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APOLLO 8
SPACECRAFT DISPERSION ANALYSIS
VOLUME II
TRANSLUNAR AND TRANSEARTH PHASES

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PROJECT APOLLO

APOLLO 8 SPACECRAFT DISPERSION ANALYSIS
VOLUME II - TRANSLUNAR AND TRANSEARTH PHASES

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December 16, 1968

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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HOUSTON, TEXAS

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APOLLO 8 SPACECRAFT DISPERSION ANALYSIS

VOLUME II - TRANSLUNAR AND TRANSEARTH PHASES

By G. C. Hitt, S. M. Kindall, and Jerome D. Yencharis

SUMMARY

Summarized herein are the results of the dispersion analysis of the Apollo 8 mission, translunar and transearth phases only.

If it can be assumed that there will be no spacecraft venting, the analysis indicates there will be no serious problems. Total service propulsion system (SPS) ΔV cost for translunar midcourse was 85.8 fps in the worst case and 0 fps for transearth midcourse. The highest total reaction control system (RCS) ΔV cost was 9.35 fps for translunar midcourse and 17.24 fps for transearth midcourse. Resulting deviations at lunar orbit insertion (LOI) and entry interface appear to be acceptably small.

If venting is considered in the problem, the preliminary results included herein point out its general effects. More midcourses need be made, ΔV cost is higher and resulting deviations are larger.

INTRODUCTION

This document contains a description of the spacecraft dispersion analysis for the translunar and transearth phases of the Apollo Mission 8. The nominal timelines for the translunar and transearth phases of Apollo 8 are shown below. The times listed for the midcourse corrections are those which were selected for use in the dispersion analyses based on requirements for MSFN tracking before and after each midcourse correction, crew timeline considerations, and results from previous simulations of Apollo Mission G. All other times were taken from the Apollo 8 operational trajectory (ref. 1) which has a December 21, 1968, launch date and 72° launch azimuth.

Translunar Phase

Event	g. e. t. (day:hr:min)	Time From TLI Cutoff (hrs)
Translunar injection (TLI) cutoff	0:02:56	0
MCC1	0:08:56	6
MCC2	1:03:56	25
MCC3	1:23:07	44 (LOI - 22 hr)
MCC4	2:13:07	58 (LOI - 8 hr)
LOI ignition	2:21:07	66
Nodal passage	2:21:08	66

Transearth Phase

Event	g. e. t. (day:hr:min)	Time From TEI Cutoff (hrs)
Transearth injection (TEI) cutoff	3:17:07	0
MCC1	4:03:07	10
MCC2	4:22:07	29
MCC3	5:22:06	53 (entry-29 hr)
MCC4	7:01:06	80 (entry-2 hr)
Entry	7:03:06	82

Several changes are being considered for the Apollo 8 operational trajectory. Most significant is decreasing the transearth trip time by one day whenever feasible. An analysis is currently underway on such a trajectory.

This document contains an analysis of a translunar trajectory with spacecraft venting. It should be emphasized that at this time, the venting data can only be considered preliminary.

It is intended that shortly a summary document will be published which will include the results of the following additional studies:

1. Effect of spacecraft venting during translunar and transearth coast.

2. Effect of one-day shorter transearth trip time.

3. Loss of communications following transearth injection (TEI).

4. Nominal transearth coast with a midcourse maneuver at entry interface - 24 hours to shift landing longitude.

5. Loss of primary guidance system prior to TEI.

6. Loss of communications after the first translunar midcourse.

The dispersion analysis presented was performed by TRW Systems Group under MSC/TRW Task A-100.

SIMULATION DESCRIPTION

The dispersion analyses for the translunar and transearth phases of Apollo 8 were performed with the TAPP VIA program, a linearized Monte Carlo program. Two hundred translunar and transearth flight simulations were performed with the program, and statistical results of the simulations were compiled with the Adaptive Statistical Processor (APROC) program.

Translunar Simulations

Each translunar simulation was initialized with a set of sample state vector deviations (actual deviations) at translunar insertion (TLI) cutoff and was terminated at the nominal time of nodal passage. Simulated midcourse corrections were targeted to node (X, Y, Z, and time at the node of the approach hyperbola and the lunar orbit plane)

and included the effects of Manned Space Flight Network (MSFN) navigation errors, errors in the estimated values for the gravitational constants of the earth and moon, and midcourse execution errors.

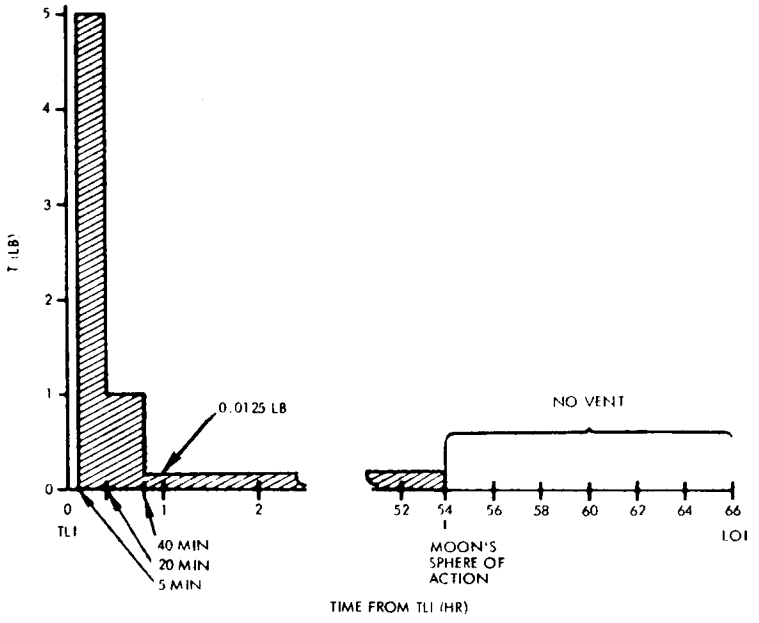
Two sets of translunar simulations were made: one set included the effects of venting, in addition to the errors mentioned above, and one set did not include venting effects.

No attempt was made to construct a rigorous venting model for Apollo 8 simulations. A rigorous model would have to consider the variation of vent direction due to passive thermal control rotation and variations in the magnitude of the venting thrust. For the translunar dispersion analysis, a simple, conservative model was employed in which the direction of the vent thrust was taken to be parallel to the vehicle velocity vector relative to the earth. It was assumed that venting thrust in this direction would be a worst case situation in that it would result in actual vehicle state deviations which would cost the most in terms of midcourse ΔV to correct, and, in addition, would produce the greatest degradation in the accuracy of the estimated vehicle state.

The magnitude of the venting thrust, T_v, was modeled to be

$$T_v = \alpha T$$

where the profile for T is shown in the graph below and α is a random scaling factor selected at the beginning of each mission simulation cycle from a normal distribution with mean equal to zero and standard deviation equal to 1.0.



Profile for T in the Translunar Vent Model

The venting effects summarized in this document should be considered as preliminary data. The venting model utilized in this simulation was set up at the start of the study. Since then, there have been many questions as to the validity of the model, the magnitude of the vent, and the resulting navigational data which were input to this study. As of this time the majority of the questions are unanswered. Two points should be made: (1) A continuous vent of 0.0125 lb along the velocity vector during translunar coast can change actual pericynthion altitude by 25 n. mi., and (2) navigational uncertainties may be increased because of the vent. Exactly how much the uncertainties are increased (if at all) will depend on real-time navigational procedures. The navigational procedures to be used if the spacecraft vents are currently under study and are not necessarily reflected in this document. However, the data presented here can be taken as a general indication of the effects of spacecraft venting.

Transearth Simulations

Transearth simulations were initialized with a set of sample actual state deviations at transearth injection (TEI) cutoff-plus-10-seconds and were terminated at entry interface (400 000 ft). Simulated transearth midcourse corrections were targeted to the nominal entry flight-path angle, with longitude and latitude of the entry point

unconstrained, and included the effects of navigation errors, errors in the estimated values for the gravitational constants of the earth and moon, and midcourse execution errors. Venting was not simulated during the transearth phase.

In both the translunar and the transearth simulations MSFN tracking data taken during the two-hour period immediately prior to a planned midcourse correction were not included in the calculation of the required ΔV.

ERROR SOURCES

Navigation Errors

MSFN tracking normal matrices and state transition matrices for the translunar and transearth phase dispersion analyses were prepared using the TAPP IV program. Navigational error sources whose effects were included in both the translunar and transearth analyses were tracking data noise and biases, MSFN tracking station location errors, error in the estimated value for the gravitational constant of the earth, and error in the estimated value for the gravitational constant for the moon. The value of the standard deviation for each of these errors was specified by the MSC Mathematical Physics Branch. In addition, one set of translunar simulations included the effects of venting until entry into the moon's sphere of action (MSA) which occurs at about TLI-plus-54-hours. The second set of translunar simulations and the transearth simulations did not include venting effects.

Midcourse Execution Errors

Translunar and transearth midcourse maneuvers were modeled as impulsive corrections, and it was assumed that all maneuvers are primary guidance, navigation, and control system (PGNCS) guided. The effects of the errors listed below were included in simulated midcourse maneuvers; the errors were modeled to have a normal distribution with mean and standard deviation as indicated. The numerical values were provided by the Guidance and Performance Branch.

Error		Mean	Standard Deviation
Initial thrust vector pointing error	:pitch	0.0	0.42 deg
	:yaw	0.0	0.42 deg
IMU platform alignment error at midcourse burn initiation[a]	:pitch	0.0	1.87×10^{-2} deg
	:roll	0.0	1.87×10^{-2} deg
	:yaw	0.0	1.87×10^{-2} deg
IMU accelerometer bias	:X-axis	0.0	6.56×10^{-3} ft/sec^2
	:Y-axis	0.0	6.56×10^{-3} ft/sec^2
	:Z-axis	0.0	6.56×10^{-3} ft/sec^2
IMU accelerometer scale factor	:X-axis	0.0	1.16×10^{-4}
	:Y-axis	0.0	1.16×10^{-4}
	:Z-axis	0.0	1.16×10^{-4}
Error in SPS thrust magnitude		0.0	66.9 lb
Error in RCS thrust magnitude (2 jet)		-0.2 lb	1.2 lb
SPS tailoff impulse error (equivalent time at full thrust)		0.0	0.04 sec

In addition to these errors, initial vehicle pitch, roll, and yaw attitude errors at maneuver ignition were simulated assuming these errors to be uniformly distributed between -0.5° and 0.5° (the deadband constraints for attitude-hold prior to ignition). Also, the fact that ΔV sensed onboard accumulates in discrete steps of 0.19 fps, rather than as a continous function of actual ΔV, was accounted for in the simulation.

[a]Includes an initial misalignment of 1.11×10^{-2} deg (1σ) and one half hour of drift at a rate of 3.0×10^{-2} deg/hr. The root-mean-square (RMS) of these two values was taken yielding 1.87×10^{-2} deg (1σ).

Nominal weights and engine performance data for the CSM were assumed to be:

Nominal CSM weight (dry), lb	23 811
Nominal propellant weights following TLI, lb .	40 734
Nominal propellant weights following TEI, lb	10 675
Nominal thrust for service propulsion system (SPS), lb	20 908
Nominal specific impulse for SPS, sec	314.2
Nominal thrust (2 jets) for reaction control system (RCS), lb	199.6
Nominal specific impulse for RCS, sec	276.0

Nominal performance values and standard deviations for errors were obtained from references 2 and 3. Curves relating ΔV errors (due to initial thrust vector pointing error) to midcourse burn time were obtained from reference 4.

Injection Errors

A covariance matrix, shown in table I, of actual state vector deviations at TLI-cutoff-plus-15.417-minutes was provided by the Guidance and Performance Branch for the translunar dispersion analysis. The matrix was mapped back to the time of TLI cutoff and used in the Monte Carlo program to generate sample initial state deviations for translunar mission simulations. The covariance matrix of actual post-TEI state deviations, used to produce initial state deviations for the transearth analysis, is also shown. The TEI matrix was also provided by the MSC Guidance and Performance Branch.

Each of the matrices in table I is actually a combined covariance and correlation matrix with covariance elements σ_{ij} in the lower triangular portion and correlation coefficients ρ_{ij} above the diagonal as illustrated below.

$$\begin{bmatrix} (\sigma_x)^2 & & & & & \\ & (\sigma_y)^2 & & & & \\ & & (\sigma_z)^2 & & \rho_{ij} & \\ & & & (\sigma_{\dot{x}})^2 & & \\ & \rho_{ij}\,\sigma_i\sigma_j & & & (\sigma_{\dot{y}})^2 & \\ & & & & & (\sigma_{\dot{z}})^2 \end{bmatrix}$$

where

σ_i = standard deviation of the ith component of the state vector deviation.

ρ_{ij} = correlation coefficient for the ith and j^{th} components

MIDCOURSE DECISION LOGIC

In the translunar and transearth simulations the decision to make or not to make a midcourse correction at each of the specified nominal midcourse times was based on the magnitude of the required ΔV relative to several different threshold values. The first of these thresholds was the midcourse correction threshold (MCCT). A maneuver was not performed unless the magnitude of the required ΔV exceeded this threshold. If $|\overline{\Delta V}_{REQ}| \geq$ MCCT then a midcourse correction was performed. If $|\overline{\Delta V}_{REQ}| \geq$ SPST, the SPS threshold, then the maneuver was performed with the SPS[a]; otherwise the maneuver was performed with the RCS.

Following a midcourse correction with the SPS the magnitude of $\overline{\Delta V}_{RES}$, the residual ΔV ($\overline{\Delta V}_{RES} = \overline{\Delta V}_{REQ} - \overline{\Delta V}_{SENSED}$), was compared with the trim threshold TRIMT and an RCS trim maneuver was performed if $|\overline{\Delta V}_{RES}| \geq$ TRIMT. However, the residual ΔV was not trimmed down to zero but down to the value of TRIMT, in accordance with a policy established by the Data Priority Techniques Working Groups.

---

[a]For transearth simulations all SPS MCC's included an RCS ullage maneuver equal to 4.0 fps. Ullage maneuvers were not performed during the translunar phase.

A diagram of the midcourse decision logic is shown in figure 1. The values of MCCT, SPST, and TRIMT for the four translunar midcourse corrections are given in table II. The values for the four transearth midcourse corrections are shown in table III.

RESULTS

Results from simulations of the translunar and transearth phases of Apollo 8 are presented in the tables and cumulative distribution function (CDF) graphs of appendices A and B, respectively. Each CDF graph shows plotted points from the sample cumulative distribution function for a particular variable. The curve shown on the graphs is a Gaussian distribution curve whose mean and standard deviation are the same as the sample mean and standard deviation for the variable. Comparison of the plotted points and the curve on each of the CDF graphs shows how closely the sample variables approached a Gaussian distribution. If the plotted points and the curve are coincident, this of course indicates that the sample variables were normally distributed.

Summary of Translunar Results

There is a significant difference between the results obtained using venting and those obtained without venting. This difference is especially noticeable in the final deviation in altitude at node. Because of a larger error in the estimated state at the time of the last midcourse correction in the venting case (resulting in a more erroneous midcourse correction than for the no venting case) the dispersion in altitude at node increased when venting was considered. Without venting, the largest positive deviation in altitude at node was about 8 n. mi., and the largest negative deviation was about -7 n. mi., both well within safe limits. When venting was included, the largest positive deviation in node went up to about 21 n. mi., and the largest negative deviation went to about -18 n. mi., or about 42 n. mi. above the lunar surface.

When venting was present a midcourse correction was required at the second midcourse decision time for 46 percent of the simulations; without venting a midcourse correction at this time was required in only 6.5 percent of the simulations. Furthermore, at the fourth midcourse decision time the simulations indicate that with or without venting there is a high probability that midcourse correction will be required. However, with venting this midcourse correction required use of the SPS in 55.5 percent of the simulations as opposed to only 2.5 percent without venting. Such differences are readily attributed to increased deviations in actual state and larger errors in the estimated state

when venting is included. Especially noticeable is the effect of a large increase in error in the estimated state at the time of the third midcourse correction when venting is included. This results in an erroneous commanded third midcourse correction and thereby increases the dispersion of the required corrective velocity at the fourth midcourse correction. The largest fourth midcourse correction increases from 6.7 fps without venting to 28.7 fps with venting. However, the largest total translunar SPS maneuver velocity and the total translunar RCS maneuver velocity are not significantly different for the two cases. The largest total SPS ΔV for all translunar midcourse corrections was 85.80 fps without venting and 95.32 fps with venting; the largest total RCS ΔV was 9.35 fps without venting and 9.87 fps with venting.

Summary of Transearth Results

The most noteworthy results from the transearth simulations are the statistics on required midcourse ΔV. The SPS was used only once during the two hundred transearth simulations which were performed. For eight of the simulations no transearth midcourse corrections were performed and about 18 percent of the simulations accumulated a total ΔV for transearth midcourse corrections of 2.0 fps or less. The largest cumulative ΔV (RCS) obtained was 17.24 fps. These results show injection errors incurred during the TEI burn to be small and correctable (targeting for nominal path angle at entry) at an unexpectedly small cost in ΔV.

Required ΔV during the transearth phase was found to be in a direction which was very nearly perpendicular to the geocentric position vector of the vehicle and in the plane of the trajectory.

Statistics on actual state deviations at entry show that the range of entry flight-path angle was -6.105° to -6.388°. This is well within the entry corridor of -5.7° (zero-lift overshoot) to -7.3° (12-g undershoot) shown in reference 1. Entry azimuth ranged from 112.370° to 112.785°, and entry speed ranged from 36 067.2 fps to 36 075.2 fps. For the Monte Carlo simulations, the nominal values for these variables were

Nominal entry flight-path angle, deg	-6.2485
Nominal entry azimuth, deg	112.6006
Nominal entry speed, fps	36 070.98

The longitude of the entry point, which was not constrained during midcourse corrections, varied over a range of -1.173° to 1.586° from the nominal entry longitude. Entry latitude deviations, which also were not constrained during midcourse corrections, ranged from -0.144° to

0.171°. These deviations give a landing point which is well within the relocation capability (about 1000 n. mi.) of the recovery ship during transearth coast (ref. 5).

CONCLUSIONS

Without venting there is no problem for translunar coast. The probability is very high that only three (and possibly only two) midcourse corrections need be made. The ΔV cost is about as expected and should be no problem in this mission. The maximum deviations in resulting altitude at the moon appears to be safe and should offer no problem to the LOI targeting scheme.

The preliminary results for venting in translunar coast show significant differences from the no-venting case. The probability of making more corrections was high; ΔV cost was slightly higher; resulting deviations at the moon were significantly larger. Some preliminary studies have been conducted with these deviations, and it appears at this point no problem would be incurred by the Real Time Computer Complex (RTCC) LOI targeting processor in targeting out any 1σ deviations at the node in the vent case. As pointed out in the text, however, the effect of venting is principally to increase navigation uncertainties. Just how much of an effect this is depends on real-time navigational procedures.

The transearth results reflect an accurate TEI maneuver resulting in very small midcourse maneuvers. The probability is almost nil that an SPS maneuver need be performed. Deviations at entry interface appeared to be entirely acceptable.

Table 1. Covariance Matrices of Actual Post-Injection State Deviations*

Covariance Matrix of Actual State Deviations at TLI + 15.417 Minutes (ft, ft/sec; Orbit Plane (UVW) Coordinates)

	1	2	3	4	5	6
1	$(4.8240521+04)^2$	7.4936522-01	-3.9534785-02	-6.9284440-01	3.0013554-01	7.7318208-02
2	4.6858998+09	$(1.2962461+05)^2$	7.5593109-04	-9.9553868-01	8.5466931-01	1.6611721-01
3	-5.0757887+07	2.6078454+06	$(2.6614122+04)^2$	-3.9332388-02	1.9854179-03	9.7657143-01
4	-2.6900467+06	-1.0386225+07	-8.4250911+04	$(8.0484476+01)^2$	-8.9210308-01	-2.0362384-01
5	6.0531507+05	4.6316702+06	2.2091039+03	-3.0017824+03	$(4.1807292+01)^2$	1.4480395-01
6	7.4481549+04	4.2998867+05	5.1900446+05	-3.2726207+02	1.2088917+02	(1.9968935+02)

Covariance Matrix of Actual State Deviations Following Transearth Injection (ft, ft/sec; Orbit Plane (UVW) Coordinates)

1	$(1.7982402+03)^2$	-4.9280595-02	-1.1207196-01	3.2423957-01	-7.4374294-01	-1.0454686-01
2	-4.4576211+05	$(5.0301330+03)^2$	6.0212579-02	-8.5692070-01	2.0238160-01	8.6393444-02
3	-1.4649898+06	2.2016922+06	$(7.2692552+03)^2$	-8.1110422-02	1.2116607-01	9.6729878-01
4	2.9517111+03	-2.1821281+04	-2.9848789+03	$(5.0624428+00)^2$	-3.7867647-01	-9.1335890-02
5	-2.5403036+03	1.9335952+03	1.6729616+03	-3.6411916+00	$(1.8993940+00)^2$	1.2861164-01
6	-1.5019540+03	3.4718282+03	5.6175700+04	-3.6940224+00	1.9516113+00	$(7.9891013+00)^2$

*Elements above the diagonal are correlation coefficients.

