THE HUBBLE SPACE TELESCOPE OBSERVATORY

The Hubble Space Telescope is scheduled to go into space this month, giving astronomers a ten-times sharper view of the stars and galaxies and an unprecedented sighting of the uv universe.

C. R. O'Dell

No other astronomy project has taken so long to develop, proven so technologically challenging or cost so much as the Hubble Space Telescope. At a development cost of about $1.5 billion, the HST is big science by the standards of modern physics. Soon after the HST is launched on 12 April, the physics community will determine if the resources and professional efforts that have gone into the HST will produce the promised scientific returns that drew hundreds of the best scientists from the US and Europe into the project.

The HST has attracted much more attention than comparable developments in particle accelerators because it has been developed under the auspices of a show-case federal agency, NASA. Building the HST was quite unlike building most big-science accelerators: The HST was not just the outcome of developing a few new components or ways of making them and then manufacturing them in large numbers. Essentially every element of the HST required new developments, with corresponding cost and schedule uncertainties.

Background

The concept of the HST can be traced to early speculations about ways to use space.[1] Hermann Oberth wrote in his thesis, which became the 1923 book *By Rockets into Interplanetary Space*,[2] that an observatory placed above the distorting and absorbing terrestrial atmosphere would allow astronomers to make observations that are impossible to realize using even the largest ground-based observatories. This idea remained largely unrecognized until Lyman Spitzer Jr issued his report[3] for the Rand Corporation in 1946. In it he wrote of the scientific uses of rockets more powerful than the German V-2 military weapon. Scores of this weapon had been captured by the Allies at the end of World War II and brought to the US for study and scientific application.

One of the first scientific studies done for NASA after its founding in 1958 identified a space observatory as one of the agency's natural long-range goals. Why NASA set a space observatory among its goals is explained by the nature of electromagnetic radiation from astronomical sources and the transmission characteristics of the Earth's atmosphere.

No known astronomical source save the cosmic background radiation exactly duplicates the radiation profile of a blackbody. However most thermal sources come close. Radiating objects emit a broad spectrum of radiation with most of it near a peak wavelength λ_{max}. That wavelength decreases with increasing temperature according to Wien's Law: $\lambda_{max} = 2897.9/T$ (where λ is in micrometers). Since the range of temperatures among stars is enormous, the radiation from stars and galaxies of significance for optical space-telescope exploration covers the electromagnetic spectrum from the infrared through the visible and into the ultraviolet.

The Earth's atmosphere only transmits radiation in the radio and visible regions; the rest of the astronomical signal is absorbed. Also, the atmosphere distorts the wavefront arriving from a distant star or planet. Before reaching the atmosphere the wavefront is essentially parallel and can be imaged with a quality limited only by the diffraction about the aperture of the telescope. But temperature inhomogeneities in the turbulent lower atmosphere produce local variations in the index of refraction, which distort the wavefront, limiting image resolution to about 1 arcsecond.

