management, and engineering? Would the engineering development Center be able to direct the science and operations Center? Which Center would coordinate communications with the telescope's customers, the astronomers? How would the Agency settle conflicts? NASA would spend years answering these questions.

The Centers began working on solutions and, by late summer 1972, had agreed that Marshall would select the project scientist with Goddard's consent. Marshall did not want a Goddard scientist in the post; James Murphy, MSFC's director of Program Development, feared that GSFC would use their person to "run the LST project." Accordingly the Centers agreed on an outsider, Dr. C. R. "Bob" O'Dell, the former director of the Yerkes Observatory at the University of Chicago. Members of the Marshall Center first believed that Lyman Spitzer should be the project scientist; in fact, Center personnel had read the acronym LST (Large Space Telescope) as Lyman Spitzer Telescope. However, Spitzer suggested O'Dell, who agreed to accept the position. O'Dell recognized the scientific and political prestige of scientists outside NASA, and wanted external astronomers to control the science aspects of the Space Telescope. His ideas coincided with Marshall's traditional use of contractor scientists and with its efforts to avoid Goddard's control. Following O'Dell's advice, Marshall proposed creating an LST science steering group to provide scientific support to the project and to facilitate communications with external astronomers. The Center argued that "NASA does not now have sufficient astronomical expertise to internally provide all necessary scientific judgment." The new advisory group would be composed of the project scientist, science officials from Headquarters, Marshall, Goddard, and eight outside astronomers.[11]

Goddard accepted the advisory group, but the two Centers disagreed about the project's science organization. Goddard and Marshall disputed which Center should manage the contracts for the scientific instruments and communications with the scientists. In November Murphy reported that the Centers were "in a state of serious disagreement" such that Marshall's "ability to effectively interface with GSFC on a daily basis at the working level has been seriously impaired," and his counterpart at Goddard agreed that "our positions on the issues . . . are fairly far apart." Murphy complained that Goddard wanted "to assume practically total science responsibility and authority, including interfacing with the scientific community" and had "prematurely assumed a design configuration and integration philosophy for LST which would maximize their management and integration role in the scientific instrument development without regard for other program considerations." To ensure effective project management, Marshall Director Rees insisted that "the main contact with the scientists had to be through the Project Scientist who is assigned to Marshall."[12]

The Centers tried to resolve their disagreements using a typical NASA matrix. Marshall would provide a contracting officer to monitor the finances of each scientific instrument contract, allowing the Center to penetrate Goddard's activities. The Centers would coordinate technical issues through overlapping science teams. Each scientific instrument would have a team of external specialists who would report to Goddard. Above this would be the LST science steering group composed of the project scientist, the leaders of the instrument teams, and some Goddard experts; this group would report to Marshall. In theory the instrument teams and steering group would assume responsibility for the project rather than for the parochial interests of the Centers.[13]

In practice, however, relations between the Centers remained problematic, and many people associated with the project would blame later problems on the troubled marriage of Marshall and Goddard. Although the Centers struggled to define overlapping responsibilities by dividing technical tasks,[14] their agreements left many problems unresolved. As early as 1976, Goddard's LST manager remarked that the difficult relationship had led to "a tremendous amount of wasted effort and dollars."[15]

Nonetheless by late 1972 Marshall had organized the project and begun preparations for Phase B activities. In December NASA issued a request for proposals inviting astronomers to join the LST teams that would help define the scientific instruments and preliminary designs. To share information about NASA's plans, O'Dell, officials from Program Development, and Goddard experts addressed scientists at Cal Tech, the University of Chicago, and Harvard; Headquarters officials presented the same material at Frascatti, Italy. In addition to their technical purpose, O'Dell said these "dog and pony shows" tended to help in "drumming up business" for the telescope. Marshall Director Rocco Petrone told Headquarters that the scientists' response had been "extremely enthusiastic" and had "justified MSFC's development of this plan and will serve to guarantee future science community support for the LST Observatory Program."[16] Marshall and the rest of the Space Telescope coalition would need this support in the trying days ahead.

Money and Machinery

While NASA worked on management, it also struggled with money. The cost of the Space Telescope would be a constant concern and create a political and technical conundrum. To get congressional support, NASA had to minimize costs; but to keep scientific support, it had to ensure the telescope's performance.[17] As Lead Center, Marshall had to balance conflicting goals and build support for the telescope. In the process the Center functioned as an engineering organization and a behind-the-scenes political machine.

Financial pressure pushed the Center's design activities and often forced it to relinquish conservative engineering principles. The Center's March 1972 project plan called for three telescopes, an engineering model, a "precursor" flight unit, and the final LST. Design and development would cost between $570 and $715 million. Headquarters believed this was too expensive. In a December 1972 meeting, NASA Administrator Fletcher "emphasized that the current NASA fiscal climate was not conducive to initiation of large projects" and suggested $300 million as a cost target.

By April 1973 Marshall had proposed three ways to cut costs. A "protoflight" approach would eliminate the engineering and precursor units; a single spacecraft would serve as test model and flight unit. The protoflight approach had been successfully tried for Department of Defense projects, and the Center expected it to reduce costs—which would please Congress—and speed progress to operations—which would please the astronomers. The telescope maintenance strategy also changed. Rather than designing for extensive repair in orbit inside a pressurized cabin, Marshall suggested a design that would eliminate the cabin and minimize repairs in orbit. The new design assumed the Space Shuttle could return the telescope to Earth for major repairs. These changes simplified the overall LST design and development scheme.

More problematic was a contracting method that used two associate contractors rather than a prime contractor for the support systems module and a subcontractor for the optical telescope assembly. NASA would pair large aerospace contractors working on the SSM with optical companies working on the OTA. Several motives determined NASA's decision. Downey recalled that NASA recognized the complexity of the optical systems and wanted two contractors to proceed with preliminary design. The Agency could then judge proposals for the OTA separate from those for the SSM and match the best contractors. In the development phase, the associate approach would allow the Center to penetrate the OTA contractor directly rather than having to go through an SSM prime contractor. Finally planners expected to save costs by making Marshall, rather than a prime contractor, responsible for systems engineering and integration activities. All these changes lowered the projected cost to between $290 and $345 million.[18]

The associate contractor approach, however, complicated an already complex management structure. In December 1972 a Headquarters report observed that the scheme was "rife with interfaces" because "MSFC itself plays several roles; study manager, project synthesizer, (dual) development contractor, integrator, with GSFC in the wings as instrument developer and ultimate systems operator, all this without mentioning the role of the astronomical profession." The report worried that the resulting management problems would drive up costs.

Looking back years later, Center officials wondered about the associate approach. Downey believed that Headquarters had at first only wanted the associate approach for the design phase; after the Agency had gained confidence in its designs and after the project received approval, they had expected to turn to a prime contractor. But Downey said management turnover at Headquarters led to a loss of memory and to perpetuation of the initial scheme. James Kingsbury, the director of Marshall's science and engineering labs, believed the associate approach was a mistake. "We were not telescope manufacturing people," he said, and since "neither one could tell the other one what to do, and it was exceedingly difficult for somebody like us to be in sufficient position to be sure what the right thing was if the two were at odds. We had to make some decisions that were made with the best knowledge and intelligence that we had and in a few cases months later we had to reverse them because they were wrong."[19]

Throughout the last half of 1973 and the first half of 1974, NASA continued to elaborate the LST design and prepare for Phase B. The telescope astronomer teams met and refined the science requirements. Their advice led to the decision to use new detectors for the telescope. Innovative electronic detectors would replace film cameras, because the astronomers worried that film would reduce data quality and increase risk, especially when astronauts replaced film canisters. Moreover, the scientists, following O'Dell's lead, also simplified the telescope's optical structure. O'Dell defined standard modular science instrument (SI) envelopes, each with identical mechanical and electrical interfaces with the telescope. This standard interface greatly simplified development and made orbital replacement of SI's practical.

Marshall's Information and Electronic Systems Lab and its Systems Dynamics Lab helped contractors with the pointing and control system. Preliminary design studies by the labs and by Martin Marietta investigated whether moving the spacecraft or moving its mirrors best met the pointing requirements. After determining that accurate pointing of the entire spacecraft was possible, they chose reaction wheels over control moment gyros to guide the spacecraft, deciding that reaction wheels were more stable, reliable, and cost effective. Contractors, while preparing proposals for Phase B, also studied how to reduce weight by using new materials and designs for the spacecraft structure. In mid-1973 the Center awarded two identical $800,000 contracts for preliminary design and program definition of the OTA to the Optical Systems Division of the Itek Corporation and the Perkin-Elmer (PE) Corporation.[20]

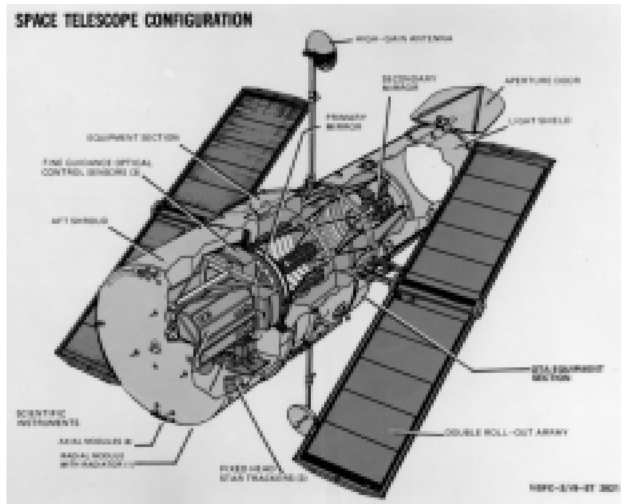
NASA intended to ask Congress for a new start for the telescope in FY 1976, but decided to list the project's Phase B funds as a separate item in the FY 1975 budget request. The strategy intended to alert Congress of the need for future money, but in effect the telescope faced the double jeopardy of two new start decisions. The plan backfired in June 1974 when the House Appropriations Committee reasoned that the LST was too ambitious and lacked support from the National Academy of Sciences. Based on this recommendation, the House deleted the project's $6.2 million from NASA's budget.[21]

The telescope coalition, including space astronomers, aerospace contractors, and optics firms quickly began lobbying to restore the money. Marshall, largely through O'Dell, facilitated the efforts from behind the scenes. From his first days as project scientist, O'Dell had mixed technical and political activity. Deputy Center Director Lucas wrote that O'Dell "is fully aware that the project may not move out as rapidly as we would like, and he considers one of his important responsibilities to be of assistance in selling this project to the scientific community." O'Dell had tried to sell the large Space Telescope through articles in popular science journals like *Sky and Telescope* and in his dog and pony shows at professional meetings. These presentations fell short of formal lobbying but blended promotional appeals in technical information, in much the same way that von Braun had publicized previous plans.[22]