Table 2. Translunar Midcourse Decision Thresholds

	MCC-1	MCC-2	MCC-3	MCC-4
MCCT (ft/sec)	3.0	1.0	1.0	0.25
SPST (ft/sec)	5.0	5.0	5.0	5.0
TRIMT (ft/sec)	0.25	0.25	0.25	0.0

Table 3. Transearth Midcourse Decision Thresholds

	MCC-1	MCC-2	MCC-3	MCC-4
MCCT (ft/sec)	2.0	2.0	1.0	1.0
SPST (ft/sec)	12.0	12.0	12.0	12.0
TRIMT (ft/sec)	0.2	0.2	0.2	0.2

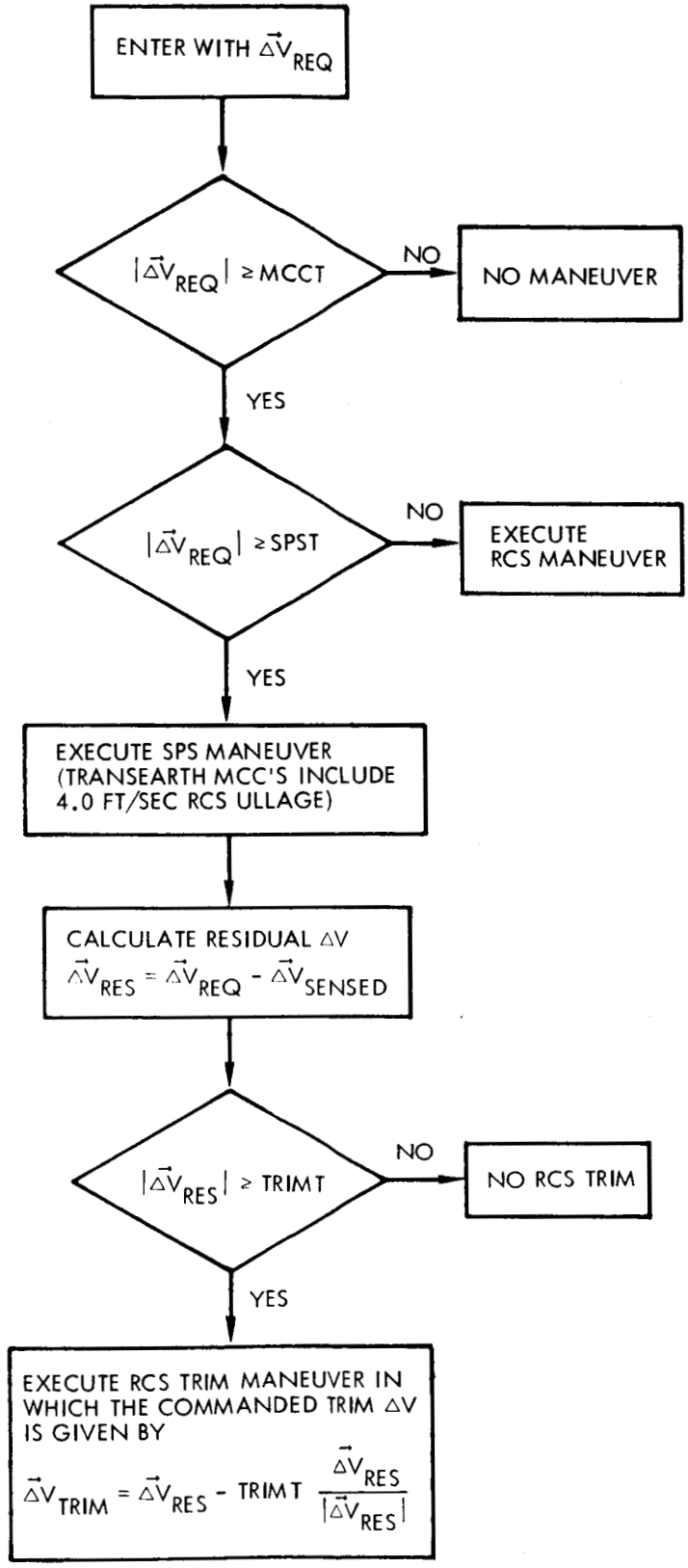


Figure 1. Midcourse Decision Logic

APPENDIX A

STATISTICAL SUMMARY OF TRANSLUNAR SIMULATION RESULTS

TABLE A-I.- Statistical Summary of the First Translunar MCC (TLI +6 Hours)*
Does Not Include Effects of Venting

RCS Summary (Sample Size 158)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	0.63
Standard Deviation	=	0.91
Smallest Sample	=	0.003
25th Percentile Sample	=	0.19
50th Percentile Sample	=	0.38
75th Percentile Sample	=	0.65
90th Percentile Sample	=	1.10
95th Percentile Sample	=	3.39
99th Percentile Sample	=	4.47
Largest Sample	=	4.85

RCS Propellant Expended (lb)		
Mean	=	4.64
Standard Deviation	=	6.79
Smallest Sample	=	0.02
25th Percentile Sample	=	1.35
50th Percentile Sample	=	2.70
75th Percentile Sample	=	4.92
90th Percentile Sample	=	8.22
95th Percentile Sample	=	25.78
99th Percentile Sample	=	33.71
Largest Sample	=	34.00

	Ullage	Maneuver	Trim
RCS Engine Usage:	0	8	150

*Of two hundred translunar cycles simulated, two cycles did not require a corrective velocity in excess of the 3.0-foot-per-second MCC-1 threshold.

TABLE A-I.- Statistical Summary of the First Translunar MCC (TLI +6 Hours)*
Does Not Include Effects of Venting (Concluded)

SPS Summary (Sample Size 190)

Magnitude of SPS ΔV Commanded (ft/sec)		
Mean	=	25.91
Standard Deviation	=	15.95
Smallest Sample	=	5.28
25th Percentile Sample	=	13.42
50th Percentile Sample	=	22.30
75th Percentile Sample	=	36.44
90th Percentile Sample	=	46.20
95th Percentile Sample	=	56.46
99th Percentile Sample	=	84.71
Largest Sample	=	85.80

SPS Propellant Expended (lb)		
Mean	=	165.09
Standard Deviation	=	101.31
Smallest Sample	=	38.02
25th Percentile Sample	=	85.35
50th Percentile Sample	=	144.97
75th Percentile Sample	=	233.38
90th Percentile Sample	=	291.29
95th Percentile Sample	=	361.14
99th Percentile Sample	=	533.00
Largest Sample	=	543.34

	Ullage	Maneuver	Trim
SPS Engine Usage:	0	190	0

*Of two hundred translunar cycles simulated, two cycles did not require a corrective velocity in excess of the 3.0-foot-per-second MCC-1 threshold.

TABLE A-II.- Statistical Summary of the Second Translunar MCC (TLI +25 Hours)*
Does Not Include Effects of Venting

RCS Summary (Sample Size 13)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	1.47
Standard Deviation	=	0.92
Smallest Sample	=	1.00
25th Percentile Sample	=	1.03
50th Percentile Sample	=	1.09
75th Percentile Sample	=	1.43
90th Percentile Sample	=	1.87
95th Percentile Sample	=	4.42
99th Percentile Sample	=	4.42
Largest Sample	=	4.42

RCS Propellant Expended (lb)		
Mean	=	11.00
Standard Deviation	=	7.34
Smallest Sample	=	7.13
25th Percentile Sample	=	7.54
50th Percentile Sample	=	8.19
75th Percentile Sample	=	9.88
90th Percentile Sample	=	14.19
95th Percentile Sample	=	34.30
99th Percentile Sample	=	34.30
Largest Sample	=	34.30

	Ullage	Maneuver	Trim
RCS Engine Usage:	0	13	0

SPS Summary

(No SPS maneuvers were performed.)

*One hundred and eighty seven of the 200 translunar cycles simulated did not require a corrective velocity in excess of the MCC-2 threshold of 1.0-foot-per-second.

TABLE A-III.- Statistical Summary of the Third Translunar MCC (LOI -22 Hours)*
Does Not Include Effects of Venting

RCS Summary (Sample Size 106)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	1.40
Standard Deviation	=	0.267
Smallest Sample	=	1.01
25th Percentile Sample	=	1.17
50th Percentile Sample	=	1.35
75th Percentile Sample	=	1.58
90th Percentile Sample	=	1.81
95th Percentile Sample	=	1.91
99th Percentile Sample	=	2.03
Largest Sample	=	2.07

RCS Propellant Expended (lb)		
Mean	=	10.14
Standard Deviation	=	2.04
Smallest Sample	=	6.91
25th Percentile Sample	=	8.58
50th Percentile Sample	=	9.86
75th Percentile Sample	=	11.52
90th Percentile Sample	=	13.42
95th Percentile Sample	=	13.79
99th Percentile Sample	=	14.75
Largest Sample	=	16.69

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	106	0

SPS Summary

(No SPS maneuvers were performed.)

*Ninety four of the 200 translunar cycles simulated did not require a corrective velocity in excess of the MCC-3 threshold value of 1.0-foot-per-second.

TABLE A-IV.- Statistical Summary of the Fourth Translunar MCC (LOI -8 Hours)*
Does Not Include Effects of Venting

RCS Summary (Sample Size 191)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	1.69
Standard Deviation	=	0.95
Smallest Sample	=	0.05
25th Percentile Sample	=	0.96
50th Percentile Sample	=	1.52
75th Percentile Sample	=	2.21
90th Percentile Sample	=	2.85
95th Percentile Sample	=	3.61
99th Percentile Sample	=	4.74
Largest Sample	=	4.79

RCS Propellant Expended (lb)		
Mean	=	12.37
Standard Deviation	=	7.11
Smallest Sample	=	0.39
25th Percentile Sample	=	7.15
50th Percentile Sample	=	11.13
75th Percentile Sample	=	16.11
90th Percentile Sample	=	20.58
95th Percentile Sample	=	26.37
99th Percentile Sample	=	36.42
Largest Sample	=	36.99

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	186	5

*Nine cycles out of 200 simulated translunar cycles did not exceed the MCC-4 threshold of 0.25-feet-per-second.

TABLE A-IV.- Statistical Summary of the Fourth Translunar MCC (LOI -8 Hours)*
Does Not Include Effects of Venting (Concluded)

SPS Summary (Sample Size 5)

Magnitude of SPS ΔV Commanded (ft/sec)		
Mean	=	5.99
Standard Deviation	=	0.45
Smallest Sample	=	5.55
25th Percentile Sample	=	5.69
50th Percentile Sample	=	5.80
75th Percentile Sample	=	6.24
90th Percentile Sample	=	6.66
95th Percentile Sample	=	6.66
99th Percentile Sample	=	6.66
Largest Sample	=	6.66

SPS Propellant Expended (lb)		
Mean	=	37.94
Standard Deviation	=	3.61
Smallest Sample	=	32.76
25th Percentile Sample	=	36.23
50th Percentile Sample	=	38.19
75th Percentile Sample	=	40.95
90th Percentile Sample	=	41.57
95th Percentile Sample	=	41.57
99th Percentile Sample	=	41.57
Largest Sample	=	41.57

SPS Engine Usage:	Ullage	Maneuver	Trim
	0	5	0

*Nine cycles out of 200 simulated translunar cycles did not exceed the MCC-4 threshold of 0.25-feet-per-second.

TABLE A-V.- Statistical Summary of Cumulative Translunar ΔV and Propellant Expenditures*
Does Not Include Effects of Venting

RCS Summary (Sample Size 200)

Cumulative RCS ΔV Magnitude (ft/sec)		
Mean	=	2.94
Standard Deviation	=	1.44
Smallest Sample	=	0.09
25th Percentile Sample	=	2.07
50th Percentile Sample	=	2.55
75th Percentile Sample	=	3.51
90th Percentile Sample	=	5.05
95th Percentile Sample	=	6.03
99th Percentile Sample	=	8.08
Largest Sample	=	9.35

Cumulative RCS Propellant Expenditures (lb)		
Mean	=	21.56
Standard Deviation	=	10.93
Smallest Sample	=	0.69
25th Percentile Sample	=	15.24
50th Percentile Sample	=	18.53
75th Percentile Sample	=	25.50
90th Percentile Sample	=	35.88
95th Percentile Sample	=	45.40
99th Percentile Sample	=	61.29
Largest Sample	=	72.76

	Ullage	Maneuver	Trim
RCS Engine Usage:	0	313	155

*Of the 200 translunar cycles simulated, 10 cycles did not require any SPS usage.

TABLE A-V.- Statistical Summary of Cumulative Translunar ΔV and Propellant Expenditures*
Does Not Include Effects of Venting (Concluded)

SPS Summary (Sample Size 200)

Cumulative SPS ΔV Magnitude (ft/sec)		
Mean	=	24.76
Standard Deviation	=	16.65
Smallest Sample	=	0.00
25th Percentile Sample	=	12.29
50th Percentile Sample	=	21.60
75th Percentile Sample	=	35.58
90th Percentile Sample	=	45.46
95th Percentile Sample	=	57.09
99th Percentile Sample	=	84.71
Largest Sample	=	85.80

Cumulative SPS Propellant Expenditure (lb)		
Mean	=	157.79
Standard Deviation	=	105.79
Smallest Sample	=	0.00
25th Percentile Sample	=	80.48
50th Percentile Sample	=	138.60
75th Percentile Sample	=	229.16
90th Percentile Sample	=	290.63
95th Percentile Sample	=	361.14
99th Percentile Sample	=	533.00
Largest Sample	=	543.34

	Ullage	Maneuver	Trim
SPS Engine Usage:	0	195	0

*Of the 200 translunar cycles simulated, 10 cycles did not require any SPS usage.

TABLE A-VI.- Sample Covariance Matrices of Required Midcourse ΔV*
Does Not Include Effects of Venting

First Translunar Midcourse Correction (TLI +6 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)

	1	2	3
1	2.0816288E+1		
2	-8.6725302E-1	2.1035509E+1	
3	-8.4124541E-1	6.3881318E-1	2.0296119E-0

Second Translunar Midcourse Correction (TLI +25 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)

	1	2	3
1	5.2397017E-1		
2	-6.0158293E-2	3.6717532E-1	
3	1.7628374E-2	-4.8594875E-1	3.5089330E-1

*Statistics based on 200 samples.

Matrices are in normalized form; i.e., the diagonal elements are the standard deviations rather than the variances, and the off-diagonal elements are the correlation coefficients.

TABLE A-VI.- Sample Covariance Matrices of Required Midcourse ΔV* Does Not Include Effects of Venting (Concluded)

Third Translunar Midcourse Correction (LOI -22 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)

	1	2	3
1	7.9034687E-1		
2	-2.4614446E-1	5.3558837E-1	
3	4.4467357E-2	-2.1405653E-1	6.0856366E-1

Fourth Translunar Midcourse Correction (LOI -8 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Selenocentric UVW Coordinates)

	1	2	3
1	1.5065109E-0		
2	4.3697642E-1	8.6316866E-1	
3	-6.4440245E-1	-4.7057434E-1	1.2192940E-0

*Statistics based on 200 samples.

Matrices are in normalized form; i.e., the diagonal elements are the standard deviations rather than the variances, and the off-diagonal elements are the correlation coefficients.

TABLE A-VII.- Statistical Summary of Post-Maneuver Actual State Deviations Propagated to Node Venting Effects Not Included*

After First Translunar Midcourse Correction (TLI +6 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(6.3590685+04)^2$	-3.9874144-01	-3.2716858-01	5.3886780-01	-9.9941993-01	2.9801624-01
2	-3.9779773+09	$(1.5688356+05)^2$	5.2961565-01	-9.8712879-01	4.2228404-01	-5.1138671-01
3	-4.3177334+08	1.7243642+09	$(2.0753472+04)^2$	-5.4063059-01	3.3537746-01	-9.0141102-01
4	3.2628678+06	-1.4746026+07	-1.0683539+06	$(9.5219029+01)^2$	-5.6078067-01	5.2838418-01
5	-2.2756327+06	2.3721533+06	2.4922138+05	-1.9119541+03	$(3.5806400+01)^2$	-3.1477095-01
6	5.1399671+05	-2.1759745+06	-5.0738841+05	1.3645846+03	-3.0569069+02	$(2.7122324+01)^2$

After Second Translunar Midcourse Correction (TLI + 25 Hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(5.0830965+04)^2$	-5.2067100-01	-3.5985590-01	6.1893274-01	-9.9915215-01	3.4323612-01
2	-4.1195199+09	$(1.5565205+05)^2$	5.3199653-01	-9.9256365-01	5.4593000-01	-5.1123253-01
3	-4.1528846+08	1.8799943+09	$(2.2703503+04)^2$	-5.3781872-01	3.6944184-01	-9.1663677-01
4	2.9656547+06	-1.4563374+07	-1.1510058+06	$(9.4264630+01)^2$	-6.4252466-01	5.2532313-01
5	-1.4641818+06	2.4497785+06	2.4180984+05	-1.7461180+03	$(2.8829360+01)^2$	-3.6206534-01
6	5.1495029+05	-2.3486445+06	-6.1423437+05	1.4615687+03	-3.0808170+02	$(2.9515079+01)^2$

*All statistics based on 200 samples. Units are feet and feet per second; UVW coordinates.

**Diagonal elements are variances; elements above the diagonal are correlation coefficients; elements below the diagonal are covariances.

TABLE A-VII.- Statistical Summary of Post-Maneuver Actual State Deviations Propagated to Node Venting Effects Not Included* (Concluded)

After Third Translunar Midcourse Correction (LOI-22 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(2.6224458+04)^2$	-7.4897128-01	-3.2462611-01	7.8740029-01	-9.9780115-01	3.0658048-01
2	-2.3510242+09	$(1.1969759+05)^2$	6.2322277-01	-9.9770342-01	7.7176782-01	-5.9327497-01
3	-2.1161541+08	1.8543257+09	$(2.4857492+04)^2$	-6.0973208-01	3.5014085-01	-9.3507978-01
4	1.4859531+06	-8.5938916+06	-1.0906850+06	$(7.1961963+01)^2$	-8.0952791-01	5.9026002-01
5	-3.9840426+05	1.4065187+06	1.3251759+05	-8.8696866+02	$(1.5225566+01)^2$	-3.4657785-01
6	2.6515277+05	-2.3420865+06	-7.6659763+05	1.4009023+03	-1.7403466+02	$(3.2980824+01)^2$

After Fourth Translunar Midcourse Correction (LOI - 8 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(1.8036775+04)^2$	-9.6186615-01	-6.1840309-01	9.6440856-01	-9.9497132-01	5.3817873-01
2	-1.7919729+09	$(1.0328991+05)^2$	7.9193300-01	-9.9923203-01	9.6789307-01	-7.2370524-01
3	-3.0347004+08	2.2255205+09	$(2.7207288+04)^2$	-7.8316784-01	6.4366712-01	-9.3824251-01
4	1.0826719+06	-6.4239355+06	-1.3262244+06	$(6.2241051+01)^2$	-9.7120245-01	7.2467282-01
5	-1.9468663+05	1.0845558+06	1.8998234+05	-6.5577271+02	$(1.0848423+01)^2$	-5.8121737-01
6	3.3629616+05	-2.5897395+06	-8.8437578+05	1.5626271+03	-2.1844479+02	$(3.4644673+01)^2$

*All statistics based on 200 samples. Units are feet and feet per second; UVW coordinates.

**Diagonal elements are variances; elements above the diagonal are correlation coefficients; elements below the diagonal are covariances.

TABLE A-VIII.- Statistical Summary of Deviations in Altitude at Node Does Not Include Effects of Venting

Deviations in Altitude at Node (ft)		
Mean	=	-785.9
Standard Deviation	=	18,036.8
Smallest Sample	=	-40,305.2
25th Percentile Sample	=	-12,709.6
50th Percentile Sample	=	-722.2
75th Percentile Sample	=	9,701.4
90th Percentile Sample	=	21,034.0
95th Percentile Sample	=	29,787.4
99th Percentile Sample	=	46,314.9
Largest Sample	=	49,714.6

TABLE A-IX.- Statistical Summary of the First Translunar MCC (TLI +6 Hours)*
Includes Effects of Venting

RCS Summary (Sample Size 152)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	0.61
Standard Deviation	=	0.80
Smallest Sample	=	0.0006
25th Percentile Sample	=	0.20
50th Percentile Sample	=	0.39
75th Percentile Sample	=	0.66
90th Percentile Sample	=	1.06
95th Percentile Sample	=	3.04
99th Percentile Sample	=	3.89
Largest Sample	=	4.65

RCS Propellant Expended (lb)		
Mean	=	4.50
Standard Deviation	=	6.12
Smallest Sample	=	0.005
25th Percentile Sample	=	1.37
50th Percentile Sample	=	2.92
75th Percentile Sample	=	4.76
90th Percentile Sample	=	7.56
95th Percentile Sample	=	21.68
99th Percentile Sample	=	29.59
Largest Sample	=	36.85

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	8	144

*Two hundred translunar cycles were simulated. For two of these cycles, the magnitude of the required corrective velocity was less than the 3.0-foot-per-second maneuver threshold.

TABLE A-IX.- Statistical Summary of the First Translunar MCC (TLI +6 Hours)*
Includes Effects of Venting (Concluded)

SPS Summary (Sample Size 190)

Magnitude of SPS ΔV Commanded (ft/sec)		
Mean	=	25.89
Standard Deviation	=	16.18
Smallest Sample	=	5.08
25th Percentile Sample	=	13.31
50th Percentile Sample	=	21.89
75th Percentile Sample	=	36.25
90th Percentile Sample	=	45.63
95th Percentile Sample	=	56.42
99th Percentile Sample	=	83.25
Largest Sample	=	87.45

SPS Propellant Expended (lb)		
Mean	=	165.03
Standard Deviation	=	102.69
Smallest Sample	=	31.66
25th Percentile Sample	=	84.80
50th Percentile Sample	=	137.86
75th Percentile Sample	=	231.10
90th Percentile Sample	=	288.18
95th Percentile Sample	=	361.93
99th Percentile Sample	=	523 75
Largest Sample	=	553.79

	Ullage	Maneuver	Trim
SPS Engine Usage:	0	190	0

*Two hundred translunar cycles were simulated. For two of these cycles, the magnitude of the required corrective velocity was less than the 3.0-foot-per-second maneuver threshold.

