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FIXED-HEAD STAR TRACKER ATTITUDE UPDATES ON THE HUBBLE SPACE TELESCOPE*

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ABSTRACT

The Hubble Space Telescope (HST) was launched in April 1990 to begin observing celestial space to the edge of the universe. National Aeronautics and Space Administration (NASA) standard fixed-head star trackers (FHSTs) are used operationally onboard the HST to regularly adjust ("update") the spacecraft attitude before the acquisition of guide stars for science observations. During the first 3 months of the mission, the FHSTs updated the spacecraft attitude successfully only 85 percent of the time. During the other periods, the trackers were unable to find the selected stars — either they failed to find any star, or worse, they selected incorrect stars and produced erroneous attitude updates. In July 1990, the HST project office at Goddard Space Flight Center (GSFC) requested that Computer Sciences Corporation (CSC) form an investigative "tiger" team to examine these FHST update failures. This paper discusses the work of the FHST tiger team, describes the investigations that led the team to identify the sources of the errors, and defines the solutions that were subsequently developed, which ultimately increased the success rate of FHST updates to approximately 98 percent.

INTRODUCTION

On April 24, 1990, the Space Shuttle Discovery was launched by the National Aeronautics and Space Administration (NASA) to deploy the Hubble Space Telescope (HST). HST contains a Ritchey-Chretien design Cassegrain telescope with a 94.5-inch primary mirror. The attitude control of the telescope is performed by HST's pointing control subsystem (PCS) (Reference 1). The PCS is supported by eight types of sensors and actuators, including fixed-head star trackers (FHSTs), fine guidance sensors (FGSs), and rate gyro assemblies (RGAs). The process whereby FHSTs update spacecraft attitude, which resulted in errors early in the HST mission, is the focus of this paper.

The NASA standard FHSTs on the HST are analog devices used to assist the ground in verifying the onboard attitude and to update the spacecraft attitude after large maneuvers. Each tracker can scan its 8.0-degree by 8.0-degree total field of view (FOV) (TFOV) to map out stars whose data can be subsequently used by ground software for attitude determination. It can also be commanded to search an approximate 1.5-degree by 1.5-degree reduced FOV (RFOV) region for a preselected reference star whose position error can be used to correct the spacecraft's attitude.

FGSs are used to obtain the precise pointing necessary during HST's science observations and as scientific instruments while in astrometry mode. Their FOV is along the telescope axis. Although variable, the accuracy of the attitude of the spacecraft is typically expected to be known to within 60 arcseconds for FGSs to acquire their guide stars and allow the HST to perform science observations.

The RGAs provide control for the vehicle during maneuvers. They also provide primary guidance for the telescope while the FGSs are occulted. Accurate calibrations of the RGAs and FHSTs are critical to the successful acquisition of guide stars by the FGSs. For more information on calibration of the HST attitude sensors, see Reference 2.

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Because of the unique value of HST science observing time, science observations are scheduled as efficiently as possible to make maximum use of unocculted time periods. To achieve this goal, vehicle attitude errors must be reduced as much as possible before FGS guide star acquisitions to minimize FGS search time and increase FGS guide star availability. In terms of FHST performance, these conditions place much more stringent demands on FHST accuracy and reliability than those experienced on previous missions. It therefore became a source of major concern when, soon after launch, it was discovered that FHST updates were correctly updating the spacecraft attitude only 85 percent of the time. The remaining time, updates resulted in two basic types of failures: timeouts and spoilers. A *timeout* failure occurs when the FHST fails to acquire the reference star or acquired the star later than the flight software (FSW) data base setting. A *spoiler* failure occurs when the FHST acquires an incorrect star or object (a spoiler), which results in the calculation of an inaccurate attitude update. These failures prevent HST's FGSs from acquiring guide stars, which in turn leads to missed science observations. The HST project at Goddard Space Flight Center (GSFC) directed CSC to form a special "tiger" team to investigate the cause of these failures. This team, which was expanded to include personnel from GSFC and other contractors, was also tasked to find solutions for this 15-percent failure rate. This paper discusses the use and "reliability calibration" of the FHSTs in their attitude update mode, the approach to the problem, investigations, solutions, and the current status of the problem.

FHST OPERATIONS ON THE HST

One of the keys to performing science observations with the HST is to first obtain an accurate attitude. After a viewing period has been completed, the spacecraft will slew to the next target and perform an FHST update. As stated previously, HST depends on calibrated RGAs to accurately reach this target. The pre-launch gyroscope scale factor alignment accuracy requirement was such as to permit errors on the order of 1 arcsecond/degree of slew following large maneuvers. In-flight calibration of the gyroscopes in July 1990 provided an accuracy on the order of 0.5 arcsecond/degree. Since the First Servicing Mission (FSM) of HST in December 1993, the accuracy has been improved to approximately 0.3 arcsecond/degree. The purpose of performing FHST updates is to remove the attitude errors that can accumulate over time (while HST maneuvers and when the FGSs are occulted) due to gyroscope errors. FHST updates typically bring the spacecraft attitude to within 15 arcseconds (1 sigma) of the planned target attitude, thereby permitting guide star acquisitions using the FGSs. The HST issues approximately 70 FHST updates per week.

