IN-FLIGHT CALIBRATION AND PERFORMANCE EVALUATION OF THE FIXED HEAD STAR TRACKERS FOR THE SOLAR MAXIMUM MISSION

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ABSTRACT

The Solar Maximum Mission (SMM) spacecraft, which was launched on February 14, 1980, provides an excellent opportunity for evaluating attitude determination accuracies achievable with star tracking instruments such as the Ball Brothers Research Corporation (BBRC) Fixed Head Star Trackers (FHSTs). SMM carries as a part of its payload a highly accurate Fine Pointing Sun Sensor (FPSS). The FPSS provides an independent check of the pitch and yaw parameters computed from observations of stars in the FHST field of view. This paper applies a method to determine the alignment of the FHSTs relative to the FPSS using spacecraft data. Also presented are two methods that were used to determine distortions in the 8-degree by 8-degree field of view of the FHSTs using spacecraft data. Finally, an evaluation is made of the attitude determination accuracy performance of the in-flight-calibrated FHSTs.

1. INTRODUCTION

Two NASA standard Fixed Head Star Trackers (FHSTs) were flown on the Solar Maximum Mission (SMM) spacecraft, which was launched on February 14, 1980. The FHSTs, manufactured by the BBRC Aerospace Systems Division, are electro-optical devices that use an image dissector to search for and track stars in an 8-degree by 8-degree field of view. The SMM provides an excellent opportunity to evaluate the attitude determination accuracies attainable with the FHSTs. Included in the SMM payload is a highly accurate Fine Pointing Sun Sensor (FPSS), which provides an independent check of the pitch and yaw parameters computed from the stellar observations made by the SMM FHSTs. Two types of error are chiefly responsible for degrading the accuracy of attitude solutions based on FHST data. Uncertainty in the position of an observed star results from distortion of its image by electro-optical irregularities over the star sensor's field of view and by temperature, magnetic field, and star intensity effects. Errors of this type are predictable and can be compensated for by careful calibration of the star cameras on the ground. Uncorrected star camera misalignments are a second source of systematic errors in attitudes computed using star sensor data. Misalignment errors typically are eliminated by appyling to FHST data biases estimated by comparing attitudes determined from FHST and a reference attitude sensor data. This paper discusses a procedure that was developed for enhancing the accuracies of attitude solutions obtained with the SMM FHSTs. The procedure is based on (1) minimizing the errors in observed star positions by adjusting the scale factors in the equations calibrating the distortions in SMM star camera measurements and (2) minimizing the differences between the pitch and yaw attitudes derived from the SMM FHSTs and the reference FPSS by adjusting the FHST misalignment parameters. Application of the procedure to the case of the SMM FHSTs resulted in a two- to three-fold improvement in attitude accuracy when data from both star cameras were used to estimate attitude, and as much as a ten-fold improvement when data from single cameras were used to determine attitude. Many details of the methods used in this paper are presented elsewhere (Reference 1) and only the main results of the calculations are given here.

2.0 EVALUATION OF FHST MEASUREMENT UNCERTAINTY

The angles θ and ϕ defining the measured star position relative to the FHST boresight are defined as shown in Figure 1. These angles are converted to a unit vector using the following equation:

$$\hat{S} = \cos\theta \cos\phi \ \hat{X} - \sin\theta \cos\phi \ \hat{Y} + \sin\phi \ Z \quad (1)$$

2.1 SMM FHST DATA REDUCTION

The raw FHST counts H and V are converted to angles θ and ϕ through a complicated set of calibration equations. The form at these calibrations is as follows (Reference 2):

$$\begin{aligned} f_1(H,V,X) = {} & C_1 + C_2V + C_3H + C_4X + C_5V^2 + C_6VH + C_7VX + C_8H^2 \\ & + C_9HX + C_{10}X^2 + C_{11}V^3 + C_{12}V^2H + C_{13}V^2X \\ & + C_{14}VH^2 + C_{15}VHX + C_{16}VX^2 + C_{17}H^3 + C_{18}H^2X \\ & + C_{19}HX^2 \end{aligned} \quad (2)$$