TABLE A-X.- Statistical Summary of the Second Translunar MCC (TLI +25 Hours)*
Includes Effects of Venting

RCS Summary (Sample Size 92)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	1.61
Standard Deviation	=	0.51
Smallest Sample	=	1.00
25th Percentile Sample	=	1.27
50th Percentile Sample	=	1.50
75th Percentile Sample	=	1.85
90th Percentile Sample	=	2.19
95th Percentile Sample	=	2.63
99th Percentile Sample	=	3.89
Largest Sample	=	3.89

RCS Propellant Expended (lb)		
Mean	=	11.82
Standard Deviation	=	3.77
Smallest Sample	=	6.82
25th Percentile Sample	=	9.48
50th Percentile Sample	=	10.87
75th Percentile Sample	=	13.60
90th Percentile Sample	=	16.34
95th Percentile Sample	=	18.64
99th Percentile Sample	=	29.39
Largest Sample	=	29.39

	Ullage	Maneuver	Trim
RCS Engine Usage	0	92	0

SPS Summary

(No SPS maneuvers were performed.)

*Two hundred translunar cycles were simulated. For 108 of these cycles, the required corrective velocity magnitudes were less than the 1.0-foot-per-second MCC-2 threshold.

TABLE A-XI.- Statistical Summary of the Third Translunar MCC (LOI - 22 Hours)*
Includes Effects of Venting

RCS Summary (Sample Size 167)

Magnitude of RCS ΔV Commanded (ft/sec)			RCS Propellant Expended (lb)		
Mean	=	2.14	Mean	=	15.44
Standard Deviation	=	0.81	Standard Deviation	=	5.89
Smallest Sample	=	0.01	Smallest Sample	=	0.10
25th Percentile Sample	=	1.58	25th Percentile Sample	=	11.14
50th Percentile Sample	=	2.06	50th Percentile Sample	=	14.77
75th Percentile Sample	=	2.64	75th Percentile Sample	=	19.09
90th Percentile Sample	=	3.14	90th Percentile Sample	=	23.99
95th Percentile Sample	=	3.57	95th Percentile Sample	=	26.23
99th Percentile Sample	=	4.57	99th Percentile Sample	=	31.64
Largest Sample	=	4.64	Largest Sample	=	33.11

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	164	3

SPS Summary (3 Samples Only)

Magnitude of SPS ΔV Commanded (ft/sec)	SPS Propellant Expended(lb)
5.04	31.41
5.16	32.16
5.34	33.28

SPS Engine Usage:	Ullage	Maneuver	Trim
	0	3	0

*Two hundred translunar cycles were simulated. For 33 of these cycles, the magnitude of the required corrective velocity did not exceed the 1.0-foot-per-second MCC-3 threshold.

TABLE A-XII.- Statistical Summary of the Fourth Translunar MCC (LOI -8 Hours) Includes Effects of Venting

RCS Summary (Sample Size 200)

Magnitude of RCS ΔV Commanded (ft/sec)			RCS Propellant Expended (lb)		
Mean	=	1.35	Mean	=	9.84
Standard Deviation	=	1.35	Standard Deviation	=	9.97
Smallest Sample	=	0.005	Smallest Sample	=	0.04
25th Percentile Sample	=	0.32	25th Percentile Sample	=	2.29
50th Percentile Sample	=	0.68	50th Percentile Sample	=	5.01
75th Percentile Sample	=	2.17	75th Percentile Sample	=	15.93
90th Percentile Sample	=	3.60	90th Percentile Sample	=	25.92
95th Percentile Sample	=	4.14	95th Percentile Sample	=	31.54
99th Percentile Sample	=	4.78	99th Percentile Sample	=	38.57
Largest Sample	=	4.78	Largest Sample	=	38.61

	Ullage	Maneuver	Trim
RCS Engine Usage:	0	89	111

TABLE A-XII.- Statistical Summary of the Fourth Translunar MCC (LOI -8 Hours) Includes Effects of Venting (Concluded)

SPS Summary (Sample Size 111)

Magnitude of SPS ΔV Commanded (ft/sec)		
Mean	=	10.73
Standard Deviation	=	4.81
Smallest Sample	=	5.03
25th Percentile Sample	=	6.78
50th Percentile Sample	=	9.75
75th Percentile Sample	=	12.80
90th Percentile Sample	=	16.91
95th Percentile Sample	=	21.33
99th Percentile Sample	=	24.40
Largest Sample	=	28.71

SPS Propellant Expended (lb)		
Mean	=	67.75
Standard Deviation	=	30.74
Smallest Sample	=	26.69
25th Percentile Sample	=	43.78
50th Percentile Sample	=	61.63
75th Percentile Sample	=	81.68
90th Percentile Sample	=	105.77
95th Percentile Sample	=	131.24
99th Percentile Sample	=	153.85
Largest Sample	=	184.19

SPS Engine Usage:	Ullage	Maneuver	Trim
	0	111	0

TABLE A-XIII.- Statistical Summary of Cumulative ΔV and Propellant Expenditures*
Includes Effects of Venting

RCS Summary (Sample Size 200)

Cumulative RCS ΔV Magnitude (ft/sec)		
Mean	=	4.34
Standard Deviation	=	1.74
Smallest Sample	=	0.88
25th Percentile Sample	=	3.08
50th Percentile Sample	=	4.31
75th Percentile Sample	=	5.41
90th Percentile Sample	=	6.60
95th Percentile Sample	=	7.46
99th Percentile Sample	=	8.97
Largest Sample	=	9.87

Cumulative RCS Propellant Expenditure (lb)		
Mean	=	31.58
Standard Deviation	=	12.79
Smallest Sample	=	7.39
25th Percentile Sample	=	21.39
50th Percentile Sample	=	30.56
75th Percentile Sample	=	39.57
90th Percentile Sample	=	49.05
95th Percentile Sample	=	55.78
99th Percentile Sample	=	67.31
Largest Sample	=	68.97

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	353	258

*Of the 200 simulated translunar cycles, 4 did not require any SPS usage.

TABLE A-XIII.- Statistical Summary of Cumulative ΔV and Propellant Expenditures* Includes Effects of Venting (Concluded)

SPS Summary (Sample Size 200)

Cumulative SPS ΔV Magnitude (ft/sec)		
Mean	=	30.62
Standard Deviation	=	18.42
Smallest Sample	=	0.00
25th Percentile Sample	=	18.28
50th Percentile Sample	=	27.63
75th Percentile Sample	=	41.25
90th Percentile Sample	=	55.49
95th Percentile Sample	=	66.66
99th Percentile Sample	=	93.70
Largest Sample	=	95.32

Cumulative SPS Propellant Expenditure (lb)		
Mean	=	194.83
Standard Deviation	=	116.62
Smallest Sample	=	0.00
25th Percentile Sample	=	117.22
50th Percentile Sample	=	175.61
75th Percentile Sample	=	262.22
90th Percentile Sample	=	355.03
95th Percentile Sample	=	416.79
99th Percentile Sample	=	593.10
Largest Sample	=	608.35

	Ullage	Maneuver	Trim
SPS Engine Usage:	0	304	0

*Of the 200 simulated translunar cycles, 4 did not require any SPS usage.

TABLE A-XIV.- Sample Covariance Matrices of Required Midcourse ΔV* Includes Effects of Venting

First Translunar Midcourse Correction (TLI +6 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)

	1	2	3
1	2.0941315E+1		
2	-8.6515345E-1	2.1046519E+1	
3	-8.2777901E-1	6.3536308E-1	2.0329174E-0

Second Translunar Midcourse Correction (TLI +25 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)

	1	2	3
1	7.5598531E-1		
2	-1.2252737E-1	3.7998470E-1	
3	7.3042212E-1	-2.3201395E-1	9.1540990E-1

*Statistics based on 200 samples.

Matrices are in normalized form; i. e., the diagonal elements are the standard deviations rather than the variances, and the off-diagonal elements are the correlation coefficients.

TABLE A-XIV.- Sample Covariance Matrices of Required Midcourse ΔV* Includes Effects of Venting (Concluded)

Third Translunar Midcourse Correction (LOI -22 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)

	1	2	3
1	1.1228851E-0		
2	2.5062925E-1	4.4585825E-1	
3	8.5204518E-1	4.0199682E-1	1.8484177E-0

Fourth Translunar Midcourse Correction (LOI -8 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Selenocentric UVW Coordinates)

	1	2	3
1	6.6513136E-0		
2	9.2671886E-1	1.4019440E-0	
3	-9.9092811E-1	-9.2795995E-1	5.8588085E-0

*Statistics based on 200 samples.

Matrices are in normalized form; i. e., the diagonal elements are the standard deviations rather than the variances, and the off-diagonal elements are the correlation coefficients.

TABLE A-XV.- Statistical Summary of Post-Maneuver Actual State Deviations Propagated to Node Venting Effects Included*

After First Translunar Midcourse Correction (TLI + 6 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(1.4625724+05)^2$	-1.9115458-01	3.5194847-01	5.4417266-01	-9.9987436-01	-3.4017411-01
2	-4.3478835+09	$(1.5551627+05)^2$	4.3168097-01	-9.2726348-01	2.0325232-01	-4.2132827-01
3	1.2658980+09	1.6509770+09	$(2.4592477+04)^2$	-2.3245362-01	-3.4651710-01	-9.2785186-01
4	8.0592728+06	-1.4602283+07	-5.7886913+05	$(1.0126090+02)^2$	-5.5461966-01	2.3588279-01
5	-1.1912286+07	2.5748010+06	-6.9415952+05	-4.5747710+03	$(8.1457734+01)^2$	3.3172145-01
6	-1.5747468+06	-2.0739035+06	-7.2222587+05	7.5601454+02	8.5525971+02	$(3.1651341+01)^2$

After Second Translunar Midcourse Correction (TLI + 25 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(7.8277358+04)^2$	4.5786408-01	-3.9806831-01	-1.4608198-01	-7.6403674-01	-3.1075843-01
2	9.7159527+09	$(2.7108946+05)^2$	6.2890448-02	-9.1832924-01	-2.3022804-01	-7.9049340-01
3	-2.9447079+09	1.6111864+09	$(9.4503625+04)^2$	-4.1438082-01	-1.9052136-01	-4.8335496-01
4	-1.5493907+06	-3.3731774+07	-5.3061101+06	$(1.3549652+02)^2$	1.3841580-01	8.3467893-01
5	-1.9632339+06	-2.0487668+06	-5.9103579+05	6.1565219+02	$(3.2826278+01)^2$	3.6001208-01
6	-1.4243817+06	-1.2548106+07	-2.6747422+06	6.6223919+03	6.9199985+02	$(5.8555447+01)^2$

*All statistics based on 200 samples. Units are feet and feet per second; UVW coordinates.

**Diagonal elements are variances; elements above the diagonal are correlation coefficients; elements below the diagonal are covariances.

TABLE A-XV.- Statistical Summary of Post-Maneuver Actual State Deviations Propagated to Node Venting Effects Included*

After Third Translunar Midcourse Correction (LOI - 22 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(6.8650177+04)^2$	-9.7922789-91	-9.0208437-01	9.8149408-01	-9.9960010-01	8.8773058-01
2	-3.4539281+10	$(5.1379263+05)^2$	9.4777909-01	-9.9990749-01	9.8299412-01	-9.3411372-01
3	-4.0517526+09	3.1860245+10	$(6.5426564+04)^2$	-9.4623827-01	9.0857941-01	-9.8913974-01
4	2.0481244+07	-1.5616176+08	-1.8818353+07	$(3.0396739+02)^2$	-9.8512278-01	9.3350166-01
5	-2.8771623+06	2.1175574+07	2.4923752+06	-1.2554915+04	$(4.1927254+01)^2$	-8.9660161-01
6	4.8942837+06	-3.8543746+07	-5.1973034+06	2.2788115+04	-3.0189938+03	$(8.0309385+01)^2$

After Fourth Translunar Midcourse Correction (LOI - 8 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Node**

	1	2	3	4	5	6
1	$(4.0687762+04)^2$	-9.6605859-01	-4.3358369-05	9.7552039-01	-9.9527525-01	2.4315224-01
2	-6.9126907+09	$(1.7586517+05)^2$	2.4448936-01	-9.9883800-01	9.8047905-01	-4.5252050-01
3	-5.3863528+04	1.3127979+09	$(3.0532196+04)^2$	-2.0700008-01	6.6709665-02	-8.9495929-01
4	4.3867951+06	-1.9414316+07	-6.9851505+05	$(1.1052160+02)^2$	-9.8662863-01	4.3027586-01
5	-8.9476962+05	3.8099773+06	4.5003991+04	-2.4093790+03	$(2.2095519+01)^2$	-2.9947047-01
6	3.6403969+05	-2.9283619+06	-1.0054673+06	1.7498500+03	-2.4348088+02	$(3.6796511+01)^2$

*All statistics based on 200 samples. Units are feet and feet per second; UVW coordinates.

**Diagonal elements are variances; elements above the diagonal are correlation coefficients; elements below the diagonal are covariances.

TABLE A-XVI.- Statistical Summary of Deviation in Altitude at Node Includes Effects of Venting

Deviation in Altitude at Node (ft)		
Mean	=	-682.4
Standard Deviation	=	40,687.8
Smallest Sample	=	-109,183.1
25th Percentile Sample	=	-26,288.1
50th Percentile Sample	=	-1,919.5
75th Percentile Sample	=	27,311.7
90th Percentile Sample	=	53,376.3
95th Percentile Sample	=	66,279.1
99th Percentile Sample	=	105,065.6
Largest Sample	=	128,555.4

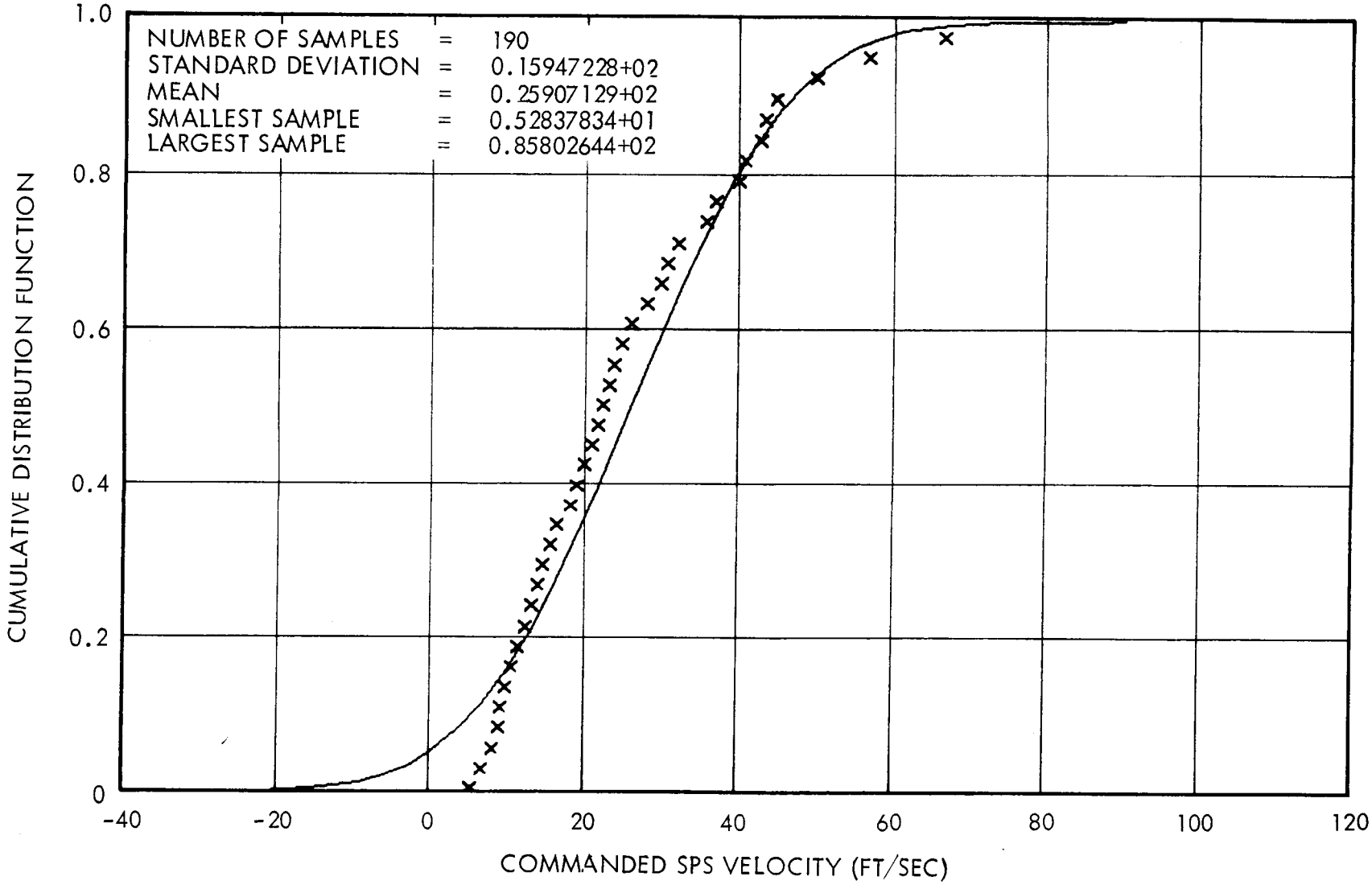


Figure A-1.- Cumulative Distribution of Commanded SPS Velocity (Without Venting) for MCC1

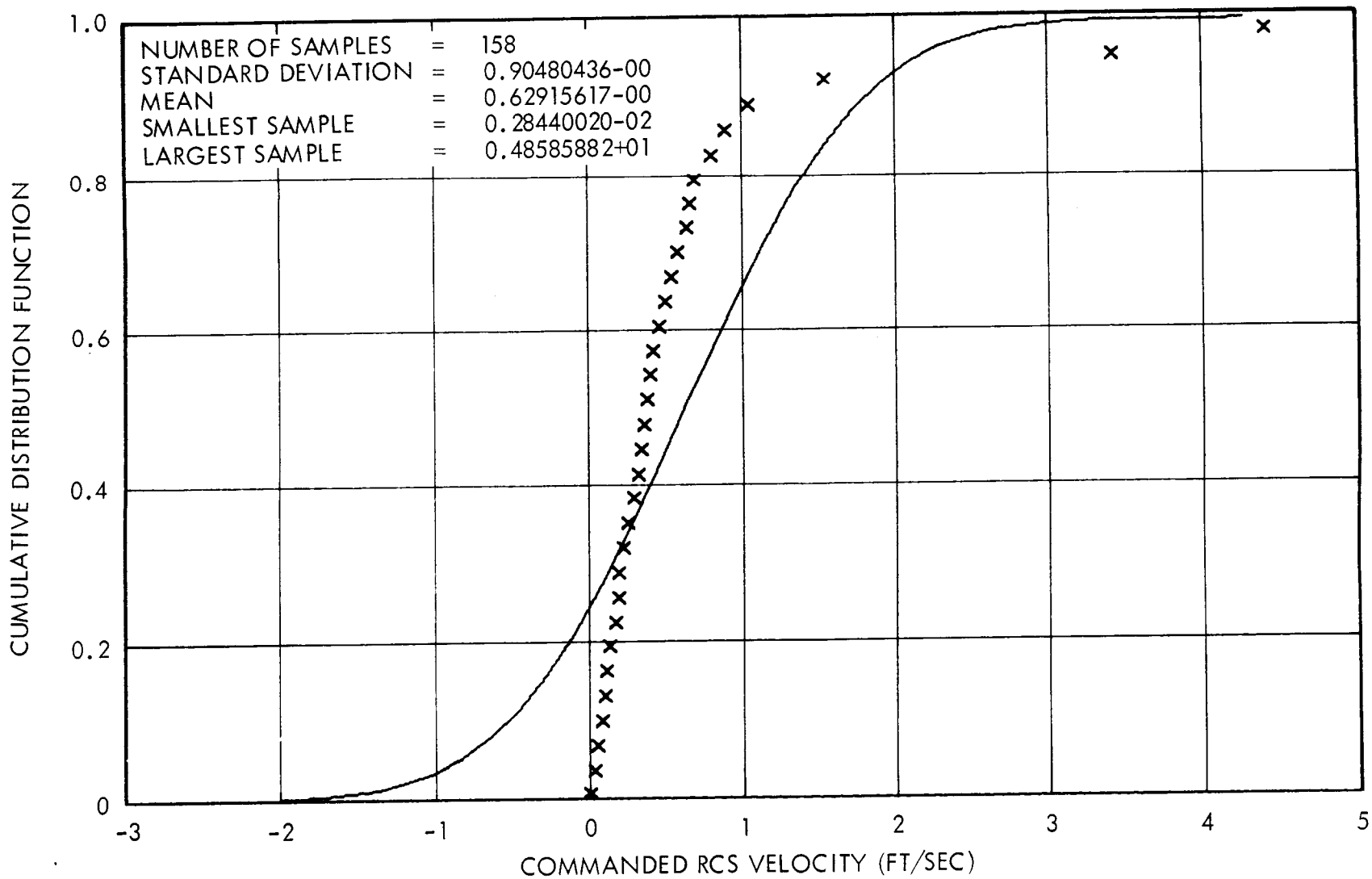


Figure A-2.- Cumulative Distribution of Commanded RCS Velocity (Without Venting) for MCC1