Immediately after the House deleted telescope funding, Headquarters' Offices of Space Science and Legislative Affairs told O'Dell "not to communicate with the scientific community." Marshall managers believed this was a mistake because the project scientist had NASA's closest contacts with astronomers. Evidently Headquarters officials agreed because they soon removed "the gag" from Dr. O'Dell. Although he could not work openly, O'Dell led part of what Space Telescope historian Smith has called the "Princeton-Huntsville axis" that fought to restore funding. O'Dell helped transform the scientists on Marshall's LST teams into lobbyists, and furnished "scientists specific names and addresses of Congressmen and their staff members that the scientists may wish to contact." He also channeled information between Agency groups, contractors, and astronomers. The coalition argued that, contrary to the House interpretation, the National Academy of Science actually supported the Space Telescope. By August, claims like this convinced the Senate and the conference committee to restore funding. After this success, new Marshall Director Lucas congratulated O'Dell for "your very substantial effort and the catalytic effect you had on the others."[23]

The coalition had won the battle, but the struggle transformed the telescope project. While approving funds, Congress cut the budget from $6 million to $2 million, thus forcing NASA to extend Phase B planning and delay the new start. Congress also wanted a less expensive telescope, and in August 1974 directed NASA to scale down the project and to get international help. Headquarters therefore told Marshall to define "a minimum 'LST class' observatory" with a total cost of $300 million and plan for a new start in FY 1977. Once again politics required that Marshall's telescope task team and science groups design to cost.[24]

In the fall, NASA decided to seek European assistance for the project. NASA expected that foreign participation would not only reduce the charges to Congress, but also raise the project's chances in Congress. Marshall's director of Program Development explained that "If we can get the UK. and/or ESRO to support a non-critical part of the LST with dollars then our chances are improved for a final 'go-ahead.'" The Center prepared for the negotiations by looking for hardware modules with clean interfaces that the Europeans could develop. Then Headquarters and Marshall project officials traveled abroad, beginning discussions of European development of various scientific instruments or parts of the spacecraft structure. These negotiations culminated in 1977 in an agreement in which the European Space Agency (or ESA, the successor of ESRO) would develop a faint object camera to observe the ultraviolet, visual, and near-infrared spectrum, build the solar energy arrays for the spacecraft, and support scientific research and orbital operations.[25]



Space Telescope configuration.

By December 1974 the Program Development task team had downsized the telescope. As before the team had to balance cost and performance and devise a design pleasing to Congress and the astronomers. Team leader Downey said the Agency wanted "to procure the lowest cost system that will provide acceptable performance" and would "be willing to trade performance for cost." Working with the LST science groups and contractors, the team reduced the telescope's primary mirror from a 3-meter aperture to 2.4 meters. This major change mainly resulted from new NASA estimates of the Space Shuttle's payload delivery capability; the Shuttle could not lift a 3-meter telescope to the required orbit. In addition, changing to a 2.4-meter mirror would lessen fabrication costs by using manufacturing technologies developed for military spy satellites. The smaller mirror would also abbreviate polishing time from 3.5 years to 2.5 years. The redesign also reduced the mass of the support systems module from 24,000 pounds to 17,000 pounds; the SSM moved from the aft of the spacecraft to one-third of the way forward and became a doughnut around the primary mirror. These changes diminished inertia and facilitated steering of the spacecraft, thus permitting a smaller pointing control system. The astronomers chose to reduce the number of scientific instruments from seven to four. Finally, the Marshall team believed that designing for repair would allow for lower quality standards. Together the changes lowered the telescope's cost to $273 million. Alois W. Schardt, the director of physics and astronomy programs at Headquarters, praised the team for doing "an outstanding job" of planning with "design to cost" criteria.[26]

The following year and a half was very trying for Marshall and the Space Telescope coalition. NASA's top management postponed the request to Congress for a new start from FY 1977 until FY 1978, fearing that more money for the telescope would mean less for the Shuttle.[27] The telescope thus became caught in the Catch-22 of the budget priorities of the Shuttle program: Agency managers justified the Shuttle by its capability to carry scientific payloads like the telescope but also justified sacrifices from science projects by the needs of the Shuttle.

During the waiting period Marshall walked a tightrope, balancing the telescope project's terrible twin needs for money and cost containment. In the fall of 1974 the Center pressed Headquarters to begin the Phase B industry study contracts. Murphy contended that the project needed the studies to learn about costs and technical problems. Moreover, delaying the contracts could disrupt the coalition and force industry to disband its telescope teams and withdraw its political backing. He told Headquarters that "we need strong industrial support at our congressional hearings" and another delay "could greatly impact all supporters of the LST." For these reasons and the need to accomplish a more thorough definition of the complete spacecraft, NASA issued a competitive solicitation to industry. This led in November 1974 to the award of preliminary design and program definition contracts for the SSM to Boeing Aerospace, Lockheed Missiles and Space, and Martin Marietta Corporation. In January 1975 the Agency extended the study contracts of Itek and Perkin-Elmer for the optical telescope assembly.[28]

At the same time the Center was spending money, however, it had to contain costs to please Congress. Balancing realism and salability was especially problematic when telescope officials tried to devise a project budget. They recognized that technical challenges would make the project expensive, especially during a period of high inflation: if they underestimated costs, they would eventually have to beg Congress for more money. On the other hand, too large a contingency would be self-defeating and make the project's budget "too high to be sold" in the first place.[29]

Given that a project without a new start was not a project, Headquarters in mid-1975 emphasized salability and directed Marshall to minimize cost estimates. Noel Hinners, associate administrator for Space Science, informed Center Director Lucas "to continue to explore every avenue towards realistically reducing the LST cost and to actively look at ways to keep early year funding as low as possible" because "our chances of obtaining a . . . new start hinge on this." Deputy Administrator George Low informed the telescope contractors that "the costs now being projected would be impossible to include in any NASA budget in the foreseeable future and the project therefore might well be canceled." He advised them to try cutting costs in half by "relaxing the requirements." Low's efforts to convince Congress that the project had purged extravagance led him to change its name from the Large Space Telescope to the Space Telescope.[30]

Lobbying for the project continued throughout this period. Because the astronomers and contractors had improved their organization since 1974, Marshall participated less. Downey, the task team manager, recalled that the Center "did a lot of kind of wringing of our hands in that period [of lobbying], because we'd done about what we could do." Even so, Project Scientist O'Dell continued to make public presentations and contribute to Headquarters' campaigns. He described the telescope's benefits in nontechnical terms, calling it a time machine that could study the history of distant stars and the origins of the universe. In addition, Marshall officials drafted a letter for North Alabama Democratic Congressmen Ronnie Flippo's signature, trying to get support from the chair of the House Appropriations Committee.[31]

Finally in 1976, Congress approved a new start for the Space Telescope. This approval owed much to Marshall's efforts to define a salable program. The search for support, however, had led to major changes, including reduction in the size and capability of the spacecraft, addition of the European Space Agency, adoption of an associate contractor approach, and, most importantly, degradation of realistic cost projections. According to historian Smith, the "price" of political support was a project that was "both oversold and underfunded," making the telescope "a program trapped by its own history."[32] Eventually the trap would squeeze tightly on Marshall and its contractors.

Design and Delay

In the late 1970s, Marshall clarified the project's organization, selected contractors, and elaborated final designs. Again the Center encountered problems squaring science and engineering, especially when working with Goddard. And even as hardware design and development progressed, the Space Telescope project showed early symptoms of organizational and financial ills.

In this period, the project's greatest controversy was a struggle to control the orbital operations, and ultimately the science, of the Space Telescope. The struggle emerged from differences among astronomers, Goddard, and Marshall. Many astronomers believed NASA should establish an independent institute, much like the institutes for ground telescopes, to manage the Space Telescope's science operations and data dissemination. Since this proposal threatened Goddard's position as NASA's space science Center, Goddard opposed it. When Marshall backed the academic astronomers, Headquarters stepped in to find a solution pleasing to both its scientific customers and its Centers.[33]

Initially Marshall's support for the telescope institute came from O'Dell. As project scientist he served as spokesman for the Science Working Group and as early as 1974 began presenting its wishes to the Agency. In a letter in 1975, O'Dell expressed the group's fears to John Naugle, associate administrator for space science. Goddard's plans for operations, he argued, were based on "Center parochialism" rather than the needs of the scientific community. "GSFC has a large body of resident astronomers, feels it must carve out a meaningful role for these people, and is unwilling to commit substantial resources to LST." Worse yet, Goddard's astronomers lacked the expertise of academic scientists but refused to accept advice. In contrast, "MSFC does not have a large body of resident astronomers, has no reservations to looking outside for guidance, has been substantially reduced in size, is looking for more business, and is willing to commit significant resources to LST." O'Dell got support from other Marshall officials. Stuhlinger, Marshall's associate director for Science, thought the telescope institute could be anywhere, raising Huntsville as a possibility. He also suggested to Headquarters that "Mission Operations should be at the Center where design, development, fabrication, integration, testing, launching, checkout, and initial operation of LST has been managed, i.e., at MSFC."[34]

Marshall's support for an institute for science operations and quest to become Lead Center for spacecraft operations put Goddard on the defensive and worsened the Centers' already troubled relationship. Goddard officials believed that they were the science Center for the telescope, but that Marshall and the academic astronomers wanted to reduce Goddard to the status of a contractor. William Keathley, who became the Marshall telescope task team manager in 1976, described "GSFC's working level attitude" as "distrustful, uncooperative and even hostile at times." By late 1976, the conflict had impaired negotiations on the intercenter agreement for the telescope. From Keathley's perspective, Goddard wanted an "associate role" in project development, and sought responsibility for the science institute, the principal investigators and all operations planning, and equal authority with Marshall for all contractual and engineering matters affecting the scientific instruments and spacecraft control.