where

H = horizontal axis output in counts

V = vertical axis output in counts

X = physical parameters as defined below

$f_1(H,V,X)$ = H value corrected for X; f_1 in counts

C = calibration coefficients corresponding to H value corrections

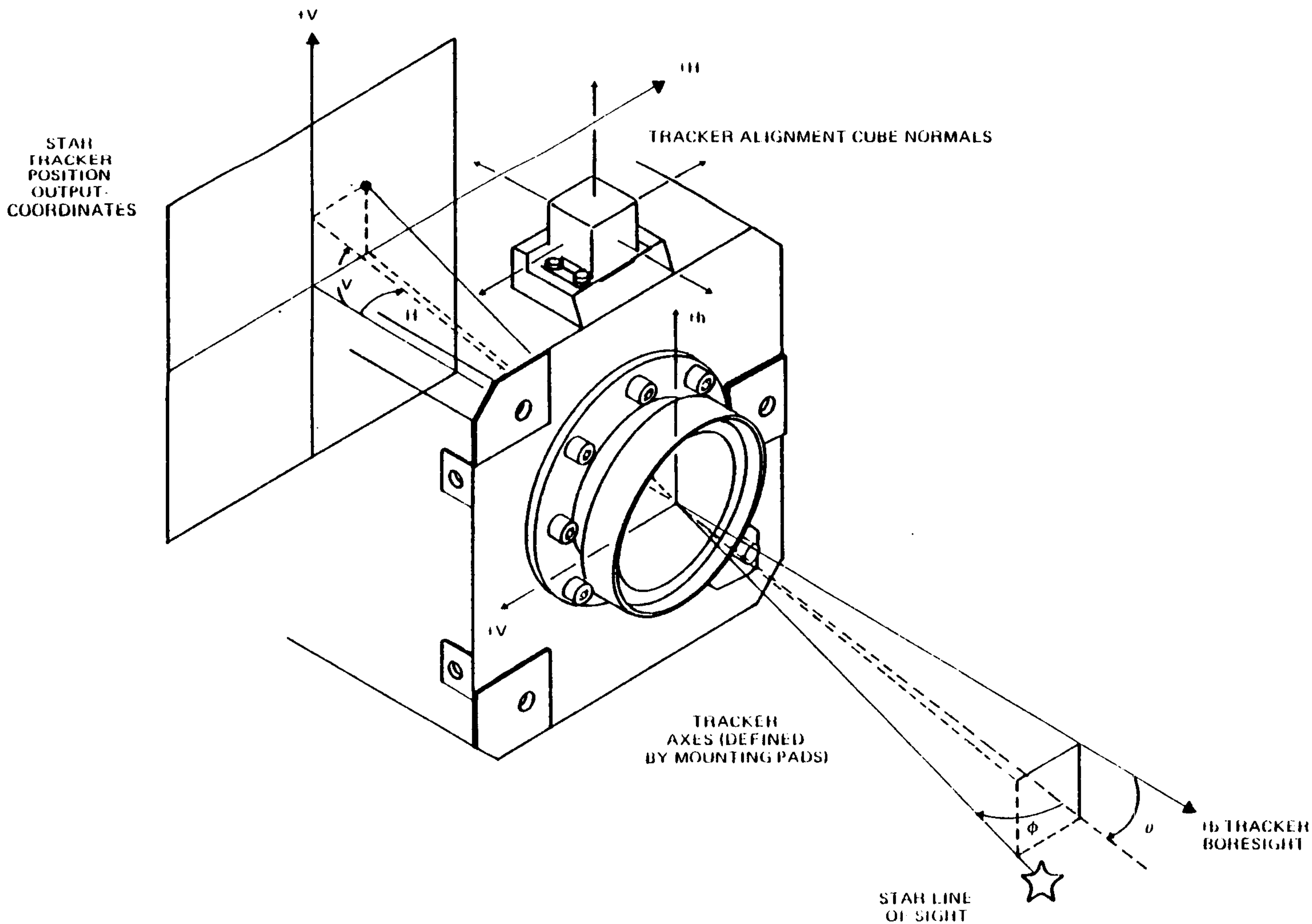

Figure 2-1. FHST Coordinate Definition (BBRC)

The expression $f_2(H,V,X)$ for the V value corrected for X is of the same form as $f_1(H,V,X)$ except for different calibration coefficients C.

