Appendix D

Appendix: HRMA Pointing at XRCF

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D.1 Introduction

In this chapter we describe the HRMA pointing actuator system, and the method that was used to reconstruct to the best extent possible the actual pointing of the HRMA during each test at XRCF.

The HRMA pointing actuator system is described elsewhere (XC-05?) in much more detail. The HRMA was mounted on a table-like fixture in the vacuum tank at XRCF. Basically, the yaw motion was controlled by two screw-type actuators symmetrically placed at the forward (actuator 4) and aft (actuator 5) ends of this fixture, one of which gets longer and the other shorter by the same amount, to rotate the HRMA about a vertical axis passing through the node. The pitch motion is similar: there are two vertical actuators at the aft end of the fixture (downstream from the x-ray beam's point of view; actuators 7 and 8 on the near and far sides, respectively as seen from the control room) and one at the front (actuator 6). Nominal operations call for the forward actuator to shorten and the two aft actuators to lengthen in order to pitch the front of the HRMA down, rotating it about a horizontal axis through its node.

There is also an axial actuator (actuator 3) that can control the motion of the HRMA along the beam direction. This can be used to compensate for axial motions of the node (if any) generated by pitch and yaw maneuvers.

The HRMA Actuator Control System (HACS) software was intended to run the actuators in the above manner, and report the output of the encoders attached to each actuator, via the DLRS, to the data archive. It was often the case, however, that the hardware was not in optimal working condition, and so the actuators were controlled manually by EKC personnel, and troubleshooting efforts were concentrated (quite properly) on getting the hardware to work, and not, in many cases, on recording the details of the tests performed. Especially in Phase 1, therefore, the record is somewhat spotty, and sometimes altogether missing.

We have done what we could to reconstruct the sequence of events and come up with a best-guess set of HRMA pitch and yaw pointing values for each known test (delimited and designated by TRW ID glyphs).

D.2 Sources of Information

There are several logs, some hand-entered and some computer-generated, which contain information on the HRMA pointing. Some are indexed on time alone, and others have more identifying information in them, such as TRW ID's. It is therefore necessary to have a list of what tests were done, what TRW ID's were used, in what order, and at what start and stop times.

D.2.1 Test Order and Times

In many cases the Test Conductor log (TC log) contains all the necessary information about times and test identification, and can be parsed by an automated script. Perhaps 90% of the tests fall into this category. The archive group has done this parsing, and generated a list of start, stop and abort times for each TRW_ID which has the appropriate entries in the TC log. The times in the TC log were generated automatically, and some of the other entries are generated by scripts and other autonomous processes. Other entries are generated manually, and so the format varies, and in some cases there are typographical errors. This renders some sections of the TC log difficult to parse with an automated script. Manual inspection is required.

Also produced by the test conductors was a spread sheet known as the Time-lines, with (manually generated) local times of starting and stopping each test, and what the disposition of the test was (executed, aborted, skipped, etc.).

A third source of information is the (manually generated) Project/Telescope Scientist's log (PTS log). This contains comments on a test-by-test basis in most cases on what was happening, cursory results, failures, etc., and has proven invaluable.

A detailed manual inspection of the entire Test Conductor log was conducted, comparing it with the Time-lines, the PTS log, and the "DRAFT as-run CMDB" (calibration measurement data base). A sequential list of tests with approximate start and stop times was assembled. In some cases there are disagreements as to what TRW_ID to use for a given test or two tests conducted simultaneously (e.g. focal plane background/setup tests and BND beam maps), and so a modicum of intelligence is required for this task.

The tables themselves are available from the MST web page,

`http://hea-www.harvard.edu/MST/simul/simul-home.pl`

under "Facility Data."

D.2.2 Actuator Encoder Readouts

The readouts of the pitch and yaw actuator readouts were (sometimes) recorded in one of three sources:

- The `hrmapos` logs, generated by the HACS software and sent to the archive via the DLRS;
- The Test Conductor Logs, in messages sent from Kodak to the test conductor containing (manually entered) actuator values; and
- The Eastman Kodak Company logs (EKC logs), written in Microsoft Word by EKC personnel, containing (manually entered) times and actuator values.