Such proposals, Marshall officials believed, would complicate management, and thereby raise costs and reduce quality. Keathley thought that the Goddard plan "limits the authority of the Project Manager and degrades the position of the Project Scientist" and risked "jeopardizing MSFC's ability to fulfill our commitments for overall management of the project."[35] O'Dell agreed, believing that "having all responsibility for operations turned over to GSFC would make the Project Scientist directly responsible to GSFC" and thus "make his role ambiguous." In discussions with Headquarters, Center Director Lucas argued that the Marshall-Goddard relationship for the scientific instruments was no different from the Johnson-Marshall relationship for the Space Shuttle main engines and that success of the project required "Marshall penetration" of Goddard. But rather than accepting subordinate status during development, Lucas believed Goddard wanted its "head of the Mission Operations Office to have veto power over the whole program." After one meeting in which each Center explained its perspective to Headquarters, he wrote that "I can't recall having participated in a meeting dealing with such an unreasonable position." Marshall not only resisted Goddard's co-management, but proposed that NASA remove Goddard from the project and give MSFC complete responsibility.[36]

Finally Headquarters arbitrated the dispute. By December 1976, Headquarters science officials, including Hinners and Warren Keller, who was the defacto program manager, had accepted the idea of an independent science institute and wanted to avoid making project development any more complicated than it already was. They informed Goddard that it had no authority over engineering details and threatened to assign the entire telescope to Marshall if Goddard refused to back down. Consequently Goddard capitulated and Headquarters revised the intercenter management agreement in order to "make it acceptable to all parties."[37] Once the Centers settled on an organization, their relationship improved. Keathley informed Lucas that the arrangement had "worked well" and that Goddard personnel in Huntsville had "established good working relationships in S&E [labs]."[38]

Another two years passed before NASA resolved the orbital operations issue. Goddard sought control of the science institute, and Marshall and the astronomers continued to resist. Lucas recalled having lunch with NASA Administrator Fletcher. Fletcher asked, "Why should this be Marshall's? Goddard is right there in the middle of Johns Hopkins and all the other universities around the Washington area. Who does Marshall have?" Lucas replied, "We have UAH [the University of Alabama in Huntsville]."[39] Fletcher was not impressed, and after he left the Agency in spring 1978, new NASA Administrator Robert Frosch decided that the astronomers would get an independent institute for science, and Goddard would control spacecraft operations and direct the institute contract. To address Marshall's concern about divided authority, Goddard's mission operations manager would co-locate in Greenbelt and Huntsville and work under the Marshall project manager. Following this decision, university consortia competed for the site of the telescope institute, and in January 1981, NASA chose Johns Hopkins University.[40]

If Headquarters resolved the basic conflicts between Marshall and Goddard, their disputes left their mark on the project. Principal investigators complained about working with two Centers, each with a unique culture, management pattern, and testing philosophy, and they believed this created waste. They also thought that rivalry contributed to poor communication between the Centers and that Goddard remained so resentful of Marshall's intrusions that it failed to assign its top talent to the project.[41] Hinners, who had helped initiate the project at Headquarters and then became Goddard director in 1982, agreed that when he took over, GSFC had "an attitude problem." He said that "the Space Telescope team here at Goddard had not really gotten the Center's support" because its leaders decided "we'll do the minimum—screw it."[42] In 1984 Dr. Nancy Roman, the chief astronomer at Headquarters in the early seventies, said that "I think an awful lot of the problems that Space Telescope has had are because of the Marshall-Goddard split."[43]

Marshall officials had similar complaints. Fred Speer, Marshall's telescope project manager from 1979 to 1983, found communications between the Centers difficult. Budget austerity restricted travel, forcing the project to rely on teleconferences, and created competition for resources, leading to "a tendency to shift responsibility to the other side." Speer thought that working with ESA was easier than with Goddard and discovered that "you can't tell another Center what to do. It tells you what it will do." Marshall's Director for Science and

Engineering Kingsbury believed that the friction arose because the Centers' early relationship was one of "competition" and Goddard felt threatened by Marshall's reliance on outsiders for scientific expertise. Lucas thought the project would have been better off if one Center had received complete management of the project. Still Marshall officials thought the relationship with Goddard improved as the project progressed and that whatever problems existed were slight compared to those with the contractors.[44]

Meanwhile Marshall helped form the contract team for the telescope and sought an organization suited to the complexity of the project. In the fall of 1977, NASA chose 18 scientists as principal investigators and members of the science working group who would advise Marshall during the project's C/D phase. They would design the scientific instruments and help NASA with the fine guidance system, optical hardware and instrumentation, and control and data systems for the telescope. In addition, in 1978 the Center established a special project review committee, an advisory panel of scientists and engineers who were not on the project or from Marshall or Goddard.[45]

In January 1977, Marshall and the Agency solicited bids for the associate contracts. In July they chose the aerospace firm Lockheed Missiles and Space for the Support Systems Module and the optics house Perkin-Elmer Corporation for the Optical Telescope Assembly.[46] Although Lockheed had little expertise on astronomy satellites, both firms were very experienced with military satellites and had worked together on the KH–9 reconnaissance satellite.[47]

Years later, because of budget overruns and technical failures, the selection of Perkin-Elmer would become controversial, and in 1977 Marshall personnel also had some reservations about the firm. The Source Evaluation Board said that "our only concern about the Perkin-Elmer approach Centers around their plan to utilize an as yet unverified computer controlled mirror polishing technique." The company compounded risks because it had no plans for an end-to-end ground test for the OTA. In contrast, Eastman Kodak, had planned to use traditional polishing technology and end-to-end tests. On management issues, the Agency also fretted that Perkin-Elmer showed "a lack of understanding of interface configuration, documentation [used in] sustaining engineering and hazard analysis requirements" and had "a performance management system that did not meet the intent of the cost and schedule performance criteria."

Such doubts would prove prescient, but at the time the board thought Perkin-Elmer's bid was superior. The board believed that the "single most significant technical discriminator involved the different approaches to the development of the fine guidance sensor" (FGS) because without an effective sensor, the telescope would be unable to lock on its targets. Based on this criterion, the board decided that the Perkin-Elmer design for the FGS was the most simple, flexible, and inexpensive. Moreover the firm's matrix organization allowed for flexible staffing, and its overall projected costs were lower than those of its competitors.[48]

Unfortunately at the beginning of the telescope's detailed design and development phase, the Marshall Space Flight Center had restrictions on its traditional systems of contractor penetration and automatic responsibility. These limitations, which would soon contribute to problems, originated in a personnel cap imposed by NASA Headquarters. Under the cap, Marshall could only assign 90 employees to the telescope. In part the limitation stemmed from an Agency agreement with the Department of Defense; Lockheed and Perkin-Elmer were working on military contracts and the Pentagon wanted to restrain NASA penetration and reduce risks of exposing secret technology. In addition, Headquarters officials believed that in the past, Marshall had over-penetrated some contractors, leading to excessive demands, gold-plated hardware, and high costs. The personnel cap obliged Marshall to assign small staffs to its project offices in Huntsville and at the contractor plants and to restrict engineering support from its laboratories.[49] In retrospect Lucas recalled that "I never thought that we had enough penetration at Perkin-Elmer" and indeed "we never had enough penetration that we had in most any other project we ever did. We had as much penetration as we were allowed to have given the resources that we could devote to it."[50]

The limitation proved unfortunate, because the Marshall team soon discovered that the design and development of the telescope was more complex and costly than anticipated. The project faced formidable, often unprecedented, technical challenges. Jean Olivier, the Center's chief engineer, recalled at the beginning that people had incorrectly believed that "this is just spitting out something using technology that we already fully understand." Experience proved, he said, that "technologies were much, much more demanding across the board than we ever realized when we got into it. We were naive." At times during the project Olivier wondered if "this whole Hubble Telescope was made out of Unobtainium!"[51]

Probably the greatest challenge was the pointing and control system. The telescope would be the largest astronomical instrument in space; the size of a semitruck, it would measure 43 feet long and 14 feet in diameter, and weigh over 12 tons. Yet this huge spacecraft would have pointing requirements more stringent than any previous satellite. To make images from faint objects, the scientific instruments needed long exposures, demanding a pointing accuracy of 0.01 arc second and holding onto a target within accuracy of 0.007 arc second. In other words if the telescope were in Washington, DC, it could focus on a dime in Boston and not stray from the width of the coin.

Early in the project, engineers had chosen reaction wheels to move the spacecraft, but had to resolve the mechanical, dynamic, and structural problems of pointing control. The Center's labs helped Perkin-Elmer with the fine guidance system, working on sensors, actuators, and control systems that would find and lock on guide stars. Lab engineers, working with Lockheed, devised requirements to prevent the communications antennas and the solar arrays from moving in ways that affected the image stability. Lockheed and the labs became concerned that the spinning of the reaction wheels could produce enough vibrations to jiggle the spacecraft off target or blur the images. Working with Sperry, the contractor for the reaction wheels, they improved the bearings and balance.[52]

The complexity of telescope development showed when Marshall's team began designing for orbital repair and replacement. The telescope was the first scientific satellite designed for maintenance in orbit and for an operational life of 15 years, a very long time for space technology. NASA had justified a repairable design as means of using the Shuttle to solve potentially calamitous problems and of containing development costs. Beginning in 1979 Marshall contributed extensively to these efforts, drawing lessons from how *Skylab* ground crews and astronauts had improvised repairs of the jammed solar array and failing gyroscopes. For the telescope the Center's labs studied reliability data from components and subsystems and identified which were most likely to fail. They designed these items, mainly the scientific instruments and communications and control systems, as replaceable modular technology with standard connectors and bolts and with latches which doubled as thermal controls and hardware mounts. Working with astronauts from the Johnson Space Center (JSC), they helped design special tools and support equipment to accommodate the limitations of astronauts. The design included 31 foot restraints for freeing the astronauts' hands, and 225 feet of handrails for crawling around the telescope without damaging it. The Marshall team confirmed their ideas using models and trial runs both in the laboratories and in the Center's Neutral Buoyancy Simulator. In the simulator's huge tank, engineers and astronauts used full-size mockups to test equipment and procedures. Finally the repair and refurbishment team planned how to store replacement units on the ground and retrieve technical information for future use.[53] Although justified at the time as a means to save development dollars by reducing hardware tests, participants in the program later argued that design-for-repair drove up costs while reducing operational risks.[54]

The incompatibility of solving complex problems and staying within cost and schedule projections showed first in work on the optical telescope assembly. This hardware had to be completed first because it would be transported from the Perkin-Elmer plant in Danbury, Connecticut, to the Lockheed facility in California to be joined to the support systems module.

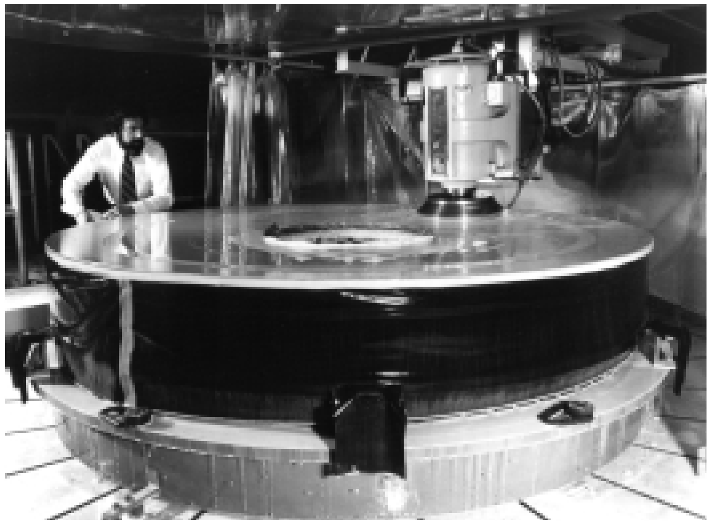
One of the first challenges was thermal control and material structure. Expansion and contraction caused by passage from direct sun to complete shade could warp the OTA and distort optical images. Part of the solution came from minimizing hardware linkages and using "kinematic joints" that isolated parts from one another and allowed independent movement.

