Interoffice Correspondence

TRW Space & Electronics Group

Subject:	Date:	From:
Response to Action Item SIMΔCDA-038	February 4, 1997 AXAF.97.220.003	D. L. Cheshire DLC
To:	cc:	Location/Phone:
Rich Rifelli	Distribution	R9/1857 Ext 46355 dave.cheshire@trw.com

References:

1. Ball SER S97-2874-MEC-193, "Focus Drive Mechanism Hysteresis", T. Yarnell, 28 January 1997.

2. SIM SDRL SE31 (IN0071-203), Rev. C, "System Error Budget & Analyses, AXAF-I Science Instrument Module (SIM)", 13 November 1996.

3. SIM SDRL SE32 (IN0071-204), Rev. C, "AXAF System Performance Predictions, AXAF-I Science Instrument Module (SIM)", 13 November 1996.

4. "AXAF-I HRMA ACIS Focus Study: Quadrant Shutters vs. Focus Frames", J. P. Hughes, D. A. Schwartz, J. Arenberg, and M. Joy, 10 February 1993.

This memo documents the response to SIM ΔCDA action item SIMΔCDA-038. Note that four (4) action items, which were submitted separately by different authors, have been combined into this single action item. The comments, requested actions, and responses to the individual action items are given below.

In support of this action item, T. Yarnell (Ball) had an action to provide R. Iwens (TRW) with additional data, which he has done (Reference 1). TRW SE&I had the action to describe how, through calibration and/or operational constraints, the focus repeatability requirement can be met, even in the worst case. Error budgets were to be reviewed, as appropriate.

Comments, Action Requested, and Response:

1. Initiator: Ralph Iwens (TRW), Ph: (310) 812-2249

Comment:
Due to hysteresis in the focus mechanism of the SIM, positioning and repeatability requirements of ±0.5 mils cannot be met under worst case conditions.

Action Requested:
TRW SE&I will document how the requirement can be met, even under worst case condition, through imposing operational constraints and/or calibration of the hysteresis.

Response:
The impact of the repeatability requirement being exceeded, and a suggested method for dealing with the out-of-spec condition, are discussed in detail in the current memo - see Detailed Discussion. The focus repeatability (and positioning accuracy) requirements can be met over much of the required focus adjustability range through use of calibration techniques - with the calibration data for the focus mechanism hysteresis obtained from analysis. There will be some remaining error, after calibration, due primarily to uncertainty in the amount of friction in the mechanism - which necessitates use of a predicted error curve for an "average" amount of friction. For focus positions in the vicinity of the Focus Approach Crossover Point (X = -0.277 inch), an operational constraint is also required, because of ambiguity in the focus mechanism "snapover" point due to uncertainty in the amount of friction. The proposed operational constraint, which we recommend for any focus position change, is to always approach a particular focus position from the same direction. (See Detailed Discussion for the rationale for this recommendation.) The direction of approach should be from +X to -X for a focus position between X = +0.4 inch and -0.277 inch, and from -X to +X for a focus position between X = -0.277 inch and -0.4 inch.

2. Initiator: Bart Graham (MSFC), Ph: (205) 544-0499

Comment:
Unclear how to interpret repeatability requirement (±0.0005 inch). Note: The comment as stated in the SIM ΔCDA minutes was "Unclear how to interpret ***stability*** requirement (***±0.005***)". The original comment has been restated as indicated, after conversation with the author.

Action Requested:
Clarify intent & implementation of requirement.

Response:
The issue here is whether the reference point for measuring repeatability should be the commanded position (or perhaps the actual position reached in response to the first commanded move to a given position), or should it be the midpoint of the range of positions reached in response to repeated commands (over time) to return to the same position. Actually, the distinction is to some degree superfluous. Remember that it is the predicted error in focus position, as a function of commanded position, which was shown in the SIM ΔCDA viewgraphs. The predicted error can be factored into the nominal response curve for an ideal mechanism to yield actual position vs. commanded position. The positioning accuracy will therefore be as good as the knowledge of the predicted error. The positioning error could theoretically be zero, if the predicted error used to bias the commanded position were known perfectly.