The analog NASA standard FHSTs on HST work by raster scanning (see Figure 1) using the instantaneous FOV (IFOV) in both TFOV (map) mode and RFOV mode. For more detail on the FHST hardware, see References 3 and 4. There are some differences between the scan modes. The TFOV mode works by scanning in an increasing positive vertical direction and across, right to left or left to right horizontally. When a star is encountered within the previously set magnitude threshold (discrete settings assigned from the ground), the FHST begins a cross-scan on the star (track mode). If five cross-scans are made, star presence is triggered and acquisition occurs (0.5 second). The star is tracked for the FSW data base time limit and then the IFOV of the tracker jumps more negatively by 0.4 degree (approximately four analog scan lines) and "blanks" (essentially ignoring all light) approximately 0.6 degree (approximately six analog scan lines) in a positive vertical direction, thereby effectively blanking in a positive vertical direction by 0.2 degree.

The RFOV also works by raster scanning toward the positive vertical direction of the RFOV. The scan begins with an offset command at the vertical center, blanks six vertical lines (including the center), and then goes to the top (vertical negative). It takes 1.5 seconds to scan an empty RFOV and 11 seconds to scan an empty TFOV. Track mode works the same way in RFOV as in TFOV, except that the intent in RFOV mode is to remain fixed on the predetermined reference star for the remainder of the FHST update period. If the scan fails to find the star or finds a star that is not within the voltage (magnitude) tolerance set by ground command, the FHST continues its search across the RFOV with no blanking or jumping. If a break track command is issued, the tracker blanks approximately 0.6 degree (flight experience has shown 0.72 degree to be a more accurate value) in a positive vertical direction before scanning continues (Reference 5). The spacecraft remains fixed on the star after acquisition so the onboard software can compare the current position of the preselected star (within the tracker frame) with the expected position of the star (uplinked to the spacecraft) at that attitude. This difference is considered to be the attitude error. The HST then updates the attitude by issuing a slew to correct for this error. When two trackers are used, the error is combined to give a three-axis attitude error that has typically been within 15 arcseconds (1 sigma) of the desired attitude as measured relative to the FGSs. Problems result when the star is not acquired or an object other than the reference star is acquired and an errant update is performed.

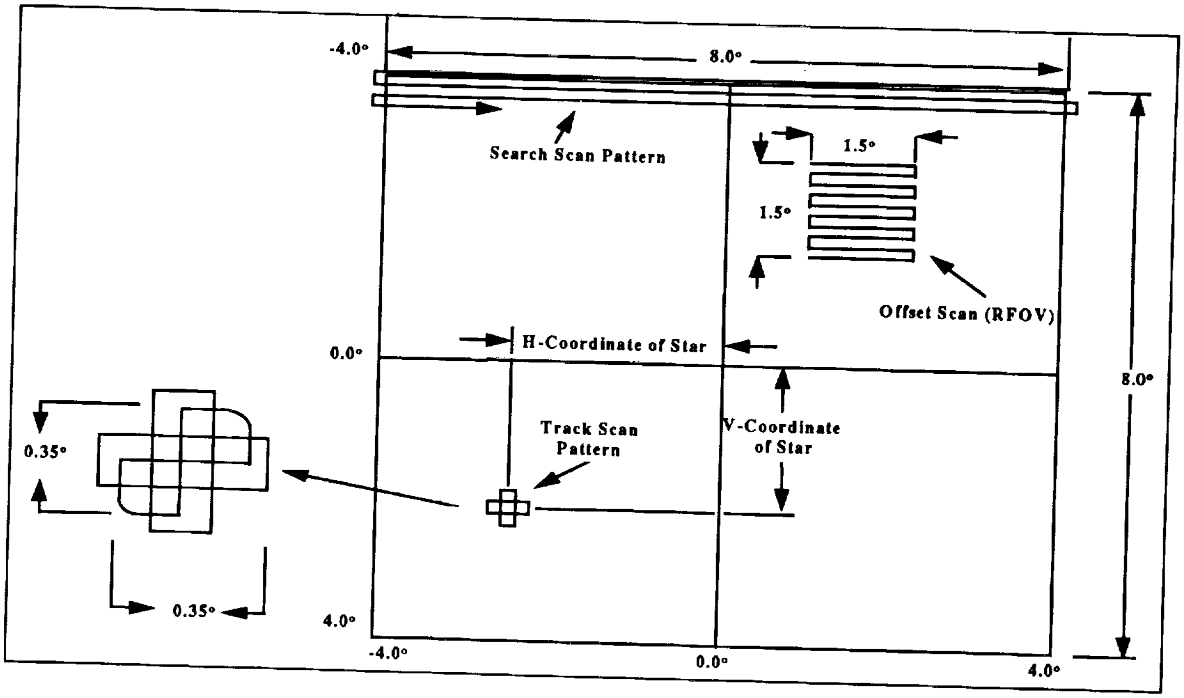

Figure 1. Generic FHST Description Diagram

UPDATE PROCEDURES

Fundamentally, FHST updates are requested through a science mission specification (SMS). The SMS acts as a script for the HST, typically describing a week's worth of activities. Among other things, it tells the spacecraft when to slew, when to perform science observations, and when to perform an FHST update. The SMS is read by the Payload Operations Control Center (POCC) Applications Software Support (PASS) command management software, which verifies constraints and generates commands. In this context, PASS plans the FHST updates. The following steps are performed by the PASS mission scheduling software to schedule an update:

1. *Check FHST availability.* The scheduling software checks to see which FHSTs are available or unavailable due to Earth and Moon occultations and Sun constraints.

