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In-Flight Scale / Distortion Calibration of the Hubble Space Telescope Fixed-Head Star Trackers[1]

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ABSTRACT

This paper describes an in-flight scale and distortion calibration procedure that has been developed for the Ball Aerospace Systems Division Fixed-Head Star Trackers (FHSTs) used on the Hubble Space Telescope (HST).

The FHST is a magnetically focused and deflected imaging sensor that is designed to track stars as faint as m_V = 5.7 over an 8-degree by 8-degree field of view. Raw FHST position measurements are accurate to approximately 200 arcseconds, but this can be improved to 10-15 arcseconds by processing the raw measurements through calibration polynomials that correct for flat field, temperature, intensity, and magnetic field effects. The coefficients for these polynomials were initially determined using ground test data.

On HST the use of three FHSTs is an integral part of the preliminary attitude update procedure required before the acquisition of guide stars for science observations. To this end, FHST-based attitude determination having single-axis errors no worse than 22 arcseconds (1σ) is required.

In early 1991 it became evident that one of the HST FHSTs was experiencing a significant change in its optical scale. By mid-1993 the size of this error had grown to the point that, if not corrected, it would correspond to a maximum position error on the order of 100 arcseconds. Subsequent investigations demonstrated that substantial, uncompensated cubic distortion effects had also developed, the maximum contribution to position errors from the cubic terms being on the order of 30 arcseconds. To ensure accurate FHST-based attitude updates, procedures have been developed to redetermine the FHST scale and distortion calibration coefficients based on in-flight data gathered during normal HST operations. These scale and distortion calibrations have proven very effective operationally, and procedures are in place to monitor FHST calibration changes on a continuing basis.

INTRODUCTION AND BACKGROUND

The Hubble Space Telescope (HST) was launched into low Earth orbit on April 24, 1990. Equipped with an Optical Telescope Assembly (OTA) capable of providing image resolution 10 times sharper than that provided by ground-based telescopes, HST must be able to place science targets into scientific instrument (SI) apertures as narrow as 0.1 arcsecond and maintain stability to an accuracy as high as 0.007 arcsecond averaged over 24 hours.

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HST is equipped with a variety of attitude sensor and control devices: three Rate Gyro Assemblies (RGAs), three Fixed-Head Star Trackers (FHSTs), three Fine Guidance Sensors (FGSs), five Coarse Sun Sensors (CSSs), two three-axis Magnetic Sensing Systems (MSSs), four Magnetic Torquing Systems (MTSs), and four Reaction Wheels (RWs). Figure 1 shows the locations for most of these instruments and defines the HST V_1-V_2-V_3 reference frame. The FGSs, FHSTs, and RGAs provide attitude information during normal operations, whereas the CSSs and MSSs are used as attitude sensors mainly during initial HST deployment and also when the spacecraft is in safemode. The RWs serve as the primary attitude torquing mechanism, and the MTSs are used as momentum dumping devices.

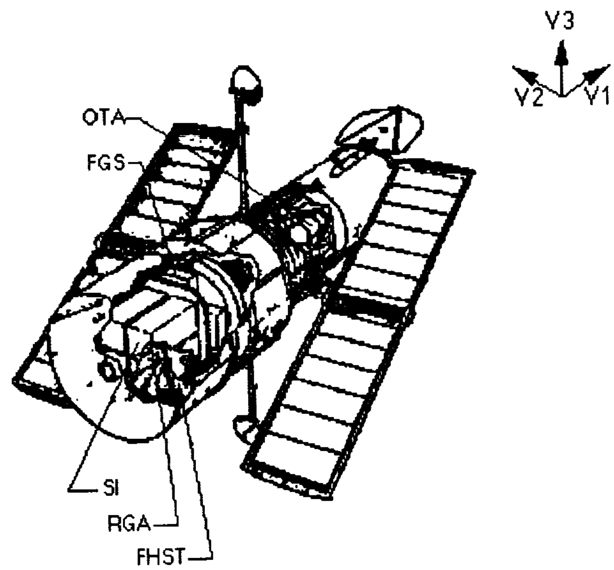

Figure 1. HST and the HST V_1-V_2-V_3 Reference Frame

The FGSs are the dominant instruments for attitude control during science operations. They are capable of tracking stars between $m_V = 9$ and $m_V = 14.5$ with a differential accuracy of ~.003 arcsecond after calibration (Welter, 1991b and 1994), and the alignments of the combined FGS field of view (FOV) relative to the SIs currently are known to within ~1 arcsecond. At present FGS guide star acquisition requires preacquisition attitude knowledge that is accurate to within ~60 arcseconds. Failure to acquire a guide star will result in the loss of a scheduled science observation.

The FHSTs are the primary attitude sensors for determining HST attitude before FGS guide star acquisition. FHST-1 is mounted with its boresight approximately along the $-V_3$ axis, whereas FHSTs 2 and 3 are mounted pointing downwards and backwards in the HST reference frame with boresights that are located in a plane rotated approximately 45 degrees around the V_2 axis away from the V_2/V_3 plane and 30 degrees to either side of the V_1/V_3 plane.

The HST FHSTs are used in two modes. In map mode the trackers scan their FOVs and provide position information for all stars detected over a fixed period of time. The fine attitude determination function of the ground-based HST Payload Operations Control Center Applications Software Support (PASS) system uses these map data to compute an attitude that can be used to initialize (e.g., after initial release from the shuttle) or reinitialize (e.g., during recovery from safemode) the onboard computer's attitude knowledge.

In update mode one or two FHSTs are commanded to locate and track preselected reference stars (one star per tracker), and the flight software uses these stars' measured positions to compute either roll or three-axis attitude updates. Roll updates usually are performed before large slews, and attitude updates are performed following large attitude slews and before attempting FGS guide star acquisition. ([Hallock, 1990] provides a thorough description of how the HST flight software uses FHST data.)

