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APOLLO MISSION D PERFORMANCE ANALYSIS OF RENDEZVOUS CHARTS

Flight Procedures Branch

FLIGHT CREW SUPPORT DIVISION

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

MSC INTERNAL NOTE MSC-CF-R-69-3

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LIST OF ACRONYMS AND ABBREVIATIONS

AGS	Abort Guidance System
CDH	Constant Differential Height
CES	Control Electronic System
CSI	Concentric Sequence Initiation
CSM	Command and Service Module
LM	Lunar Module
LOS	Line-of-Sight Between LM and CSM
MC1	First Mid-Course Correction
MC2	Second Mid-Course Correction
TPI	Terminal Phase Initialization
TPF	Terminal Phase Finalization
ΔT	Change in Time
ΔV	Change in Velocity
σ	Standard Deviation
CSI ΔV_H	Horizontal Component of CSI Solution
CDH ΔV_V	Vertical Component of CDH Solution
CDH ΔV_H	Horizontal Component of CDH Solution
TPI ΔV_{LOS}	Along Line-of-Sight Component of TPI Solution
TPI ΔV_N	Normal to Line-of-Sight Component of TPI Solution
MC1 ΔV_{LOS}	Along Line-of-Sight Component of MC1 Solution
MC1 ΔV_N	Along Line-of-Sight Component of MC2 Solution
MC2 ΔV_N	Normal to Line-of-Sight Component of MC2 Solution
CSI $\Delta\Delta V_H$	Error in Horizontal Component of CSI Solution
CDH $\Delta\Delta V_V$	Error in Vertical Component of CDH Solution
CDH $\Delta\Delta V_H$	Error in Horizontal Component of CDH Solution
TPI $\Delta\Delta V_{LOS}$	Error in Along Line-of-Sight Component of TPI Solution
TPI $\Delta\Delta V_N$	Error in Normal to Line-of-Sight Component of TPI Solution
MC1 $\Delta\Delta V_{LOS}$	Error in Along Line-of-Sight Component of MC1 Solution
MC1 $\Delta\Delta V_N$	Error in Normal to Line-of-Sight Component of MC1 Solution
MC2 $\Delta\Delta V_{LOS}$	Error in Along Line-of-Sight Component of MC2 Solution
MC2 $\Delta\Delta V_N$	Error is Normal to Line-of-Sight Component of MC2 Solution

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APOLLO MISSION D PERFORMANCE ANALYSIS OF RENDEZVOUS CHARTS

1.0 Summary

A digital analysis of the D Mission backup rendezvous charts has been performed to verify their ability to predict CSI, CDH, TPI, and midcourse corrections in the presence of system and application errors and trajectory dispersions. Procedures for data acquisition were as defined in the current LM Rendezvous Procedures Document (Reference 1). The charts simulated were those from the LM 3 onboard data package. The mission situation simulated represented the PNGS inoperative, rendezvous radar information available from the tapemeter, attitude data from the AGS and control by the CES. However, use of the CSI and CDH charts is presently ground ruled out by Reference 2. The study showed that the standard deviation of the arrival time at TPI was 5.5 minutes. The mean ΔT from TPI to intercept with braking and line-of-sight control was 35.8 minutes with a standard deviation of 1.5 minutes. If no braking or line-of-sight control was executed after the second midcourse correction, the mean miss distance would have been 0.6 n.m. with a standard deviation of .35 n.m. The mean total translational ΔV required after insertion was 158 ft/sec with a standard deviation of 20 ft/sec.

2.0 Discussion

This analysis was performed to determine the ability of the charts to predict all maneuvers after insertion required to complete the LM-active D mission rendezvous. One hundred independent sets of initial conditions (IC's) were selected by adding random errors to the 6 components of the nominal relative state vector between the LM and CSM. Half of the relative error was incorporated into the inertial state vector of each vehicle.

The 100 cases were run including system and execution errors with braking and line-of-sight (LOS) control. The runs were repeated omitting braking and LOS control to obtain miss distance. The results of the 100 Monte Carlo runs were processed to obtain statistical data for the parameters of interest.

The first 25 cases were also run without system or application errors to establish the theoretical chart capabilities.

2.1 Study Rules

The following ground rules consistent with D Mission procedures and planning were used in this study:

1. CSI occurs 40 min 56 sec after insertion.
2. CDH occurs 44 min 26 sec after CSI.
3. TPI was assumed to occur 8 minutes after the elevation angle of 19.73 degrees was reached.
4. The first midcourse correction (MC1) occurred 10 minutes after TPI and the second midcourse correction (MC2) occurred at 22 minutes after TPI.
5. CSI and CDH were burned in local vertical coordinates using impulsive thrust.
6. TPI, MC1, MC2, braking, and LOS control were executed along and normal to the line-of-sight using finite thrust, burning each component individually.
7. 130 degrees of CSM orbit travel between TPI and TPF.
8. No out-of-plane corrections were made prior to LOS control during the braking phase.

2.2 Digital Program

In the analysis, functions describing the backup rendezvous charts were programmed into a digital routine which integrated the equations of motion of two particles about an oblate planet. These functions allowed simulation of the procedures for using the backup rendezvous charts by incorporating elevation angle (AGS address 304), range, and range rate from the tapemeter at the times called for by the backup data sequence. System errors were included in the data taken at each point and an appropriate error of application was included in each maneuver.

The runs included effects of both bias and random errors as defined in Section 2.5. Bias errors were selected by the program at the beginning of each run and held constant for that run. Random errors were selected at each point data were taken.

2.3 Charts

The charts modeled in the study were those which will be carried on the D Mission, and are shown in Figures 1-6. The data sequence was obtained from Reference 1 and is summarized on the relative motion plot of the nominal trajectory from CSI-40 to TPF (Figure 7).

2.3.1 CSI

The CSI chart solution is based on a Maclaurin's expansion of four variables for the delta V at CSI (range rate at 30, 20, and 10 minutes prior to CSI and range 10 minutes prior to CSI). The coefficients are determined by the simultaneous solution of several expansions, each representing a dispersed trajectory prior to CSI.

2.3.2 CDH

The CDH chart solution utilizes the sinusoidal time history of range rate variations from coellipticity and relative velocity errors from coellipticity. Range rate data for the CDH chart are taken 29, 18, and 7 minutes prior to CDH.

2.3.3 TPI and MCC

The TPI charts solve for the relative position and velocity at TPI resolved into normal and along the line-of-sight (LOS) coordinates. The measured relative conditons are differenced from the required conditions for intercept in 130 degrees of orbit travel. Information required for the TPI charts is the elevation angle at 8 and 5 minutes prior to TPI and range and range rate at 5 minutes before

TPI. In a similar manner, the MCC charts maintain the time of TPF consistent with the TPI maneuver. Data are taken for the midcourses 5 and 8 minutes after TPI for MC1 and at 17 and 20 minutes after TPI for MC2. The same measurement sequence as used at TPI is used for both midcourse corrections.

2.4 Initial Conditons

The initial conditions were generated by perturbing the nominal state vectors of the LM and CSM with errors supplied by a relative covariance matrix. Half the relative error was applied to the state vector of each vehicle.

The nominal vectors relative to the LM orbital plane were derived from Reference 3 and are summarized as follows:

Table 2-1
Initial Conditions
Insertion + 56 Sec
(95 hrs 41 min 48 sec)

LM Altitude	863730 feet
CSM Altitude	798403 feet
LM Total Velocity	25431.2 ft/sec
CSM Total Velocity	25468.7 ft/sec
LM Flight Path Angle	-.00563 deg
CSM Flight Path Angle	-.00652 deg
In Plane Central Angle	.401 deg
LM Latitude	1.4 deg
Out of Plane Distance	-31.3 feet
Out of Plane Velocity	-.02 ft/sec
Heading Angle (relative to equator)	29 deg

The covariance matrix used for initialization of the Monte Carlo runs is as follows:

Table 2-2
Covariance Matrix

9725775.	-358310.0	11.8853	799.127	-205.801	-.043464
-358310.0	12124470.	-6.36828	-887.559	199.080	.0249741
11.8853	-6.36828	6262300.	.0189843	-.004047	20.2459
799.127	-887.559	.0189843	11.35113	-.42248	-.0000708
-205.801	199.080	-.004047	-.42248	3.202925	.00001599
-0434646	.029741	20.2459	-.0000708	.00001599	2.394625

It was obtained by increasing between 9 and 25 times the diagonal elements of a post insertion covariance matrix provided by Math Physics Branch.