2. *Determine candidate stars.* For the expected attitude, the ground software will look for candidates that are within the TFOV, between the bright and dim limits set (originally between 2.0 m_V and 5.7 m_V, currently between 2.0 m_V and 6.0 m_V), are not variable or double stars, do not have a large proper motion or position uncertainty, and are not in the BADSTARS file. The BADSTARS file is a sequential file that can be updated to exclude undesirable stars from reference star consideration. The star information used to support ground-based predictions and processing is generated from the PASS SKYMAP run catalog. This run catalog is a subset of the SKYMAP master catalog that is generated by the National Space Science Data Center and contains approximately 250,000 stars. The ground software for HST requires a subset of this catalog. Only stars that the trackers are capable of seeing are necessary for this run catalog.

3. *Determine reference stars.* The software chooses one of the stars from step 2. It verifies that the star is within a data base distance of the boresight, that its RFOV center is within an allowable range, that it is within a data base value of the edge of the RFOV, and that it is well isolated from potential spoiler stars.

4. *Determine the best reference star.* If several stars pass step 3, one star is chosen based on its not being in an undesirable region (a region where update failures have been known to exist or where the tracker is determined to be less sensitive) of the FHST TFOV, being furthest from the TFOV and RFOV edges (within data-base-specified tolerances), being furthest from its potential spoilers (within a data-base-specified tolerance), and being the brightest star.

If all of these tests are passed, the reference stars are chosen and commanding is generated for uplink to the HST. If none are chosen, then no update is performed. If a three-axis update (two FHSTs) is requested, but only one star passes the reference star tests, then the FHST update becomes a single-axis update using only one tracker. The following information, contained in the commands for the FHST update, is then prepared for uplink to the HST DF-224 onboard computer (OBC), to be used in conjunction with tracker alignment data:

- *Location of desired star at expected attitude* – The position of the star, in horizontal and vertical counts, in FHST coordinates, are taken from steps 3 and 4 of the previous procedure.

- *RFOV center coordinates* – The ground software chooses a RFOV (from a discrete set of values, each offset from the previous value by 0.5 degree) that can best isolate the chosen reference star. This will increase the chances of acquisition.

- *Reduced set of distortion coefficients* – Distortion effects are computed for each reference star and packaged in a format appropriate for use by the OBC. A discussion of the calibration of FHST distortion and scale is presented in Reference 3.

- *Type of update* – The onboard software needs to know whether a three-axis (two FHSTs) or one-axis (one or two FHSTs) update is expected to be performed and whether to issue the resulting attitude correction at the time of computation (maneuver mode) or wait until requested to issue the update (delayed mode).

- *Magnitude threshold setting for the FHST* – The FHSTs have four threshold settings, each of which is hardware-voltage dependent. The voltages correspond, approximately, to magnitudes 3, 4, 5, and 6 (commonly referred to as a "wide open" value). When set to these values, the FHST will be sensitive to stars brighter than the limit. For example, if the tracker is set to a threshold of 5, it will be capable of seeing any star that is brighter than the original hardware voltage setting, which, if set perfectly, would mean any star brighter than 5 m_V. A setting of 6 means that the FHST is capable of seeing down to the hardware creation limit of the internal photocathode tubes. The first sensitivity study of the trackers discovered that FHSTs 1, 2, and 3 had seen stars as dim as 7.12 m_V, 6.80 m_V, and 6.64 m_V, respectively (see Reference 6). Hardware acceptance test data showed that the threshold voltages differ significantly from the voltage values that actually map to the integer values of 3, 4, 5, and 6 for the magnitude.

The spacecraft then executes the stored commands (and therefore, the attitude updates). It was at this point that problems were first noticed. Additional information on the PCS is presented in *HST Flight Software Examination for the PCS* (Reference 7).

PROBLEM APPROACH

On July 6, 1990, GSFC requested that CSC assemble a "tiger team" to investigate, and, if possible, solve the FHST update failure problem. The team decided that the best approach to the problem was to create a data base of FHST update failures and successes, analyze successful updates to obtain the correct signature of an update, analyze all failures and categorize them, perform correlation studies, and publish a weekly report to keep the customer (GSFC) apprised of the situation.