As can be seen from this description, improper knowledge of reference star positioning within the FHST FOV will lead to degraded onboard attitude knowledge and potential failure of FGS guide star acquisition. Failure of FGS acquisition, in turn, will cause a loss of science data. Hence it is critical that the FHSTs be calibrated to perform at the limit of their measuring potential. To this end, FHST-based attitude determination having single-axis errors no worse than 22 arcseconds (1σ) is required (Fallon, 1983).

The present paper describes an in-flight calibration of the HST FHSTs that was undertaken in response to uncompensated scale factor and distortion phenomena that were noted in the FHST measurements following launch--phenomena that on occasion were causing FGS guide star acquisition failures. The following sections provide a general description of the FHST hardware and FHST calibration procedures, an historical recounting of how the scale factor and distortion effects were uncovered and the steps that were taken to reduce these effects to a minimum, and a brief description of future FHST calibration activities along with recommendations for FHST calibrations on other spacecraft missions.

DESCRIPTION OF FHST AND FHST DATA PROCESSING ON HST

The FHST, also known as the NASA standard star tracker, was developed by Ball Aerospace Systems Division (BASD) and has been used as an attitude sensor on numerous NASA missions beginning with the Solar Maximum Mission (SMM). At present, FHSTs are in use on the Compton Gamma Ray Observatory (GRO), the Upper Atmosphere Research Satellite (UARS), and the Extreme Ultraviolet Explorer (EUVE) in addition to HST. A complete description of the FHST can be found in (BASD, 1981).

Employing a 70mm, f/1.2 objective lens, the FHST uses an electronic scan to search its FOV and acquire reference stars. The heart of the FHST is an ITT F4012 RP image dissector. The objective lens forms an image on the dissector's photocathode (Figure 2). Light from star images on the photocathode generates an electron stream that is deflected toward a fixed receiving aperture by magnetic coils. As the magnetic deflecting coils' currents are varied, different active portions of the photocathode direct their electrons toward the aperture and from there to an electron multiplier. Therefore, through proper selection of the coil currents, the light impacting any portion of the photocathode surface can be sampled. The size of the region sampled is the FHST's instantaneous FOV (IFOV) and is defined by the size of the fixed aperture to be 9-arcminutes-by-9-arcminutes.

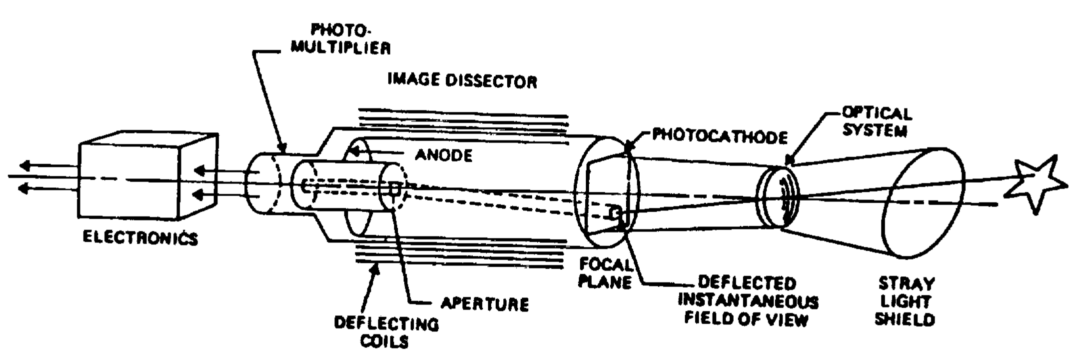

Figure 2. Cutaway Diagram of an FHST

As illustrated in Figure 3, when first turned on or when so commanded, an FHST scans either its 8-degree-by-8-degree total FOV (TFOV) or a ground-commanded 1.5-degree-by-1.5-degree reduced FOV until it encounters an object brighter than a commanded threshold. (These FOV dimensions are approximate. Although BASD designed the FHST to observe stars to $m_V = 5.7$, one of the HST FHSTs has regularly tracked stars as dim as $m_V = 7$ [Davenport, 1991, and Welter, 1992].) The FHST then enters a smaller cross-pattern scan centered on this object and forms output position and intensity information. The FHST will continue to track the object until it leaves the TFOV, its observed intensity falls below the commanded threshold, or a command is issued to break track.