2.5 Errors in Sensors and Execution

The 1σ errors in sensor and maneuver executions were:

1. System Errors

   A. Noise

      1) Range — .333%

      2) Range Rate — .433% or .433 ft/sec which ever is larger

      3) Elevation Angle — .12 degree

   B. Biases and Drifts (constant for a given run)

      1) Range Rate — .333 ft/sec

      2) Initial Pitch Bias — .1 deg (assumes calibrated COAS)

      3) Pitch Drift Rate — .23 deg/hr

2. Execution Errors

   A. Reading Tapemeter

      1) Range Rate — .25 ft/sec

      2) Range

         a) Outer Scale — 2400 ft

         b) Middle Scale — 100 ft

   B. Application of Burns — .5 ft/sec (per axis)

   C. Time Measurements — 1.0 sec

2.6 Braking Schedule and LOS Angular Rate Deadbands

The braking schedule used in this simulation consisted of five gates and a lower limit on the range rate. The first gate was at 13500 feet. At this point only LOS control was executed because the allowed range rate was 80 ft/sec. The second gate was at 6000 ft with an allowed range rate of 30 ft/sec. The nominal range rate at this range was 29 ft/sec. The remaining gates were 20 ft/sec at 3000 ft, 10 ft/sec at 1500 ft and 5 ft/sec at 500 ft. The lower range rate limit consisted of a straight line connecting 20 ft/sec at 13500 ft and 0 ft/sec at intercept.

Both the upper and lower range rate limits are shown in Figure 8. LOS control procedures were simulated by sampling inertial drift of the LOS inplane and normal to the orbit plane every 15 seconds beginning at a range of 13500 ft. When the LOS rates exceeded .3 mr/sec at a sampling time, thrust was applied in the appropriate axis in increments of 1 second until the LOS rate was reduced below the threshold. The 15 seconds were allowed to elapse before sampling again.

3.0 Results

Several sets of Monte Carlo runs were made to obtain statistical data for determination of the effects of errors, trajectory dispersions, and braking on the size of maneuvers, arrival time at TPI, and total translational ΔV. The sets of runs are identified in the following table:

Table 3-1
Run Summary

Set	Number of Runs	Errors in Maneuver Solutions	Maneuvers Applied	LOS Control and Braking
A	100	Yes	With Errors	Yes
		No		
B	100	Yes	With Errors	No
C	25	No	No Errors	No
D	25	No	No Errors	Yes

Solutions for the maneuvers in SET A were obtained with and without errors so that the effect of sensor and reading errors on the chart solutions could be determined. However, all maneuvers for SET A were made usi...; the solutions with errors. The runs for SET B were identical to SET A, but with braking and LOS control ommitted to establish miss distance.

SETS, C and D were run to establish baseline data for chart performance. It was felt that a reduced number of runs would suffice to obtain statistically meaningf·ıl results since only initial conditions were varied. Examination of significant parameters such as maneuver solution and miss distances revealed nearly normal statistical distributions, confirming the adequacy of the 25 runs for those sets. The runs for SETS C and D were made with the same initial conditions as the first 25 runs of SET A.

3.1 Maneuver Values

The nominal chart solutions, average, mean, and standard deviation for each maneuver in SET A and SET D are shown in Table 3-2 on Page 3-4. The data given for SET A are the solutions with errors. The average, mean, and standard deviation for the difference between the error solution and the no error solution computed for each maneuver in SET A are shown in Table 3-3 on Page 3-5.

It can be noted from the data on Tables 3-2 and 3-3 that the chart solutions with errors progressively decrease in accuracy from CSI to CDH to TPI. The trend then reverses with MCC1 more accurate than TPI and MCC2 being the most accurate of the maneuvers.

Table 3-2

Magnitude of Maneuvers

Maneuvers	Nominal Chart Solution ft/sec	Average		Mean		Standard Deviation	
		SET D ft/sec	SET A ft/sec	SET D ft/sec	SET A ft/sec	SET D ft/sec	SET A ft/sec
CSI ΔV_H	-37.13	37.43	36.81	-37.43	-36.81	2.52	2.57
CDH ΔV_V	1.61	2.41	2.75	1.57	1.50	2.49	3.08
CDH ΔV_H	-37.97	38.52	37.47	-38.52	-37.47	4.58	4.57
TPI ΔV_{LOS}	21.55	21.76	21.38	21.76	21.38	1.74	3.17
TPI ΔV_N	.35	.35	2.52	.34	.43	.21	3.14
MCC1 ΔV_{LOS}	1.02	1.08	3.81	1.08	.96	.39	4.83
MCC1 ΔV_N	.99	.85	3.02	.85	.53	.33	3.79
MCC2 ΔV_{LOS}	.42	.63	8.03	-.30	1.16	.73	10.08
MCC2 ΔV_N	.61	.62	2.81	.61	.29	.31	3.70

Table 3-3

Differences Between Chart Solutions
With Errors and Without Errors in SET A

Maneuver	Average ft/sec	Mean ft/sec	Standard Deviation ft/sec
CSI $\Delta\Delta V_H$	.79	.01	1.02
CDh $\Delta\Delta V_V$	.94	.07	1.24
CDH $\Delta\Delta V_H$	.48	-.06	.59
TPI $\Delta\Delta V_{LOS}$	2.31	-.04	2.89
TPI $\Delta\Delta V_N$	2.06	-.08	2.57
MCC1 $\Delta\Delta V_{LOS}$	2.50	-.24	3.07
MCC1 $\Delta\Delta V_N$	1.19	-.14	1.45
MCC2 $\Delta\Delta V_{LOS}$	.47	-.00	.59
MCC2 $\Delta\Delta V_N$	.54	.02	.66

The data of Table 3-2 indicates the amount of error directly attributable to the sensor and reading errors listed in Section 2.5.

3.2 Miss Distance

The miss distance was established by sets B and C. The average in plane miss distance at the point of closest approach for the 25 cases without errors (SET C) was 513 feet, and for the 100 cases with errors (SET B) was 2505 feet.

The average, mean, and standard deviation of the components of the miss distance in a local vertical coordinate system with X along the radius vector of the LM, Z along the angular momentum vector of the LM, and Y completing the right-handed system were as follows:

Table 3-4
Coordinates at Closest Approach

Axis	Average		Mean		Standard Deviation	
	SET B Feet	SET C Feet	SET B Feet	SET C Feet	SET B Feet	SET C Feet
X	1482	375	-915	-375	1802	219
Y	2020	350	-802	-350	2710	188
Z	1844	1508	-124	- 95	2332	1879

3.3 ΔV Used

The mean total translation ΔV used in the 25 cases without errors (SET D) was 138.2 ft/sec with a standard deviation of 13.4 ft/sec while the mean for the 100 cases with errors (SET A) was 158.7 ft/sec with a standard deviation of 20.5 ft/sec.

The minimum and maximum ΔV cases without errors required 108.2 ft/sec and 170.8 ft/sec, respectively, while with errors minimum and maximum ΔV cases required 100.0 ft/sec and 227.0 ft/sec. Figure 9 shows the distribution of total ΔV.

A breakdown of how the ΔV was used is shown in the following table:

Table 3-5

Translation ΔV

Maneuver	ΔV (SET D) Average Without Errors ft/sec	ΔV (SET A) Average With Errors ft/sec
CSI	37.4	36.8
CDH	40.9	40.2
TPI	22.1	24.0
MCC1	1.9	6.8
MCC2	1.3	10.8
Braking and LOS Control	35.2	40.0

3.4 Arrival Time at TPI

The mean arrival at TPI for the 25 cases without errors (SET C) was 5 seconds later than nominal with a standard deviation of 18 seconds, while the mean for the 100 cases with errors (SET A) was 12 seconds late with a standard deviation of 5 min and 35 seconds.

