TECHNICAL REPORT

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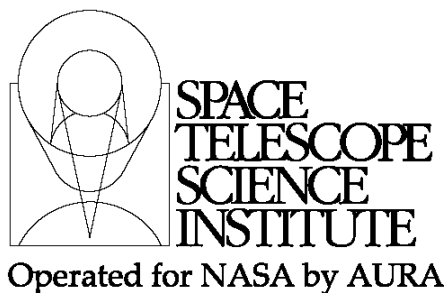
Title: Calibration of ACS/WFC Absolute Scale and Rotation for Use in Creation of a JWST Astrometric Reference Field	Doc #: JWST-STScI-001136, SM-12
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1.0   Abstract

Astrometric calibrations of JWST will use observations of a reference field in the Large Magellanic Cloud. This field will itself be astrometrically calibrated using observations with ACS/WFC on HST. The higher-order geometric distortions of ACS/WFC have previously been calibrated to high accuracy. However, the absolute scale and orientation of ACS/WFC are not known with similar accuracy. We therefore performed observations of the open cluster M35 to calibrate the absolute scale and orientation of ACS/WFC. Astrometric positions for stars in this field are obtained by combining a catalog obtained from many years of HST/FGS observations with the astrometry in the UCAC2 catalog. We also use several years of repeated observations of 47 Tuc to demonstrate the stability with time of the ACS/WFC scale and rotation. The understanding of the ACS/WFC scale and rotation obtained through these analyses is sufficiently accurate to meet the JWST astrometric requirements.

2.0   Introduction

One of the Mission Level requirements of the James Webb Space Telescope (JWST) is that "After calibration, the field distortion uncertainty within any science instrument and the guider shall not exceed 0.005 arcsec, 1 sigma per axis" (MR-120, OBS-93). To perform astrometric calibrations that meet this requirement, STScI is planning to use observations of a reference field, to be performed no more frequently than once every 9 months. Desirable characteristics of such a field are that it has a suitable stellar density, small proper motions, and that it resides in the JWST Continuous Viewing Zone so that it can be observed with JWST whenever necessary (Rhoads 2005). A field in the Large

Magellanic Cloud (LMC) was identified that meets these requirements (Diaz-Miller 2006). The sources in this field do not already have positions known to better than 5 milliarc-sec (mas) accuracy (nor does any other field that might have been suitable as reference field for JWST). The field must therefore be calibrated astrometrically through observations with another observatory before the JWST launch. The most logical choice to perform such calibration observations was the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST). Its Wide Field Channel (WFC) has excellent astrometric accuracy (Anderson 2005) and it has a similar field of view as the NIRCam instrument on JWST.

ACS/WFC observed the LMC reference field in April and July 2006 in the context of program 10753. Exposures were taken at different telescope orientations and with various telescope offsets. This will allow verification or recalibration of the higher-order geometric distortion solutions for ACS/WFC previously derived by Anderson (2005, 2007). With such solutions it should be possible to create a star catalog that is free of skew terms and higher-order geometric distortions to 1-2 mas relative accuracy (Diaz-Miller et al. 2006, 2007). However, the observations cannot constrain four unknown linear transformation quantities, namely an overall two-dimensional translation, rotation, and scale. Translational uncertainties are of little concern in the present context, and will be present in any JWST observation anyway because of the finite accuracy of its guide star catalog. Appropriate target acquisition procedures will remedy this. However, uncertainties in rotation and scale can have a more important impact on JWST calibrations. It is therefore important that the rotation and scale of ACS/WFC be properly calibrated. This is the subject of the present report.

A primary driver for the astrometric requirements of JWST is the need to be able to use NIRCam images to prepare NIRSpec spectroscopic masks. The low-level requirements that will guarantee this (the exact wording of which is still under review) demand that NIRCam and NIRSpec should be calibrated to the same relative rotation and scale. Since both will be calibrated using the same astrometric reference field, errors in the absolute rotation and scale of the astrometric reference field do no affect this requirement. Nonetheless, there are at least three different reasons why accurate absolute rotation and scale calibrations are still important: (1) There may be instances in which it is desirable to prepare NIRSpec spectroscopic masks on the basis of coordinates or images obtained from other observatories. In such cases it is important that JWST be accurately calibrated in an absolute sense (modulo translations). (2) During commissioning there will be a need to calibrate the relative orientations of the JWST Star Tracker Assemblies to the ISIM focal plane. The availability of an astrometric reference field with a carefully calibrated rotation will assist this calibration. (3) Through the use of an astrometric reference field, any errors in the absolute rotation and scale of HST/ACS will be directly imprinted into all calibrated data to emerge from the JWST calibration pipelines. Since we cannot at this time foresee all possible science that may be pursued with JWST, there is a desire to minimize these errors. We therefore aim here to calibrate HST/ACS to sufficient accuracy to meet the Mission-level Requirement of 5 mas. An error of 8.3×10^{-5} radians (0.0048 degrees) in rotation or a fractional error of 8.3×10^{-5} in scale corresponds to a 5

mas shift for a source that is 1 arcmin from the field center. A circle of 1-2 arcmin radius provides a reasonable approximation to the field of view of most instruments. Fractional calibration accuracies below $\sim 5 \times 10^{-5}$ are therefore the aim of this report.

The most accurate method to calibrate the ACS/WFC rotation and scale is through observations of a known astrometric reference field. This is the method that we employ here. As target we use the open cluster M35, which has been used for many years as the standard calibration target of the HST Fine Guidance Sensors (FGSs). In Section 3 we describe the construction of an astrometric reference star catalog for this cluster. In Section 4 we describe ACS/WCS observations that were obtained of a field in this cluster in December 2006, and the analysis of the data. Comparison to the FGS catalog yields an accurate calibration of the ACS/WFC rotation and scale. In Section 5 we present an analysis of time variations in the ACS rotation, scale, and skew terms, using repeated observations of the globular cluster 47 Tuc. This establishes that the results obtained using M35 are applicable also to the observations of the LMC reference field, which were obtained at earlier times. In Section 6 we present an alternative calibration of the ACS/WFC rotation and scale. This combines relative shifts in pixels between 47 Tuc observations with absolute slew sizes in arcsec commanded to the telescope. This method was used to establish the ACS rotation and scale soon after the ACS installation during servicing mission SM3b, and these have been used by the HST/ACS pipeline since. We show that this method yields results that are consistent with the M35 analysis, but with lower accuracy. In Section 7 we present our conclusions.

3.0   The M35 FGS-UCAC2 Reference Catalog

The open cluster M35 is the standard calibration target of the HST FGSs. It has been observed repeatedly over time using various telescope orientations and pointings. These observations have been used to obtain an accurate calibration of the Optical Field Angle Distortion (OFAD) of the FGSs (e.g., Jefferys et al. 1993; McArthur et al. 2002). A byproduct of this work has been a catalog of stars in M35 with relative positional accuracies below ~ 1 mas, and proper motion accuracies below ~ 0.2 mas/yr (McNamara et al. 2007).

Barbara McArthur of the FGS Science Team kindly provided us the latest FGS catalog of positions and proper motions for 97 stars in M35. The main quantities provided for each star were two position coordinates (ξ, η) at epoch 1992.91992 in a tangent-plane sky projection frame, and the corresponding proper motions in this frame. Individual uncertainties were not provided for these quantities. In the analysis that follows we assigned all stars equal weight, which implies that we assumed that the positional uncertainties are the same for all stars. We excluded from our subsequent analysis the five stars for which only positions were provided, but not proper motions. This reduced the catalog size to 92.

Although the M35 FGS catalog has high relative positional accuracy, this does not imply high absolute positional accuracy. In particular, the FGS calibration observations can only determine star positions modulo four unknown linear transformation quantities, namely an overall two-dimensional translation, rotation, and scale. These quantities can only be estimated by matching the relative star positions using linear transformations to some other astrometric catalog with known (RA,dec) values for the stars. This had in fact been done by the FGS Science Team, so that their catalog of (ξ,η) positions has nominal units of 1 arcsec, with ξ pointing nominally West and η pointing nominally South. The (RA,dec) position of the tangent point T used for the sky projection ($\xi=\eta=0$ by definition) was not provided to us. However, this does not matter because we decided to redo the linear matching transformations to achieve better accuracy. This was motivated by the discovery from cursory inspection that there was a significant rotation between the (ξ,η) frame and the actual West and South directions.

