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TITLE- XYZT Targeting of the First Translunar Midcourse Correction

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DATE- February 11, 1970

FILING CASE NO(S)- 310

AUTHOR(S)- S. L. Levie, Jr.

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ABSTRACT

A comparison of XYZT targeting and FRBAP (free-return, best adaptive path) targeting for the first translunar midcourse correction reveals that:

1. XYZT targeting and FRBAP targeting result in nearly identical midcourse correction statistics.

2. XYZT-targeted trajectories lie very close to the reference trajectory, assuming a covariance matrix of TLI dispersions which was applicable to Apollo 8.

From these two properties it follows that XYZT targeting and FRBAP targeting may be used interchangeably.

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SUBJECT: XYZT Targeting of the First Translunar Midcourse Correction - Case 310

DATE: February 11, 1970

FROM: S. L. Levie, Jr.

TM-70-2014-4

TECHNICAL MEMORANDUM

INTRODUCTION

Of the translunar midcourse correction schemes available to Apollo, the simplest uses XYZT targeting. This method finds a trajectory which passes through the node (XYZ) of the desired lunar parking orbit and the nominal translunar approach hyperbola at the time (T) of nodal crossing on the nominal mission. Because of this defining property, XYZT targeting of the midcourse correction for a trajectory which is close to nominal will yield a trajectory which remains close to nominal. Thus, an interesting question arises as to whether TLI dispersions will be small enough at the time of the first translunar midcourse correction to allow a XYZT-targeted trajectory to be close to nominal.

Unfortunately, if the answer to this question is affirmative, an exhaustive study would be needed to demonstrate it. Thus, it was decided to ask for less and compare XYZT targeting performance at the first translunar midcourse correction with free-return best adaptive path (FRBAP) targeting, which reoptimizes the entire translunar mission subject to a free-return constraint. As will be shown, the principal result of this comparison is that on a statistical basis, and also on an individual sample basis, the two targeting schemes are nearly indistinguishable. From this result, which depends strongly on the assumed covariance matrix of TLI dispersions, certain generalizations are made in the conclusion of this paper.

DESCRIPTION OF METHODS USED

In an earlier study [1, 2], which addressed the problem of the best time for the first midcourse correction for Apollo 8, a large body of data was gathered for FRBAP targeting of the first midcourse correction. For input to that study, a set of 100 sample state vectors was taken from a covariance matrix of TLI dispersions prepared for the Apollo 8 mission. Using this same set of state vectors and a target taken from the free-return reference trajectory of that study, this paper compares XYZT and FRBAP targeting data.

Assumptions

Conic trajectories were used throughout this study to allow direct comparison with the FRBAP study, which used only conics. Since the midcourse correction statistics for conic and integrated trajectories are nearly the same far from MSI, the results of both studies should be very nearly representative of the results which would be obtained using integrated trajectories.

The idealizations of a perfect state vector update prior to a correction and perfect maneuver execution are assumed.

XYZT Targeting Program

A computer program has been written to solve the XYZT targeting problem and to generate the XYZT data for this study. The program and its design philosophy are described in Reference 3.

Figure of Merit

Each XYZT-targeted trajectory in this study was assigned a figure of merit by computing the hypothetical velocity correction required at the target to return to the reference trajectory. This correction is nearly the same as that which would be required if integrated trajectories were used, since the target is quite close to perilune. Thus, this velocity correction may be compared directly to a typical RCS fuel budget to get a measure of the closeness of the nominal and the XYZT-targeted trajectories.

Reference Trajectory

The reference trajectory for this study is the patched conic analog of the integrated reference trajectory used in Reference 4 to develop the covariance matrix of TLI errors. It provides a December 21, 1968 launch to Orbiter Site II-P-II on a free-return trajectory. Launch azimuth was 72° and a Pacific injection was assumed. Flight path azimuth over the landing site was -78°. The trajectory was targeted for the center of the entry corridor, having an entry velocity of 36,114 fps and an entry flight path angle of -6.4°. Other significant parameters of the reference trajectory and the vehicle are listed in Table 1.

TLI Errors

A covariance matrix of actual state vector deviations after TLI was obtained from Reference 4. The matrix, which is presented in Table 2, includes the effects of launch vehicle execution errors, earth orbit venting, and the post-TLI propulsive blow down. It is a preliminary matrix for the Apollo C' mission. The matrix is valid for the time of nominal TLI cutoff plus 15 minutes, second TLI opportunity. It is presented in the UVW coordinate system, in which U is along the position vector, W is out of plane in the direction of the angular momentum vector, and V completes the right-handed orthogonal coordinate system. The units are feet and feet per second.

Dispersions at Midcourse Correction Points

One hundred random samples were taken from the covariance matrix of errors at TLI + 15 minutes. These samples were added to the nominal conic state vector valid for the same time. These state vectors were saved and also conically propagated to the various midcourse times, namely TLI + 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 hours. The resulting state vectors were used in the XYZT targeting program to determine the required midcourse ΔV. These ΔV's were then analyzed as a function of the time of execution of the midcourse correction and compared with FRBAP results.

Scheduling Statistics

It is important to verify that XYZT-targeted trajectories will stay close the the reference trajectory even if the first midcourse correction is delayed until TLI + 24 hours, the scheduled time of the second midcourse correction. A reasonable way to check this is to process each of the 100 samples with the scheduling logic used for the Apollo F and G, which is quoted from Reference 5:

> The first translunar midcourse correction will be performed at the scheduled time (TLI + 9 hours) if the following conditions are satisfied:
>
> a) The MCC ΔV would exceed 25 feet per second if delayed until LOI-22 hours (scheduled time of MCC-3).
>
> b) The MCC ΔV at TLI + 9 hours must exceed 20 feet per second.

Figure 1A presents plots of four typical samples of the required first translunar midcourse ΔV magnitude as a function of time after TLI. These are the same samples that were plotted in Figure 1 of the FRBAP study [2]. In that study, these samples were selected to demonstrate that the minimum required ΔV may occur at widely varying times after TLI. Except for the captions, the two figures are nearly indistinguishable.

For the same four samples, Figure 1B shows the ΔV which would be required at the target to return to the reference trajectory, as a function of the time of the first translunar midcourse correction. If the first translunar midcourse correction is made close to TLI, the resulting XYZT-targeted trajectory is close enough to the reference that only a small correction is required at the target. However, as the correction is delayed, the XYZT-targeted trajectory tends to suffer growing deviations from the reference, and the correction at the target grows accordingly. These effects are displayed in the figure.

If the deviations become excessive, the XYZT-targeted trajectories will become intolerably far from the reference trajectory. In the case of a free-return reference a deviation could be considered excessive if a correction greater than about 120 fps, which is approximately the CSM RCS capability with the LM attached, were required to restore the entry conditions. To investigate this possibility, the statistically expected behavior of the target correction was computed as a function of the time of the first translunar correction, for two probability levels. The results are presented in Figure 1C, which carries the time of the first translunar correction as far as TLI + 24 hours, the scheduled time of the <u>second</u> translunar correction. For a correction at TLI + 24 hours, the median target correction is 28 fps, and the 99.865% level (the probability level of the three sigma point of a normal distribution) is 130 fps, which is approximately the CSM RCS capability. These figures provide a favorable measure of the closeness of the XYZT-targeted trajectories to the reference trajectory. As an added bonus, all the XYZT-targeted trajectories have perilune altitudes within 2 nm of perilune altitude on the reference trajectory.

Figure 2 presents the statistically expected behavior of the first translunar midcourse correction as a function of time, for various probability levels. The plots indicate that the required ΔV will be less than the plotted quantity with the specified probabilities. The probability level of 84.134%,

97.725%, and 98.865% were selected to conform to the probabilities of the one, two, and three sigma points of a normal distribution -- they are not the one, two, and three sigma points for this distribution. In addition, the mean and the 50% (median) points are plotted.