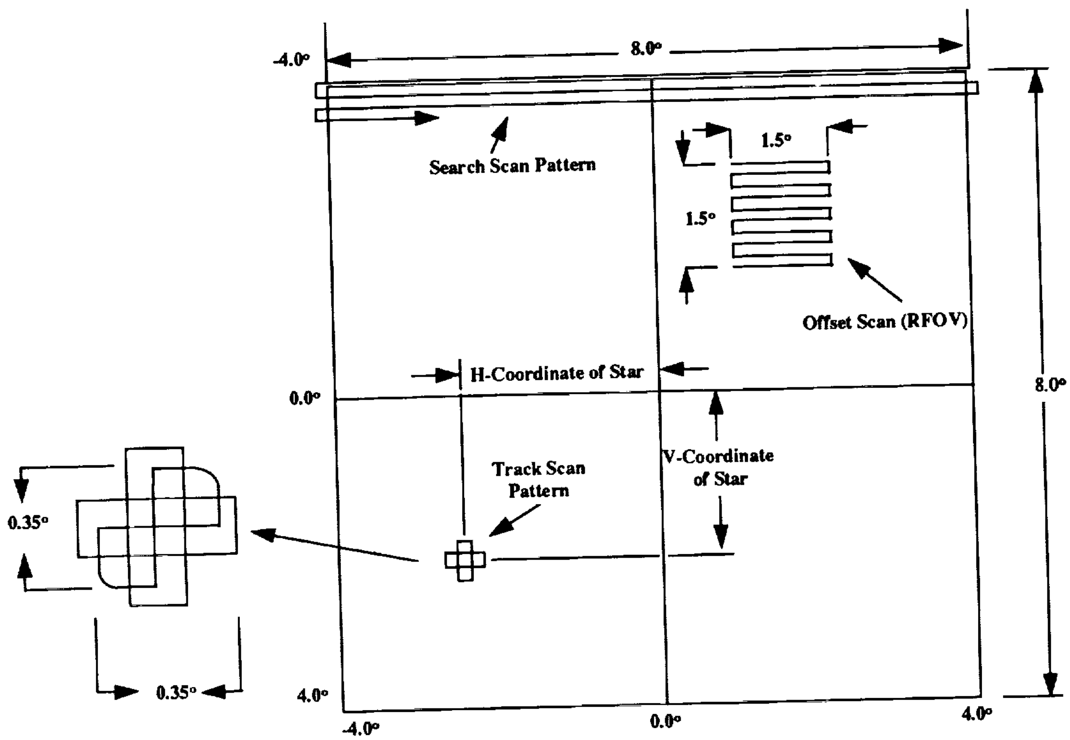

Figure 3. FHST Scan Geometry

Raw FHST vertical (V) and horizontal (H) positions are measured over a range of ±2048 counts, which can be converted to angular measurements through application of a standard BASD-specified scale factor of 0.002079 degrees per counts. The raw measurements are subject to a variety of distortions than can offset a star's observed position by several hundred arcseconds from its true position. The largest of these are the flat field effects, which result from aberrations in the objective lens and the fact that the positions of stars on a curved celestial sphere are being measured on a plane surface (the photocathode). For the HST trackers, flat field effects are in the range of 300-500 arcseconds.

Temperature changes produce the second largest distortion in raw FHST measurements. At the center of the TFOV, for example, a change in temperature from the operational minimum (-10°C) to the operational maximum (+50°C) will result in an apparent position shift of up to 110 arcseconds.

Intensity and magnetic field effects produce smaller distortions in the raw FHST position measurements. For example, a star's position as measured when there is a -0.5-gauss magnetic field component parallel to the tracker boresight may differ by as much as 5-10 arcseconds from the same measurement made in a +0.5-gauss field. Changes in a star's measured intensity over the tracker's operational range produce shifts that are on the same order.

For any given FHST, BASD characterizes the distorting influences of flat field, temperature, intensity, and magnetic field effects through an extensive series of ground tests whereby the tracker observes a grid of artificial "stars" that are evenly distributed over the TFOV under varying conditions of temperature, intensity, and magnetic field strength. Based on these observations, one can determine a set of distorted-to-true coefficients that can be used in a polynomial calibration function to remove the effects of distortion. BASD traditionally has used a polynomial that requires 190 coefficients per FHST (BASD, 1981). Based on operational experience with the SMM trackers (McCutcheon, 1982), a somewhat simpler version requiring only 48 coefficients per tracker has been adopted for the HST mission:

$$
\begin{aligned}
V_c = {} & (\alpha_{00} + \alpha_{01}T + \alpha_{02}T^2 + \alpha_{03}I + \alpha_{04}I^2 + \alpha_{05}I^3) + \\
& (\alpha_{10} + \alpha_{11}T + \alpha_{12}T^2 + \alpha_{13}B)V + (\alpha_{20} + \alpha_{21}T + \alpha_{22}T^2 + \alpha_{23}B)H + \\
& (\alpha_{30} + \alpha_{31}T)V^2 + (\alpha_{40} + \alpha_{41}T)VH + (\alpha_{50} + \alpha_{51}T)H^2 + \\
& \alpha_{60}V^3 + \alpha_{70}V^2H + \alpha_{80}VH^2 + \alpha_{90}H^3
\end{aligned}
$$

$$
\begin{aligned}
H_c = {} & (\beta_{00} + \beta_{01}T + \beta_{02}T^2 + \beta_{03}I + \beta_{04}I^2 + \beta_{05}I^3) + \\
& (\beta_{10} + \beta_{11}T + \beta_{12}T^2 + \beta_{13}B)V + (\beta_{20} + \beta_{21}T + \beta_{22}T^2 + \beta_{23}B)H + \\
& (\beta_{30} + \beta_{31}T)V^2 + (\beta_{40} + \beta_{41}T)VH + (\beta_{50} + \beta_{51}T)H^2 + \\
& \beta_{60}V^3 + \beta_{70}V^2H + \beta_{80}VH^2 + \beta_{90}H^3
\end{aligned}
$$

where

V, H = raw vertical and horizontal position (counts)
V_C, H_C = calibrated vertical and horizontal positions (counts)
T = temperature (volts)
I = intensity (volts)
B = magnetic field component parallel to tracker boresight (gauss)
α_{ij}, β_{ij} = distorted-to-true calibration coefficients

GSFC Flight Dynamics Facility (FDF) personnel used the original BASD test data for the HST trackers to determine coefficients for this simplified calibration equation (Challoner, 1983 and 1984; McLaughlin, 1989). After application of the computed coefficients to the test data, they found root-mean-square (rms) residuals over all observations in the range of 6-9 arcseconds for the three HST FHSTs. Similarly, they found maximum residuals in the range of 23-38 arcseconds, with the maximum residuals generally located in the corners of the TFOV. (When the computed coefficients were applied only over an 8-degree circular FOV, the maximum residuals were reduced to between 17 and 19 arcseconds.)

In addition to determining distorted-to-true calibration coefficients (α,β), FDF personnel determined inverse true-to-distorted coefficients $(\alpha,\beta)^{-1}$ that can be used to add the corrupting distortion effects to ideal, "true" star positions (Challoner, 1984; McLaughlin, 1989). The HST PASS mission scheduling (MS) software is responsible for selecting FHST reference stars. For each reference star, the MS software in combination with the flight software uses these inverse coefficients to determine where a selected reference star should appear in the FHST TFOV (Hallock, 1990). The flight software then computes attitude updates based on a comparison of expected with actual reference star positions. Any inaccuracies in the FHST calibration coefficients will translate directly into attitude errors that will reduce the efficiency of FGS guide star acquisition.