Figure 10 shows the distribution of arrival time at TPI over intervals of two minutes for the 100 cases with errors.

3.5 ΔT from TPI to TPF

The mean ΔT from TPI to close approach without braking for the 25 cases in SET C was 1980 seconds with a standard deviation of 18 seconds while the mean ΔT of transfer without braking for the 100 cases in SET B was 1963 seconds with a standard deviation of 72 seconds.

The mean ΔT from TPI to intercept with braking and LOS control for the 25 cases in SET D was 2121 seconds with a standard deviation of 22 seconds while the mean ΔT of transfer with braking for the 100 in SET A was 2148 seconds with a standard deviation of 87 seconds. The nominal case required 2115 seconds with braking and LOS control.

Figure 11 shows the distribution of the ΔT transfer with braking for the 100 cases with errors.

4.0 References

1. LM Rendezvous Procedures D Mission, Flight Crew Support Division, dated December 3, 1968.

2. S-PA-8M-036, Apollo Mission Techniques Mission D Rendezvous, Volume 1, dated December 20, 1968.

3. Apollo Mission D (AS-504/CSM-104/LM-3) Spacecraft Operational Trajectory, Volume 1, Mission Profile, dated December 2, 1968.

CSI BACK-UP TABLE: MISSION D

$\dot{R}_{30}$	F_{30}	$\dot{R}_{20}$	F_{20}	$\dot{R}_{10}$	F_{10}	R_{10}	G_{10}
87.	-72.8	87.	104.7	87.	-57.4	35.	-2.9
88.	-73.7	88.	105.9	88.	-58.0	36.	-2.9
89.	-74.5	89.	107.1	89.	-58.7	37.	-3.0
90.	-75.3	90.	108.3	90.	-59.3	38.	-3.1
91.	-76.2	91.	109.5	91.	-60.0	39.	-3.2
92.	-77.0	92.	110.7	92.	-60.7	40.	-3.3
93.	-77.8	93.	111.9	93.	-61.3	41.	-3.3
94.	-78.7	94.	113.1	94.	-62.0	42.	-3.4
95.	-79.5	95.	114.4	95.	-62.6	43.	-3.5
96.	-80.4	96.	115.6	96.	-63.3	44.	-3.6
97.	-81.2	97.	116.8	97.	-64.0	45.	-3.7
98.	-82.0	98.	118.0	98.	-64.6	46.	-3.7
99.	-82.9	99.	119.2	99.	-65.3	47.	-3.8
100.	-83.7	100.	120.4	100.	-65.9	48.	-3.9
101.	-84.5	101.	121.6	101.	-66.6	49.	-4.0
102.	-85.4	102.	122.8	102.	-67.3	50.	-4.1
103.	-86.2	103.	124.0	103.	-67.9	51.	-4.2
104.	-87.1	104.	125.2	104.	-68.6	52.	-4.2
105.	-87.9	105.	126.4	105.	-69.2	53.	-4.3
106.	-88.7	106.	127.6	106.	-69.9	54.	-4.4
107.	-89.6	107.	128.8	107.	-70.6	55.	-4.5
108.	-90.4	108.	130.0	108.	-71.2	56.	-4.6
109.	-91.2	109.	131.2	109.	-71.9	57.	-4.6
110.	-92.1	110.	132.4	110.	-72.5	58.	-4.7
111.	-92.9	111.	133.6	111.	-73.2	59.	-4.8
112.	-93.7	112.	134.8	112.	-73.9	60.	-4.9
113.	-94.6	113.	136.0	113.	-74.5	61.	-5.0
114.	-95.4	114.	137.2	114.	-75.2	62.	-5.0
115.	-96.3	115.	138.4	115.	-75.8	63.	-5.1
116.	-97.1	116.	139.6	116.	-76.5	64.	-5.2
117.	-97.9	117.	140.8	117.	-77.1	65.	-5.3
118.	-98.8	118.	142.0	118.	-77.8	66.	-5.4
119.	-99.6	119.	143.2	119.	-78.5	67.	-5.5

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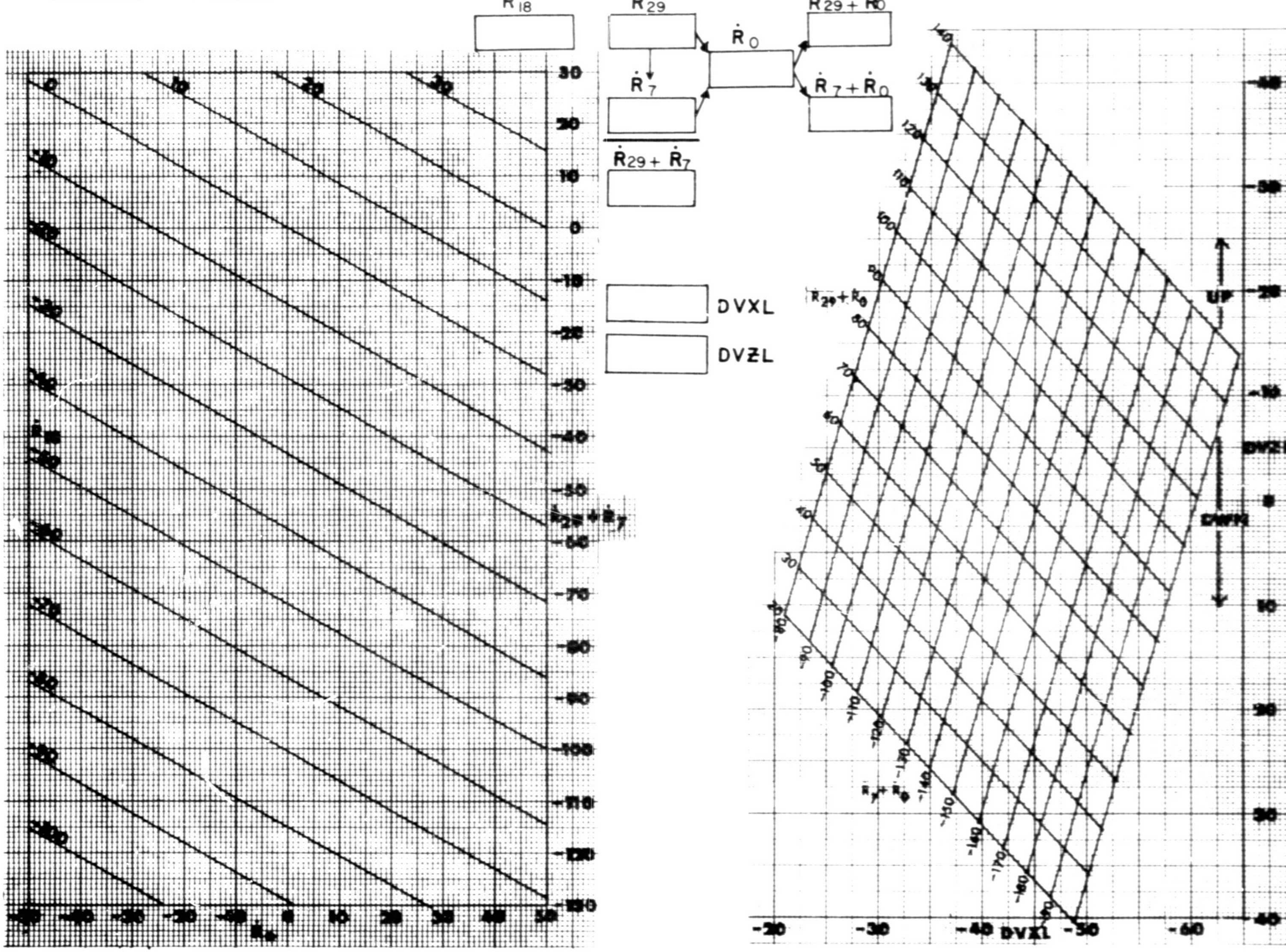
CSI BACK-UP TABLE: MISSION D