To perform an improved linear calibration of the M35 FGS catalog we retrieved the stars in the M35 area of the sky from the Second US Naval Observatory CCD Astrograph Catalog (UCAC2; Zacharias et al. 2004). This is the most accurate all-sky astrometric catalog currently available for this purpose. The Hipparcos catalog does not contain enough M35 stars for a meaningful cross-comparison. We matched the stars in the M35 FGS catalog to the UCAC2 stars using APT/Aladin's catalog cross-match tool. Matches were found for 85 stars. For each of these we retrieved the UCAC2 (RA,dec) J2000.0 coordinates, which pertain to epoch 2000.0. We calculated the uncertainty in the position for each star as prescribed by Zacharias et al. (2004). We used the proper motions given in the FGS M35 catalog to transform the tangent-plane coordinates (ξ,η) for each star in that catalog to epoch 2000.0 as well.

We used the following procedure to match the catalogs at epoch 2000.0 using linear transformations. First, we make an initial guess (RA_T, dec_T) for the coordinates of the tangent point T. We then determine for each set of UCAC2 coordinates (RA_U, dec_U) the corresponding coordinates (ξ_U,η_U) of a tangent plane projection with tangent point (RA_T, dec_T), using the formulae given in Smart (1997). We then apply a linear transformation to the FGS catalog coordinates (ξ,η) to obtain new coordinates (ξ',η'). We find the linear transformation parameters that minimize the χ^2 residual between the coordinates (ξ_U,η_U) and (ξ',η') summed over all the stars. In calculating the χ^2 of the residuals we weight the residuals with the uncertainties in the UCAC2 coordinates. After having performed this procedure once, we repeat it with an improved choice of the tangent point T. The improved choice is obtained by shifting the original guess using the translation implied by the best-fitting linear transformation. This procedure is iterated until there is zero translation (usually after only a few iterations) between the coordinate frames (ξ_U,η_U) and (ξ',η'). The (RA_T, dec_T) have then converged to the correct coordinates of the tangent point. Following convergence, we apply the inverse transformations from the tangent plane to the sky plane (Smart 1977) to transform the coordinates (ξ',η') derived from the FGS catalog to (RA,dec) coordinates. This yields the final sky J2000.0 coordinates at epoch 2000.0 for all the FGS catalog stars, with linear terms (translation, rotation, and

scale) that best match the UCAC2 coordinates of the same stars. The resulting catalog is provided in Table 1.

Table 1. M35 star catalog from FGS observations, with linear terms chosen to match the UCAC2

ID (here)	ID (UCAC2)	ID (PASSOPS)	RA (deg)	DEC (deg)	PM_RA (mas/yr)	PM_DEC (mas/yr)
1	40321713	34	92.08923859	24.36399262	2.53	3.97
2	40321583	3	92.02250056	24.36284299	−2.35	0.38
3	40321781	67	92.12221252	24.34724986	2.28	0.43
4	40322561	506	92.47243179	24.30225707	−3.68	4.91
5	40322563	507	92.47395732	24.37367717	−3.27	−0.37
6	40322334	397	92.35784918	24.35867625	−1.32	0.19
7	−1	254	92.26858978	24.36519441	0.71	−8.38
8	40322409	433	92.39330686	24.32650737	−1.28	1.29
9	40322445	454	92.40482207	24.35634424	−6.09	−5.06
10	40322255	350	92.32693911	24.36831663	−0.68	0.17
11	40322055	218	92.23558811	24.35986521	0.08	−0.12
12	40321961	163	92.20007227	24.35248787	0.81	0.39
13	40321963	165	92.20063809	24.31379514	0.52	0.33
14	40321811	77	92.13408450	24.35661389	1.29	−0.21
15	40321765	62	92.11316930	24.33505180	1.69	0.88
16	40322144	257	92.27115243	24.34422574	0.05	−0.11
17	40322476	472	92.41919309	24.32401938	−2.90	−0.22
19	40321775	64	92.11996808	24.31137461	1.44	0.67
21	40322388	426	92.38168889	24.33235718	−1.35	0.05
22	40322411	434	92.39370153	24.33947765	−0.26	0.22
23	40322024	203	92.22568984	24.36927687	0.33	0.12
24	40321914	130	92.17958373	24.31880149	0.22	0.99
25	40321764	59	92.11301254	24.32878565	−1.73	1.16
26	40321763	60	92.11299244	24.32181644	7.56	6.15
27	40321804	73	92.13131847	24.36472533	3.23	0.97
28	40322279	364	92.33629895	24.36918912	−0.54	0.14
29	40322346	405	92.36376822	24.36788051	−0.99	−0.09
30	40322241	338	92.32124991	24.33803871	−0.38	0.05
31	40322302	375	92.34490373	24.34061777	−0.17	−0.46
32	40322278	363	92.33607834	24.32099697	0.08	−0.36
33	40322104	243	92.25351763	24.36490007	0.30	0.13
34	40322331	394	92.35619030	24.36690397	−2.88	−9.18
35	−1	498	92.45514242	24.36972339	−4.74	−0.74
36	40322192	298	92.29499456	24.35183370	−0.86	0.06
37	40321847	−1	92.15169973	24.34395325	−0.12	0.54
38	40321853	98	92.15343084	24.36208783	1.35	−0.06
39	40322454	457	92.40831508	24.32464470	−0.26	−0.19
40	40322131	250	92.26214997	24.36483465	−0.02	0.16
41	40322120	247	92.25907656	24.37429017	−0.26	−0.25
42	40322134	251	92.26458407	24.35972943	1.10	0.51
43	40321893	120	92.17088694	24.35862437	0.36	0.75
44	40322539	502	92.45695192	24.35909166	−2.02	−0.04
45	40322464	466	92.41246286	24.34750148	−1.44	0.20
46	40321999	188	92.21522775	24.35713750	0.41	0.31
47	40322102	240	92.25199188	24.40410653	−0.62	−0.35
48	40322169	277	92.28242248	24.37547979	0.09	−0.30
49	40321760	61	92.11242588	24.43257179	1.88	−2.96
51	40322438	449	92.40275981	24.41982659	−1.93	−5.29
52	40322191	297	92.29340497	24.39028164	−0.28	−0.23
53	40322180	288	92.28866604	24.38807587	−0.99	−0.76
54	40321809	76	92.13315229	24.48642930	1.24	−0.56
55	40321754	55	92.10868910	24.40115993	0.80	0.18
56	40321778	66	92.12118880	24.40705316	1.25	−1.09
57	−1	341	92.32200185	24.42123887	−1.68	2.07
58	40321880	113	92.16612312	24.45321274	−0.30	−0.27
59	40321919	134	92.18188983	24.42055175	0.95	0.05
60	−1	129	92.17888535	24.40556726	0.50	−1.18

Check with the JWST SOCCER Database at: http://soccer.stsci.edu/DmsProdAgile/PLMServlet
To verify that this is the current version.

