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The Optical Field Angle Distortion Calibration of HST Fine Guidance Sensors 1R and 3

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Abstract. To date five OFAD (Optical Field Angle Distortion) calibrations have been performed with a star field in M35, four on FGS3 and one on FGS1, all analyzed by the Astrometry Science Team. We have recently completed an improved FGS1R OFAD calibration. The ongoing Long Term Stability Tests have also been analyzed and incorporated into these calibrations, which are time-dependent due to on-orbit changes in the FGS. Descriptions of these tests and the results of our OFAD modeling are given. Because all OFAD calibrations use the same star field, we calibrate FGS 1 and FGS 3 simultaneously. This increases the precision of our input catalog,resulting in an improvement in both the FGS 1 and FGS 3 calibrations. A redetermination of the proper motions,using 12 years of HST data has significantly improved our calibration. Residuals to our OFAD modeling indicate that FGS 1 will provide astrometry superior to FGS 3 by $\sim$ 20%. Past and future FGS 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 (FGS's) is the Optical Field Angle Distortion (OFAD). Description of previous analyses can be found in McArthur et al. (2002, 1997), 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 within an FGS. They also provide indicators that a new OFAD calibration is necessary. This paper reports the results of the continuing OFAD calibration of FGS 3 and a newest OFAD calibration for FGS 1, including the LTSTAB tests. Past astrometry 2 and future astrometric results anticipated from FGS 1 are 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, after In the spring of 1997 a five orbit OFAD was performed on FGS3 after the second servicing mission. In December of 2000,a 14 orbit OFAD was performed on FGS1R, which replaced FGS3 as the prime astrometer for scientific observations. FGS1R, an enhanced FGS with an adjustable fold-flat mirror that can be commanded from the ground, had replaced the original FGS1 instrument in February of 1997 in SM2(Servicing Mission 2). Seventy LTSTABS (Long Term Stability Tests) have been performed in both FGS1R and FGS3 to assess time-dependent changes. A current list of the OFAD and LTSTAB tests is shown in Table 1.

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:

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

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).

Table 1: LTSTAB and OFAD Observations.