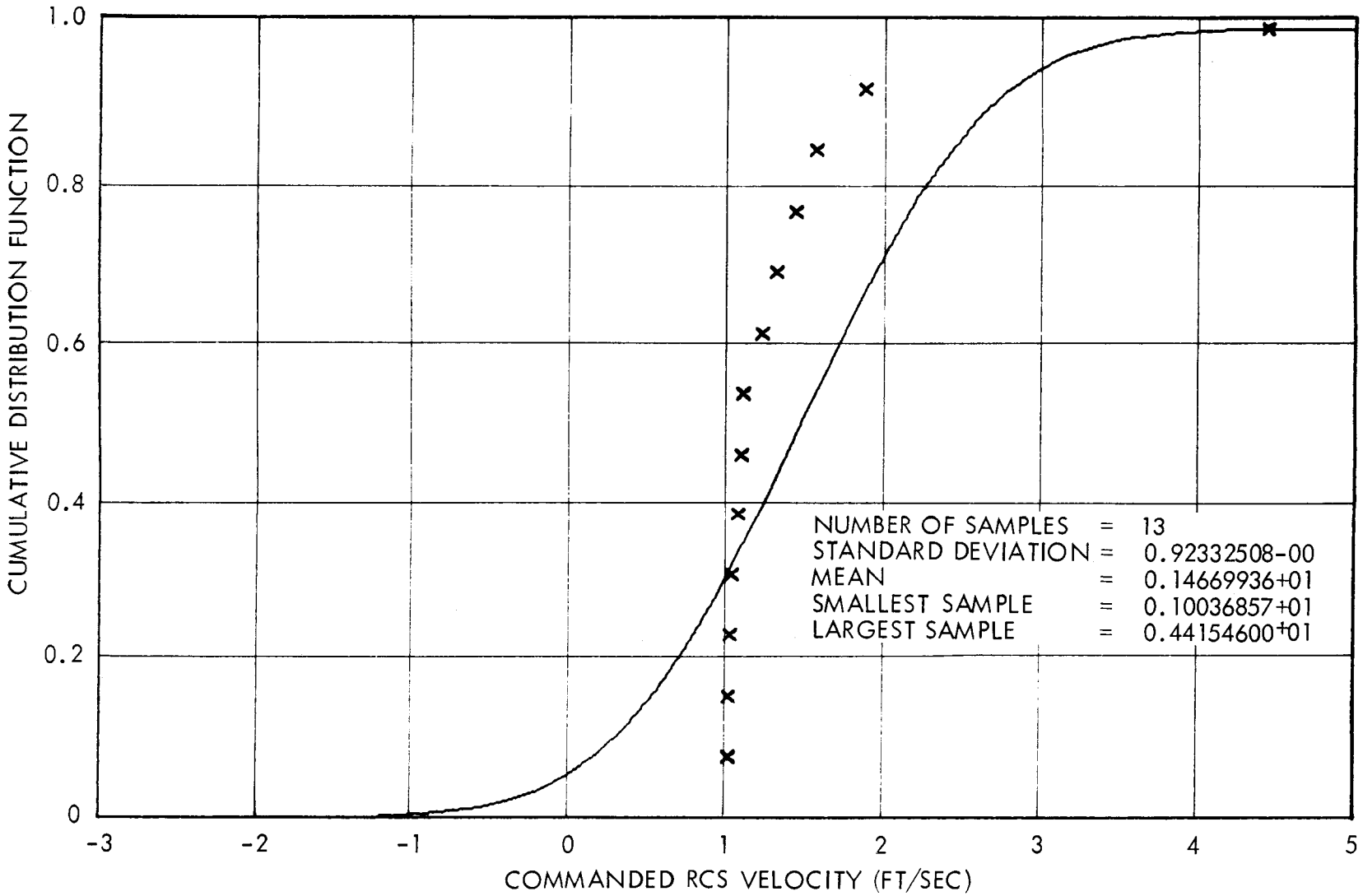


Figure A-3.- Cumulative Distribution of Commanded RCS Velocity (Without Venting) for MCC2

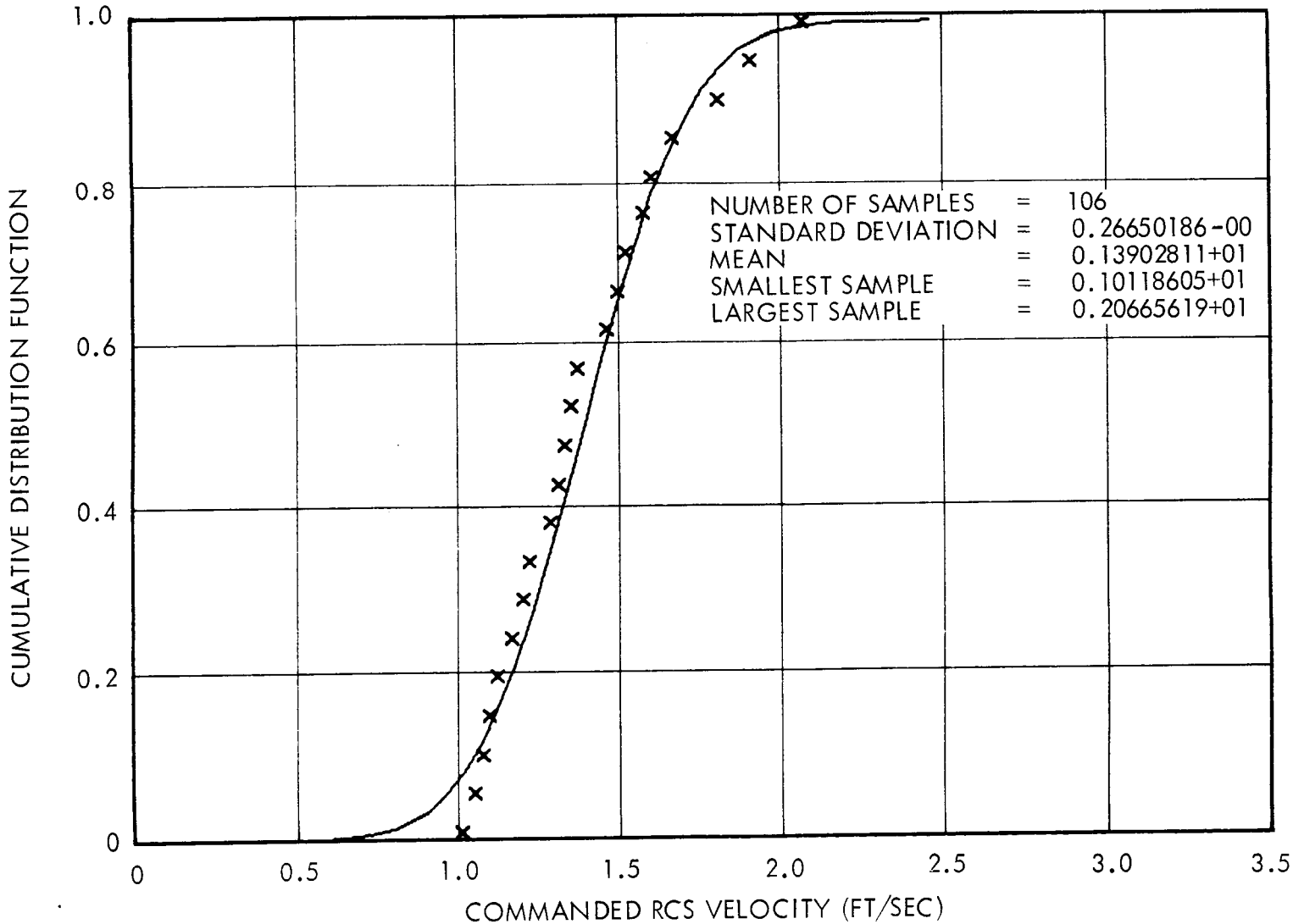


Figure A-4.- Cumulative Distribution of Commanded RCS Velocity (Without Venting) for MCC3

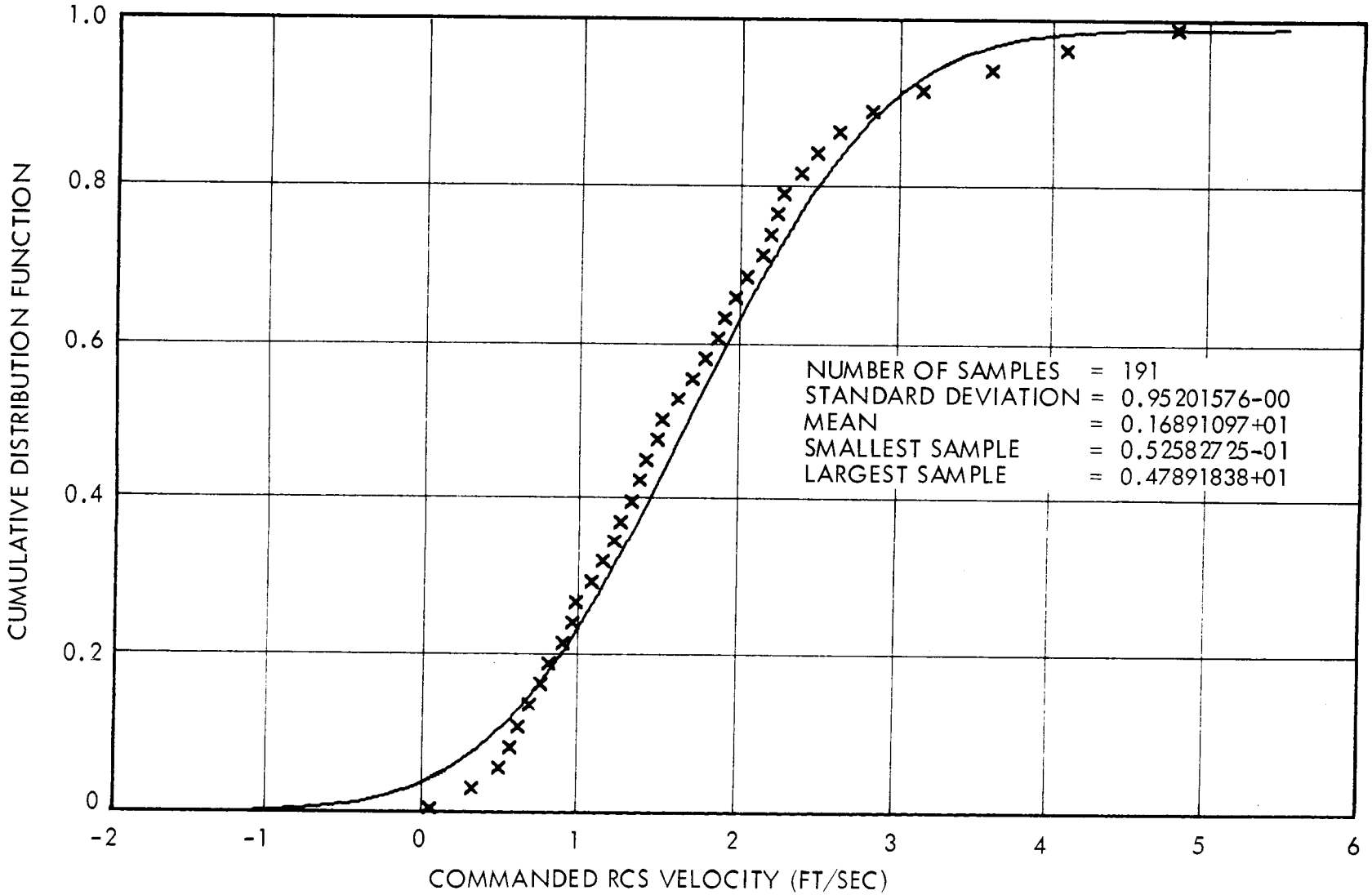


Figure A-5.- Cumulative Distribution of Commanded RCS Velocity (Without Venting) for MCC4

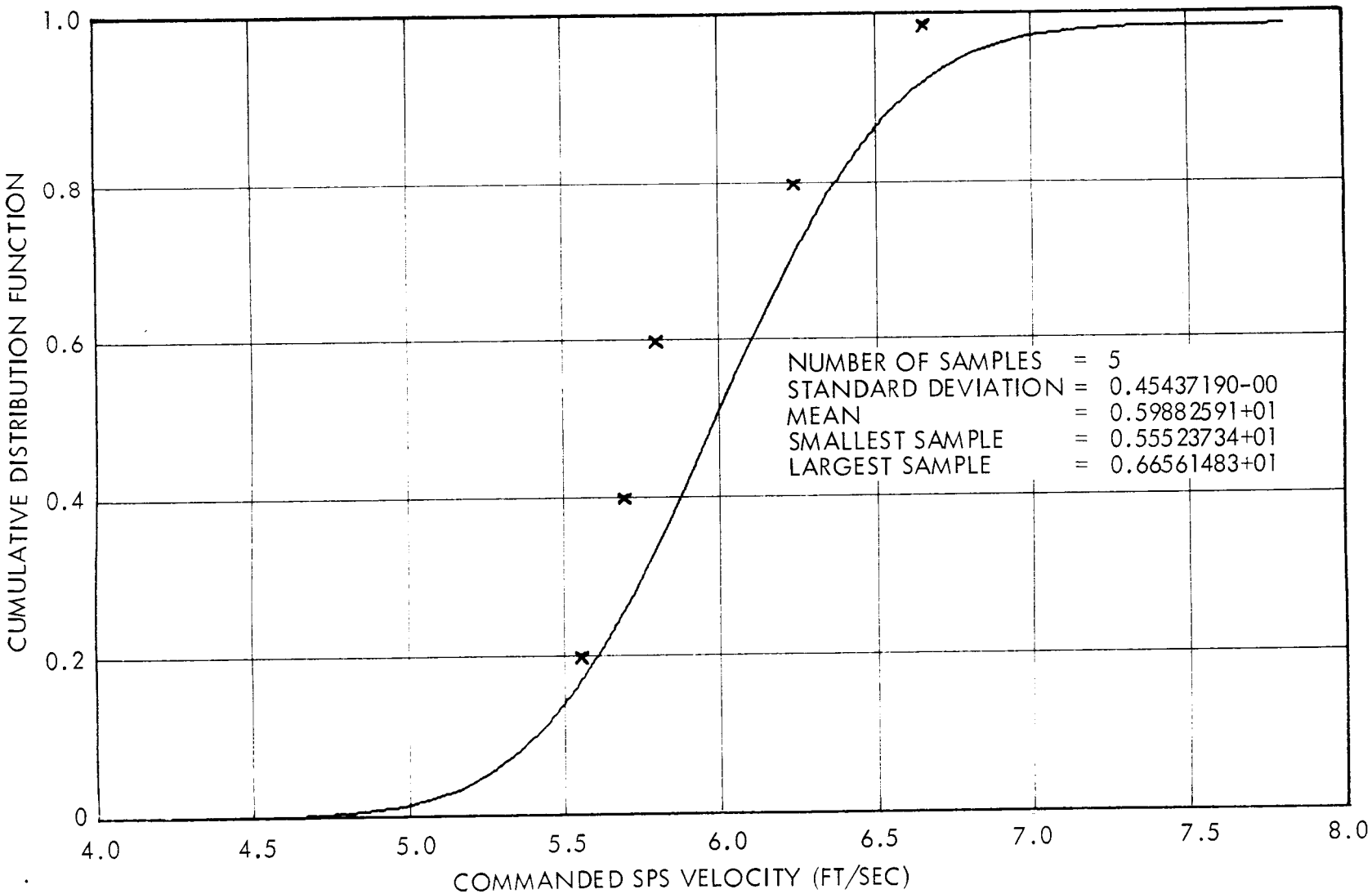


Figure A-6.- Cumulative Distribution of Commanded SPS Velocity (Without Venting) for MCC4

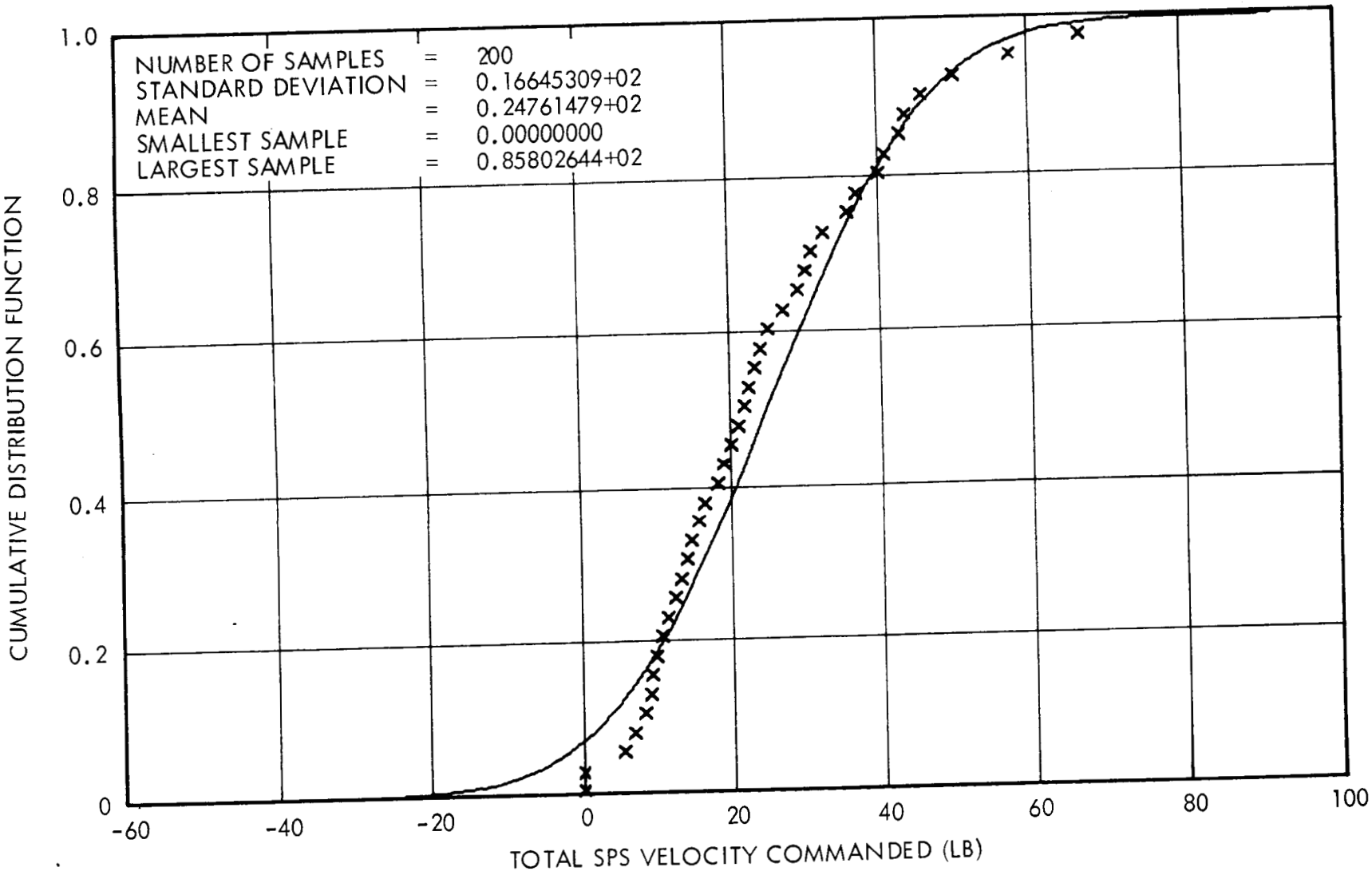


Figure A-7.- Cumulative Distribution of Total SPS Velocity Commanded (Without Venting)

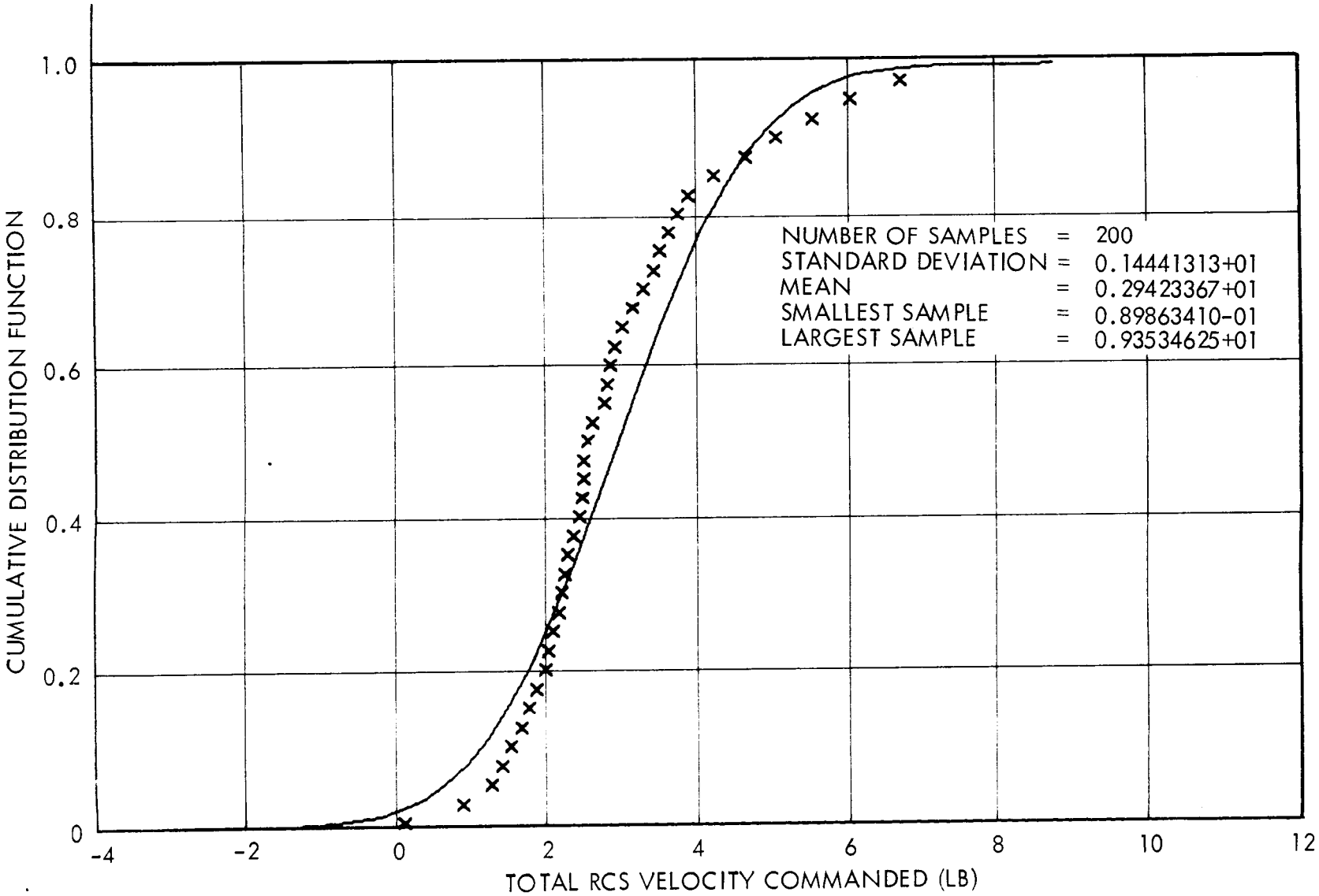


Figure A-8.- Cumulative Distribution of Total RCS Velocity Commanded (Without Venting)