After studying several materials, Marshall's Structures and Propulsion Lab recommended graphite epoxy for the OTA metering truss and focal-plane structures. These systems precisely aligned the mirrors, scientific instruments, and fine guidance system. Graphite epoxy was a new composite that was lightweight, low in thermal expansion characteristics, and nonmagnetic. The material was relatively untried for space hardware, and Marshall and Boeing, Perkin-Elmer's subcontractor for the metering truss, conducted more tests than originally planned to prove its proficiency.[55]

Marshall's Materials and Processes Lab worked on other materials problems. The designers became concerned that particulate contamination from dust and lubricants and molecular emissions from nonmetallic materials could foul the optical systems. Contamination of the primary mirror could scatter ultraviolet light and reduce the telescope's capability to see faint objects. Consequently the lab tested and qualified for flight all nonmetallic materials on the spacecraft. Later, engineers on the project learned how atomic oxygen in Earth orbit caused many materials to decompose. The lab retested materials for the impact of atomic oxygen and selected a clear polymer as a protective coating for exposed surfaces. Protecting the telescope from contamination became a major cost, requiring not only careful selection of materials, but also sophisticated cleanrooms and transportation systems.[56]

Another major challenge for Perkin-Elmer was the primary mirror. The 2.4-meter primary mirror would be the largest in space, yet it had to be lightweight and provide a precise reflecting surface. The company's subcontractor, Corning Glass, made the mirror blank from ultra-low expansion glass. The mirror would have a 94-inch (2.4-meter) aperture and would be a foot thick with a Center hole two feet in diameter. To save weight, the mirror's solid, one-inch-thick top and bottom plates would sandwich a lattice with open cells much like a honeycomb. From the beginning Marshall officials recognized that "the telescope will never be better than its mirrors" and that "telescope image quality begins with the mirror figures [curvature]." A Center report noted that a flaw in the mirror figure could result from "manufacturing error due to polishing limitations" or "measuring limitations."[57] To protect the program schedule in case Perkin-Elmer ran into problems polishing the primary mirror, Marshall had Eastman-Kodak develop a back-up mirror using conventional grinding technology and required that Perkin-Elmer try its new computer controlled polishing technique on a smaller 1.5-meter mirror.[58]

Troubles plagued the polishing of the 1.5-meter mirror in 1978 and 1979. Perkin-Elmer initially had difficulties calibrating an interferometer, which checked the mirror's figure, and later had problems with the polisher, which damaged the mirror. Following the polishing incident, a center engineer reported in the Weekly Notes that "the history of problems with computer controlled polishing coupled with the criticality of this process call for unusual penetration by NASA to ensure that safeguards are adequate." He observed that Perkin-Elmer's quality inspectors were dependent on the firm's OTA manager and so recommended that Marshall undertake "substantial participation" in all technical reviews. The company eventually completed the 1.5-meter mirror, and this success made project officials confident about the subsequent polishing of the larger flight model.[59]



Initial polishing of space telescope primary mirror blank at Perkin-Elmer, Danbury, Connecticut, May 1979.

Not withstanding Perkin-Elmer's technical progress, by spring 1979 Marshall officials began worrying that the firm lacked the management systems necessary for a project as complex as the telescope. One Center manager noted the "continued concern on Perkin-Elmer planning" and worried that the company's delays were generating "so much bad news." But Marshall believed that its pressure was making the firm become more systematic. By summer the official argued that Perkin-Elmer "was making considerable progress in improving their schedule control" although it was over budget.[60]

Unfortunately by fall 1979, adjustments to unforeseen problems had subverted the project plan and the Center could no longer meet milestones with fixed resources. In October 1979 NASA Headquarters led a cost review and participants discussed the merit of either adding money to maintain the schedule and performance or debasing performance to maintain the schedule and budget. Marshall helped convince the Agency to draw on the project's reserve to stay on schedule for a December 1983 launch, perhaps fearing that a delay would encourage contractor laxity. This proved only a stopgap measure, however, because the Center ran out of reserve money by spring 1980. When Lucas informed Headquarters that the reserve "will not be adequate," Thomas Mutch, the associate administrator for Space Science, expressed reluctance to provide more money and warned that "specific actions must be taken to control the rate of reserve usage that had been experienced to date." Marshall reassured Headquarters that "we will continue a very tight budget policy in all project elements."[61]

Even so by summer 1980, Marshall realized that NASA had underestimated the cost of meeting the telescope's technical requirements. Perkin-Elmer needed more personnel; its mirror polishing was behind schedule. Lockheed was over budget. Some of the scientific instruments were overweight, and the project had added several costly orbital replacement units. In July, Marshall established an assessment team and its report was bleak. The "engineering budget for total program [was] approximately 2/3 spent, approximately 1/3 work accomplished" and the "manufacturing budget [was] approximately 1/2 spent, approximately 1/4 work accomplished." The project was 4 to 6 months behind schedule. The team attributed the problems to "unrecognized hardware and management interface complexity" and "unrecognized tasks recently discovered." Lucas, in a handwritten notation on the report, believed that Perkin-Elmer had a "good tech[nical] understanding of job—not a good understanding of cost." Lockheed had similar problems and could not plan properly because Goddard and Perkin-Elmer communicated changing requirements ineffectively. The assessment team recommended improvements in systems engineering and planning, elimination of unnecessary tests, transfer of tests from contractors to Marshall, elimination of some back-up systems and orbital replacement units, and reduction of technical requirements.[62]

The Center's proposal to reduce technical requirements, or in the parlance of space engineers, "descope," revealed how it was walking a tightrope. Marshall needed to contain costs because continued overruns could lead to cancellation of the telescope and threaten the Center's reputation. Moreover Headquarters instructed the Center to stay within budget because deficits would hamper the Agency's ability to get future funding. Simultaneously, however, Marshall had to preserve scientific performance, because scientists would reject a gutted instrument. Speer, who left Marshall's HEAO project to become telescope manager in February 1979, had saved HEAO by descoping. He proposed to do the same for the telescope and suggested elimination of two scientific instruments. In project meetings in late July, Headquarters, Goddard, and the science working group opposed the plan, but Speer forced Headquarters to acknowledge that the program lacked resources. Accordingly Marshall received permission to exceed the personnel cap and plan a later launch.[63]

By the end of 1980, the Agency had restructured the telescope program without removing any scientific instruments. The new plan would free money for present problems by delaying work and pushing higher costs into later fiscal years.

Marshall would implement most of the assessment team's recommendations, which included using contract incentives to curb cost growth, assigning 40 more people to the project, limiting technical changes, reducing the orbital replacement units from 124 to less than 20, and stopping work on the Kodak back-up mirror. The new plan pushed back the launch date 10 months to October 1984 and would raise the overall cost from $575 million to $645 million. In December the science working group congratulated Speer for his ability to "balance the conflicting needs of the Project to produce a viable plan which we can all enthusiastically support."[64]

The studies by Headquarters and Marshall showed that systems engineering remained uncertain. Marshall attributed the problem to Lockheed's having "a 'prime's' responsibility with associate contractor's authority and accountability." The Center's solutions included appointing a NASA co-chair for all technical teams, setting up more teams, requiring that Lockheed assign a chief systems engineer to the project, and establishing a Space Telescope Systems Engineering Branch within Marshall's Science and Engineering labs.[65]

Despite the changes, the reforms had not addressed some problems that had been raised during the reassessment. A Goddard report lamented that the program had "almost no spare hardware and was already down to an absolute minimum level of testing" and that "there is no provision for new unanticipated problems." William Lilly, NASA's associate administrator and comptroller, also worried that the project still had a "success oriented" schedule and questioned the Marshall review process since "the team did not see indices of the problems that occurred this year."[66]

Toil and Trouble

In the next two years Marshall oversaw progress in several technical areas. By late 1982, however, a crisis developed within the telescope project, mainly as a result of politically expedient decisions made during program design. Congress and NASA Headquarters conducted thorough investigations but sometimes unfairly blamed the problems on Marshall.

Marshall helped the project pass several milestones in 1981 and 1982. In May 1981 Perkin-Elmer completed the shaping of the primary mirror. The company proclaimed that the mirror was "within microinches of perfection" and NASA bragged about "the finest mirror of its size anywhere in the world." By year's end, the firm had applied a reflective coating of aluminum three millionths of an inch thick and a protective coating of one millionth of an inch. In mid-1981 ESA's contractor for the solar wings began deployment tests, and in early 1982 Marshall tested the solar power cells and began work to improve their interconnects. By the end of 1982 fabrication of the scientific instruments neared completion, Perkin-Elmer had begun final construction of the OTA, and Lockheed had held major design reviews and started fabrication of all major parts of the support systems module.[67]

Again, however, progress came at a slower pace and a higher cost than NASA had predicted, and again Marshall attributed most of the problems to management failings at Perkin-Elmer. Indeed the Center experienced constant frustration with the contractor. Kingsbury, director of MSFC's Science and Engineering labs, remembered getting a phone call from a distraught Center engineer in Danbury who reported that Perkin-Elmer intended to support the primary mirror with two cloth straps and move it with a ceiling crane, thereby risking months of polishing.[68] In October 1981 Marshall Director Lucas told the firm that it had put the telescope in "serious jeopardy" because of "lack of sound planning, insufficient schedule discipline, many instances of engineering deficiencies, and inadequate subcontractor support." Consequently in one quarter of FY 1982 the firm's cost projections had increased 35 percent over its recently rebaselined budget. In reply the vice president in charge of the corporation's optical division admitted that "a viable plan for implementing the OTA Program for Space Telescope does not exist." After one meeting between Perkin-Elmer and Marshall, a software consultant from JSC recorded amazement that the firm admitted they had left a "problem open after 1 1/2 years of work!" and that corporate officials gave "a very unsatisfactory response to Dr. Lucas' question 'How can this be'?" A Marshall report on the company in February 1982 summarized the problems: "schedules always too optimistic, funding and manpower estimates always too low, analyses frequently lag design and fabrication, hardware rework extensive."[69]

Marshall tried numerous methods to control Perkin-Elmer. The Center increased the number of personnel devoted to the project from 150 to more than 200 and expanded the resident office staff. But attempts at deeper penetration did not lead to significant improvement. After Perkin-Elmer used improper test procedures and damaged orbital replacement latches, Lucas asked, "Do we need more QC [Quality Control] penetration? We must get this situation under control." Kingsbury replied that "we have provided more support than one usually expects for a problem such as this one; however, as you note, we haven't found the formula for success." Perkin-Elmer responded that the shortage of funds would necessitate personnel layoffs and cause more delays. Marshall pressured the firm to implement scheduling systems, which it did in April 1981, and change project managers, which it did in October 1981, but problems only worsened.[70]