Orbit	Julian Date	Year	Day	FGS	Observation	Coefficient Set
1	2448959.340822	1992	337	3	LTSTAB	1
2	2448971.061435	1992	349	3	LTSTAB	1
3-21	2448997.782164	1993	10	3	OFAD	1
22	2449082.954086	1993	95	3	LTSTAB	1
23	2449095.742836	1993	108	3	LTSTAB	1
24	2449096.613044	1993	109	3	LTSTAB	1
25	2449226.341817	1993	238	3	LTSTAB	1
26	2449255.529236	1993	268	3	LTSTAB	1
27	2449283.771053	1993	296	3	LTSTAB	1
28	2449309.341898	1993	321	3	LTSTAB	1
29	2449379.838241	1994	27	3	LTSTAB	2
30	2449408.794850	1994	56	3	LTSTAB	2
31	2449437.560417	1994	85	3	LTSTAB	2
32	2449468.662153	1994	116	3	LTSTAB	2
33-37	2449469.602118	1994	117	3	Spring Delta-OFAD	2
38	2449593.554884	1994	241	3	LTSTAB	2
39	2449624.182975	1994	271	3	LTSTAB	2
40	2449652.274942	1994	299	3	LTSTAB	2
41	2449683.371435	1994	330	3	LTSTAB	2
42	2449711.665382	1994	359	3	LTSTAB	2
43	2449749.996910	1995	32	3	LTSTAB	2
44	2449780.160903	1995	62	3	LTSTAB	2
45	2449811.662894	1995	94	3	LTSTAB	2
46	2449838.070301	1995	120	3	LTSTAB	2
47	2449990.553542	1995	273	3	LTSTAB	3
48	2450018.625255	1995	301	3	LTSTAB	3
49	2450042.360197	1995	324	3	LTSTAB	3
50-60	2450052.674838	1995	335	3	Fall Delta-OFAD	3
61	2450112.122350	1996	29	3	LTSTAB	3
62	2450133.837824	1996	51	3	LTSTAB	3
63	2450158.835440	1996	76	3	LTSTAB	3
64	2450174.716192	1996	92	3	LTSTAB	3
65	2450199.778704	1996	117	3	LTSTAB	3
66	2450321.550822	1996	239	3	LTSTAB	3
67	2450353.777465	1996	271	3	LTSTAB	3
68	2450377.443275	1996	294	3	LTSTAB	3
69	2450416.366701	1996	333	3	LTSTAB	3
70	2450480.031933	1997	31	3	LTSTAB	3
71	2450518.768090	1997	70	3	LTSTAB	3
72-76	2450560.517523	1997	112	3	Spring Delta-OFAD	3
77	2450717.416169	1997	268	3	LTSTAB	3
78	2450743.225891	1997	294	3	LTSTAB	3
79	2450783.224190	1997	334	3	LTSTAB	3
80	2450822.077315	1998	8	3	LTSTAB	3
81	2450847.955266	1998	34	3	LTSTAB	3
82	2450904.886979	1998	91	1	LTSTAB	4
83	2450924.644942	1998	111	3	LTSTAB	3
84	2451054.361725	1998	240	3	LTSTAB	3
85	2451113.296366	1998	299	3	LTSTAB	3
86	2451121.224560	1998	307	1	LTSTAB	4
87	2451153.943299	1998	340	3	LTSTAB	3
88	2451163.019213	1998	349	1	LTSTAB	4
89	2451184.786771	1999	6	1	LTSTAB	4
90	2451189.556088	1999	11	3	LTSTAB	3
91	2451300.596829	1999	122	3	LTSTAB	3
92	2451300.664236	1999	121.2	1	LTSTAB	4
93	2451416.507917	1999	238	3	LTSTAB	3
94	2451430.269572	1999	251	1	LTSTAB	4
95	2451555.127963	2000	11	1	LTSTAB	4
96	2451555.199688	2000	11	3	LTSTAB	3
97	2451649.638229	2000	106	1	LTSTAB	4
98	2451653.660590	2000	110	3	LTSTAB	3
99	2451783.159410	2000	239	1	LTSTAB	4
100	2451830.321088	2000	286	1	LTSTAB	4
101-114	2451899.105289	2000	355	1	OFAD	4
115	2451968.923102	2001	59	1	LTSTAB	4
116	2452021.654896	2001	112	1	LTSTAB	4
117	2452137.970671	2001	228	1	LTSTAB	4
118	2452201.355764	2001	291	1	LTSTAB	4
119	2452263.961701	2001	354	1	LTSTAB	4
120	2452274.313264	2001	364	1	LTSTAB	4
121	2452295.219942	2002	20	3	LTSTAB	3
122	2452370.867882	2002	96	1	LTSTAB	4
123	2452384.694618	2002	110	1	LTSTAB	4
124	2452520.528970	2002	246	1	LTSTAB	4
125	2452581.074271	2002	306	1	LTSTAB	4
126	2452631.260370	2002	356	1	LTSTAB	4
127	2452700.778437	2003	0610	1	LTSTAB	4
128	2452749.608044	2003	110	1	LTSTAB	4
129	2452883.589838	2003	244	1	LTSTAB	4
130	2452953.9450698	2003	314	1	LTSTAB	4
131	2452997.011609	2003	357	1	LTSTAB	4
132	2453002.8817249	2003	363	1	LTSTAB	4
133	2453066.547211	2004	62	1	LTSTAB	4
134	2453118.7410301	2004	114	1	LTSTAB	4
135	2453234.513866	2004	234	1	LTSTAB	4
136	2453359.537685	2004	355	1	LTSTAB	4
137	2453363.535428	2004	359	1	LTSTAB	4
138	2453431.767731	2005	61	1	LTSTAB	4
139	2453480.676921	2005	110	1	LTSTAB	4
140	2453599.337049	2005	228	1	LTSTAB	4
141	2453639.847894	2005	269	1	LTSTAB	4
142	2453680.156250	2005	309	1	LTSTAB	4

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 in FGS3.

An eleven orbit delta-OFAD was performed in the late fall of 1995, to analyze temporal changes, and upgrade the y-axis coverage. The star catalog was redetermined with input from the three OFAD experiments of 1993, 1994 and 1995 to minimize the OFAD distortion that could have been absorbed by the catalog positions. A more complete analyses of this delta-OFAD can be found in McArthur 1997.

