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IN-FLIGHT CALIBRATION OF THE FINE POINTING SUN SENSOR ON THE SOLAR MAXIMUM MISSION

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ABSTRACT

The attitude control objectives of Solar Maximum Mission (SMM) are to point the boresight of the payload Fine Pointing Sun Sensor (FPSS) to any point within 30 arc-minutes of the Sun's center with an accuracy of 5 arc-seconds (3σ, pitch and yaw) and a jitter of less than 3 arc-seconds (3σ). To meet these stringent accuracy requirements, a procedure was developed for in-flight calibration of the FPSS. The spacecraft was maneuvered using FPSS offset commands to position the Sun at different points within the FPSS field of view. The coefficients of the FPSS digital-to-analog nonlinear transfer function were determined by minimizing the residuals between the pitch and yaw angles computed from the FPSS measurements and the corresponding reference angles obtained from Inertial Reference Unit (IRU) measurements.

In this paper, the actual in-flight calibration and the calibration algorithm are discussed. Spacecraft data are used to assess the range of validity of the FPSS transfer function. The Sun's diameter is computed with the FPSS calibration results and the Ultraviolet Spectrometer and Polarimeter (UVSP) experimenters' data. This calculation gives an independent verification of the calibration results.

1. INTRODUCTION

The attitude control objectives of the SMM are to point the boresight of the payload FPSS to any point within 30 arc-minutes of the Sun's center with an accuracy of 5 arc-seconds (3σ, pitch and yaw) and a jitter of less than 3 arc-seconds (3σ). To meet these stringent accuracy requirements, a procedure was developed for in-flight calibration of the FPSS. The spacecraft was maneuvered using FPSS offset commands to position the Sun at different points within the FPSS field of view. The coefficients of the FPSS digital-to-analog non-linear transfer function were determined by minimizing the residuals between the pitch and yaw angles computed from the FPSS measurements and the corresponding reference angles obtained from Inertial Reference Unit (IRU) measurements.

In this paper, spacecraft data are used to assess the range and validity of the FPSS transfer function. In addition, the Sun's diameter is computed with the FPSS calibration results and the Ultraviolet Spectrometer and Polarimeter (UVSP) experimenters' data.

2. EQUATIONS AND PROCEDURE

The Adcole transfer functions for each FPSS are (Reference 1)

$$\alpha = A_1 + A_2 N_\alpha + A_3 \sin (A_4 N_\alpha + A_5) + A_6 \sin (A_7 N_\alpha + A_8) \quad (1)$$

and

$$\beta = B_1 + B_2 N_\beta + B_3 \sin (B_4 N_\beta + B_5) + B_6 \sin (B_7 N_\beta + B_8) \quad (2)$$

where A_i and B_i $(1 \le i \le 8)$ are constants, N_α and N_β are the FPSS digital outputs, and the angles α and β are in radians.

During the calibration phase of the SMM mission, the spacecraft was maneuvered such that the Sun was positioned at different points within the reduced FPSS field of view. The angular displacement of each sample point from the FPSS null was measured independently by the FPSS and the calibrated SMM gyros. The coefficients A_i $(2 \le i \le 8)$ and B_i $(2 \le i \le 8)$ of the FPSS calibration equations were determined by minimizing the differences between the FPSS observed changes in pitch and yaw angles and the corresponding changes in the reference pitch and yaw angles measured by the gyros at each off-null sample point. The FPSS calibration algorithm employs a recursive least squares procedure which processes changes in pitch and yaw angles rather than absolute pitch and yaw angles to take advantage of the extreme accuracy with which gyros measure attitude changes. The coefficients A_1 and B_1 for each FPSS were determined from the equations

$$\begin{aligned} \alpha &= 0 \\ \beta &= 0 \end{aligned} \qquad (3)$$

Calibration data were obtained using a discrete slew maneuver method and a continuous slew maneuver method. In the discrete slew maneuver method, the spacecraft was commanded to perform a series of slews (along the pitch and yaw axes) over the 1-degree by 1-degree FPSS reduced field of view. Gyro readings and FPSS readings were taken at each commanded slew position. To reduce the accumulation of errors, each slew maneuver was between null attitude and a specified off-null attitude. Changes in attitude resulting from a null attitude to an off-null attitude slew were input into the recursive least squares algorithm. The changes in attitude from an off-null attitude to a null attitude slew were also input.