HISTORY OF FHST SCALE FACTOR/DISTORTION CHANGES ON HST

The requirements for HST attitude determination and attitude sensor calibration (Hallock et al., 1987) made no provision for in-flight updates to the FHST scale factors and/or distortion coefficients. These were to be used "as is," and only the FHST alignment matrices were to be updated regularly based on in-flight data. (For a discussion of the post-launch calibration of the HST attitude sensors, see [Welter, 1991a]. For a discussion of early postlaunch difficulties with the HST FHSTs, see [Nadelman, 1994].)

By early 1991, however, it had become apparent that ground attitudes computed using FHST-3 data were less accurate than those computed using data from the other two trackers. In addition, on occasion FHST-3 was having difficulty locating its commanded reference stars. By computing angular separations between observed FHST-3 stars and comparing these to angular separations computed from reference star catalog information, it was determined that the baseline FHST scale factor, 0.002079 degrees per count, understated the true scale by about 0.25 percent. From this point forward, PASS personnel began monitoring the scale factors for all three FHSTs on a regular basis.

Figure 4 shows the development of scale factor changes from shortly after launch through the middle of 1993. This figure shows clearly that the FHST-1 and FHST-2 scale factors have remained essentially constant, albeit differing slightly from their design values, whereas the FHST-3 scale factor increased rapidly through the end of 1991. Since that time the scale factor has continued to increase, although somewhat more slowly, and by August 1993 it had reached a level 0.45 percent above its original value. For a star near the corner of the FHST TFOV, such an increase corresponds to a position change on the order of 100 arcseconds; errors of this magnitude are quite large in comparison to the attitude accuracy required for successful FGS guide star acquisition.

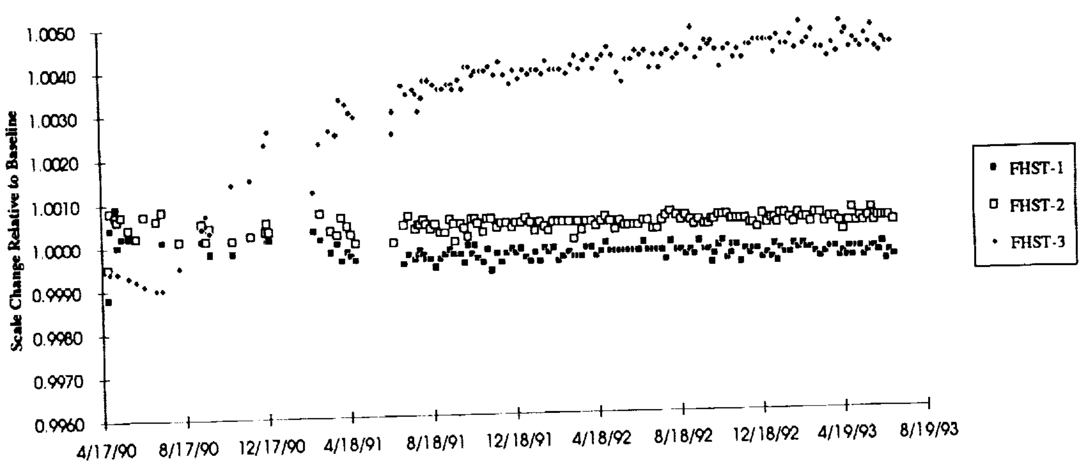

Figure 4. FHST Scale Factor Changes Relative to Baseline Value

PASS personnel made appropriate changes to the HST project data base (PDB) to reflect these increases in the FHST-3 scale factor, and these changes greatly improved the accuracy of attitudes computed using FHST-3 data, thereby improving the reliability of FGS guide star acquisition. By the middle of 1992, however, it became apparent that even with PDB updates for the new scale factor, FHST-3 still was not performing at the same level as FHST 1 or 2. This led to the suspicion that the FHST-3 calibration coefficients themselves had changed since launch.

To investigate possible changes in the FHST-3 coefficients, PASS personnel modified the FHST alignment software (FALIGN) to compare observed and reference FHST star positions. The input to FALIGN consists of observed and reference star vectors as well as attitude information generated by the PASS fine attitude determination software (FINATT). (The observed vectors have already been corrected for distortion within FINATT.) FALIGN begins by separating the observations into constant attitude frames, and for each frame it then performs an optimal rotation to transform the reference vectors from the geocentric intertial (GCI) reference frame to the FHST reference frame. (The data for the PASS analysis were usually taken with the vehicle under RGA control. RGA bias characteristics ensure attitude stability on the order of 2.5 arcseconds maximum average error over the time frame of a typical FHST map.) FALIGN next converts the vectors to V and H coordinates and forms residuals by taking the differences between the observed and reference positions.

Figures 5, 6, and 7 show the residual plots in V and H for all three trackers using post-HST Servicing Mission data from 1993.351 through 1994.062. (Data in these figures were processed using the updated FHST-3 scale factor. The plots were subjected only to minimal editing and include data for 3015, 2868, and 2005 stars for FHSTs 1, 2, and 3, respectively.) These figures show, first of all, the expected result that the largest residuals for all three trackers are at the edges of the TFOV. The slight slope in the residuals for FHSTs 1 and 2 may reflect the effect of slightly off-nominal scale terms already observed in Figure 4. Most dramatically, however, Figure 7 clearly shows the effects of uncompensated distortions as large as 30 arcseconds in regions that are still far from the edges of the TFOV.

With this evidence of uncompensated distortion in hand, PASS personnel made further modifications to FALIGN to allow it to compute new FHST flat field coefficients (α_{i0}, β_{i0}, i=1-10) using a standard linear least-squares approach. To carry out this solution, it is necessary first to "de-calibrate" the observed star positions using the inverse (i.e., true-to-distorted) coefficients in order to recover the original raw FHST V and H positions. Temperature, intensity, and magnetic field data are not readily available to FALIGN, and thus it was not possible to consider effects due to these factors in this analysis.