In the region from zero to 5 hours past TLI, the curves almost appear to be tracings of the corresponding curves in the FRBAP study, which are indicated by dashed lines. Starting at TLI + 5 hours, however, the XYZT curves begin to require more ΔV than the FRBAP curves. The difference is greatest at TLI + 10 hours, where the XYZT ΔV's are about 1% greater than the FRBAP ΔV's. Since this translates to about a 2 fps difference at the 99.865% level, the XYZT statistics may be regarded as essentially the same as the FRBAP statistics.

For each of the 100 samples, the point with the smallest required correction and the two adjacent points were fitted with a parabola in order to interpolate for the time and magnitude of the minimum correction. Checking revealed that this interpolation method was only valid to plus or minus about 15 minutes, but that was felt to be sufficiently accurate. Figure 3 presents the cumulative distribution function of the time of the minimum correction, and Figure 4 represents the cumulative distribution of the corresponding ΔV magnitudes. The median of the minimum midcourse time occurs at about TLI + 3.8 hours, the mean is at TLI + 4.5 hours, and the standard deviation is 3.3 hours. The median of the minimum midcourse correction was 13.0 fps, and the mean was 19.8 fps. Comparing these numbers with their FRBAP counterparts, the standard deviations agreed to 0.2 fps and the medians agreed to 0.8 fps.

Scheduling Statistics

Each of the 100 TLI covariance matrix state vector samples was processed with the scheduling logic shown in Figure 5 in order to find the statistics of the time and magnitude of the actual midcourse correction. The results are given in Figures 6, 7, and 8.

A cumulative distribution of the times of these corrections is given in Figure 6. Notice that 43% of the corrections were made at TLI + 9 hours and that 38% of the corrections were delayed unitl TLI + 24 hours, the scheduled time of the second midcourse. The remaining 19% seem to be scattered evenly between these two boundaries. The clustering at the boundaries may be expected from the following considerations. By waiting until TLI + 9 hours as the earliest time

for the corrections, some sizeable corrections may accumulate, and all of these must be dealt with as soon as possible. On the other hand, even if one waits until TLI + 24 hours to make the correction there will be a group of trajectories which still clusters about the reference trajectory. These will all be dealt with at the last possible moment. Because these considerations are implicit in the scheduling logic, they will hold for any midcourse targeting method. However, the detailed structure of the distribution of midcourse times will vary with the targeting method and with the reference trajectory.

Figure 7A gives the cumulative distribution of the ΔV's for each of the actual midcourse corrections. The mean value was 25 fps, and the ΔV corresponding to the 99% probability level was 76 fps. This figure was taken from the cumulative distribution. To assist in the interpretation of Figure 7A, a histogram of the correction magnitudes is presented in Figure 7B. The outstanding feature of this figure is the strong peak at 20 fps, which is the threshold value which no correction may be made, except at TLI + 24 hours. Thus the events with $\Delta V < 20$ fps all occurred at TLI + 24 hours. The presence of the threshold requirement provides the shape for $\Delta V < 20$ fps, and the removal of this requirement allows the "natural" shape seen for $\Delta V > 20$ fps. As in Figure 6, the detailed structure in Figures 7A and 7B will vary with the targeting method and the reference trajectory. However, the general features just discussed are implicit in the scheduling logic itself.

Figure 8 shows the cumulative distribution of the hypothetical velocity corrections at the target for each of the translunar midcourse corrections presented in Figures 6 and 7. The distribution has a mean of 16 fps, a median of 13 fps and 99.865% probability level of 59 fps. These values are substantially smaller than might have been expected on the basis of Figure 1C. The reason is that the scheduling logic (Figure 5) selects a midcourse correction time in such a way that the pre-correction trajectory never lies too far from the reference trajectory. This is accomplished with the check of the ΔV at LOI -22 hours. Because this number is kept fairly small, the pre-correction trajectory -- and consequently the post-correction trajectory as well -- is forced to be close to the reference trajectory.

Correlations

In an attempt to discern trends in the XYZT and FRBAP data, various correlations were computed between the following sets:

1) XYZT UVW midcourse correction components and magnitudes vs. errors in the Keplerian elements.*

2) FRBAP UVW midcourse correction components and magnitudes vs. errors in the Keplerian elements.*

3) XYZT UVW midcourse correction components and magnitudes vs FRBAP UVW midcourse correction components and magnitudes.

All midcourse corrections were computed at TLI + 10 hours. The correlations are presented in Tables III and IV along with the means and the standard deviations of the correction components and magnitudes.

An examination of the correlations, means, and standard deviations in Tables III and IV reveals the following salient trends:

1) U and V-components of XYZT and FRBAP corrections exhibit the same correlations with the errors in the elements. The W-components do not.

2) The corrections are predominently in-plane for both XYZT and FRBAP targeting.

3) The XYZT and FRBAP in-plane correction components are correlated equally strongly to true anomaly error, energy error and eccentricity error and, to a lesser degree, to error in argument of perigee.

4) The out-of-plane corrections are associated mostly with node error, for both XYZT and FRBAP targeting.

5) The XYZT out-of-plane correction component is more strongly correlated to true anomaly, energy, eccentricity, and node errors than is the case for the FRBAP out-of-plane correction.

6) For both XYZT and FRBAP targeting, the correction magnitude is not strongly correlated with any single error in the elements.

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*Error in an element is computed as the value of the element after TLI, but before the midcourse correction, minus the value of the same element for the reference trajectory.

SUMMARY AND CONCLUSIONS

The statistics computed for this study of XYZT targeting of the first translunar midcourse correction were nearly identical with the statistics presented in a similar study for FRBAP targeting. Furthermore, the two targeting schemes showed the same behavior of the midcourse ΔV as a function of time past TLI. The correlations between insertion errors and midcourse ΔV were not strong for either targeting scheme. The XYZT-targeted trajectories were all close to the (free-return) reference trajectory in the sense that at the 99.865% probability level, the required velocity correction at the target (to return to the reference trajectory) was only about 56 fps if the first translunar midcourse correction is made at TLI + 10 hours. This figure grows to 130 fps if the correction is delayed until TLI + 24 hours, the latest the first translunar midcourse correction would be made.

The value 130 fps is approximately the limit of the CSM RCS capability (with the LM attached). In addition, all the XYZT-targeted trajectories in the study had perilune altitudes within 2 nm of perilune altitude on the reference trajectory. Thus, with respect to an assumed free-return reference trajectory and the assumed covariance matrix of TLI dispersions, XYZT targeting may be said to produce satisfactorily small deviations from the reference trajectory. This conclusion would also apply to the case of the non-free-return reference trajectory, although for this case the size of the deviations becomes less important.

Because the smallness of the deviations of XYZT-targeted trajectories is important to the utility of XYZT targeting, the above conclusion was checked by computing XYZT-targeted corrections with the midcourse scheduling logic used for Apollo F and G. This logic places the first translunar midcourse correction at some time between TLI + 9 hours and TLI + 24 hours. The midcourse correction corresponding to the 99% confidence level was found to be 76 fps, and the hypothetical velocity correction at the target for 99.865% confidence was found to be 59 fps. It is concluded that the scheduling logic enforces the closeness of the post-correction and reference trajectories.

It is thought that the general relations presented in the last few paragraphs are largely independent of the fact that a free-return reference trajectory was selected. However, they certainly depend on the assumed form of the TLI dispersions, which for this study was taken to be the same as for studies of Apollo 8. If it is assumed that these dispersions are applicable to later Apollo missions as well, then XYZT and FRBAP targeting

clearly may be used interchangeably at the first translunar midcourse correction. This is interpreted as meaning that the time constraint in XYZT targeting and the free-return constraint in FRBAP targeting are equally stringent constraints in the presence of the assumed TLI dispersions. However, in midcourse correction targeting for non-free-return reference trajectories, best adaptive path targeting, which is not burdened by the free-return constraint, may be expected to have the edge over XYZT targeting.

In summary: XYZT targeting is simple; it stays very close to the reference trajectory given expected Apollo TLI errors; it preserves the perilune constraint, and it is statistically equivalent to FRBAP targeting. This should not be construed as a recommendation to replace best adaptive path targeting with XYZT targeting. Indeed, best adaptive path targeting should be kept available in real-time for the remote possibility of large, unexpected TLI errors which only it could correct while preserving the perilune altitude constraint.