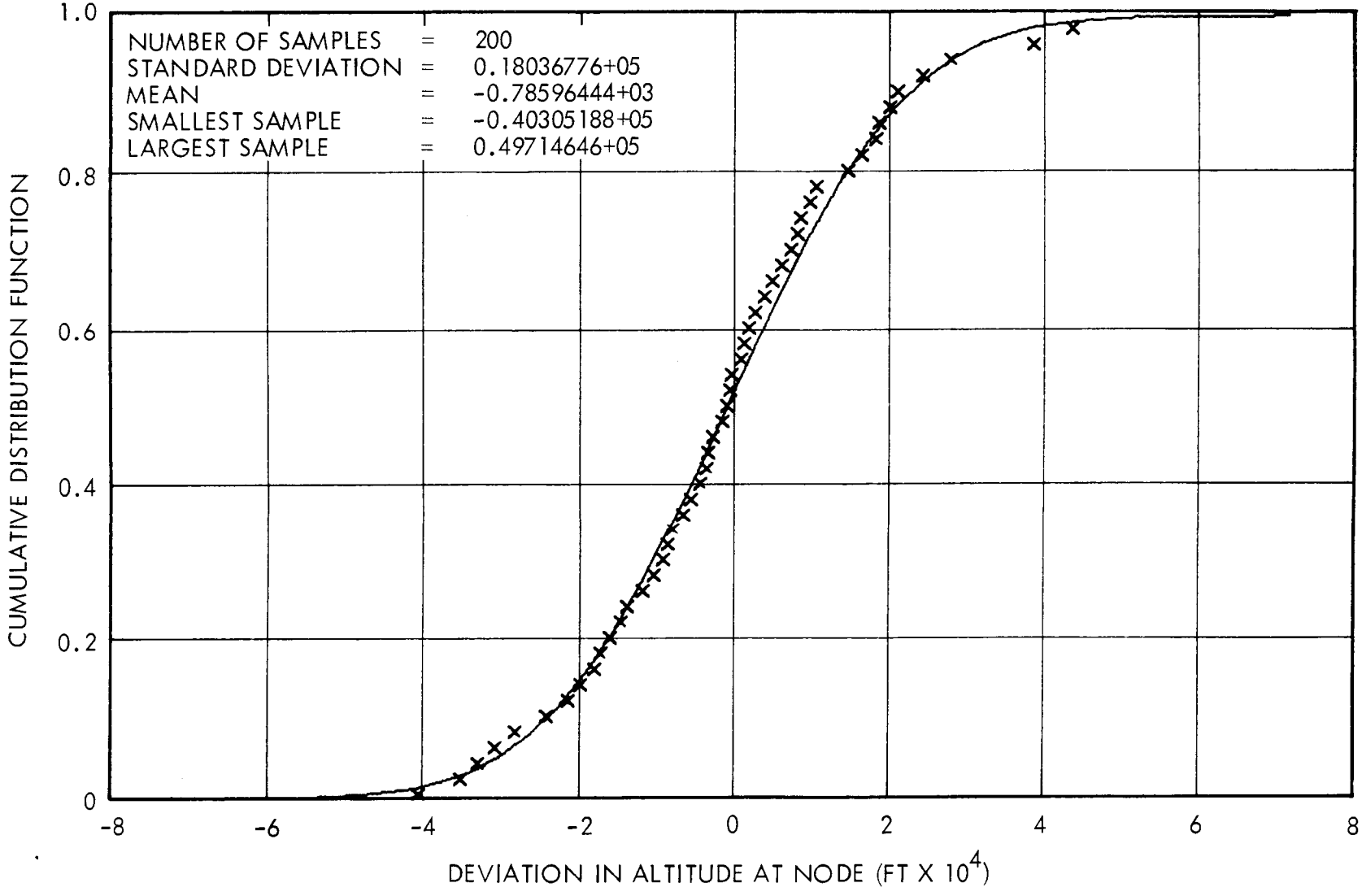


Figure A-9.- Cumulative Distribution of Deviation in Altitude at Node (Without Venting)

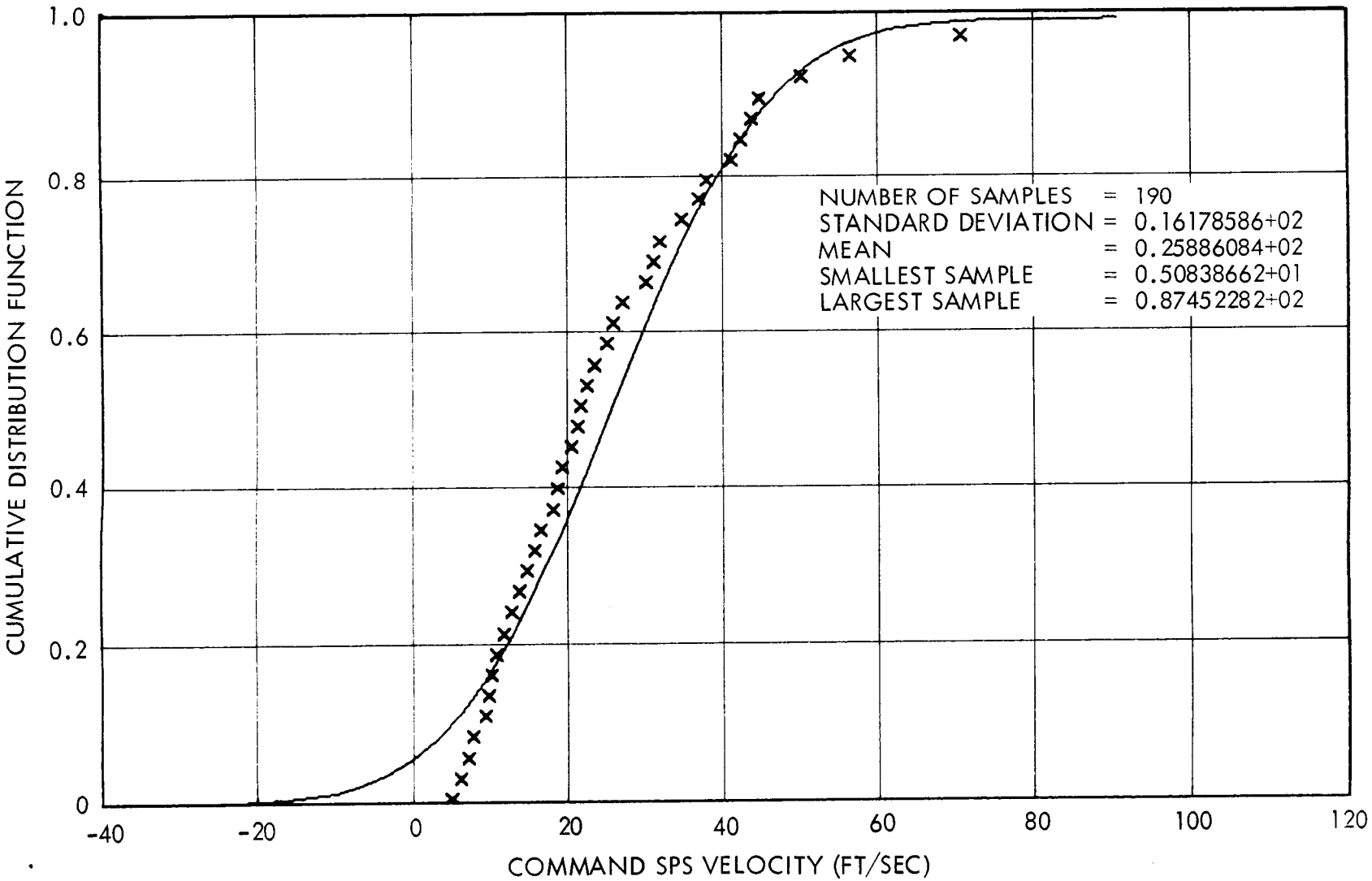


Figure A-10.- Cumulative Distribution of Commanded SPS Velocity (With Venting) for MCC1

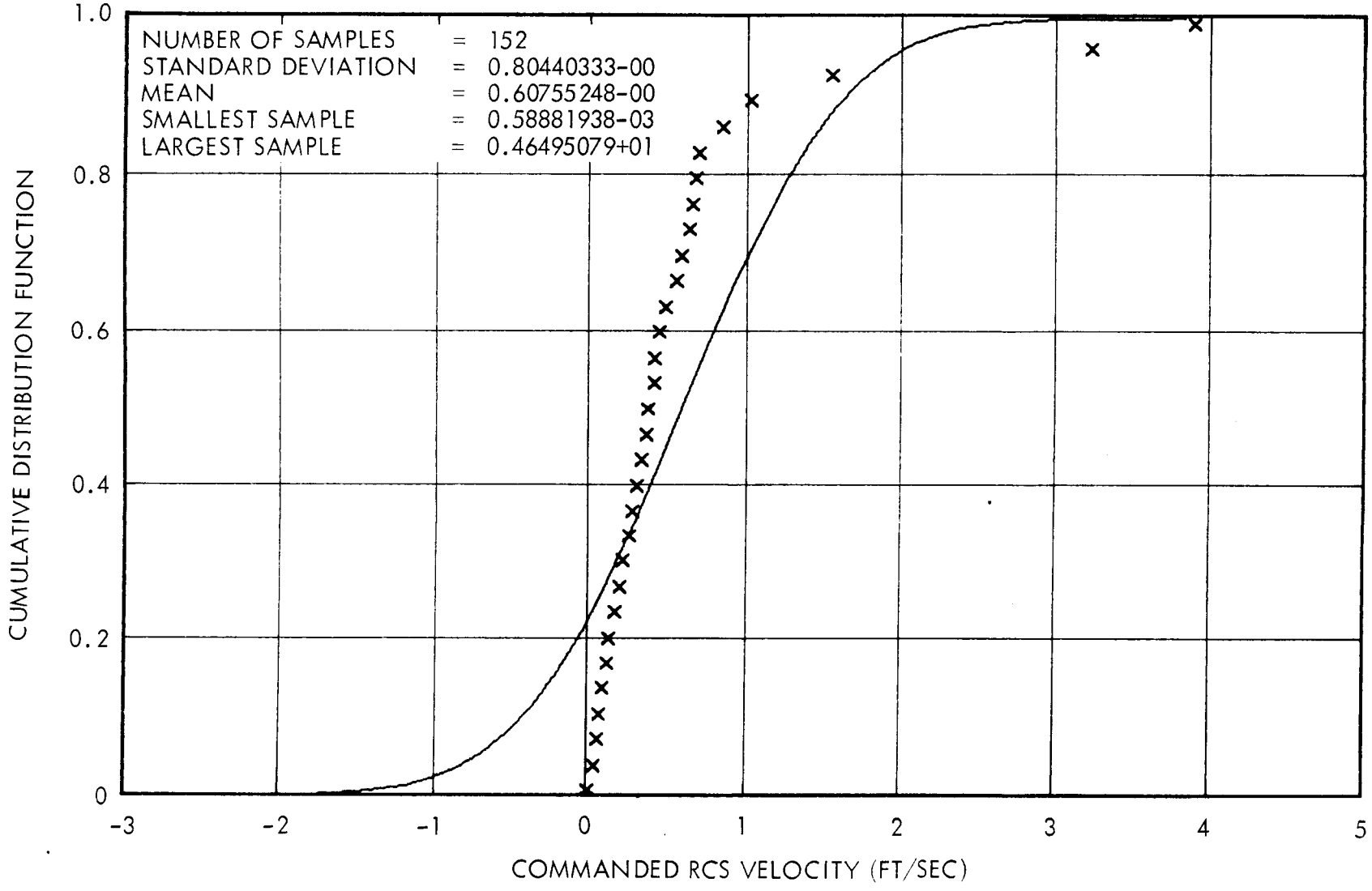


Figure A-11.- Cumulative Distribution of Commanded RCS Velocity (With Venting) for MCC1

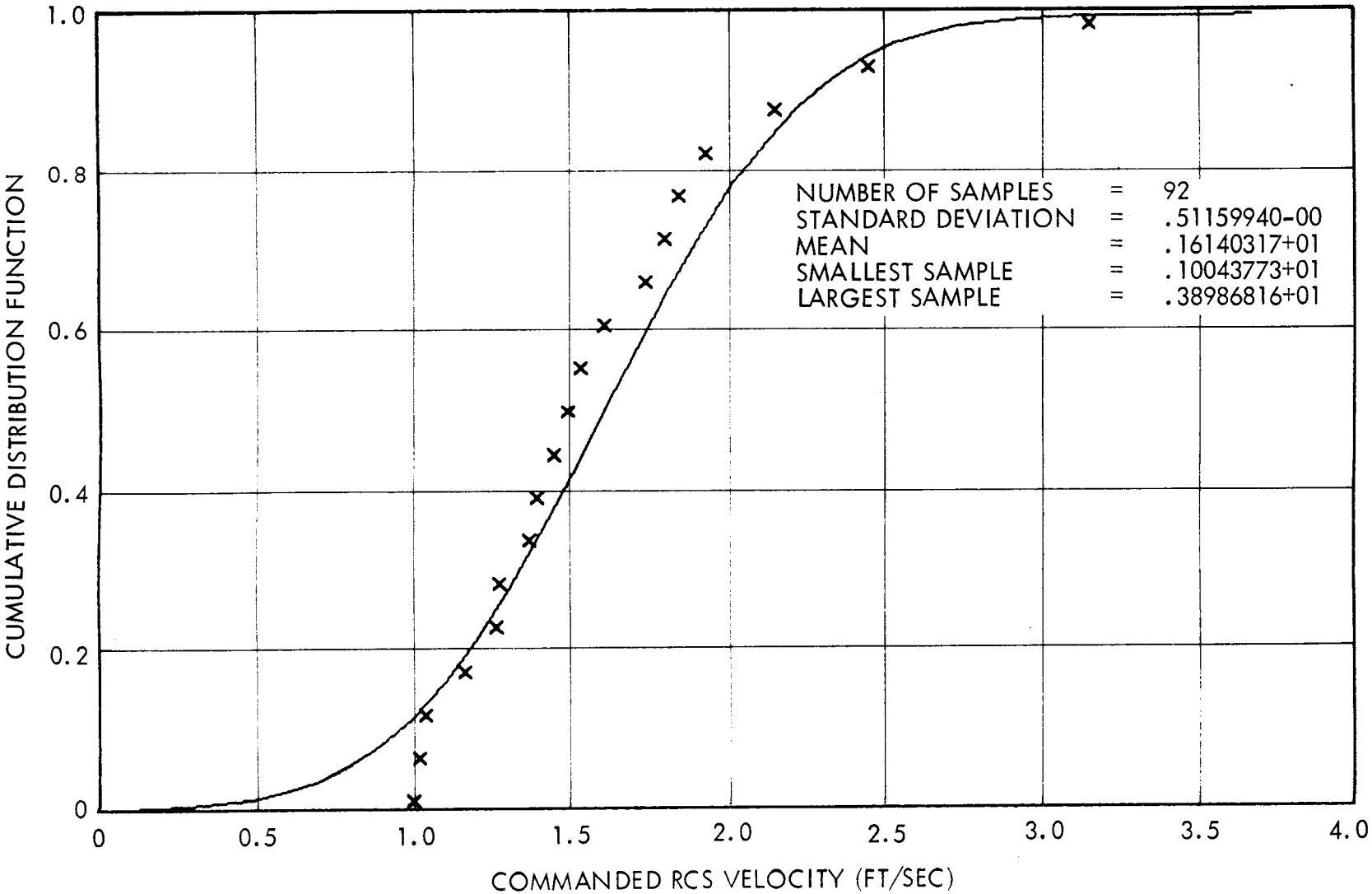


Figure A-12.- Cumulative Distribution of Commanded RCS Velocity (With Venting) for MCC2

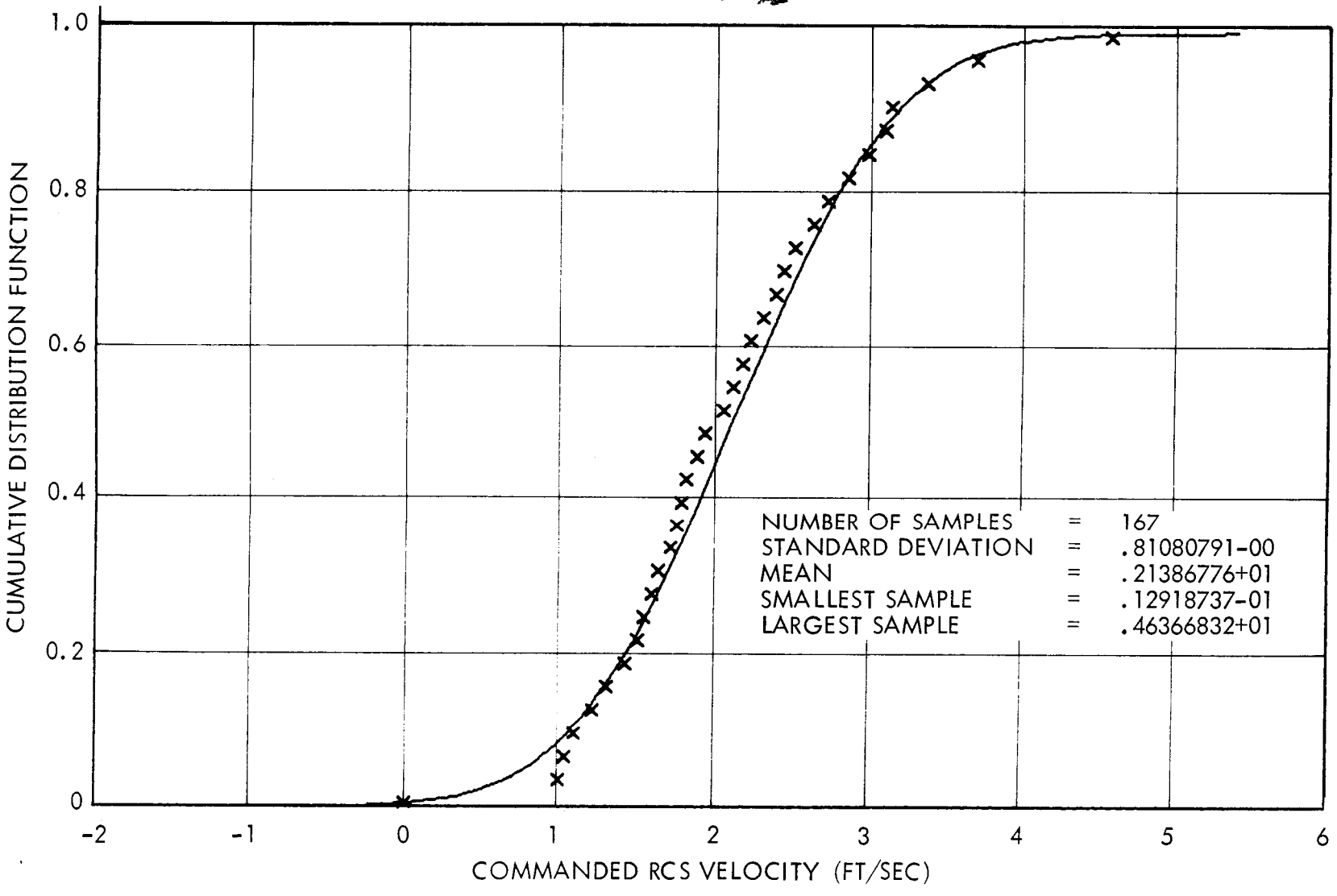


Figure A-13.- Cumulative Distribution of Commanded RCS Velocity (With Venting) for MCC3

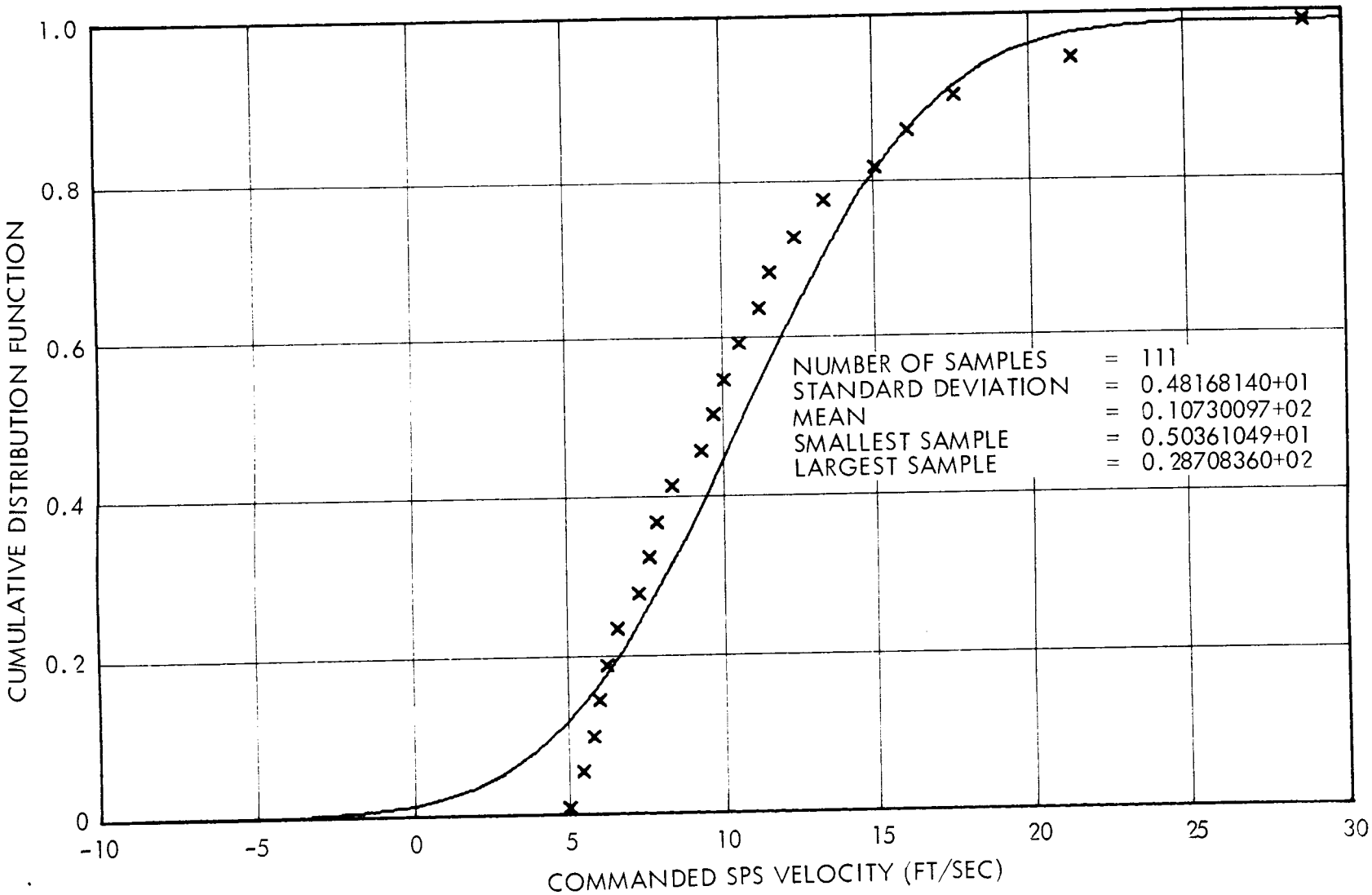


Figure A-14.- Cumulative Distribution of Commanded SPS Velocity (With Venting) for MCC4

