MEMO

December 11, 1997

TO: Mark Skinner
FROM: John Catch

SUBJECT: **FAM Positional Accuracy Investigation**

BACKGROUND:

For the testing recently completed at XRCF, issues were raised regarding FAM stated position and corresponding positions as reported by ACIS 2C and HRC. These reported deviations were exclusively noted during "true" dithering moves.

Hank Donnelly at SAO reported variations between the FAM and HRC data of about 0.6% RMS on tests using the "SERPINE" dither file. This relates to an ~1 micron position adjustment for a 22 micron FAM step. This is likely within the resolution of the FAM and therefore not a problem. He also reports that during spatial linearity tests he had no problems at all. The spatial linearity tests were not true dithering, in that they used the fast speed and hunt move modes.

For ACIS 2C, John Nousek & Eugene Moskalenko of Penn State reported that for a pure horizontal move in the "Y" axis an ~3% difference was noted between the FAM stated position and an equivalent ACIS CCD pixel position. Dither file "SUBPIX2.FAM" was used which had 27 micron moves every 50 seconds over an ~430 micron field and return. Deviations for both directions were the same. It should be noted that FAM resolution is specified at 2 microns. Typically the performance was closer to 1 micron which is still ~3.5% uncertainty in a 27 micron move.

Steve Murray had two comments regarding FAM performance. IRIG time as reported between FAM and CTUE varied from 1-10 seconds. However, it should be noted that during the testing in question, MSFC's IRIG clock system malfunctioned. This is probably not a FAM problem but a reflection of the situation at that time. The other issue was a reported increase of ~20 microns (FWHM) of telescope/instrument point spread for dithered data vs. normal undithered data. This occurred during "DITHER1.FAM or DITHER2.FAM" tests.

FAM CONSTRUCTION:

The FAM is a large weldment that has provisions for mounting instruments on the integral LASSZ carrier. It has three feet each fitted with actuators to provide movement in the X, Y, Z directions and also limited rotation about each axis. In addition, the LASSZ may move in a pseudo Z direction.

As viewed from the rear; the left foot is “A”, the right foot is “B”, and the center foot is “C”. Each actuator assembly is connected through a gimbal or rotary joint to the FAM weldment. The “A” foot has drives/encoders for motion in the X, Y, & Z directions. The “B” foot has drives/encoders for motion in the X, & Z directions. The “C” foot has a drive/encoder for only the “Z” direction. LASSZ has its own separate drive/encoder. Each actuator includes a set of aligning rails, motor/lead screw assembly, and optical encoder. Where a foot does not have an actuator for a particular direction, there are still alignment rails for guidance in all directions.

The FAM was manufactured to BALL specification by New England Affiliated Technologies (NEAT). The actuator drives use stepper motors, precision ground rails, and lead ball/screw assemblies. The optical encoders use a sophisticated IR electronics package and are manufactured by Renishaw PLC of England.

Overall control of the FAM is performed using a BALL developed LabVIEW software program. LabVIEW communicates via serial link to the required NEAT actuator electronics to send commands and receive positional data.

FAM OPERATION:

A move is accomplished through LabVIEW by issuing a command to the NEAT motor controllers for a set of positional changes. This command is calculated using a system of equations for the required location & rotation of the FAM and instrument under test (See SER by M. Duncan 1/7/97). The developed coordinates for each directional move are then reduced to equivalent motor steps based on move distance, and “motor steps/unit distance”. Motor steps/unit distance is a constant, and was developed from the hardware i.e. gear ratio, and lead screw pitch. This command is then sent via serial link to the NEAT controller for execution. The optical encoders are used to report back via the link the actual obtained position.

Two basic FAM moves are allowed; a “go to position” and “dithering”. When moving to a new “go to position”, LabVIEW has two steps; first a fast move to near position, and then a series of slower hunting moves to within the position deviation limit. In “dithering”, only a slow move without hunting is allowed. Consequently, position deviation for dithering may be considerably greater than for a go to position move. No negative comments were received relative to FAM position while performing “go to position” moves.

ITEMS of INVESTIGATION:

In order to ascertain the source of FAM/ACIS deviations, we undertook an analytical review of the existing materials relative to FAM design and performance. The following topics were reviewed.