PASS personnel used FALIGN to compute new coefficients, and the distortion coefficients in the HST PDB were updated with this new solution in December 1993. That the new coefficients improve the accuracy of FHST-3 measurements is shown in Figure 8, which plots residuals for the same data as in Figure 7. It should be noted that the largest FHST-3 residuals are now at the edges of the TFOV and that the general character of Figure 8 is now similar to that of Figures 5 and 6.

Figures 9 and 10 provide a three-dimensional visualization of the combined V and H residuals (using the same data as in Figures 7 and 8) over the FHST-3 TFOV using the old and new distortion solutions. Now, however, the TFOV has been subdivided into roughly 1-degree-by-1-degree squares, and the residuals for stars in each square have been combined to form local rms residuals. These figures demonstrate the "flattening" effect of the new solution in the inner portions of the TFOV, and they also clearly show the expected result that the corners of the TFOV are subject to the largest distortions.

Operational experience with the new FHST-3 calibration solution confirms what is illustrated by Figures 8 and 10: the new scale factor and distortion coefficients have improved the accuracy of attitudes computed using FHST-3 data. With this new distortion solution, HST can continue its science operations with increased confidence that FGS guide star acquisition will not fail because of degraded FHST performance.

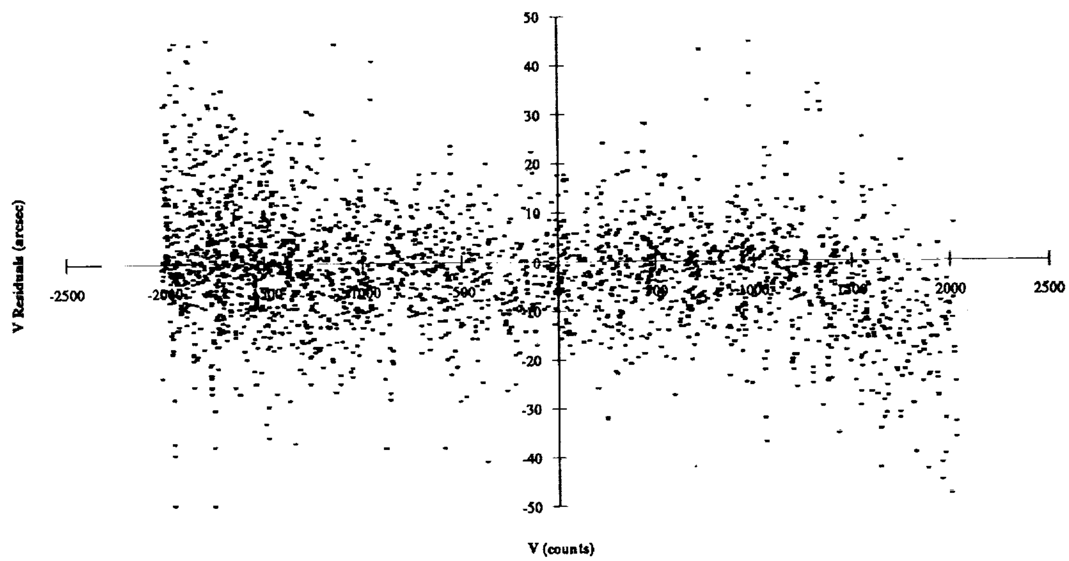

Figure 5a. FHST-1 V Residuals vs. V

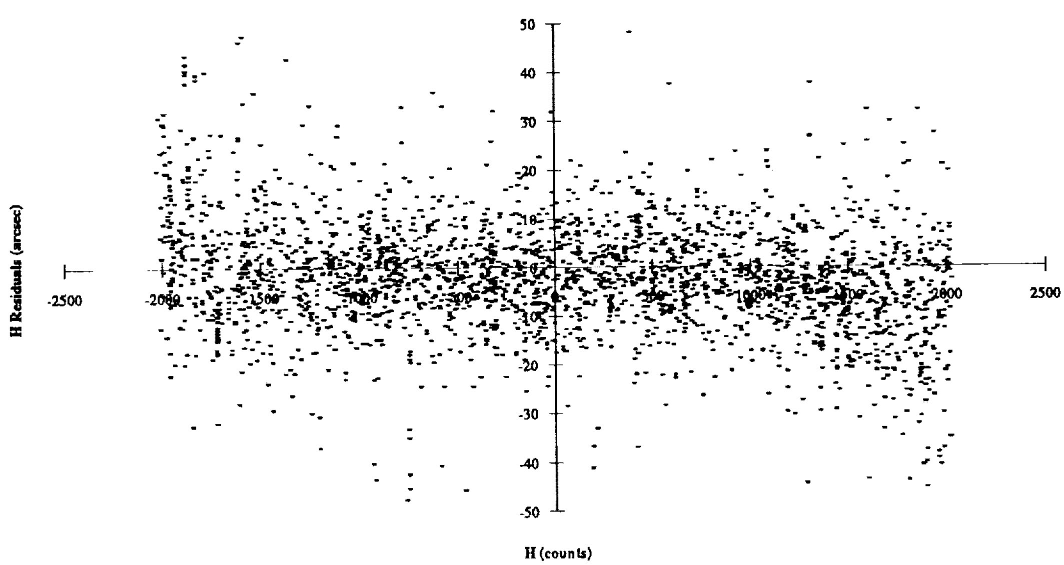

Figure 5b. FHST-1 H Residuals vs. H

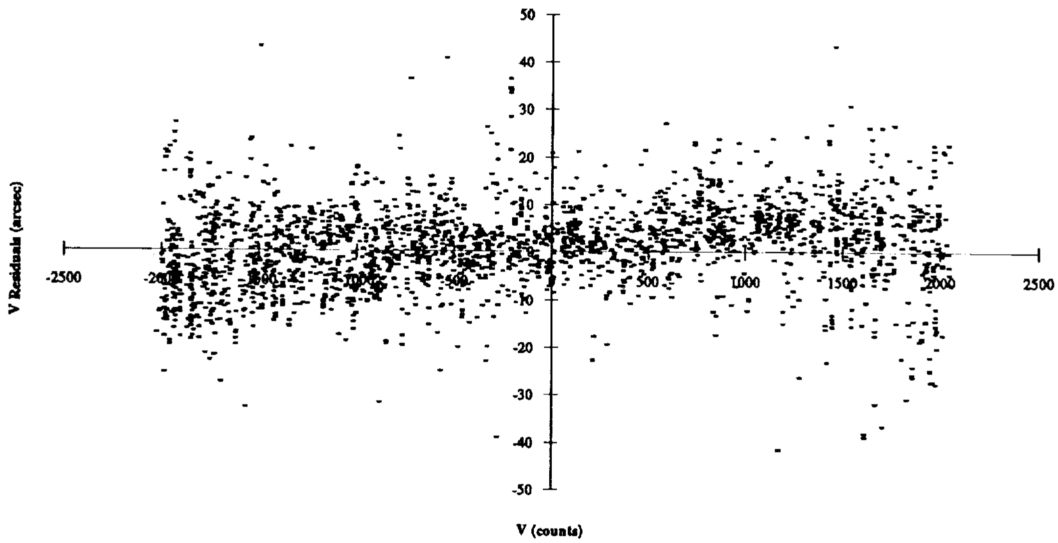

Figure 6a. FHST-2 V Residuals vs. V

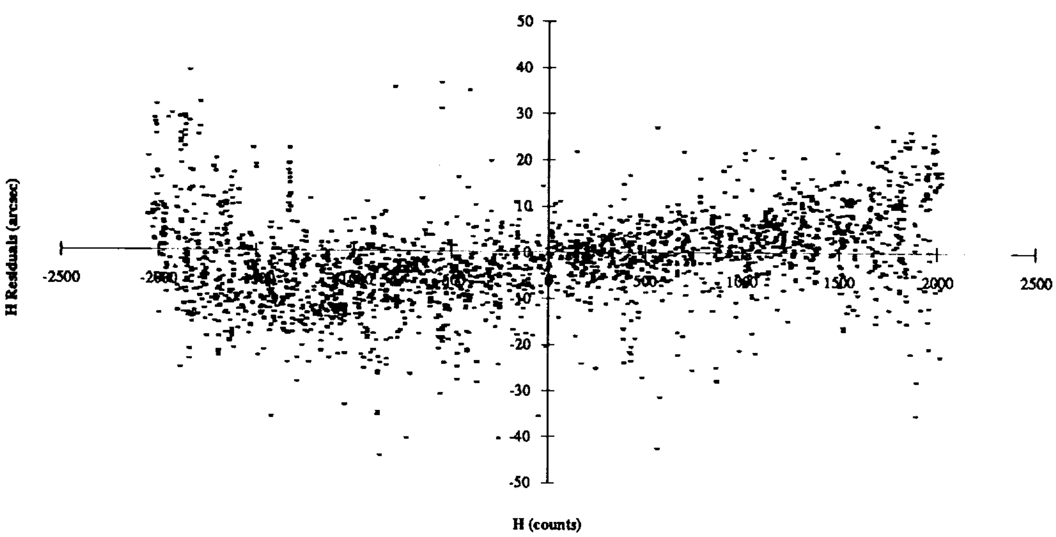

Figure 6b. FHST-2 H Residuals vs. H

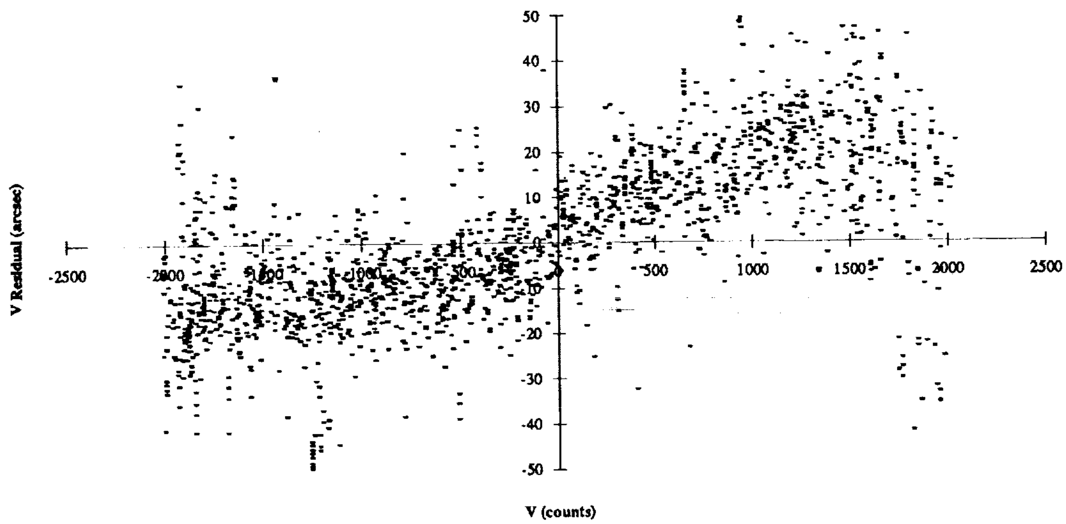