The Center also tried strong-arm tactics, insisting that the firm stay on schedule and within budget and applied the financial clauses in Perkin-Elmer's contract. But this was also ineffective because penalties for cost overruns and schedule slips were less than awards for technical excellence, and so the firm lacked incentive to assign its best people and overhaul project organization.[71] Lucas believed that Perkin-Elmer was "probably, from the corporate level, the least responsive contractor we've ever dealt with. Their top management really didn't give a lot of attention, it appeared to us, to this program." He attributed their lack of responsiveness to the fact that the OTA "didn't constitute a sufficiently significant part of their total business base" and they were not worried about NASA moving the project, because the Agency had nowhere else to take it. Kingsbury agreed and considered the telescope as "absolutely the most frustrating program I've ever worked in." He remembered that Marshall's people in Danbury "were almost out of their minds" trying to get action.[72]

In August 1981, NASA Administrator James Beggs requested a special briefing on the telescope, and Marshall began special investigations of Perkin-Elmer. The next month four lab directors and the assistant Center Director for policy and review studied the firm's management. The Marshall Program Assessment team found "Perkin-Elmer seems very proficient on optical testing" but had skills in nothing else. Perkin-Elmer's managers thought their problems stemmed from lack of money and manpower. The Marshall team believed, however, that "past schedule performance, current hardware status, and planning do not support PE's position." Perkin-Elmer's project organization suffered from "lack of management discipline across the board" with "schedules not in place, ability to meet schedules highly uncertain, manpower and budget requirements unknown." The "schedule is very unsettled and changing daily." Consequently "PE will likely need both additional dollars and time" with perhaps a 6-month launch delay. In addition, the team believed, Marshall would have to "increase surveillance and control" and "day-to-day interaction between MSFC and PE responsible engineers." Most importantly, the Center would have to teach Perkin-Elmer how to plan. Lucas's notes described the situation at the contractor as "disorganized, no discipline, sloppy habits, attitude problem, no systems, lack of exp[erience] on big systems job;" the firm's plans had "no credibility" because there was "nobody steering ship."[73]

Unfortunately the Marshall briefing to Beggs on 3 November 1982 did not include this account of Perkin-Elmer's organizational failings. The briefing, presented by Marshall's telescope project office, acknowledged the firm's hardware development problems, especially with orbital replacement latches, but assumed that the existing organization could solve these problems with modest amounts of extra time and money. Lockheed's problems also resulted from a shortage of $11.2 million. The remainder of the briefing was upbeat, emphasizing progress on the solar arrays and scientific instruments. With infusions of cash and a launch delay to April 1985, the office said, the telescope would soon be on target.[74]

Meanwhile Marshall had sent the deputy project manager and a team of planning experts to the contractor plant. Their goal, according to Lucas, was to "enforce schedule discipline at PE." Lucas himself took a special trip to Danbury. His preparatory notes for discussions with the contractor reveal his consternation. Despite "at least 2 major rebaselinings," he wrote, "OTA project has never been comfortably under control." The "schedule had been slipping about 1 wk/mo up to rebaselining on Jan. 1, 1982," but afterwards "slip continued at approximately mo quarterly" and "now we seem to have gone critical—current rate of slip greatest of any time in the program." The Center Director believed that the company had an "attitude problem" and its pride in its technical excellence contributed to managerial complacency. All in all there was "very little progress evident in overcoming a lack of experience on big systems." After the trip Lucas demanded that the project office penetrate the contractor more; "it is time to get some of our experts deeply involved."[75]

Only in late December 1982 could Marshall appreciate the scope of the crisis. Former Goddard Manager Dr. Donald Fordyce, now the new Perkin-Elmer telescope manager, opened the company to Marshall for perhaps the first time. The Center's team helped the contractor install a scheduling system and for "the first time" tried "to assure that all jobs are identified and accounted for." During the Christmas holidays, they discovered, in Fordyce's words, "we didn't have a program."[76]

On 14 January 1983 Marshall broke the bad news to NASA Administrator Beggs. Describing the firm's technical problems, the Center said that the orbital replacement latches could not align the instruments precisely, the fine guidance system could not meet pointing requirements, and the primary mirror had a layer of dust. Perkin-Elmer's poor scheduling and planning systems and poor communications between engineering and manufacturing groups had stymied progress. The firm needed additional test equipment, manpower, and engineering analyses, but had not planned for them. Technical teams had learned by costly experience that the protoflight concept required step-by-step rehearsal of any work in order to avoid damage to flight hardware. At times Perkin-Elmer groups had fallen behind schedule milestones by a day or more for each day of work. The delays on the optical telescope assembly would slow progress and hence impose costs on the support systems module and on the scientific instruments. Perkin-Elmer needed another 8 months delay to a launch date in March 1986 and "significant funding increases"—perhaps as much as $100 million.[77]

The news upset Headquarters officials. After Marshall's report, Samuel Keller, the NASA deputy assistant administrator for Space Sciences, said that the telescope program was "out of control." Administrator Beggs was angry; he had told Congress after Marshall's November briefing that the project was on track, but now he would have to beg for more money. Witnesses said that he told Lucas, "you have done dirt to this Agency."[78]

Not surprisingly the program underwent a new round of inquiries by Headquarters officials, by a NASA team led by James Welch, by the House Surveys and Investigations Staff, and by the House Subcommittee on Space Science and Applications. The investigations confirmed that Perkin-Elmer had major management problems; in an ironic moment at these reviews, the contractor verified its weaknesses in scheduling by failing to reserve a meeting room for the NASA committee.[79] But the contractor's crisis also led to discussion of Agency management and why NASA had been unable to understand and solve the problems.

Participants believed that communication broke down between Marshall and Headquarters. The House study quoted an unnamed senior NASA official who said that communications between Marshall and Headquarters were "at best 'horrible.'" Beggs told Congress that the information flow was "poor." In part

Beggs blamed administrative turnover for rupturing continuity at Headquarters; the Office of Space Sciences (OSS) had four associate administrators and four telescope program managers after 1977.[80] OSS had never managed two field Centers and two associate contractors on such a technically complex program. Its small staff, Lucas recalled, never penetrated the project like the Office of Manned Space Flight routinely did and so never fully understood the Center's problems.[81]

In part the poor communications was Marshall's responsibility. Astronomers and Headquarters officials believed that the formal reviews emphasized good news. Dr. Robert Bless, one of the principal investigators, said that "Quarterly reviews in some instances became jokes." Reviews "were often designed to give the impression that everything was going well, that any problems were understood and being solved, and that schedules were being met. However, conversations among participants in the hallway or over a beer often revealed drastically different pictures."[82] In an interview with the *Huntsville Times,* Sam Keller said "I don't think they lied to us. It's not that sort of thing. All engineers think they're going to find the answer tomorrow. But I think they should've told us earlier that you can't get from here to there. I think they were very optimistic and 'had their head in the sand.'"[83] A memo from 1983 reveals the Center's desire to avoid damaging publicity. In June a senior Marshall official complained that the telescope scientists had shown the project's dirty laundry to congressional investigators. He was "extremely disappointed in the large number of negative comments attributed to members of the science community" and wanted project scientist O'Dell to "let his colleagues know what their irresponsible comments are doing to their project."[84]

At the time Marshall disputed criticism about miscommunication with Headquarters. Project manager Speer believed that "Sam Keller is starting with an incorrect premise" that information was "hidden." Actually "there is no lack of communications on any level within the ST program." The Center had communicated the bad news when it was available in late December 1982. Center Director Lucas agreed, believing that the formal reviews and reports "provided an effective means for communicating the very best information available."[85] In 1990, however, Speer acknowledged clogged communications. Marshall was so worried that overruns could lead to project cancellation, he said, that "we were very concerned about the wrong message getting out. The press couldn't be told anything, Headquarters couldn't be told anything, the other Centers shouldn't be told anything."[86]

Even so, the greatest failure of communication occurred between Perkin-Elmer and Marshall. Part of the problem rested with the two parties. Beggs believed the firm had deliberately hidden its problems, and he told Congress that "the contractor was not coming clean . . . to Marshall" and was "covering over what were problems."[87] Likewise Marshall managers admitted to House investigators that they had overestimated Perkin-Elmer's abilities and had underpenetrated. "Marshall 'assumed' that Perkin-Elmer Corporation was capable of doing contracted work with the same level of NASA supervision as large aerospace firms—this proved to be a grievous and costly error."[88] A March 1983 Marshall review of its reports to Headquarters revealed that the Center had typically neglected to report managerial problems at the contractor. The Marshall review found that "there were little or no references to management or systems engineering difficulties. Instead, technical problems, underestimation of complexity, underestimation of subcontractor costs, and growth in engineering and manufacturing were provided as reasons for schedule slips and cost increases."[89]

Structural problems, however, were more important in slowing information and retarding Marshall's responses. Center officials and the House and Welch reports blamed Agency procurement policy and the agreement with the Department of Defense. Marshall had no prime contractor to compensate for Perkin-Elmer's weaknesses. Center officials lamented the limitations of a "procurement strategy that required use of an optics house to do a major systems job."[90] The Center's personnel cap initially limited it to 35 project officials and 65 support engineers, less than half the normal staff of similar programs. Although the Agency removed the cap in 1979, the limitations had hampered management planning and engineering analysis and an increase to 250 people was too little, too late.[91] Speer said that "on a complex program of the magnitude of Hubble, you just need almost a comparable number to Apollo, to really look at everything in depth and to stand up and say, 'Yes, this will work.'"

Likewise the defense agreement and the "black world" of military secrecy had restricted the Center's access to Perkin-Elmer work sites and information. Speer recalled that when his people went to Danbury they continually encountered "locked doors" and closed books. Consequently Marshall had little choice but to accept the firm's word.[92] Moreover, early in the project Headquarters had believed that autonomous contractors would contain costs and had therefore directed the Center to change its traditional practices and minimize penetration.