Five separate applications of Equation (2) are necessary for each axis. The first application is a flat-field temperature calibration; X is the temperature in volts. The second application is for intensity, with X being the star intensity in volts. The third application has X equal to the magnetic field along the boresight axis in gauss; the fourth application has X equal to the magnetic field along the star tracker h axis in gauss; and the fifth application has X equal to the magnetic field along the star tracker v axis.

The angle θ and ϕ are then given by

$$\begin{aligned} \phi &= -S_H f_1 \\ \theta &= -S_V f_2 \end{aligned} \tag{3}$$

where S_H and S_V are the scale factors for a particular FHST in degrees per count.

2.2 SMM FHST MEASUREMENT ERRORS WITH PRELAUNCH SCALE FACTORS

Star tracker flight data taken on March 2 and March 3, 1980, were used to evaluate this calibration. These data are composed of three different passes, referred to as ACN-I, ACN-II, and HAW. The data were rich in star information and represented the best data at the time the calibrations were completed. The stars present in each pass were identified, and the angle between each pair of stars was computed in the FHST reference frame. These angles were compared to the corresponding angles computed from catalog stars. The difference between the catalog star separation angles and the measured separation angles was computed for every possible observed pair. The mean and standard deviation were computed for each of the three passes. These results are shown in Table 1.

Table 1. Mean and Standard Deviations of Differences Between Observed Star Pairs and the Corresponding Catalog Star Pairs

Pass	FHST1 Mean (arc-sec)	FHST1 σ[a] (arc-sec)	FHST2 Mean (arc-sec)	FHST2 σ[a] (arc-sec)
ACN-I	40.1	31.2	94.9	42.1
ACN-II	52.5	39.6	105.2	42.0
HAW	73.6	44.9	98.2	36.8

[a] σ = Standard deviation

The results shown in Table 1 are independent of the overall FHST alignment, since only angles between stars in one reference frame (the FHST frame) are being compared to the corresponding angles in a rotated reference frame (the geocentric inertial frame). Hence, these results reflect the inherent accuracy of the FHST data. The results in Table 1 indicate that the preflight calibration, when applied to actual flight data, leads to star position errors that are much larger than the 10- to 20-arc-second range desired for SMM.

Since temperature effects can greatly influence the FHST calibration, FHST temperature data around the SMM orbit were examined. There was virtually no change in temperature as the spacecraft made day-to-night transitions. In addition, the temperatures have been virtually the same from the time of launch through August 1980.

2.3 SMM FHST MEASUREMENT ERROR WITH REFINED SCALE FACTORS

Because of the large errors in star position given by the calibrated FHST data, as discussed in the previous subsection, it was decided to attempt an in-flight calibration of the FHST by treating the scale factors in Equation (3) as free parameters. These scale factors were originally specified by the manufacturer in the prelaunch specifications (Reference 2).

First it is assumed that $S^{(1)} = S_V^{(1)} = S_H^{(1)}$ and $S^{(2)} = S_V^{(2)} = S_H^{(2)}$; i.e., each FHST has only one scale factor associated with it. With this assumption, a straight line is expected when the angle between measured stars is plotted versus the angle between corresponding catalog stars. The deviation of the slope of this line from unity is related to the actual value of the scale factor.

Starting with a scale factor of 0.002079 degree per count, the following results were obtained:

$S^{(1)}$ = 0.0020683 degree per count for FHST1

$S^{(2)}$ = 0.0020673 degree per count for FHST2

These results, with the mean and standard deviation of the data, are given in Tables 2 and 3.

Separate horizontal axis and vertical axis scale factors were determined for each FHST by minimizing the angular differences in positions of three stars at one time and averaging the scale factors over as many triplets in the field of view as possible. For this method, stars that were near the edge of the field of view, that were very faint, or that for any reason showed large standard deviations in their positions were rejected.