The `hrmapos` logs are available only when the HACS software was being used to control HRMA pitch and yaw pointing. This time period covers about 20 hours on December 31, 1996 (the beginning of Phase D), and nearly all of Phase 2 of XRCF testing (sub-phases F, G, and H). The contents of these data records include irig times, readouts of all actuators, and intended and actual pitch and yaw. Where these are available, they are used.

Where the `hrmapos` logs are not available, it is often the case that either the TC log or the EKC logs (or both) have entries recording actuator values. Both logs have manually entered actuator values, and are subject to typographical errors (mercifully quite rare). The time tags are also the times the values are recorded, not the time of the maneuver that changed them. Often, but not always, the actuator values are reported during the data-taking phase of the test they apply to, so a large majority of the tests can be associated with actuator values by taking the last set of actuator values prior to the test's end time. An even larger number of tests can be accommodated in this manner by presuming that the clock used in the EKC logs is about 1 minute slow, compared to the TC clock (which was irig-synchronized).

D.3 Initial Actuator Position (IAP)

There was considerable confusion early in Phase D of the XRCF testing about the relative pointing of the x-ray optics (the HRMA) and the optical XRCF Alignment Reference Mirror (the ARM-X). This, and the failure of the aft far pitch actuator, resulted in the issuance of multiple sets of "Initial Actuator Positions," i.e. a table of what the actuator readouts are when the telescope is pointed on-axis. Some of these were known later to be in error, and are superseded by later IAPs. In the case of the Phase 1 IAP5, it was eventually decided that the ARM-X alignment, IAP4, was closer to the truth than IAP5 (generated from x-ray data). IAP5 was used for most of Phase D, so there is a systematic error in pointing by one arcminute in yaw for most of the Phase D tests.

The IAP table given in Table D.1 is based on the one in Matthews (1997), updated and completed based on information mostly from the EKC logs. We have added entries for phase 2 (the bottom half of the table), phase 1C (first entry), and several IAP7c entries not in Matthews' table. The columns are:

- IAP: the identifier of the inital actuator position system. Note that names are re-used in phase 2.
- "true start": for those IAPs believed to be close to the truth, this is the starting IRIG time when they are effective.
- "start": the IRIG time when the IAP was established.
- "el" and "az": for phase 1D IAPs, this is the offset between the IAP and IAP4, which we ultimately chose as the truth.
- a3–a8: actuator readouts at pitch = yaw = 0.
- "comments": comments on alignment standard, etc.

D.4 Actuator Failures

Phase 1, sub-phase C of the testing (December 20–24, 1996) was conducted with the HRMA blocked in place, aligned optically to the ARM-X, as the pitch and yaw actuators were not yet ready for use. We have presumed that these pitches and yaws are zero, though x-ray evidence for this is lacking (or has not been examined in detail).