On the basis of the result that the XYZT-targeted trajectory stays close to the reference trajectory, it is speculated that XYZT-targeting will provide a satisfactory solution to the problem of real-time targeting of the hybrid trajectory midcourse correction.

Sterling Levie Jr.

2014-SLL-ksc

S. L. Levie, Jr.

Attachments
Tables 1-4
Figures 1A-8

REFERENCES

1. Corey, D. A. and Levie, S. L., Jr., "Analysis of the First Translunar Midcourse Correction for the Apollo C' Mission," Bellcomm Technical Memorandum 68-2011-2, December 9, 1969.

2. Corey, D. A. and Levie, S. L., Jr., "Analysis of the First Translunar Midcourse Correction for the Apollo C' Mission - Corrected Figures," Case 310, Bellcomm Memorandum for File, December 13, 1969.

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4. Rother, M. R., "Preliminary Launch Vehicle Covariance Matrix for C' Mission," U.S. Government Memorandum Number 68-FM73-489, FM7/Guidance and Performance Branch/ Guidance Analysis Section, Manned Spacecraft Center, October 23, 1968.

5. Tindall, H. W., "Missions F and G Translunar Injection, Midcourse Correction and Lunar Orbit Insertion (change pages)," U.S. Government Memorandum 69-PA-T-90A, Manned Spacecraft Center, June 10, 1969.

6. Bixhorn, H. J. and Niedfeldt, B. G., "A Simple Method for Approximating Quantiles of the Random Variables $X_1^2 + X_2^2 + X_3^2$," Bellcomm Memorandum for File, August 9, 1968.

TABLE 1

SUMMARY OF REFERENCE TRAJECTORY CHARACTERISTICS

Launch Date	December 21, 1968
Launch Azimuth	72°
Lunar Landing Site	II-P-II, 2.725°N, 34.4°E
Translunar Flight Time	66.137 hours
Transearth Flight Time	80.1098 hours
Earth Landing Point	4.9897°S, 170.0°W
Landing Site Approach Azimuth	-78°
Sun Elevation at Lunar Landing	8.4768°
Sun Azimuth at Lunar Landing	10.0553°
Entry Flight Path Angle	-6.4°
Total Spacecraft Weight at Injection	64540 lbs.
Translunar Midcourse ΔV Budget	130 fps
Transearth Midcourse ΔV Budget	62 fps
Spacecraft Weight Prior to CM/SM Separation	35199.4 lbs.
SPS Thrust	20,000 lbs.
SPS Specific Impulse	311 sec.

TABLE 2

COVARIANCE MATRIX OF ERRORS AT TLI + 15 MINUTES

SECOND OPPORTUNITY DECEMBER 21, 1968 LAUNCH

	U	V	W	$\dot{U}$	$\dot{V}$	$\dot{W}$
U	.23271480+10	.46858996+10	-.50757886+08	-.26900468+07	.60531505+06	.74481547+05
V	.46858996+10	.16802540+11	.26078454+07	-.10386225+08	.46316702+07	.42998867+06
W	-.50757886+08	.26078454+07	.70831154+09	-.84250911+05	.22091040+04	.51900446+06
$\dot{U}$	-.26900468+07	-.10386225+08	-.84250911+05	.64777511+04	-.30017825+04	-.32726207+03
$\dot{V}$	.60531505+06	.46316702+07	.22091040+04	-.30017825+04	.17478498+04	.12088917+03
$\dot{W}$	.74481547+05	.42998867+06	.51900446+06	-.32726207+03	.12088917+03	.39875840+03

TABLE 3

CORRECTION COEFFICIENTS, STANDARD DEVIATIONS, AND MEANS FOR XYZT AND FRBAP TARGETING OF TRANSLUNAR MIDCOURSE CORRECTIONS AT TLI + 10 HOURS (100 SAMPLES)

	Δ TRUE ANOMALY	Δ ENERGY	Δ ECCENTRICITY	Δ INCLINATION	Δ NODE	Δ ARGUMENT OF PERIGEE	STANDARD DEVIATION	MEAN
$\dot{U}_{XYZT}$	.99	-.99	-.99	.43	.69	.75	21.1	-3.5
$\dot{V}_{XYZT}$	-.82	.80	.80	-.14	-.43	.97	20.9	1.5
$\dot{W}_{XYZT}$	-.86	.85	.85	-.52	-.84	-.54	1.7	0.2
MAG_{XYZT}	-.53	.52	.51	-.14	-.28	-.38	18.4	23.5
$\dot{U}_{FRBAP}$	.99	-.99	-.99	.43	.68	.75	20.7	-3.8
$\dot{V}_{FRBAP}$	-.82	.80	.79	-.14	-.42	-.97	20.7	1.8
$\dot{W}_{FRBAP}$	-.60	.57	.56	-.23	-.61	-.51	1.0	0.6
MAG_{FRBAP}	-.55	.53	.53	-.14	-.29	-.40	18.2	23.2

TABLE 4

SOME CORRELATION COEFFICIENTS BETWEEN COMPONENTS AND MAGNITUDES OF XYZT AND FRBAP TRANSLUNAR MIDCOURSE CORRECTIONS AT TLI + 10 HOURS.

	$\dot{U}_{FRBAP}$	$\dot{V}_{FRBAP}$	$\dot{W}_{FRBAP}$	MAG_{FRBAP}
$\dot{U}_{XYZT}$	1.00	—	—	—
$\dot{V}_{XYZT}$	—	1.00	—	—
$\dot{W}_{XYZT}$	—	—	0.89	—
$\dot{M}AG_{XYZT}$	—	—	—	1.0