1. **Confirm data reduction & 3% non-linearity.** In order to better understand the reported deviations we obtained, reduced, and plotted the original ACIS data. The data had been generated while using the SUBPIX2.FAM dither file. This file generated pure dithering moves (no Hi-Lo speed, or hunting modes) of a nominal 27 microns in the Y axis direction. It should be noted that this value was chosen since previous files with 5 micron moves were very inconsistent. We can concur that when FAM vs. ACIS position data is plotted, a less than perfect 1:1 slope is presented. This slope is about 0.968 * FAM = ACIS. The plot as shown in figure 1 is very nearly linear with no apparent discontinuities (suggesting no affects from stiction, hysteresis, etc.). Points in the forward transverse direction and the return align themselves appropriately. Point deviations from this calculated slope were; -7.29 to +2.23% or -3.9 to +3.4 microns. Figure 2 is a plot of each discreet step for both FAM and ACIS. The distribution of points shows a varying spread (vertical gap) between FAM and ACIS for the same point. Also noted was that the spread would go from positive to negative in some cases by up to 10 microns in a single nominal 27 micron move.
2. **Confirm correct dither file.** The dither file (SUBPIX2.FAM) was compared between FAM and ACIS data and it was noted that the position, and timing were correctly reported.
3. **Review of test log books for anomalies during tests in questions.** While the author was an operator during most of the testing at XRCF, for the dither file in question (SUBPIX2.FAM) I was not present. However, a review of the test log showed nothing during this test out of the ordinary. During other dithering operations other than some "stalls", nothing was noted. A stall is reported by LabVIEW when the encoder counts do not follow the commanded motor steps. Stalling was somewhat common for very small moves, likely due to stiction or hysteresis. Since the recorded encoder positions are used, data during stalls is still valid.
4. **Review timing of various dither files & move timing.** Since the FAM takes a finite amount of time to reach a desired location, the timing of the dither files must be such that the FAM has reached stabilization at the desired point before data is taken. It is estimated that this time allowance needs to be about 2-4 seconds for computation & communication plus the necessary time to physically move the desired distance. The FAM will move at about 100 microns per second (Y axis) while in true dithering mode. Consequently for a dither move of 27 microns, an allotment of 5 seconds is required. The dither files reviewed had timing greater than 5 seconds and some had multiple redundant points.

It should be noted that redundant points do not guarantee that the FAM is stationary, as each command is independent. Consequently, the FAM will attempt a move even if it is at the given point. A hysteresis affect was noted on some occasions with redundant moves. After the first few dither files were run at XRCF, the files were modified to compensate for the above timing requirements. Timing then does not appear to have created the noted deviations.

5. **Investigate reported FAM move vs. encoder counts.** Data was reviewed from the LAN script which recorded among other things encoder counts and the actual reported FAM position. A number of cases were checked including the first 17 steps of the dither move, all during the SUBPIX2.FAM dither file. Agreement between actual reported position and actual encoder counts was +/-2.75% or better. Typically the deviation was better than +/-1%. No systematic bias or trend was noted. These deviations are most likely due to encoder resolution, encoder stability, and precision of the matrix geometric mathematics. The encoders provide an integer output translating to precisely 0.5 microns/count. Consequently, for a 27 micron move this translates to a +/-1.85% resolution. Every time the FAM moves, all feet are reset. This generated a 2 count variation in the X axis and a one count variation in Z. Combined with a 0.5 arc second change in Theta X and a 0.02 arc second change in Theta Z, these factors contribute to numerical noise and round off imprecision. Internally then, LabVIEW and the encoders were consistent to each other.
6. **Investigate actual vs. commanded position.** Typically there will be some difference between the FAM commanded position and the actually obtained position (from the encoders). Concern was raised that ACIS had incorrectly applied the commanded position data. My review showed that the ACIS data was the correct encoder obtained position.
7. **Investigate actual LAN data vs. verbal ACIS data.** It was determined that during SUBPIX2.FAM dithering, ACIS had used verbal data transfer from the LabVIEW computer for recording FAM position in its data base. A comparison with the actual UNIX LAN data shows no significant deviation from the actually reported FAM positions.
8. **Investigate LabVIEW code for inconsistencies (precision, logic errors, etc.).** The LabVIEW program code was reviewed for logic errors, numeric precision, round off, and truncation errors. No obvious flaws were detected that could generate the somewhat random deviations as reported.
9. **Investigate 0.5 micron/step as used by LabVIEW.** Because it is somewhat unusual to use a single digit in such a precise measurement scheme; we reviewed this value with Renishaw. Due to the design of the optics and circuitry, the value is precisely 0.5 microns/step and not some higher digit calibrated number. LabVIEW correctly uses 0.5 microns/step in its calculations.
10. **Investigate orthogonality affect.** The SER of 1/7/97 by M. Duncan details the mathematics used in the LabVIEW program. The logic was not re-analyzed since in general precise and correct FAM movements were obtained. Because of the complexity of these calculations, the LabVIEW code was reviewed for the necessary

mathematical precision. No errors were detected. It was noted that for a 3% error in the Y axis, a cosine alignment error of ~14 degrees would be required. This amount would have easily been noted and corrected during setup at XRCF.