For the continuous slew maneuver method, the spacecraft is commanded to perform bang-bang slews along the pitch and yaw axes of the FPSS 1-degree by 1-degree field of view. Gyro data and FPSS data were taken during the slew maneuver every 0.96 second.

The calibration results are presented in the following section.

The continuous slew data were not used because of the large residuals between the FPSS data and the gyro data. The large residuals resulted from the high slew rate of the spacecraft and the slight data sampling time shift between the FPSS and gyro data. Hence, the FPSS was calibrated with discrete slew data only.

The FPSS calibration uses the gyros as a reference and is dependent on the accuracy of the gyro calibration. The FPSS was calibrated with the gyro alignment/scale factor matrix, and gyro drifts computed in flight. The drift rates were adjusted slightly at each FPSS calibration to be consistent with that particular set of data.

3. CALIBRATION RESULTS

The results of the FPSS calibration algorithm are presented here and the accuracy of the algorithm is assessed. The FPSS was calibrated in flight on March 18, June 11, June 27, July 17, August 27, and September 4, 1980. These calibrations are summarized in Table 1, and the corresponding FPSS coefficients are given in Tables A-1 through A-7 in the appendix.

The mean pitch residuals $|\Delta P_{FPSS} - \Delta P_{GYRO}|$ and yaw residuals $|\Delta Y_{FPSS} - \Delta Y_{GYRO}|$ are a measure of the accuracy of the calibration algorithm. A comparison of the FPSS calibration residuals from all of our calibrations as of this writing are given in Table 1. The maximum residuals are also tabulated.

After the March 18 calibration, the spacecraft was slewed +179 arc-seconds in pitch and -111 arc-seconds in yaw to facilitate the solar experiments on SMM. This will affect the A_1 and B_1 coefficients on calibrations III through V. Furthermore, on August 22 the spacecraft was slewed +44 arc-seconds in yaw. This will affect the A_1 and B_1 coefficients in calibration VI.

Both FPSSs have degraded since July 31, 1980. The overall degradation in FPSS1 is shown in Figures 1 and 2, where the FPSS1 pitch and yaw differences between various calibrations are shown.

As an independent verification of the calibration results, calibration VI was used to compute the solar diameter on August 6. This was accomplished by noting the FPSS raw counts when the UVSP experimental boresight made crossings of the Sun's limb, (Reference 2). These results are presented in Table 2. The results show that the Sun's diameter computed with the calibration results is consistent with the accepted value of the Sun's diameter for August 6.

Table 1. Summary of FPSS Calibration

CALIBRATION NO.	PITCH CALIB.	YAW CALIB.	FPSS	DATE OF CALIB.	DATE OF DATA	DATE OF GYRO CALIB.	RANGE OF CALIB. (deg)	MEAN RESIDUAL (arc-sec)	MAXIMUM RESIDUAL (arc-sec)	NO. OF DATA PTS.
PRELAUNCH	*		1					5.14 ± 5.58		
		*						9.38 ± 6.43		
	*		2					3.27 ± 2.24		
		*						6.22 ± 7.11		
I	*		1	3/18	3/5	3/18	0.43 TO −0.40	0.53 ± 0.03	1.3	25
		*					0.42 TO −0.39	0.40 ± 0.41	1.5	16
	*		2				0.43 TO −0.40	0.52 ± 0.43	1.7	25
		*					0.42 TO −0.39	0.56 ± 0.50	1.4	16
II	*		1	6/11	3/5	5/19	0.43 TO −0.40	–	0.9	25
		*					0.42 TO −0.39	–	1.2	16
	*		2				0.43 TO −0.40	–	1.2	25
		*					0.42 TO −0.39	–	1.2	16
III	*		1	6/27	6/21	5/19	0.25 TO −0.25	–	1.9	4
		*					0.41 TO −0.41	–	1.9	6
	*		2				0.25 TO −0.25	–	2.1	4
		*					0.41 TO −0.41	–	1.7	6
IV	*		1	7/17	7/3	5/19	0.32 TO −0.32	0.79 ± 0.72	1.7	10
		*					0.36 TO −0.38	0.68 ± 0.47	2.1	11
	*		2				0.32 TO −0.32	0.78 ± 0.93	1.7	10
		*					0.36 TO −0.38	0.68 ± 0.52	1.6	11
V	*		1	8/27	7/31	8/18	0.35 TO −0.32	0.28 ± 0.26	1.1	19
		*					0.35 TO −0.34	0.38 ± 0.46	1.0	21
	*		2				0.35 TO −0.32	0.26 ± 0.27	1.2	19
		*					0.35 TO −0.34	0.46 ± 0.50	1.0	21
VI	*		1	9/4	8/24	8/18	0.35 TO −0.36	0.29 ± 0.26	1.2	19
		*			8/25		0.35 TO −0.37	0.29 ± 0.23	1.0	21
	*		2		8/24		0.35 TO −0.36	0.31 ± 0.24	0.9	19
		*			8/25		0.35 TO −0.37	0.33 ± 0.22	0.9	21