To fully analyze and categorize FHST update failures, a system of data collection that included both predictive and post-failure data was used. All of the predictive data for FHST updates were provided by reports from the PASS mission scheduling subsystem. The PASS mission scheduling subsystem selects the appropriate reference star(s), generates the predictive horizontal and vertical coordinates for that star, the RFOV center, the FHST threshold setting, and the reference star's SKYMAP number, visual magnitude, and right ascension and declination from the PASS SKYMAP run catalog. The mission scheduling subsystem also provides FHST scheduling timelines and a predictive TFOV plot that includes the RFOV, the reference star, and all nearby spoiler stars.

Once the update is executed onboard HST, near-real-time data concerning the event can be monitored or snapped from a PCS console display or plotted on a strip chart plotter in the HST Mission Operations Room (MOR). If an FHST anomaly is observed, a console engineer writes an HST anomaly report (HSTAR). FHST failure analysis begins after the tiger team receives the HSTAR.

Examination of FHST failures can be accomplished in several ways. The raw horizontal and vertical counts and the observation intensity (volts) of the FHST scan can be reviewed, after the fact, using plots created by the PASS fine attitude determination software. The position and magnitude data of the FHST scan can also be provided by plots generated by the HST engineering support system. It is typically from these data, in comparison with the predictive data, that a failure can be categorized. The DF-224 Analysis and Software Development Facility (DASDF) real-time graphics system was used by the tiger team to obtain history data of FHST updates that had occurred weeks and months in the past. This system replays the HST engineering telemetry stream using history tapes and outputs MOC console PCS displays. The DASDF system was used extensively to create a history of early FHST successes and failures.

In cases where spoiler objects were acquired, many resources were available for the spoiler object's identification. The SKYMAP and Smithsonian Astrophysical Observatory (SAO) catalogs were commonly used to identify spoiler stars acquired during the update. For other spoiler objects, the Astrophysics Data System (ADS), and the Atlas Coeli 1950.0 and SAO sky atlases were used. ADS is an on-line, Internet-accessible data system, supported by NASA, that provides access to astrophysics catalog data.

The first determination resulting from this analysis revealed that HST's FHSTs were more sensitive than originally expected. It had been documented that FHSTs could see down to a magnitude of 5.7 and the first reference star catalog contained stars downs to 6.7 m_V. Spacecraft data clearly showed that it was necessary to extend the SKYMAP run catalog to include dimmer stars. Although reference stars dimmer than 5.7 m_V were not selected, dimmer stars (down to 7.1 m_V) that were being seen within the RFOV acted as spoilers, forcing attitude update failures. The catalog was adjusted to include stars down to 7.1 m_V. An earlier change to the catalog and selection algorithm was to prevent double stars, variable stars, and stars with large proper motion from being chosen as reference stars, but to retain them as potential spoiler stars. This action thereby allowed the software to choose an alternate reference star if one of these spoilers was in the RFOV, bringing the success rate up to approximately 90 percent.

The data base of update successes and failures was begun on July 12, 1990. It consisted of 3,515 updates at completion. The following information was kept on each update: date, time, FHST number, telemetry slot, category, SKYMAP number, expected position (right ascension and declination) of star, expected and observed position of star in FHST, magnitude, intensity, threshold setting, RFOV center coordinates, and spacecraft attitude (right ascension, declination, and roll). By reviewing these updates, the tiger team was able to define 13 distinct update failure categories that required investigation; subsequent analysis identified two additional categories. Each category is described in detail in Appendix A. The following studies were set up to analyze these failures:

- FHST sensitivity (References 6, 8, 9, and 10)
- Data correlations (stellar magnitude versus failure, RFOV position versus failure, RFOV position versus success, day/night transitions versus success/failure, solar array angle versus success/failure)
- Examination of stars from updates that failed, using information from other star catalogs (e.g., SAO)
- Discussions with the hardware manufacturer
- Possible algorithmic modifications
- Creation of a FSW reference star quality test (the "error box")
- Tuning the ground star selection algorithm

Reports and status summaries of these studies were presented by the tiger team on September 7, October 25, and October 26, 1990; and on February 22, 1991 (References 11, 12, and 13).

By studying the data and the various categories, solutions were developed. Solutions were reduced to the following main subject areas:

1. *Star catalog issues*, where the PASS SKYMAP run catalog had to be updated twice to account for the dimmest stars the trackers could see, which acted as spoilers, and an additional time to correct for magnitude errors in the master catalog.

2. *Hardware properties*, which ranged from gaining operational experience (e.g., in flight calibrations) for the sizes of the TFOV, RFOV, and voltage (magnitude) threshold limits, to supporting less sensitive areas on the trackers, to making corresponding software algorithmic and data base changes to accommodate these updates.

3. *Commanding problems*, which ranged from command group information corrections to command timing modifications.

4. *Implementation of an error box* to add a flight-proven [on the High-Energy Astronomy Observatory (HEAO)] check in the FSW. This allowed the ground software to better isolate a reference star (the size of the error box is smaller than the RFOV), and to increase the likelihood of finding the correct star.

These solutions may be useful to others with similar problems with FHSTs, or for review before designing a new system with FHSTs. A detailed list of these solutions containing a description, the category affected, the problem solved, and a description of new problems created is presented in Appendix B.