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61  40322470  468  92.41473861  24.43124116   0.21   3.27
62  40322403  432  92.39035187  24.47368997   0.31   0.09
63  40321749   53  92.10661399  24.39334528   1.41   0.03
64  40322147  260  92.27202444  24.38761510  -0.10  -0.28
65  40322385   -1  92.37987650  24.41447975  -1.26  -1.36
66  40322455  456  92.40833543  24.39283597  -1.90  -0.62
67  40322213  316  92.30382994  24.40610391  -0.85  -0.54
68  40321985  179  92.20960185  24.43416324   0.21  -0.57
69        -1  294  92.29155691  24.39458566  -0.60  -0.76
70  40321949  154  92.19392638  24.47241107   0.17  -0.14
71  40322393  428  92.38422629  24.39088210  -0.77  -0.02
72  40322493  478  92.43139639  24.46185372   2.43   0.93
73  40322212  315  92.30376542  24.42401331  -1.22  -0.36
74  40322047  213  92.23295738  24.40253344   0.19  -0.41
75  40321951  155  92.19520708  24.39622274  -5.03  -4.15
76  40322441  451  92.40412484  24.37828360  -1.43  -0.41
77  40321820   82  92.13900999  24.44980509   0.45   0.32
78  40322340  401  92.36011727  24.38038170  -1.09   0.08
79  40322288  369  92.34123600  24.43649638  -0.75  -0.61
80  40322317  386  92.35084154  24.42425944  -1.05   0.52
81  40322067  220  92.24072200  24.39600311  -0.85  -0.30
82  40322703   -1  92.55989009  24.37937199  -0.02   0.01
83  40321882  114  92.16644336  24.40134994   0.82  -0.05
84        -1  122  92.17219477  24.44271017   2.14  -2.60
85  40322015  196  92.22252749  24.38458411   0.45   0.04
86  40321972  171  92.20465416  24.42579658   0.40  -0.87
87  40322277  361  92.33565288  24.39328896  -0.43   0.03
88  40322332  396  92.35687913  24.40567589  -1.10   0.00
89  40321887  116  92.16750420  24.37507498   1.12   0.72
90  40322365  412  92.37230427  24.39937330  -3.52  -0.21
92  40321944  152  92.19199883  24.38222768  -0.82   0.29
93  40321987  180  92.21013867  24.37515459   0.28   0.15
95  40322137  252  92.26682791  24.39675382  -0.27   0.11
96        -1   -1  92.27219293  24.42648549   3.13   5.84
97  40322263  352  92.32951262  24.42665254  -5.24   1.90
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Notes to Table: Column (1) is a running ID number. The stars used in our ACS analysis have IDs: 11,12,23,33,46,47,74,75,81,85. Star 93 was also in the ACS field of view, but was not used because of its faintness. Column (2) is the ID number of the star in the UCAC2. Column (3) is the HST PASSOPS catalog number (used internally at STScI and GSFC, Kimmel 2007 priv. comm.). A value of -1 indicates that the star is not in the catalog. Columns (4) and (5) give the J2000.0 (RA,dec) coordinates at epoch 2000.0 in degrees. These are based in a relative sense on many years of FGS calibration observations, but with linear terms (2 translations, rotation, and scale) chosen to best match the UCAC2. Columns (5) and (6) give the proper motions in mas/yr in the East and North directions, also determined from the FGS calibration observations. Individual accuracies are not available, but global accuracies are discussed in the text.

For determination of the best-fitting linear transformations we write the comparison between the (ξ_U, η_U) and (ξ', η') as an over-determined matrix equation. This is solved using singular value decomposition by means of a Fortran program written for this purpose. This also yields the random uncertainties on the transformation parameters (and their covariances) using standard statistical and algebraic techniques (e.g., Press et al. 1992). When iterating to convergence as described above we also apply sigma clipping. We rejected stars from the sample (only 3 in this case) for which the residuals of the fit exceed 3 times the sample RMS.

The fit thus performed has an RMS residual per coordinate of 21 mas. This is more-or-less consistent with expectation (the χ^2 per degree of freedom is 1.62), given the positional uncertainties in the UCAC2. The relative positional uncertainties in the FGS catalog are negligible by comparison. The random uncertainties on the linear fit parameters are d scale/ scale = 0.6×10^{-5}, d rotation = 0.6×10^{-5} radians, d RA_T = 5 mas, and d dec_T = 5 mas. These numbers take into account the propagation of random uncertainties, but they do not account for potential systematic errors. Those errors must therefore be assessed separately.

One potential source of systematic error is residual skew terms. To check for this we also performed our analysis using a 6-parameter linear fit in the transformations, rather than a 4-parameter linear fit. The two additional skew terms of a 6-parameter fit can be characterized by the quantities v and u, defined as: (a) the relative difference in scale between the ξ and η axes (i.e., v = 0.5 * ($scale_\xi$ - $scale_\eta$) / scale); and (b) the difference in the rotation angles by which the ξ and η axes need to be rotated to align them with West and South (u = 0.5 * ($rotation_\xi$ - $rotation_\eta$)). If the FGS catalog and the UCAC2 were both properly corrected for geometric distortion, then we should find v=u=0. Indeed, our results are consistent with this: v = $(1.1 \pm 0.9) \times 10^{-5}$ and u = $(-0.6 \pm 0.8) \times 10^{-5}$ radians.

Another possible source of systematic error is through systematic errors in the linear terms of the UCAC2 itself. To check for this we used also the Second Guide Star Catalog 2 (GSC2; Bucciarelli et al. 2001). Both the UCAC2 and the GSC2 are calibrated to the ICRS (International Celestial Reference System; see http://aa.usno.navy.mil/faq/docs/ICRS_doc.html). Any difference in the linear terms between these catalogs must therefore be attributed to systematic errors. To determine the difference in the linear terms we identified all stars in common between the UCAC2 and the GSC2 catalogs in the M35 area of the sky. We then found the best-fitting linear transformations between these star coordinates. With 797 stars, this yields an RMS residual per coordinate of 96 mas. This is mostly due to the positional uncertainties in the GSC2, which are a factor of ~4 larger than those in the UCAC2. The inferred difference in scale is ($scale_{GSC2}$ - $scale_{UCAC2}$) / $scale_{UCAC2}$ = $(0.6 \pm 0.6) \times 10^{-5}$ and the difference in rotation ($rotation_{GSC2}$ - $rotation_{UCAC2}$) = $(3.9 \pm 0.6) \times 10^{-5}$ rad. We interpret these results as upper limits to the systematic errors in the linear terms of the UCAC2. Translations are not relevant for our analysis, but we note that there is also a small shift between the GSC2 and UCAC2 catalogs, RA_{GSC2} - RA_{UCAC2} = 8 ± 3 mas and dec_{GSC2} - dec_{UCAC2} = 54 ± 3 mas.

We conclude that the catalog in Table 1 has relative scale uncertainties of 0.6×10^{-5} (random) and $\leq 0.6 \times 10^{-5}$ (systematic), rotation uncertainties of 0.6×10^{-5} radians (random) and $\leq 3.9 \times 10^{-5}$ radians (systematic), and remaining skew terms $\leq 1.1 \times 10^{-5}$ (systematic).

We performed two other comparisons. First, we compared how the linear terms inferred by us using the UCAC2 differ from those inferred by the FGS Science Team. We find a difference in scale ($scale_{FGS}$ - $scale_{UCAC2}$) / $scale_{UCAC2}$ = $(-2.5 \pm 0.6) \times 10^{-5}$ and a difference

in rotation (rotation$_{FGS}$ - rotation$_{UCAC2}$) = (873.2 ± 0.6) × 10^{-5} rad. Second, we compared how the linear terms change if we use the M35 ground-based astrometric catalog of McNamara & Sekiguchi (1986) instead of the UCAC2. This catalog was updated as quoted in Jefferys et al. (1994) to utilize knowledge of then available distortion maps and color/magnitude calibration for the HST FGSs. This revised version is referred to internally at STScI and GSFC as the PASSOPS catalog, after the group at GSFC that created it (where PASSOPS is a nested acronym, standing for POCC Applications Support Systems Operations, where POCC stands for Payload Operations Control Center). The most recent version of this catalog was kindly provided to us by Ed Kimmer at GSFC. Alignment of the M35 FGS catalog with the PASSOPS version of the McNamara & Sekiguchi catalog yields an RMS residual per coordinate of 22 mas, indicating that the relative astrometric accuracy of the latter catalog is similar to that of the UCAC2. The inferred difference in scale is (scale$_{McN}$ - scale$_{UCAC2}$) / scale$_{UCAC2}$ = (-1.4 ± 0.9) × 10^{-5} and the difference in rotation is (rotation$_{McN}$ - rotation$_{UCAC2}$) = (556.4 ± 0.9) × 10^{-5} rad. The differences in rotation, amounting to several tenths of a degree, are particularly noteworthy in both comparisons. The inferred scales agree much better with those of the UCAC2. We do not know how McNamara & Sekiguchi and the FGS Science Team set the linear terms of their catalogs, so we do not wish to attach much meaning to these comparisons. However, it seems clear that both these catalogs have a large systematic error in absolute rotation as compared to the well-calibrated and well-understood UCAC2 and GSC2 all-sky catalogs.

4.0   M35 ACS Observations

An extensive set of calibration observations of M35 was recently performed in the context of HST program CAL/OTA-11021. The main goal of this program was to determine an improved focal plane calibration of HST, and in particular to recalibrate the positions of the FGSs and science instruments with respect to each other. However, it was decided to also use 1 orbit of ACS observations (visit 13) to calibrate the scale and rotation of the WFC.