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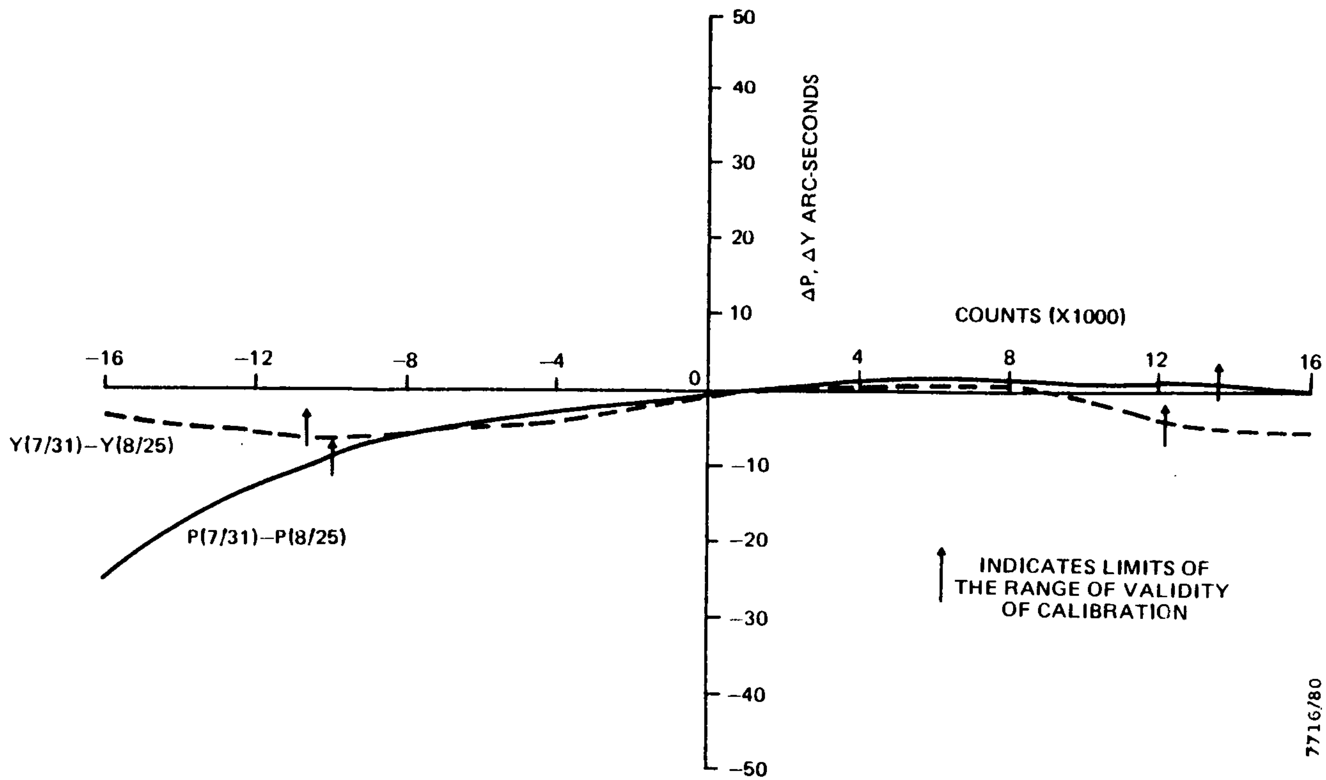

