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Color/Magnitude Calibration for National Aeronautics and Space Administration (NASA) Standard Fixed-Head Star Trackers (FHST)*

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Abstract

This paper characterizes and analyzes the spectral response of Ball Aerospace Fixed-Head Star Trackers (FHSTs) currently in use on some three-axis stabilized spacecraft. The FHST output is a function of the frequency and intensity of the incident light and the position of the star image in the field of view. The FHSTs on board the Extreme Ultraviolet Explorer (EUVE) have had occasional problems identifying stars with a high B-V value. These problems are characterized by inaccurate intensity counts observed by the tracker. The inaccuracies are due to errors in the observed star magnitude values. These errors are unique to each individual FHST. For this reason, data were also collected and analyzed from the Upper Atmosphere Research Satellite (UARS). As a consequence of this work, the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) hopes to improve the attitude accuracy on these missions and to adopt better star selection procedures for catalogs.

Introduction

The Extreme Ultraviolet Explorer (EUVE) satellite was launched in June 1992. It began its mission operations during the survey mode phase, where EUVE scanned the entire sky in the extreme ultraviolet wavelength to make a complete extreme ultraviolet sky map. After the mapping phase was completed, EUVE went on to observe specific ultraviolet sources. This was the spectroscopy or inertial phase of the mission. Survey mode is also the mission configuration where the attitude determination instruments are calibrated, so EUVE enters survey mode periodically for calibration.

The primary instrument used for attitude determination (AD) on EUVE are the two National Aeronautics and Space Administration (NASA) Standard Fixed-Head Star Trackers (FHSTs). If a problem were to occur with the one or both of the FHSTs, the AD would have to be done using the fine Sun sensor (FSS), which is less accurate (60 arcseconds (arcsec) as opposed to 10 arcsec for FHSTs). Therefore, it has been standard practice to analyze thoroughly any anomalies with the FHSTs to ensure their proper performance. Most star acquisition problems with the FHSTs can be attributed to stars in the field of view (FOV) being optical binaries or to a bright star in the FOV. But since EUVE's launch, there have been several anomalies in FHST1 that could not be explained by either of these two explanations. The FHST would scan the FOV for a cataloged guide star and would never identify any stars. When EUVE is in inertial mode, it usually has no more than one or two stars in the FOV of each FHST that can be used for AD. If one of the FHSTs is unable to acquire a star in its FOV, the AD must be done using only one FHST and the FSS, therefore making the attitude determination less accurate.

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Preliminary analysis indicated that the FHST was unable to maintain a lock on the stars. When an FHST scans for stars, it returns two pieces of data: (1) an observed intensity count value and (2) a position in the FOV. The FHST scanning the FOV for the cataloged guide star would actually "see" the star. The OBC would not identify the star because of an error in the observed intensity of the star (Reference 1)and would break track on the star. This led to the FHST continuously scanning the FOV but never having the OBC identify anything. Many times when this problem occurred, the star in the FOV was a dim star with a high blue minus visual (B-V) value. A star's B-V value is defined as its color index. Because stars have different temperatures, their spectral energy curves peak at different wavelengths. Therefore, hotter stars are bluish, and cooler stars are reddish. Using the B-V color index, it can be seen that a bluish star has a negative B-V value because it is brighter in blue (smaller B magnitude) than at longer wavelengths (larger V magnitude). Conversely, a reddish star has a positive color index because it is brighter in V than in B (Reference 2). This color index value considers the interstellar medium. It measures the star temperature and the scattering of blue wavelengths due to interstellar gas and dust. The following Hirshfeld table (Table 1) provides the approximate correspondence between the value of the color index and the observed color.

Table 1. Hirshfeld Table

Color Index	Visual Color
Less than 0.0	Blue
0.0 to 0.3	Blue to White
0.3 to 0.6	White
0.6 to 1.1	White to Yellow
1.1 to 1.5	Orange to Red
Greater than 1.5	Red

Because EUVE and the Gamma Ray Observatory (GRO) FHSTs have both experienced these types of problems (Reference 3), it was decided to evaluate the Upper Atmosphere Research Satellite's (UARS) FHSTs to determine if it was experiencing similar problems. The UARS, which was launched in September 1991, is an Earth-pointing satellite with a constant pitch rate of 1 revolution per orbit (RPO). This creates a scenario where the FHSTs are constantly acquiring new stars in their FOV. Therefore, a problem with observed magnitudes could go unnoticed unless specifically tracked. It should be noted that since each FHST has its own spectral response, analysis must be performed on each FHST independently.

EUVE/UARS Spacecraft Overview

The EUVE spacecraft (Figure 1) consists of a Multi-Mission Modular Spacecraft (MMS), a Platform Equipment Deck (PED), and a Payload Module. The MMS is triangular prism in shape with three basic submodules attached: the Modular Power Subsystem (MPS), Modular Attitude Control Subsystem (MACS), and Communications and Data Handling (C&DH) Subsystem. The MMS components are used for attitude/orbit determination and control and for communications with the ground through the Tracking and Data Relay Satellite System(TDRSS).

The coordinate system of the Attitude Control System (ACS) is defined as follows: the X-axis points toward the payload module and is aligned with the Deep Survey Photometer/Spectrometer pointing direction (opposite the high-gain antenna); the Y-axis points toward the FHSTs; and the Z-axis is normal to the outward face of the Signal Conditioning and Control Unit (SC&CU). The coordinate system is often referred to as the ACS coordinate system. The FHSTs are attached to the MACS module. The EUVE FHSTs boresights are approximately 76 degrees (deg) apart.

The EUVE spacecraft has two nominal modes of operation: survey mode and inertial pointing mode. During survey mode, the spacecraft is rotating about the ACS X-axis at 3 revolutions per orbital period corresponding to a roll rate of 0.19 degrees/second (deg/sec). The 3 revolutions per orbital period ensure that one revolution will occur every orbit night. At every orbit sunrise, the -X-axis is repointed at the Sun and held in that direction until the next orbit sunrise. The 1-deg per day average motion of the Earth about the Sun allowed EUVE to scan the entire celestial sphere in 6 months. In inertial mode the spacecraft is three-axis stabilized, and the ACS X-axis points at the target extreme ultraviolet source.