Table 2. Angular Separation of Stars for FHST1 in Geocentric Inertial (GCI) and Pseudo-Geocentric Inertial (PGCI) Frames

FHST1 STAR PAIR	GCI SEPARATION (DEGREES)	PGCI SEPARATION[a] (DEGREES)	ANGULAR DIFFERENCE[b] (ARC-SECONDS)	PGCI[c] (DEGREES)	ANGULAR DIFFERENCE[d] (ARC-SECONDS)
1-2	2.6690691	2.6901166	-75.77	2.6916143	81.16
1-3	5.8430880	5.8559311	-46.24	5.85924730	-58.17
1-4	8.5593707	8.5717052	-44.40	8.57752340	-65.35
1-6	4.2783210	4.2864809	-29.38	4.28850445	-36.66
1-7	9.1755633	9.1740970	5.28	9.1792283	13.19
2-3	3.1760332	3.1677620	29.78	3.16958235	23.22
2-4	5.9347617	5.9266711	29.13	5.9308240	14.18
2-6	1.6897312	1.6770099	45.80	1.67765498	43.47
2-7	6.5068470	6.4844566	80.61	6.48801936	67.78
3-4	2.8523522	2.8528839	-1.91	2.8552865	-10.56
3-6	1.8074348	1.8078567	-1.52	1.80933849	-6.85
3-7	3.3448504	3.3309729	49.96	3.33272267	43.66
4-6	4.6575541	4.6588012	-4.49	4.6629900	-18.52
4-7	1.5609355	1.5600399	3.22	1.56080533	0.47
6-7	4.9774255	4.9656321	42.46	4.96875089	31.23

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[a] H&V SCALE FACTOR - 0.0020683 DEGREE PER COUNT

[b] MEAN = 5.50 ARC-SECONDS; σ = 42.22 ARC-SECONDS

[c] HSF = 0.0020690 DEGREE PER COUNT; VSF = 0.0020704 DEGREE PER COUNT

[d] MEAN = 2.67 ARC-SECONDS; σ = 43.31 ARC-SECONDS

Table 3. Angular Separation of Stars for FHST2 in GCI and PGCI Frames

FHST2 STAR PAIR	GCI SEPARATION (DEGREES)	PGCI SEPARATION[a] (DEGREES)	ANGULAR DIFFERENCE[b] (ARC-SECONDS)	PGCI[c] SEPARATION (DEGREES)	ANGULAR DIFFERENCE[d] (ARC-SECONDS)
9-10	1.99021294	1.9884488	6.35	1.98811031	7.57
9-12	5.18220145	5.18623851	-14.53	5.18555249	-12.06
9-13	3.10987769	3.10728594	9.33	3.10448100	19.43
9-17	3.49565583	3.49513002	1.89	3.49318537	8.89
10-12	3.83780618	3.83427703	12.70	3.83287884	17.74
10-13	3.30020267	3.30492505	-17.00	3.30333513	-11.28
10-17	1.99636914	2.00586208	-34.17	2.00413461	-27.96
12-13	7.11550992	7.11557903	-0.25	7.112602589	10.47
12-17	5.02159070	5.0259217	-15.62	5.02254775	-3.45
13-17	2.73095274	2.72621958	17.04	2.72608318	17.53

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[a] H&V SCALE FACTORS = 0.0020673 DEGREE PER COUNT

[b] MEAN = 3.43 ARC-SECONDS; σ = 16.25 ARC-SECONDS

[c] HSF = 0.0020654 DEGREE PER COUNT; VSF = 0.0020672 DEGREE PER COUNT

[d] MEAN = 2.69 ARC-SECONDS; σ = 15.77 ARC-SECONDS

The following scale factors were obtained using the ACN data of March 2, 1980, at 9:23 GMT (see also Tables 2 and 3):

Tracker	Axis	Scale Factor (degree per count)
FHST1	Horizontal	0.0020690
FHST1	Vertical	0.0020704
FHST2	Horizontal	0.0020654
FHST2	Vertical	0.0020672

Table 4 shows the same pairs of stars used in scale factor determination with the prelaunch value.