Figure 2. Plot of FPSS1 Pitch and Yaw Angle Difference Between July 31, 1980 (V) and August 25, 1980 (VI)

Table 2. UVSP Limb Crossing Results for August 6, 1980

Limb	FPSS Counts[a]	Time (HHMMSSMMM)	Pitch (arc-sec)	Yaw[b] (arc-sec)
South	+10394.5	0.104933450	946.5	
North	-6517.0	0.105327950	-945.8	
East	-7363.5	0.110137730		957.9
West	9812.0	0.110533200		-942.2

[a]Obtained from Reference 2 by dividing the numbers presented there by +0.109866 and -0.109866 (for pitch and yaw, respectively).

[b]The calibrated FPSS pitch and yaw angles were computed from the transfer function determined from the August 24, 1980, and the August 25, 1980 calibration slews.

NOTES: N-S diameter = 1892.3 arc-seconds
E-W diameter = 1900.1 arc-seconds
Accepted diameter for August 6, 1980 = 1895.36 arc-seconds (Reference 3)

APPENDIX A. SUMMARY OF FPSS COEFFICIENTS

Table A-1. I Prelaunch Calibration Coefficients

Coefficient	FPSS1	FPSS2
A_1	0.1090831×10^{-3}	$-0.8047742 \times 10^{-3}$
A_2	0.5326322×10^{-6}	0.5326322×10^{-6}
A_3	0.1335975×10^{-4}	0.2808313×10^{-4}
A_4	0.1917476×10^{-3}	0.1917476×10^{-3}
A_5	$0.29628831 \times 10^{+1}$	$-0.1695882 \times 10^{+1}$
A_6	0.1745964×10^{-4}	0.1150606×10^{-4}
A_7	0.3834951×10^{-3}	0.3834928×10^{-3}
A_8	0.8659915	$0.1223491 \times 10^{+1}$
B_1	-0.172264×10^{-3}	$-0.5874911 \times 10^{-3}$
B_2	0.5326322×10^{-6}	0.5326322×10^{-6}
B_3	0.1207313×10^{-4}	0.1443567×10^{-4}
B_4	0.1917476×10^{-3}	0.1917476×10^{-3}
B_5	$-0.1390673 \times 10^{+1}$	$-0.2480650 \times 10^{+1}$
B_6	0.1523304×10^{-4}	0.9449009×10^{-5}
B_7	0.3834951×10^{-3}	0.3834951×10^{-3}
B_8	$0.1206903 \times 10^{+1}$	0.9041772

Table A-2. I Postlaunch Calibration Coefficients Determined March 18, 1980

Coefficients	FPSS1	FPSS2
A_1	$-0.8467783 \times 10^{-4}$	0.8337881×10^{-3}
A_2	0.5320264×10^{-6}	0.5300202×10^{-6}
A_3	$-0.3860728 \times 10^{-5}$	$-0.3292304 \times 10^{-4}$
A_4	0.3072369×10^{-3}	0.1634355×10^{-3}
A_5	$0.3092502 \times 10^{+1}$	$-0.1704371 \times 10^{+1}$
A_6	$-0.2778208 \times 10^{-4}$	$-0.6869980 \times 10^{-5}$
A_7	0.2594346×10^{-3}	0.3717518×10^{-3}
A_8	$0.1737169 \times 10^{+1}$	$0.1595601 \times 10^{+1}$
B_1	$-0.1869254 \times 10^{-3}$	0.5601689×10^{-3}
B_2	0.5312469×10^{-6}	0.5317111×10^{-6}
B_3	0.1416509×10^{-4}	$-0.1834644 \times 10^{-4}$
B_4	0.4284356×10^{-3}	0.2224163×10^{-3}
B_5	$-0.1017843 \times 10^{+1}$	$-0.2684492 \times 10^{+1}$
B_6	0.2674199×10^{-4}	0.4998647×10^{-5}
B_7	0.2226275×10^{-3}	0.5214850×10^{-3}
B_8	$0.1267732 \times 10^{+1}$	$-0.3890319 \times 10^{-1}$