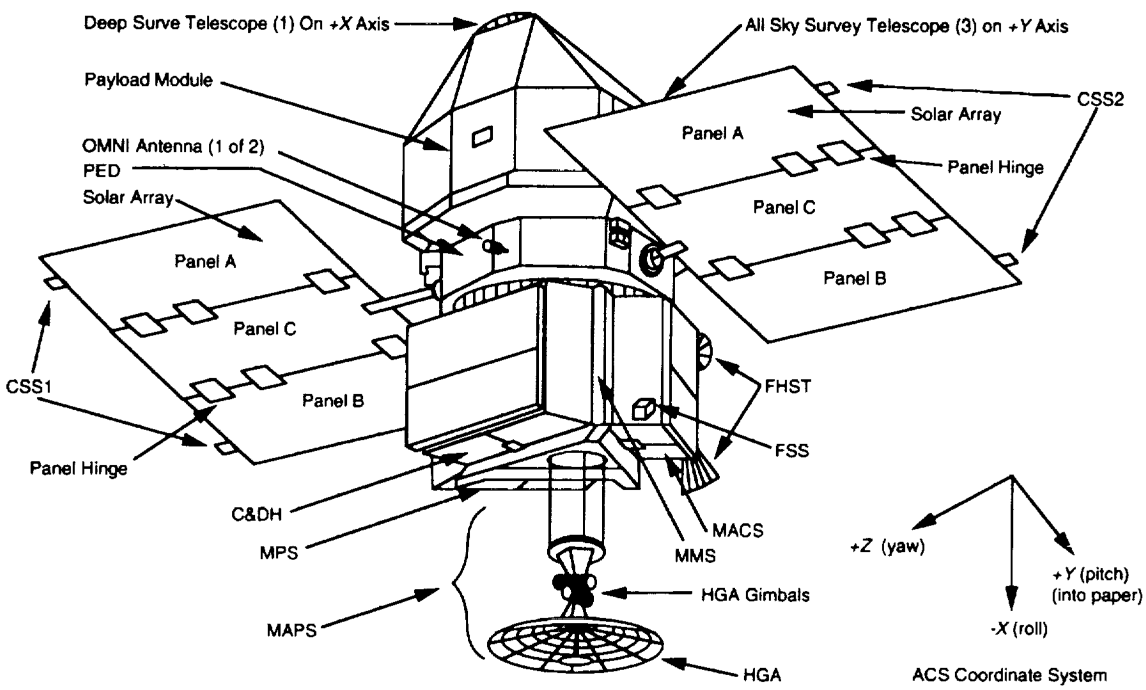


Figure 1. EUVE Spacecraft

The UARS spacecraft (Figure 2) is also an MMS. The nominal MCS is defined by the MACS alignment cube and is nominally parallel to the body coordinate system (BCS). The coordinate system of the MACS is defined as follows: the X-axis points toward the Solar Stellar Pointing Platform (SSPP); the Y-axis points towards the FHSTs; and the Z-axis is nadir pointing toward the Earth. The coordinate system is often referred to as the ACS coordinate system. As with EUVE, the FHSTs are attached to the MACS module and are approximately 76 deg apart.

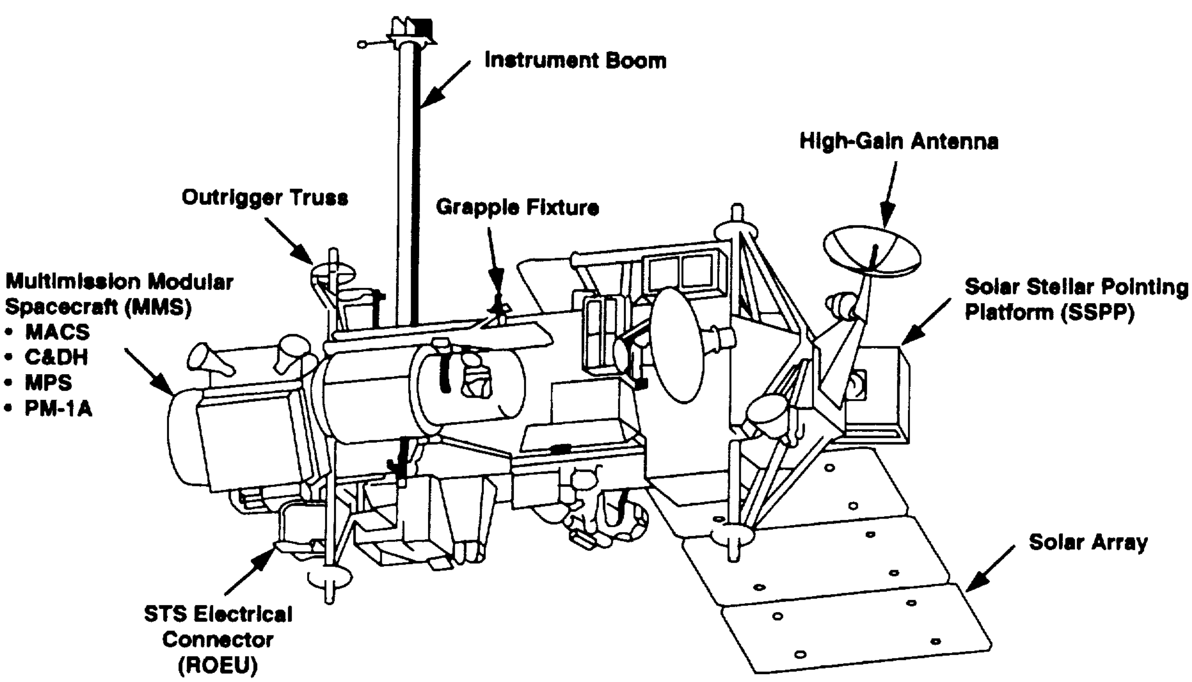


Figure 2. UARS Spacecraft

The UARS spacecraft normally operates in Earth-pointing mode. During Earth-pointing mode at 0 deg yaw, the spacecraft is rotating at 1 RPO about the ACS Y-axis, with the X-axis pointing along the velocity vector and the Z-axis nadir pointing at all times. Approximately once every 35 days, a 180-deg yaw maneuver is performed to keep the solar arrays aligned with the Sun and the science instruments out of the Sun. When the spacecraft is at 180 deg yaw, rotation at 1 RPO occurs about the ACS negative (-) Y-axis, with the X-axis pointing along the negative velocity vector, while the Z-axis maintains nadir pointing.

FHST Overview

The primary attitude sensors included on board EUVE and UARS are two pairs of FHSTs. The FHSTs used are NASA standard star trackers built by Ball Electro-Optics/Cryogenics Division. These sensors search for, detect, and track stars by focusing light from the object being tracked on the photocathode of an image dissector tube determining the intensity and position of the star. The FHSTs can track stars in the instrumental magnitude range of 2.0 to 5.7. (The instrumental magnitude is the magnitude that is expected of a star based on its intensity and color along with an averaged standard spectral response of an FHST.) As a star passes through the FOV of the FHST, a 0.2 magnitude fluctuation is expected.