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. The coefficients produced by this 5 orbit delta-OFAD did not provide a better calibration than the 11 orbit Fall of 1995 delta-OFAD calibration, so these orbits were used instead as LTSTABS. 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.

At the end of 2000, a 14 orbit OFAD was executed in FGS1R, for a total of approximately observations. Figure 1 shows the rotations and offsets of FGS1R in this OFAD calibration. In the first FGS1R OFAD, we entered the McNamara (1986) proper motion values as observations with error in a quasi-Bayesian fashion, instead of being applied as constants. More recently, we carefully examined the HST derived proper motions on their own, in cases where there were significant numbers of observations over significant time spans. These HST derived motions, are used in a weighted solution with the McNamara proper motions for the stars not so frequently observed. For this calibration, we ran a model which performed a simultaneous solution of OFAD polynomials, star selector encoder (sse) parameters, proper motions, drift parameters, and catalog positions. This model had over 15,000 equations of conditions using all 142 OFAD and LTSTAB plates. Only the OFAD plates determined the OFAD polynomials and complete sse parameters, while the LTSTAB combined with the OFAD plates contributed to a time-varying rhoA and kA, proper motions, and catalog positions. Each plate formed its own drift and rotation parameters. A systematic signature in the X residuals from the four OFAD analysis remains. This signature differs between FGS3 and FGS1. It appears as a very distinctive curve in the x

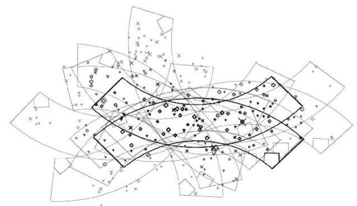

Figure 1: Rotation and Offsets of FGS1R Winter 2000 OFAD

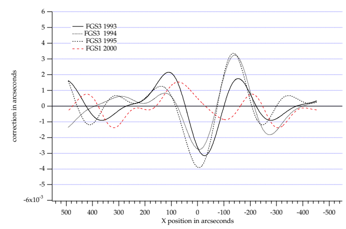

Figure 2: Four frequency Fourier series correction of systematic signature in X Residuals

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 7 mas in FGS3. The FGS1 systematic is much smaller with a peak to peak of about 2.5 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.

On the basis of almost ten 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.

Five 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 FGS3 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)in FGS3.

Each LTSTAB is associated with a specific set of coefficients Table 1. In the boundary area betweeen two OFAD experiments, the 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 in FGSs 1 and 2 are illustrated in Figure 3,5, 4and 6. The error bars for these determination are smaller than the symbols. For reduction of science astrometry data, the ρ_A κ_A parameters are determined by interpolation of the two nearest LTSTABS in time.

The most recent analysis of the OFAD, which includes the HST determined proper motions, presents a significantly improved distortion calibration as seen in Table 2, listed as the New Winter 2000. The residual profile of the fgs1R stars is shown in Figure 7. The LTSTABS which have been performed since the implementation of two-gyro mode have been consistent with previous LTSTABS and we do not expect any deterioration in this mode of the calibration of the FGS.

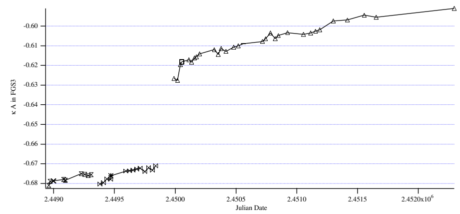

Figure 3: κ_A fit of the LTSTABS in FGS3

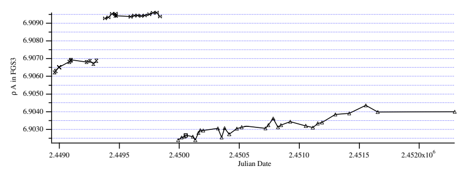

Figure 4: ρ_A fit of the LTSTABS in FGS3

Table 2: OFAD σ in millseconds of arc

OFAD	FGS	σ X	σ Y
Winter 2000	3	2.3	2.2
Winter 2000	1	1.6	1.7
New Winter 2000	3	1.5	1.8
New Winter 2000	1	1.3	1.3

In addition to the OFAD calibration, both Lateral Color and Cross Filter calibrations have been determined. Each FGS contains refractive elements. The position measured for a target star (relative to a differently colored set of reference stars) could depend on its intrinsic color, hence the lateral color corrections are applied. The large dynamic range in magnitudes (3 ? V ? 17) requires a neutral-density filter. There is a small shift in position (due to filter wedge) when comparing the positions of a bright star to a faint reference frame. This shift is determined in the Cross Filter calibration.