Table A-3. II Postlaunch Calibration Coefficients Determined June 11, 1980

Coefficient	FPSS1	FPSS2
A_1	$-0.8367909 \times 10^{-4}$	0.8259816×10^{-3}
A_2	0.5318888×10^{-6}	0.5300066×10^{-6}
A_3	$-0.4074826 \times 10^{-5}$	$-0.4318272 \times 10^{-4}$
A_4	0.2879776×10^{-3}	0.1498738×10^{-3}
A_5	$0.3085873 \times 10^{+1}$	$-0.1640329 \times 10^{+1}$
A_6	$-0.2873860 \times 10^{-4}$	$-0.9401628 \times 10^{-5}$
A_7	0.2495391×10^{-3}	0.3194979×10^{-3}
A_8	$0.1739822 \times 10^{+1}$	$0.1708081 \times 10^{+1}$
B_1	$-0.1922094 \times 10^{-3}$	0.5554837×10^{-3}
B_2	0.5310392×10^{-6}	0.5305829×10^{-6}
B_3	0.1485801×10^{-4}	$-0.2491201 \times 10^{-4}$
B_4	0.4229986×10^{-3}	0.1562029×10^{-3}
B_5	-0.7733552	$-0.2638508 \times 10^{+1}$
B_6	0.2962723×10^{-4}	0.6656607×10^{-5}
B_7	0.1890266×10^{-3}	0.4382294×10^{-3}
B_8	$0.1361674 \times 10^{+1}$	$-0.9191982 \times 10^{+1}$

Table A-4. III Postlaunch Calibration Coefficients Determined June 27, 1980

Coefficients	FPSS1	FPSS2
A_1	$-0.5005656 \times 10^{-3}$	0.3856357×10^{-3}
A_2	0.5321897×10^{-6}	0.5316871×10^{-6}
A_3	0.2804029×10^{-4}	0.8814421×10^{-5}
A_4	0.3004984×10^{-3}	0.5507673×10^{-3}
A_5	$0.4356816 \times 10^{+1}$	$-0.2294463 \times 10^{+1}$
A_6	$-0.1210886 \times 10^{-3}$	$-0.3935267 \times 10^{-4}$
A_7	0.1686625×10^{-3}	0.3279436×10^{-3}
A_8	$0.1556701 \times 10^{+1}$	$0.2645207 \times 10^{+1}$
B_1	$-0.1086737 \times 10^{-2}$	$-0.2948222 \times 10^{-3}$
B_2	0.5458022×10^{-6}	0.5415047×10^{-6}
B_3	0.2859741×10^{-4}	0.2531778×10^{-4}
B_4	0.4699715×10^{-3}	$-0.3735274 \times 10^{-3}$
B_5	$-0.1037046 \times 10^{+1}$	$-0.2593021 \times 10^{+1}$
B_6	0.2968237×10^{-4}	0.3284074×10^{-4}
B_7	0.1812999×10^{-3}	$-0.1052192 \times 10^{-3}$
B_8	$0.1252416 \times 10^{+1}$	$-0.1360665 \times 10^{+1}$