For use on EUVE, the magnitudes of allowable stars to track is limited by the flight operations team (FOT), depending on the mission phase. While in survey mode, the magnitudes are limited to a range from 2 to 4.25. When the spacecraft is rotating, a narrow magnitude limit is preferable because of the large numbers of stars passing through the FOV of the FHSTs. While EUVE is inertial-pointing mode, however, the magnitude limits are increased to include stars to a magnitude of 5.25 because of the lower numbers of stars available to ensure that there is a star available in each tracker.

Each FHST has an 8-deg-by-8-deg square FOV, with a digital resolution of 7.78 arcsec. The manufacturer's specified position accuracy is 10 arcsec (1 σ) within an 8-deg circular central FOV. Each telemetry count is equivalent to 7 arcsec of position in the FOV. For consistency, the FOV's coordinate system is defined as follows. From the inside of the FHST looking outward, the vertical position is referred to as theta with negative theta being in the upward direction. The horizontal position is referred to as phi with negative phi being to the left.

On the ground, the FHST's measurements are handled as follows. The FHST position output consists of two angles measured sequentially, each requiring a 50 milliseconds (msec) measurement time. The position determined is approximately that of the star at the middle of the measurement period, 25 msec before the measurement becomes available for sampling. Since the 100 msec FHST measurement cycle is independent of the onboard computer (OBC) sampling cycle, and, therefore, the time since the measurements were updated is unknown; the time of the star position measurement is at least 25 msec and as much as 125 msec before the time at which the measurement is sampled. Due to this timing error in conjunction with the roll rate, position errors can be in the range of +/- 20.3 arcsec. The position is then corrected for using known alignments and calibrated misalignments.

The FHST manufacturer provides a transfer function for the calibration of the star tracker's FOV. It consists of a polynomial in tracker temperature, ambient magnetic field, star intensity, and star position in the FOV. Each FHST also has a FOV scale factor. These values are used to convert from horizontal and vertical counts in the FOV to angular measurements. Nominally, these values are 0.002162 deg per count. The scale factor value for UARS FHST1 is drifting at a quasi-linear rate making the FHST1 values 0.002130 deg per count as of October 28, 1993. The values for the EUVE FHSTs presently show no drifting. This drift in the UARS value must be accounted for when analyzing any FHST1 data.

The intensity information is also unpacked and converted from counts to volts (0.02 volt per count) and eventually to star instrumental magnitude. The conversion equations are given below as

$$I_{obs} = 0.02 * (\text{intensity counts}) \tag{1}$$

$$M_I = A * \text{Log}_{10}(I_{obs} - I_{ref}) + M_{bias} \tag{2}$$

where I_{obs} is the observed intensity in volts, I_{ref} is the reference intensity, M_{bias} is the magnitude bias, M_I is the calculated observed magnitude, and A is a constant. Since each FHST needs to be calibrated independently, each FHST can have its own values. The values for both spacecraft and each FHST are listed in Table 2.

Table 2. Intensity Conversion Constants

Intensity Conversion Constants	EUVE	UARS
A(FHST1)	-2.5	-2.5
A(FHST2)	-2.5	-2.5
M_{bias} (FHST1)	3.500	3.533
M_{bias} (FHST2)	3.423	3.533
I_{ref} (Both)	0.0	0.0

The star observations are later corrected for stellar aberration and identified by propagating all star observations to a common time and then comparing the positions of the stars with the reference positions and magnitudes of known stars included in the onboard star catalog. The positions are determined assuming a known a priori attitude, usually the OBC attitude.

Analysis

Because of the large volume of FHST data collected during the EUVE/UARS mission, data reduction was necessary. It was assumed that any processes that changed the FHST readings were not instantaneous and that noticeable changes took 6 months to a year to occur (Reference 4). Currently, EUVE has been in orbit for just over 1-1/2 years and UARS for almost 2.5 years. Since there is no definite amount of time for a FHST to degrade, it was uncertain whether time degradation effects could even be noticed.

Data were chosen for EUVE from the survey phase of the mission. More different stars are acquired during survey mode, so trends and patterns become more evident than with inertial mode data. Approximately one-orbit of data for seven different timespans were chosen for analysis. For processing of UARS data, five 1-orbit spans of data were chosen, spanning approximately 15 months (see Table 3). Data were chosen throughout the length of the missions to determine if there were any time dependencies or degradation effects involved.

Table 3. Data Spans

EUVE Greenwich mean time (YYMMDD.HHMMSS)	UARS Greenwich mean time (YYMMDD.HHMMSS)
921217.114517-134517	920819.162835-.182349
930207.041018-061017	921119.163604-.182315
930325.015017-035017	930219.163002-.182411
930425.080017-100017	930715.163105-.181727
930517.024517-044517	931102.163033-.182320
930613.024517-044517	
930717.084518-104518	

Each timespan was processed using the Multimission Three-Axis Stabilized Spacecraft (MTASS) Attitude Determination System (ADS). Uncorrected counts for star intensity and horizontal and vertical positions in the FOV were extracted from spacecraft telemetry data using the Telemetry Processor (TP) subsystem. These data were then converted from counts to engineering units, adjusted for biases, and corrected for temperature and magnetic effects using the Data Adjuster (DA) subsystem. For UARS, a new FOV scale factor was used for each timespan due to its quasi-linear degradation (about 1 percent). After all the data were corrected, the FHST-observed positions and magnitudes were used to identify the stars using the Star Identification (SI) subsystem. Once the stars were identified, the data were converted to the sensor reference frames using known FHST alignments and misalignments.

The difference between the instrumental magnitude and the observed magnitude is referred to here as the delta magnitude (Instrumental Magnitude – Observed Magnitude) or magnitude error. A positive error implies that the FHST is seeing the star too bright. The primary plots and comparisons analyzed here are as follows:

- Delta Magnitude versus B-V
- Delta Magnitude versus Instrumental Magnitude
- Delta Magnitude versus FOV Position

The first type was chosen because it demonstrates the FHST's inaccuracies as a function of the color index of the stars. The second shows the FHST's accuracy as a function of the brightness of the incident light. The third displays any position dependencies in the FHST's FOV.

Table 4 provides basic statistics for the magnitude errors of each FHST for each spacecraft.