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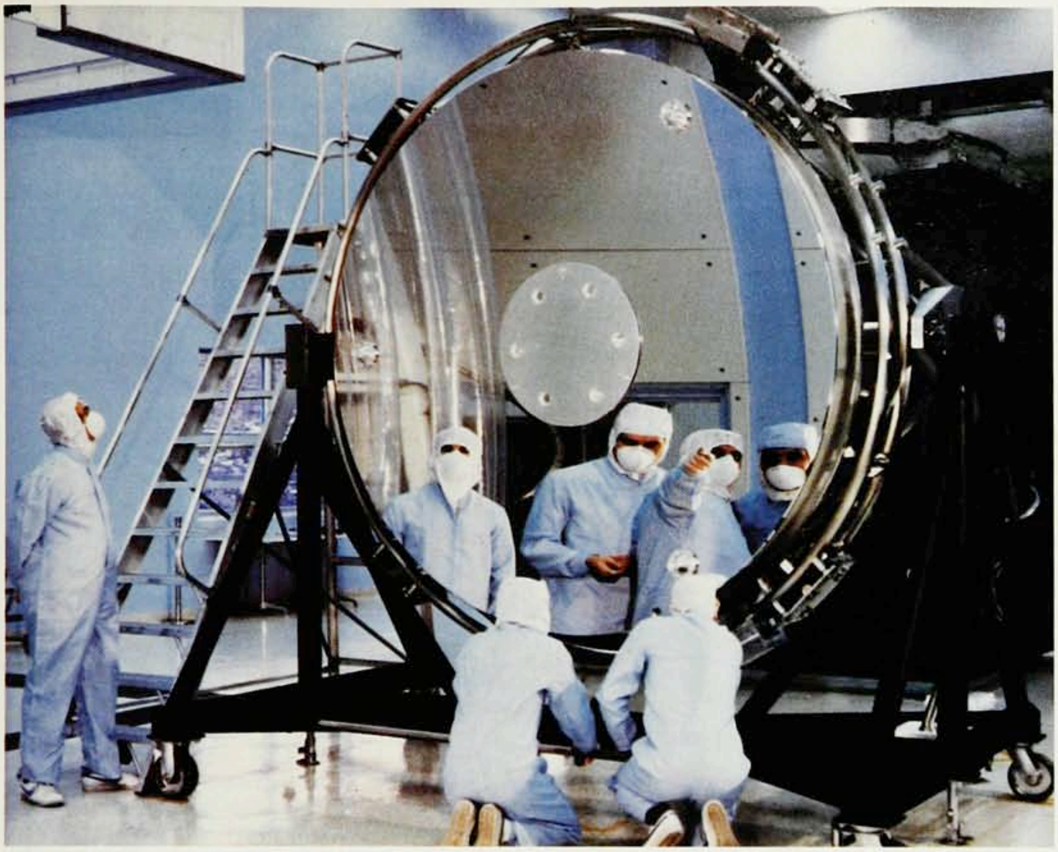


The optical performance of the HST's mirror exceeds NASA specifications. Reflective coating is aluminum because it absorbs little uv. The three circles at approximately 1, 5 and 9 o'clock on the mirror are hoist-bolt locations.

During the first three decades of NASA's space science program, the agency used a series of rocket and satellite telescopes to exploit the improved wavelength coverage from space. The two successful Orbiting Astronomical Observatories demonstrated the advantages of photometry and spectroscopy from low Earth orbit. Since the late 1970s, the highly successful International Ultraviolet Explorer has been providing a wealth of spectroscopic data from geosynchronous orbit. None of these observatories[4] fully exploited the better imaging potential afforded from space. To some extent, however, that was done with a series of balloon-borne telescope flights in the Stratoscope program.

The telescope portion

The HST observatory has three major systems: the optical telescope assembly, which collects the light and forms an image; the scientific instruments, which use the image to generate astronomical data; and the support-systems module, which allows the other two systems to function as a complete observatory.

The flight mirror and the rest of the optical telescope assembly were built by the Perkin–Elmer Corporation (now Hughes Danbury Optical Systems) using a new technique involving small polishing tools directly controlled by a computer. (A backup mirror was made by Eastman Kodak using a more traditional large-tool process.)

The telescope optics are the Ritchey–Chrétien variation of the Cassegrainian configuration. This combination of a non-conic-section concave primary mirror and a convex secondary mirror produces a curved focal surface free of coma—the principal off-axis aberration of telescopes. The primary and secondary mirrors are held in alignment using a graphite–epoxy truss structure developed by Boeing.

It is not possible to avoid adding other aberration when eliminating coma from a two-mirror system. The design used in the HST introduces astigmatism, but at an acceptably large off-axis angle. The telescopes thus can obtain diffraction-limited images over a field of view much larger than that of any other imaging detector foreseen for the next decade.