Table A-5. IV Postlaunch Calibration Coefficients Determined July 17, 1980

Coefficients	FPSS1	FPSS2
A_1	$-0.4818073 \times 10^{-3}$	0.3970052×10^{-3}
A_2	0.5318731×10^{-6}	0.5325560×10^{-6}
A_3	0.3316726×10^{-4}	$-0.3573487 \times 10^{-5}$
A_4	0.3004717×10^{-3}	0.5203074×10^{-3}
A_5	$0.3788808 \times 10^{+1}$	$-0.2229115 \times 10^{+1}$
A_6	$-0.1440138 \times 10^{-3}$	$-0.4843318 \times 10^{-4}$
A_7	0.1678243×10^{-3}	0.2682219×10^{-3}
A_8	$0.1678735 \times 10^{+1}$	$0.2263416 \times 10^{+1}$
B_1	$-0.1086574 \times 10^{-2}$	$-0.3003116 \times 10^{-3}$
B_2	0.5408410×10^{-6}	0.5396636×10^{-6}
B_3	0.4516499×10^{-4}	0.3816943×10^{-4}
B_4	0.3423773×10^{-3}	$-0.3097056 \times 10^{-3}$
B_5	-0.7504307	$-0.2698493 \times 10^{+1}$
B_6	0.3953853×10^{-4}	0.3490103×10^{-4}
B_7	0.1394383×10^{-3}	$-0.1010980 \times 10^{-3}$
B_8	$0.1192923 \times 10^{+1}$	$-0.1339042 \times 10^{+1}$

Table A-6. Postlaunch Calibration Coefficients Determined August 27, 1980

Coefficients	FPSS1	FPSS2
A_1	$-0.4508724 \times 10^{-3}$	0.4214450×10^{-3}
A_2	0.5289703×10^{-6}	0.5309641×10^{-6}
A_3	0.3533130×10^{-4}	$-0.3210337 \times 10^{-5}$
A_4	0.3166422×10^{-3}	0.5288627×10^{-3}
A_5	$0.3402219 \times 10^{+1}$	$-0.2474054 \times 10^{+1}$
A_6	$-0.1872402 \times 10^{-3}$	$-0.6040415 \times 10^{-4}$
A_7	0.1720052×10^{-3}	0.2535198×10^{-3}
A_8	$0.1743850 \times 10^{+1}$	$0.2169274 \times 10^{+1}$
B_1	$-0.1088536 \times 10^{-2}$	$-0.2967559 \times 10^{-3}$
B_2	0.5404148×10^{-6}	0.5396493×10^{-6}
B_3	0.5595529×10^{-4}	0.4825613×10^{-4}
B_4	0.3116594×10^{-3}	$-0.2824294 \times 10^{-3}$
B_5	-0.4978371	$-0.2923239 \times 10^{+1}$
B_6	0.3268151×10^{-4}	0.3803778×10^{-4}
B_7	0.1127492×10^{-3}	$-0.1327780 \times 10^{-3}$
B_8	$0.1187505 \times 10^{+1}$	$-0.1339587 \times 10^{+1}$

Table A-7. Postlaunch Calibration Coefficients Determined September 4, 1980

Coefficients	FPSS1	FPSS2
A_1	$-0.6776863 \times 10^{-3}$	0.1946652×10^{-3}
A_2	0.5284552×10^{-6}	0.5323566×10^{-6}
A_3	0.2988950×10^{-4}	$-0.4638057 \times 10^{-5}$
A_4	0.3252105×10^{-3}	0.4797970×10^{-3}
A_5	$0.3388264 \times 10^{+1}$	$-0.2600997 \times 10^{+1}$
A_6	$-0.1827369 \times 10^{-3}$	$-0.4252801 \times 10^{-4}$
A_7	0.1706592×10^{-3}	0.2589267×10^{-3}
A_8	$0.1830159 \times 10^{+1}$	$0.2113208 \times 10^{+1}$
B_1	$-0.1081432 \times 10^{-2}$	$-0.3001880 \times 10^{-3}$
B_2	0.5378218×10^{-6}	0.5367186×10^{-6}
B_3	0.6281060×10^{-4}	0.6410728×10^{-4}
B_4	0.2800354×10^{-3}	$-0.2461689 \times 10^{-3}$
B_5	-0.4471897	$-0.3109232 \times 10^{+1}$
B_6	0.3239203×10^{-4}	0.4965452×10^{-4}
B_7	0.1877559×10^{-5}	$-0.1906793 \times 10^{-3}$
B_8	$0.1180826 \times 10^{+1}$	$-0.1393259 \times 10^{+1}$

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