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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

INTERNAL NOTE MSC - EG - 69 - 18

PROJECT APOLLO

PERFORMANCE OF APOLLO BLOCK II THRUST VECTOR CONTROL USING THE PGNCS (PRIMARY GUIDANCE NAVIGATION AND CONTROL SYSTEM)

SYSTEMS ANALYSIS BRANCH
GUIDANCE AND CONTROL DIVISION

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

April 8, 1969

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INTERNAL NOTE

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SUMMARY

The Guidance and Control Division has developed all digital functional simulators of the Apollo Block II TVC (Thrust Vector Control), during SPS (Service Propulsion System) thrusting, including the combined guidance and DAP (Digital Autopilot) dynamics. These functional simulators have been used as design and analysis tools and provide detailed performance data. This report presents the results of a performance analysis comparison of the COLOSSUS I and COLOSSUS II TVC DAP designs using these simulators. Alternate designs for the COLOSSUS II program were also evaluated. The primary effort of the study was concentrated on the CSM/LM configuration as the CSM DAP is identical for both programs and has already been flight tested.

The results of this study showed that (1) The COLOSSUS II design gives far superior performance and is adequate for the lunar mission; (2) One of the three alternate designs for COLOSSUS II is unacceptable because of unstable propellant dynamics; and (3) The other two alternate designs are adequate.

INTRODUCTION

In an effort to improve the short burn performance and pilot monitoring capability during the initial portion of an SPS engine burn under PGNCS control, maximum use was made of the latest structural dynamics data to develop the COLOSSUS II CSM/LM TVC DAP. This new design (ref. 1) was based on the structural test data obtained from the Structures and Mechanics Division (Ref. 2) which has far less uncertainty than the previous analytically determined data. The stability characteristics of this design are presented in Ref. 3.

In addition to the present nominal COLOSSUS II CSM/LM TVC DAP filter, alternate filter designs were also evaluated. For purposes of identification in this document, the various DAP filter designs will be referred to as COLOSSUS I, COLOSSUS II-LB, COLOSSUS II-HB, ALTERNATE I, ALTERNATE II and ALTERNATE III. The filter forms and coefficients are shown in Figures 1 and 2. It should be noted that the COLOSSUS II-HB coefficients are in erasable memory, whereas the COLOSSUS II-LB and COLOSSUS I coefficients are in fixed memory.

$$D(Z) = K_Z \frac{1 + N_1 Z^{-1} + N_2 Z^{-2} + \cdots + N_7 Z^{-7}}{1 + D_1 Z^{-1} + D_2 Z^{-2} + \cdots + D_6 Z^{-6}}$$

$N_1 = 2.9708385$	$D_1 = -4.7798977$
$N_2 = 3.1947342$	$D_2 = 9.4452763$
$N_3 = -0.40962906$	$D_3 = -9.8593475$
$N_4 = 2.5780275$	$D_4 = 5.7231811$
$N_5 = 2.9629319$	$D_5 = 1.7434750$
$N_6 = -1.5101470$	$D_6 = 0.21933335$
$N_7 = 0.31243224$	

$K_Z = (T1_x/I) = 7.6 \times 10^{-3}$ — 40 ms MAP

1.8×10^{-3} — 30 ms MAP

COLOSSUS I

FIGURE I

$$D_Z = K_Z \frac{N_{10} + 2(\frac{N_{11}}{2})Z^{-1} + N_{12}Z^{-2}}{1 + 2(\frac{D_{11}}{2})Z^{-1} + D_{12}Z^{-2}} \times \frac{N_{20} + 2(\frac{N_{21}}{2})Z^{-1} + N_{22}Z^{-2}}{1 + 2(\frac{D_{21}}{2})Z^{-1} + D_{22}Z^{-2}} \times \frac{N_{30} + 2(\frac{N_{31}}{2})Z^{-1} + N_{32}Z^{-2}}{1 + 2(\frac{D_{31}}{2})Z^{-1} + D_{32}Z^{-2}}$$

COEFF.	COLOSSUS II-HB	COLOSSUS II-LB	ALTERNATE I	ALTERNATE II	ALTERNATE III
N_{10}	1.0	1.0	1.0	1.0	1.0
$N_{11}/2$	0.0	-0.3285	-0.43195	-0.66175	0.6674
N_{12}	0.0	-0.3301	-0.0869	0.3416	[illegible].3435
$D_{11}/2$	-0.6103	-0.9101	-0.53195	-0.71655	-[illegible]15
D_{12}	0.5350	0.84[illegible]0	0.4[illegible]	0.6213	0.0626
N_{20}	1.0	1.0	1.0	0.250	0.0625
$N_{21}/2$	-0.4811	0.0	-0.0909	0.0	0.0058
N_{22}	0.0	0.0	0.0083	0.0	0.0376
$D_{21}/2$	-0.6103	-0.9101	-0.53195	-0.71655	-0.8428
D_{22}	0.5350	0.3460	0.484	0.6213	0.[illegible]1
N_{30}	1.0	0.5	1.0	1.0	0.0625
$N_{31}/2$	-0.5252	-0.47115	-0.45565	-0.5808	-0.025
N_{32}	0.8480	0.4749	0.8396	0.8549	0.0437
$D_{31}/2$	-0.7206	-0.9558	-0.6447	-0.7509	-0.[illegible]
D_{32}	0.7882	0.9372	0.7603	0.8012	0.7503
$K_Z\ (\frac{\Pi x}{I})$	0.0275	0.058	1.22	1.18	5.358