Table 4. Magnitude Error Statistics

Star Tracker	Average Error	Standard Deviation of Error
EUVE FHST 1	-0.131	0.199
EUVE FHST 2	0.042	0.112
UARS FHST 1	0.106	0.113
UARS FHST 2	-0.103	0.105

As evident in Table 4, EUVE's FHST 1 is experiencing the most problems with magnitude errors, and EUVE's FHST2 is having the least.

EUVE Data and Results

When data were examined for EUVE for degradation effects, a plot of the delta magnitude versus FOV position for December 1992 was compared to the same plot for July 1993 (for each FHST). Data were averaged across the FOV to determine any sensitive regions. The plots showed less than a +/-0.1 magnitude difference between them across the FOV. Since a star traveling through the FOV can be expected to have a 0.2 magnitude fluctuation, no time dependence is evident for FOV position. When plots were also analyzed as a function of the B-V value, still no time dependence showed. Therefore, the remainder of the EUVE analysis was performed by combining all data spans together into one database. Also, EUVE magnitude errors were averaged for each star passing through the FOV to eliminate the 0.2 magnitude fluctuations seen across the FOV.

Table 5. Statistics for Regression of Delta Magnitude Versus B-V

Parameter	EUVE FHST1	EUVE FHST2	UARS FHST1	UARS FHST2
Intercept	-0.048	0.064	0.177	-0.112
Slope	-0.188	-0.041	-0.100	0.013
R Square	0.535	0.062	0.286	0.005
Stand. Error	0.106	0.100	0.095	0.105

EUVE's FHST1 was the FHST that prompted this study. As illustrated in Figure 3, the FHST1 has an almost linear dependence on B-V value. Conversely, FHST2 has no evident color dependence. Table 5 shows statistics for regression analysis with these data. This analysis shows that FHST1 has a high slope value and a high dependence on the B-V value, with the R Square value indicating more than 50 percent of the correlation coming from the B-V value. FHST2 has almost zero slope in comparison, with a much lower dependence on the B-V value. (R Square is a measure of how much influence X has on the Y value.)

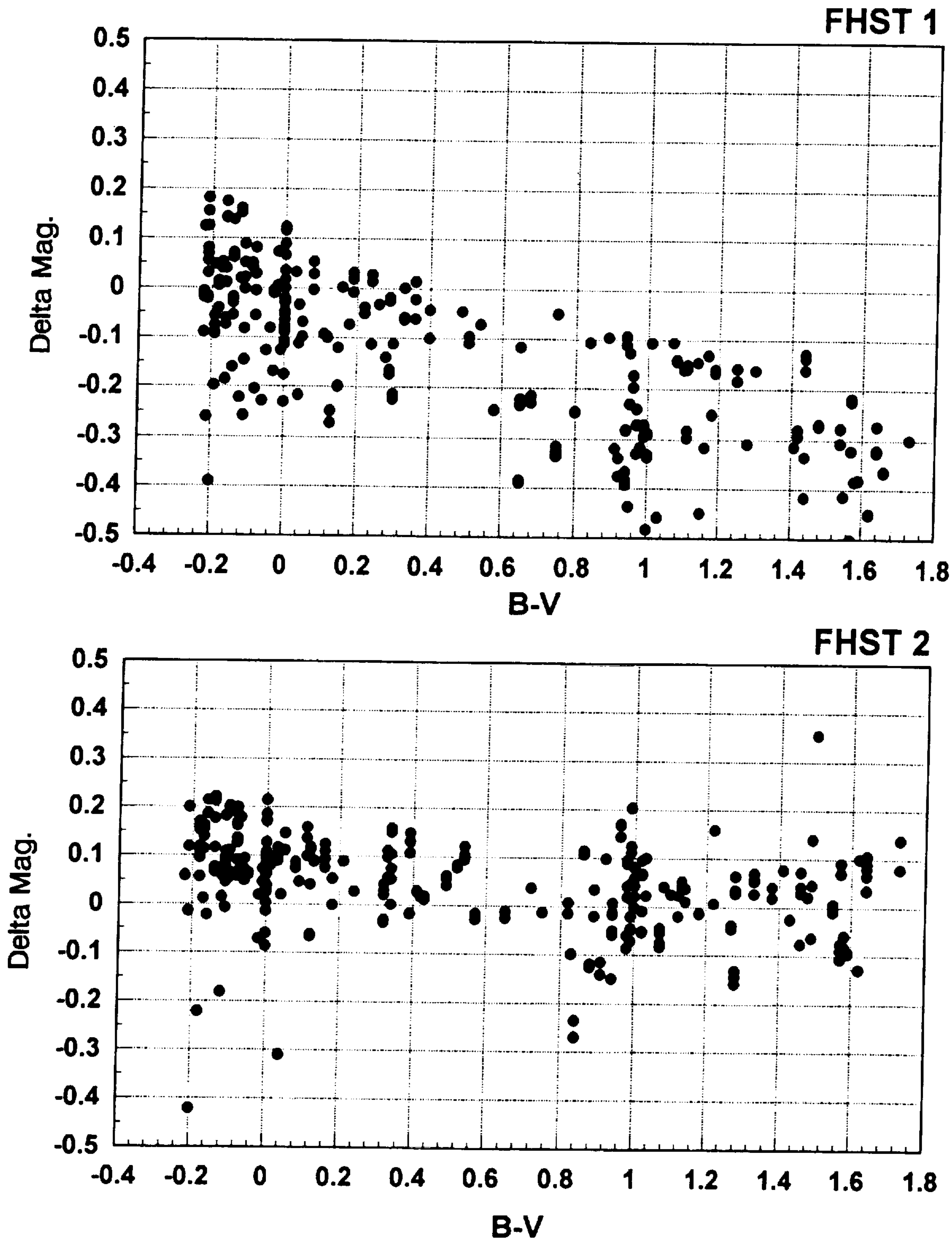


Figure 3. Delta Magnitude Versus B–V (EUVE)

EUVE's FHST1 does display a trend in the position in the FOV. Figure 4 shows that the negative theta position (the top half of the FOV) displays a definite shift in the magnitude error. Also, visual inspection of the surface plot may seem to show a problem with the outermost corner of the first quadrant. Since that area is outside the central FOV, where the OBC is supposed to break track, more data are required in that position to make an accurate determination of any trend. When the position in the FOV was examined as a function of the star's B-V values, no trend was evident. Of the stars sampled in the negative theta region of the FOV, only 21 percent of them had B-V values greater than 1.0, while in the upper half This demonstrates that the magnitude errors that occur in the upper half of the FOV do not occur just because there is a high sampling of high B-V stars in that region. That portion of the FOV is actually giving erroneous measurements. Twenty-five percent had high B-V values.