The ACS/WFC field of view (FOV) is much smaller than the coverage of the M35 FGS catalog in Table 1. The pointing was therefore chosen to optimize the number of catalog stars in the FOV. The adopted pointing with J2000 (RA,dec) = (92.219833, 24.37675) degrees is close to the catalog center and yields a total of 11 catalog stars in the FOV (5 on the WFC1 CCD and 6 on the WFC2 CCD). We did not use the faintest star (visual magnitude 14.7) and the remaining 10 stars form the basis of our subsequent analysis. Their catalog IDs are listed in the notes to Table 1. These stars are all quite bright, with visual magnitudes ranging from 8.0 to 12.8, with a median of 11.0. The ACS/WFC allows a minimum exposure time of 0.5 sec, and the majority of the stars would have saturated in exposures with a broad-band filter. We therefore observed with F658N, for which good empirical PSFs (Anderson & King 2006) and accurate geometric distortion solutions (Anderson 2005) exist.

We obtained 4 images in a semi+integer pixel dither pattern. The dataset names and relative positionings are: j9ug13llq at (0.0,0.0); j9ug13lnq at (1.5,1.0); j9ug13lpq at (2.0,2.5); and j9ug13lrq at (0.5,1.5). Each image was exposed for 2 seconds. Figure 1 shows an image of the ACS data. The stars used in our analysis are labeled.
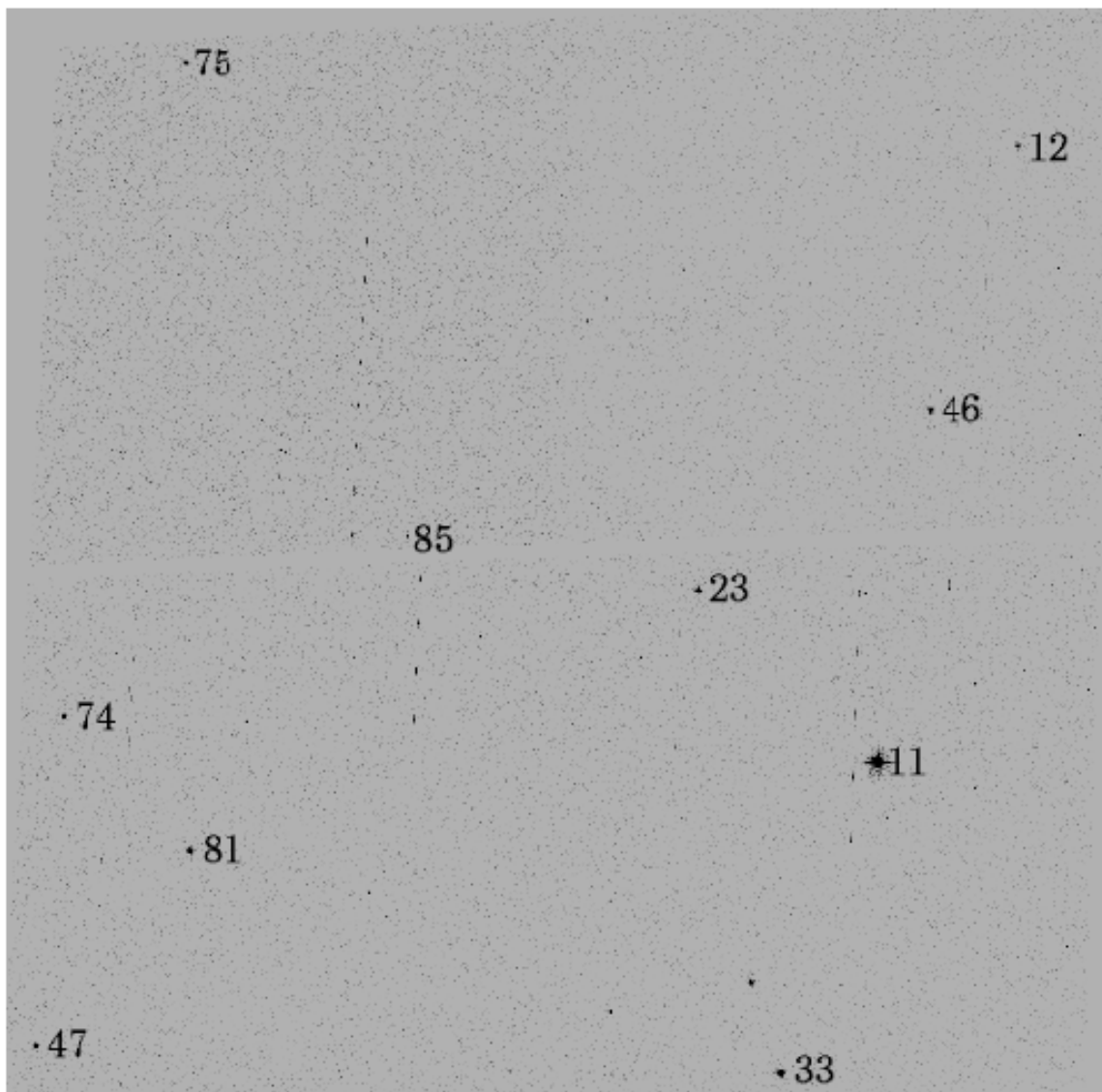
Figure 1. ACS/WFC image of the subject area in the open cluster M35. The displayed image is a median-combined version of the *_drz.fits images created by the HST/ACS pipeline for the four individual 2-sec exposures in F658N. The actual astrometric analysis was performed on the individual *_flt.fits exposures. Stars in the M35 FGS/UCAC2 catalog are labeled with their ID number in column (1) of Table 1. Dashed lines that appear almost vertical are residual artifacts of bad CCD columns.

We used the software described in Anderson & King (2006) to fit position-dependent empirical PSFs to the individual star images in each of the calibrated *_flt.fits images. The ACS/WFC PSFs generally vary as a function of telescope focus. Our fits therefore included a perturbation PSF, as described in Anderson & King (2006), to optimize the PSF fits for the specific datasets at hand. The fits yield for each star in each exposure the raw pixel coordinates (x_r, y_r). We then used the geometric distortion solutions and software of Anderson (2005) to calculate for each star the corresponding position (x_c, y_c) in the distortion corrected frame (DCF). We included the correction for time-dependent skew variation described by Anderson (2007). All this follows the standard procedure for astrometric correction of any ACS/WFC dataset.

The DCF is defined by the following properties: (a) it has no residual skew terms and higher-order distortions; (b) the y-axis of the DCF is such that it is parallel to the detector y-axis at the center of the WFC2 CCD (pixel (2048,1024) in a *_flt.fits[1] image extension); (c) the scale of the DCF is such that at the center of the WFC2 CCD it is identical to the pixel scale of the detector, as measured along a line that is perpendicular on the sky to the detector y-axis. To obtain an absolute astrometric calibration for the ACS/WFC we need to find expressions for two quantities: the scale S of the DCF, and the angle P by which the y-axis of the DCF must be rotated counterclockwise to align it with North. Translations are of no particular concern in the present context.

The scale S is affected by differential velocity aberration. Velocity aberration causes a shift in the position of a target by an amount that depends on the angle between the velocity vector of the telescope and the direction vector towards the target. The mean shift is corrected by the telescope pointing software while the velocity vector changes during an orbit (through rotation of the telescope around the Earth) and over the course of a year (through rotation of the Earth around the Sun). However, the angle varies over the field of view, and this cannot be corrected. It can be shown that this causes a pure scale change in an image, with a maximum value of 12×10^{-5} (Cox & Gilliland 2002). The exact value of the change is captured for every observation in the header keyword VAFACTOR. The scale S therefore satisfies

(1)   S = s * VAFACTOR ,

where s is independent of differential velocity aberration.

The angle P depends on the orientation of the telescope at the time of the observations. This orientation is usually expressed with the help of the HST (V1,V2,V3) coordinate system. The V1 axis is the optical axis of the telescope. We define the HST tangent plane projection frame (HTPPF) to be a tangent plane projection of the sky, with the pointing coordinates of the V1 axis as tangent point. The V2 and V3 axes are orthogonal axes in the HTPPF and have a fixed orientation with respect to the telescope hardware. The angle PA_V3 is the position angle of the V3 axis as measured at the telescope V1 axis, which is captured for every observation as a header keyword. With the help of this angle we can write

(2) $P = - (PA\_V3 + b - c)$.