IAP	true start	start	el	az	a3	a4	a5	a6	a7	a8	comments
C	355/03:00:00	355/03:00:00	0	0							Dummy for phase C
IAP		364/18:00:00	0	0	105511	−1299	1732	−77341	−195144	−194671	original pre−vacuum IAP
IAP2		001/05:00:00	−1.07	−1.33	105511	−1299	1732	−209714	−327517	−302289	Initial failure IAP (calculated on encoder counts)
IAP3		001/12:15:00	−1.47	−0.51	108177	−4499	4919	−199949	−327517	−302289	X−ray beam scans (−0.4 El, 0.918 Az wrt IAP2)
IAP4	364/18:00:00	002/18:22:00	0.00	0.00	105513	−9000	4388	−235959	−326740	−302863	Vacuum alignment to ARM−X Autocol. from Source End
IAP5		005/16:11:00	0.00	−1.00	105513	−5098	503	−235959	−326740	−302863	−1 min Az bias from IAP 4 based on X−ray data
IAP6	026/08:08:00	026/08:08:00	0.00	−1.00	0	0	0	0	0	0	Same as IAP5 just encoders were zeroed with rack shut off
7−air		027/20:00:00			105512	−7124	2621	−690294	0	0	Aligned ARM−X air, GSE at 70 degrees F
IAP7		028/15:01:00			109977	−6410	1907	−674729	0	0	Aligned ARM−X, GSE at 67 degrees F
IAP7a		029/16:52:00			109977	−9007	4504	−674729	0	0	Aligned ARM−X, GSE @ 55 degrees F (47 arcsec in yaw from IAP7a)
IAP7b		029/20:32:00			108450	−9007	4504	−680054	0	0	Aligned ARM−X, GSE @ 54 degrees F (7 arcsec in pitch from IAP7a)
IAP7c1		031/19:34:00			106688	−9006	4500	−686918	0	0	+32 arcsec pitch wrt ARM−X (filled in from EKC log 031/19:34)
IAP7c2	027/20:00:00	031/21:07:00			110914	−9006	4500	−672068	0	0	ref: Texter via O'Dell 9 Jun 1998 e−mail (filled in from TC log 031/21:29:25)
IAP8	040/09:30:00	040/09:30:00			0	0	0	0	0	0	Aligned ARM−X, GSE @ 52.5 (encoders not zero at home)
IAP1	051/17:38:00	051/17:38:00			−52184	253479	95507	−49082	−286211	−286111	YPP=−.4411" ZPP=−.2285"
IAP2	059/09:14:00	059/09:14:00									first mention of IAP2
IAP3	059/17:38:00	059/17:38:00									see EKC log this date
IAP4	064/20:38:00	064/20:38:00									see EKC log this date
IAP5	079/06:53:00	079/06:53:00			−50569	253282	95862	−47306	−276427	−276278	see EKC worksheet
IAP6	100/08:00:00	100/08:00:00									see EKC log this date
IAP5	100/09:30:00	100/09:30:00			−50569	253282	95862	−47306	−276427	−276278	see EKC log this date (return to IAP5)
IAP7	109/14:30:00	109/14:30:00			−48718	253282	95901	−42699	−278746	−278611	see EKC log this date

Table D.1: IAP table for both phases.

The first day of phase D, at about 22:57 GMT on December 31, 1996, the aft far pitch actuator (actuator 8) got stuck in a non-zero pitch position. After much consultation, the decision was made to keep the aft near pitch actuator matched with the far one, and (after finishing a set of pitch alignment tests then in progress) shorten the forward pitch actuator (number 6) to align to the beam. This resulted in the entire telescope being $\sim$ 500 microns lower than the design position. Phase D was then conducted using pitch fixed at zero, though many non-zero yaw tests were performed. The zero-reference for the pitch was apparently taken with respect to the ARM-X.

For a period of about 3–4 days following the actuator failure, no data are available about the pointing of the mirror. We have therefore had no choice but to adopt the CMDB pitches and yaws as "as-run" values, and corrected them to "true" values using the azimuth and elevation offsets from IAP4 from the IAP table. This presumes that EKC was successful in executing the planned CMDB maneuvers.

A similar difficulty was encountered in phase E, but the workaround consisted of fixing both aft pitch actuators, and using the forward pitch actuator to pitch the HRMA, rotating not about the node (as designed) but about the stuck actuators. This results in vertical motion of the node, and so the image moves vertically by about 323.9 microns per arcminute of pitch. In most cases this motion was not recorded in the FOA tables of the HXDS equipment, and so the `calcstage4` script cannot correctly compute the Z distance from the aperture center to the beam. Pitch corrections have been applied to the data when appropriate (notably wing scans).

It appears to this author [RJE] that the pitch and yaw actuators and the HACS software worked as designed throughout phase 2 of the XRCF testing. Data from the `hrmapos` log is available for all but a few of the phase 2 tests, and we have used them almost exclusively for phase 2.

D.5 Data Processing

We have constructed a script that parses the EKC logs (turned into ASCII files by Terry Gaetz, saving them as text from Microsoft Word, running under Citrix, a Windows emulator) and returns an RDB table containing times and actuator values. A similar script parses the actuator values out of the TC log. These are then merged with the `hrmapos` log and the table of TRW_ID start & stop times, augmented with `HRMA_pitch` and `HRMA_yaw` fields out of the DRAFT as-run CMDB (the version dated 26 January 1999). The results are sorted on time, using the end time for each TRW_ID.