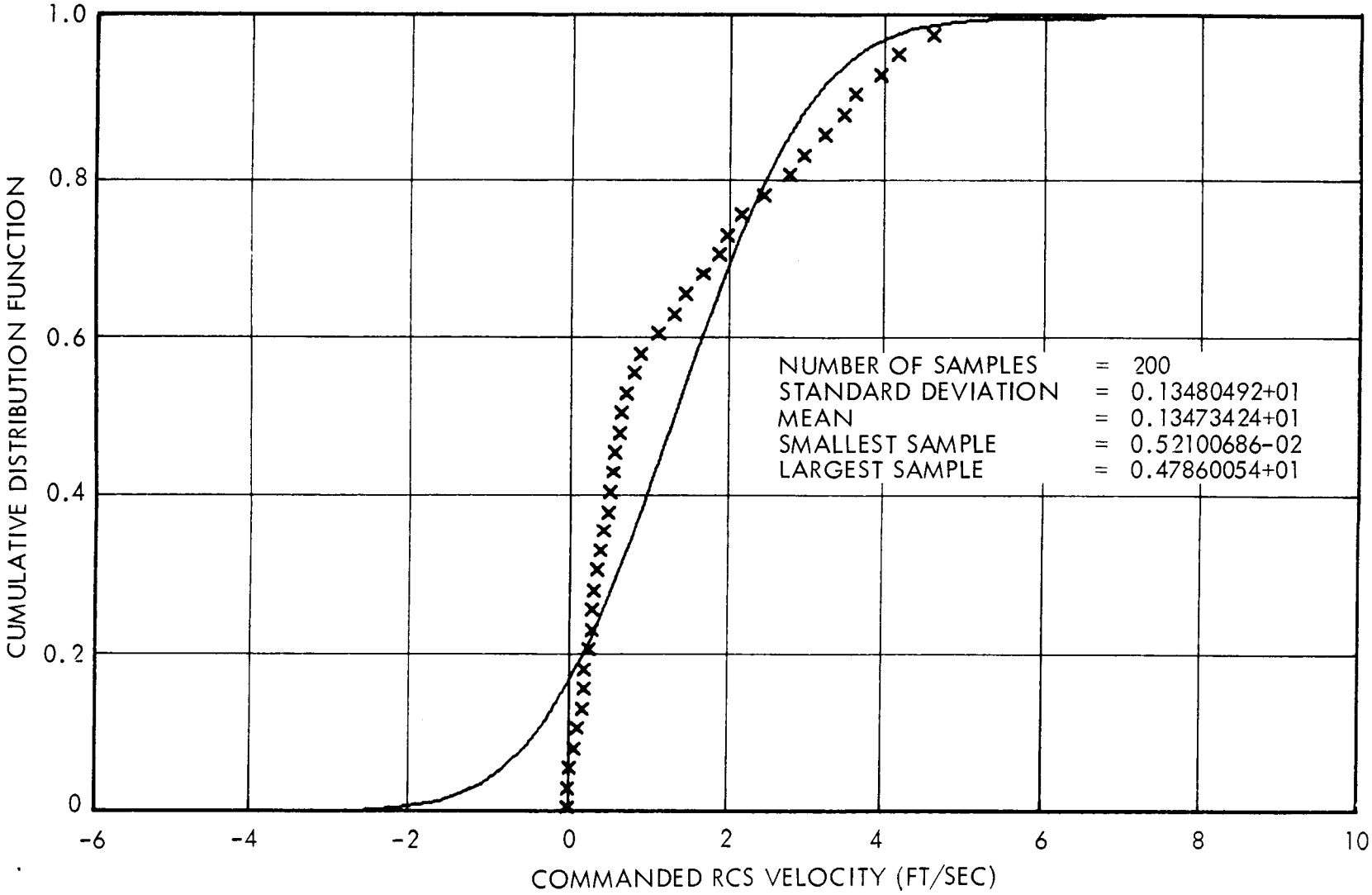


Figure A-15.- Cumulative Distribution of Commanded RCS Velocity (With Venting) for MCC4

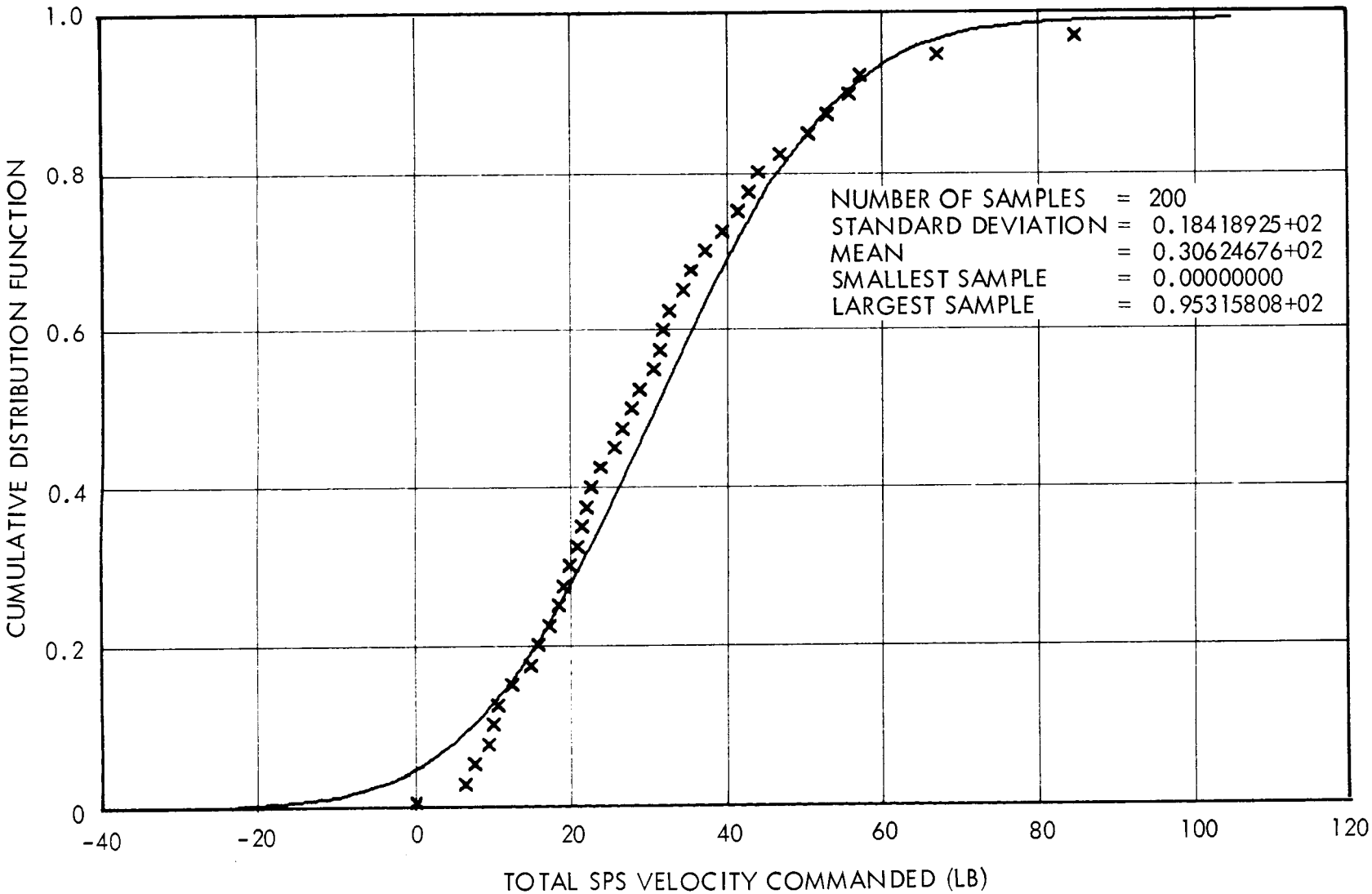


Figure A-16.- Cumulative Distribution of Total SPS Velocity Commanded (With Venting)

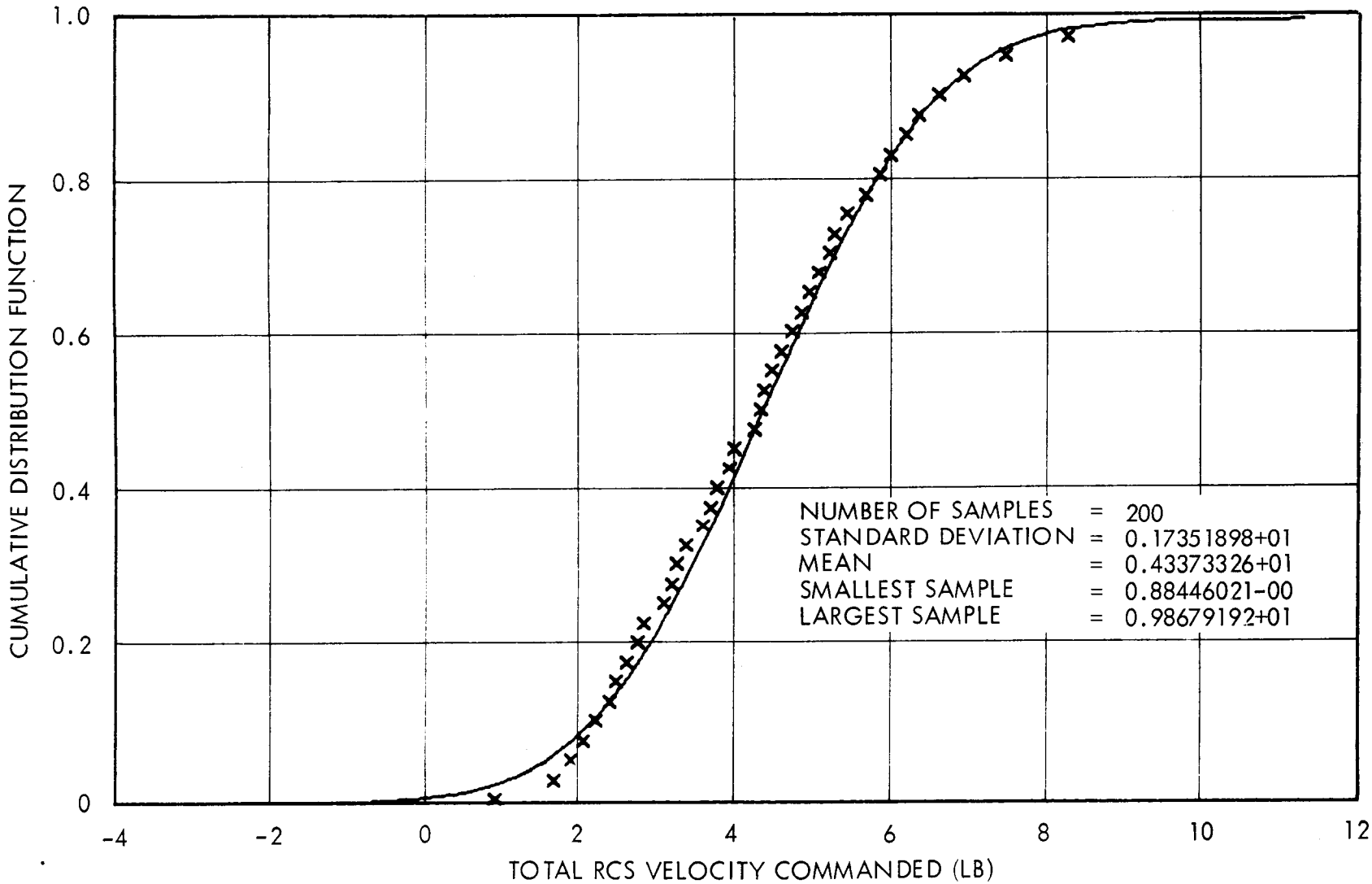


Figure A-17.- Cumulative Distribution of Total RCS Velocity Commanded (With Venting)

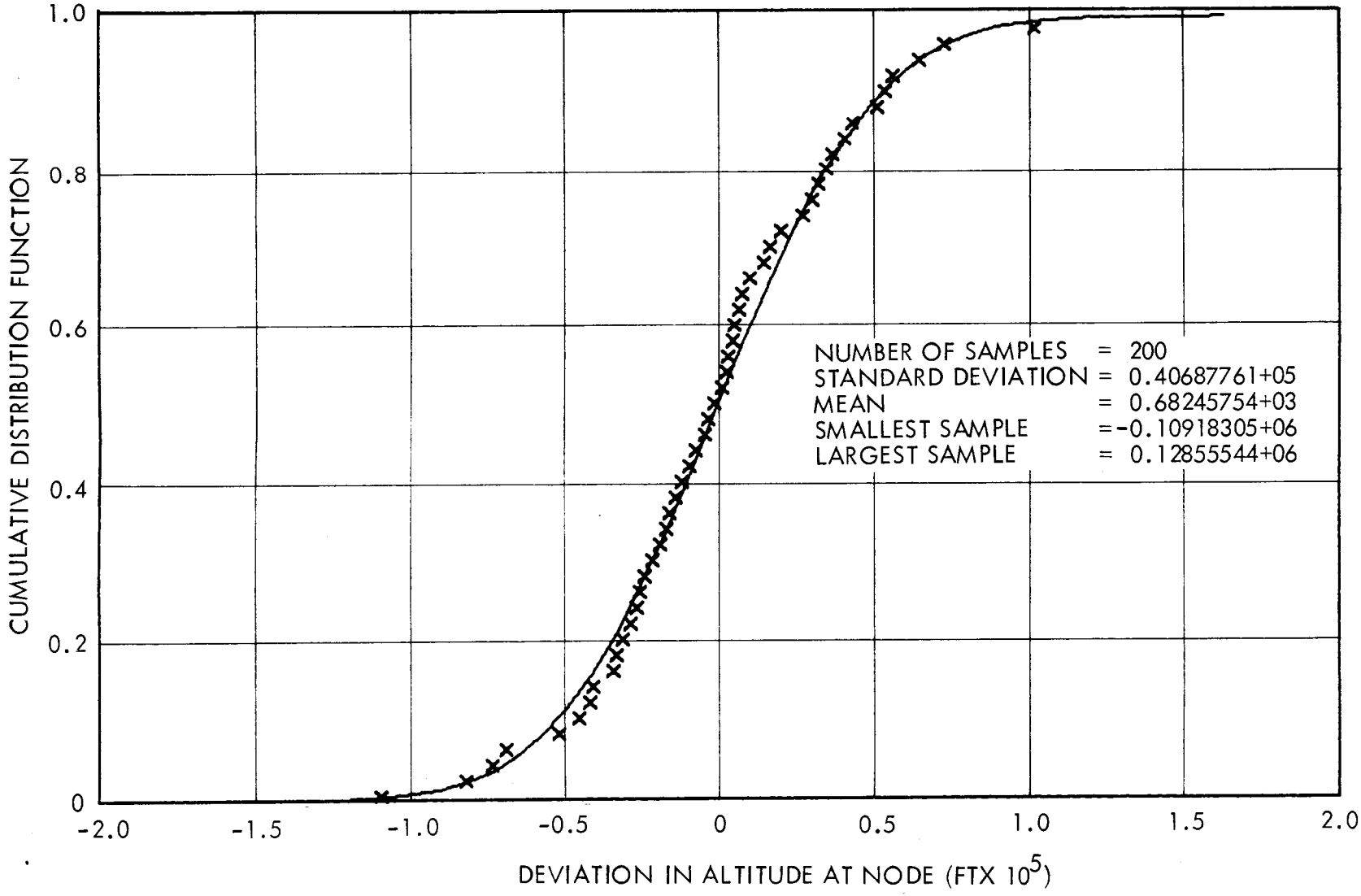


Figure A-18.- Cumulative Distribution of Deviation in Altitude at Node (With Venting)

APPENDIX B

STATISTICAL SUMMARY OF TRANSEARTH SIMULATION RESULTS

TABLE B-I.- Statistical Summary of the First Transearth MCC (TEI + 10 Hours)*

RCS Summary (Sample Size 114)

Magnitude of RCS ΔV Commanded (ft/sec)			RCS Propellant Expended (lb)		
Mean	=	4.40	Mean	=	17.12
Standard Deviation	=	1.96	Standard Deviation	=	7.68
Smallest Sample	=	2.00	Smallest Sample	=	7.81
25th Percentile Sample	=	3.05	25th Percentile Sample	=	11.51
50th Percentile Sample	=	3.88	50th Percentile Sample	=	15.40
75th Percentile Sample	=	5.24	75th Percentile Sample	=	20.99
90th Percentile Sample	=	6.95	90th Percentile Sample	=	28.02
95th Percentile Sample	=	8.34	95th Percentile Sample	=	32.48
99th Percentile Sample	=	10.53	99th Percentile Sample	=	42.13
Largest Sample	=	11.48	Largest Sample	=	42.58

RCS Engine Usage:	Ullage	Maneuver	Trim
	1	113	1

SPS Summary (Sample Size 1)

Magnitude of SPS ΔV Commanded (Single Sample) = 8.01 ft/sec
SPS Propellant Expended (Single Sample) = 27.20 lbs

*Two hundred transearth simulation cycles were performed. For 86 of the simulation cycles the magnitude of the required ΔV was less than the 2.0-foot-per-second threshold at this point in the mission and no MCC was performed.

TABLE B-II.- Statistical Summary of the Second Transearth MCC (TEI + 29 Hours)*

RCS Summary (Sample Size 31)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	2.58
Standard Deviation	=	0.47
Smallest Sample	=	2.00
25th Percentile Sample	=	2.30
50th Percentile Sample	=	2.46
75th Percentile Sample	=	2.80
90th Percentile Sample	=	3.26
95th Percentile Sample	=	3.47
99th Percentile Sample	=	4.11
Largest Sample	=	4.11

RCS Propellant Expended (lb)		
Mean	=	10.10
Standard Deviation	=	1.86
Smallest Sample	=	7.43
25th Percentile Sample	=	8.94
50th Percentile Sample	=	9.70
75th Percentile Sample	=	10.77
90th Percentile Sample	=	12.53
95th Percentile Sample	=	13.69
99th Percentile Sample	=	15.95
Largest Sample	=	15.95

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	31	0

SPS Summary

(No SPS Maneuvers were performed.)

*Two hundred transearth simulation cycles were performed. For 169 of the cycles the magnitude of required ΔV was less than the 2.0-foot-per-second threshold at this point in the mission, and no MCC was performed.

TABLE B-III.- Statistical Summary of the Third Transearth MCC (Entry -29 Hours)*

RCS Summary (Sample Size 92)

Magnitude of RCS ΔV Commanded (ft/sec)		
Mean	=	1.78
Standard Deviation	=	0.55
Smallest Sample	=	1.00
25th Percentile Sample	=	1.36
50th Percentile Sample	=	1.70
75th Percentile Sample	=	2.05
90th Percentile Sample	=	2.50
95th Percentile Sample	=	2.77
99th Percentile Sample	=	3.95
Largest Sample	=	3.95

RCS Propellant Expended (lb)		
Mean	=	6.95
Standard Deviation	=	2.14
Smallest Sample	=	3.95
25th Percentile Sample	=	5.37
50th Percentile Sample	=	6.85
75th Percentile Sample	=	8.17
90th Percentile Sample	=	9.98
95th Percentile Sample	=	10.47
99th Percentile Sample	=	15.38
Largest Sample	=	15.38

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	92	0

SPS Summary

(No SPS maneuvers were performed.)

*Two hundred transearth simulation cycles were performed. For 108 of the simulation cycles the magnitude of required ΔV was less than the 1.0-foot-per-second threshold at this point in the mission, and no MCC was performed.