At 2.4 meters diameter, the HST is not a giant telescope by today's standards. The challenge of its construction was to make it perform at the diffraction limit. Meeting this performance goal involves keeping the wavefront distortion of the total system to less than about $\frac{1}{12}$ the wavelength of the light being imaged. This stipulation in turn requires that each of the two mirror surfaces conforms to design shape to within $\frac{1}{48}$ of a wavelength. Since the telescope is tested using the neon laser line at 632.8 nm, the allowed root-mean-square surface deviation can be only 13 nm. However, the designers wanted to exploit the mirror's performance in the ultraviolet. Since the angle at the core of an imaged Rayleigh pattern decreases with wavelength, the primary mirror was finished to better than $\frac{1}{60}$ of the neon-laser-

Characteristics of the Scientific Instruments

Wide-Field and Planetary Camera
Principal investigator: James A. Westphal (Caltech)
Focal ratios: 12.9 and 30
Fields of view: 2.6×2.6 arcminute and 1.1×1.1 arcminute
Detector: Texas Instruments 800×800 CCDs with 15-μm pixels
Angular resolution: 0.1 arcsecond/pixel (WFC) and 0.043 arcsecond/pixel (PC)
Wavelength range: 130–1100 nm
Limiting magnitude star: 27 (PC) and 28 (WFC)

Faint Object Camera
Principal investigator: F. Duccio Machetto (European Space Agency)
Focal ratios: 48, 96 and 288
Fields of view: 22.5×22.5, 11.3×11.3, and 4×4 arcseconds
Detector: Photon-counting image intensifier television combination with 25-μm resolution.
Angular resolution: 0.044, 0.022 and 0.007 arcsecond/pixel
Wavelength range: 115–650 nm
Limiting magnitude: 29, 30 and 30

Faint Object Spectrograph
Principal investigator: Richard J. Harms (Applied Research Corporation)
Detector: Linear-array digicon of 512 50-μm detectors
Wavelength resolution: 100–1200
Wavelength range: 105–850 nm

Goddard High Resolution Spectrograph
Principal investigators: John C. Brandt (University of Colorado) and Sarah R. Heap (Goddard Space Flight Center)
Detector: Linear-array digicon of 512 50-μm detectors
Wavelength resolution: 2 000–100 000
Wavelength range: 105–320 nm

High Speed Photometer
Principal investigator: Robert C. Bless (University of Wisconsin)
Detectors: Four image dissectors and a photomultiplier
Wavelength range: 120–700 nm
Time resolution: 10 μsec
Name: Fine Guidance Sensors
Astrometry team leader: William H. Jeffreys (University of Texas)
Detectors: Photomultiplier pairs behind Koesters prisms
Field of view: 4×17 arcminutes
Positional accuracy: 0.003 arcsecond

line wavelength.

The field of view behind the primary mirror is large enough to dedicate sections of it to individual scientific instruments and to portions of the guidance system called the fine-guidance sensors. This arrangement allows each instrument to be rigidly mounted at a particular location along the focal surface and avoids the mechanical complexities and positional uncertainties of a moving carousel. To switch instruments being used, the telescope's pointing is adjusted to bring the star or galaxy onto the entrance aperture of the desired instrument.

The scientific instruments

The complement of scientific instruments aboard the Hubble Space Telescope emphasizes digital imaging, spectroscopy and photometry and thus is quite similar to that used for a large ground-based telescope. Unlike many telescopes, the HST also has a powerful astrometric capability. In addition to the present set of scientific instruments, new instruments are under construction that will expand and improve the capabilities of the observatory.

The responsibility for developing scientific capability lies with the scientific council for the HST. The council is headed by project scientist Albert Boggess of the Goddard Space Flight Center. This group at Goddard largely includes the leaders of instrument development teams and a unit of more interdisciplinary scientists responsible for telescope operations, who are collectively called the Observatory Scientists Team.

Five specific scientific instruments have been developed solely to make use of the telescope's image to do science.[5,6] (See the box on this page.) Two of them primarily do imaging onto an array of light-sensitive picture elements or pixels. The Wide Field and Planetary Camera and the Faint Object Camera incorporate two and three focal lengths, or modes, respectively. These multimodes compensate for the fixed linear size of the light-sensitive arrays and the finite number of pixels they contain.

