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Maintaining the FGS3 Optical Field Angle Distortion Calibration

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Abstract. To date four OFAD (Optical Field Angle Distortion) calibrations have been performed on FGS3 in M35 and analyzed by the Astrometry Science Team. Two have been performed since the last HST (Hubble Space Telescope) Calibration Workshop. The ongoing Long Term Stability Tests have also been analyzed and incorporated into the calibration. A lateral color calibration has been derived from calibration and science data. Descriptions of these tests and the results of our analysis of the resulting data are given. The astrometric science supported by these calibrations is briefly reviewed.

1. Introduction

The largest source of error in reducing star positions from observations with the Hubble Space Telescope (HST) Fine Guidance Sensors (FGSs) is the Optical Field Angle Distortion (OFAD). Description of past analyses can be found in Jefferys et al., (1994), and Whipple et al., (1994, 1996). The precise calibration of the distortion can only be determined with analysis of on-orbit observations. The Long Term STABility tests (LTSTAB), initiated in fall 1992, are an essential component of the OFAD calibration, and provide information on temporal changes. They also provide indicators that a new OFAD calibration is necessary. The lateral color correction has been redetermined with Science Verification data from 1994 and with new analyses of GTO and GO science data. This paper reports the results of the continuing OFAD and LTSTAB tests and the Lateral Color calibration. The astrometric science enabled by the maintenance of these calibrations is briefly reviewed.

2. Motivation and Observations

A nineteen orbit OFAD (Optical Field Angle Distortion) was performed in the spring of 1993 for the initial on-orbit calibration of the OFAD in FGS3. The First Servicing Mission made no changes to the internal optics of the three Fine Guidance Sensors (FGS) that are used for guiding and astrometry on HST. However, the subsequent movement of the secondary mirror of the telescope to the so-called "zero coma" position did change the morphology of the FGS transfer functions (Ftaclas et al. 1993). Therefore, a five orbit post servicing mission delta-OFAD calibration plan was designed and executed. After detection by the LTSTAB of increasing incompatibility with the spring 1994 delta-OFAD calibration, an 11 orbit OFAD was performed in the fall of 1995 to recover the error budget for astrometry. In the spring of 1997 a five orbit OFAD was performed on FGS3 after the second servicing mission. Thirty-five LTSTABS (Long Term Stability Tests) have been performed to assess time-dependent changes. A current list of the OFAD and LTSTAB tests is shown in Table 1.

Table 1. LTSTAB and OFAD Observations.

Orbit	Julian Date	Year	Day	Observation	Coefficient Set
1	2448959.340822	1992	337	FALL LTSTAB	1
2	2448971.061435	1992	349	FALL LTSTAB	1
3-21	2448997.782164	1993	10	SPRING OFAD	1
22	2449082.954086	1993	95	SPRING LTSTAB	1
23	2449095.742836	1993	108	SPRING LTSTAB	1
24	2449096.613044	1993	109	SPRING LTSTAB	1
25	2449226.341817	1993	238	FALL LTSTAB	1
26	2449255.529236	1993	268	FALL LTSTAB	1
27	2449283.771053	1993	296	FALL LTSTAB	1
28	2449309.341898	1993	321	FALL LTSTAB	1
	First Servicing Mission				
29	2449379.838241	1994	27	SPRING LTSTAB	2
30	2449408.794850	1994	56	SPRING LTSTAB	2
31	2449437.560417	1994	85	SPRING LTSTAB	2
32	2449468.662153	1994	116	SPRING LTSTAB	2
33-37	2449469.602118	1994	117	SPRING DELTA-OFAD	2
38	2449593.554884	1994	241	FALL LTSTAB	2
39	2449624.182975	1994	271	FALL LTSTAB	2
40	2449652.274942	1994	299	FALL LTSTAB	2
41	2449683.371435	1994	330	FALL LTSTAB	2
42	2449711.665382	1994	359	FALL LTSTAB	2
43	2449749.996910	1995	32	SPRING LTSTAB	2
44	2449780.160903	1995	62	SPRING LTSTAB	2
45	2449811.662894	1995	94	SPRING LTSTAB	2
46	2449838.070301	1995	120	SPRING LTSTAB	2
47	2449990.553542	1995	273	FALL LTSTAB	3
48	2450018.625255	1995	301	FALL LTSTAB	3
49	2450042.360197	1995	324	FALL LTSTAB	3
50-60	2450052.674838	1995	335	FALL DELTA-OFAD	3
61	2450112.122350	1996	29	SPRING LTSTAB	3
62	2450133.837824	1996	51	SPRING LTSTAB	3
63	2450158.835440	1996	76	SPRING LTSTAB	3
64	2450174.716192	1996	92	SPRING LTSTAB	3
65	2450199.778704	1996	117	SPRING LTSTAB	3
66	2450321.550822	1996	239	FALL LTSTAB	3
67	2450353.777465	1996	271	FALL LTSTAB	3
68	2450377.443275	1996	294	FALL LTSTAB	3
69	2450416.366701	1996	333	FALL LTSTAB	3
70	2450480.031933	1997	31	SPRING LTSTAB	3
	Second Servicing Mission				
71	2450518.768090	1997	70	SPRING LTSTAB	3
72-76	2450560.517523	1997	112	SPRING DELTA-OFAD	4