Figure 2. - Filter forms and coefficients

SIMULATOR DESCRIPTION

In cooperation with the Computation and Analysis Division, functional simulators of the COLOSSUS I and COLOSSUS II TVC DAP's have been developed for engineering evaluation of the TVC systems. These simulators made use of the flight environments tape developed by MIT/IL for flight program testing. All data presented in this document came from testing done on these functional simulators. These simulations are described in reference 4.

RESULTS

As was noted in the introduction, the primary reason for development of the COLOSSUS II CSM/LM TVC DAP was to improve the short burn performance and the pilot monitoring of the CSM/LM TVC DAP. As a measure of the performance, two parameters were generally considered: (1) Peak attitude error, and (2) final cross-axis velocity. The initial thrust misalignment in both axes is one degree (3 sigma misalignments are very close to one degree).

Figures 3 and 4 are time responses of the attitude error, and cross-axis velocity error, with the COLOSSUS I CSM/LM TVC DAP, for a burn duration of approximately ten seconds. The attitude errors in both axes are continuously increasing because the combined guidance and control system time constants are too large. The final velocity error is greater than six feet per second. Figures 5 and 6 are time responses of the same system for a burn of approximately fifty seconds. The attitude errors peak at about nine degrees and are oscillatory. The final cross-axis velocity error approaches zero. The two runs demonstrate the need to improve the performance over that available in COLOSSUS I system. It is readily apparent that the short burn final cross-axis velocity and the peak attitude error for any length burn are too large to be considered acceptable.

Figures 7 and 8 are time responses of the attitude error and cross-axis velocity, with the COLOSSUS II-LB CSM/LM TVC DAP, for a burn duration of approximately ten seconds. The attitude error peaks at about 1.7 degrees and decreases to about 1.0 degrees at engine cutoff. The final cross-axis velocity is less than three feet per second. Figure 9 and 10 are time responses of the same system for a burn of approximately fifty seconds. The peak attitude error is about 1.75 degrees and decreases to about zero at engine cutoff. The final cross-axis velocity is zero. These two runs, when compared to the previous runs for COLOSSUS I, demonstrate the great improvement in short burn pointing accuracy and attitude error transient due to initial thrust mistrim.

Figures 11 and 12 are time responses of the attitude error and cross-axis velocity with the COLOSSUS II-HB CSM/LM TVC DAP controlling an LOI burn. The peak attitude error is about 1.1 degrees and is zero at engine cutoff. The final cross-axis velocity is about zero. The velocity limit cycling performance is due to quantization of the velocity measurement. Figures 13 and 14 are time response taken under the same conditions except the control was switched to the COLOSSUS II-LB CSM/LM TVC DAP at 10 seconds after engine ignition. This switchover can be accomplished at anytime after ignition by verb 46E to the CMC. (Presumably the only reason for making this switchover would be to provide additional phase compensation to the sloshing propellant dynamics. Such an event would probably occur early in the burn.) With the switchover at 10 seconds, the peak attitude error reaches a magnitude of about 3.2 degrees. This increase is due to the lower system gain and slower response. The final cross-axis velocity is about zero. In summary, this run demonstrates that the LOI maneuver can be completed with the low bandwidth system.

Figures 15 and 16 are time responses of the attitude error and cross-axis velocity error with Alternate I controlling a burn of about fifty seconds. The peak attitude error for this system was about the same as for the COLOSSUS II-HB. However, it has a faster response because it is a wider bandwidth system. The final cross-axis velocity is approximately zero.

The attitude error and cross-axis velocity time responses for a burn of about fifty seconds with Alternate II controlling are shown in Figures 17 and 18. These responses show a more degraded performance than the COLOSSUS II-HB as the peak attitude errors are about 2.7 degrees. The final cross-axis velocity error is about zero.

Figures 19 and 20 are the attitude errors and cross-axis velocity errors with alternate III controlling. Alternate III is a sixth order representation of the COLOSSUS I DAP prior to switchover. Therefore, the performance is similar: Peak attitude error is about nine degrees and is slow to damp, and the final cross-axis velocity approaches zero. However, this particular design has unstable slosh characteristics as is demonstrated in the engine time response shown in Figure 21. Although the instability has not reached significant proportions for this burn, the engine oscillations at the end of an LOI length burn are about 1.2 degrees peak-to-peak. This characteristic makes this alternate unacceptable.