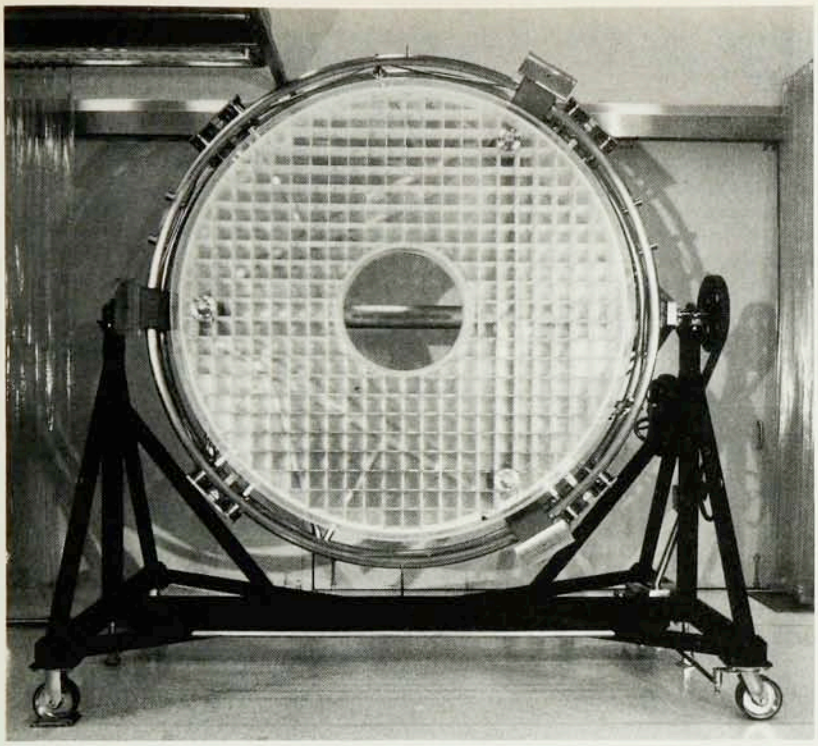
The lowest focal ratio of the Wide Field and Planetary Camera gives the widest field of view but the lowest angular resolution of any camera mode; this camera will produce the most images and is expected to be the "workhorse" instrument of the observatory.

The Faint Object Camera—built by the European Space Agency—gives the smallest field of view but the highest angular resolution. The camera's detector has been designed for maximal rejection of background light and the capability to count single photons. This allows camera imaging of the faintest stars detected by the HST.

There are two spectrographic instruments, and both use the same type of linear-array detector. The Goddard High Resolution Spectrograph is an ultraviolet instrument that offers resolutions almost as high as the natural limit imposed by the intrinsic width of the interstellar absorption lines—the narrowest known. The Faint Object Spectrograph covers the light spectrum from the ultraviolet through the visual. Because its resolution requirements are less stringent, the instrument can analyze sources that are nearly as faint as those detected by the imaging instruments.

The High Speed Photometer is the simplest of the scientific instruments. It is a set of image-dissector tubes with fixed arrays of small filters in front of their cathodes. Different cathode–filter combinations are selected by repointing the HST; thus, within the photometer itself, nothing moves but electrons. The unique feature of this instrument is its ability to measure light flux with the highest time resolution of any of the HST's instruments.

The fine-guidance sensors were developed as part of the support-systems module. However, they also form a



Primary mirror blank for the Hubble Space Telescope. For weight saving, the blank was cast as two thin plates sandwiching a 144-cell "pigeon hole" configuration formed from slender glass slats. The entire blank was then heated and allowed to sag over a mushroom-shaped mold to get the right shape.

powerful astrometric device. While two of the three sensors are locked onto guide stars at the edge of the telescope's field of view, the third can systematically measure the positions of stars with unprecedented accuracy—0.003 arcsecond.