3. Optical Field Angle Distortion Calibration and Long Term Stability Test

The Optical Telescope Assembly (OTA) of the HST (Hubble Space Telescope) is a Aplanatic Cassegrain telescope of Ritchey-Chrètien design. The aberration of the OTA, along with the optics of the FGS comprise the OFAD. The largest component of the design distortion, which consists of several arcseconds, is an effect that mimics a change in plate scale. The magnitude of non-linear, low frequency distortions is on the order of 0.5 seconds of arc over the FGS field of view. The OFAD is the most significant source of systematic error in position mode astrometry done with the FGS. We have adopted a pre-launch functional form originally developed by Perkin-Elmer (Dente, 1984). It can be described (and modeled to the level of one millisecond of arc) by the two dimensional fifth order polynomial:

$$\begin{aligned} x' = a_{00} + a_{10}x + a_{01}y + a_{20}x^2 + a_{02}y^2 + a_{11}xy + a_{30}x(x^2+y^2) + a_{21}x(x^2-y^2) \\ + a_{12}y(y^2-x^2) + a_{03}y(y^2+x^2) + a_{50}x(x^2+y^2)^2 + a_{41}y(y^2+x^2)^2 \\ + a_{32}x(x^4-y^4) + a_{23}y(y^4-x^4) + a_{14}x(x^2-y^2)^2 + a_{05}y(y^2-x^2)^2 \end{aligned}$$

$$\begin{aligned} y' = b_{00} + b_{10}x + b_{01}y + b_{20}x^2 + b_{02}y^2 + b_{11}xy + b_{30}x(x^2+y^2) + b_{21}x(x^2-y^2) \\ +b_{12}y((y^2-x^2) + b_{03}y(y^2+x^2) + b_{50}x(x^2+y^2)^2 + b_{41}y(y^2+x^2)^2 \\ +b_{32}x((x^4-y^4) + b_{23}y(y^4-x^4) + b_{14}x(x^2-y^2)^2 + b_{05}y(y^2-x^2)^2 \end{aligned} \tag{1}$$

where x, y are the observed position within the FGS field of view, x', y' are the corrected position, and the numerical values of the coefficients a_{ij} and b_{ij} are determined by calibration. Although ray-traces were used for the initial estimation of the OFAD, gravity release, outgassing of the graphite-epoxy structures, and post-launch adjustment of the HST secondary mirror required that the final determination of the OFAD coefficients a_{ij} and b_{ij} be made by an on-orbit calibration.

M35 was chosen as the calibration field. Since the ground-based positions of our target calibration stars were known only to 23 milliseconds of arc, the positions of the stars were estimated simultaneously with the distortion parameters. This was accomplished during a nineteen orbit calibration, executed on 10 January 1993 in FGS number 3. GaussFit (Jefferys, 1988), a least squares and robust estimation package, was used to simultaneously estimate the relative star positions, the pointing and roll of the telescope during each orbit (by quaternions), the magnification of the telescope, the OFAD polynomial coefficients, and these parameters that describe the star selector optics inside the FGS: ρ_A and ρ_B (the arm lengths of the star selectors A and B), and κ_A and κ_B (the offset angles of the star selectors). Because of the linear relationship between ρ_A, ρ_A , κ_A and κ_B, the value of κ_B is constrained to be zero. A complete description of that calibration, the analysis of the data, and the results are given in Jefferys et al. (1994).