Lucas thought that "we were somewhat victimized in this by the thought that 'Hey, we've got to learn new ways of doing things to lower costs and let the contractor do it.'" But Perkin-Elmer had learned bad habits working on defense contracts and preferred to solve problems by spending money.[93] All in all, according to a report prepared for the Welch team, the "level of detail needed to see deficiencies [was] not [the] normal level at which MSFC manages."[94]

Short schedules and tight budgets also confined Marshall. Robert Smith, the historian of the project, has suggested that the problems mainly stemmed from how NASA had oversold and underfunded the project. The Center tried to work within unrealistic program plans, mainly because both Headquarters and Marshall managers wanted to avoid surfacing problems until necessary. Headquarters wanted to keep its promises to Congress. Marshall believed that failure to follow plans could result in canceling the project or closing the Center. This reluctance to confront reality not only led to misinformation about progress, but contributed to engineering difficulties.[95] The House staff report argued that "the applied 'design to cost' theory precluded engineering test models and resulted in a 'rush to hardware.'" The Welch group questioned Marshall's emphasis "on technical problems as opposed to management difficulties" and its "commitment to fiscal year constraints ([which] forced deferred work [and] increased 'bow-wave' effect)."[96]

Looking back, project manager Speer believed that the Center was trapped by "a system that I was totally unable to change." He said that "you can really put it on a nice, simple denominator: the program was underfunded. You cannot get something like that for the money that was set aside." Consequently "almost every month we found a gap. Every gap we found meant additional money was to be spent." Money shortages created a crisis atmosphere and "you are always with the overtone of 'who is responsible for this?'" rather than "how do we solve the problem?" Speer thought the Space Telescope was "a good case history for how not to run a big program."[97] Lucas agreed, arguing that the telescope proved "there is no low cost way of doing a job half way. This is just a costly business to do a new, first time invention."[98]

In a letter to Beggs, Lucas summarized how the crisis had occurred. He believed Marshall was "not able to fully recover from the inherent problems introduced into the program as a result of those early decisions" about protoflight and procurement. Nonetheless, he wrote, "I believe we have made considerable technical progress on the development of the Space Telescope. The extreme complexity and demanding requirements, coupled with the inherent problems associated with some early decisions, have made it extremely difficult to assess schedule progress or accurately predict cost requirements in a timely and effective manner. The inability to do this and the perceived necessity to remain under annual and budgetary commitments caused us to continuously understate our budgetary needs. This understatement of budgetary needs resulted in certain critical program decisions being made that, in retrospect, would be judged to have introduced too much risk into a project of such complexity and importance. They were, however, made with full knowledge of all parties at the time they were made. While I do not offer the above as an excuse, or justification, for the problems now confronting the Space Telescope, I do believe that appropriate consideration must be given them in assessing what went wrong, if for no other reason than to preclude similar decisions being made on future projects."[99]

Reorganization and Realization

Even before the completion of the investigations in March 1983, Marshall had started reorienting the telescope project and helping the coalition reorganize. New infusions of talent and cash enabled development to proceed without the previous crisis atmosphere. The born-again project received a new name in October 1983, when NASA renamed it the Edwin P. Hubble Space Telescope in honor of one of America's foremost astronomers.[100]

Headquarters assigned the Space Telescope project a higher priority within the Agency and gave it resources to match. Beggs wrote Lucas that "the Large Space Telescope is the second most important program you have at Marshall, coming only a little behind your activities on the Space Shuttle, and I therefore believe that we should apply as much of the best talent available at Marshall without, of course, sacrificing any attention from the Shuttle." The Agency delayed the launch to the fall of 1986 to give ample time for development and testing. NASA also received forgiveness and money from Congress, amounting to a total budget of $1,175 million, far above the original 1977 projected cost of $475 million. The telescope program thus transcended its origins and its buy-in, design-to-cost strategy and for the first time had resources consistent with its technical difficulty.[101]

The Agency also reorganized the program, with NASA Headquarters assuming greater responsibility and authority. The goal, Keller wrote, was to prevent "a management situation such as had existed at Perkin-Elmer to surprise us" and to "ensure a much higher level of knowledge regarding this project." Without this information the Agency could not rationally distribute resources and maintain a favorable relationship with Congress and the Office of Management and Budget. Keller tried to reassure the Centers that his goal was "penetration rather than management." He said that he was "concerned that we do not bring the project management function into Headquarters and that Washington 'micromanage' the project." Nevertheless, Marshall officials worried that Headquarters would get too involved in details. During a conversation in which Administrator Beggs vented displeasure with the "massive problem" of Perkin-Elmer and Marshall, Center Director Lucas wrote "micro-manage" on his notepad and underlined it 10 times.[102]

The reforms transferred power from the field Centers to Washington. Headquarters expanded its telescope staff from 4 people to 15, created a new Space Telescope Development Division, and hired a systems engineering contractor. Welch, who had managed development of military satellites and conducted the program review, became the new program manager. Welch took responsibility for Level I engineering decisions, which reduced Marshall's authority. Moreover Keller insisted that the Marshall project office immediately report any departures from the program plan and provide monthly briefings in addition to the formal reviews. Headquarters also supported the principal investigators' efforts to reassert their influence. The scientists had found that the science working group was too large and met too infrequently to affect development decisions. Accordingly the astronomers created a smaller executive committee called the Space Telescope Observatory Performance and Assessment Team that reported to Headquarters rather than MSFC.[103]

These resources allowed the project to reduce risks and restore engineering conservatism. "Penny-wise, pound-foolish judgments," Welch believed, had been forced on Marshall by years of cost-cutting. NASA, goaded by the scientists, increased funding, added time for more tests, and increased the number of spares and back-ups (notably one for the Wide-Field Planetary Camera, arguably the most important instrument on the telescope). Marshall also reduced risk by increasing the number of orbital replacement units to 49; it had fallen to 20 after having been as high as 120.[104]

Rather than being demoralized by the crisis, criticism, and changes, Marshall redoubled its efforts. Director Lucas, explaining the telescope's reorientation to the project staff, expressed renewed determination. "As usual," he said, "the press has amplified bad news," but "when you get into the situation we are in, no amount of talking will help—performance is the only answer—so we'll just have to 'hang-in' and deliver the Agency's and the world's most outstanding telescope."[105] Already Marshall had implemented changes in personnel. Speer became associate Center Director for science and would advise Lucas on the project. Jim Odom, who had proven effective in the development of the Shuttle's external tank, became the new telescope project manager. One of the astronomers said that "Odom more than any one individual, at least at Marshall, deserves a heck of a lot of credit for turning around what was almost a disaster in '83, into perhaps not a smoothly running project but certainly, considering the complexity of this one, [a] well done project." Another suggested that "the whole flavor of the program changed. You could discuss problems in a open way and nobody would think less of you." Odom observed that discussing problems was much easier after 1983 because the Agency had the money to fix them.[106]

Marshall made several improvements in the project. To facilitate penetration of the contractors, the project office created separate OTA and SSM offices. To maintain control over interfaces, Marshall improved its systems engineering. Odom and Fred Wojtalik, who became deputy project manager for systems engineering, recalled that before 1983 the Center had lacked resources to fund both hardware development and integration activities, and so had concentrated on development. Although engineers on the project did not get much credit, Odom said, they had done excellent work on design of the pieces and on interface control documentation. After 1983, Wojtalik said the pieces and subsystems were largely built, and Marshall had to provide the money and staff to integrate them. The Center created a new systems engineering office for the project and expanded the telescope systems engineering branch in the Center's Systems Analysis and Integration Lab to a division. Marshall also established interdisciplinary panels in a dozen functional areas and assigned responsibility for ensuring technical support to high-ranking lab personnel. Lockheed also received more responsibility and resources for systems engineering.[107]

The Center also penetrated Perkin-Elmer more deeply. Marshall sent its OTA project office to Danbury, thus increasing the size of its resident office from 4 to more than 25. Lucas said that "I don't recall any case where the deficiencies of project management were equivalent to what we encountered at Perkin-Elmer" and so the team had to help the firm apply new planning systems.[108] Marshall also pressured the firm to select new managers. NASA, goaded by publicity about the delays, also obliged the firm to pay back $1.4 million in previously awarded fees and revised the OTA contract so that subsequent overruns would be "non-fee bearing" and Perkin-Elmer would not profit from its incompetence.

Penetration soon showed results. By May 1984, Jerry Richardson, Marshall's OTA project manager, reported that although the firm still missed 40 to 45 percent of its production deadlines, this showed "some improvement" and corporate management had assumed a "take charge—can do" attitude. Still progress mainly came because extra money allowed Perkin-Elmer to add 100 more people to the project, and in December Marshall was still complaining about the firm's mismanagement.[109]

The Center also helped its contractor overcome several technical challenges. Fordyce, the Perkin-Elmer project manager, said Marshall's team was "probably the finest team that I've seen NASA yield—a good technical team. They're not continuously yelling at us for why don't we do this, why don't we do that. They're trying to help us solve problems."[110]

Marshall's labs contributed to the latches for the orbital replacement units and scientific instruments. NASA and Perkin-Elmer had underestimated the difficulty of designing the 20 different latches. Project manager Odom said that "to call those devices latches is a tremendous understatement and misnomer. You are literally taking devices that are thermal insulators and that have to hold phone booth size objects within one or two ten thousandths of an inch through a thermal gradient that you get in each orbit, as well as handling the launch and ground handling tasks."[111] Dynamic tests showed that the latches experienced "galling," in which the outer layer of aluminum oxide rubbed off and resulted in misalignment. Early in 1983, officials identified the latches as the telescope's primary technical problem. By late in the year, however, Marshall engineers proposed a tungsten carbide coating which withstood galling tests.[112]

Although the Center still complained about its contractor's overruns and delays, the OTA project had overcome major hurdles by late 1984. The guidance system passed pointing and tracking tests in April, and in June a cleaning system, using jets of nitrogen gas, removed the layer of dust that had accumulated on the primary mirror. In May, Marshall engineers completed development of a balance beam to help ground crews install the telescope's fine guidance sensors and scientific instruments. In November, Marshall handled transportation of the OTA from Danbury, Connecticut, to Lockheed's plant in Sunnyvale, California, for mating with the SSM; a surplus *Skylab*-Apollo Telescope Mount canister protected the optical system. In 1985 the National Society of Professional Engineers recognized the optical telescope assembly as one of 1984's top 10 engineering achievements.[113]

As work on the telescope moved from fabrication of the pieces to putting them together, Marshall's attention increasingly turned to Lockheed. Now Lockheed began experiencing problems of systems management and engineering similar to those at Perkin-Elmer. Odom informed Lucas in July 1984 that "the most significant area of attention had been to try to instill in Lockheed a felt sense of systems responsibility, rather than a reactive mode of response to MSFC direction." A Marshall report that fall worried that a "team relationship between Lockheed Missile and Space Corporation (LMSC) management and MSFC, GSFC, and P-E on-site personnel does not exist." Marshall sought to help by transferring its project office to Sunnyvale. Nevertheless, the integration and testing of such complicated technology and complex organizations proved more expensive and time-consuming than anticipated. By summer 1985 Lockheed fell three months behind and went 30 percent over budget, and Center Director Lucas warned the project office that the telescope was "dangerously close to breaking the congressional ceiling on the budget."[114]

The Hubble teams received an unwelcome respite from the *Challenger* disaster. NASA had planned to launch the telescope in the second half of 1986, but the January accident grounded the Shuttle fleet. Marshall worried that the launch delay could lead key personnel to desert the project, but many stayed on. Government and contractor teams continued assembly and verification tasks, completing a major thermal-vacuum test in June 1986. After this time they reworked problem areas, adding more powerful solar panels, enhancing redundancy, improving software, installing better connectors, and labeling orbital maintenance features. Marshall and Lockheed also changed battery type, worrying that nickel-cadmium batteries had a history of failure. Although nickel-hydrogen batteries had never flown in low-Earth orbit, the Center's Astrionics Lab used the extra time and resources to build a simulator of the whole telescope power system, test the nickel-hydrogen batteries, and confirm their reliability. The lab also improved the controls for the power system to prevent overcharging the batteries. The various telescope organizations also rehearsed procedures for orbital verification and operations.