Figure 22 is a final cross-axis velocity error plot versus burn time for the CSM alone TVC DAP. This DAP is the same for both COLOSSUS I and COLOSSUS II. The error is seen to build up to a peak for a burn time of approximately 10 seconds and approach zero for burn lengths greater than twenty seconds. The initial engine mistrim for all burn times was one degree.

CONCLUSIONS

The following conclusions can be drawn from the results of this study:

a. The COLOSSUS II performance is far superior to that of COLOSSUS I.

b. Alternate I and AlternateII CSM/LM TVC DAP designs have good performance characteristics but neither is recommended as primary because of the additional verification which would be required. Alternate I is considered to be a good backup design.

c. The Alternate III CSM/LM TVC DAP design is unstable and therefore unacceptable.

d. The CSM TVC DAP has good performance characteristics as has been demonstrated during flight of Apollo 7, 8, and 9.

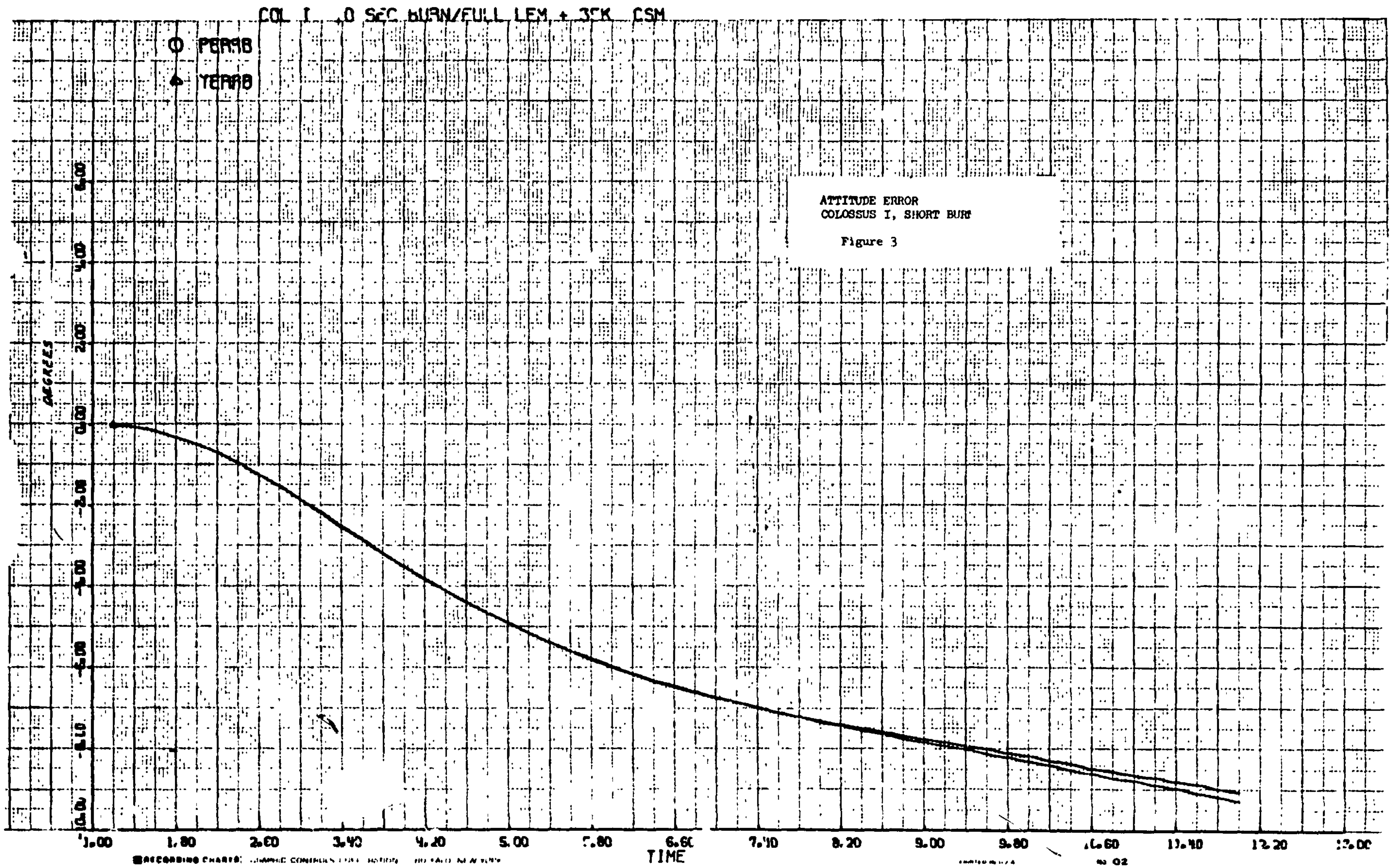
REFERENCES

1. GSOP (Guidance System Operations Plan for Manned CM Earth Orbital and Lunar Missions using Program COLOSSUS 2 (COMANCHE Rev. 44), Section 3 Digital Autopilots (Rev. 4), February 1969, MIT/IL.