In late fall 1992, just prior to the 1993 OFAD calibration, a series of one orbit long-term stability tests (LTSTAB) was initiated. These tests had two seasonal orientations, a spring orientation taken from an orbit of the OFAD, and a fall orientation, which was a 180 degree flip of the spring orientation. LTSTABs have been performed several times in each of the orientations, spring and fall, every year.

The LTSTAB is sensitive to scale and low order distortion changes. It is an indicator of the validity of the current OFAD coefficients and the need for recalibration. The LTSTAB series immediately showed that the scale measured by the FGS was changing with time. The indication of this change was seen in the large increase with time in the post-fit residuals from a solution that solved for a constant sets of star positions, star selector encoder (SSE) parameters, and OFAD parameters. The amount of scale change is too large to be due to true magnification changes in the HST optical telescope assembly. These changes could be due to water desorption in the graphite-epoxy components within the FGS. Initially the scale -like change was modeled by allowing a variation in the star-selector-A effective lever arm(ρ_A). Since 1995, the change has been modeled by allowing a change in both ρ_A and κ_A(the offset angle of the star selector).

A five orbit delta-OFAD was performed on 27 April 1994 after the first servicing mission to assess the distortion changes caused by the secondary mirror movement to the zero coma position. Significant effects in the OFAD (in addition to the scale-like changes) at the level of 10 mas were found. The LTSTAB tests have revealed continued permutations in the FGS. In addition to the scale changes, in mid-1995 we began to recognize higher order distortion changes. These changes manifested themselves as something that looks like a radial scale variation and is fairly well modeled by alterations in the third order terms in Eq. (1). We had also noted that the residuals from the fall orientation LTSTABS are consistently higher than for the spring.

An eleven orbit delta-OFAD was performed in the late fall of 1995, to analyze temporal changes, and upgrade the y-axis coverage. Initially puzzling poor results were the result of deterioration of the S-curve in the negative X region of the pickle, causing locks on the wrong zero-crossings. These incorrect locks produced an island of large negative residuals in the negative X region of the pickle (Figure 1). With the removal of these observations, the delta-OFAD was successfully completed.

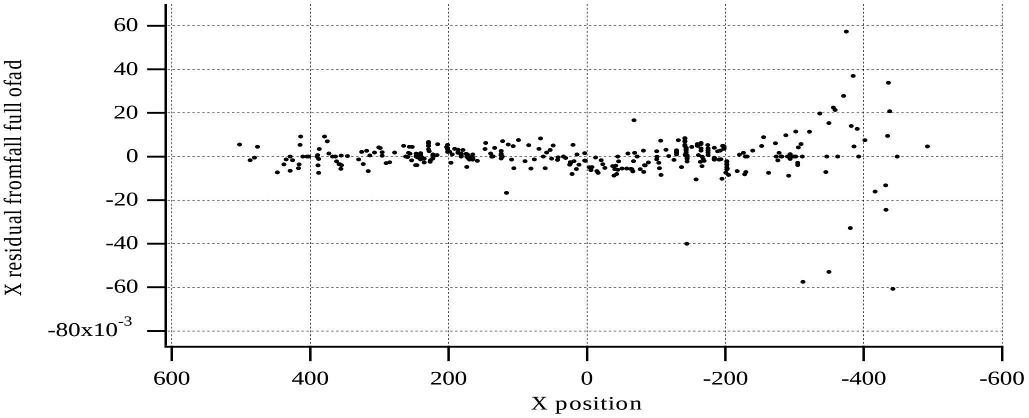

Figure 1. Large residuals in negative X pickle region indicate deterioration of S-curves in that area.

Further analysis suggested redetermining the star catalog, which was done with input from the three OFAD experiments of 1993, 1994 and 1995. This was done to minimize the OFAD distortion that could have been absorbed by the catalog positions.

In the spring of 1997 a Second Servicing Mission replaced FGS1. A five orbit delta-OFAD was performed in FGS3, repeating the orientation of spring 1994. Two LTSTABS were performed in Spring 1997, one before and one after the second servicing mission. With scale and offset removed, a comparison yielded an rms of 0.965 mas, indicating stability of FGS3 across the servicing mission.