Figure 5 shows magnitude error versus instrumental magnitude. Data for FHST1 shows no correlation between magnitude and magnitude error, while FHST2 does show a slight correlation. With FHST1, magnitude errors can occur at any magnitude. FHST2 shows the general trend of being less accurate at dimmer magnitudes. This is expected as the visual to instrumental magnitude conversions are less accurate at dimmer magnitudes.

UARS Data and Results

As with EUVE, when data were analyzed to look for any time-related effects, none were evident. Once again, data were combined and viewed as a whole, rather than as time dependent. UARS data wee not averaged since its data rate is 64 times less than EUVE's.

For UARS, the color dependencies looked surprising upon first glance (Figure 6). FHST1 shows UARS to be seeing low B-V value stars that are too bright, while FHST2 shows no correlation with color. Table 5 shows statistics similar to EUVE. For FHST1, there is a higher dependence upon B-V value with 30 percent of the correlation due to the B-V value. The slope is also higher for FHST1 by about a factor of seven. FHST2 indicates no color dependence. These numbers and visual inspection seem to demonstrate a problem similar to EUVE's, with the exception that it is unlikely that FHST1 is seeing low B-V stars too bright. For an FHST to see stars that are too bright would require the electronics to be better than 100 percent efficient. It is more likely that the M_{bias} value in the magnitude calibration equation, Equation (2) is in error. A change in this value will move the data downward on the graph. This will show the FHST as actually seeing high B-V stars that are too dim, as with EUVE. To be sure, this will require some future analysis.

UARS's FHST2 also displays a trend in the position in the FOV. Since FHST2 shows no color dependencies, no color dependency versus FOV position needs to be analyzed. Figure 7 shows that the problem areas are the second quadrant (negative theta, positive phi), and the outermost corner of the first quadrant. These seem to be actual problem regions of the FOV. Once again, as with EUVE, the erroneous data in the first quadrant is outside the central FOV and is never used by the OBC for attitude determination.

Figure 8 shows plots of magnitude error versus instrumental magnitude. Both plots show higher magnitude errors as the magnitude gets dimmer. It is expected that as stars get dimmer, there should be larger standard deviation in the error measurements. These plots indicate a slope in the error measurements for both FHSTs. This implies a calibration coefficient problem for the A value in the magnitude calibration equation, Equation (2). More analysis is necessary to determine what the corrected values should be.

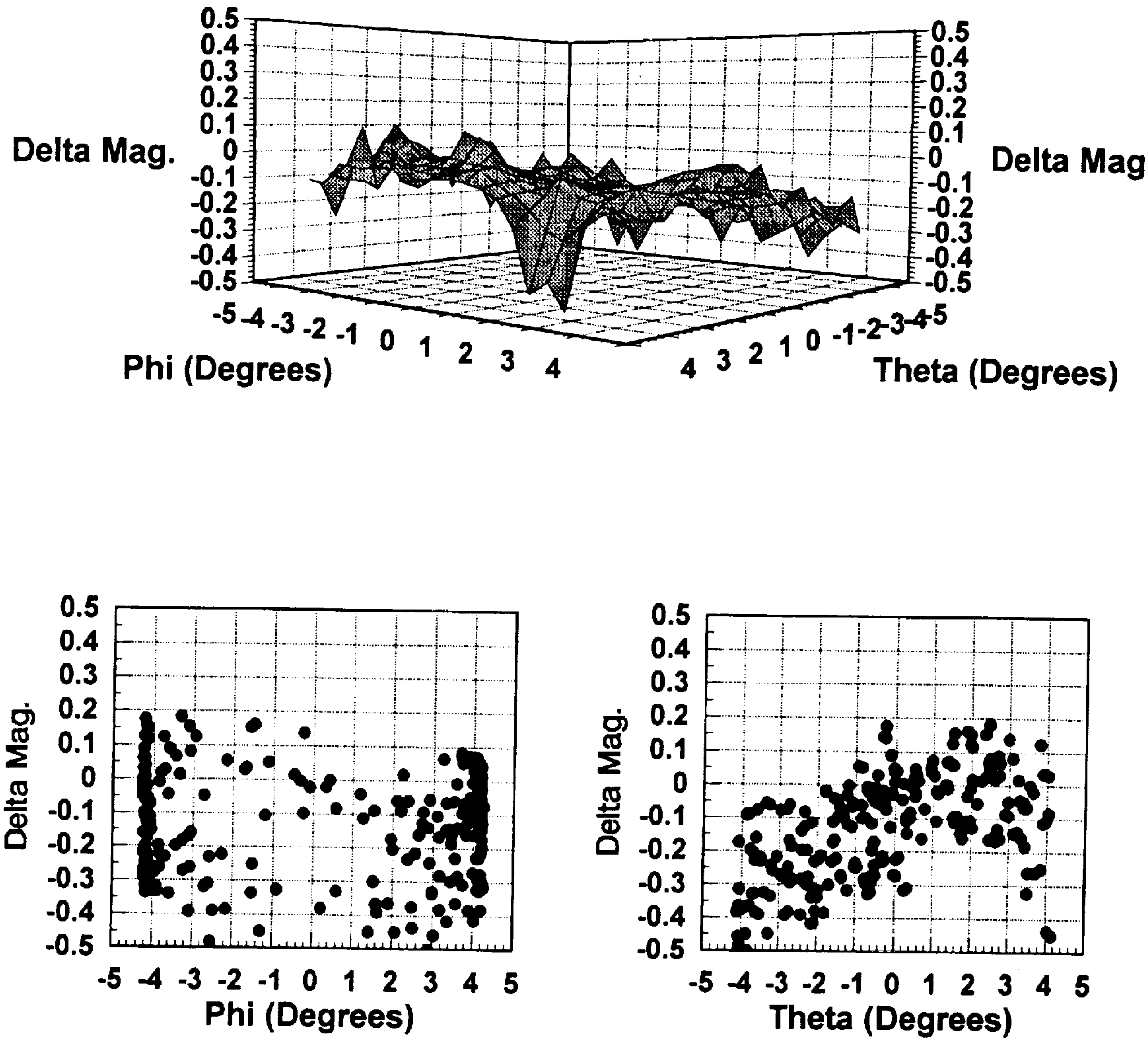
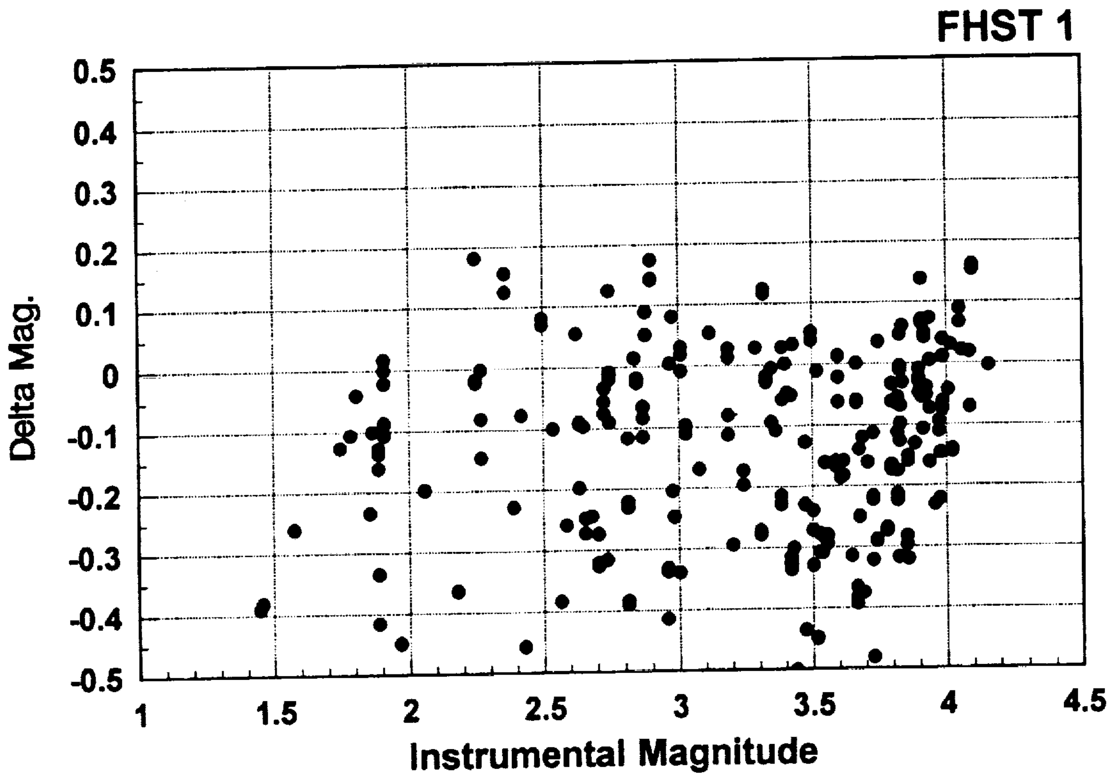