4. Past and Ongoing Astrometric Science with HST FGS

FGS 3 has been used to determine the first astrometrically determined mass of an extrasolar planet, which is around the star GL 876 (ApJ letters, in press). It has been used to obtain many trignometric parallaxes. Targets included distance scale calibrators (δCep - Benedict et al., 2002b; RR Lyr - Benedict et al., 2002a), interacting binaries (Feige 24 - Benedict et al., 2000), and cataclysmic variables (RW Tri - McArthur et al., 1999; TV Col- McArthur et al., 2001; SS Cyg, U Gem & SS Aur, Harrison et. al, 1999). It was 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- Benedict et al., 2001). The average parallax precision resulting from FGS 3 was $\sigma_\pi = 0.26$ mas.

FGS 1 has been used to determine the parallaxes of several cataclysmic variables (EX Hya, EF Eri, V1223 Sgr)(Beuermann et al., 2003, 2004; Harrison et al., 2004), parallaxes of a representative set of AM CVn stars, an independent parallax of the Pleiades (Soderblom et al., 2005), a parallax of the central star of NGC 6853 (Benedict et al., 2003) and the masses of extrasolar planets around 55 Cancri (McArthur et al., 2004) and ϵ Eridani. The masses of the extrasolar planets around υ Andromeda and additional planets are now being studied. A distance determination to the Cepheids is being calculated at present from HST

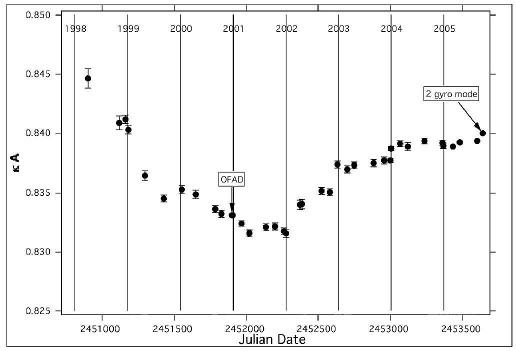

Figure 5: κ_A fit of the LTSTABS in FGS1

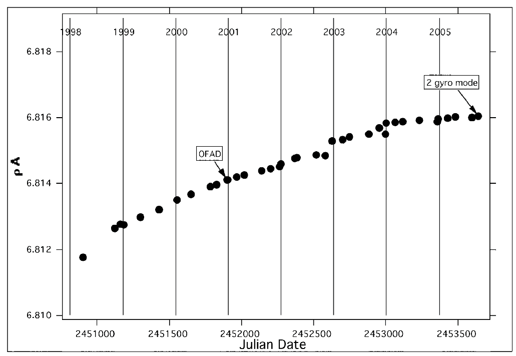

Figure 6: ρ_A fit of the LTSTABS in FGS1

parallaxes. FGS 1 is also involved in an ongoing effort to obtain masses and mass ratios for additional set of low-mass M stars.

A continued program of LTSTAB monitoring and OFAD updates is essential to the success of these long-term investigations with FGS 1.

5. 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 FGS's to the level of less than 2 mas. However, changes in the FGS units continue to occur, even twelve years after launch. These changes require periodic updates to the OFAD to maintain this critical calibration.