TABLE B-IV.- Statistical Summary of the Fourth Transearth MCC (Entry-2 hours)*

RCS Summary (Sample Size 124)

Magnitude of RCS ΔV Commanded (ft/sec)			RCS Propellant Expended (lb)		
Mean	=	2.77	Mean	=	10.83
Standard Deviation	=	1.69	Standard Deviation	=	6.52
Smallest Sample	=	1.01	Smallest Sample	=	4.00
25th Percentile Sample	=	1.47	25th Percentile Sample	=	5.81
50th Percentile Sample	=	2.20	50th Percentile Sample	=	9.12
75th Percentile Sample	=	3.65	75th Percentile Sample	=	14.38
90th Percentile Sample	=	5.05	90th Percentile Sample	=	19.36
95th Percentile Sample	=	6.41	95th Percentile Sample	=	23.82
99th Percentile Sample	=	8.09	99th Percentile Sample	=	31.43
Largest Sample	=	9.11	Largest Sample	=	35.61

RCS Engine Usage:	Ullage	Maneuver	Trim
	0	124	0

SPS Summary

(No SPS maneuvers were performed.)

*Two hundred transearth simulation cycles were performed. For 76 of the simulation cycles the magnitude of required ΔV was less than the 1.0-foot-per-second threshold at this point in the mission, and no MCC was performed.

TABLE B-V.- Statistical Summary of Cumulative Transearth ΔV and Propellant Expenditures

RCS Summary (Sample Size 200)

Cumulative RCS ΔV Magnitude (ft/sec)		
Mean	=	5.45
Standard Deviation	=	3.31
Smallest Sample	=	0.00
25th Percentile Sample	=	2.82
50th Percentile Sample	=	5.10
75th Percentile Sample	=	7.43
90th Percentile Sample	=	10.01
95th Percentile Sample	=	11.75
99th Percentile Sample	=	14.53
Largest Sample	=	17.24

Cumulative RCS Propellant Expenditure (lb)		
Mean	=	21.24
Standard Deviation	=	12.95
Smallest Sample	=	0.00
25th Percentile Sample	=	10.69
50th Percentile Sample	=	20.07
75th Percentile Sample	=	28.81
90th Percentile Sample	=	39.48
95th Percentile Sample	=	45.47
99th Percentile Sample	=	56.90
Largest Sample	=	69.98

	Ullage	Maneuver	Trim
Total RCS Engine Usage:	1	360	1

SPS Summary

Magnitude of SPS ΔV Commanded (Single Sample) = 8.01 ft/sec

SPS Propellant Expended (Single Sample) = 27.20 lb

TABLE B-VI.- Sample Covariance Matrices of Required Midcourse ΔV*

First Transearth Midcourse Correction (TEI + 10 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Selenocentric UVW Coordinates)

	1	2	3
1	3.4545887+000		Symmetric
2	-9.9999999-001	1.5517987+000	
3	-9.9999999-001	9.9999999-001	3.3432991-001

Second Transearth Midcourse Correction (TEI + 29 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)**

	1	2	3
1	6.1580735-003		Symmetric
2	9.9999999-001	1.3641577+000	
3	9.9999999-001	9.9999999-001	5.1101480-003

*Statistics based on 200 samples.

Matrices are in normalized form; i.e., the diagonal elements are the standard deviations rather than the variances, and the off-diagonal elements are the correlation coefficients.

**The dominance of the v-component and the high correlation between components indicates that MC $\Delta\vec{V}$ was always in a direction nearly parallel to the v-axis.

TABLE B-VI.- Sample Covariance Matrices of Required Midcourse ΔV* (Concluded)

Third Transearth Midcourse Correction (Entry - 29 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)**

	1	2	3
1	3.3034899-004		Symmetric
2	9.9999999-001	1.3210815+000	
3	9.9999999-001	9.9999999-001	4.3023843-004

Fourth Transearth Midcourse Correction (Entry - 2 hr)

Sample Covariance Matrix of Required Midcourse ΔV (ft/sec; Geocentric UVW Coordinates)**

	1	2	3
1	1.5257668-001		Symmetric
2	9.9999999-001	2.5817601+000	
3	-9.9999999-001	-9.9999999-001	8.4849182-004

*Statistics based on 200 samples.

Matrices are in normalized form; diagonal elements are the standard deviations and off-diagonal elements are the correlation coefficients.

**The dominance of the v-component and the high correlation between components indicates that MC $\Delta\vec{V}$ was always in a direction nearly parallel to the v-axis.

TABLE B-VII.- Statistical Summary of Post-Maneuver State Deviations Propagated to Entry Interface*

First Transearth Midcourse Correction (TEI + 10 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Entry Interface**

	1	2	3	4	5	6
1	2.7609442-03	9.8673592-02	-5.3061083-01	-1.0059053-01	-1.1983042-01	3.8001123-01
2	3.5811625+03	4.7707595+11	-1.4130679-02	-9.9999487-01	-9.9981094-01	-1.3863946-02
3	-2.7692212+02	-9.6941041+07	9.8651514+07	1.4387368-02	2.4963919-02	-9.8534161-01
4	-3.0965739+00	-4.0465657+08	8.3720798+04	3.4323388+05	9.9984781-01	1.3997414-02
5	-4.0494498-01	-4.4413214+07	1.5946553+04	3.7672944+04	4.1361964+03	6.3035560-03
6	9.9344292-01	-4.7642800+05	-4.8691852+05	4.0799958+02	2.0169950+01	2.4753425+03

Square Roots of Diagonal Elements

5.2544688-02	6.9070685+05	9.9323469+03	5.8586166+02	6.4313268+01	4.9752814+01

Sample Mean of Actual State Deviations Propagated to Entry Interface

1.0197290-03	1.0470505+05	5.1200743+01	-8.8800053+01	-9.7512694+00	-5.9026494-01

*All statistics based on 200 samples of actual state deviations following MCC-1. Units are feet and feet per second; UVW coordinates.

**Elements above the diagonal are correlation coefficients.

TABLE B-VII.- Statistical Summary of Post-Maneuver State Deviations Propagated to Entry Interface* (Continued)

Second Transearth Midcourse Correction (TEI + 29 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Entry Interface**

	1	2	3	4	5	6
1	2.7380417-03	3.6262383-02	-5.2689717-01	-3.8958428-02	-6.4796721-02	3.7546307-01
2	9.8002475+02	2.6675952+11	9.2599070-02	-9.9998801-01	-9.9976400-01	-1.1607480-01
3	-2.7300451+02	4.7357780+08	9.8050411+07	-9.2154779-02	-7.6958018-02	-9.8719969-01
4	-8.9255977-01	-2.2613611+08	-3.9953769+05	1.9170363+05	9.9984882-01	1.1606656-01
5	-1.6284939-01	-2.4801078+07	-3.6600960+04	2.1026286+04	2.3068863+03	1.0588575-01
6	9.7802234-01	-2.9844154+06	-4.8662148+05	2.5297845+03	2.5317001+02	2.4781244+03

Square Roots of Diagonal Elements

5.2326300-02	5.1648768+05	9.9020407+03	4.3783973+02	4.8030056+01	4.9780763+01

Sample Mean of Actual State Deviations Propagated to Entry Interface

5.3747621-04	2.4155604+04	8.0842152+01	-2.0656832+01	-2.2676395+00	-6.0202237-01

*All statistics based on 200 samples of actual state deviations following MCC-2. Units are feet and feet per second; UVW coordinates.

**Elements above the diagonal are correlation coefficients.

TABLE B-VII.- Statistical Summary of Post-Maneuver State Deviations Propagated to Entry Interface *(Continued)

Third Transearth Midcourse Correction (Entry - 29 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Entry Interface**

	1	2	3	4	5	6
1	2.7391158-03	9.9790458-02	-5.2853626-01	-1.0780348-01	-1.8634019-01	3.7797635-01
2	8.6652290+02	2.7527817+10	2.2793844-02	-9.9969438-01	-9.9721635-01	-4.9160009-02
3	-2.7421378+02	3.7488972+07	9.8269519+07	-2.3729308-02	2.0909052-02	-9.8720366-01
4	-7.9285541-01	-2.3308238+07	-3.3056391+04	1.9747522+04	9.9803547-01	5.1438244-02
5	-1.5195956-01	-2.5780515+06	3.2296345+03	2.1853381+03	2.4279106+02	1.9716551-02
6	9.8479652-01	-4.0604485+05	-4.8718359+05	3.5984794+02	1.5294098+01	2.4782971+03

Square Roots of Diagonal Elements

5.2336563-02	1.6591509+05	9.9130984+03	1.4052588+02	1.5581754+01	4.9782498+01

Sample Mean of Actual State Deviations Propagated to Entry Interface

4.8151992-04	3.3536188+03	8.2124602+01	-3.1477822+00	-3.4812784-01	-5.9006305-01

*All statistics based on 200 samples of actual state deviations following MCC-3. Units are feet and feet per second; UVW coordinates.

**Elements above the diagonal are correlation coefficients.

TABLE B-VII.- Statistical Summary of Post-Maneuver State Deviations Propagated to Entry Interface* (Concluded)

Fourth Transearth Midcourse Correction (Entry - 2 hr)

Sample Covariance Matrix of Actual State Deviations Propagated to Entry Interface**

	1	2	3	4	5	6
1	1.4376078-02	-6.0173152-01	2.8798484-01	6.0019693-01	6.7302317-01	-2.0655474-01
2	-2.8098560+03	1.5167784+09	-1.7988911-01	-9.7705469-01	-9.1358428-01	1.4702815-01
3	3.4286170+02	-6.9565690+07	9.8595767+07	1.5809696-01	2.8444602-01	-9.8532840-01
4	2.4541442+00	-1.2976753+06	5.3535119+04	1.1629798+03	9.5790056-01	-1.1614820-01
5	3.5023226-01	-1.5442429+05	1.2258432+04	1.4177917+02	1.8837004+01	-2.0418638-01
6	-1.2323255+00	2.8492572+05	-4.8683322+05	-1.9709185+02	-4.4096362+01	2.4759401+03

Square Roots of Diagonal Elements

1.1990028-01	3.8945840+04	9.9295401+03	3.4102490+01	4.3401617+00	4.9758819+01

Sample Mean of Actual State Deviations Propagated to Entry Interface

-1.0614997-02	2.7332612+03	8.0022233+01	-2.6472831+00	-2.9493733-01	-5.8745462-01

*All statistics based on 200 samples of actual state deviations following MCC-4. Units are feet and feet per second; UVW coordinates.

**Elements above the diagonal are correlation coefficients.

TABLE B-VIII.- Statistical Summary of Actual State at Entry Interface*

Magnitude of Entry Position Miss (ft)		
Mean	=	32395.57
Standard Deviation	=	23835.73
Smallest Sample	=	1416.29
25th Percentile Sample	=	15280.60
50th Percentile Sample	=	25888.66
75th Percentile Sample	=	41669.64
90th Percentile Sample	=	66368.60
95th Percentile Sample	=	90970.36
99th Percentile Sample	=	104791.25
Largest Sample	=	115821.92

Entry Velocity Magnitude (ft/sec)		
Mean	=	36070.58
Standard Deviation	=	1.311465
Smallest Sample	=	36067.24
25th Percentile Sample	=	36069.76
50th Percentile Sample	=	36070.55
75th Percentile Sample	=	36071.37
90th Percentile Sample	=	36072.25
95th Percentile Sample	=	36072.95
99th Percentile Sample	=	36074.28
Largest Sample	=	36075.22

Entry Longitude Deviation (deg)		
Mean	=	0.001
Standard Deviation	=	0.511
Smallest Sample	=	-1.172
25th Percentile Sample	=	-0.337
50th Percentile Sample	=	0.025
75th Percentile Sample	=	0.300
90th Percentile Sample	=	0.655
95th Percentile Sample	=	0.896
99th Percentile Sample	=	1.435
Largest Sample	=	1.586

Entry Flight-Path Angle (deg)		
Mean	=	-6.244
Standard Deviation	=	0.053
Smallest Sample	=	-6.388
25th Percentile Sample	=	-6.278
50th Percentile Sample	=	-6.242
75th Percentile Sample	=	-6.212
90th Percentile Sample	=	-6.183
95th Percentile Sample	=	-6.161
99th Percentile Sample	=	-6.116
Largest Sample	=	-6.105

*All statistics based on 200 samples.

TABLE B-VIII.- Statistical Summary of Actual State at Entry Interface* (Concluded)

Entry Latitude Deviation (deg)			Entry Azimuth (deg)		
Mean	=	-0.002	Mean	=	112.604
Standard Deviation	=	0.051	Standard Deviation	=	0.080
Smallest Sample	=	-0.144	Smallest Sample	=	112.370
25th Percentile Sample	=	-0.040	25th Percentile Sample	=	112.554
50th Percentile Sample	=	-0.001	50th Percentile Sample	=	112.607
75th Percentile Sample	=	0.030	75th Percentile Sample	=	112.658
90th Percentile Sample	=	0.057	90th Percentile Sample	=	112.702
95th Percentile Sample	=	0.090	95th Percentile Sample	=	112.740
99th Percentile Sample	=	0.125	99th Percentile Sample	=	112.778
Largest Sample	=	0.171	Largest Sample	=	112.785

*All statistics based on 200 samples.