This initial set of scientific instruments will be replaced, in orbit, during the 15-year lifetime expected for the observatory. This capability is important because the present spectrographs are limited by the linear nature of their detectors. A two-dimensional detector spectrograph that will extend the function of both of the HST's spectrographic instruments is being developed. An improved version of the Wide Field and Planetary Camera will be available about two years from now, and a cryogenically cooled infrared camera–spectrometer will be available soon after that. Instrument changes will be determined by the needs of the observatory and the technology of the day.

Capabilities

The performance of the HST reflects the combined characteristics of the scientific instruments and the observatory. The former, as just explained, will evolve during the life of the observatory, so I will limit my discussion to the capabilities expected upon putting the telescope into operation.

The images will be about 0.08 arcsecond (full width at half of maximum intensity) at 632.8 nm, with a similar value for the Rayleigh resolution ($1.22\lambda/d$ where $d=$ diameter of objective lens). The FWHM should narrow as the wavelength of observation decreases, until wavefront irregularities approach the size for the wavelength; at this point the angular size will become constant. This minimum FWHM should be about 0.03 arcsecond. Such resolution can only be recorded with the long-focal-ratio option of the Faint Object Camera.

The HST's ability to detect very faint stars involves both collecting enough photons and discriminating the signal of a star from the background sky signal. The images will be concentrated into an area that is less than 1% that of a ground-based telescope's. The HST will thus reject more than 99% of the sky's background light, enhancing the contrast of the stellar image. Measuring and then factoring out lower-orbital sky brightness (mostly scattered sunlight from interplanetary dust) will also help. The HST therefore should be able to detect stars at least 30 times fainter than can be "seen" with the largest operational telescope, the 5-m Hale telescope on Palomar Mountain. Since faint-star detection capability grows only linearly with telescope diameter, the HST should remain unequaled in this regard compared with foreseeable ground-based telescopes.

The HST's spectroscopic capability will also be unique. If it is as expected, no ground or satellite telescope will be able to address objects as faint in the ultraviolet or with as much spatial resolution. The High Speed Photometer will be able to measure rapid variations of light well beyond the limits set by scintillation in the atmosphere, and the fine-guidance sensors will permit measurement of star positions to 0.003 arcsecond.

Support systems

Probably the most difficult challenge of the HST's design and construction was meeting the need to point the telescope precisely while holding its position during exposures. Four massive variable-speed rotors known as reaction-wheel assemblies will move the spacecraft. Owing to conservation of angular momentum, as these assemblies are spun (the maximum speed is 3000 rpm), the HST will move in their opposite sense (at up to about 5° per minute). Fine guidance is realized by small variations in the speed of the assemblies. Pointing accuracy will be controllable to 0.01 arcsecond, and pointing jitter will be 0.007 arcsecond rms.

The pointing signal will come from several sources. The initial orientation signal will be from a set of small telescopes pointing out of the side of the HST. These telescopes will determine the positions of bright stars to an accuracy of about 1 arcminute. Next the fine-guidance system will locate predetermined guide stars positioned at accurately known distances from the object to be studied. The HST will then be automatically pointed to the correct position. The system that will monitor the guide stars employs pairs of Koesters prisms to correct for the precession of the gyroscope assemblies that provide the reference signal to the reaction-wheel assemblies.

The HST's electric power will derive from two large arrays of solar cells (provided by the European Space Agency). Electric energy will be stored in sets of high-pressure NiH_2 cells.

Spacecraft commands and scientific data will be handled by on-board computers and tape recorders. Communication will be provided by two systems, the first operating at only a few kilobits per second, the second, at 1 megabit per second. The high-bit-rate system uses a steerable high-gain antenna, which will continuously point at one of the tracking and data relay satellites located in geosynchronous orbit. The geosynchronous satellites will beam signals to a ground antenna linked to the control facility at the Goddard Space Flight Center.