$\dot{R}_{30}$	F_{30}	$\dot{R}_{20}$	F_{20}	$\dot{R}_{10}$	F_{10}	R_{10}	G_{10}
120.	-100.4	120.	144.4	120.	-79.1	68.	-5.5
121.	-101.3	121.	145.6	121.	-79.8	69.	-5.6
122.	-102.1	122.	146.9	122.	-80.4	70.	-5.7
123.	-103.0	123.	148.1	123.	-81.1	71.	-5.8
124.	-103.8	124.	149.3	124.	-81.8	72.	-5.9
125.	-104.6	125.	150.5	125.	-82.4	73.	-5.9
126.	-105.5	126.	151.7	126.	-83.1	74.	-6.0
127.	-106.3	127.	152.9	127.	-83.7	75.	-6.1
128.	-107.1	128.	154.1	128.	-84.4	76.	-6.2
129.	-108.0	129.	155.3	129.	-85.1	77.	-6.3
130.	-108.8	130.	156.5	130.	-85.7	78.	-6.4
131.	-109.7	131.	157.7	131.	-86.4	79.	-6.4
132.	-110.5	132.	158.9	132.	-87.0	80.	-6.5
133.	-111.3	133.	160.1	133.	-87.7	81.	-6.6
134.	-112.2	134.	161.3	134.	-88.4	82.	-6.7
135.	-113.0	135.	162.5	135.	-89.0	83.	-6.8
136.	-113.8	136.	163.7	136.	-89.7	84.	-6.8
137.	-114.7	137.	164.9	137.	-90.3	85.	-6.9
138.	-115.5	138.	166.1	138.	-91.0	86.	-7.0
139.	-116.3	139.	167.3	139.	-91.7	87.	-7.1

	(NOM)		(NOM)
$\dot{R}_{30}$ ______	(109.8)	F_{30} = ______	(-91.9)
$\dot{R}_{10}$ ______	(112.6)	F_{10} = ______	(-75.4)
R_{10} ______	(60.5)	G_{10} = ______	(- 4.9)
		$F_{30}+F_{10}+G_{10}$ = ______	(-172.2)
$\dot{R}_{20}$ ______	(114.4)	F_{20} ______	(135.5)
		ΔV_{CSI} = ______	(-36.7)

FCSD 12/3/68

D MISSION CDH CHART



"D" MISSION

LM-120 CSM-130
130 DEGREE TRANSFER
9 — 17 — 68

TERMINAL PHASE INITIATION

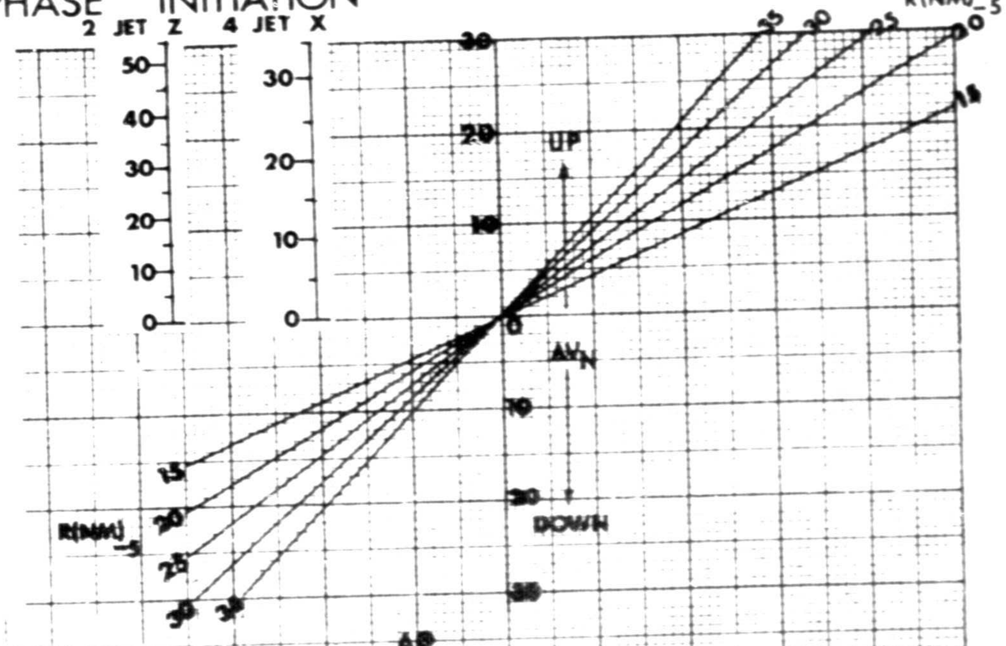
$\dot{R}_{REQ}$ ________ 120.7

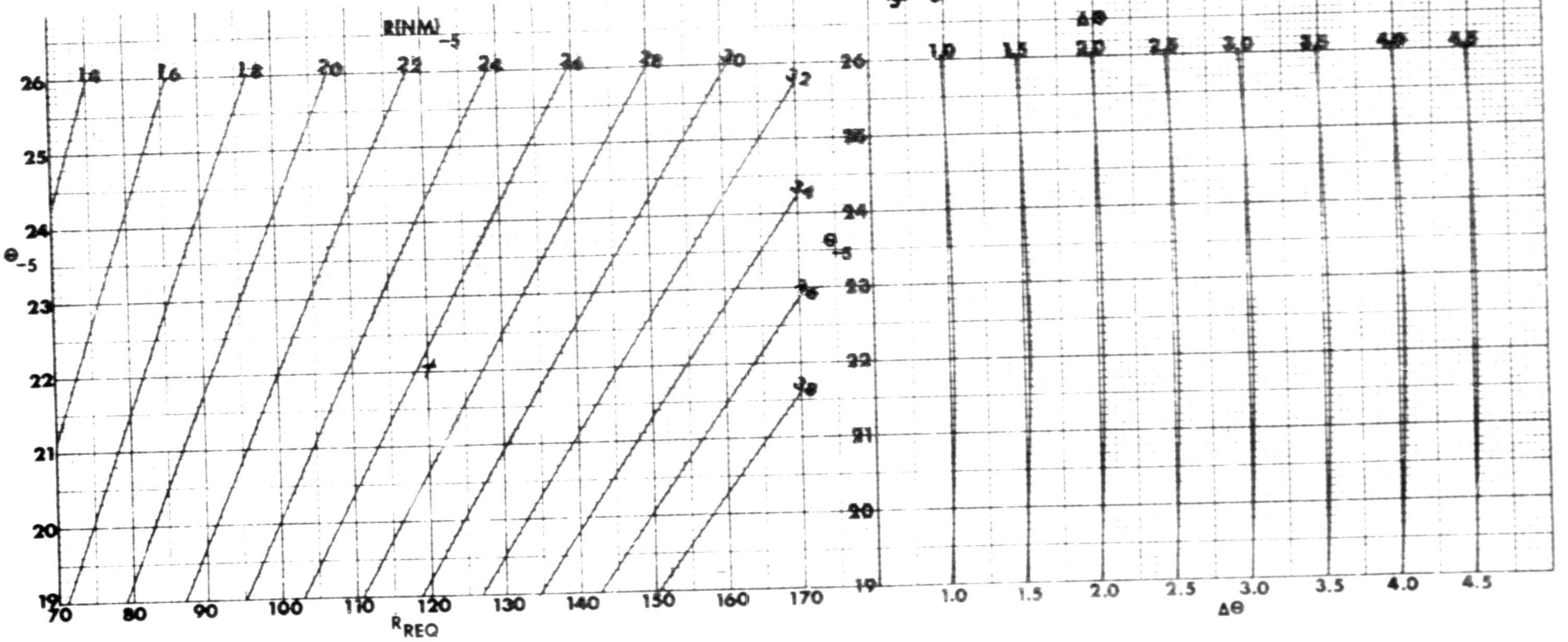
Θ_{-5} ________ 22.12 R_{-5} ________ 26.25 $\dot{R}_{-5}^{-}$ ________ 98.9