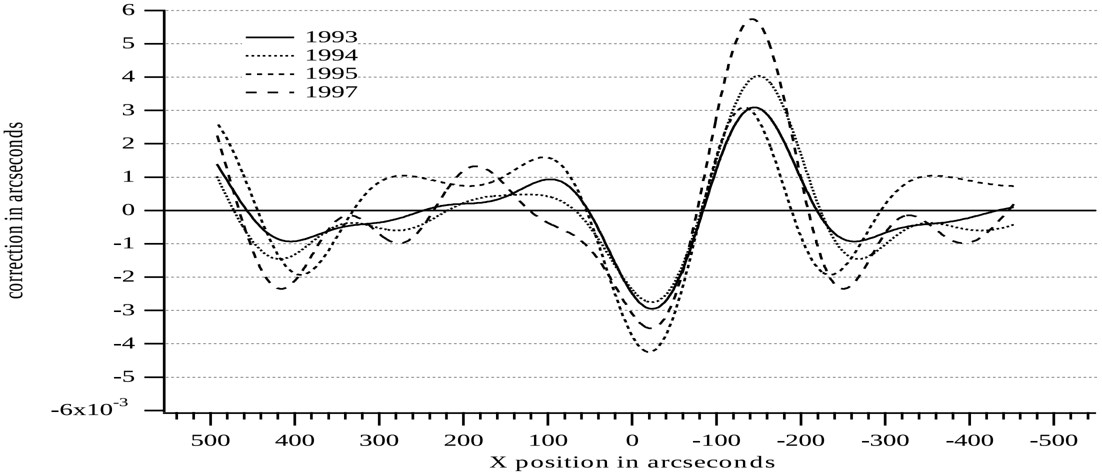

Figure 2. Four frequency Fourier series correction of systematic signature in X Residuals

A systematic signature in the X residuals from the four OFAD analysis remains. This appears as a very distinctive curve in the x component residuals as a function of position angle in the FGS field of view (Figure 2). The curve cannot be modeled by the fifth order polynomial. We have used a four frequency Fourier series to remove this effect. The size of this effect, in an RMS sense over the entire field of view of the FGS, is about one millisecond of arc. However, the peak-to-peak values near the center of the field of view can be as large as 8 mas. The source of this unexpected distortion is not yet known but it may be due to the way the FGS responds to the spherically aberrated HST beam.

A small signature in the Y residuals of the ρ_A κ_A fit of the LTSTAB to the OFAD coefficients has also been found. It appears as a quadratic. This signature is not found in the OFAD residuals. Currently it is not removed from the data.

On the basis of almost five years of monitoring the distortions in FGS 3 we have concluded that at the level of a few milliseconds of arc, the optical field angle distortion in HST FGS 3 changes with time. These changes can be monitored and modeled by continuing the LTSTAB tests, which also alerts us to the need for a new OFAD calibration. There remains some dichotomy between the OFAD calibration data taken in the spring and that taken in the fall.

Four sets of OFAD coefficients (Eq. 1) and star selector parameters (M, ρ_A, ρ_B,κ_A and κ_B) have been derived for reductions of astrometry observations. The average plate residuals for these determinations are listed in Table 2. Comparisons of grids created with each set of OFAD coefficients and distortion parameters indicate that the OFAD has changed around 10 milliseconds of arc in non-scalar distortion between calibrations (which have spanned 12–18 months). These changes in the OFAD with x and y scale and offset (a 6 parameter plate fit) removed can be seen in Figures 3, 4 and 5.

Table 2. OFAD Residuals.

OFAD	Xrms	Yrms	RSS	Number of Residuals	Orbits
Spring 1993	0.0020	0.0024	0.0027	548	19
Spring 1994	0.0020	0.0020	0.0024	144	5
Fall 1995	0.0019	0.0022	0.0026	354	11
Spring 1997	0.0025	0.0026	0.0029	121	5

Each LTSTAB is associated with a specific set of coefficients Table 1. In the boundary area betweeen two OFAD experiments, the LTSTAB observations are reduced with both sets of OFAD separately to determine which coeffecients produce the best ρ_A κ_A fit of the LTSTAB.