This procedure reduces absolute (or "offset") error, which affects positioning accuracy. The variation in actual position which remains is the repeatability error. At a minimum,

repeated moves to the same targeted focus position should result in an actual focus position which is always within ±0.0005 inch of the targeted position. This means that two positions could be as much as 0.0010 inch apart (+0.0005 inch and -0.0005 inch, relative to the targeted position) and still satisfy this interpretation of the requirement. A more stringent interpretation would be to require that the difference in the positions reached in any two moves to a given focus position not be greater than 0.0005 inch. I believe the first interpretation is the correct one, but if the operational constraint recommended in this memo is adopted, the requirement will be satisfied with either interpretation.

3. Initiator: Rob Cameron (SAO), Ph: (617) 496-7521

Comment:
In implementing an operational constraint to fix focus mechanism hysteresis effects, the hysteresis must be calibrated in both lifting and lowering directions to identify magnitude of hysteresis and zero point of hysteresis curve. Also, Ball must demonstrate that, after calibration of the hysteresis, the hysteresis curve is known with sufficient accuracy to meet repeatability requirements.

Action Requested: Demonstrate by analysis that hysteresis curve can be calibrated to an accuracy to meet repeatability requirement.

Response:
This action has been assigned to Ball, as per the intent of the action item. Ball needs to demonstrate that the error bars on the hysteresis curves obtained from their model are sufficiently small, so that the methods described in the current memo (and recommended by Ball at the SIM ΔCDA) to ensure that the repeatability requirement can always be met, are valid. Actually, the requested action may have already been answered by Ball. As reported in Reference 1:

"Analysis of the movement has been done for Best, Nominal and Worst cases and the movement hysteresis for each of these cases is understood. The error bars for a given set of assumptions (i.e., best, nominal or worst case) are small, less than 0.0001 inches, except in the areas around the focus approach crossover point (top dead center)."

Possibilities for ground and on-orbit calibration of the hysteresis are also discussed in Reference 1, but neither appears to be promising.

4. Initiator: Armando Martos (TRW), Ph: (310) 813-9582

Comment:
When discussing the actuator lifetime requirement of 10,000 changes, the statement was made that placing an operational constraint to always approach a repositioning movement from the same direction might be considered as two changes.

Action Requested: This action should be combined with the action placed on evaluating the possibilities of reducing hysteresis effects through operational constraints. Specifically, whatever operational constraint is eventually recommended should also be evaluated for its impact on the total stress crossings impacts on the mechanisms.

Response:
The predicted performance capability presented at the ΔCDA was ">30,000" changes (moves to a new focus position), versus the requirement of 10,000 changes. However, if the operational constraint of always approaching a new focus position from the same direction is adopted, more than one movement of the focus mechanism, on the average, will be required per change in focus position. Hence, the required number of focus mechanism movements is increased. (Although just a matter of terminology, it is nevertheless important to keep in mind the distinction between a "change of focus position" and a "focus mechanism movement".) Since most focus position changes will probably involve ping-ponging back and forth between the best focus positions for ACIS and HRC, roughly half of these changes will involve two focus mechanism movements, and the other half, one movement. This is within the design capability of the focus mechanism and will be accounted for in the SIM MQT.

Detailed Discussion:

The SIM requirement for focus repeatability, which is given in Paragraph 3.2.1.2.1.3.1 of the SIM CEI Specification (SY24-4, Rev. C), is ±0.0005 inch. The SIM also has a related requirement for focus positioning accuracy, a.k.a. "focus selection" and "maximum step size". The positioning accuracy requirement, which is given in Paragraph 3.2.1.2.1.3 of the SIM CEI Spec, is that the SIM focus mechanism shall be able to position any point on the active focal plane of either SI so that the X-coordinate of that point is within ±0.0005 inch of the desired axial location. Focus repeatability (which includes the variation in step size) is a contributing factor - in fact, the major contributor - to focus positioning accuracy. (See Sections 3.4 and 3.5 of References 2-3.) Since both the positioning accuracy and repeatability requirements have been given the same allocation (±0.0005 inch), the design value for focus repeatability has to be better than ±0.0005 inch in order to meet the focus positioning accuracy requirement of ±0.0005 inch.

