I. CURRENT MISSIONS

THE HUBBLE SPACE TELESCOPE

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Abstract. The Hubble Space Telescope was launched from the Kennedy Space Center on April 24, 1990. Its initial check-out indicates that all sub-systems of the satellite are working very well, with two key exceptions: The line-of-sight pointing is subject to occasional jitter apparently induced by thermal stresses in the solar arrays; this is expected to be overcome. The telescope mirrors are found to contain approximately 0.5 wave rms of spherical aberration which cannot be overcome by any controls on board the satellite. This defect will limit the scientific performance of the telescope in the short run. However, the aberration can be fully corrected in the optical designs of future replacement instruments, and the delivery schedules of these instruments are being accelerated.

1. Introduction

Those of us associated with the Hubble Space Telescope wished to commemorate this IAU colloquium and to lend some sense of immediacy to its deliberations and so arranged to have the HST launched on Space Shuttle Discovery at 8:33 EDT on the morning of the opening session. We hope the astronauts' saga during the following days of deploying the telescope and establishing it as an independent free flyer provided an interesting backdrop for the meetings. The satellite is still in the midst of its engineering check-out phase and it is too soon to predict the ultimate performance of the telescope in orbit, other than to note the serious problem of spherical aberration in the telescope optics. The following paragraphs summarize what has been learned so far.

2. Launch preparations and deployment

The pre-launch preparations at the Kennedy Space Center went very smoothly for the most part. The satellite was shipped to Kennedy from the Lockheed plant in Sunnyvale, California last October, and tests quickly showed that it had arrived in good shape. The Wide Field/Planetary Camera, which had been shipped to JPL for refurbishment of some electronics boards, arrived in December and was installed without incident. Other refurbished electronics parts were installed on schedule in February and the HST was declared ready for launch. The principal remaining concern was to be sure that the flight batteries could be fully enough charged at launch to provide power to HST during the critical several-hour period from the time that supporting shuttle power would be removed in orbit until the solar arrays could be extended. The logistics necessary to allow batteries to be trickle-charged until very late in the countdown was carefully coordinated between the spacecraft and launch crews.

The initial launch attempt was on the morning of April 10. The countdown proceeded smoothly until a few seconds before lift-off, when a failed Auxiliary Power

Y. Kondo (ed.), Observatories in Earth Orbit and Beyond, 3–7.

Unit in the shuttle orbiter forced the launch to be scrubbed. Launch was rescheduled for April 24 and went flawlessly. The shuttle established a 613 km circular orbit, about 2 km higher than requested, which removes a need for reboost until the next solar cycle. On orbit, the astronauts deployed the satellite on the manipulator arm and then extended the high gain antennas and the solar arrays. One solar array was a cause for concern because monitors indicated that the tension on the array became high as it was extended. The procedure was stopped and some time spent carefully analyzing the situation to decide whether it was safe to continue. In the meantime two of the astronauts, Kathy Sullivan and Bruce McCandless, made preparations for an Extra-Vehicular Activity in order to unfurl the array manually. To everyone's relief (except perhaps for Kathy and Bruce), the array did extend fully when commanded on a subsequent attempt and the HST was ready to be released from the shuttle. A second problem soon became apparent when one of the high gain antennas, designed to be pointed toward the Tracking and Data Relay Satellites in geosynchronous orbit, encountered resistance when commanded to rotate through its full pointing range. After examining documentation photographs taken during assembly and after modeling the motions of the antenna, it was concluded that at some orientations an antenna counterweight could rub against a flexure loop in the wiring harness. These orientations proved to be easily avoided during regular operation of the antennae and the deployment sequence was allowed to proceed.

TABLE I
Hubble Space Telescope Spacecraft Characteristics

Length	13 m
Diameter (without arrays)	4.3 m
Mass	11,500 Kg
Power	2,400 w
Communications	1 Mbps through TDRSS
Tracking accuracy	0.01 arc-sec
Tracking jitter	0.007 arc-sec
Telescope aperture	2.4 m
Telescope figure	Ritchey-Chretien
Primary focal ratio	f/2.3
Secondary focal ratio	f/24
Plate scale	3.58 arc-sec/mm
Image FWHM at 540 nm	0.08 arc-sec
Radius of 70 % encircled energy	0.6 arc-sec

The final step was to back the shuttle orbiter far enough away that its emissions could not contaminate the telescope optics while the door was opened at the front end of the telescope tube. That actuation was the last task of the deployment sequence that called for back-up help from the astronauts, and so they and the shuttle were released to complete their mission and return to Earth. The engineers and ground controllers were then left with the task of learning the actual operating characteristics of HST in orbit and of developing their techniques for scheduling and using the satellite.