Θ_{-8} ________ 19.73 $\Delta\dot{R}$ ________ 21.8

$\Delta\Theta$ ________ 2.39

	PNGS	GND	CHARTS
$\overset{+}{F}$/A			
$\overset{+}{R}$/L			
$\overset{+}{D}$/U			





"D" MISSION

LM-120 CSM-130
130 DEGREE TRANSFER
9—17—68

FIRST MIDCOURSE CORRECTION

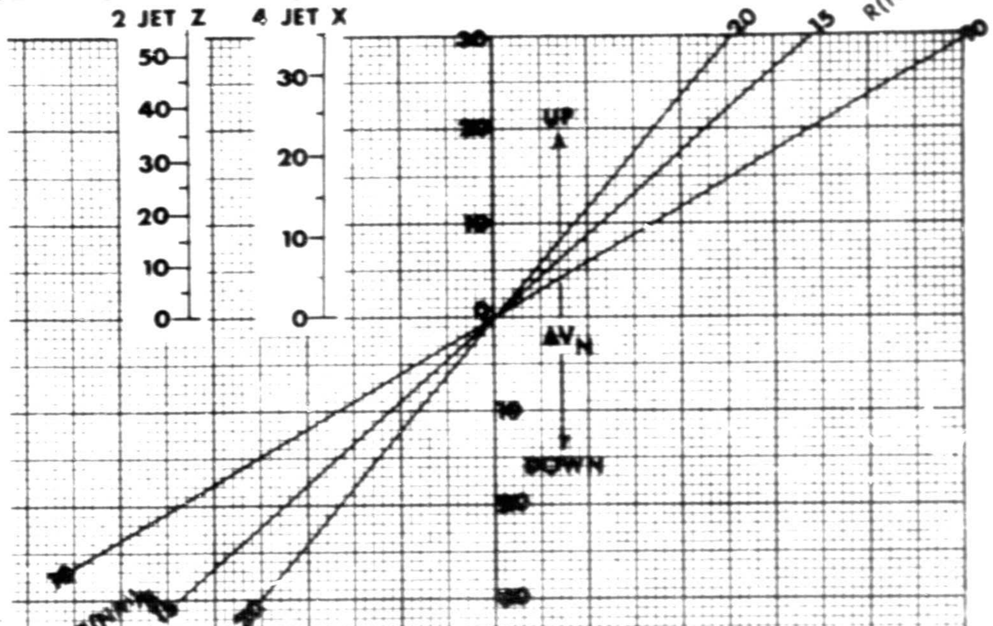
$\dot{R}_{REQ}$ ________ 97.4

Θ_8 ________ 40.24 R_8 ________ 12.90 $\dot{R}_8$ — ________ 97.4

Θ_5 ________ 34.86 $\Delta\dot{R}$ ________ 0.0

$\Delta\Theta$ ________ 5.38

	PNGS	GND	CHARTS
F/A			
R/L			
D/U			



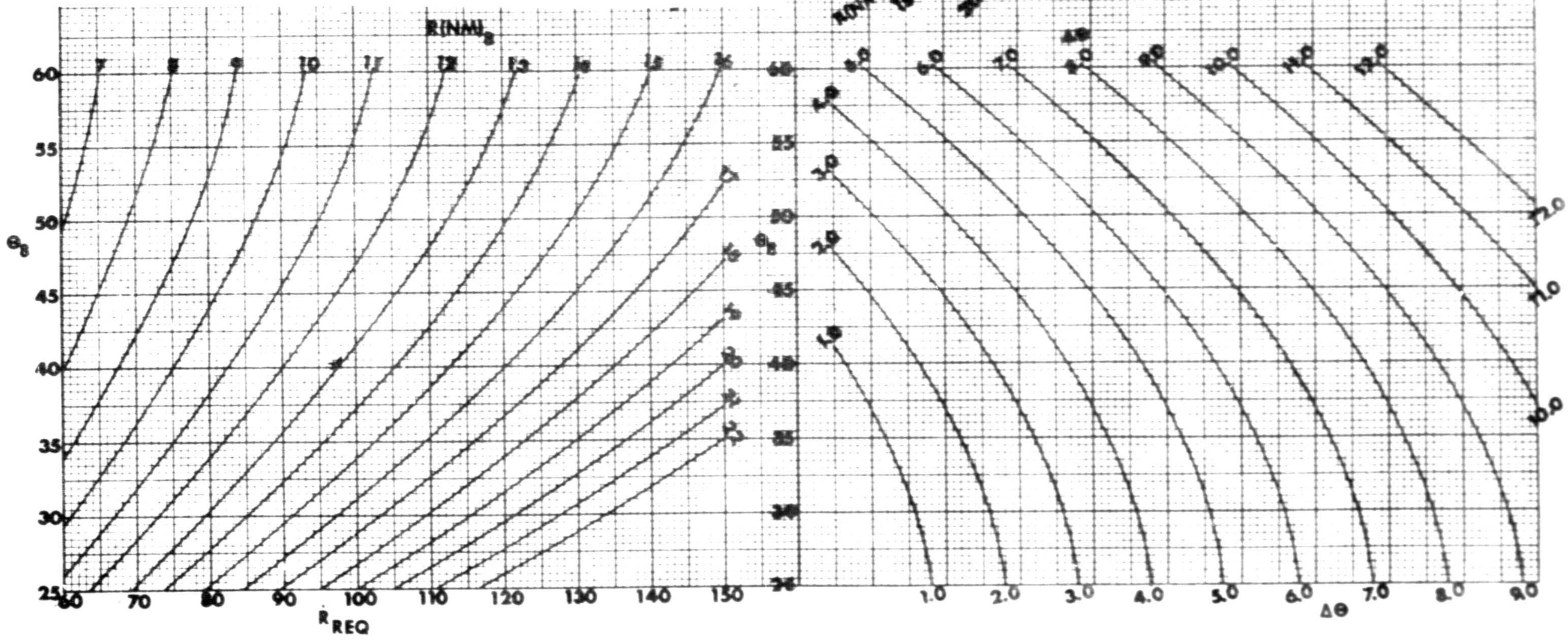


Figure 5

"D" MISSION

SECOND MIDCOURSE CORRECTION

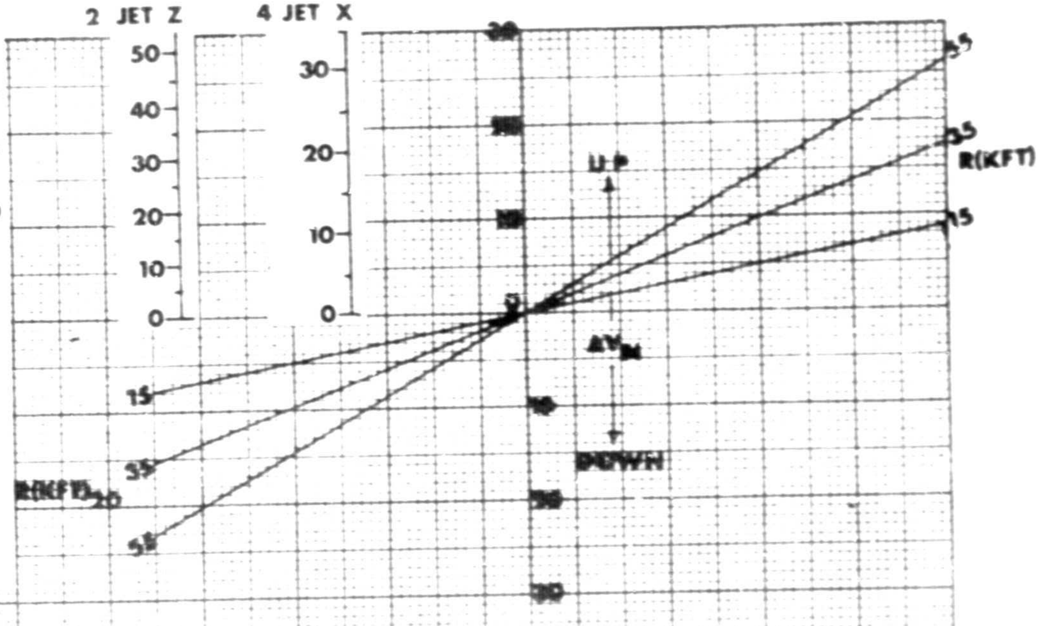
LM-120 CSM-130
130 DEGREE TRANSFER
9-17-68