The values of ρ_A and κ_A determined by the LTSTABS and OFADS are illustrated in Figure 6 and Figure 7. The error bars for these determination are smaller than the symbols. The rms errors of these determinations are shown in Figure 8. ρ_A and κ_A initially appeared to be smooth exponential changes over time. Since the fall of 1995, ρ_A, the scale-like sse parameter has been less predictable. Therefore, for reduction of science astrometry data, the ρ_A κ_A parameters are determined by interpolation of the two nearest LTSTABs in time. The 1997 Spring OFAD shows a dramatic drop in ρ_A, evidence of a significant scale change occurring. Interestingly, the Spring 1997 OFAD shows approximately the same value of ρ_A as the Spring 1994 OFAD. These two OFAD observation proposals were almost identical.

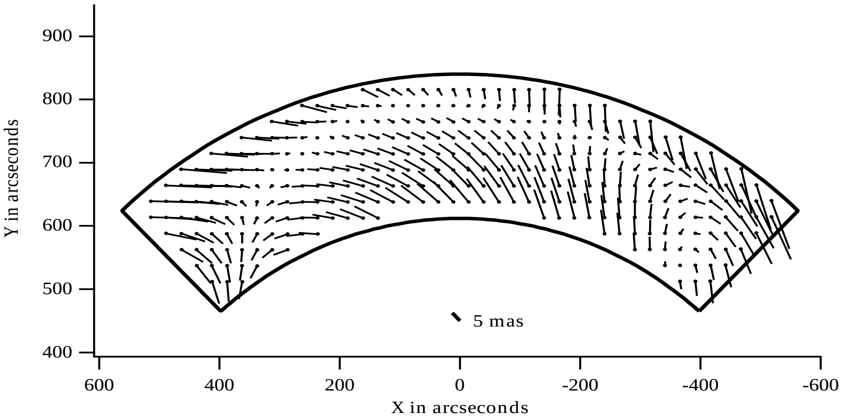

Figure 3. OFAD change between Spring 1993 and Spring 1994. The rss of the change is 10.6 milliseconds of arc.

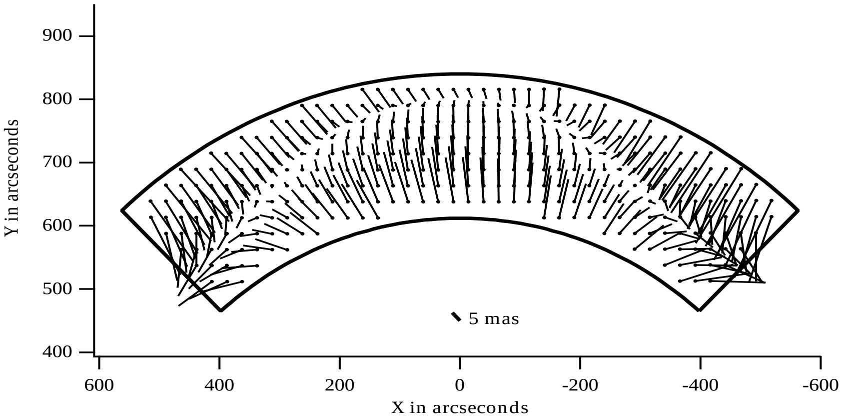

Figure 4. OFAD change between Spring 1994 and Fall 1995. The rss of the change is 17.5 milliseconds of arc

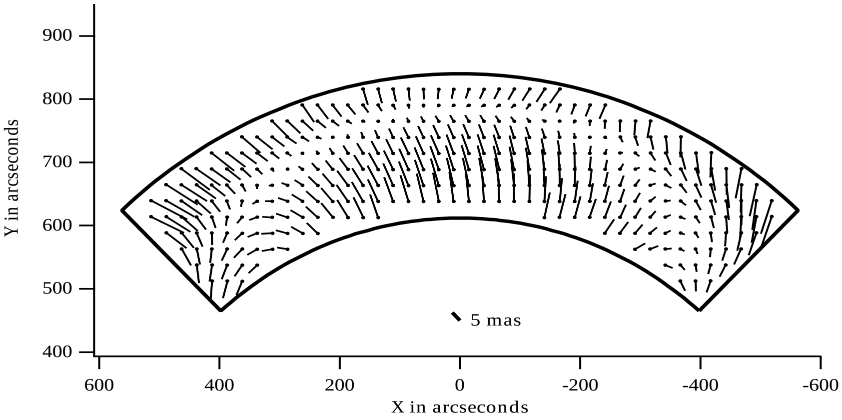

Figure 5. OFAD change between Fall 1995 and Spring 1997. The rss of the change is 9.3 milliseconds of arc.