Figure 4. Delta Magnitude Versus FOV Position (EUVE, FHST1, Averaged)



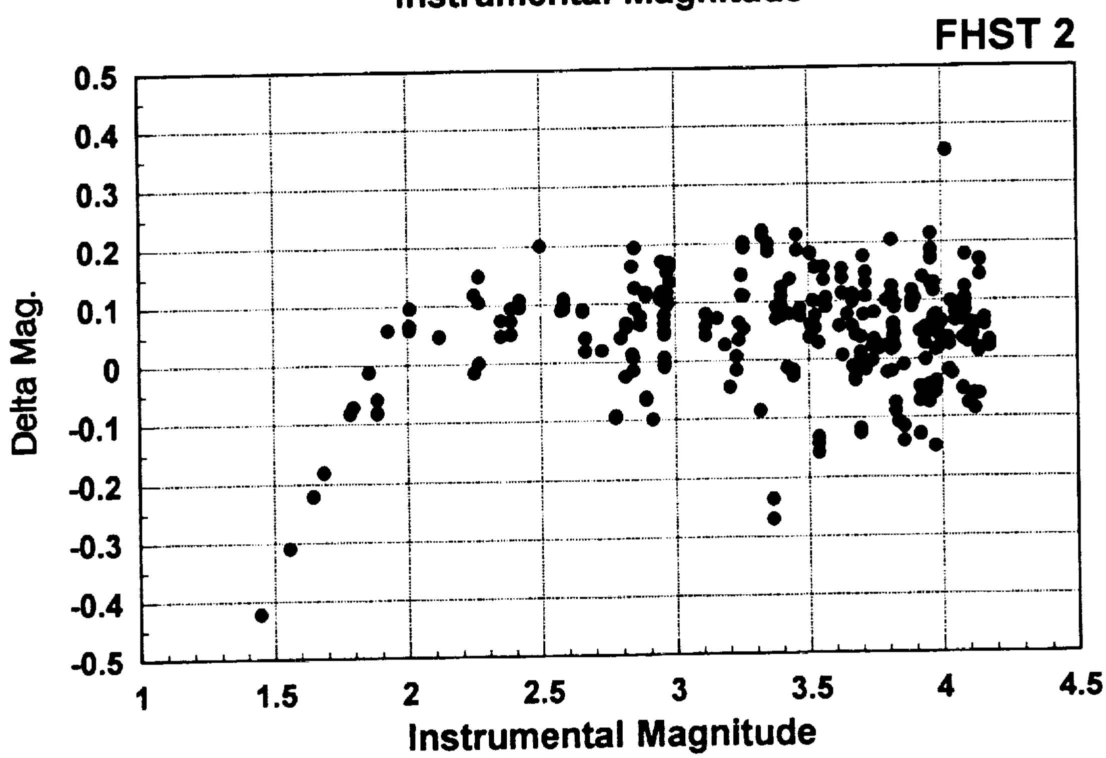


Figure 5. Delta Magnitude Versus Instrumental Magnitude (EUVE, Averaged)