Figure 7a. FHST-3 V Residuals vs. V

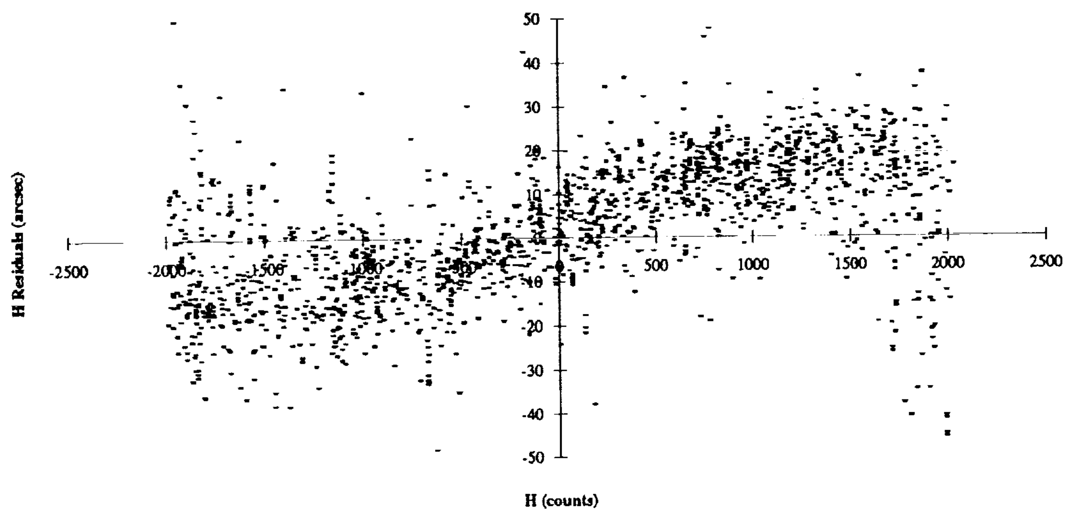

Figure 7b. FHST-3 H Residuals vs. H

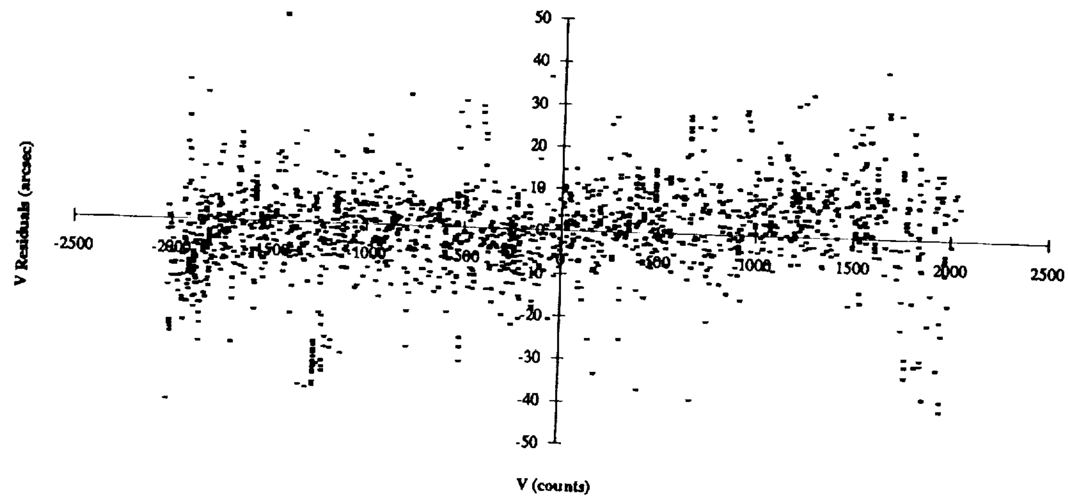

Figure 8a. FHST-3 V Residuals vs. V With New Calibration

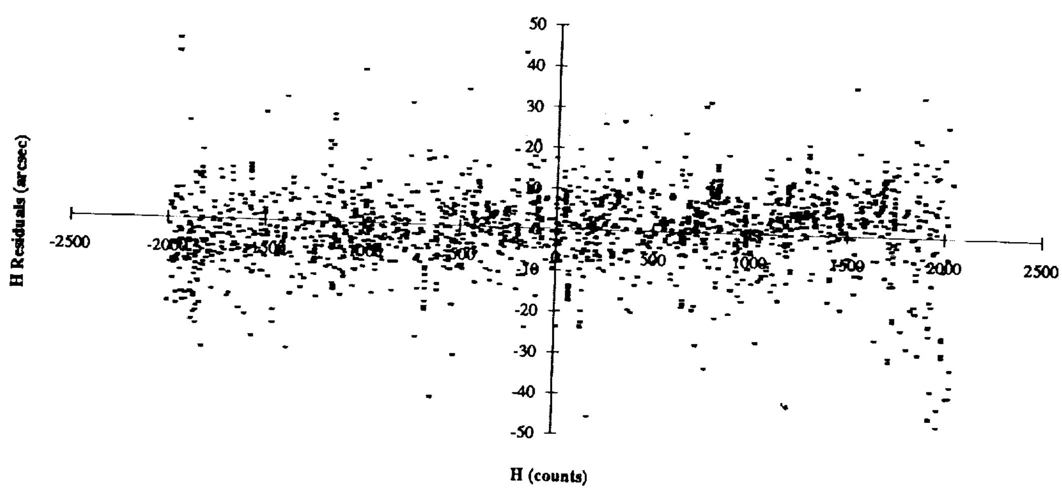

Figure 8b. FHST-3 H Residuals vs. H With New Calibration

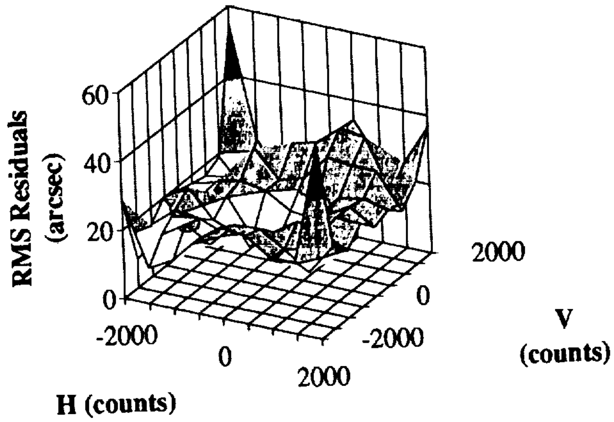

Figure 9. FHST-3 Local rms Residuals With Old Calibration

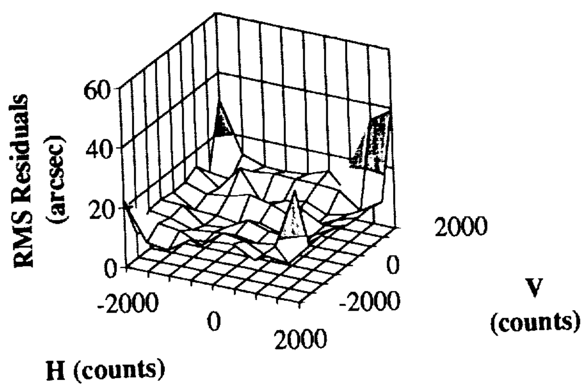

Figure 10. FHST-3 Local rms Residuals With New Calibration

CONCLUSIONS

The in-flight FHST scale factor and distortion calibration described in this paper has greatly improved the reliability of FHST-3 for use in HST attitude determination and control. To ensure trouble-free acquisition of FGS guide stars and, hence, science data, HST PASS personnel intend to monitor the scale and distortion of all three FHSTs throughout the rest of the HST mission.

The primary conclusion to be drawn from this experience with the HST FHSTs is that the distortion and scale characteristics of FHSTs under flight conditions may differ from those on the ground. Further evidence in support of this conclusion comes from the GRO, EUVE, and UARS missions (Davis, 1992 and 1993; Hashmall, 1993), which have reported similar changes in their FHSTs. GRO, in particular, has experienced FHST scale factor changes far above those described here for FHST-3. A secondary conclusion is that it is possible to adjust the FHST calibration coefficients by performing a calibration using in-flight data, confirming the experience of Davis (1992 and 1993) and Hashmall (1993).

The recommendation that follows from these conclusions is that future missions equipped with FHSTs should be prepared to verify scale factor and distortion characteristics as part of the normal post-launch attitude sensor alignment and calibration sequence. This monitoring process and, if necessary, recomputation of scale and distortion should be repeated at periodic intervals.