Given actuator values, it is possible to compute pitch and yaw, using a recipe and formulae from Gary Matthews' excellent document "Encoder Values, IAP, and What It Means To Me" [Matthews (1997)]. This document describes the geometry, the operation of the actuator system with a stuck actuator, and how to compute HRMA pointing given actuator readout values.

The output of these scripts is a table of pitch and yaw as a function of time and TRW_ID, sometimes with multiple sources and sometimes with no source at all (other than the CMDB). As-run pitches and yaws can then be compared to as-ordered pitches and yaws from the CMDB, and discrepancies noted and investigated. In a few dozen cases, there are obvious typographical errors (extra commas, missing or duplicated digits, etc.), or time errors (caused in general by reporting the values after the following test had begun). These were corrected, by a script which runs on the fly during the log file parsing and table generation process. The remaining tests which differ by more than a few hundredths of an arcminute are listed in §D.6, with conjectures about the cause of the discrepancy.

Another script was then developed that took the above merged log, selected one source for each test, recorded the best-available values for the pitch and yaw actuators, and then used two IAP

bases to compute the pitch and yaw. These then represent the "as-run" values (what the operators on the floor at the time of the test would have seen), and the "true" values (what we believe with benefit of hindsight were the pointings relative to the facility optical axis). Also included for reference were the "planned" values from the CMDB.

Work is in progress to analyze other x-ray data to obtain better values for the offsets between the mirror axis and the facility optical axis. Data which bear on the question include some of the line shape function tests (slit scans of the focused image) and off-axis images, whose detailed structure provides much information on the alignment and pointing of each shell of the telescope.

D.6 Discrepant Tests

There were a few tests where the final results show a discrepancy of more than 0.04 arcminutes between the CMDB planned pitch and/or yaw, and the as-run values. These are listed below for reference, with my opinions [RJE] about the cause of the discrepancy.

D.6.1 Phase 1

- Tests D-IXH-PI-3.00[67][ab] were changed on the floor from $(p, y) = (0, 0)$ to yaws of ± 1 arcminute.
- Tests D-LXH-3D-20.00[89] requested yaw of 1 arcmin, and seem to have $-1'$ with respect to the then-current IAP5. Because of the $1'$ yaw difference between IAP5 and IAP4 (believed to be correct), this gives actual yaws of $-2'$ This seems to be a mistake on the part of EKC.
- Test D-LXH-3D-30.001 requested yaw of $+1'$ and was run with zero with respect to the then-current IAP5. As above, this results in actual yaw of $-1'$
- Tests E-IXH-PI-52.00[1234] were off-axis single-shell hsi images. The planned pointing was $(17.6777, 17.6777)$, but the pitch actuator pegged when it reached $16.437'$ with respect to IAP8. The tests were run in this position.
- IAP7 was known to be "off" by 15 arcsec in yaw, but was used anyway. This results in a series of tests from irig time 028/21:11 to 029/10:40 with as-run yaw 0.25 arcmin larger than the planned yaw. These tests include carbon EIPS tests E-IXH-PI-13.001, E-IXH-SF-12.001, the E-IXF-PW-2 series, and the E-IXS-MC-16 series.
- There appears to be a sign error in reporting actuator A3 at 031/03:58. If something is done with the axial position of the HRMA, this should be investigated. Tests E-IXH-SF-15.01[1-4] and E-IXH-PI-6.003 are the only ones impacted.

D.6.2 Phase 2

- IAP1 was a bit off, but this was known at the time, so the as-run pitch was $0.280'$ too high, and the as-run yaw is $0.055'$ too high. But the actuals are right on.
- There is an error or bug in the `hrmapos` data for test F-I2C-EA-11.002a, at irig time 062/10:40. This causes the as-run pitch to be erroneously reported as zero. The actual pitch is correct, however.