The performance prediction for focus repeatability presented at the SIM ΔCDA (chart SPJ-21) is "< ±0.0003 inch", which is within the requirement of ±0.0005 inch. However, in the discussion of this chart at the review, it was noted that the actual focus positions reached in response to repeated moves to the same focus position could differ by more than 0.0005 inch, which would appear to violate the repeatability requirement.

During on-orbit operation, the response curve of actual (or "true") focus position as a function of commanded position can vary from the ideal curve due to the following two effects (See Reference 1):

1) The force on the Focus Drive Mechanism push-rods changes from compressive to tensile in the upper quarter (-X direction) of the focus range. This can result in a "snapover" on each one of the foot assemblies, which could result in a change in focus position.

2) Due to friction and clearances in the foot assembly pivot bushings, the mechanism focus position changes from the nominal position depending on whether it is lifting or lowering the instruments. The eccentric lever, for each of the three foot assemblies, either rolls up or down within the bushing until it slips. The effect is illustrated in SIM ΔCDA presentation chart RDR-11.

The worst-case result of these two effects is a positional hysteresis that can be greater than the repeatability requirement of ±0.0005 inch. Ball has analyzed the movement hysteresis for best, nominal, and worst cases of the friction, and other contributors, and the movement hysteresis for each of the cases is understood. However, the actual hysteresis of the flight hardware cannot be predicted any better than as being somewhere between these best and worst cases, since the amount of friction will not be known on orbit.

Nevertheless, it is possible to correct for hysteresis effects to the extent that the motion is known. The predicted error can be factored into the nominal response curve for the focus mechanism to yield actual or "true" position vs. commanded position. The predicted error can be quite large, but if the error is known (i.e., calibrated), it can be biased out. The resulting positioning accuracy will be as good as the knowledge of the predicted error used for the correction. Theoretically, the positioning error could be zero, if the predicted error used to bias the commanded position were known perfectly.

Repeatability error is the variation in the actual position reached, in response to repeated commands to move to the same focus position. For a real focus mechanism, there will be uncertainty in the predicted error, which results in positioning error, and variation in the predicted error, which results in repeatability error. For a given amount of friction, the Ball model produces two different curves for the predicted error (which translates into true position) vs. commanded position: one for when the mechanism is moving in the "lifting" direction; and the other, for when it is moving in the "lowering" direction. If a particular focus position is approached from either direction, the actual position reached will be one of two values - corresponding to the different predicted errors obtained from the two curves. However, since the direction of approach will be known, the appropriate predicted error curve can be used to bias the nominal response curve, thus limiting the positioning error to the uncertainty in the predicted error curve used for the correction. This method for meeting the accuracy and repeatability requirements can be categorized as "based on calibration", and would not (in the absence of complications described below) require any operational constraints.

The next issue to address is the accuracy of the predicted error (hysteresis) curves. The primary source of error (uncertainty) in the predicted error curves is lack of knowledge of the amount of on-orbit friction. Since we can't measure the amount of friction on-orbit, nor do we have a practical method for calibrating the hysteresis curves directly, the predicted error will be bounded by the hysteresis curves for minimum and maximum friction.

The hysteresis curves exhibit a more complex behavior in the focus position region where mechanism "snapover" occurs (see Reference 1), since the snapover point can vary, depending on the amount of friction. It is because of this uncertainty in the snapover point that the focus repeatability requirement cannot be met solely through calibration techniques, and operational constraints are required.