A new generation of charge-coupled device (CCD) star trackers may ultimately replace FHSTs as the standard NASA star tracker, and it is uncertain how many more NASA missions will be equipped with FHSTs. Whether or not the new CCD trackers will have scale and distortion characteristics similar to those of the FHST has yet to be seen, but it would be prudent for users of these new trackers to be prepared for possible postlaunch calibration changes.

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REFERENCES

BASD, "Users' Guide for the Standard Star Tracker," TM79-04A, June 1981.

E. Challoner and S. McLaughlin, *Results of Processing Space Telescope (ST) Fixed-Head Star Tracker (FHST) Calibration Data*, CSC, CSC/TM-83/6111, December 1983.

E. Challoner, S. McLaughlin, and S. Talukdar, *Final Space Telescope Fixed-Head Star Tracker Inverted Calibration Coefficients*, CSC, CSC/TM-84/6073, June 1984.

P. Davenport, *HST FHST Intensity to Visual Magnitude Calibration II*, CSC memorandum, June 6, 1991.

W. Davis, J. Hashmall, and R. Harman, *Recent Goddard Space Flight Center (GSFC) Experience with On-Board Calibration of Attitude Sensors*, 43rd Congress of the International Astronautical Federation, IAF-92-0049, August 1992.

W. Davis, J. Hashmall, and R. Harman, *Postlaunch Calibration of Spacecraft Attitude Instruments*, AAS/GSFC International Symposium on Space Flight Dynamics, AAS 93-325, April 1993.

L. Fallon, *Space Telescope POCC Applications Software Support (PASS) Functional Requirements (Revision B)*, CSC, CSC/SD-82/6069, September 1985.

L. Hallock et al., *Space Telescope POCC Applications Software Support (PASS) Requirements Specification (Revision E)*, CSC, CSC/TM-82/6045, September 1987.