This work resolved weaknesses that had crept into the program before 1983. By the time Hubble Space Telescope was ready for launch in April 1990, it had cost over $2 billion and become the most expensive scientific instrument ever built.[115]

Mirror, Mirror

In the weeks before launch, Marshall's Hubble team felt a deep sense of accomplishment. "Many people here and at our contractors have devoted their best years in developing that system," said Wojtalik, the project manager since 1987. Everywhere expectations about Hubble were high. NASA had been promoting the telescope project for years; Administrator Beggs had liked to call the Space Telescope the "eighth wonder of the world." Marshall had contributed to the public relations campaign with releases like "The Amazing Space Telescope" which described the technical wonders of the pointing and optics systems; it promised that Hubble would yield spatial resolution 10 times better than any previous telescope and could "detect the light from a typical two-battery flashlight from a quarter of a million miles away."[116]

Unfortunately, the boosterism set up Marshall for a fall when the telescope did not perform as anticipated. MSFC located a team of engineers at the GSFC Hubble Space Telescope Operations Control Center to direct orbital verification of the Hubble for two months, until Goddard took over operations and the Lead Center role. Following the successful launch, the team encountered glitches in communications and control. Such glitches were normal for scientific satellites. MSFC's Max Rosenthal, a test support team manager, said "no matter how much testing and research you do on a piece of hardware on the ground, there are some things you just can't do" and "so you make adjustments." The controllers struggled with drifty star trackers, and signal disruptions caused by unexpectedly high radiation over the South Atlantic Anomaly where the Van Allen belts dip close to Earth. A communications antennae kept snagging on its coaxial cable loop, and until controllers compensated for it, the spacecraft periodically shut down in safe mode.

Initially Marshall had the most difficulties with vibrations in the solar panel booms. Dr. Gerald Nurre, Marshall's chief scientist for pointing control systems, recalled noticing the problem almost immediately. As the telescope traveled in and out of Earth's shadow, temperature changes bent materials in the booms. Project engineers had anticipated minor deformations, but ESA had predicted no serious problems would result. What they had not expected was the array's deployment and orientation mechanisms to magnify the deformations and bounce the whole telescope. The vibrations were severe enough to prevent the guidance system from locking on guide stars and to cause "jitter" in the optical images. The booms only stabilized in the last few minutes of daylight, and so the pointing system initially met its design specifications in about 10 percent of its orbit. Nurre's team in Marshall's Structures and Dynamics Lab worked with Lockheed to change the control program in the telescope's computer, directing the pointing and control system to counteract the vibrations. The new program brought the pointing system within the telescope's stringent specifications in 95 percent of the orbit.

Nurre drew lessons from the problems with the antenna and solar arrays, arguing that financial and organizational limitations had helped cause both. Noting that travel restrictions prevented pointing-and-control experts from inspecting key processes, he speculated that if they had attended integration of the Hubble in the Shuttle payload bay at Kennedy Space Center (KSC), they could have noticed the antenna cable loop, and if they had attended deployment tests of the solar booms in England, they might also have spotted their mechanical weaknesses. Moreover, the associate contractor arrangement, the agreement with ESA, and the lack of a prime contractor limited Marshall's ability to perform systems engineering and analyze the telescope's complex interfaces between power, communications, and pointing systems.[117]

The mission controllers made progress and by 21 May began receiving the first optical images from the telescope. These views of a double star in the Carina system, scientists believed, were much clearer than those from ground-based telescopes.[118] Such success left project officials surprised on the weekend of 23–24 June when the telescope failed a focus test.

The controllers had moved the telescope's secondary mirror to focus the light, but a hazy ring or "halo" encircled the best images. Subsequent tests determined that the blurry images resulted from the "spherical aberration" of the primary mirror; spherical aberration reflected light to several focal points rather than to one. It occurred because Perkin-Elmer had removed too much glass, polishing it too flat by 1/50th of the width of a human hair. This seemingly slight mistake, however, prevented the telescope from making sharp images.[119]

Disappointment and outrage characterized the initial reaction from project participants, politicians, and the press. NASA scientist Ed Weiler said "the Hubble is comparable to a very good ground telescope on a very good night, but it's not better than the best." Charles O. Jones, Marshall's deputy chief of guidance, control and optical systems remarked that "we are rather astounded at this error." Senator Barbara Mikulski (D–MD) protested about the waste of $2 billion and called the telescope a "techno-turkey." Senator Al Gore (D–TN), chair of a panel on science and space, referred to the solid rocket boosters, observing "this is the second time in five years that a major project has encountered serious disruption by a serious flaw that was built in 10 years before launch and went undetected by NASA's quality control procedures." Humorist David Letterman made a list of "Top 10 Hubble Telescope Excuses," which included "bum with squeegee smeared lens at red light." Editorialists pointed out the Marshall connection of the *Challenger* and Hubble failures. One asked "Is it coincidence that NASA's Marshall Space Flight Center was in charge of the telescope program, as well as the faulty solid rocket boosters that caused the *Challenger* accident?"[120]

Space pundits analyzed the Agency's institutional weaknesses. John Logsdon described how the problem emerged in the late seventies, "a time when the Agency was not being honest with itself or with anyone else. It was an Agency not expected to have problems or to fail, but it didn't have the resources required to assure success. In that situation, you can't say stop, and you can't say I need more money. You take risks and hope they work out." Howard McCurdy said the Agency's "whole philosophy had changed from the Sixties when they knew there would be trouble and they planned for it" and "in the Seventies, they didn't plan for trouble and prayed that it wouldn't come."[121]

NASA established an investigating committee under the chairmanship of Lew Allen, director of the Jet Propulsion Laboratory. The Allen Report attributed the technical failure to misassembly of the reflective null corrector, an optical device was used to determine the figure of the mirror. The commission found the device intact and discovered enough evidence to interpret what happened.

Technicians in the Optical Operations Division had mismeasured the location of a lens in the device, mistaking a spot on a metering rod where an end cap had worn away as valid scale, and thus erred in spacing the lens by 1.3 mm. Consequently the null corrector guided the polisher to shape a perfectly smooth mirror with the wrong curvature. Analysis of data from Hubble showed that the curvature flaw in the primary mirror exactly matched the flaw in the null corrector.

The device also tested the mirror perfectly, but verified that the mirror's curvature matched the wrong pattern. Basically the tests compared light reflected from a flat reference mirror with light reflected from the curved primary mirror, as modified by passage through the null corrector. Technicians compared light beams from the two mirrors and photographed the interference patterns. In each test, the patterns matched and hence they concluded that the mirror was perfect. The technicians had contrary evidence from similar tests using two other null correctors; their interference patterns showed the flaw in the primary mirror. But rather than interpreting discrepant data as proof of a problem, the firm's optical operations personnel dismissed the evidence as itself flawed. They believed the other two null correctors were less accurate than the reflective null corrector and so could not verify its reliability. Since they assumed the perfection of the mirror and reflective null corrector, they rejected falsifying information from independent tests, believed no problems existed, and reported only good news.[122]

The Allen Commission emphasized that the technical failures rested on managerial failures. It noted that the mistakes occurred in 1981 and 1982 when Perkin-Elmer and Marshall managers were distracted by cost and schedule problems. Nevertheless, Perkin-Elmer had serious failings in quality control and communications that Marshall did not correct. The use of a single test instrument "should have alerted NASA management to the fragility of the process, the possibility of gross error (that is, a mistake in the process), and the need for continued care and consideration of independent tests." The project required no formal certification for the reflective null corrector despite its use as the primary test device. The project had not established clear test criteria or formal documentation to assure compliance with quality procedures. Perkin-Elmer's Optical Operations Division operated "in an artisan, closed-door mode." The commission also found that "the Department of Defense project did not prohibit NASA Quality Assurance from monitoring the P-E activity." Even so the Center had concurred in the firm's decision to exclude even its own quality assurance personnel from the work area during key times. The quality people who did participate were not optical experts but "concentrated mainly on safety issues" and reported to the same managers they were monitoring. Perkin-Elmer did not use its optical scientists to monitor fabrication and testing and neither did Marshall require this.[123]

Other factors also prevented independent verification. The commission believed that "the NASA project management did not have the necessary expertise to critically monitor the optical activities." Marshall's managers did not compensate by using Eastman-Kodak, Perkin-Elmer's subcontractor that had worked on a back-up mirror, to verify the flight mirror. Instead the project office relied on its science working group, who had the necessary theoretical expertise and should have questioned the process, but lacked experience with fabrication and testing. If the contractor and Center had not made such mistakes, the commission believed, they would have caught the technical mistakes and "have been aware that communications were failing with the Optical Operations Division." Finally the Allen Commission noted that "poor communications" and the containment of problems "at the lowest possible level" also resulted from the "apparent philosophy at MSFC at the time" to "consider problems that surfaced at reviews to be indications of bad management."[124]

The mirror problem depressed Marshall people deeply. One official said that the aberration was the most disappointing part of his career and lamented that because of one bad measurement Center personnel became "goats" rather than "heroes." Even so, many sought to learn lessons that could be applied to later projects. Olivier, the chief engineer, recalled how the team had discussed end-to-end optical tests, but had ruled them out because of their cost, imprecision, or potential to contaminate the telescope. In worrying about the need for precise tests, however, he said they had overlooked the desirability of a simple "sanity check" which could detect a gross error and failed to conduct tests with independent experts using different measuring instruments. "That was a paramount lesson learned," Olivier said, "be sure to have cross-checks." He noted that Congress required that NASA prove the optical system on AXAF, the Advanced X-Ray Astrophysics Facility, before proceeding with funding for the whole satellite.[125]

Other Marshall officials pointed out the limitations imposed on them. Speer, the project manager at the time, recalled the difficulty of penetrating Perkin-

Elmer, especially given the defense regulations and Marshall's resource shortages.[126] Kingsbury, director of the Center's labs, explained how Marshall had trusted the contractor's expertise. He said that "The Marshall Space Flight Center is not now, nor was it ever, the optics Center of the world. We employed a contractor who was one of the three recognized and accepted optics Centers of the world. All we could do was assure that which we knew he should do . . . he did properly. But in the particular scheme of polishing, nobody [at MSFC] knew anything about polishing mirrors. We are propulsion people. We had a very, very marginal contractor. I used to say, 'If you want a piece of glass, a perfect mirror, get Perkin-Elmer. Don't ask them to do anything else, but they can polish glass.' Now I'm not sure."[127]