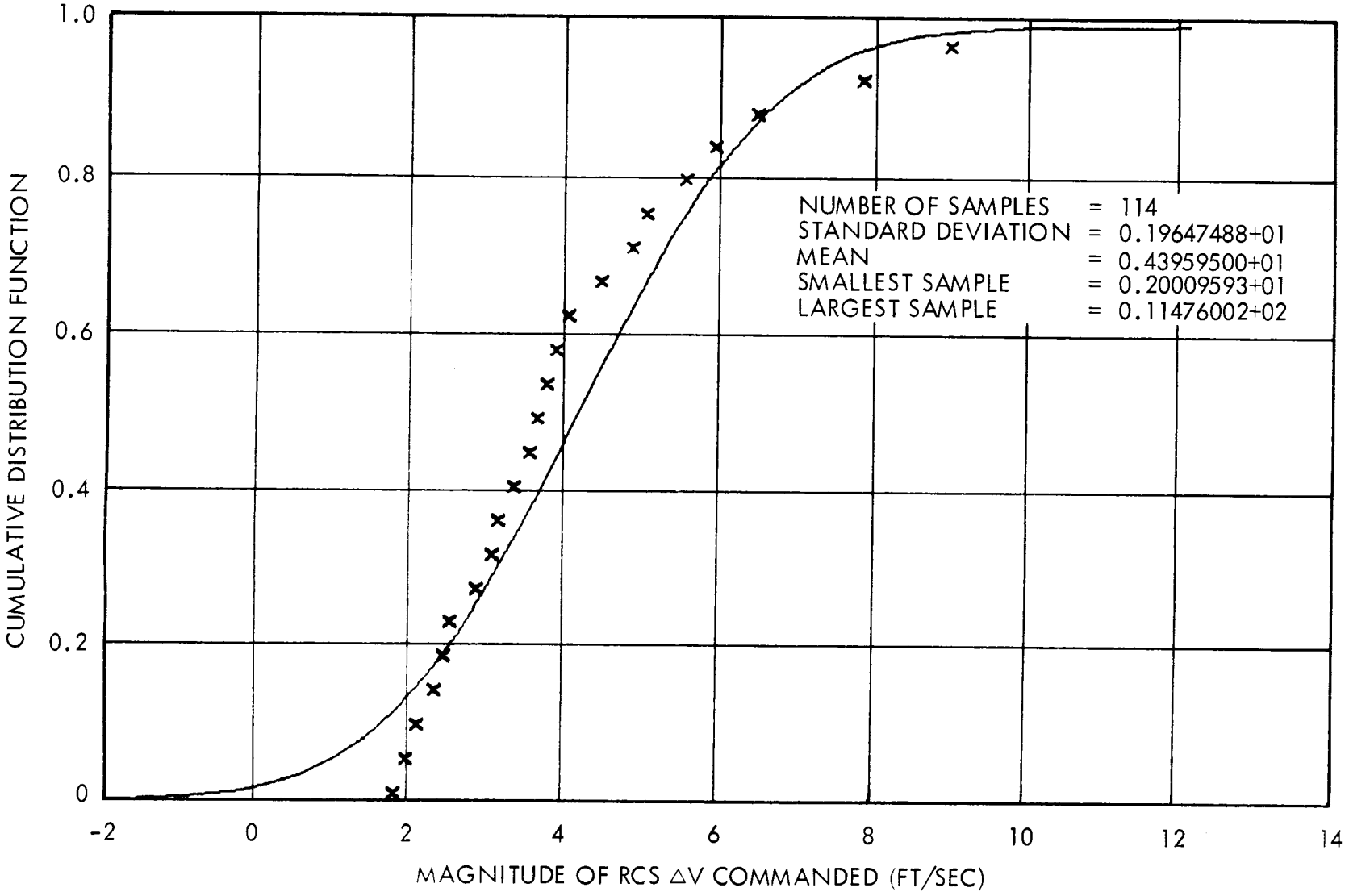


Figure B-1.- Cumulative Distribution of Magnitude of RCS ΔV Commanded in MCC-1

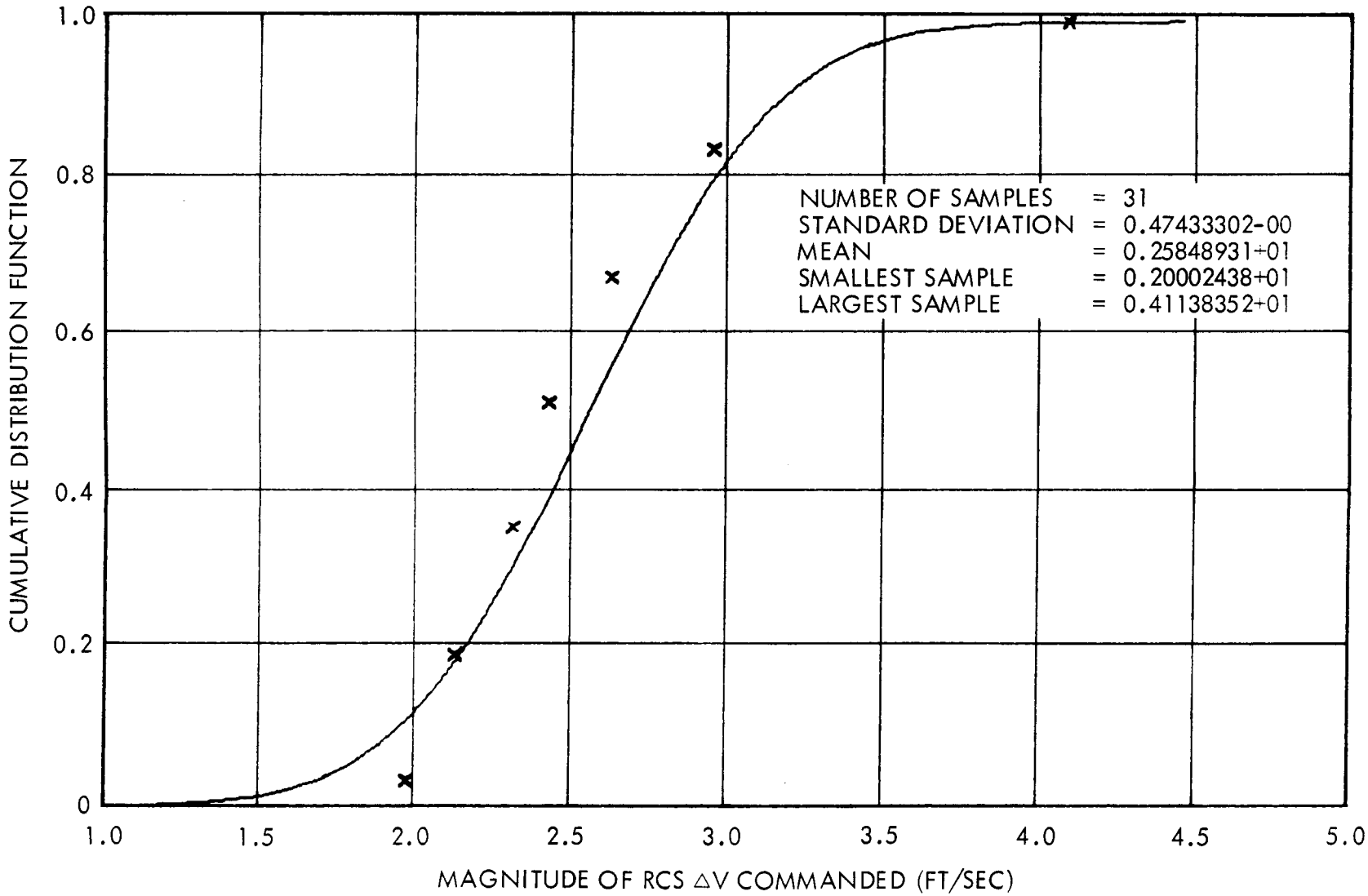


Figure B-2.- Cumulative Distribution of Magnitude of RCS ΔV Commanded in MCC-2

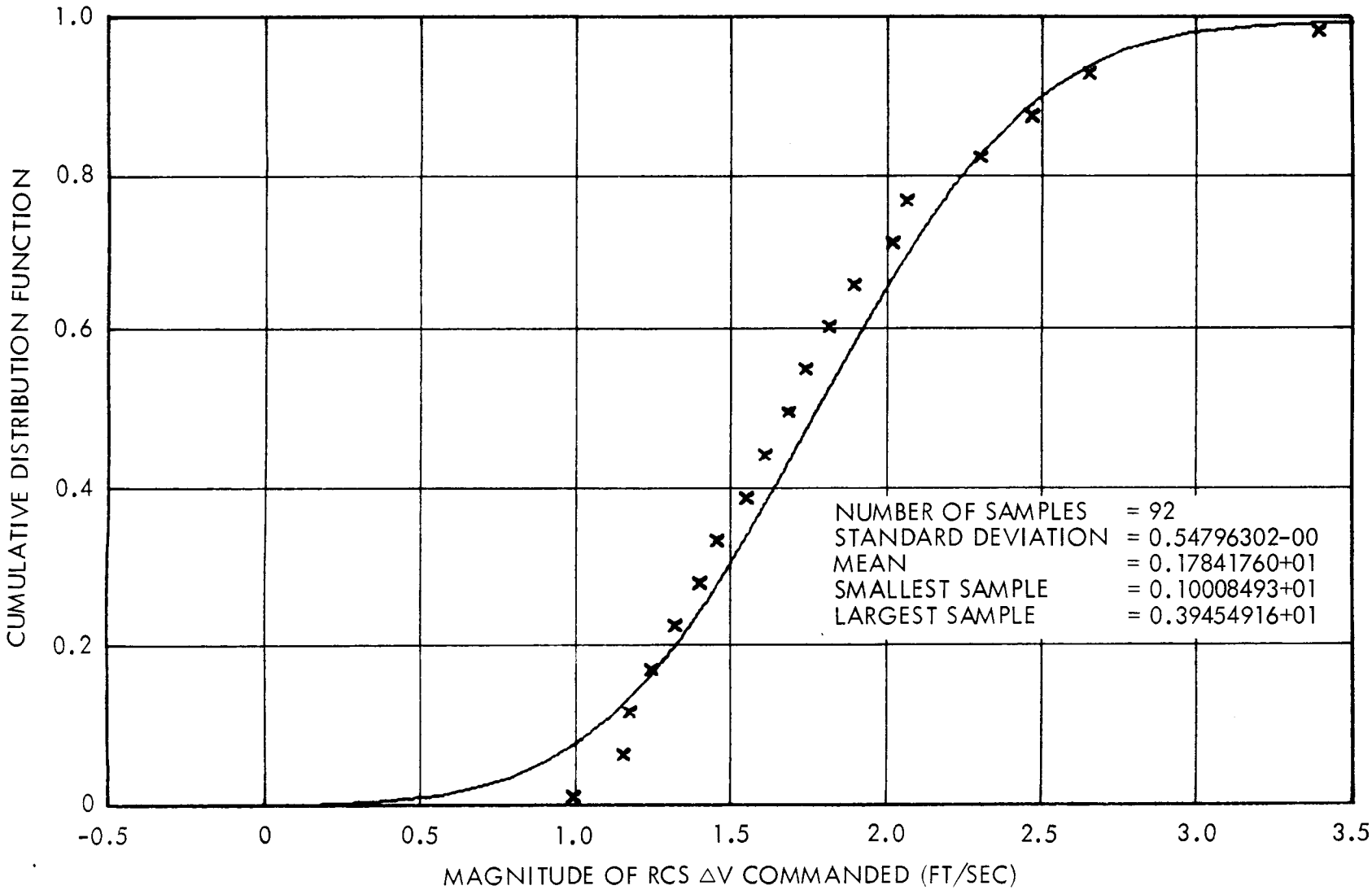


Figure B-3.- Cumulative Distribution of Magnitude of RCS ΔV Commanded in MCC-3

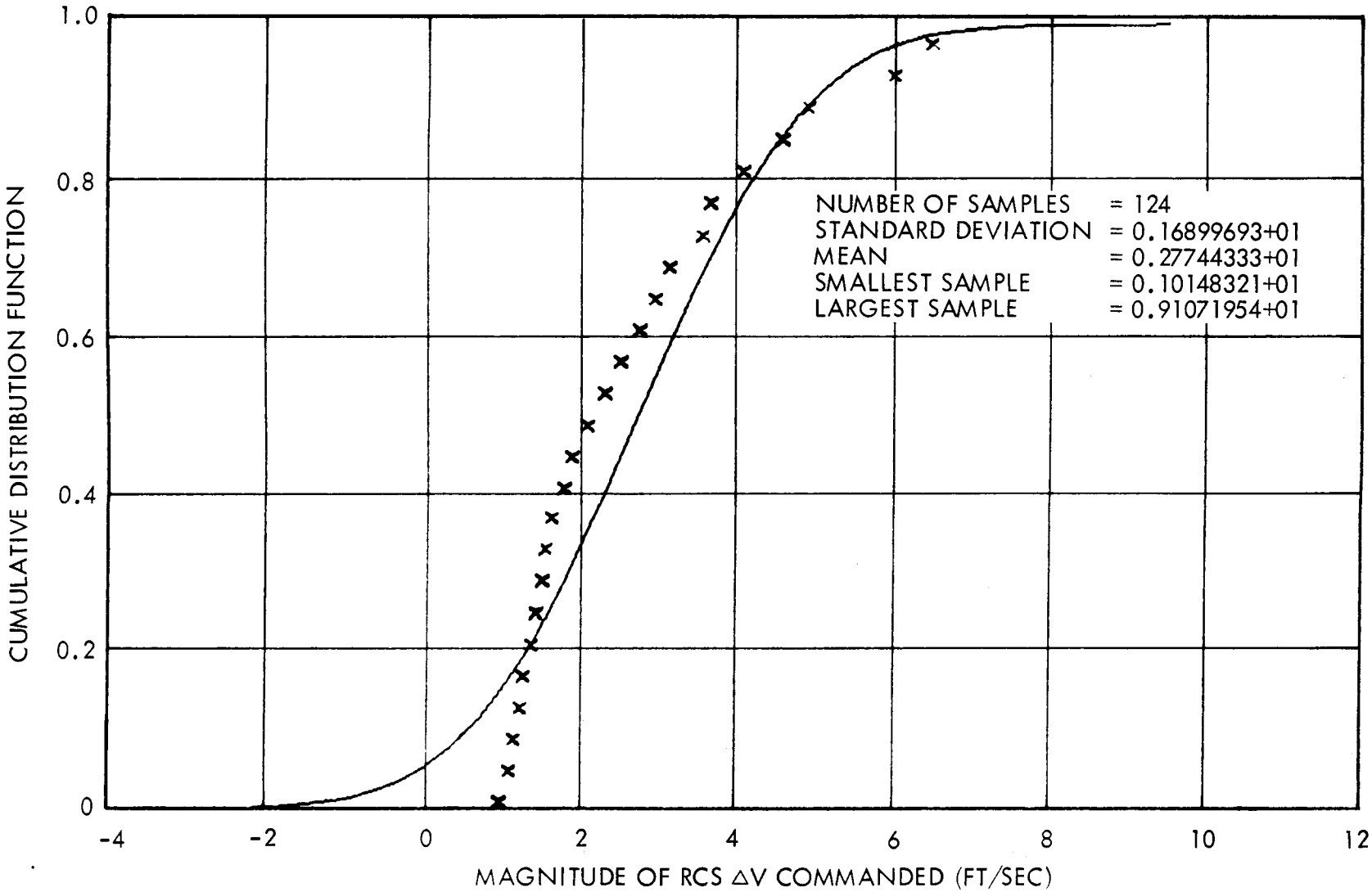


Figure B-4.- Cumulative Distribution of RCS ΔV Commanded in MCC-4

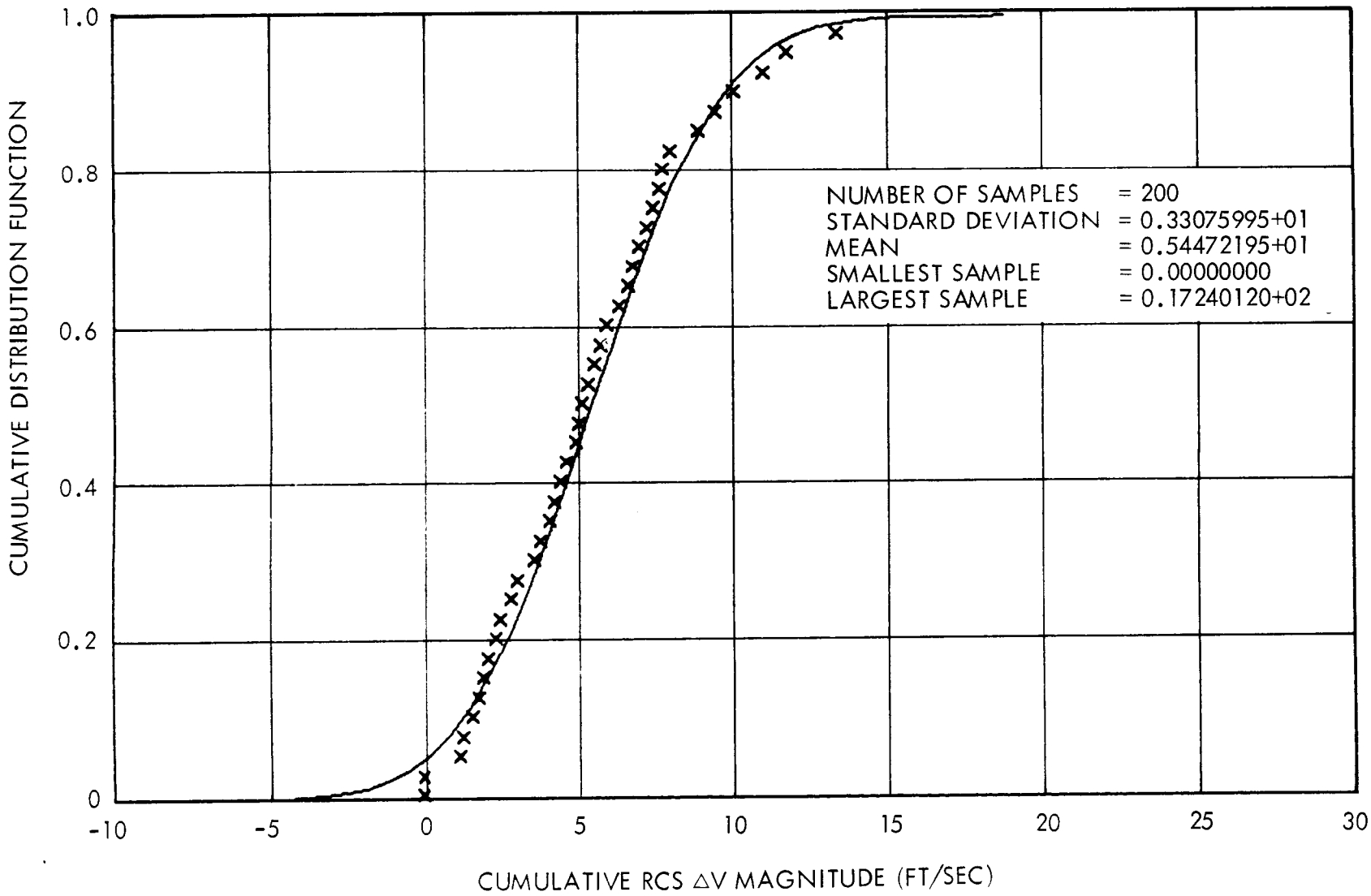


Figure B-5.- Cumulative Distribution of Total RCS ΔV

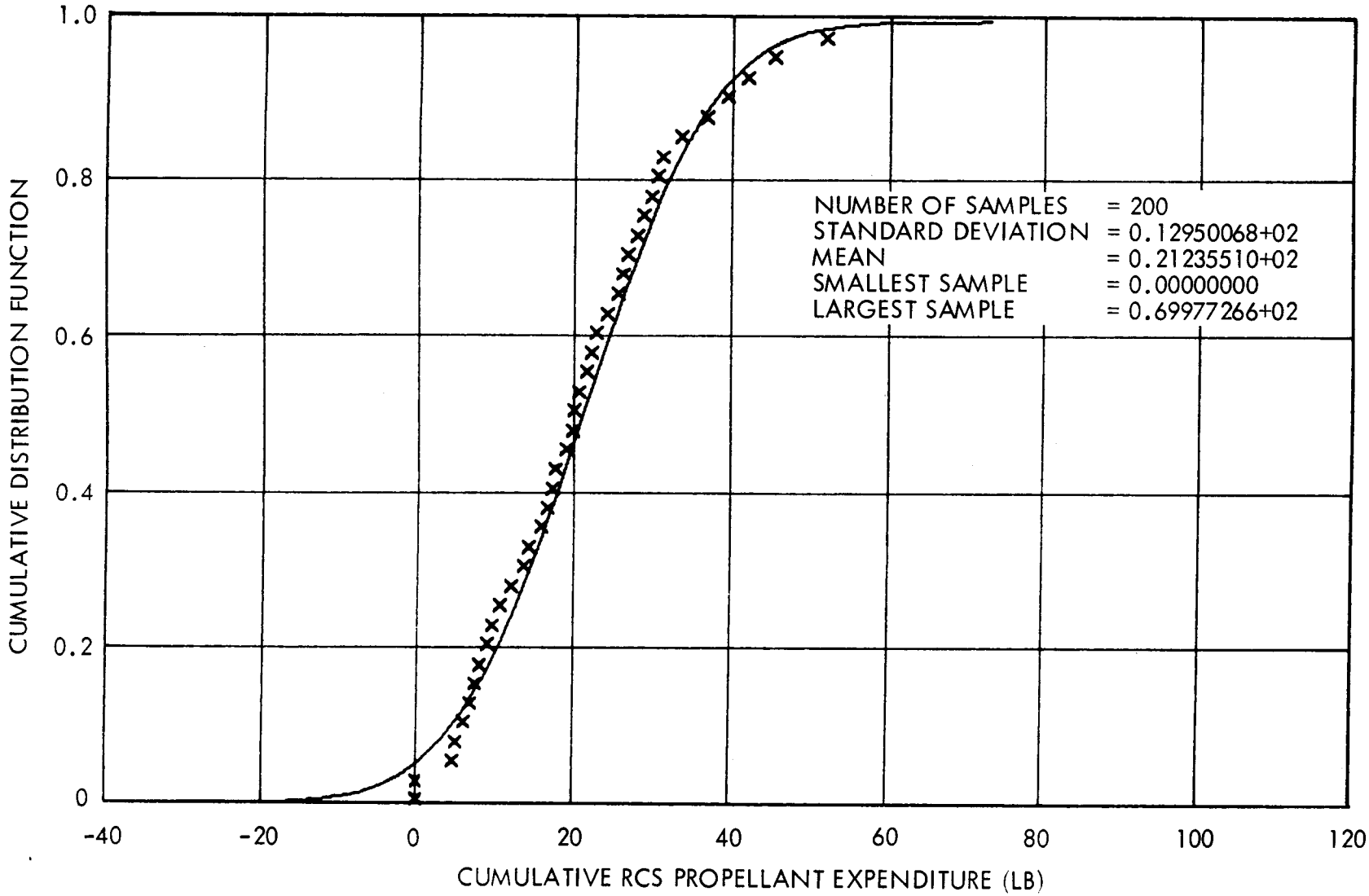


Figure B-6.- Cumulative Distribution of Total RCS Propellant Expenditure

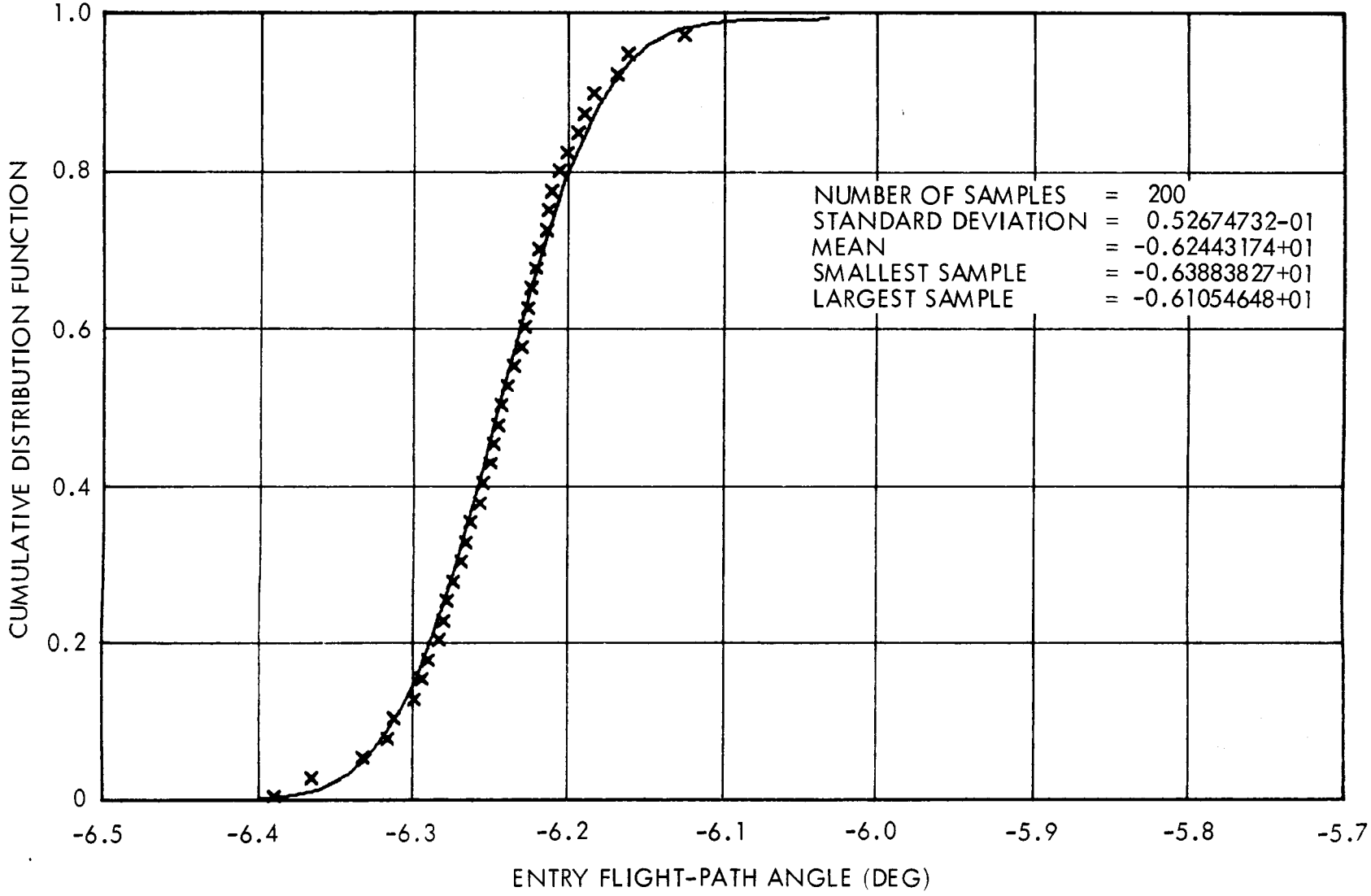


Figure B-7.- Cumulative Distribution of Entry Flight-path Angle

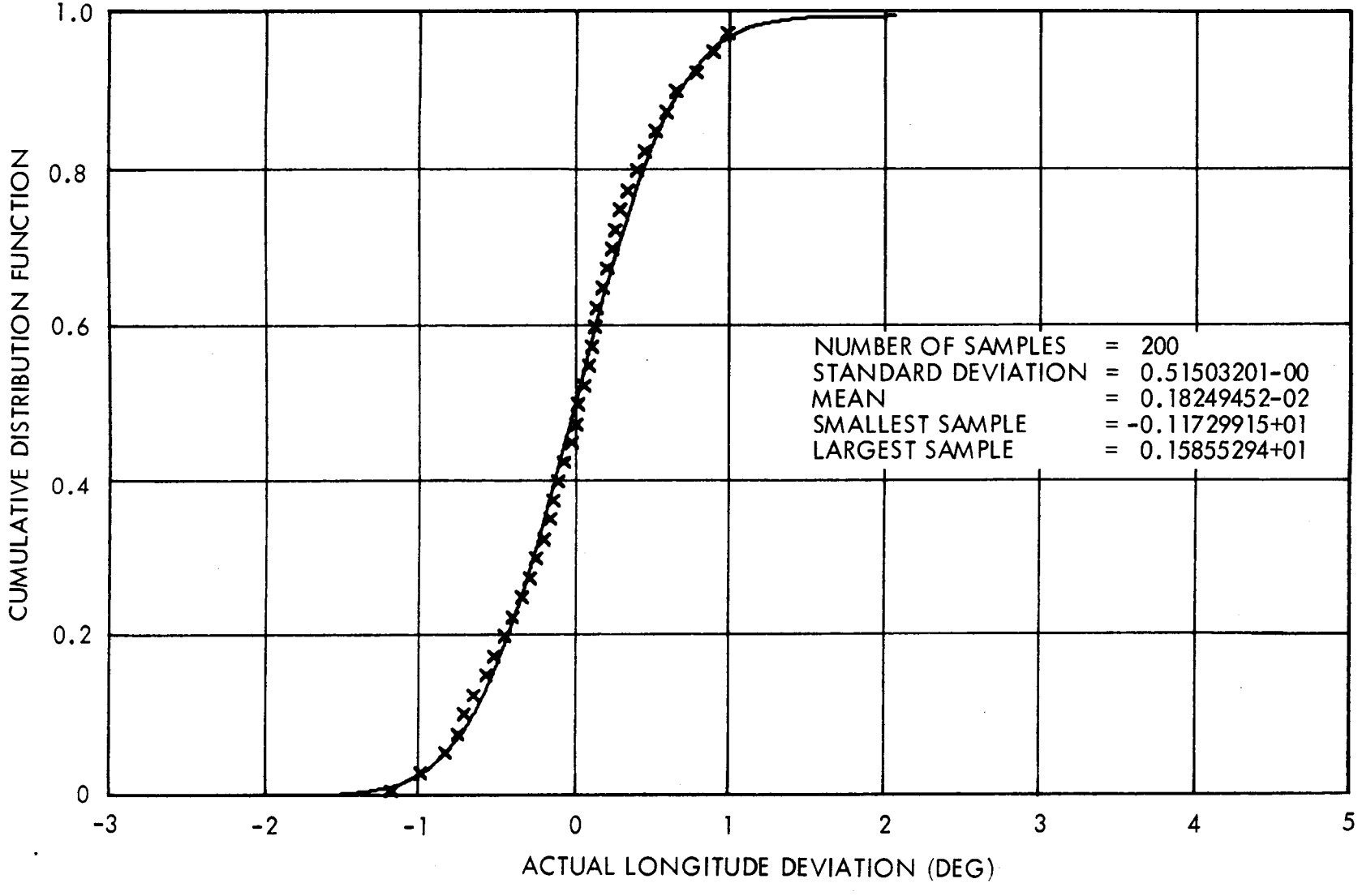


Figure B-8.- Cumulative Distribution of Actual Longitude Deviation

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