- On day 083 a change was made on the floor with the concurrence of the PTS and TC. G-IHS-EA tests with CMDB pitches of ±2.9, 2.95, or 3.0 arcmin were run with the same sign, but with the absolute value of the pitch equal to 2.68′
- On day 088 the IRIG clock problem makes synchronizing the `hrmapos` data with the test list very hard. The correct moves were (mostly) done in the correct order, so application of a time offset yields the plausible result that everything was done as planned.
- On day 093 there were changes made in tests G-IHS-EA-60.032 and 036. The CMDB yaw of 14.8′ was changed to 13.8′
- On days 094 through 096 there were occasional changes of sign in pitch or yaw, attributable to EKC operator error (in my opinion). The tests in question are G-IHI-EA-3.109, 3.067, 4.016, 3.075, and 3.083.
- Nine tests in the 99 series in phases G and H have erroneous pitch and/or yaw values in the CMDB. This is not surprising since 99-series tests are created on the floor and the CMDB is reconstructed after the fact.
- The test conductor ordered various non-CMDB pitches and yaws on day 112, in tests H-IAS-PI-7.010, 015, 011, 016, 002, 005, and H-HAS-PI-1.012.

D.7 The Pitch Problem and its Effect on Wing Scan Data

D.7.1 History of the Pitch Problem

For the XRCF data, the pinhole positions relative to the focus were calculated using `calcstage4`. In the `calcstage4` calculation the pinhole location relative to the focus is determined by using the stage logs and the contemporaneous focus position appropriate to the shell(s) in use is determined from the FOA tables. The distance (X, Y, Z) of the pinhole from the focus is evaluated by differencing the two sets of values:

$$X = X_{pinhole} - X_{focus} \tag{D.1}$$
$$Y = Y_{pinhole} - Y_{focus} \tag{D.2}$$
$$Z = Z_{pinhole} - Z_{focus} \tag{D.3}$$

Note that currently the only information that `calcstage4` has about the focus position is that found in the FOA tables; if the FOA table is incorrect about where the focus happens to be, then `calcstage4` will get the wrong answer.

Because an aft vertical actuator was stuck during phase 1E, pitch motions during phase 1E were carried out using only the forward vertical actuator. This resulted in a pitch motion about a point other than the HRMA node, so any pitch motions caused the HRMA node (and hence, the finite conjugate focal point) to shift vertically. These vertical shifts in focus location can be large ($\lesssim 1$ mm) compared to the size of the smallest pinhole used in the wing scans (1 mm diameter). It is therefore important to understand the relation between HRMA pitch moves and the FOA tables.

In order to determine how the experiment was really performed, the XRCF 2nd Floor Shift Reports, the Project Science/Telescope Scientist logs, and the EKC shift reports were examined. The first wing scan experiment in Phase 1E was a wing scan of quadrant 6B with an EIPS C-Kα source and with the HRMA pitched by $-1.88'$. A set of Y-scans was performed (E-IXF-PW-2.001–5, day 028/029) followed by a set of Z-scans (E-IXF-PW-2.010–13, day 029). During the the first

sequence of 1 mm pinhole Y-scan measurements (E-IXF-PW-2.001) it was discovered that the scan was approximately 500 μm too low. It was realized that this was because the pinhole positions were calculated relative to the FOA values for the focus position and that the FOA value was now offset from the real focus of the pitched HRMA. In order to compensate for this, the FOA table was adjusted by 504 μm in Z for the rest of the quadrant 6B C-Kα wing scans (4 mm, 10 mm, 20 mm, 35 mm Y-scans, 1 mm, 4 mm, 10 mm, 20 mm Z-scans) based on a beam centering with the 70 μm pinhole. Following the C-Kα wing scans, the FOA values were reset back to the nominal values. The actual pitch correction should have been 609 μm in Z, so the FOA table correction was about 105 μm shy of the appropriate correction. Consequently, the `calcstage4` values for the distance of the pinhole from the focus were nearly correct for these pinholes, but additional $\Delta Z_{focus} = +105$ μm pitch correction needs to be applied. (The additional pitch correction we actually applied was $\Delta Z_{focus} = +94$ μm; the effect of the remaining 11 μm discrepency is negligible for these wing scan measurements.)