Center officials also blamed the contractor for not surfacing bad news. Project manager Speer, chief engineer Olivier, and chief scientist O'Dell denied receiving any information about the problem and the commission found no evidence that any NASA official saw the discrepant data. Marshall personnel also denied that their Center had a history of suppressing bad news. Wojtalik said, "I don't know of any time in any project I've been in where people were told 'don't bring me something that's a problem.' I've been here 33 years."[128] Downey argued that after *Challenger*, Marshall had become the Agency's "whipping boy" and "scapegoat." "If there was anything that Bill Lucas drilled into us," Downey said, it "was 'If you have a problem, I don't want to be surprised. Please, please communicate it to me.'"[129] Kingsbury said he had never had a contractor hide something, but "this one hid it." To discover the secret, Marshall would have needed a one-for-one match of contractor personnel with civil servants. Kingsbury wondered if resource starvation had not stifled contractor officials; they may have avoided reporting problems because "they were always behind schedule and over budget. We did beat on them mercilessly to get on top of this thing."[130] Basically accepting the idea that Perkin-Elmer had been at fault, Congress in 1991 considered changing government regulations to make contractors liable for their mistakes.[131] Nonetheless, in retrospect, it was a mistake not to have NASA experts, supported by specialists in optical testing, present during the crucial tests of the main mirror; Marshall's suspicions about Perkin-Elmer's competence during this time certainly justified such a presence and the Department of Defense did not prohibit such monitors.[132]

Despite its flaws, Hubble remained a powerful scientific instrument, in large part because its operators found ways to compensate. Not only did NASA engineers compensate for the vibrations of the solar arrays, but they also made similar adjustments to the mirror flaw. Luckily NASA had intended to use computer processing to improve the images and the aberration was so perfectly symmetrical that software could eliminate some of the blurry halo and sharpen the images.[133]

Spherical aberration limited Hubble's performance in some areas more than others. It most affected the telescope's wide field/planetary camera, faint object camera, and the use of fine guidance sensors for making astronomic measurements. The flaw hampered spatial resolution and faint object imaging because the halo effect blurred fine details and wiped out dim images, making Hubble performance similar to the best ground-based telescopes. The computer processing, however, could remove much of the aberration for bright, high contrast objects and for these bodies Hubble was much superior to ground-based instruments.

Spectroscopy, the analysis of radiation wavelengths, could still be done because the instruments required less focused light. By increasing exposure time, scientists could still perform most of their tasks. The faint object spectrograph performed well in imaging bright objects and determining a target's physical and chemical properties. Users of the high resolution spectrograph, which studied ultraviolet radiation, found that the aberration flawed "crowded field" observations of overlapping images. But their images were unmatched because ultraviolet radiation could not be studied by earthbound instruments. Unfortunately scientists found that the jitter from the solar arrays rendered the high-speed photometer, designed to measure light intensity and fluctuations, almost useless. The small aperture of the device could not focus because of the tremors.

Nonetheless, in the first 18 months of operation, the telescope carried out more than 1,900 observations of nearly 900 objects. The information attained was high in quantity and quality; at the January 1992 meeting of the American Astronomical Society, 25 percent of all papers on space observations described Hubble results. Exciting images included Pluto's satellite Charon, storms on Saturn, star generation in 47 Tucanae, planetary formation around Beta Pictoris, and remnants of Supernova 1987A in the Large Magellanic Cloud.[134]

Almost as soon as NASA became aware of the telescope's problems, the Agency began planning repair missions. It had planned maintenance missions for every

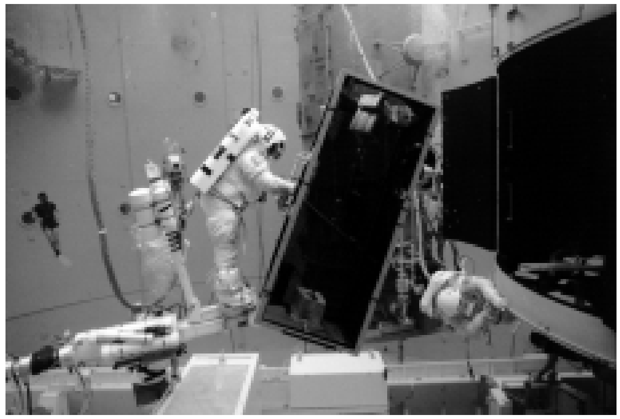
3 years of the 15-year lifespan of the telescope. Although the primary mirror was not one of the replaceable units, its aberration could be corrected, much like the way an eye doctor corrects poor vision with spectacles, by modifications to “second generation” scientific instruments. COSTAR, the corrective optics Space Telescope axial replacement, would replace the high speed photometer and use relay mirrors mounted on movable arms to focus the scattered light.

Marshall’s contributions would be part technical support and part training. The Center characterized the spherical aberration, measuring the error in the null corrector, correlating it with results from the telescope, and thus providing information for the corrective optics. Marshall operated a simulator of the Hubble battery and power system to help Goddard understand flight problems. In addition, the Center upgraded its Neutral Buoyancy Simulator to support the long training sessions required for the six-hour-long spacewalks.

NASA’s repair of Hubble in December 1993 was a spectacular success. The astronauts successfully conducted a series of spacewalks of several hours each, using the tools, modular technology, and space support equipment that Marshall had helped design years before. The astronauts installed new optics, changed failing gyroscopes, and replaced shaky solar arrays. Goddard found, however, that Marshall’s modified control software was still needed to compensate for array jitter. Within a few weeks, Hubble’s performance was much closer to the Agency’s expectations and had the potential to accomplish most of its scientific goals. The telescope began making images of faint objects never seen before. Images of Galaxy M87 confirmed theories that predicted the existence of black holes. Crowded starfields, which before the fix appeared as clouds of lights, afterwards became visible in detail and revealed stellar collisions and rejuvenation. Other images included the formation of planetary systems in the Orion sector, the bending of light by gravity, and the effects of comet impact on Jupiter.[135]

For years after launch, Marshall continued to support the Hubble Space Telescope. Indeed Marshall’s history and the project’s coincided and shaped one another for more than two decades. The project suffered from some of Marshall’s own ills, experiencing the troubles created by diversification, reliance on contractors, management, and communication of complex technological projects, and technological invention in an era of scarce resources. Both Marshall and the telescope often got more publicity from failures than from successes.

Finally the Center, more than any other organization, made the Space Telescope what it was, designing its systems, shaping its team, managing its resources, fixing its problems, more than once saving it from crisis, even oblivion. The Hubble became Marshall's greatest contribution to science, embodying its dream of forging instruments for exploring the heavens.



Astronauts practice installing the corrective optics module into the Hubble Space Telescope mock-up in MSFC's Neutral Buoyancy Simulator, June 1992.

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1 Robert W. Smith, with contributions by Paul A. Hanle, Robert H. Kargon, and Joseph N. Tatarewicz, *The Space Telescope: A Study of NASA, Science, Technology, and Politics* (Cambridge: Cambridge University Press, 1989), p. 64. Smith's book is one of the best in the field of space history and we have relied heavily on it; nonetheless, it sometimes reflects the perspective of NASA Headquarters and the Hubble scientists.

2 Smith, pp. 68–71, 76–79.

3 Von Braun quoted in Smith, p. 84; E. Stuhlinger to E. Rees, 29 August, and 31 August 1970, LST 1971 folder, MSFC Archives; E. Stuhlinger, "Chapter Comments," 21 November 1994.

4 James A. Downey, III, Oral History Interview by Stephen P. Waring (hereinafter OHI by SPW), Madison, AL, 14 December 1990, pp. 25–27, quoted p. 25; James A. Downey, III, OHI by Robert Smith, National Air and Space Museum (NASM) Oral History Program, 18 January 1984, pp. 1–8, quoted p. 15; Jean Olivier, OHI by Robert Smith, NASM Oral History Program, 18 January 1984, pp. 1–4; Jean Olivier, Personal Communication to Robert Smith, NASA Oral History Program, no date, pp. 1–2; Program Development, "LST Systems Definition Study (RAM) Concept," May 1971, LST 1971 folder, MSFC Archives.

5 Myers quoted in W. Lucas to E. Rees, note attached to "OSSA 'LST Program' presentation to Dr. Low, NASA HQ," 9 November 1970, LST 1971 folder, MSFC Archives; Smith, pp. 82–84.

6 Smith, pp. 82–84; J. A. Bethay, MSFC, to H. Gorman, HQ, 31 March 1972, LST 1972 folder, MSFC Archives; E. Stuhlinger to J. Murphy, 10 January 1972, LST 1972 folder, MSFC Archives; Robert Bless, OHI by Robert Smith, 3 November 1983, quoted p. 23,

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7 Smith, pp. 82–84, quoted p. 84.

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10 "J. Mitchell's Remarks Concerning Dr. Naugle's Visit (1/27/72)," 27 January 1972, LST 1972 folder; E. Stuhlinger to E. Rees, 19 July 1971; E. Rees to W. Lucas and J. Murphy, "LST," 14 September 1971; J. Murphy to E. Rees, 22 September 1971, LST 1971 folder; E. Rees to J. Naugle, "LST Program Data," 21 March 1972; MSFC, "LST" n.d., LST 1972 folder, MSFC Archives. In this last document, Marshall also informed Headquarters that "MSFC has the desire, capability and capacity to handle the SIP, if such would be desired by OSS[A]."

11 J. Murphy, PD to E. Rees, 27 June 1972; MSFC–GSFC, "Memorandum of Agreement on LST Project," 19 July 1972; W. Lucas to E. Rees, 12 September 1972; "LST Project Review to Dr. John Naugle," 25 October 1972, LST 1972 folder, MSFC Archives; Smith, pp. 93–95; E. Stuhlinger, "Chapter Comments."

12 J. T. Murphy to E. Rees, 3 November 1972; J. T. Murphy to G. Pieper, GSFC, "Clarification of Memorandum of Agreement on LST Project," 9 November 1972; E. Rees, "LST Cooperation with GSFC and Delineation of Work, Memorandum for Record," 13 November 1972; G. F. Pieper, GSFC, "Clarification of Memorandum of Agreement on the LST Project," 17 November 1972, LST 1972 folder, MSFC Archives.

13 C. R. O'Dell through J. Murphy to E. Rees, "Clarification of Points of Debate Between MSFC and GSFC in the Implementation of the Center Directors' Agreement on LST," LST 1972 folder, MSFC Archives.

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16 MSFC PR–72–162, "Scientists to Help Plan Space Telescope," 20 December 1972, MSFC History Office; O'Dell quoted in Smith, p. 96; R. Petrone to J. Mitchell, HQ, "LST Instrumentation," 6 February 1972, LST 1973 folder, MSFC Archives.

17 Smith, p. 87.

18 W. Lucas to J. Murphy, 30 November 1972, LST 1972 folder; J. Downey, "Memo for Record, LST Meetings, NASA Headquarters, 21 December 1972," 9 January 1973, LST 1973 folder; "LST Planning Strategy," 13 April 1973, Meeting with Dr. Low, Washington, DC, 4/13/73 folder, MSFC Archives; Downey OHI, 18 January 1984, pp. 12–13; Jean Olivier, OHI by Robert Smith, 18 January 1984, p. 15, NASM Oral History Program; Jim Downey to Mike Wright, 28 September 1993, MSFC History Office; Smith, pp. 86–91, 99–100.

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