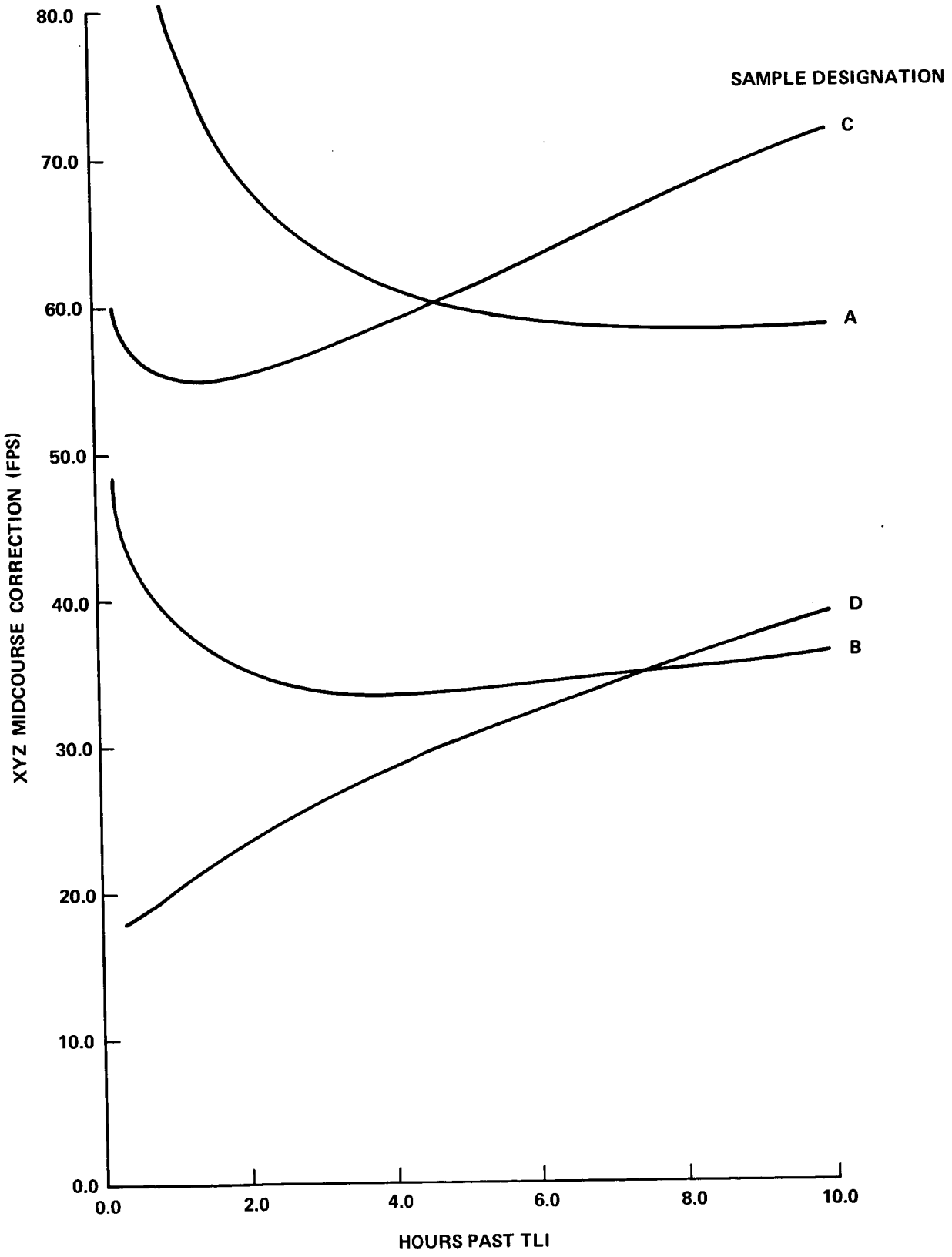

FIGURE 1A -XYZT MIDCOURSE CORRECTION VS. TIME PAST TLI, FOR TYPICAL TLI SAMPLES

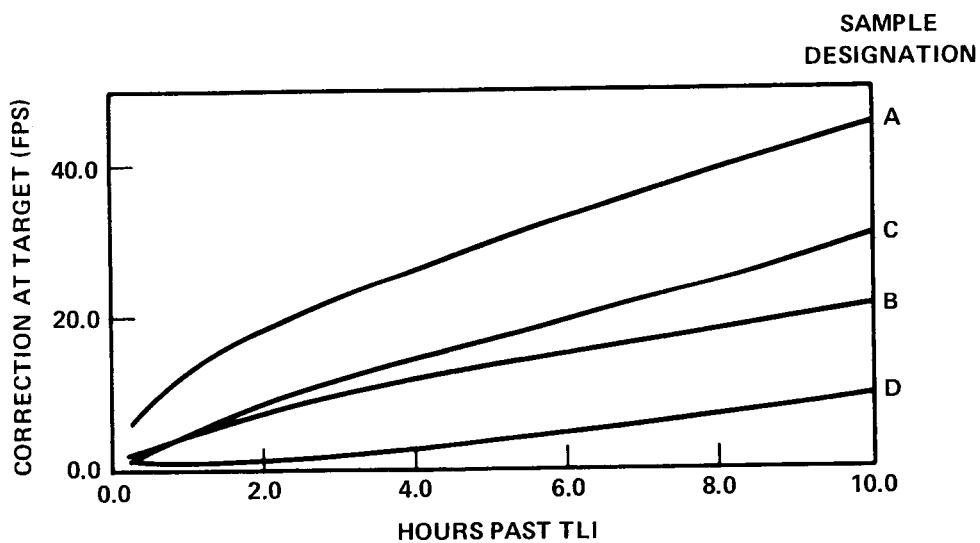

FIGURE 1B—CORRECTION AT TARGET TO RETURN TO REFERENCE TRAJECTORY VS. TIME OF FIRST TRANSLUNAR MIDCOURSE CORRECTION, FOR TYPICAL TLI SAMPLES.

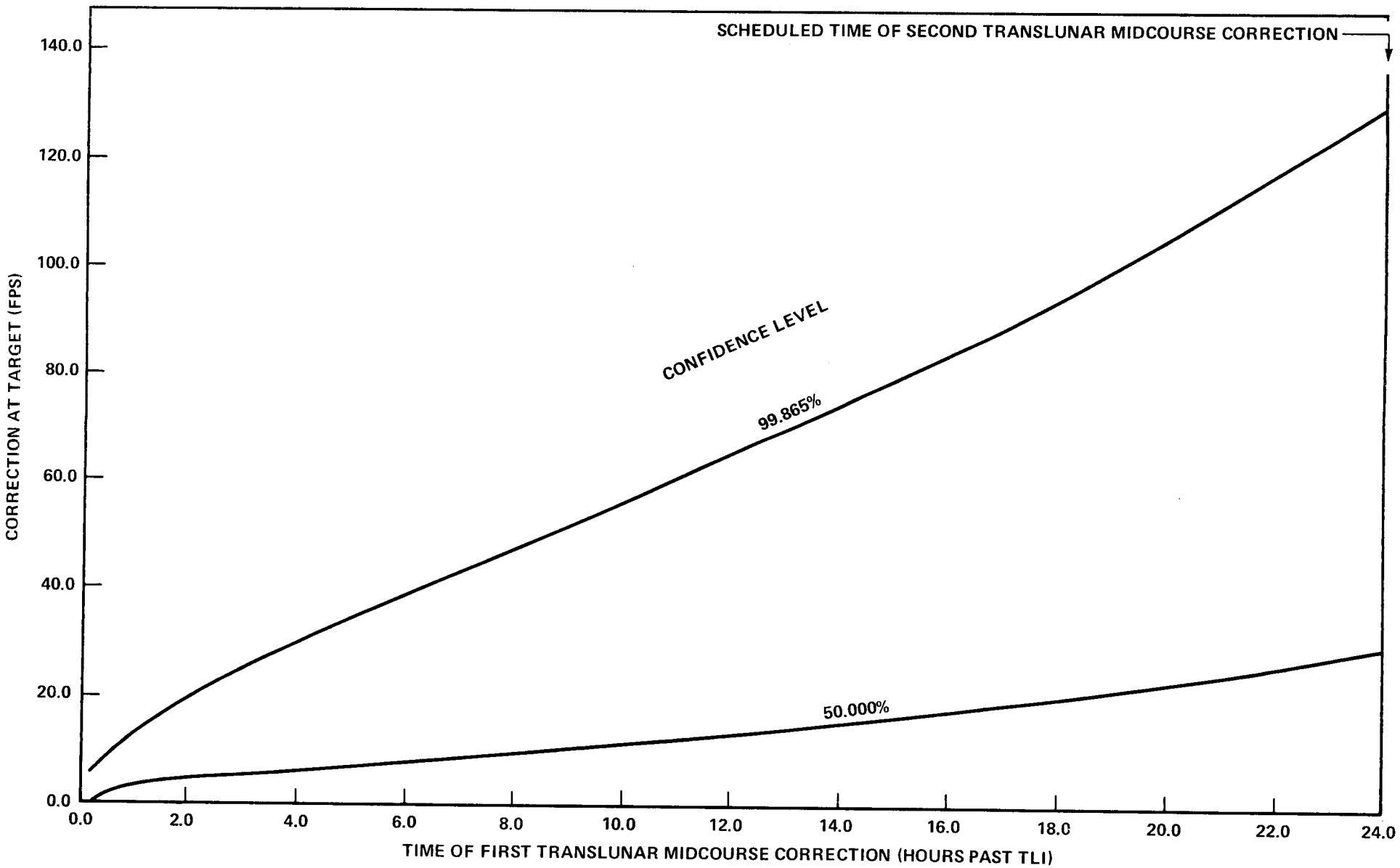

FIGURE 1C–CORRECTION AT TARGET TO RETURN TO REFERENCE TRAJECTORY VS. TIME OF FIRST XYZT TRANSLUNAR MIDCOURSE CORRECTION, FOR TWO CONFIDENCE LEVELS