The key components of every major system are designed to allow their replacement by space-suited astronauts after the HST docks to a special fixture in the payload bay of a space shuttle. Batteries, reaction-wheel assemblies, fine-guidance sensors—even individual scientific instruments—and solar arrays will be replaced with equal or better hardware.

Achieving such a maintainable observatory required the close interaction of astronauts with engineers at the Marshall Space Flight Center and the Lockheed Missiles and Space Company. (Marshall had overall responsibility for construction of the HST, and Lockheed had responsibility for the support systems and their integration into a functional observatory.)

The Space Telescope Science Institute

The anticipated longevity of the HST distinguishes this observatory from other NASA science projects. The need for smooth long-term operation led to the creation of a special facility, the Space Telescope Science Institute.

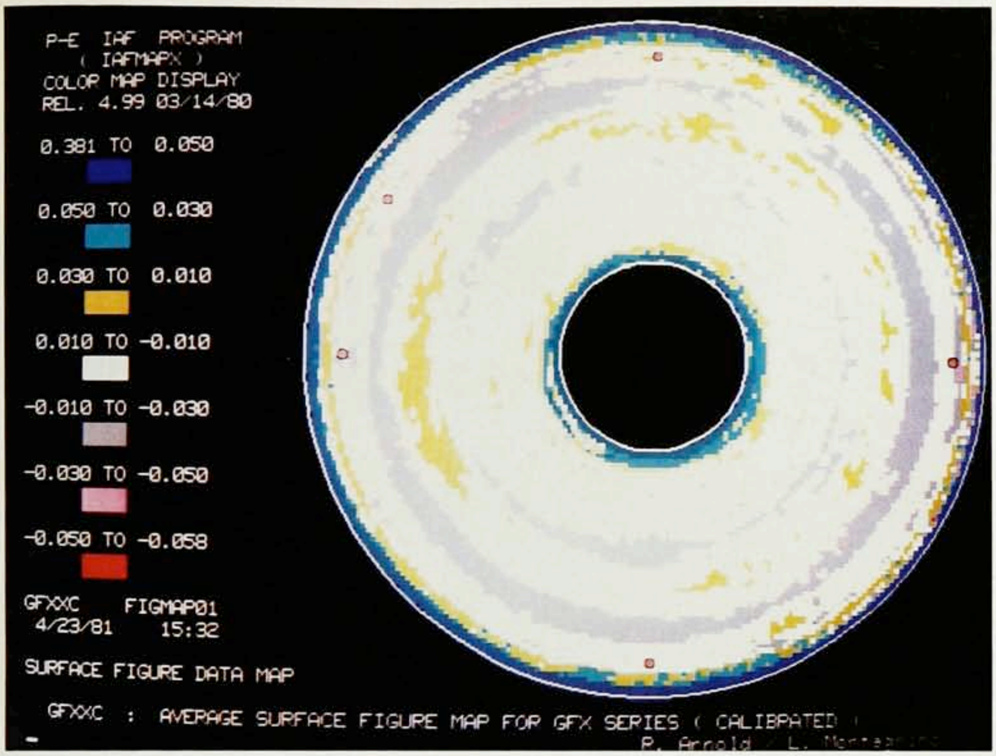
Although NASA has many good space scientists, the vast majority of the HST users are expected to be in university environments. NASA therefore sought a way to optimize "university" use of the telescope.

The idea of a Space Telescope Science Institute originated in 1972 during the preliminary design of the HST and quickly gained the support of the HST astronomers. Later, in 1976, a summer study group, sponsored by the National Academy of Sciences at NASA's request, recommended that a contract organization implement the science of the HST. The positive experiences of the national optical and radio observatories also entered into NASA's decision to accept the idea. NASA competitively selected the Association of Universities for Research in Astronomy to create and operate the Space Telescope Science Institute. (This consortium also operates the National Optical Astronomy Observatories, with locations in Arizona and Chile.)

The institute is essentially a "cradle to grave" operation. Its functions include the support of science done at other locations, provision of many central services and selection of the scientific users of the HST.