3. Orbital verification

The principal tasks of Orbital Verification have been to evaluate the capabilities of the various spacecraft sub-systems and learn how to operate them. These sub-systems include such areas as pointing control, telescope optics, thermal control, power, communications, command and data handling, and the scientific instruments. Of these, all are working well except the first two. The thermal control system is doing its job routinely and the passive thermal system is running somewhat warmer than intended, reducing the need for heater power. This in turn results in a total power consumption about ten percent less than expected, which can permit greater operational and observing flexibility in the early years and should delay the future date at which batteries and solar arrays will need to be replaced. The communications system is working well. Some procedural problems in establishing links through TDRSS have been identified and corrected. The link margins from the ground through TDRSS to HST and return are larger than expected, which is advantageous to operational flexibility. The command and data handling system is performing properly, although some minor problems were found and corrected in the use of the on-board tape recorders. All of the scientific instruments have been turned on and have completed their internal engineering checks. Successful exposures have been made with the two cameras, and the narrow-field instruments are awaiting the mapping of their entrance apertures in order to observe external sources.

The pointing control system is very complex and has been correspondingly difficult to make operational. The system consists of control algorithms in the spacecraft computer which accept input data from gyroscopes and star sensors and which issue pointing commands to momentum wheels. Momentum is managed through the use of magnetic torquers. The gyros control large slews and can also be used to maintain spacecraft pointing in the absence of star sensor data. There are two types of star sensors: three Fixed-Head Star Trackers pointed in various directions away from the telescope axis in order to measure approximate spacecraft orientations with respect to bright stars and three Fine Guidance Sensors mounted in the telescope focal plane to provide precise pointing information. In order to make the system useful the gyro drifts must be monitored and compensated, the angular relationships between the momentum wheel axes, the gyro axes, the Fixed-Head Star Tracker and Fine Guidance Sensor axes, the telescope axis and the positions of the entrance apertures of the various science instruments must all be measured precisely, and of course the techniques for using and integrating the data from all of these control sources must work smoothly. Further, the star trackers and guidance sensors have photometric calibrations and complex operating modes that need to be evaluated. While all of this equipment does not yet operate together in a routine way, the components do work according to their specifications and routine operations should come with experience. However, there is an unexpected disturbance source that has not yet been overcome. It appears that, during transitions from sunlight to darkness and from darkness to sunlight, thermal stresses are induced in the solar arrays which cause them to oscillate and introduce torques into the spacecraft. Although the major disturbances occur at day-night transitions, smaller disturbances occur randomly throughout the orbit and their cause is poorly understood. The oscillations are sinusoidal at the ten-second natural period of the solar arrays. Under gyro control their amplitudes are typically several arc-seconds, which is reduced to a few tenths arc-second under Fine Guidance control. In order to meet specification, which is expressed as 0.007 arc-sec rms, the pointing performance will have to be improved by more than a factor of twenty. Such an improvement appears to be possible by revising the control law algorithms specifically to accommodate torques of the frequency and amplitude that are observed. The flight control software is currently being rewritten to implement these changes.

4. Optical evaluation

Attempts to focus the telescope and to understand its optical quality have been complicated by the relative instability of the pointing system. Each of the Fine Guidance Sensors contains an interferometer designed to measure the wavefront produced by the telescope optics. The interferograms produced by these three instruments were designed to provide information on how to move the secondary mirror, which has five degrees of freedom, in order to remove focus, coma and astigmatism errors. The fringe visibility in the interferograms is greatly reduced by telescope jitter. In retrospect, it is apparent that their visibility is also low because the interferometers were not designed to work in the presence of large amounts of spherical aberration. After engineering checks were completed of the Wide Field/Planetary Camera and the Faint Object Camera, they were used to obtain stellar images at a variety of positions of the secondary mirror, and the analysis of these images made it plain that spherical aberration is present. Although the exact amount has not been finally measured as of this writing, the present data indicate it to be about 0.4 wave rms at a wavelength of 0.5 micron, with an uncertainty of about 0.1. This corresponds to an error in the profile of the primary mirror between the inner and outer masks of about 2 microns, in the sense that the curvature is too shallow. The point spread function produced by these optics consists of a sharp inner core whose full width at half maximum is about 0.08 arc-second and a faint outer skirt with a radius of about 0.7 arc-sec. Unfortunately, the inner core contains only about 15 percent of the total energy in the image.

The present plans are to set the secondary at an optimum position, proceed with instrument calibration and begin science observing as soon as possible. The objective of the focus optimization will be to remove coma and astigmatism and to maximize the energy in the central core. Pictures taken with this point spread function will be useful for many types of morphological studies and are potentially good candidates for the application of sophisticated image deconvolution techniques. Exciting scientific observations can be carried out at ultraviolet wavelengths with the cameras, spectrographs and photometer, and the astrometric programs should be able to proceed with little or no compromise. Looking to the future it appears that the surface quality of the mirrors is well within specification, so that future instruments built to compensate for the spherical aberration should achieve the full image quality that has been intended. Preliminary studies show that the three new instruments presently being developed will be able to incorporate the aberration compensation in a straightforward manner. Thus the replacement camera (WFPC II), the imaging spectrograph (STIS), and the near infrared instrument (NICMOS) can produce data that will met or exceed the original HST expectations. NASA is currently examining ways to accelerate the construction and deployment of these instruments.