Here b is the angle from the V3 axis to the direction of the detector y-axis at the center of the WFC2 CCD, as measured in the HTPPF. The angle c is the angle in the HTPPF from the North direction at the V1 axis to the North direction at the center of the WFC2 CCD. This angle is not zero because the sky looks distorted when projected onto a plane, especially near the celestial poles (e.g., see Figure 4 of van der Marel & Cioni 2001).

The quantities in equations (1) and (2) that we need to calibrate using the observations of M35 are s and b. The quantities VAFACTOR and PA_V3 are available for any observation as header keywords. The angle c can be computed for any observation from header keywords. A fortran program based on the tangent plane projection formulae of Smart (1977) was written for this purpose. The program requires as input the (RA,dec) coordinates of both the V1 axis and the center of the WFC2 CCD. The former are stored for any observation in the header keywords RA_V1 and DEC_V1 in the *_spt.fits file. The latter are stored as the header keywords CRVAL1 and CRVAL2 in the *_flt.fits[1] extension of any WFC image.

For each of the four M35 exposures with ACS we used the following approach. We identified the 10 stars in Table 1 that compose the ACS sample, and calculated their (RA,dec) positions at the epoch 2006.93082 of the ACS observations. We then applied a tangent plane projection to calculate corresponding (ξ, η) coordinates. As tangent point for the projection we used the (RA,dec) position of the center of the WFC2 CCD, obtained as described above. We then apply a 4-parameter linear transformation to the positions (x_c, y_c) of the stars in the DCF, obtained from the ACS observations as described above, to obtain new coordinates (x'_c, y'_c). We find the linear transformation parameters that minimize the χ^2 residual between the coordinates (ξ, η) and (x'_c, y'_c) of the stars. All 10 stars are weighted equally in the χ^2. The numerical implementation of the χ^2 minimization was similar to that described in Section 3. The scale and rotation angle of the transformation are equal by definition to the quantities S and P, respectively. The quantities that we are interested in then follow from s = S/VAFACTOR and b = - (P + PA_V3 - c), where the quantities on the right hand side are all known.

The fits yield consistent results for the four M35 exposures, with differences similar to the random errors in the fits. The RMS residual of the fit per coordinate ranges from 1.3 to 2.0 mas. This is consistent with expectation. The FGS catalog has random errors at or below ~1 mas, and the same is true for the accuracy of ACS position determinations for bright stars with the methods of Anderson (2005). The average results for the unknowns are

(3)   s = 0.0497248 arcsec/pixel

and

(4)   b = 177.7612 degrees .

The random uncertainties in these results are ds/s = db/radians = 0.6×10^{-5}. These numbers reflect the propagation of the RMS residuals with which the (ξ, η) and (x'_c, y'_c) can be aligned. We did not divide the errors by $\sqrt{4}$, because the errors between the individual exposures are likely to be correlated. The random errors do not include the uncertainties that are already inherent in the linear terms of the M35 catalog in Table 1. When those uncertainties (listed towards the end of Section 3) are included, we conclude that our result for s has a relative uncertainty of 0.9×10^{-5} (random) and $\leq 0.6 \times 10^{-5}$ (systematic), and the result for b has an uncertainty of 0.9×10^{-5} radians (random) and $\leq 3.9 \times 10^{-5}$ radians (systematic).

The brightest star of the sample (ID 11, see Figure 1) was saturated in its central three pixels. By masking the saturated pixels as described in Appendix C.5 of Anderson & King (2004) it was still possible to measure accurate positions for this star. To double check that this does not introduce biases, we verified that the fit residuals for this star do not stand out compared to the residuals for the other stars. Also, we performed fits of the quantities s and b without inclusion of the saturated star, and found that compared to equations (3) and (4) the results only changed by much less than the random errors.

We also performed 6-parameter linear fits. If both the Anderson (2005) DCF and the M35 FGS catalog are completely free of distortion, then we would not expect to find any remaining skew terms. In fact, the skew terms of the fit are $v = (1.3 \pm 0.5) \times 10^{-5}$ and $u = (0.7 \pm 0.5) \times 10^{-5}$. So there is a some evidence for remaining skew terms that are statistically significant. However, the skew terms that we find are small and of similar size as the systematic errors in the skew terms of the M35 catalog (listed towards the end of Section 2). We conclude that the DCF is skew free to a level of $\leq 1.3 \times 10^{-5}$ (systematic).

Limited Charge Transfer Efficiency (CTE) could be a contributor to the inferred skew terms. CTE causes charge-deferred tails primarily along the detector y-axis, which are larger for stars further from a CCD amplifier. If these CTE tails cause slight astrometric shifts, then a skew may be introduced. To get a more direct handle on the possible impact of CTE we have also performed the fits separately to the x- and y-coordinates of the stars. The y-coordinate is expected to be much more impacted by CTE than the x-coordinate. However, we find that the scale changes between these fits only by a fractional amount of $\pm 0.8 \times 10^{-5}$ and the rotation only changes by $\pm 0.8 \times 10^{-5}$ radians. We conclude from this and from the small size of the skew terms that limited CTE does not introduce significant uncertainties in the analysis of the linear geometric distortion terms. A detailed

discussion of the effect of CTE on higher-order (non-linear) astrometric residuals will be presented in Kozhurina-Platais et al. (2007).

The results for s and b obtained here can be compared to existing estimates. Information on the scales, rotations and positions of the HST science instruments is maintained in the HST Science Instrument Aperture File (SIAF, http://www.stsci.edu/hst/observatory/apertures/siaf.html). However, this file only contains information for a finite set of pre-defined "apertures". While there is an aperture WFC2-FIX (called JWFC2FIX in the SIAF file) near the center of the WFC2 CCD, this aperture is 24 pixels away from the position adopted by Anderson (2005). So instead of using information in the SIAF file, we went back to the original transformation equations from which the values in the SIAF file were derived. These transformations are also used by the HST/ACS pipeline to correct ACS/WCS images for geometric distortion to create *_drz.fits images with the multidrizzle software. The transformations are described in the header information of the program WFCgenerate6.F, which was disseminated as part of the Anderson (2005) distortion solutions. They are based on the absolute scale and rotation solutions derived by Meurer (2002), which used the technique discussed in Section 6 below. As discussed there, this is believed to be less accurate than the M35 method discussed in the present section. When the old Anderson/Meurer transformations are used to calculate the scale s and the rotation b we find s = 0.0497332 arcsec/pixel and b = 177.7687 degrees[1]. Our new value for s differs in a relative sense from the existing calibration by 17.0×10^{-5}. Our new value for b differs from the existing calibration by 13.0×10^{-5} radians. These differences exceed by an order of magnitude the uncertainties in our results.

We have also measured the positions of the same 10 M35 stars on the multidrizzled *_drz.fits images produced by the HST/ACS pipeline. Since accurate PSFs are not available that apply to multidrizzled data, we measured the positions by simple Gaussian fits. We matched these positions to the (RA,dec) from Table 1 using a four-parameter linear transformation. The RMS of this fit is 5.8 mas. This exceeds the RMS of the fit for the *_flt.fits file analysis because use of a PSF library provides more accurate centroiding. The nominal scale of *_drz.fits images is 0.05 arcsec/pixel. By contrast, the fit yields for the scale of the multidrizzle frame (MDF) $S_d = 0.0499932$ arcsec/pixel with a fractional random uncertainty of 2.0×10^{-5}. The inferred position angle of the image y axis exceeds the value given in the header keyword ORIENTAT by $P_d = -0.0038$ degrees (-6.7×10^{-5} radians), with a random uncertainty of 2.0×10^{-5} radians. A six-parameter fit reveals some skew terms in the MDF, consistent with the findings of Anderson (2007) that the skew terms of ACS/WFC are changing with time (see the bottom panels of Figure 2 in Section 5 below). This time variation in the skew terms has not yet been implemented in the Multidrizzle software, but probably will be eventually.

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[1]As expected, the value of b is very close to the value of the angle $beta_y = 177.7655$ listed in the SIAF file for aperture JWFC2FIX. The value of s cannot be directly compared to the scales s_x and s_y listed in the SIAF file for this aperture, because s_x and s_y are measured along the detector axes, whereas s is defined as the scale along an axis perpendicular on the sky to the detector y-axis.