3.0 EVALUATION OF SMM GHST ATTITUDE DETERMINATION ACCURACY PERFORMANCE

The misalignment angles are defined as corrections to the nominal 1-3-1 rotation from the Modular Attitude Control System (MACS) to FHST reference frame. This transformation is given by the following equation:

$$M \text{ (MACS to FHST)} = T_1(\beta_1 + \alpha_1)\; T_3(\beta_2 + \alpha_2)\; T_1(\beta_3 + \alpha_3) \quad (4)$$

where the β's are the nominal angles, the α's are the small misalignment angles, and T_i represents a rotation about the ith axis. The β's are given by the following:

FHST	β_3	β_2	β_1
1	-19.7724	53.34892	102.0137
2	-19.73046	126.5083	258.0593

3.1 FHST MISALIGNMENT BIAS DETERMINATION

To determine the misalignments, the attitude as computed from the FHST is adjusted to match the FPSS attitude for the pitch and yaw angles. Since there is no roll reference for the FHST, the absolute α_3 misalignment is not determined.

Table 4. Comparisons of Catalog and Observation Star Vector Separation With Prelaunch Scale Factors

FHST1 STAR PAIR	CATALOG ANGLE (DEGREES)	PGCI ANGLE (DEGREES)	ANGULAR DIFFERENCE* (ARC-SECONDS)
1–2	2.6690691	2.702847	−119.47
1–3	5.8430880	5.885778	−115.04
1–4	8.5593707	8.616201	−204.59
1–6	4.2783210	4.308378	−108.24
1–7	9.175563	9.221828	−166.55
2–3	3.176033	3.182881	−26.72
2–4	5.9347617	5.956749	−78.34
2–6	1.6897312	1.684136	20.85
2–7	6.506847	6.517856	−40.19
3–4	2.852352	2.866830	−55.27
3–6	1.8074348	1.816287	−38.73
3–7	3.3448504	3.348180	−17.14
4–6	4.6575541	4.682731	−90.90
4–7	1.5609355	1.568525	−31.18
6–7	4.9774255	4.991619	−53.00

FHST2 STAR PAIR	CATALOG ANGLE (DEGREES)	PGCI ANGLE (DEGREES)	ANGULAR DIFFERENCE** (ARC-SECONDS)
9–10	1.9902129	1.999312	−32.76
9–12	5.1822015	5.215897	−121.30
9–13	3.1098777	3.124387	−52.23
9–17	3.4956558	3.514408	−67.51
10–12	3.8378062	3.856123	−65.94
10–13	3.3002027	3.323802	−84.96
10–17	1.9963691	2.016582	−72.77
12–13	7.1155099	7.156287	−146.80
12–17	5.0215907	5.054222	−117.47
13–17	2.7309527	2.741496	−37.96

*MEAN = −74.97 ARC-SECONDS; σ = 59.95 ARC-SECONDS

**MEAN = −79.97 ARC-SECONDS; σ = 37.67 ARC-SECONDS

However, $(\alpha_3)_{FHST2} - (\alpha_3)_{FHST1}$ is determined from the difference in the roll attitude computed independently with each star tracker at null atitude. The difference $(\alpha_3)_{FHST_2} - (\alpha_3)_{FHST1}$ was computed as 0.04378 degree.

3.2 <u>PARTIAL DERIVATIVE METHOD FOR MINIMIZING ATTITUDE ERROR</u>

The method used to obtain the α_1 and α_2 misalignments is referred to as the partial derivative method. The attitude is expanded in terms of the alignment angles about their nominal values. Using the FPSS as a reference produces a set of linear equations that result in solutions for α's. These solutions are given by the following set of equations:

$$\delta\alpha_1^{(1)} = \left(\delta Y^{(1)} \frac{\partial P^{(1)}}{\partial \alpha_2^{(1)}} - \delta P^{(1)} \frac{\partial Y^{(1)}}{\partial \alpha_2^{(1)}}\right) \Big/ J \tag{5}$$

$$\delta\alpha_2^{(1)} = \left(-\delta Y^{(1)} \frac{\delta P^{(1)}}{\delta \alpha_1^{(1)}} + \delta P^{(1)} \frac{\delta P^{(1)}}{\delta \alpha_1^{(1)}}\right) \Big/ J \tag{6}$$

where

$$J = \frac{\partial Y^{(1)}}{\partial \alpha_1^{(1)}} \frac{\partial P^{(1)}}{\partial \alpha_2^{(1)}} - \frac{\partial P^{(1)}}{\partial \alpha_1^{(1)}} \frac{\partial Y^{(1)}}{\partial \alpha_2^{(1)}} \tag{7}$$