11. **Investigate setup procedure at XRCF.** During setup at XRCF a closely followed written procedure was used to assure good alignment of the FAM to the test bed. Additionally, an optic setup technique was used for each of the instruments (ACIS, HRC). These tests used a telescope beam. Unfortunately, while these tests likely assured specified accuracy, they in themselves were not of high enough precision to detect the reported deviations. TRW personnel who actually did the setup did not notice anything that would suggest an accuracy of movement problem.
12. **Investigate electrical noise.** The potential for EMI or RF noise to affect the measuring system was not rigorously tested before or during operation of the FAM. However, this type of interference tends to be erratic and significant in magnitude. Such interference would likely have been noticed during the hundreds of tests at XRCF. Since the FAM electronics was in an environment with other sensitive equipment that had no problems, it is unlikely that there was a noise problem.
13. **Review NEAT / FAM test report. Y vs. Z.** SER dated 6/10/96 by M. Duncan details the results of performance testing of the FAM at NEAT prior to receipt by BALL. It was noted that the performance of the FAM met or exceeded the original performance specification with only some questionable attributes of repeatability. Unfortunately, the laser interferometer setup for X & Y axis was not rigorous to fully rule out any potential problems in this area However, in the Z direction the interferometer setup was rigorous. During this test the position encoders agreed to 1.5 microns or better. This suggests that the encoders do have the ability to meet their stated (by Renishaw) 0.5 micron resolution specification. It was also noted during the acceptance test that after the required dis- and re-assembly with different lubricant, etc. performance could possibly change, and that the simulated loads were less and different from the actual loads.
14. **Investigate natural encoder accuracy - SDE.** The reported deviations between FAM and ACIS are ~3% suggesting significant error. Consequently we reviewed the inherent accuracy of the Renishaw encoders. Properly installed, the encoder readhead to reference mark should be within 0.5 micron with a linearity of better than 3 microns per meter. Testing at NEAT in the Z axis substantiated this performance. Since, the X & Y axis testing was somewhat inconclusive, an analytical review of the encoders was undertaken. The attached articles “New Approach to Encoder Design…” and “Renishaw Encoder Systems Technical Support Notes” detail the basic operational principals and potential errors. Because of the small movements during the dithering files, we reviewed the material for an analysis of sub-divisional error (SDE). Each physical “step” is broken down using optics and electronics into 16 sub-divisional steps. It was determined that unless gross assembly practices were used, the encoders were by themselves not the source of error. The testing at NEAT suggested proper installation was used.

15. **Investigate NEAT mounting precision.** While the encoders appear to be accurate we also reviewed their mounting by NEAT. Attached is a drawing from NEAT showing location and orientation details. Mounting appears to follow Renishaw requirements.
16. **Investigate hysteresis error.** Since position is determined by the frictionless encoder system, mechanical hysteresis of the actuator in unimportant. However, the LabVIEW program does have a compensation for mechanical hysteresis. During early setup testing at XRCF this feature was used. This initial testing showed that this feature was not necessary, consequently during the actual tests no hysteresis allowance was used.
17. **Investigate stiction error.** As in hysteresis, stiction is only a factor with the mechanical actuator not the encoder system. Consequently, it plays no part in the accuracy of the position measurement.
18. **Investigate encoder error with NEAT.** Mark Longmuir at NEAT was contacted for assistance in evaluating the FAM position measurement system. Mark Longmuir had been involved from the early stages of FAM design and therefore quite familiar with its design and operation. Researching his records he found that an unofficial calibration of FAM Y movement was performed. For a 51.914mm move per a Laser Interferometer, the FAM moved 104138 encoder counts or 52.069mm (0.5 micron/count). This is a deviation of +155 microns or +0.299%. Assuming that this is a linear error, over a 27 micron move (as in the dither test) this is only a 0.08 micron error which is below the encoder's resolution. One subtle area of actuator design that could lead to error is what is known as Abbe' error. Per the attached technical article, Abbe' error is not an alignment (cosine) problem, but is caused from the alignment rails not being perfectly straight. Since these rails are ground using a circular wheel they may take on a less than infinite radius. This radius when applied over a significant offset distance can create substantial error. The NEAT specification for the rails is 80 arc seconds or better straightness. Generally the rails are much better than this (<10 arc seconds). With a FAM offset length of about 39", an angle of only 5 arc seconds would generate a 24 micron error. Typically, Abbe' errors are very repeatable and cyclical. Over longer moves this effect may only result in a 1-2 micron change. There may also be other subtle geometric situations that could lead to error such as rail parallelism between feet, non level mounting, FAM flexure under load, etc.
19. **Speed & settling time.** Initial design concerns were voiced regarding the FAM's required time to move and stabilize. During the acceptance testing performed at NEAT (SER dated 6/10/96 by M. Duncan) this issue was reviewed. Because of the very slow speeds involved, it was found that no discernible stability issue could be detected.
20. **Investigate IRIG time problem.** During the dither test in question MSFC had a problem with the IRIG time. This affected all test parties, but perhaps to somewhat different degrees. This is because each computer had its own time generator. Since IRIG time for the FAM only impacted the time stamping of LAN data and not