Θ_{20} ____ 73.72 R_{20} ____ 25.3 $\dot{R}_{REQ}$ ____ 49.4

Θ_{17} ____ 63.13 $\dot{R}_{20}$ ____ 49.4

$\Delta\Theta$ ____ 10.59 $\Delta\dot{R}$ ____ 0.0

	PNGS	GND	CHARTS
$\overset{+}{F}/A$			
$\overset{+}{R}/L$			
$\overset{+}{D}/U$			



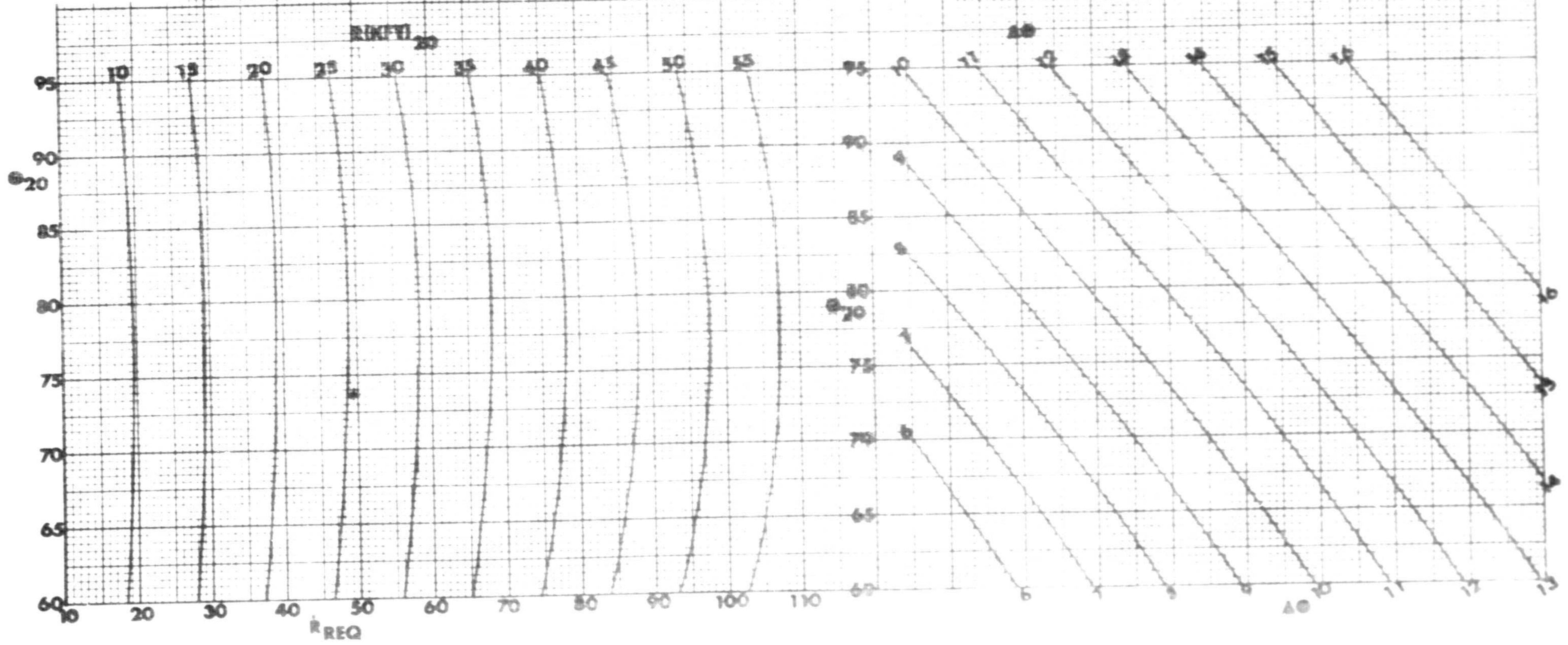
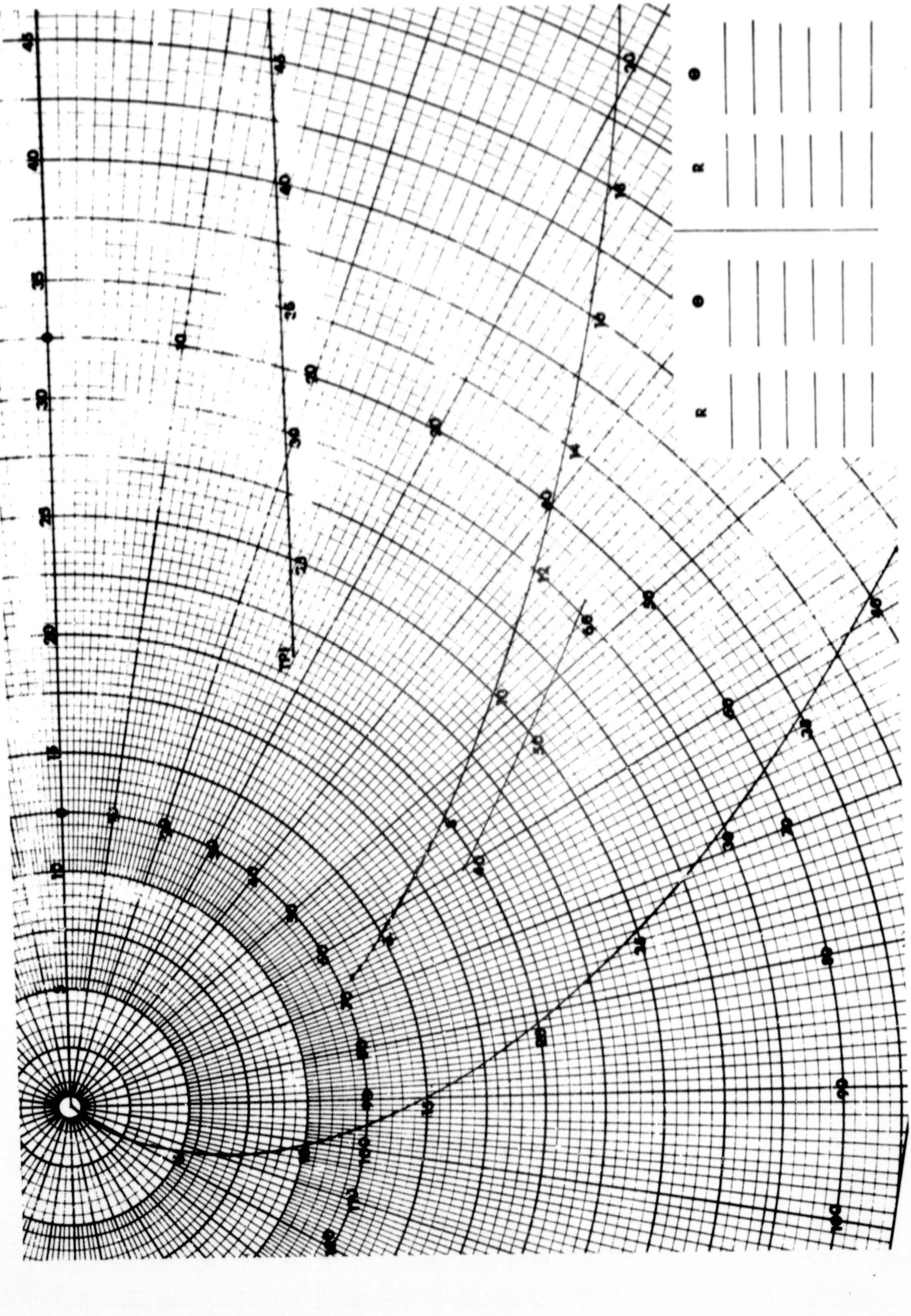