Analysis results for the nominal friction case were presented at the SIM ΔCDA in chart RDR-12. An updated version of this chart, which incorporates some improvements to the model, and a more realistic choice for the y-axis origin (zero error), is provided in Reference 1, and included in the current memo as Figure 1. The origin for the plot in SIM ΔCDA chart RDR-12 was based on an "ideal" focus mechanism. In Figure 1, the origin is based on a quasi-realistic focus mechanism, i.e., with as-built clearances, but with no roll-up or roll-down of the eccentric levers (a reasonable approximation at the launch lock position), and no friction. Adding friction to the model displaces the two curves symmetrically from the origin, with the magnitude of the displacement proportional to the amount of friction. Note that in Figure 1, as in the SIM ΔCDA chart, it is the deviation or "delta" from the nominal focus position, i.e., the focus position error, that is plotted versus the nominal (commanded) focus position.

Two trajectories are shown in Figure 1: one, for the mechanism moving in the -X direction ("lifting"); and the other, for the mechanism moving in the +X direction ("lowering"). Over most of the focus range, the predicted error is within the requirement of ±0.0005 inch. For this portion of the focus position range, for nominal friction, biasing the nominal focus mechanism response curve to take out the predicted error would probably be considered superfluous. However, for focus positions between X = -0.2 inch and X = -0.4 inch, the predicted error increases dramatically due to "snapover" of the mechanism. However, the calibration technique described above would still be valid for this focus range, if the predicted error were known well enough. Unfortunately, the error bars on the predicted error curves are larger near the snapover point. Even worse, the snapover point itself is uncertain, since it is a function of the amount of friction present - which will not be known on orbit. When approaching a focus position in this region, snapover may or may not occur, depending on the direction of approach and the amount of friction. Consequently, the uncertainty in the actual focus position (i.e., the difference between the predicted error before and after snapover) is large, and the repeatability requirement may be exceeded.

The analysis results for worst-case friction were presented at the SIM ΔCDA in chart RDR-12A. An updated version of this chart, which incorporates the model improvements and change of origin (zero error) mentioned in the discussion for Figure 1, is provided in Reference 1, and included in the current memo as Figure 2. Similarly, the error or "delta height" from the nominal focus position is plotted versus commanded position. For worst-case friction, there is more separation between the trajectories for "lowering" and "lifting" of the focus mechanism than was evident for the nominal-friction case (Figure 1). The conclusions to be drawn from this figure are the same as for the nominal friction case, however. In the region to the left of the snapover point (e.g., X > -0.1 inch), the predicted error is always less than ±0.0005 inch, or within the repeatability requirement. However, there is a large discontinuity in the predicted error as the

mechanism passes through the snapover point, with a consequent ambiguity in the actual focus position which can lead to the repeatability requirement being exceeded.

The effect of uncertainty in the amount of friction on the predicted error is illustrated in Figure 3, in which the hysteresis curves for nominal and worst-case friction (Figures 1 and 2, respectively) are combined in one plot. Consider a case where the mechanism is lowering, from a starting point near X = -0.4 inch, and a destination focus position of X = -0.15 inch. With nominal friction, snapover occurs during this movement, and the predicted error at the destination focus position is +0.00005 inch. However, with worst-case friction, snapover does not occur for the same movement, and the predicted error is -0.0010 inch. The difference in actual focus positions reached is 0.00105 inch, or about twice the variability allowed by the repeatability requirement. On the other hand, if the mechanism is lifting, i.e., going to the same destination (X = -0.15 inch), but from a starting position further to the left (+X direction) in Figure 3, the predicted errors are -0.0001 inch and -0.00035 inch, for nominal and worst-case friction, respectively. Now, the difference in actual focus position reached is only 0.00025 inch.

A focus reposition movement which might (or might not) go through the snapover point from the other (+X to -X) direction leads to the same difficulty. In general, if we don't know whether snapover occurs or not, the predicted error can be uncertain by the difference in the values before and after snapover - a large amount, which can exceed the repeatability requirement. The operational solution to this problem is to require that the direction of approach to a new focus position always be in the direction towards the Focus Approach Crossover Point, or "top dead center" for movement of the upper arms of the eccentric levers on each of the three foot assemblies, as recommended in Reference 1. The rationale for this is that the snapover always occurs after passing through the focus approach crossover point. Therefore, the mechanism will not snapover while approaching the targeted focus position, and there is no ambiguity as to which portion of the predicted error curve to use in biasing the commanded position.