operation, no performance degradation was anticipated. The LabVIEW UNIX computer had PCB hardware that was synchronized by the MSFC IRIG generator.

21. **Investigate the effect of loading.** The actual loads imposed on the FAM at XRCF were considerably higher than the original design parameters. Undoubtedly some small flexure took place that was greater than originally anticipated. However, because of the low dynamics of the FAM movement and the axis of concern (Y), it is difficult to imagine that affects were created that would have caused the measurement deviations. No rigorous analysis was performed to review this situation.
22. **Cocking on move initialization.** Because of the large mass of the FAM assembly, one could assume that some initial stiction may have been present on move initialization. In addition this stiction could have been different at each of the three feet positions. If this were the case, cocking or an initial misalignment could have been generated. Similar to Abbe' error, this action potentially could have created an error. However, since the data plot appears continuous and nearly linear it doesn't appear that cocking occurred.

SUMMARY:

An analytical review of available materials regarding FAM performance has been completed. Discussions have been held with the manufacturers of the equipment as well as with other involved personnel. In addition a review of the controlling LabVIEW software has also been performed. While certain issues have been raised, no particular item or items have been uncovered that would have definitely created the reported deviations.

Issues of note were;

Ref. Par. 1: Even though in general the FAM vs. ACIS data plotted linear with no inconsistencies; plotted data of individual points (Fig. 2) for FAM and ACIS did show inconstancies. Data frequently toggled between + and - deviations from point to point. Over the dither moves of 27 microns, the reported ACIS position would not follow the FAM by as much as 10 microns. Consequently adjusting ACIS pixel size by a constant offset would not resolve this issue.

Ref. Par. 5: Although the agreement between the reported position and encoder counts appears to be less precise than one would anticipate, no bias or trend was noted. Even the worse noted error was only 0.67 microns. This then suggests that there are no systematic errors within the FAM orthogonal matrix mathematics that likely would have caused the deviation to ACIS coordinates.

Ref. Par. 18: An unofficial calibration at NEAT of the loaded FAM in the Y axis revealed an error of only 0.299% or 155 microns in a 52mm move. While not conclusive, this suggests that the FAM accuracy was very good and much better than 3%.

Ref. Par. 18 & 22: There may be subtle geometric reasons which when taken in whole could give way to substantial deviations.

Ref. Attached FAX of 9/29/97 from Eugene Moskalenko of Penn State; this is the reduced data of the verbally recorded positions for the FAM Y and ACIS X & Y. Both the event mode and simulated integration mode are listed. I am told that the sim. int. mode is the more accurate of the two. However, there are only minor differences between the two. Noted was that the FAM Y is to correlate to the ACIS X axis in reverse orientation (+Y to -X, etc.). It was also noted that of the typical 250-300 total events at a given point only some 70-75% of the events occur at grade 0, with a distribution of grades (2 to 14% of grade 0 events) from that point on. It was commented that moves in the FAM Z axis show a similar deviation to moves in the discussed FAM Y axis. This is curious since at the NEAT acceptance test, the FAM Z axis calibrated near perfectly with the laser interferometer (see Par. 13.). The issue of thermal stability of the ACIS CCD was apparently discussed by others and deemed to be a non-factor.

SUGGESTED COURSE OF ACTION:

Because of the inconclusive nature of this report, likely a more aggressive approach is required. A full scale test at XRCF of the loaded FAM with a calibrated laser interferometer may ultimately be the only recourse. Such a test could likely determine the source(s) for such deviations and possibly quantify deviations so that they could be used in further analysis of ACIS and HRC data.

Even a full scale test is not without its uncertainties. Items such as lubricant, foreign material, hardware wear, etc. could have influenced a particular test or a retest. Such uncertainties may lead to a test that is still less than fully conclusive.

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