5.0   Time stability of ACS distortions from 47 Tuc observations

The ACS/WFC observations of M35 were obtained half a year later than the ACS/WFC observations of the JWST astrometric reference field in the LMC. Before we can use the values of s and b derived in Section 4 to calibrate the LMC field we must therefore establish whether there are any variations in these quantities as a function of time. For this we use an extensive dataset of 193 ACS/WFC observations in F606W of the globular cluster 47 Tuc, which has been observed repeatedly over the years since ACS was installed on HST.

The 47 Tuc dataset was analyzed astrometrically by Anderson (2007). He used the data to establish a master catalog of stars in 47 Tuc on a geometrically corrected frame that is (nominally) free of skew terms and higher-order distortions. The 47 Tuc data do not themselves constrain the absolute scale and rotation of this frame. The latter were therefore chosen to match the output of the HST/ACS pipeline task multidrizzle for one of the images (j91c01cbq_drz.fits). The scale and rotation used by multidrizzle are ultimately based on the calibrations of Meurer (2002). For each observation of 47 Tuc in the dataset the following approach was taken. First the raw positions in the *_flt.fits image were determined for all the stars using the same procedure discussed in Section 4. Then the positions were converted to the DCF using the geometric distortion solutions of Anderson (2005). And finally the best-fitting six-parameter linear transformation was found that matches the DCF positions of the stars to their positions in the master catalog. The transformation is characterized by two translation parameters and the four coefficients of a transformation matrix of the form

$$(5) \qquad \begin{pmatrix} A & B \\ C & D \end{pmatrix} \ .$$

The coefficients A, B, C, and D formed the starting point of the analysis presented here.

A transformation matrix of the form (5) can also be characterized by the four quantities

$$(6) \qquad \begin{aligned} S &= \sqrt{(AD - BC)} \\ P &= \mathrm{ATAN2}(B-C,\ A+D) \\ f_1 &= (A-D)\ /\ 2S \\ f_2 &= (B+C)\ /\ 2S \ . \end{aligned}$$

Here S is the average scale of the transformation, P is the average rotation angle of the transformation, and f_1 and f_2 are two skew terms. These skew terms are related to a difference in scale and a departure from orthogonality between the two principle axes. The skew terms f_1 and f_2 can be difficult to interpret because a fixed skew in one of the frames can manifest itself as either f_1 and f_2 (or both), depending on the rotation angle between the frames. This can be avoided by writing the matrix (5) as the product of a pure rotation matrix and a pure skew matrix:

(7)   (A B) = (S' cos P'   S' sin P')   (1+v   u)
        (C D)   (-S' sin P'   S' cos P')   (u   1-v)   .

Here $v \neq 0$ corresponds to a difference in scale between the two principal axes. If u,v<<1 then the scale along the principal axes has a relative difference of ±v from the mean scale. A value of $u \neq 0$ corresponds to a departure from orthogonality between the two axes. If u,v<<1 then the departure from orthogonality will be ±u radians. Evaluation of equations (6) and (7) shows that

(8) S $= S' \sqrt{(1-[u^2+v^2])}$
        P $= P'$
        f_1 $= u \sin P + v \cos P$
        f_2 $= u \cos P - v \sin P$.

For u,v<<1 we have that $S = S'$ (e.g., a skew of u or v of 1.0×10^{-5} causes a fractional difference between S and S' of only 5.0×10^{-11}). The skew terms f_1 and f_2 are related to u and v through a simple rotation matrix. This can be inverted to yield:

(9) u $= f_1 \sin P + f_2 \cos P$
        v $= f_1 \cos P - f_2 \sin P$.

In other words, the vector (v,u) is obtained from the vector (f_1,f_2) by rotation over an angle equal to -P. We use equations (6) and (9) to characterize each linear transformation through the quantities S, P, u and v.

As described in Section 4, the scale S will vary over time as a result of differential velocity aberration. Therefore we write

(10) $\sigma = S / VAFACTOR$,

where σ is independent of velocity aberration. The quantity σ satisfies $\sigma = s / Sm$, where the scale s is defined in Section 4 and S_m is the absolute scale of the Anderson's (2007) 47 Tuc master catalog. The rotation angle P depends on the orientation of the telescope at the time of the observations. In analogy with Section 4 we may write

(11) $\zeta = - (P + PA\_V3 - d)$,

The angle d is the angle in the HTPPF from the North direction at the V1 axis to the North direction at the center of the 47 Tuc master catalog (the tangent point of the sky projection for that frame). As for the angle c in Section 4, this angle is not zero because the sky looks distorted when projected onto a plane. The angle zeta satisfies zeta = b - P_m, where the angle b is defined in Section 4 and P_m is the position angle on the sky (measured from North over East) of the y-axis of Anderson's (2007) 47 Tuc master catalog frame (MCF).

The nominal values of Sm and Pm are 0.05 arcsec/pixel and 0 degrees, respectively. The true values will be slightly different, because of inaccuracies in the absolute scale and rotation determinations of Meurer (2002). The true values can be estimated using the equations

(12) $S_m = s / <\sigma>$

(13) $P_m = b - <\zeta>$,

where s and b are as calibrated in Section 4. The quantities $<\sigma>$ and $<\zeta>$ are the time averages of the inferred σ and ζ values, which we find to be $<\sigma> = 0.9946294$ and $<\zeta> = -182.2382$. This yields $S_m = 0.0499933$ arcsec/pixel and $P_m = -0.0006$ degrees. The random errors on these results are the same as the random errors on s and b derived in Section 4. The errors on $<\sigma>$ and $<\zeta>$ are negligible by comparison, because of the large number of 193 independent measurements on which these quantities are based. The results for S_m and P_m differ from the nominal values by a fraction 13.4×10^{-5} and -1.1×10^{-5} radians, respectively.

In the present context we are interested more in the variations of s and b with time than in the absolute values of S_m and P_m. The fractional variations in s and b are measured by

(14) $ds = (\sigma/<\sigma>) - 1$, $db = \zeta - <\zeta>$ (in radians) .

Figure 2 shows the variations of ds, db, u and v with time. The abscissa in each panel runs from -10.0×10^{-5} to 10.0×10^{-5}. The scale in the top left panel shows a smooth long-term variation with time, as well as some scatter at fixed date. Variations in telescope focus may be a contributing factor to this. Either way, the time variation in scale is minimal and the RMS of ds is only 0.6×10^{-5}. The angle b in the top right panel shows mostly scatter, and no obvious trend with time. The RMS of db is 4.7×10^{-5} radians (0.0027 degrees). This is presumably due to the limited accuracy with which HST can achieve a given roll angle. The nominal accuracy of this 0.003 degrees, which is consistent with our results.

The skew terms u and v in the bottom panels both show a pronounced linear trend with time. This was previously reported by Anderson (2007), who parameterized these trends as linear variations with time of the quantities $\alpha=2048*u$ and $\beta=2048*v$. The underlying cause of these trends is unknown. The straight lines in Figure 2 show Anderson's empirical fits. These fits were used for the M35 analysis in Section 4. As a consequence, we found very little residual skew in that analysis. If we omit the linear skew corrections in the analysis of Section 4 then the M35 data actually provide an independent determination of u and v. These determinations are shown as red data points in Figure 2. The M35 results are consistent at the ~1 sigma level with the 47 Tuc analysis. When the 47 Tuc data themselves are corrected using the linear skew variations with time proposed by Anderson (2007) then the remaining skew variations are very small, with RMS values in u and v of only 0.3×10^{-5} and 0.2×10^{-5}, respectively.