As an example, consider the case of a move to a focus position of X = -0.2 inch, from a starting position of X = -0.4 inch. The procedure would be to move in the +X direction past the target position a sufficient distance (Ball recommends at least 50 motor steps), then reverse direction and approach the target position going in the -X direction. (See Figure 3.) The mechanism will be lifting as the target is approached, and snapover will

moved 0.1 inch in the +X direction, the predicted error is given by the "lowering" curve - for a given amount of friction. Thus the predicted error, from Figure 3, would be somewhere between about 0.0001 inch (nominal friction) and 0.0004 inch (worst-case friction). For any amount of friction between these extremes, the error will be within the repeatability requirement of ±0.0005 inch. Alternatively, if this same target position is approached in the +X to -X position, the predicted error is given by the "lifting" curves, and will be between 0.0000 inch and -0.0002 inch (for worst-case friction), which is also within the repeatability requirement. However, the difference in the actual positions reached in approaching from either direction, is about 0.0006 inch (for worst-case friction), which stresses the interpretation of the repeatability requirement. However, if the suggested operational constraint is followed, the variation in actual position reached would be only about 0.0002 inch.

Clearly, the best way to minimize error is to always approach a new focus position from the same direction. On orbit, there will always be some (unpredictable) amount of friction which will result in positioning error. Once on orbit, the amount of friction will change only slowly with time, and repeated returns to the same focus position will result in very little repeatability error. There is no need to put up with a repeatability error of 0.0006 inch due solely to approaching the focus position from two different directions. Admittedly, some of this error could be taken out by calibration, but the residual error will never be as good as could be obtained by always approaching a focus position from the same direction.

The downside of the suggested operational constraint is that two position moves (including a change in direction) would be required in some cases, where only a single-direction move would otherwise be required. Hence, the effect on lifetime of the mechanism needs to be considered. (See part 4 of the current action item.) Also, some modifications would be required to the ground software which constructs the command blocks for implementing focus repositions, but this would be required anyway for the cases which would otherwise be out-of-spec due to snapover ambiguity. It would seem preferrable to have the software always follow the same rules (the operational procedure as described above) rather than only invoking the procedure in cases where the predicted error would exceed spec. But there is a choice - for the cases where snapover ambiguity is not an issue.

Calibration of Hysteresis Curves:

The issue of calibration of the hysteresis curves was raised during the SIM ΔCDA presentation. Unfortunately, there is no on-board sensor for measuring the actual or "true" X-position, as a function of commanded position. The only relevant measurement which could be performed is a focus calibration. However, a focus calibration is very time-consuming, and probably not of sufficient accuracy for the current application. Previous analyses (see Reference 4) have indicated a predicted accuracy of about ±0.0010 inch for on-orbit determination of the best-focus position.

Nevertheless, it is implicit in the procedure described in the current memo, for meeting the repeatability requirement, that the hysteresis curves are known or "calibrated" to a certain level of accuracy. Calibration performed on the ground is not sufficient, since

the performance on-orbit is totally different after 1-G release. (See Reference 1.) Therefore, the calibration data have to be obtained by analysis.

Ball had an action (part 3 of the current action item) to demonstrate that the on-orbit hysteresis curves can be calibrated to the accuracy needed to meet the repeatability requirement. However, according to Reference 1, the estimated error in the hysteresis curves, excluding error due to uncertainty in the amount of friction, is ±0.0001 inch - except in the vicinity of the focus approach cross-over point, where the error bars are larger. This level of accuracy in the predicted error curves is compatible with the procedure described in the current memo.