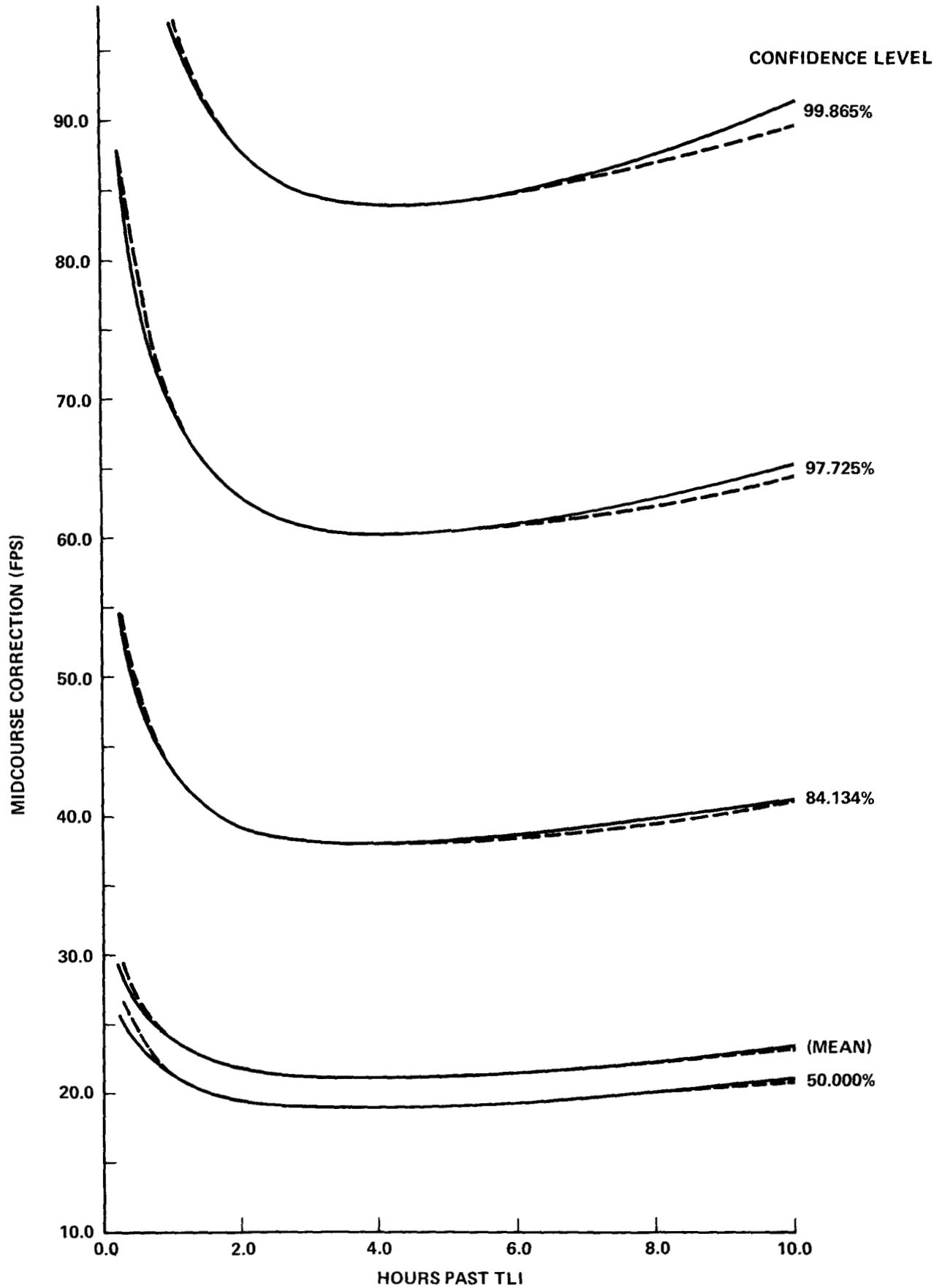

FIGURE 2 - XYZT MIDCOURSE CORRECTION VS. TIME PAST TLI, FOR VARIOUS CONFIDENCE LEVELS (DASHED CURVES WERE OBTAINED IN FRBAP STUDY)