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References

Benedict, G.F., Nelan, E., McArthur, B., Story, D., van Altena, W., Ting-Gao, Y., Hemenway, P.D., Shelus, P.J., Whipple, A.L., Franz, O.G., Fredrick, L.W., and R.L. Duncombe. 1993, PASP105, 487- 493

New FGS1 OFAD

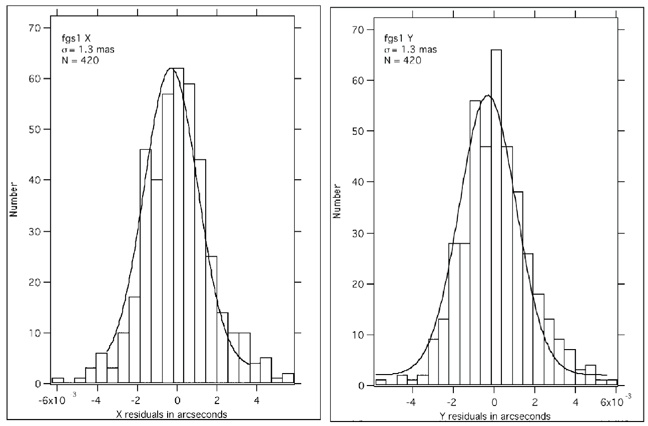

Figure 7: Residual Histrogram from OFAD calibration of FGS1R

Benedict, G. F., McArthur, B., Chappell, D. W., Nelan, E., Jefferys, W. H., van Altena, W., Lee, J., Cornell, D., Shelus, P. J., Hemenway, P. D., Franz, O. G., Wasserman, L. H., Duncombe, R. L., Story, D., Whipple, A., & Fredrick, L. W. 1999, AJ, 118, 1086

Benedict, G. F., McArthur, B. E., Franz, O. G., Wasserman, L. H., Nelan, E., Lee, J., Fredrick, L. W., Jefferys, W. H., van Altena, W., Robinson, E. L., Spiesman, W. J., Shelus, P. J., Hemenway, P. D., Duncombe, R. L., Story, D., Whipple, A. L., & Bradley, A. 2000, AJ, 119, 2382

Benedict, G. F., McArthur, B. E., Franz, O. G., Wasserman, L. H., Henry, T. J., Takato, T., Strateva, I. V., Crawford, J. L., Ianna, P. A., McCarthy, D. W., Nelan, E., Jefferys, W. H., van Altena, W., Shelus, P. J., Hemenway, P. D., Duncombe, R. L., Story, D., Whipple, A. L., Bradley, A. J., Fredrick, L. W. 2001, AJ, 121, 1607

Benedict, G. Fritz, McArthur, B. E., Fredr ick, L. W., Harrison, T. E., Lee, J., Slesnick, C. L., Rhee, J., Patterson, R. J ., Nelan, E., Jefferys, W. H., van Altena, W., Shelus, P. J., Franz, O. G., Wass erman, L. H., Hemenway, P. D., Duncombe, R. L., Story, D., Whipple, A. L., & Br adley, A. J. 2002A, AJ123, 473

Benedict, G. F., McArthur, B. E., Fredrick, L. W., Harrison, T. E., Slesnick, C. L., Rhee, J., Patterson, R. J., Skrutskie, M. F., Franz, O. G., & Wasserman, L. H. 2002B, AJ124, 1695

Benedict, G. F., McArthur, B. E., Fredrick, L. W., Harrison, T. E., Skrutskie, M. F., Slesnick, C. L., Rhee, J., Patterson, R. J., Nelan, E., Jefferys, W. H., van Altena, W., Montemayor, T., Shelus, P. J., Franz, O. G., Wasserman, L. H., Hemenway, P. D., Duncombe, R. L., Story, D., Whipple, A. L., & Bradley, A. J. 2003, AJ, 126, 2549

Beuermann, K., Harrison, T. E., McArthur, B. E., Benedict, G. F., & Gänsicke, B. T. 2004, A&A, 419, 291

Beuermann, K., Harrison, T. E., McArthur, B. E., Benedict, G. F., & Gänsicke, B. T. 2003, A&A, 412, 821

Bradley, A., Abramowicz-Reed, L., Story, D., Benedict, G., and W. Jefferys. 1991, PASP, 103, 317

Dente, G. and Abramowitz-Reed, L. Space Telescope Optical Field Angle Distortion Calibration Algorithm. 1984, Perkin-Elmer ST-SE-3336.