It was initially suggested that a similar FOA adjustment be made for all the subsequent HRMA pitch moves. It was decided instead to aim for an automated approach whereby the pitch correction would be applied to the pinhole locations during the CMDB processing; these fixes were incorporated into the software during shift A, 1997 Feb 2 (day 033). Note that for the period between the end of the 6B C-Kα wing scans on day 029 and CMDB fixes of day 033, any pitch corrections would have been entered manually into the pinhole locations files.

Node Shift in HRMA Pitch Moves

Because the HRMA pitch motions were performed with the aft vertical actuators fixed, the actual pitch motion was a rotation about the line defined by the aft vertical actuator locations. This produced a vertical shift of the HRMA node which displaced the focal point at the instrument plane.

In comparing the raytraces to the XRCF pinhole data, the XRCF Z coordinates relative to the contemporary FOA were corrected for the shift in the focus by subtracting off a pitch correction. To first order, the vertical shift in the node is the product of the sine of the pitch angle change and the axial offset between the fixed actuator station and the node. The axial distance between the node and the actuator is 43 inches (= 1092.2 mm), from which

$$\Delta Z_{node} = -1092.2 \ \sin \Delta\theta_{pitch} \text{ mm} \tag{D.4}$$

where $\Delta\theta_{pitch}$ is the change (in radians) in the HRMA pitch. In the thin lens approximation, the focus moves by

$$\Delta Z_{focus} = \frac{\Delta Z_{node}}{D_{source}} \times (D_{source} + D_{focus}) \tag{D.5}$$

where $D_{source} = 527297$ mm is the distance between the HRMA node and the X-ray source, and $D_{focus} = 10256$ mm is the nominal distance from the HRMA node to the finite conjugate focus. In making the above estimates, the node was assumed to be 18.1 mm aft of CAP "Datum A". Substituting for the various distances, the vertical shift in focus is approximately:

$$\Delta Z_{focus} = -1.1134 \times 10^6 \sin\theta_{pitch} \, \mu\text{m} \tag{D.6}$$

or,

$$\frac{\Delta Z_{focus}}{\Delta\theta_{pitch}} \simeq -323.9 \ \mu\text{m/arcmin}. \tag{D.7}$$

Pitch Corrections Applied

Most of the wing scans with HRMA at nonzero pitch were performed with the FOA table values appropriate to HRMA at zero pitch; the requisite pitch corrections were applied to the requested pinhole locations. `calcstage4` calculates the pinhole location based on the stage logs; the resulting physical location for the pinhole will be calculated correctly. In analyzing the wing scans, the distance of the pinhole center from the current focal point is needed; the `calcstage4` evaluation of the focus position is based on the FOA entry and that is incorrect because of the HRMA node shift (and resultant shift in focus). `calcstage4` reports the difference between the pinhole location and the focus position, so a pitch correction needs to be *subtracted* from the `calcstage4` Z value. Based on equation (Eq. D.6), the pinhole Z value reported by `calcstage4` was corrected by

$$\Delta Z_{corr} = Z - \Delta Z_{focus}. \tag{D.8}$$

An exception was the wing scan for shell 6B for which the FOA was partially compensated for the pitch-induced focus change (§D.7.1); in this case, the Z values were corrected by -94 μm to account for the slight under correction of the FOA adjustment.

D.7.2 Yaw Reference Error

Early in Phase 1D, an attempt was made to determine the HRMA X-ray bore sight by using the variation of effective area as the HRMA was pitched and yawed. At the time, the presence of the coma-free decenter error in the HRMA mirror alignment was not yet known; this error causes the off-axis effective area profiles to be non-symmetric about the optical axis. This led to an initial confusion as to alignment of the mirror bore sight to the facility optical axis; the reference axis for pitch and yaw ended up being offset by about $1'$ in yaw starting at IAP 5 (day 005, 16:11) through the end of phase 1D. Consequently, the actual yaws ended up being offset by $1'$ from the requested values, and because of this, some yaw values in Table 14.3 differ from the requested CMDB values. This does not directly affect the XRCF data reduction; the yaws were off, but the FOA was determined based on the contemporary yaw zero reference. However, this offset does need to be included in the comparison raytraces.