A group of scientists called "guaranteed-time observers" has spent more than ten years in developing the HST and its science program. These scientists will have total use of the first two months of HST observations. Subsequently they will receive a rapidly dwindling fraction of the observing time, phasing out entirely about three years

Two laser beams bounced off the surface of the Hubble primary mirror produced this pattern of wavy interference bands. Computer analysis of such interferograms revealed bumps and hollows as small as 10 billionths of an inch.



Nearly perfect contour of the HST's primary mirror. The mirror was ground using new small grinding tools controlled by computers. Highs and lows in the mirror were frequently checked through surface mappings, such as the one shown. The new grinding method shaped the blank so that no part of its surface deviated from that for its theoretical form by more than 1/78 of the red laser-line wavelength of neon. Color scale at left gives deviations in steps of 13 nm.

after launch. General observers will gradually come into the observing schedule within the first year and will quickly become the primary users.

Each year, the Space Telescope Science Institute is responsible for competitively selecting the general observers by peer-review process. It then funds these investigators and provides them with support services. These services include:

▷ providing positions of targets and guide stars
▷ scheduling observations for maximum efficiency
▷ providing the detailed requirements to the Goddard Space Flight Center
▷ overseeing the actual operations.

Some observers may come to the institute for their observations. Most will not, since observations will be made at irregular intervals imposed by an efficient, integrated time line that meshes many different observing programs. After every 24 hours of observation, the institute will extract the scientific data from the data stream. It will then provide standard reduction processing and send the reduced data to the observer, while also storing it at the institute. The STScI will also provide data-analysis software programs to the observers as needed.

All scientific data from the HST will enter the public domain one year after delivery to the observers. These data will be easily distributed in digital form and thus should quickly become an enormous resource for all scientists. The Space Telescope Science Institute is now beginning to establish an archiving and distribution system for efficient identification and use of the stored data.

Project evolution

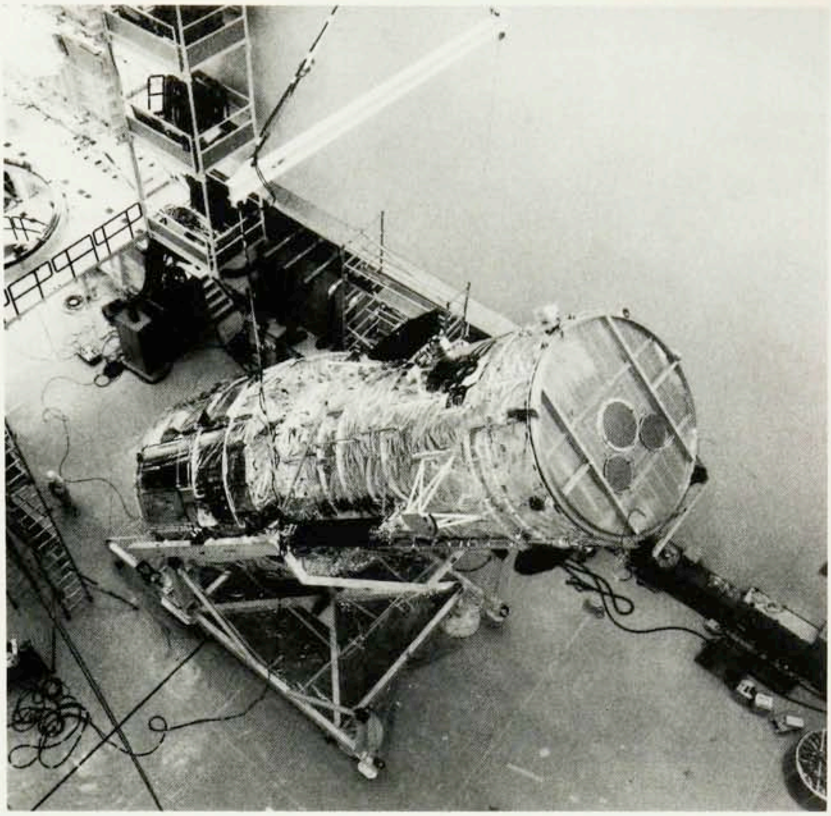
I have been involved with the HST since the summer of 1971 and have seen many changes in the program. Some things we did right the first time; others needed to be changed. One thing we did right was the set-up structure for involving scientists.