Ftaclas, C., Nonnenmacher, A., Weindling, F., Story, D., and E. Nelan. 1993, Ap. Opt. 32, 1696

Harrison, T. E., McNamara, B., Szkody, P., McArthur, B. E., Benedict, G. F.,Klemola, A., & Gilliland, R. L. 1999, ApJ, 515, L93

Harrison, T. E., Johnson, J. J., McArthur, B. E., Benedict, G. F., Szkody, P., Howell, S. B., & Gelino, D. M. 2004, AJ, 127, 460

Jefferys, W., Fitzpatrick, J., and McArthur, B. 1988 Celest. Mech. 41, 39.

Jefferys, W.J., Whipple, A., Wang, Q., McArthur, B., Benedict, G.F., Nelan, E., Story, D, and L. Abramowicz-Reed. 1994, in Calibrating Hubble Space Telescope, J.C. Blades and S.J. Osmer (Baltimore: STScI) 353-374.

McArthur, B. E., Benedict, G. F., Jefferys, W. H., and Nelan, E. 1997, in The 1997 *HST Calibration Workshop : Hubble after the Installation of the ACS and the NICMOS Cooling System*, Santiago Arribas, Anton Koekemoer, and Brad Whitmore (Baltimore: STScI) 373.

McArthur, B. E., Benedict, G. F., Jefferys, W. H., and Nelan, E. 2003, in *Proc. 2002 HST Calibration Workshop*, ed. S. Arribas, A. Koekemoer, & B. Whitmore (Baltimore: STScI), p. 472.

McArthur, B. E., Benedict, G. F., Lee, J., Lu, C. -L., van Altena, W. F., Deliyannis, C. P., Girard, T., Fredrick, L. W., Nelan, E., Duncombe, R. L., Hemenway, P. D., Jefferys, W. H., Shelus, P. J., Franz, O. G. & Wasserman, L. H. 1999, ApJ, 520, L59

McArthur, B. E. Benedict, G. F., Lee, J., van Altena, W. F., Slesnick, C. L., Rhee, J., Patterson, R. J., Fredrick, L. W., Harrison, T. E., Spiesman, W. J., Nelan, E., Duncombe, R. L., Hemenway, P. D., Jefferys, W. H., Shelus, P. J., Franz, O. G., Wasserman, L. H., 2001, ApJ, 560, 907

McArthur, B. E., Endl, M., Cochran, W. D., Benedict, G. F., Fischer, D. A.;,Marcy, G. W., Butler, R. P., Naef, D., Mayor, M., Queloz, D.,Udry, S., Harrison, T. E., 2004 ApJ614, L81

McNamara, B., & Sekiguchi, K., 1986. AJ91, 557

Soderblom, D.R.,Nelan, E., Benedict, G. F., McArthur, B., Ramirez, I., Spiesman, W., Jones, Burton F., 2005, AJ129, 1616S

van Altena, W. F., Lu, C. -L., Lee, J. T., Girard, T. M., Guo, X., Deliyannis, C., Platais, I., Kozhurina-Platais, V., McArthur, B., Benedict, G. F., Duncombe, R. L., Hemenway, P. D., Jefferys, W. H., King, J. R., Nelan, E., Shelus, P. S., Story, D., Whipple, A., Franz, O. G., Wasserman, L., Fredrick, L. W., Hanson, R. B., Klemola, A. R., Jones, B. F., Mendez, R., Tsay, W. -S., Bradley, A. 1997. ApJ Lett, 486, 123

Wang, Q., and Jefferys, W. 1990, in Satatistical Analysis of the Optical Field Angle Distortion of the Hubble Space Telescope Using the Bootstrap Method, Austin:Univesrity of Texas, Department of Astronomy Institute, 1-99.

Whipple, A., Jefferys, W., Wang, Q., McArthur, B., Benedict, G.F., Nelan, E., Story, D., and L. Abramowicz-Reed. 1994, in Calibrating Hubble Space Telescope, J C. Blades and S.J. Osmer ed(s)., (Baltimore: STScI) 375-379.

Whipple, A., McArthur, B., Wang, Q., Jefferys, W., Benedict, G.F.,Lalich, A.M., Hemenway, P.D., Nelan, E., Shelus, P.J., and Story, D.. 1995, in Calibrating Hubble Space Telescope:Post Servicing Mission, A. Koratkar and C. Leitherer ed(s)., (Baltimore: STScI) 119-127.