Figure 6

LM RELATIVE REFERENCE TRAJECTORY



LM CENTERED RELATIVE MOTION PLOT

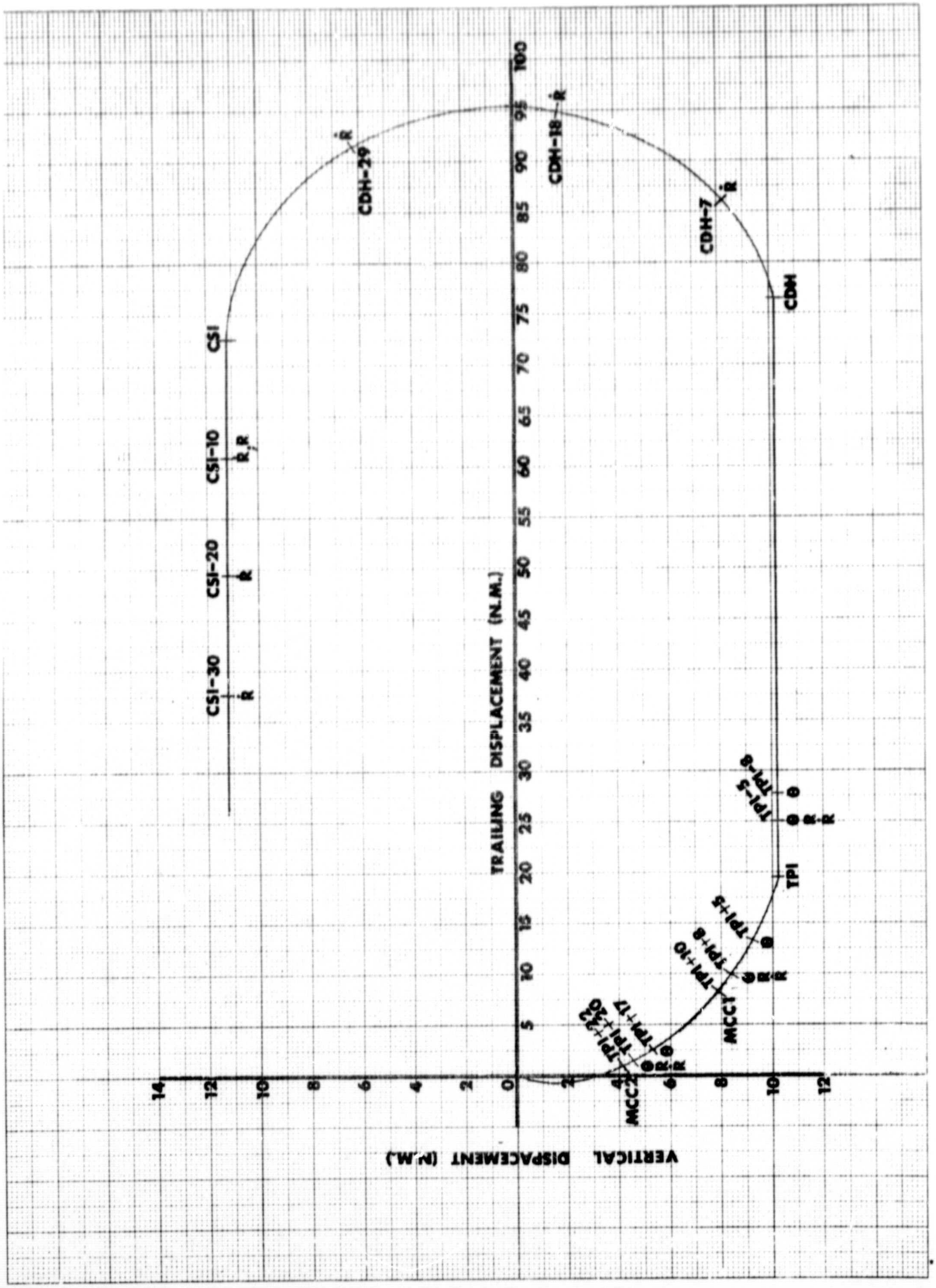


FIGURE 8

BRAKING SCHEDULE

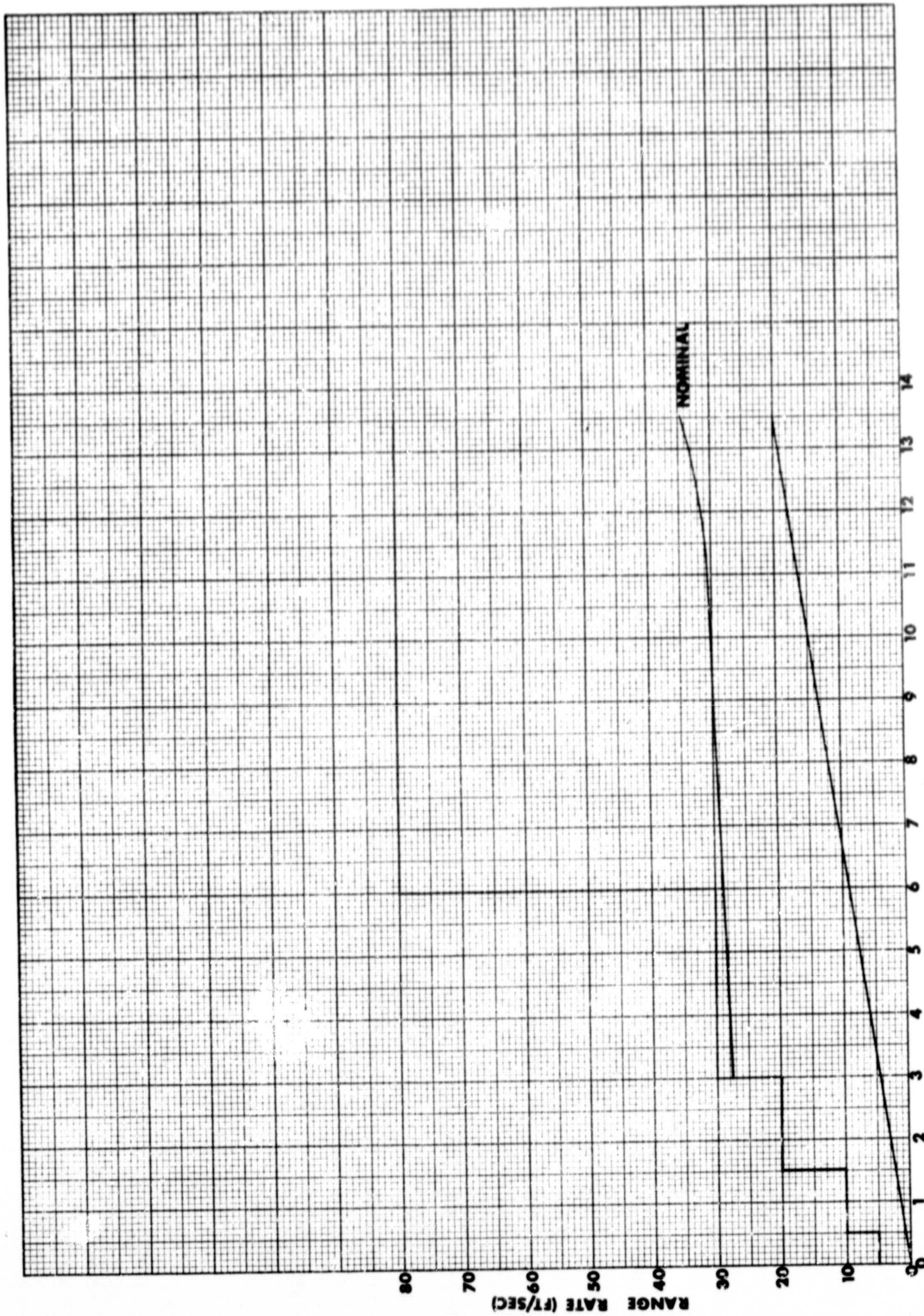