When the M35 calibrations of s and b from Section 4 are applied to data obtained at different times then this introduces additional uncertainties that must be added in quadrature to the uncertainties in the M35 analysis itself. This yields total relative uncertainties in the scale S and the rotation P of the DCF (eqs. 1 and 2) of 1.1×10^{-5} (random) and $\leq 0.6 \times 10^{-5}$ (systematic) in scale, and 4.8×10^{-5} radians (random) and $\leq 3.9 \times 10^{-5}$ radians (systematic) in rotation. Any remaining skew in the DCF should be $\leq 0.3 \times 10^{-5}$ (random) and $\leq 1.3 \times 10^{-5}$ (systematic).
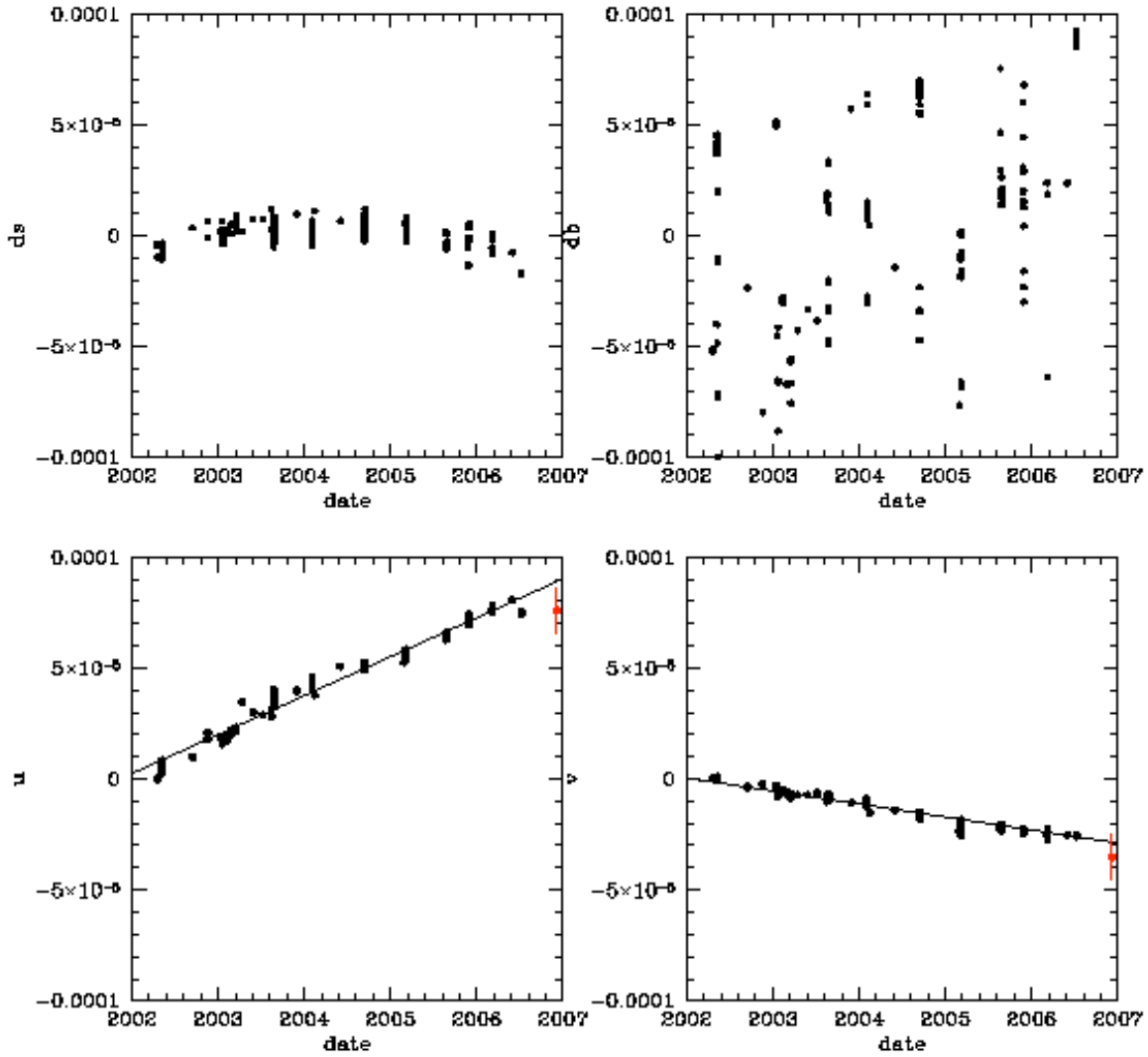
Figure 2. Variation with time of the linear quantities that describe the geometry of the Anderson (2005) Distortion Corrected Frame (DCF), as inferred from repeated observations of 47 Tuc. Top left: fractional variation in scale ds; Top Right: variation in rotation angle db in radians (see eq. 14); Bottom Left: skew term u, measuring the difference of the axes from orthogonality in radians; Bottom Right: skew term v, measuring the fractional difference in scale between the two principal axes. The red data points are the skew terms of the Anderson DCF implied by the M35 observations described in Section 4. The straight lines in the bottom panels show the empirical correction for time-dependent skew variation derived by Anderson (2007). These should be applied in astrometric studies that desire high accuracy.

One subtlety that we have ignored so far is that the M35 observations were obtained with the F658N filter while the 47 Tuc observations discussed in this section were obtained

with the F606W filter. This difference should not affect the analysis. While the Anderson (2005) geometric distortion corrections are filter dependent, they were derived so as to put data obtained with different filters all onto a common Distortion Corrected Frame (DCF). The accuracy with which the solutions are matched between filters should be very high. Bright stars can be centroided to an accuracy approaching 0.01 pixels. Matching two stars on opposite ends of the detector then yields a scale error of order $0.01/4096 = 0.2 \times 10^{-5}$. In practice this number will decrease by a large $\sqrt{N}$ factor, because Anderson (2005) had access to many 47 Tuc observations in different filters, and each contains thousands of stars. The results of the present work allow us to independently verify this. We derived the scale S_m and rotation P_m of the 47 Tuc MCF, which were matched to the multidrizzle output of one of the F606W images of 47 Tuc. We also derived the scale S_d and rotation P_d of the multidrizzle output of the F658N images of M35. We find that the scales S_m and S_d differ in a fractional sense by $[0.2 \pm 2.3 \text{ (random)} \pm 0.6 \text{ (systematic)}] \times 10^{-5}$. The rotations P_m and P_d differ by $[5.6 \pm 5.2 \text{ (random)} \pm 3.9 \text{ (systematic)}] \times 10^{-5}$ radians. Therefore, these measurements in different filters indeed yield consistent results to within the uncertainties.

6.0   Consistency check on ACS scale and orientation from 47 Tuc observations

A fixed position (x_{ref}, y_{ref}) in the DCF corresponds to a fixed position on the ACS/WFC detectors and hence a fixed position in the HST focal plane. When the telescope is commanded to slew between observations, this corresponds to a shift of the (RA,dec) that falls on (x_{ref}, y_{ref}). A shift between consecutive observations can be executed fairly accurately, provided that the observations are obtained in the same visit (i.e., with the same guide stars). The shift in arcsec is captured by the header keywords POSTARG1 and POSTARG2 in the *_flt.fits file. These measure shifts along orthogonal axes, with POSTARG2 nominally along the position angle stored in the header keyword PAAPER. The analysis of Section 5 provides for each 47 Tuc observation the six-parameter linear transformation that matches the DCF positions of the stars to their positions in the 47 Tuc master catalog. This transformation determines the position (x_{mas}, y_{mas}) in the master catalog frame (MCF) that corresponds to (x_{ref}, y_{ref}). A pixel shift in (x_{mas}, y_{mas}) between consecutive observations corresponds to minus the arcsec shift captured in (POSTARG1,POSTARG2). Matching the pixel shifts to the arcsec shifts using a linear transformation yields the scale S_m of the MCF and a rotation angle P. The rotation P_m of the MCF follows from $P_m = P - \text{PAAPER}$. With the help of equations (12) and (13) we can then estimate $s = S_m <\sigma>$ and $b = P_m + <\zeta>$, where $<\sigma>$ and $<\zeta>$ were derived in Section 5. This provides a method for estimating s and b that is independent of M35, and which can be used as a cross-check on the results of Section 4. This is in essence the method by which Meurer et al. (2002) estimated the absolute scale and rotation of ACS/WFC.

We identified all the 47 Tuc visits in the dataset of Anderson (2007) that included observations with two or more slews that were not all along a single line. The latter criterion allows analysis of possible skew terms in the telescope POSTARG system. For each of the nine visits thus identified we performed a single six-parameter linear fit to

match all the master frame shifts to the POSTARG shifts. This yields S_m and P_m for each visit. To quantify the difference between the implied results for s and b and the M35 determinations we define

(15) $ds = (S_m <\sigma> / s) - 1$, $db = P_m + <\zeta> - b$ (in radians) ,

where s and b are the values from Section 4. Figure 3 shows the values of ds and db implied by this analysis, as function of observation date.