$$\delta\alpha_1^{(1)} = \alpha_1^{(1)} - \alpha_1^{(1)} \quad (0) \tag{8}$$

$$\delta\alpha_2^{(1)} = \alpha_2^{(1)} - \alpha_2^{(1)} \quad (0) \tag{9}$$

where $\alpha_1^{(1)}$ and $\alpha_2^{(1)}$ are the misalignments that are taken to force FHST1 to yield the same pitch and yaw as given by the FPSS and $\alpha_1^{(1)}(0)$ and $\alpha_2^{(1)}(0)$ are the starting values,

$$\delta P^{(1)} = P_{FPSS} - P^{(1)}(0) \tag{10}$$

$$\delta Y^{(1)} = Y_{FPSS} - Y^{(1)}(0) \tag{11}$$

where P_{FPSS} and Y_{FPSS} are the FPSS pitch and yaw and $P^{(1)}(0)$, $Y^{(1)}(0)$ is the attitude determined with the trial misalignments.

Since there is no absolute reference to determine α_3, the dependence of the attitudes on this parameter is ignored. This could lead to some difficulty, since the misalignment will also indirectly affect the determination of α_1 and α_2.

3.3 ATTITUDE ACCURACY RESULTS

Using the standard sets of data--ACN-I, ACN-II, and HAW--the best set of misalignment parameters is determined. These results are shown in Table 5, with the averaged values and the corresponding root-mean-square (rms) deviations. Certain conclusions are readily apparent from these computations. The misalignment around the boresight of the camera, α_1, is very poorly determined by the data. This result will not greatly affect the two-tracker attitudes. The misalignment α_2 is quite well determined, as shown by the results in Table 5.

Table 5. Misalignment Parameters

DATA	FHST1		FHST2	
	$\alpha_1^{(1)}$ (DEGREES)	$\alpha_2^{(1)}$ (DEGREES)	$\alpha_1^{(2)}$ (DEGREES)	$\alpha_2^{(2)}$ (DEGREES)
ACN-I	−0.059	0.1073	0.1696	−0.00555
ACN-II	−0.01867	0.1105	0.192	−0.0089
HAW	0.0108	0.1078	0.216	−0.0076
AVERAGED VALUES	−0.0223	0.1085	0.193	−0.0074
ROOT-MEAN-SQUARE DEVIATIONS	126 ARC-SECONDS	6 ARC-SECONDS	84 ARC-SECONDS	6 ARC-SECONDS

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NOTE: THE MISALIGNMENT PARAMETERS ARE SHOWN FOR FHST1 AND FHST2 FOR THREE SETS OF DATA. THE AVERAGED VALUES AND RMS DEVIATIONS IN ARC SEC ARE ALSO SHOWN.

The attitudes before and after the misalignments have been applied are shown in Table 6. It is apparent that a general overall improvement has been obtained in the computation of the pitch and yaw attitude components by the determined misalignments.

The overall attitude accuracy based on these results is on the order of ±30 arc-seconds.

ACKNOWLEDGMENTS

The authors thank R. Byrne, G. Nair, and J. Buckley of CSC and R. Werking of GSFC for countless discussions concerning the calibrations of the SMM FHST.

Table 6. Attitude Comparisons

DATA	FHST1				FHST2				BOTH			
	NEW		OLD		NEW		OLD		NEW		OLD	
	δP*	δY**	δP	δY	δP	δY	δP	δY	δP	δY	δP	δY
ACN-I	-30.1	46.1	25.2	-32.8	17.6	18.5	-23.6	4.4	23.5	-24.1	-34.1	34.6
ACN-II	4.2	10.1	104.4	-108.0	12.2	29.5	21.6	64.8	17.28	-28.8	-50.8	47.2
HAW	37.4	33.5	147.2	171.7	61.9	-83.0	61.2	105.8	13.3	-15.5	47.9	54.5

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*$\delta P = P_{FPSS} - P_{FHST}$ (ARC SECONDS)

**$\delta Y = Y_{FPSS} - Y_{FHST}$ (ARC-SECONDS)

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