Figure 5a

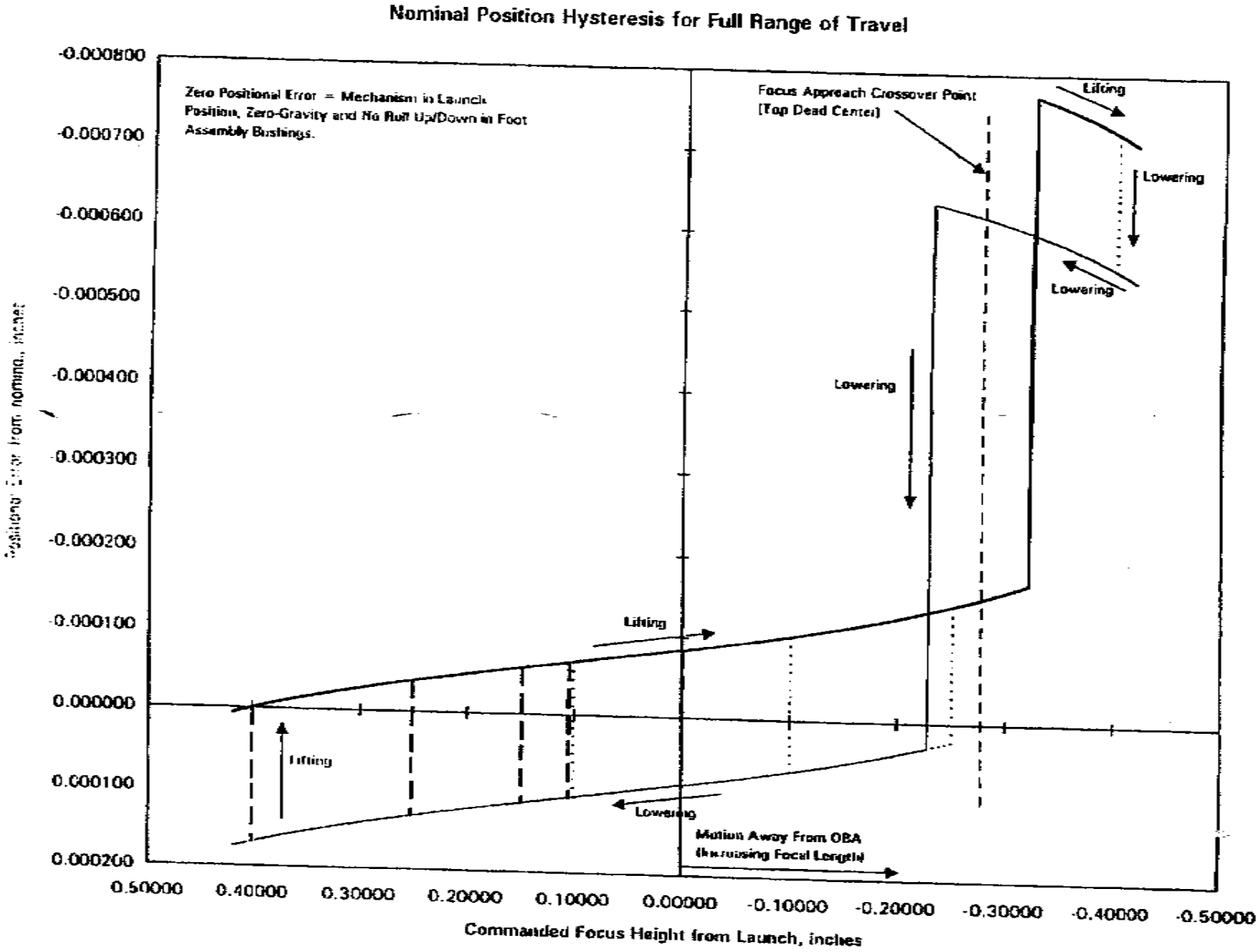

FIGURE 1. PREDICTED ERROR CURVES FOR NOMINAL FRICTION (BALL SER NO. S97-2874-MEC-193, FIGURE 5A)