The early involvement of scientists helped sell the program to Congress and NASA. These institutions and individuals associated with the HST could see that it was in their interest for the HST to be built.

At the start of the project many people within the government assumed that NASA would be the primary developer of the HST and would run it for the user community. However the open competition for the developers of the scientific instruments and the operators of the Space Telescope Science Institute introduced ideas by many people, often representing different backgrounds. Also, in the case of the instruments, the competition came from different technologies. This benefited the program. Open competitions for participation of scientist teams also were held, even at the beginning of the preliminary design phase, without assurance that the teams would continue into the development phase. In fact, competition for the construction phase produced an almost complete change of personnel on the scientific-instrument teams. I believe that this turnover came about because many of the preliminary design-phase teams had locked themselves into detector technologies that were overtaken by continuing developments.

The biggest program changes occurred in the preliminary design phase. The first change involved redesigning the HST for the space shuttle and NASA's plans for frequent, low-cost flights. All major HST payloads had to undergo this redesign. The HST's designers, believing that the shuttle would make it easy to replace poorly functioning or failed components, took higher risks in an attempt to cut costs and save development money. These early sanguine expectations for shuttle capability never materialized. The designers have therefore had to redirect their objectives and stress reliability.

Probably the biggest accommodation the HST's designers made to fit shuttle requirements involved mirror size: The original 3-m-aperture design was reduced to 2.4



The Hubble Space Telescope is removed from its assembly structure at Lockheed.

m. The reduced-diameter mirror is the largest possible one that provides a low moment-of-inertia package and fits into the shuttle's payload bay. The remaining diameter of the HST package is taken up by most of the support hardware, which occupies a ring outside the primary mirror. This design greatly simplified the point-and-control system, which is the most complex of the observatory's components.

There have been many delays during the development phase. When the program started in 1978, launch was due late in 1982. Numerous technical problems and budget reductions caused a series of schedule slips extending through November 1986. The Challenger accident and the subsequent hiatus in launches led to the HST's launch being rescheduled to the spring of 1990. During this period the program became the object of some bad press. For example, the press frequently reported that keeping the HST in storage cost $3 million per week. Actually, the physical warehousing of the HST represented but a small fraction of that cost. Most of the $3 million went to improving preparations to operate the HST, to making repairs and adjustments (not making them, however, would not have caused a launch delay) and to upgrading some of the key systems as better technology came along. Among the upgrades were the substitution of higher-performance solar-cell arrays and the inclusion of high-pressure NiH_2 batteries.

The only recent uncertainties have not been of NASA's doing. We are now experiencing the strongest solar activity encountered since the first artificial satellites were launched. The Sun's increased magnetic activity and ultraviolet luminosity heat the uppermost layers of the Earth's atmosphere, causing it to swell and become denser at orbital altitudes. The current solar cycle now appears to have peaked. At a 380-mile altitude, the HST will be as high as the shuttle can take it. The HST orbit should decay slowly enough in the shrinking atmosphere following the solar maximum so that it presents no problem for the next several years. Almost certainly the HST will need reboosting prior to the next solar maximum, 11 years from now.

The rewards to the astronomical community, however, have begun even before the HST launch. They include the circulation of the catalog of guide-star positions and the creation of new research jobs. Most significant is the National Science Foundation's distribution of Texas Instruments-developed charged-couple-device detectors left over from the construction of the Wide Field Planetary Camera. These remain the standard of comparison in the race to increase the number of pixels and decrease the readout noise of CCDs. Unfortunately, the optical technology of the HST has not similarly spread into the new generation of giant ground-based telescopes.

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