The mean values are $<ds> = (-3.4 \pm 10.6) \times 10^{-5}$ and $<db> = (-36.0 \pm 21.7) \times 10^{-5}$. Therefore the scale result is consistent with that derived from the M35 data, whereas the rotation result differs at the 1.6-sigma level. However, the error bars on the results from 47 Tuc are some 10 times larger than those obtained from the M35 analysis. Therefore, the 47 Tuc analysis gives us no reason to mistrust the M35 results. Figure 3 shows that the cause of the large error bars is due to significant scatter in the results as a function of observation date. The error bars on the individual measurements are actually quite small. The results for the scale show no obvious trend with time. However, the results for the rotation suggest a 1-year periodicity. We also find that our linear transformations have significant skew terms, with typical values of a few times 1.0×10^{-4}. Since we have already established that Anderson's DCF and MCF are relatively skew-free, this must be attributed to skew in the telescope POSTARG system. The likely cause of all these findings is that the header keywords POSTARG1 and POSTARG2 do not accurately reflect the actual slew sizes executed by the telescope commanding software at the ACS/WFC position in the focal plane. We have not been able to identify the cause of this. Either way, this method based on telescope slews will even in an ideal situation not be as accurate as the M35 analysis of Section 4. The present analysis therefore serves primarily as a successful consistency check.
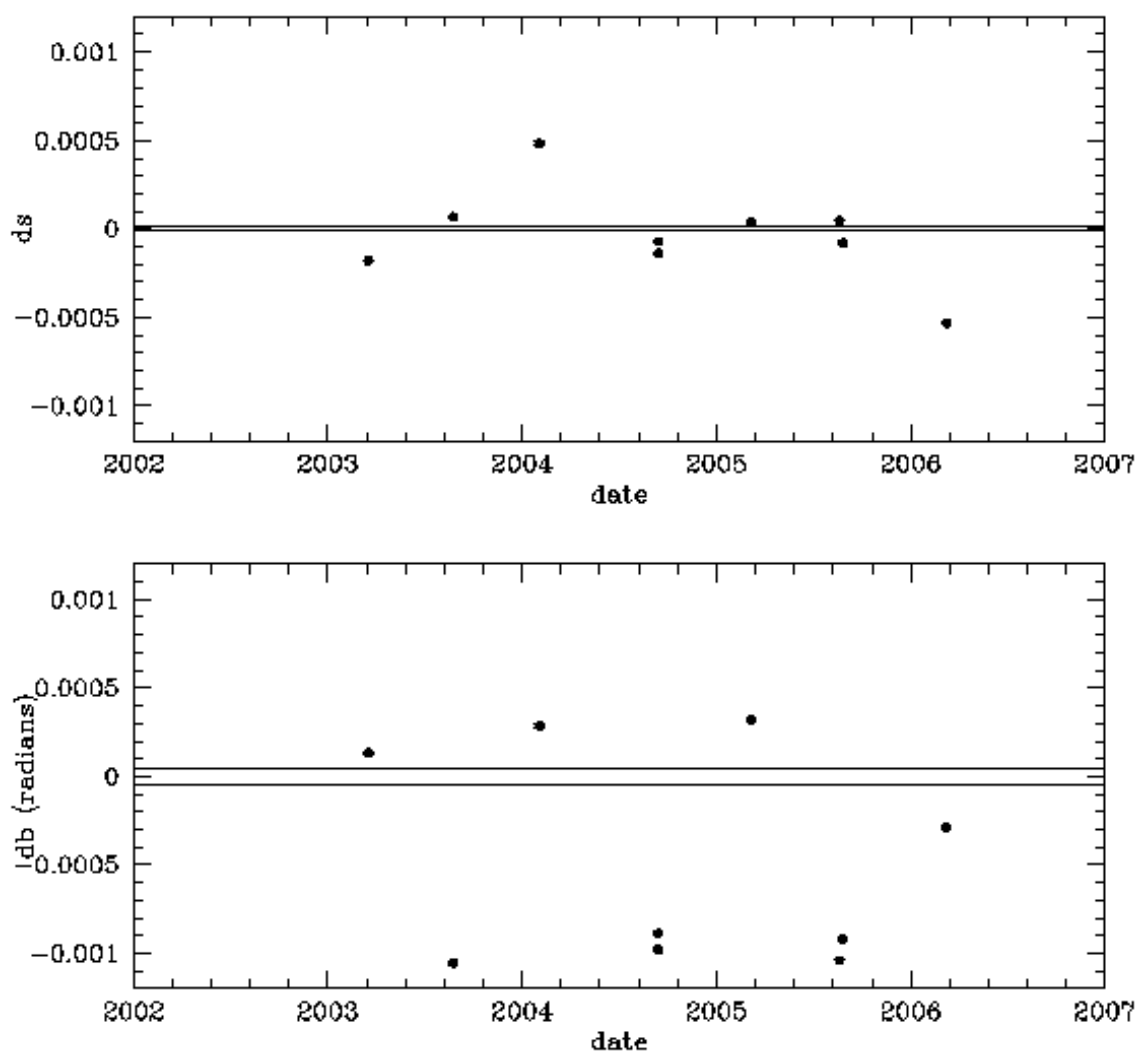
Figure 3. Fractional differences in the Anderson (2005) Distortion Corrected Frame
(DCF) scale (ds) and rotation (db in radians; see eq. 15) between the calibration based on
47 Tuc data and telescope slews and the M35 calibration. Results are shown as function
of observation date. Each data point represents a visits of 47 Tuc observations that
included observations with two or more slews that were not all along a single line. Error
bars are shown, but are generally smaller than the data points. The horizontal bands
correspond to the determination of s and b from M35, with the width indicating the 1-
sigma confidence region around the M35 results. The M35 calibrations are considerably
more accurate than what can be obtained from the telescope slew analysis.

7.0   Discussion and Conclusions

The results of this report yield the following procedure for absolute astrometric calibration of a JWST reference field observed with HST/ACS:

(1) Determine the positions of the stars in the Distortion Corrected Frame (DCF). This involves the following steps: (a) measure the raw detector positions in a *_flt.fits file using the PSF fitting software of Anderson (2006); (b) apply the geometric distortion corrections of Anderson (2005); (c) apply the corrections for time-dependent skew derived by Anderson (2007). Software to perform these operations is available from Jay Anderson. (Note: for the particular case of the observations described by Diaz-Miller 2007 an additional correction will be necessary for the fact that HST was somewhat out of focus for one set of observations).

(2) Determine the scale $S = s *$ VAFACTOR (eq. 1) and the rotation $P = - (PA\_V3 + b - c)$ (eq. 2) of the DCF; P is the angle by which the y-axis of the DCF must be rotated counterclockwise to align it with North. Here $s = 0.0497248$ arcsec/pixel (eq. 3) and $b = 177.7612$ degrees (eq. 4). VAFACTOR and PA_V3 are given as header keywords in the *_flt.fits file. The angle c is defined in Section 4 and can be calculated with software that is available from Roeland van der Marel. This requires as input the header keywords RA_V1 and DEC_V1 in the *_spt.fits file and the header keywords CRVAL1 and CRVAL2 in the *_flt.fits[1] extension (note: it is important to use only the first extension, which corresponds to the WFC2 CCD).

The uncertainties in the scale S and the rotation P of the DCF (see end of Section 5) are 1.1×10^{-5} (random) and $\leq 0.6 \times 10^{-5}$ (systematic) in scale, and 4.8×10^{-5} radians (random) and $\leq 3.9 \times 10^{-5}$ radians (systematic) in rotation. Any remaining skew in the DCF is $\leq 0.3 \times 10^{-5}$ (random) and $\leq 1.3 \times 10^{-5}$ (systematic). The primary uncertainty in the absolute astrometric calibration of any ACS/WFC field is therefore in the absolute rotation angle. However, all the uncertainties are below the level of $\sim 5 \times 10^{-5}$ (Section 2) required to ensure accuracy better than 5 mas over a 1-2 arcmin radius field. Therefore, the ACS/WFC is now well enough calibrated for construction of an astrometric reference field for JWST. The observations of the actual target field in the LMC will be described in (Diaz-Miller et al. 2007).

8.0   References

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