L. Hallock, *Hubble Space Telescope Flight Software Examination for the Pointing Control Subsystem (Revision 2)*, CSC, CSC/TM-88/6103, March 1990.

J. Hashmall, W. Davis, and R. Harman, *The Attitude Accuracy Consequences of On-Orbit Calibration of the Extreme Ultraviolet Explorer Attitude Sensors by the Flight Dynamics Facility at Goddard Space Flight Center*, AAS/AIAA Spaceflight Mechanics Meeting, AAS 93-103, February 1993.

R. McCutcheon and C. Anderson, *Analysis of Calibration Procedures for the Space Telescope Fixed-Head Star Trackers*, CSC, CSC/TM-82/6173, December 1982.

S. McLaughlin and J. Epelboim, *Calibration of Fixed-Head Star Trackers (FHSTs) Using STARCAL*, CSC, CSC/SD-89/6164, September 1989.

M. Nadelman, J. Karl, and L. Hallock, *Fixed-Head Star Tracker Attitude Updates on the HST*, Proceedings of the GSFC Flight Mechanics / Estimation Theory Symposium 1994, May 1994.

G. Welter, *The In-Flight Calibration of the Hubble Space Telescope Attitude Sensors*, Proceedings of the GSFC Flight Mechanics / Estimation Theory Symposium 1991, NASA Conference Publication 3123, May 1991.

G. Welter, L. Abramowicz-Reed, A. Guha, L. Hallock, and E. Kimmer, *The In-flight Calibration of the Hubble Space Telescope Fine Guidance Sensors*, Proceedings of the Third International Symposium on Spacecraft Flight Dynamics, ESA Publication SP-326, October 1991.

G. Welter and J. Karl, *HST FHST Intensity to Visual Magnitude Calibration III*, CSC memorandum Ref: 20:0292-058-GW, March 1992.

G. Welter, L. Abramowicz-Reed, A. Guha, L. Hallock, and E. Kimmer, *The In-flight Calibration of the Hubble Space Telescope Fine Guidance Sensors II (A Success Story)*, Proceedings of the GSFC Flight Mechanics / Estimation Theory Symposium 1994, May 1994.