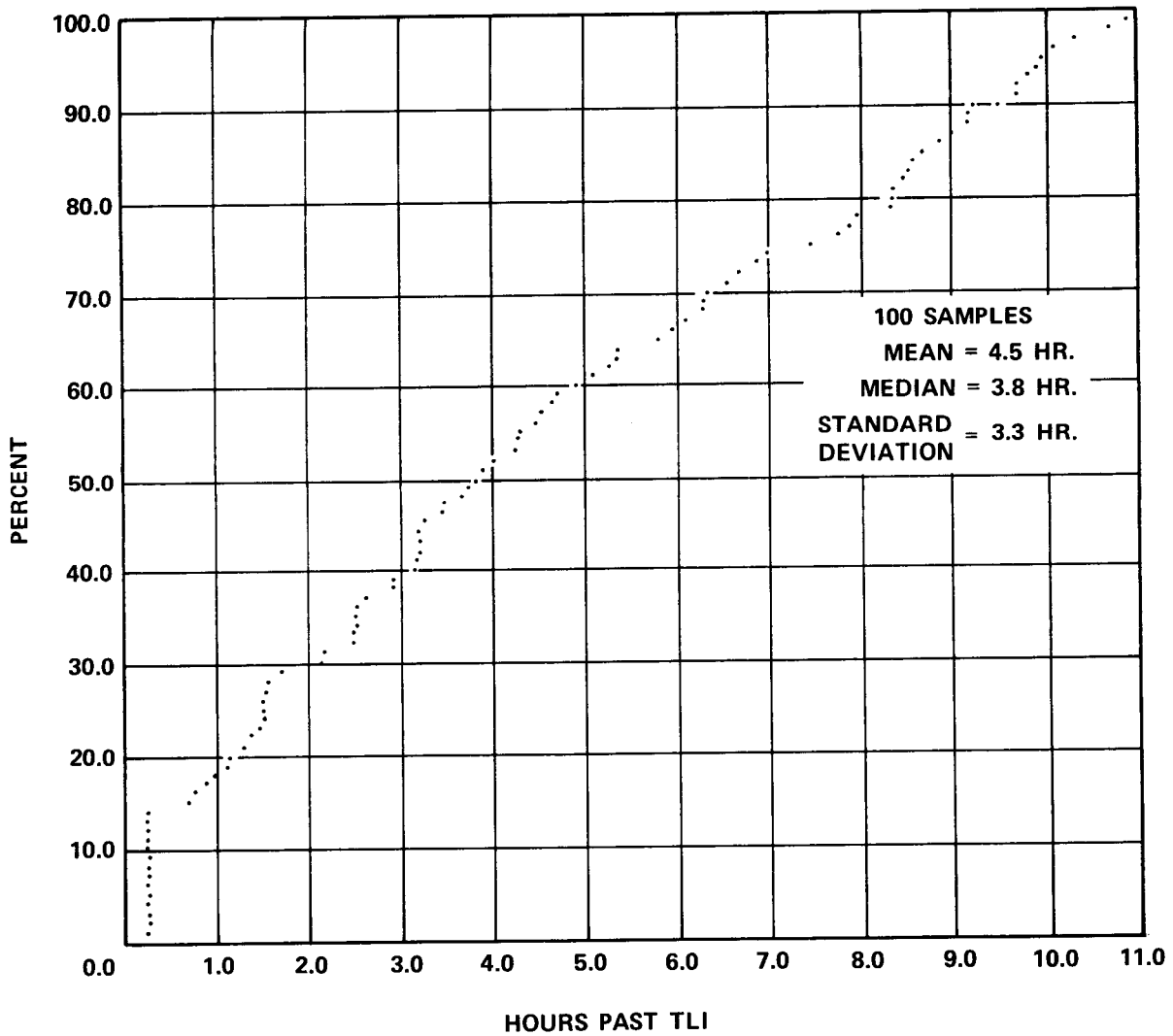

FIGURE 3 - CUMULATIVE DISTRIBUTION OF MIDCOURSE EXECUTION TIMES REQUIRING MINIMUM XYZT MIDCOURSE CORRECTION

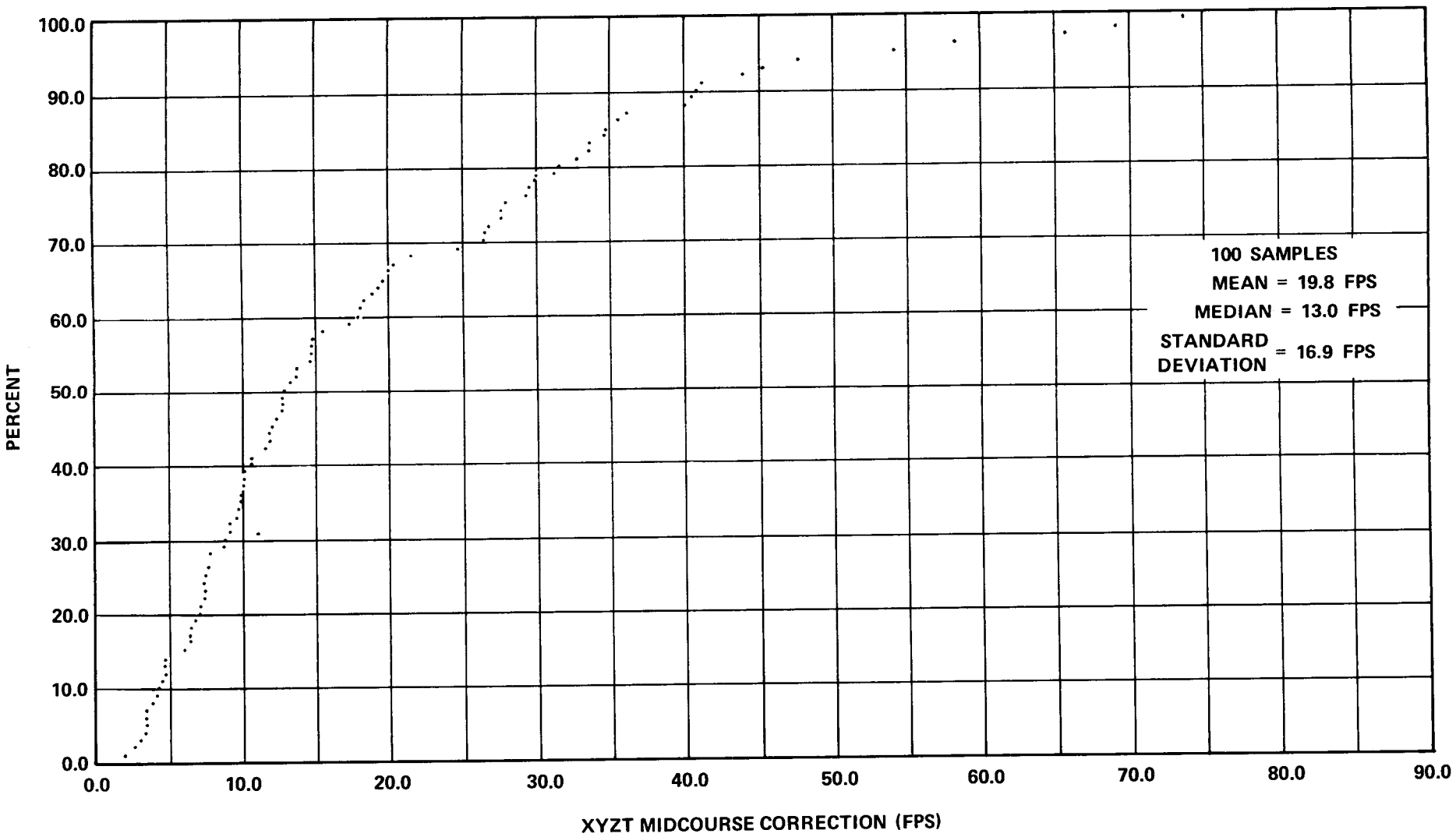

FIGURE 4 - CUMULATIVE DISTRIBUTION OF MINIMUM XYZT MIDCOURSE CORRECTIONS

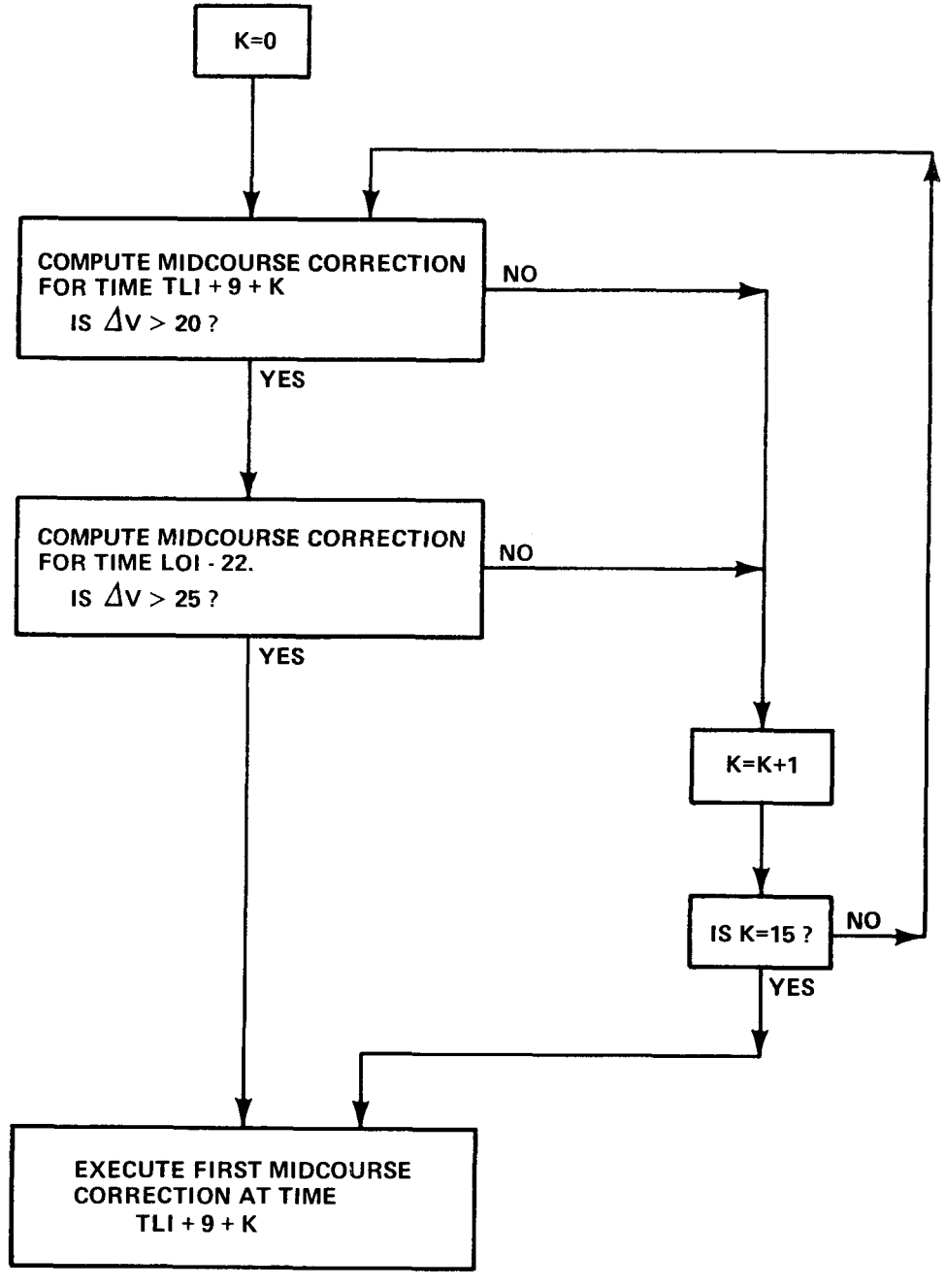