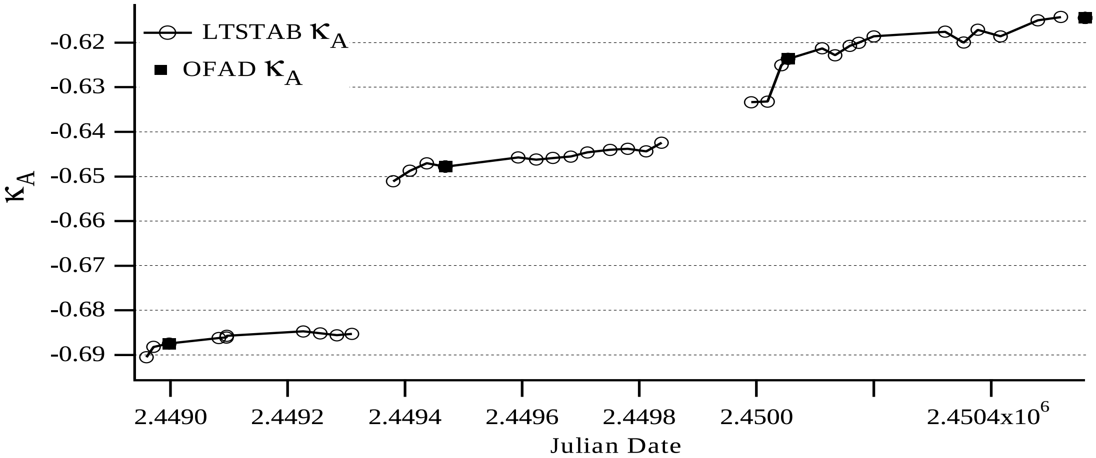

Figure 6. κ_A fit of the LTSTABS

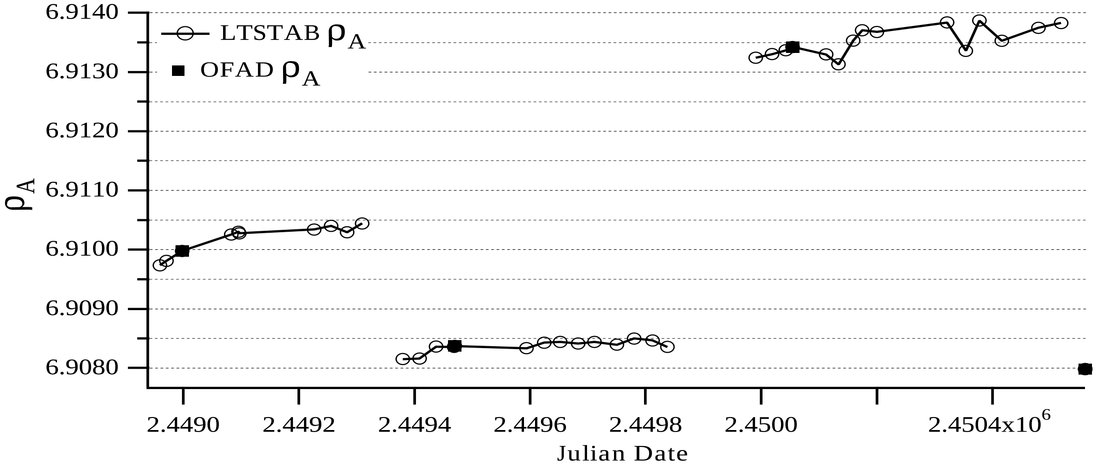

Figure 7. ρ_A fit of the LTSTABS

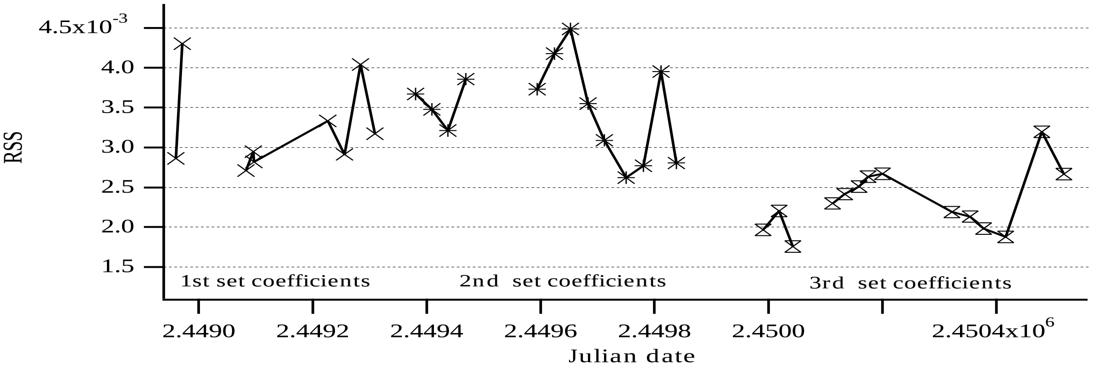

Figure 8. RSS of ρ_A κ_A fit of LTSTABS

4. Lateral Color

Since each FGS contains refractive elements (Bradley et al. 1991), it is possible that the position measured for a star could depend on its intrinsic color. Changes in position would depend on star color, but the direction of shift is expected to be constant, relative to the FGS axes. This lateral color shift would be unimportant, as long as target and reference stars have similar color. However, this is not always the case (e.g., Proxima Centauri, Benedict et al. 1993), hence our interest. Pre-launch ground testing indicated for FGS 3 a lateral color effect predominantly in the x direction, with magnitude a few milliseconds of arc per unit change in B−V color index. The effect is modeled (for example in X)

$$X' = X + ctx * (B - V) \tag{2}$$

We have recently completed the lateral color calibration. This two-pronged attack consisted of a reanalysis of the Science Verification Lateral Color Test data (aquired in late 1994) and an analysis of the Proxima Cen reference frame (a mix of SV, GTO and GO data acquired 1992-1997). The SV Lateral Color field was chosen to have a very wide range of stellar colors ($\Delta B - V \sim 2$). The Proxima Cen reference frame makes up in sheer volume of data (68 data sets) what it lacks in color range ($\Delta B - V \sim 1$). Neither approach is ideal, since the original SV test was exceedingly sparse. From the 1994 SV test we obtain $ctx = -0.0009 \pm 0.0002$ and $cty = -0.0002 \pm 0.0003$. The Proxima Cen data yield $ctx = -0.0010 \pm 0.0005$ and $cty = +0.0003 \pm 0.0004$. We adopt as the Lateral Color calibration a weighted average of the two results: $ctx = -0.0009 \pm 0.0002$ and $cty = -0.0000 \pm 0.0002$