FIGURE 9

TOTAL ΔV

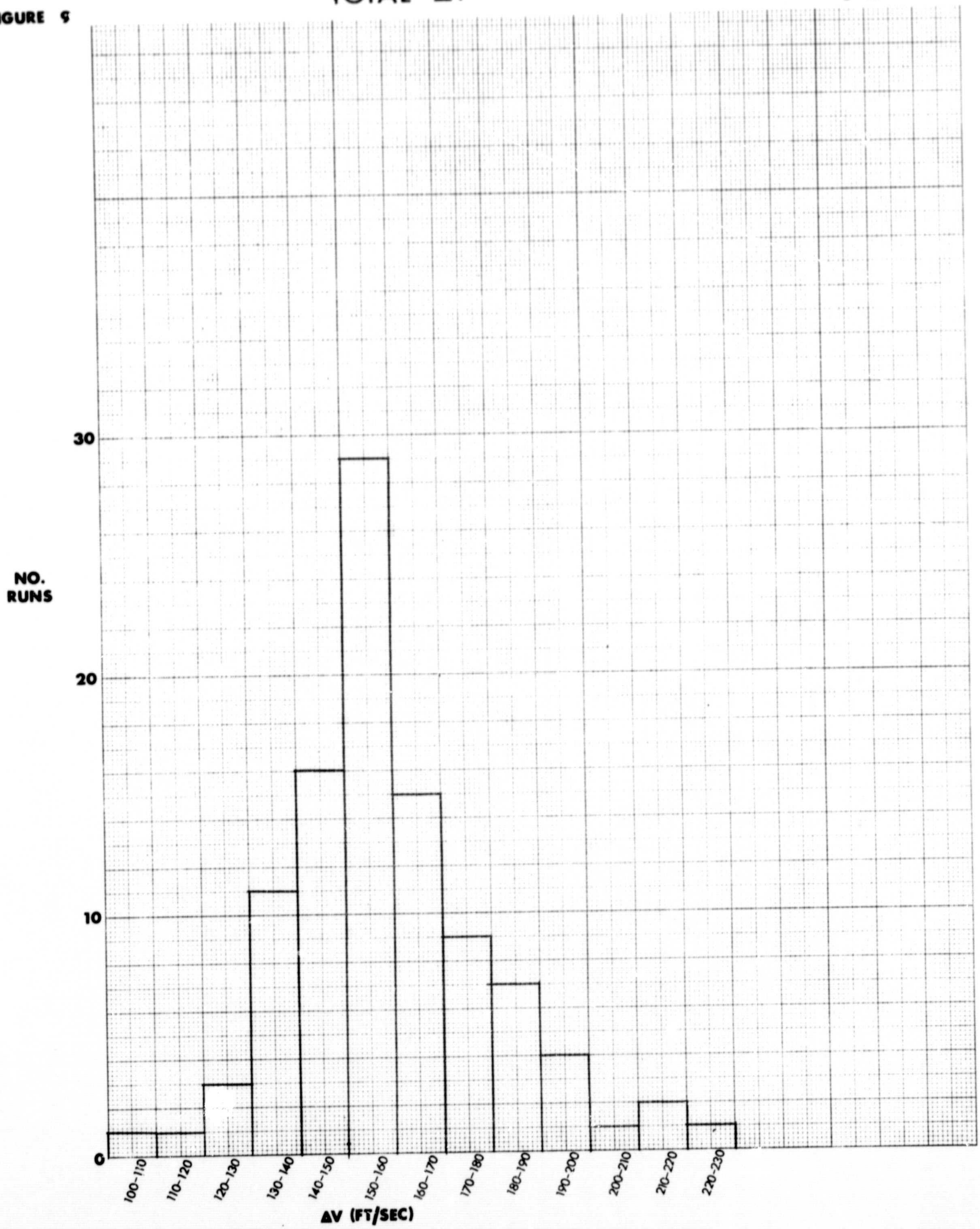


FIGURE 10

TIME OF TPI

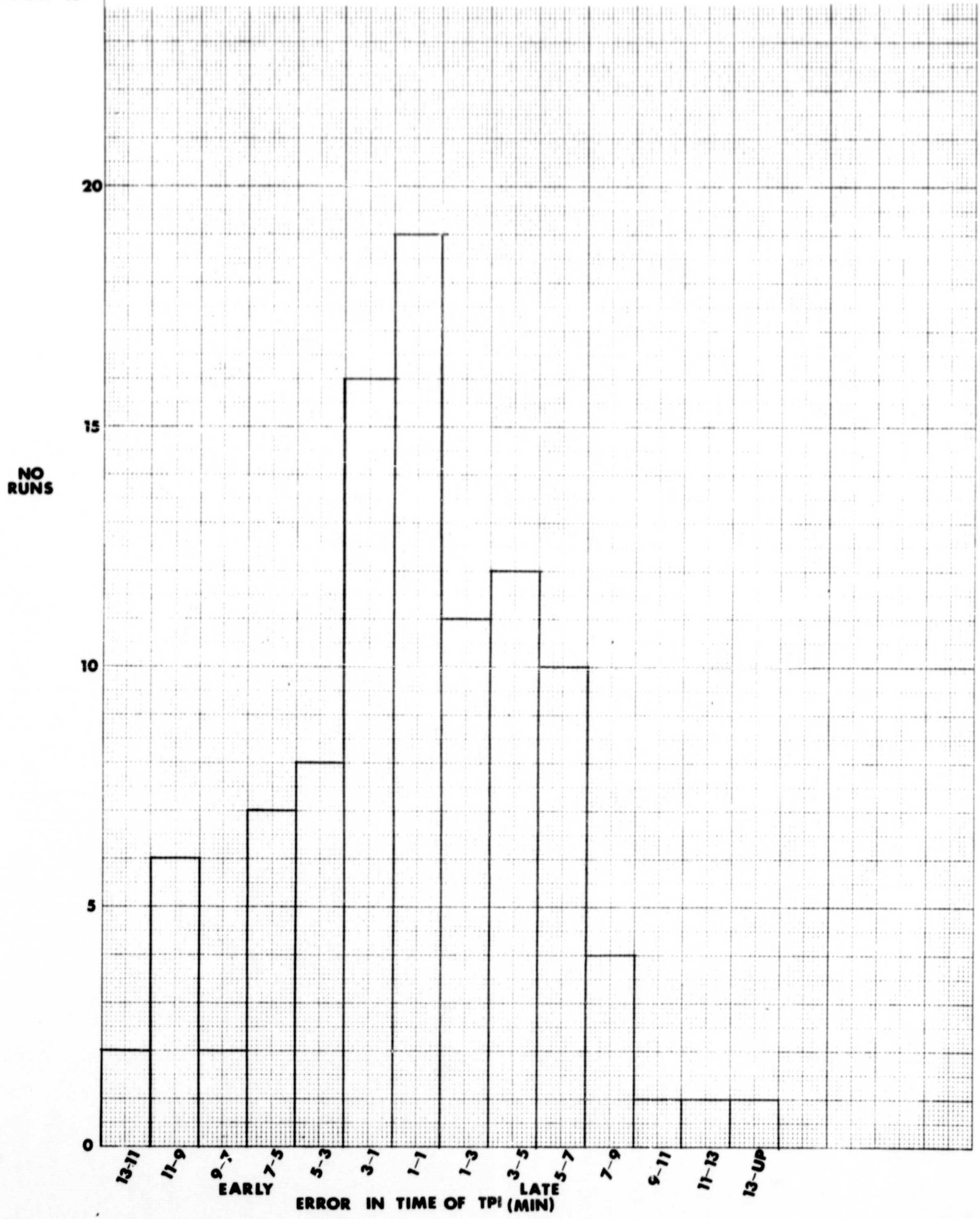


FIGURE 11

ΔT FROM TPI TPF