CURRENT STATUS

On December 2, 1993, the Space Shuttle Endeavour embarked on HST's FSM to correct the telescope's optical errors, replace failed equipment, and add the new wide field/planetary camera (WFPC). Although no FSM repairs were performed on the FHSTs, there was concern that the trackers might be accidentally damaged or misaligned because they are located in the same local compartment on the HST as the gyroscopes that were replaced. Following the FSM, it was verified that FHST calibration and response characteristics remained unchanged and FHST updates and maps worked as expected.

From October 1993 to March 1994, 1,326 attitude updates were issued with 22 recorded failures. Six of these failures were caused by attitude errors in excess of 300 arcseconds following the FSM. The ground system has been set up to assume that during normal operations, attitude errors are well contained and should never exceed 300 arcseconds. Due to the changeout of uncalibrated RGAs during the FSM, these types of errors were not unexpected. These failures were therefore not due to errors within the FHST hardware or software systems. Excluding these failures from computations gives a success rate of 98.79 percent over the most recent 130 days. The breakdown of the 16 remaining failures is as follows (the category number is as indicated in Appendix A):

- Seven category 2 failures, all on the same reference star, which was located less than 400 arcseconds from the RFOV edge
- Two failures of the same back-to-back spoiler acquisition caused by a RFOV problem
- Two delayed-mode update duration problems
- Two blanking problems
- Two potential Artificial Earth Satellite (AES) acquisitions
- One category 9 failure, when the FHST acquired a bright open cluster

Of all of these failures, only the potential AES acquisitions cannot be solved with simple data base changes. Figure 2 shows a plot of FHST update successes versus time. Each point on the plot represents the success rate for a 1-month period. Note that no data were collected for May and June 1991 and September 1992 through September 1993. The anomalous point in December 1994 contains the seven category 2 failures of the same star. Data base changes are being made to prevent this failure from occurring again.

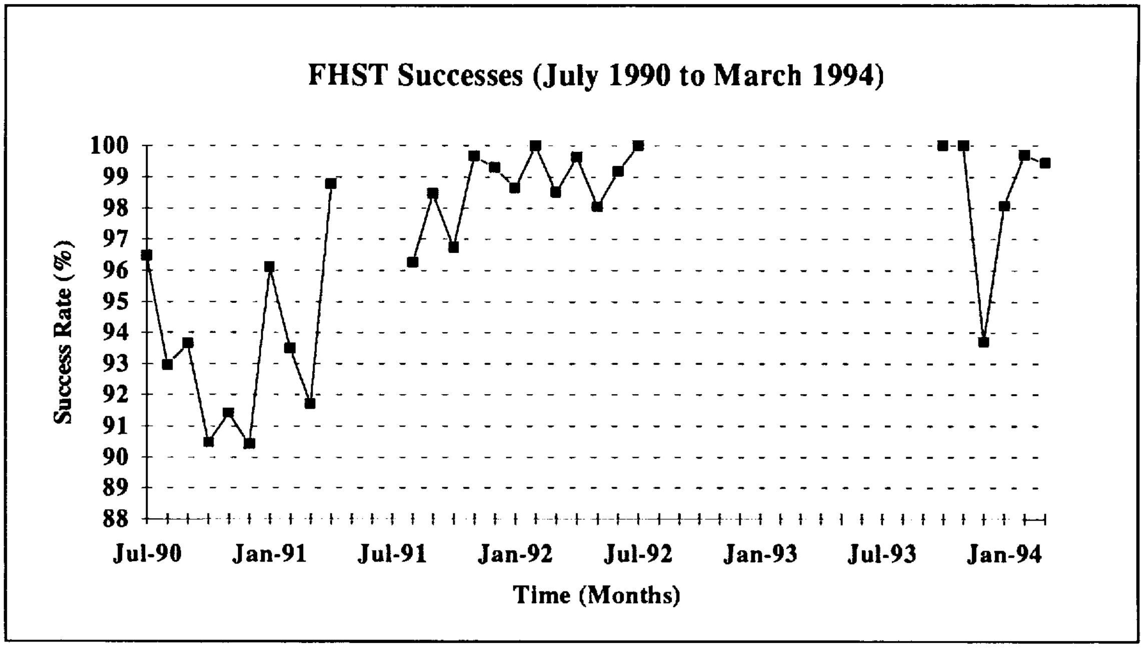

Figure 2. FHST Successes (July 1990 to March 1994)

Analysis of FHST failures will continue on HST. Adjustments may need to be made to RFOV and error box blanking sizes to reduce or eliminate these failure categories. Category 9 spoiler problems can be solved with updates to the BADSTARS file or by installing future versions of the SKYMAP catalog that will contain updated star information. No software or data base changes are planned to prevent potential AES problems because they occur too infrequently (only three have occurred in the last 2 years) to impact FHST operations. Further work on the least understood failure types (categories 1, 2, and 3) is in progress. Many category 2 failures have been reclassified as other anomalies, including the recent discovery and fix of the delayed-mode update duration problem. The last category 1 and 3 failures were recorded in September and July of 1993, respectively. These failure types are not currently impacting FHST operations. As of March 1994, the FHST update success rate was approximately 99 percent.