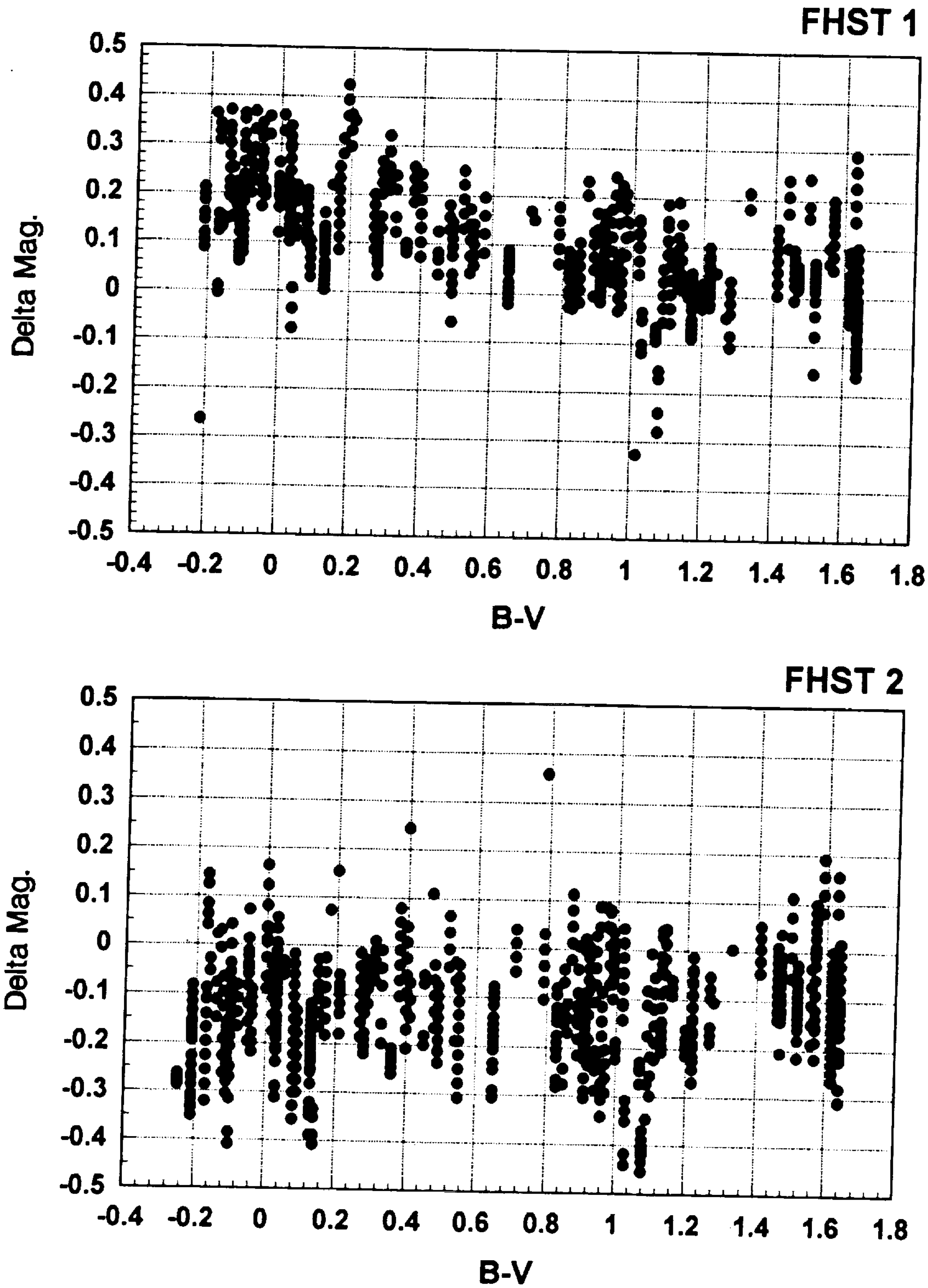


Figure 6. Delta Magnitude Versus B–V (UARS)

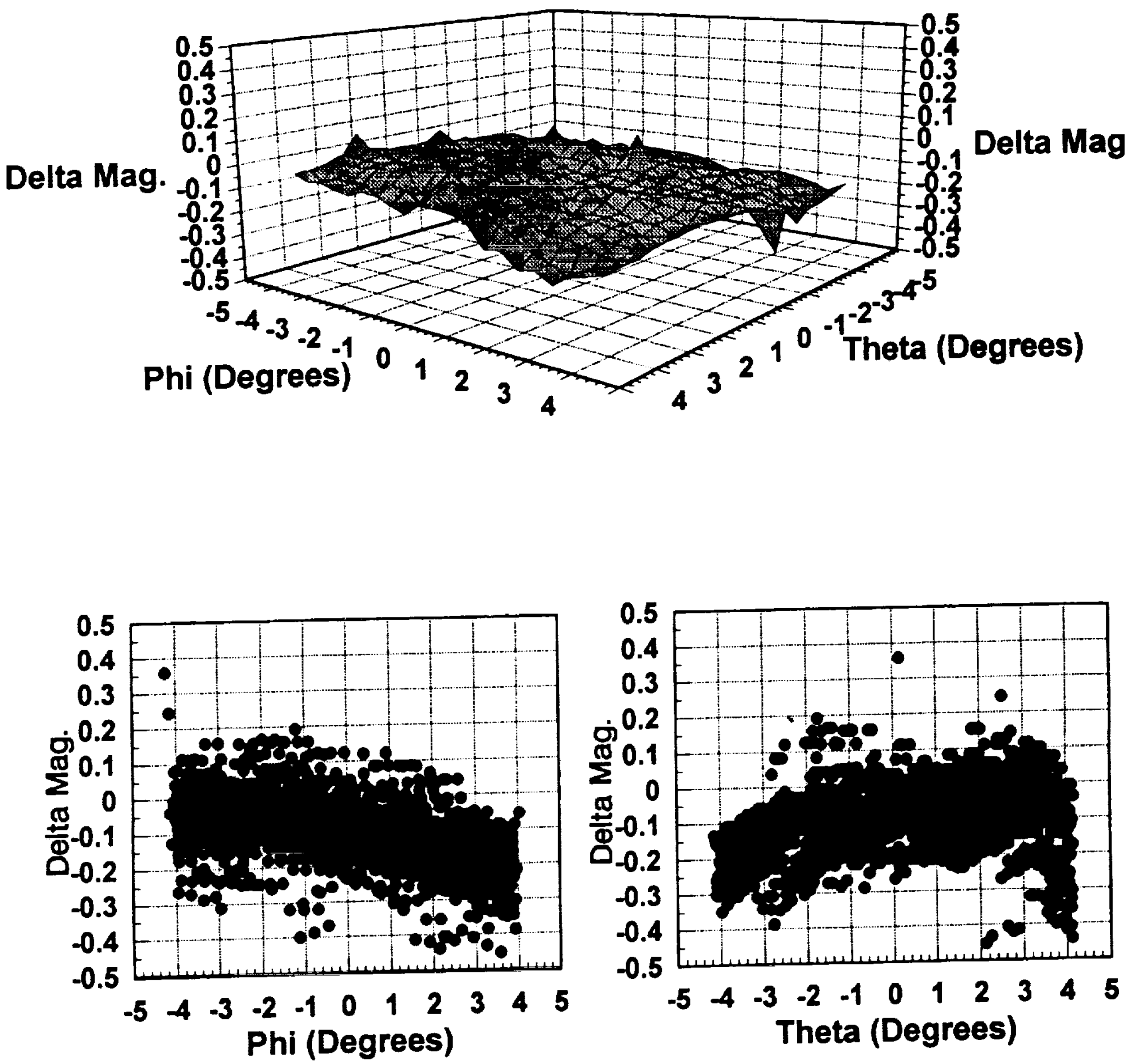


Figure 7. Delta Magnitude Versus FOV Position (UARS, FHST2)