FIGURE 5 - FLOW DIAGRAM OF LOGIC USED FOR SCHEDULING FIRST TRANSLUNAR MIDCOURSE CORRECTION

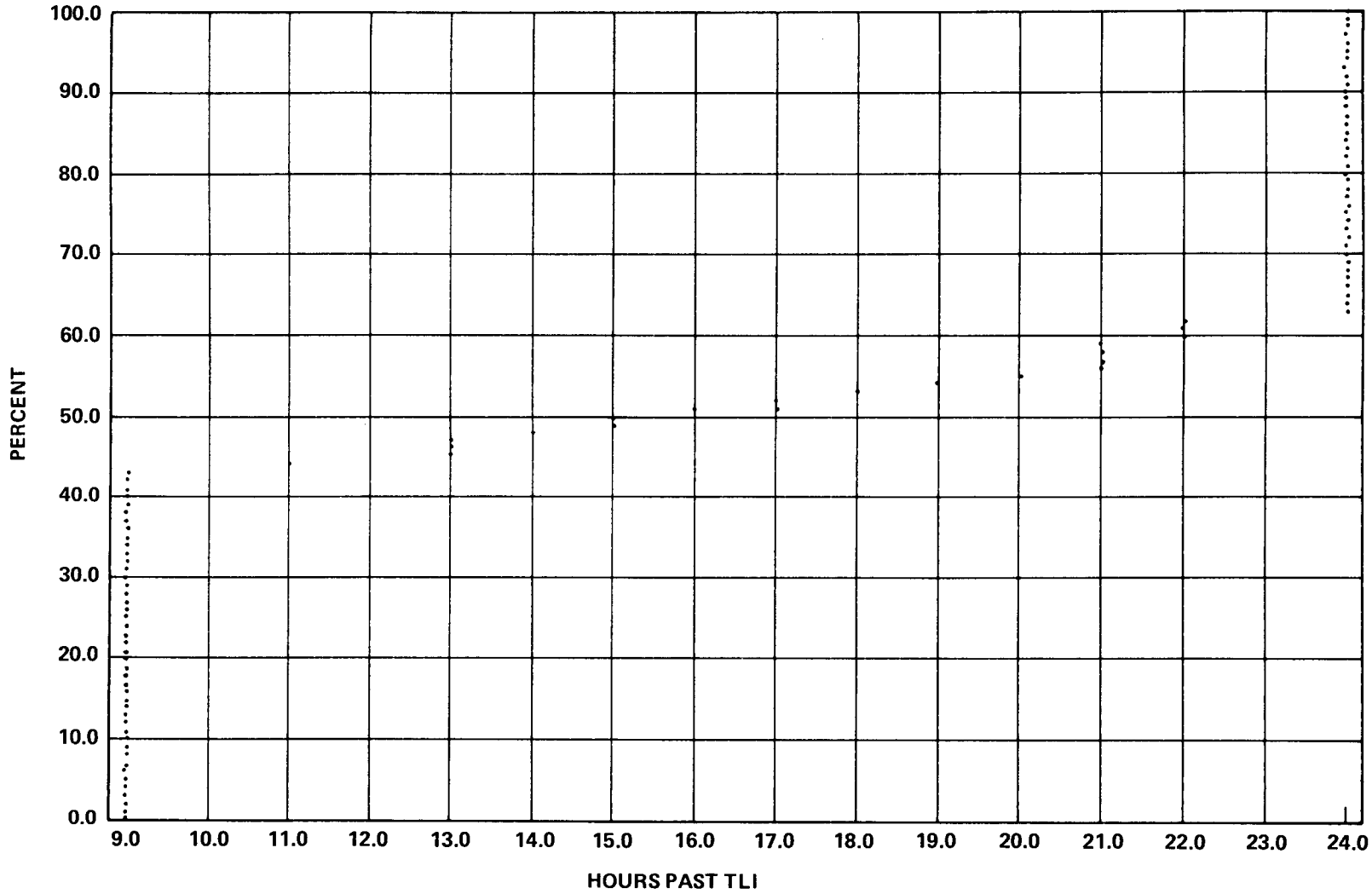

FIGURE 6- CUMULATIVE DISTRIBUTION OF TIMES OF ACTUAL XYZT MIDCOURSE CORRECTIONS, USING SCHEDULING LOGIC

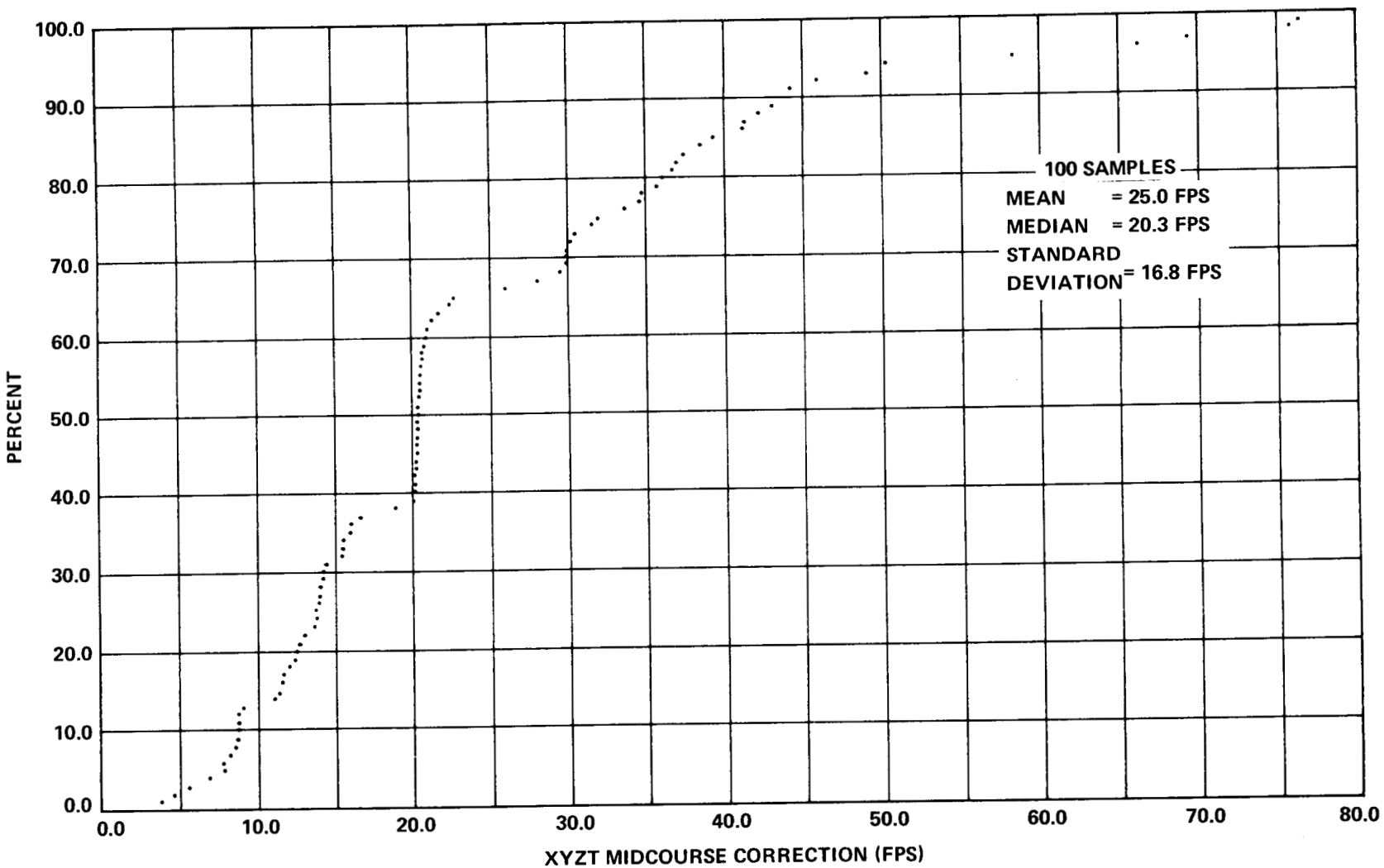

FIGURE 7A - CUMULATIVE DISTRIBUTION OF XYZT MIDCOURSE CORRESTIONS; USING SCHEDULING LOGIC