5. Ongoing Astrometric Science with FGS 3

FGS 3 is being used to obtain many series of data from which trigonometric parallaxes will be derived. Targets include distance scale calibrators (δCep, RR Lyr), interacting binaries (Feige 24), a central star of a planetary nebula (NGC 6853), an old Nova (RW Tri), and several dwarf novae (e.g., SS Cyg). It is also involved in an intensive effort to obtain masses and mass ratios for a number of very low-mass M stars (for example, GJ 22, GJ 791.2, GJ 623, and GJ 748). We have completed parallax determinations for Proxima Cen and Barnard's Star and obtained 0.5 mas precisions (Benedict et al. 1997). For most of the targets mentioned above we will have far fewer sets of observations. Our recent analyses of Hyades parallax data sets, containing a similarly small number of epochs (van Altena et al. 1997), suggest that we will obtain parallax precisions of 1 mas for most of these targets. A continued program of LTSTAB monitoring and OFAD updates is essential to the success of these ongoing, long-term investigations.

6. Conclusions

We have shown that continued OFAD calibration of the Fine Guidance Sensors can reduce this source of systematic error in positions measured by the FGSs to the level of 2 mas. However, changes in the FGS units continue to occur, even seven years after launch. These changes require periodic updates to the OFAD to maintain this critical calibration. The OFAD calibration is an ongoing process, every new observation set is used to not only expand the timeline, but re-evaluate the previous calibrations. A lateral color calibration in FGS 3 has been determined using Science Verification and GTO data.

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