Figure 7a

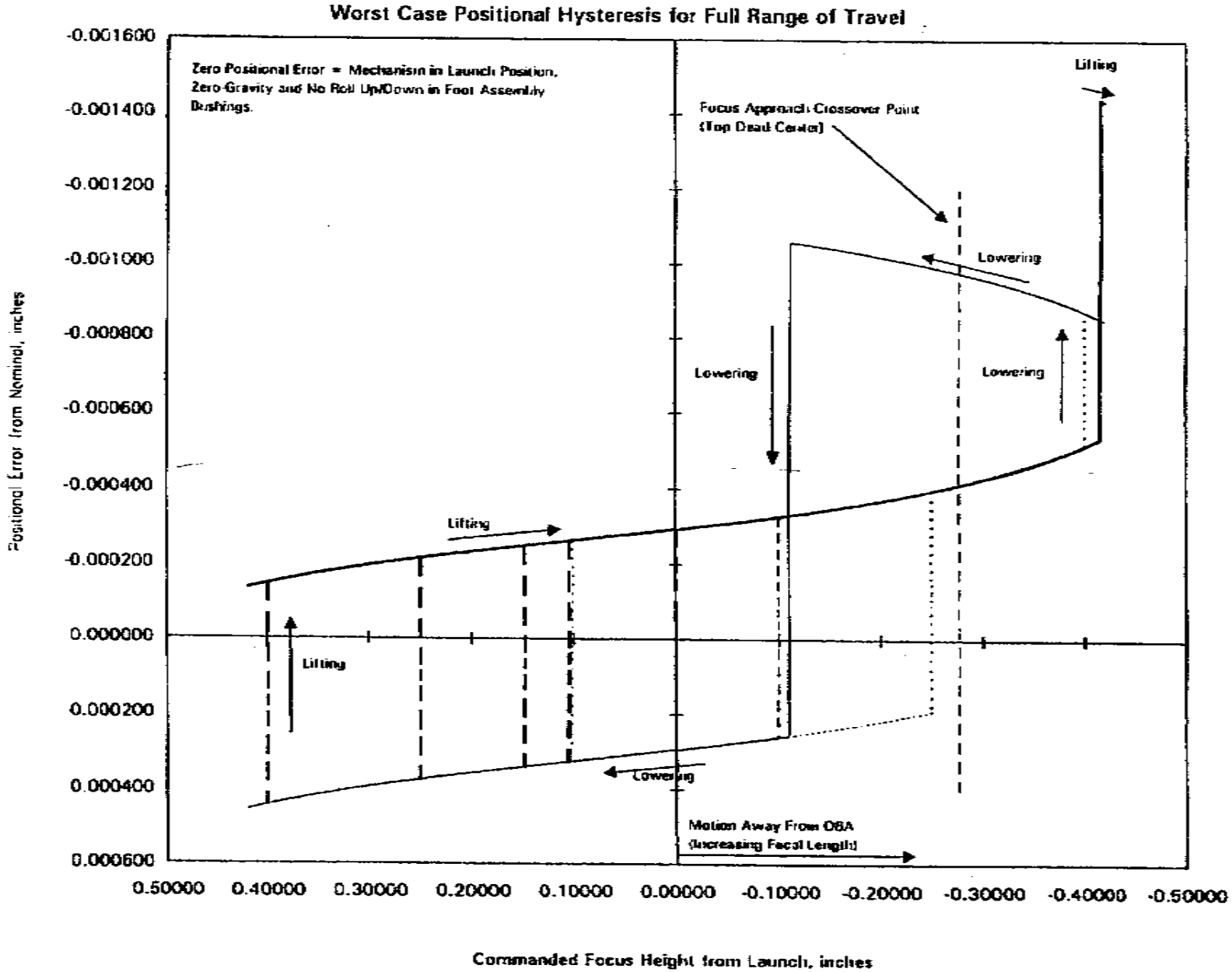

FIGURE 2. PREDICTED ERROR CURVES FOR WORST-CASE FRICTION (BALL SER NO. S97-2874-MEC-193, FIGURE 7A)