SUMMARY

This paper has presented a review of investigations undertaken to improve the reliability of FHST attitude updates performed by the HST. An update failure rate of roughly 15 percent, with an associated significant loss of science, was experienced during the beginning of the HST mission. Extensive investigations have led to a categorization of the 15 types of update failures and the development of operational solutions that have reduced the failure rate to roughly 1 percent. Investigations continue with the goal of improving FHST update reliability even further.

APPENDIX A - FHST FAILURE CATEGORIES

This appendix lists the FHST failure categories that were determined by the tiger team. Each failure that was examined was analyzed and assigned a category. For each category, the symptoms of the failure are described, the causes or suspected causes listed, and the current status (as of March 1994) is given.

Table A-1. FHST Failure Categories (1 of 2)

Category	Title	Symptoms	Causes	Status
1	RFOV Excursions With Noise Spikes	The raw data show a noisy scan in both horizontal and vertical directions with excursions outside the RFOV. Intensity spikes greater than the expected reference star intensity are seen.	Under study. The noise in the data implies that bright light is in the RFOV. Stray light from reflections off the sun shades or solar arrays has been considered a possible source.	Under analysis. These failures are responsible for 8% of all failures since April 1992.
2	Star Not Acquired in RFOV; No Noise on Magnitude	Clean, blank scans in both horizontal and vertical directions are observed with no recorded intensity beyond typical background noise.	Under study. The blank scan and lack of intensity imply that the RFOV is empty or that the shutter for the FHST is closed. Some category 2 anomalies have been attributed to commanding errors, reference star magnitude errors, and large HST attitude errors.	Partially corrected. Software and data base changes have eliminated some of these failures but other unexplained ones continue to occur. Category 2 failures are responsible for 16% of all failures since April 1992.
3	Star Not Acquired in RFOV; Magnitude Spikes	Clean, blank scans in both horizontal and vertical directions are observed with recorded intensity spikes typically up to the expected reference star intensity.	Under study. The intensity spikes for this anomaly imply that some object with brightness close to the reference star is in the RFOV, but for whatever reason cannot be acquired. Many of these anomalies have been caused by thresholds being improperly set.	Partially corrected. Software and data base changes have eliminated some category 3 failures identified as threshold problems (see below) but other unexplained category 3 failures continue to occur. Category 3 failures responsible for 16% of all failures since April 1992.
4	Acquired Spoiler Star Outside RFOV; No Intensity Noise	A spoiler star is acquired outside the predicted RFOV.	The true FHST RFOV sizes are not precisely known.	Corrected
5	Reference Star Outside RFOV Due to Attitude Error	Clean, blank scans in both horizontal and vertical directions are observed with no recorded intensity beyond typical background noise (similar to category 2)	The reference star selected had a predicted position too close to the edge of the RFOV. Large HST attitude errors positioned the reference star outside the RFOV.	Corrected
6	Flight Software Command Timing Error	The A channel for FHST data appears empty while the B channel contains the expected A channel data.	Internal FSW had a A/B channel, DF-224 40Hz/1Hz processor timing problem.	Corrected
7	Ground Commanding Error	The FHST update was not issued. No data were available (FHST shutters closed).	An error existed in the set-up of ground software command groups.	Corrected
8	Spoiler Star; Uncertainties of Attitude Position	The acquisition of a spoiler star inside the predicted RFOV.	The spoiler star, with a predicted position outside the RFOV, was relocated inside the RFOV due to spacecraft attitude error.	Corrected

Table A-1. FHST Failure Categories (2 of 2)