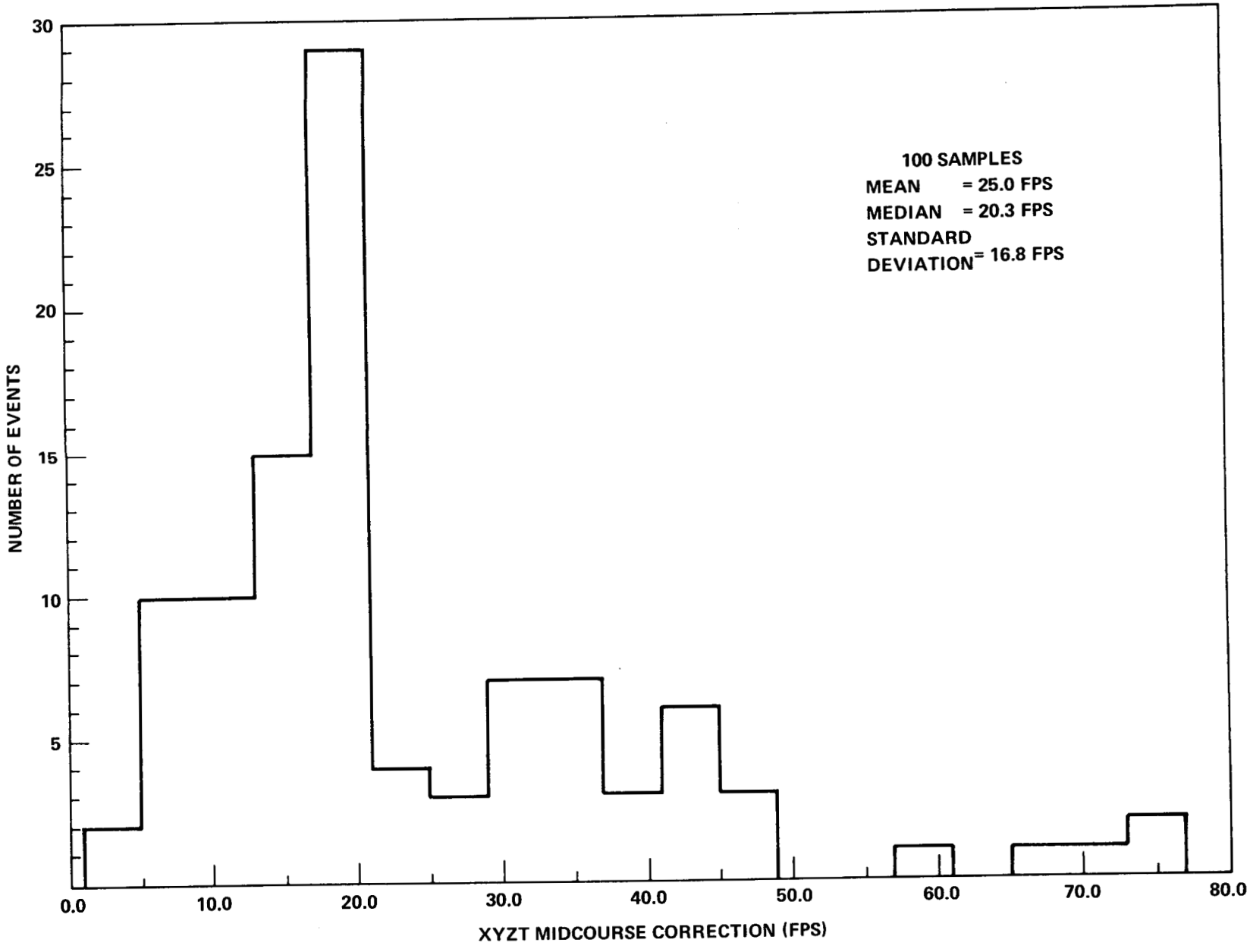

FIGURE 7B - HISTOGRAM OF XYZT MIDCOURSE CORRECTIONS, USING SCHEDULING LOGIC

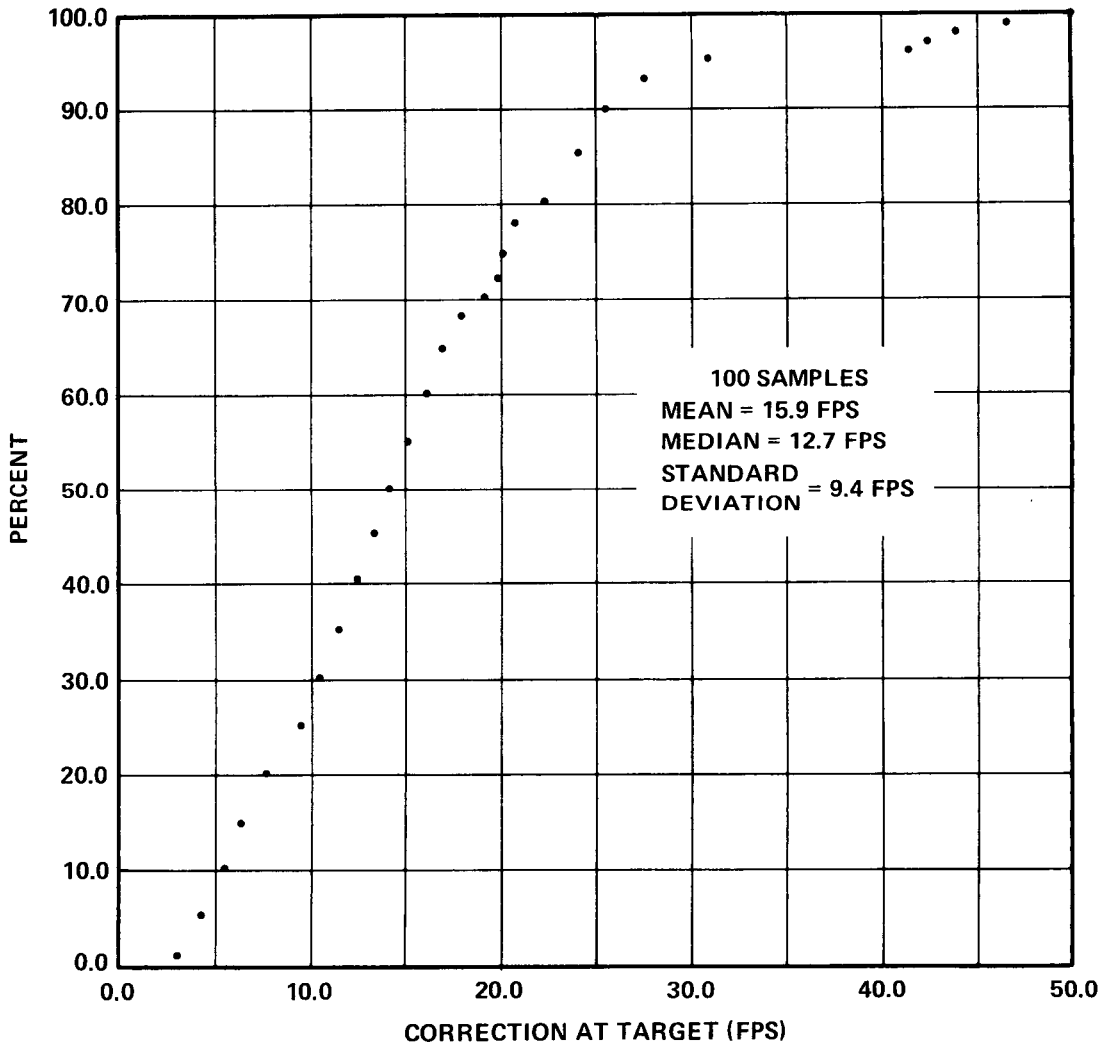

FIGURE 8—CUMULATIVE DISTRIBUTION OF CORRECTIONS AT TARGET TO RETURN TO REFERENCE TRAJECTORY, USING SCHEDULING LOGIC.