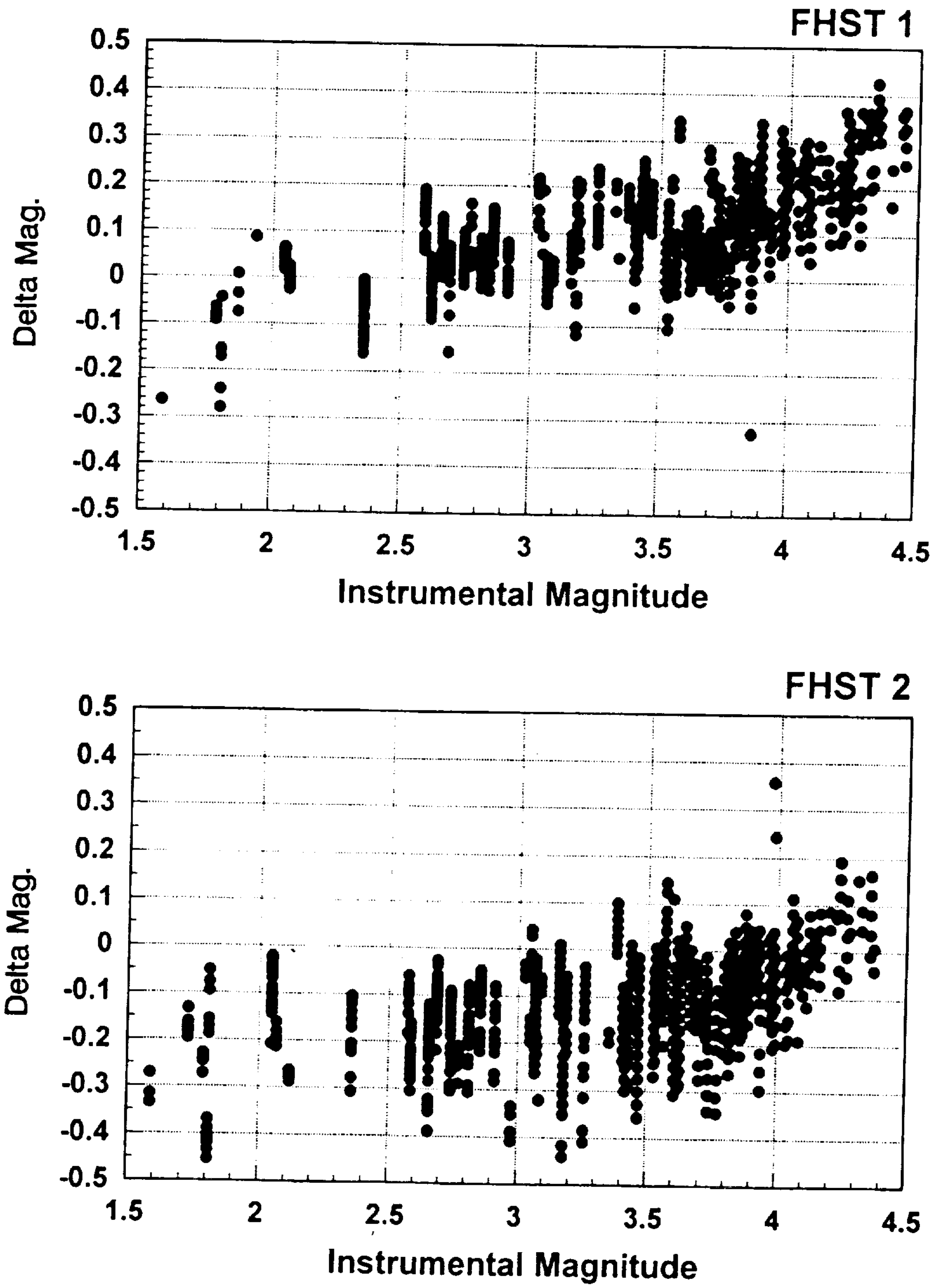


Figure 8. Delta Magnitude Versus Instrumental Magnitude (UARS)

Conclusions

Plots of theta versus phi indicate that the study has used a uniform distribution of stars across each FHST's FOV. None of the FHSTs analyzed in this paper have displayed a noticeable time dependence. Since EUVE's data spans covered 8 months and UARS's covered over a year, the processes that influence an FHST's degradation take longer than these spans.

Color index has an effect on two of the FHSTs: EUVE FHST 1 and UARS FHST 1. Both show a significant correlation between magnitude error and B-V value. It should be noted that these two FHSTs have serial numbers of SN005 (UARS FHST1) and SN006 (EUVE FHST1). EUVE and UARS swapped star trackers before launch due to a problem with the SN006 FHST. UARS was launched with EUVE's original FHST1 in place of its original FHST2. Once the problem with SN006 was repaired, it was put onboard EUVE as its FHST1. It is assumed that since these two FHSTs were the original ones built for UARS, they were built at the same time. These color-caused magnitude errors could have some dependence upon the manufacturing process of the FHSTs. This should be considered in the future when new missions are launched using the Charged Coupled Device (CCD) star trackers since these are even more sensitive to reddish colors than the Image Dissector Tube FHSTs.

Position dependence due to magnitude errors is evident in two of the FHSTs: EUVE FHST 1 and UARS FHST 2. Both FHSTs display position dependencies with similar results. Currently, it is unknown why certain areas in the FOV seem to have more errors than the other since no time dependence is seen, but future analysis may provide answers.

More analysis of the magnitude calibration equation for UARS is necessary. Data from the Delta Magnitude/B-V and Delta Magnitude/Instrumental Magnitude plots supports the need for new coefficients in Equation (2). This has already been done for EUVE. These calibrations should allow for more stars to be identified properly and, therefore, more accurate attitude determinations.

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