Category	Title	Symptoms	Causes	Status
9	Spoiler Object; Not Identified in PASS Star Catalog	The acquisition of a spoiler object inside the predicted RFOV.	1) A star too dim to be in the PASS reference star catalog but bright enough to be acquired by the FHSTs; 2) open clusters, globular clusters, and bright galaxies (none of which are in the PASS star catalog); or 3) very bright planets or stars not predicted to be located in the RFOV, but inside due to large FHST distortion calculation errors.	Corrected for causes 1 and 3. Cause 2 failures can be corrected on a case by case basis using the BADSTARS file. Cause 2 failures of category 9 account for 14% of all failures since April 1992.
10	RFOV Outside the TFOV	Clean, blank scans in both horizontal and vertical directions are observed with no recorded intensity beyond typical background noise.	RFOVs were allowed to extend outside the TFOV. Reference stars could be scheduled outside the TFOV and therefore not acquired.	Corrected
11	Catalog Magnitude Error	Clean, blank scans in both horizontal and vertical directions are observed with no recorded intensity beyond typical background noise (similar to category 2).	The SKYMAP Master catalog, used as the source for the PASS reference star catalog, contained magnitude errors for some reference stars used. Updates using reference stars whose magnitude were too dim to be acquired could be scheduled.	Corrected
12	Potential Artificial Earth Satellite (AES) Interference	A good acquisition of reference star; interruption by bright, moving object, is observed.	Possible AESs. Past suspects included the Space Shuttle, GRO, and TDRS.	Uncorrected. Category 12 failures account for 5% of all failures since April 1992.
13	Threshold Problem, Reference Star Not Observed in RFOV	Clean, blank scans in both horizontal and vertical directions are observed with recorded intensity spikes typically up to the expected reference star intensity (similar to category 3)	The PASS software assigned a FHST threshold setting (3,4,5, and 6) for reference stars assuming the hardware used 3.0, 4.0, 5.0, and 6.0 magnitudes, respectively, as accurate threshold cutoffs. A reference star could be scheduled with an incorrect threshold setting and therefore not acquired.	Corrected
Blanking	FHST Error Box Blanking Problem	A spoiler star, with an expected position inside the RFOV but outside the allowable reference star region, is acquired. FHST breaks track off the spoiler but the reference star is not acquired.	The blanking sizes of each FHST are not precisely known.	Partially corrected. True blanking sizes are currently being studied. Blanking failures account for 24% of all failures since April 1992.
TFOV Problem	Reference Star Too Close to the TFOV Edge	Clean, blank scans in both horizontal and vertical directions are observed with no recorded intensity beyond typical background noise (similar to category 2).	The FHST update was scheduled with the reference star too close to the TFOV edge. The TFOV sizes of each FHST are not precisely known and large flat-field distortion exists near the edges.	Under analysis. TFOV problems account for 6 % of all failures since April 1992.

APPENDIX B - FHST FAILURE SOLUTIONS

This appendix lists the FHST failure solutions that were determined by the tiger team. For each solution, a title and description is provided along with a list of the categories (from Appendix A) affected and descriptions of problems solved and created during the solution process. Solutions are grouped according to the following types:

1. Star catalog issues
2. Hardware properties
3. Commanding problems
4. Implementation of an error box

Table B-1. FHST Failure Solutions - Star Catalog Issues

Title	Description	Categories Affected	Problems Solved	Problems Created
Modified BADSTARS File	Stars were added to a PASS software namelist to prevent a particular star from being selected as a reference star.	3, 9, 11	Stars with SKYMAP catalog magnitude errors (category 11) were placed in the BADSTARS file until SKYMAP master catalog and then run catalog updates became available. Many stars were added as a result of comparing SKYMAP with the TYCHO star catalog. Reference stars located near bright stellar objects not in the PASS star catalog were placed in the file on a case-by-case basis to solve category 9 failures. Particular troublesome reference stars with category 3 failure behavior were also placed in the BADSTARS file to prevent their selection in the future.	The reduction of the number of reference stars available can make FHST update scheduling slightly more difficult.
Updated PASS Star Catalog	The PASS reference star catalog was updated to increase the limiting star magnitude from 6.7 m_V to 7.1 m_V (containing close to 25,000 stars) and finally to 7.5 m_V (containing over 40,000 stars). This magnitude limit was increased based on stars observed by the FHSTs. This change allowed inclusion of stars where the catalog listed a them as very dim but with large errors on the magnitude or variables.	9	The catalog updates eliminated many of the category 9 failures where the spoiler star was too dim to be in the PASS star catalog (see References 6, 8, 9, and 10).	The increased number of potential spoilers for sensitive FHSTs reduced the number of available updates.
Installed SKYMAP Star Catalogs, Versions 3.5 and 3.7	SKYMAP master star catalog has been updated twice since the launch of HST. These newer versions of SKYMAP contained more accurate star data as well as corrections to previous errors in star magnitudes and positions.	11	The SKYMAP updates prevented all previous category 11 failures from reoccurring and allowed the removal of many stars from the BADSTARS file.	None

Table B-2. FHST Failure Solutions - Hardware Properties (1 of 2)

Title	Description	Categories Affected	Problems Solved	Problems Created
Modified FHST Threshold Tolerances	The PASS software data base was modified to increase the tolerances on FHST threshold settings. These tolerances are used to isolate reference stars from spoiler stars.	1, 2, 3	This fix, implemented shortly after launch, greatly reduced the number of timeout failures. By increasing these threshold tolerances, many reference stars previously selected when there were spoilers inside the RFOV were now rejected.	The number of updates that could be scheduled was reduced.
Increased FHST Update Search Times	The FSW data base was modified to increase the FHST update search time for a reference star from 20 seconds to 45 seconds.	1, 2, 3	Some of these time-out failures appeared to have eventually acquired their reference stars. This increase in FHST update search time was thought to eliminate those failures.	None
Used FHST Undesirable Regions	The PASS software data base was modified to apply an undesirable region to the one-third most negative horizontal portion of the FHST-3 FOV. This allowed a reference star to be selected in this region only if no other candidate stars existed.	1, 2, 3	A large number of time-out failures occurred in this region of FHST-3. Avoiding this region was thought to have helped schedule better updates.	By not selecting a reference star in the undesirable region, the reference star selection algorithm was forced to attempt to select a star that may be less preferred by other predetermined criteria.
Installed Rectangular RFOVs	The PASS software was modified to model the dimensions of each FHST's RFOV as rectangles instead of 1.5-degree squares. Hardware acceptance test data show these modifications: FHST H° V° 1 1.65 1.52 2 1.64 1.53 3 1.56 1.41 Operational experiences show the RFOV to be the following for reference star selection and spoiler protection, respectively: FHST H° V° 1 1.338 1.340 2 1.300 1.300 3 1.380 1.240 FHST H° V° 1 1.818 1.553 2 1.808 1.563 3 1.728 1.443	4	The PASS software change eliminated most of the category 4 failures. The change also greatly improved the quality of update scheduling by allowing better spoiler protection control via data base parameters. It also eliminated awkward data base workarounds.	Occasional update failures caused by the true RFOV sizes not being consistent with the hardware acceptance test data still occur.