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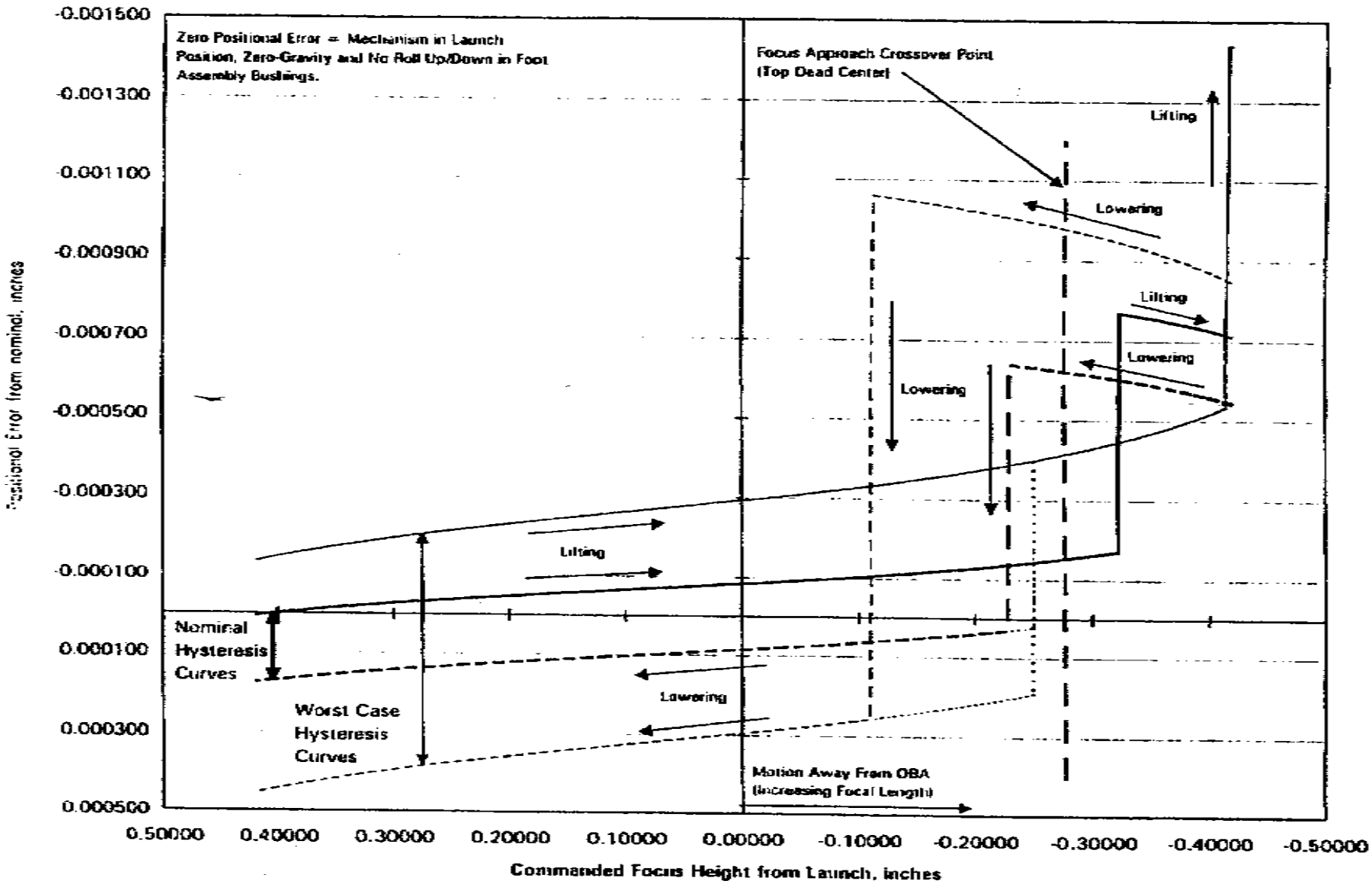
Figure 9

Nominal and Worst Case Position Hysteresis for Full Range of Travel



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