Table B-2. FHST Failure Solutions - Hardware Properties (2 of 2)

Title	Description	Categories Affected	Problems Solved	Problems Created
Restricted Reference Star RFOV Positions	PASS software data base modifications were made to restrict the position of reference stars sufficiently away from the RFOV edge.	2, 5	The PASS software change eliminated the category 5 failures. Forcing the reference star towards the interior of the RFOV was also thought to have reduced category 2 failures.	None
Added TFOV Pad	The PASS software was modified to include a pad around the TFOV for spoiler checking. This pad is used when a FHST RFOV is selected near the edge of the TFOV.	8	Eliminated category 8 failures where the spoiler was expected to be outside the TFOV (and therefore not in the RFOV) but came in due to attitude error. (Discussions with the manufacturer revealed that the TFOV can actually extend to 8.5 degrees, although it is not usable for placing reference stars.) The software modification allowed for more control on the size of the TFOV and the removal of complicated data base workarounds.	None
Improved Magnitude to Intensity Conversion Model	The PASS software was modified to more accurately convert very bright planets' and stars' visual magnitudes to voltage intensities for FHST FOV distortion calculations. This improvement eliminated large predicted position error for bright objects.	9	The PASS software change eliminated all category 9 failures caused by very bright planets or stars.	None
Restricted FHST RFOV Centers	The PASS software data base was modified to prevent FHST RFOVs from overlapping the TFOV.	10	The data base modification eliminated all category 10 failures.	None
Improved FHST Threshold Settings	The PASS software was modified to allow the FHST reference star selection algorithm to use more accurate voltage intensity threshold settings instead of rough magnitude approximations. These threshold settings were assigned values based on FHST hardware acceptance test data and operational experience.	13	The PASS software change eliminated category 13 failures and allowed the removal of complicated data base workarounds.	None

Table B-3. FHST Failure Solutions - Commanding Problems

Title	Description	Categories Affected	Problems Solved	Problems Created
Increased Delayed-Mode Update Durations	The PASS software data base was modified to increase the duration of delayed-mode updates to allow sufficient time for full onboard processing.	2	Special time-out failures where a delayed-mode update was scheduled shortly before the HST entered occultation were eliminated. Several of these failures were initially placed in category 2.	None
Corrected Flight Software Command Timing	The FSW was modified to correct the DF-224 40 Hz/1 Hz processor timing problem.	6	The FSW change eliminated all category 6 failures.	None
Modified Ground Command Groups	The operational ground software command groups were changed to prevent a known FHST update commanding error.	7	The modified command groups eliminated all category 7 failures.	None

Table B-4. FHST Failure Solutions - Implementation of an Error Box

Title	Description	Categories Affected	Problems Solved	Problems Created
Implemented FHST Error Box Checks	The error box check is a method implemented in both the ground and FSW to allow the OBC to quickly determine whether or not the desired reference star is being observed by the FHST. The PASS software schedules an update with a reference star inside a special data-base-sized isolation region within the selected RFOV.	4, 8, 9	Most spoiler problems occur where the spoiler object is located outside the error box. This change in PASS software increased the number of reference stars available for an FHST update because the required reference star isolation region was reduced.	Spoiler star failures caused by improperly predicted blanking by the FHSTs (blanking category) were introduced.
	This isolation region should be equal to the expected FHST hardware blanking size plus the expected HST attitude error. This new reference star isolation algorithm allows for spoiler stars to reside within the RFOV as long as they are outside the specified isolation region. Once isolated, the reference star position in observation coordinates are uplinked to the spacecraft. When the FHST observes a star, the error box check requires that the observed coordinates be directly compared with the uplinked coordinates. If the comparison is successful within the bounds of the anticipated attitude error, the FHST can proceed with the attitude update. If the error box check fails, a break track command is issued, the FHST blanks six or seven scan lines (approximately 0.72 degree) (as described in the RFOV description in the BACKGROUND section), and the search for the reference star continues. Currently, three error box checks are issued each update. The third of the checks must be successful or the update fails. (see Reference 14). This operation was verified in a spacecraft test that occurred during the week of August 12, 1991 (see References 14, 15, and 16).			

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