2. NASA/MSC letter ES2-L33-68 to North American Rockwell Corporation, Downey, California, regarding comparison of experimental and analytical results for the CSM/LM Docked Modal Test, December 9, 1968.

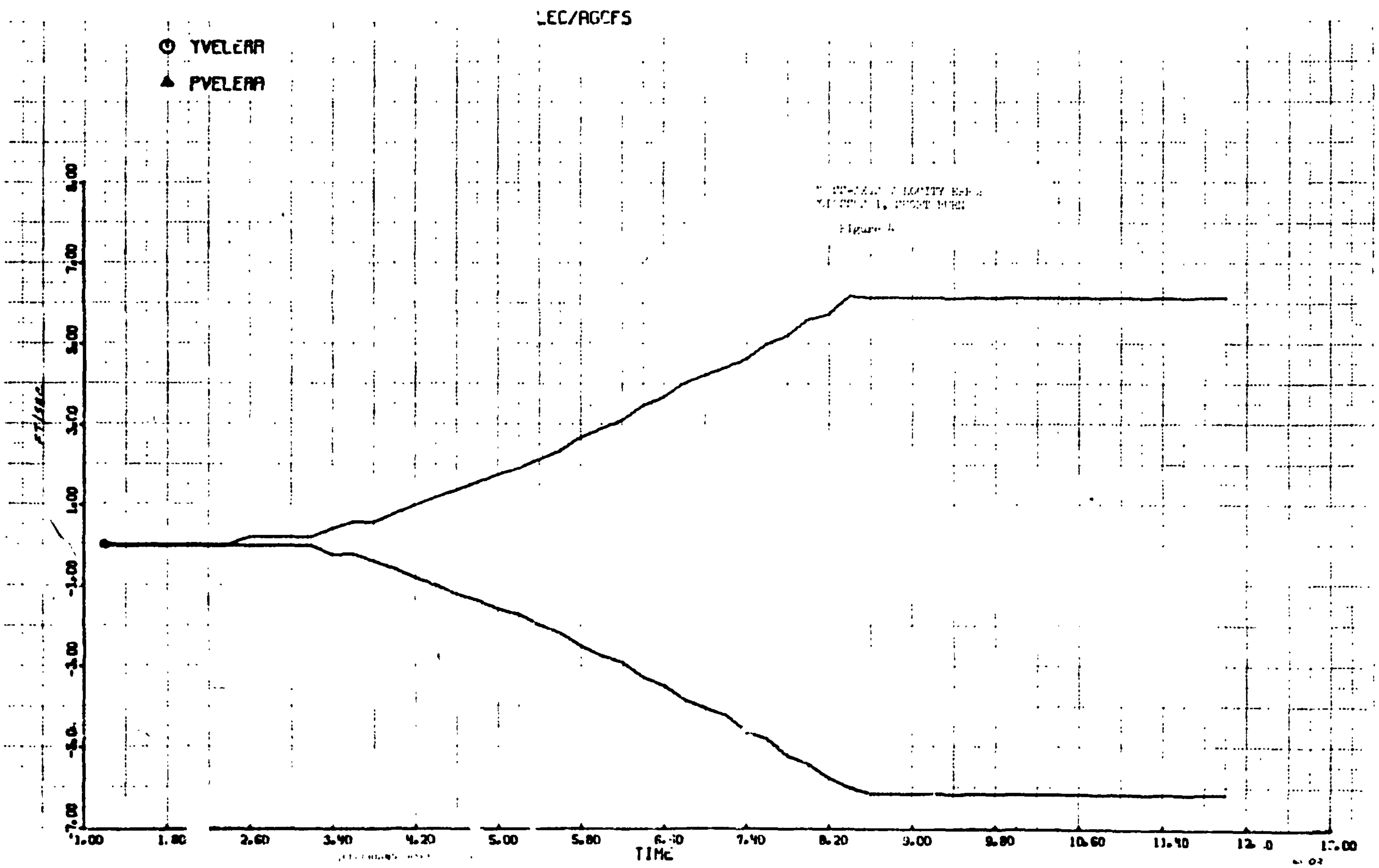
3. MSC Internal Note MSC-EG-69-16, Stability Analysis of Apollo Block II CSM/LM Thrust Vector Control Systems, by Emery E. Smith, Jr.

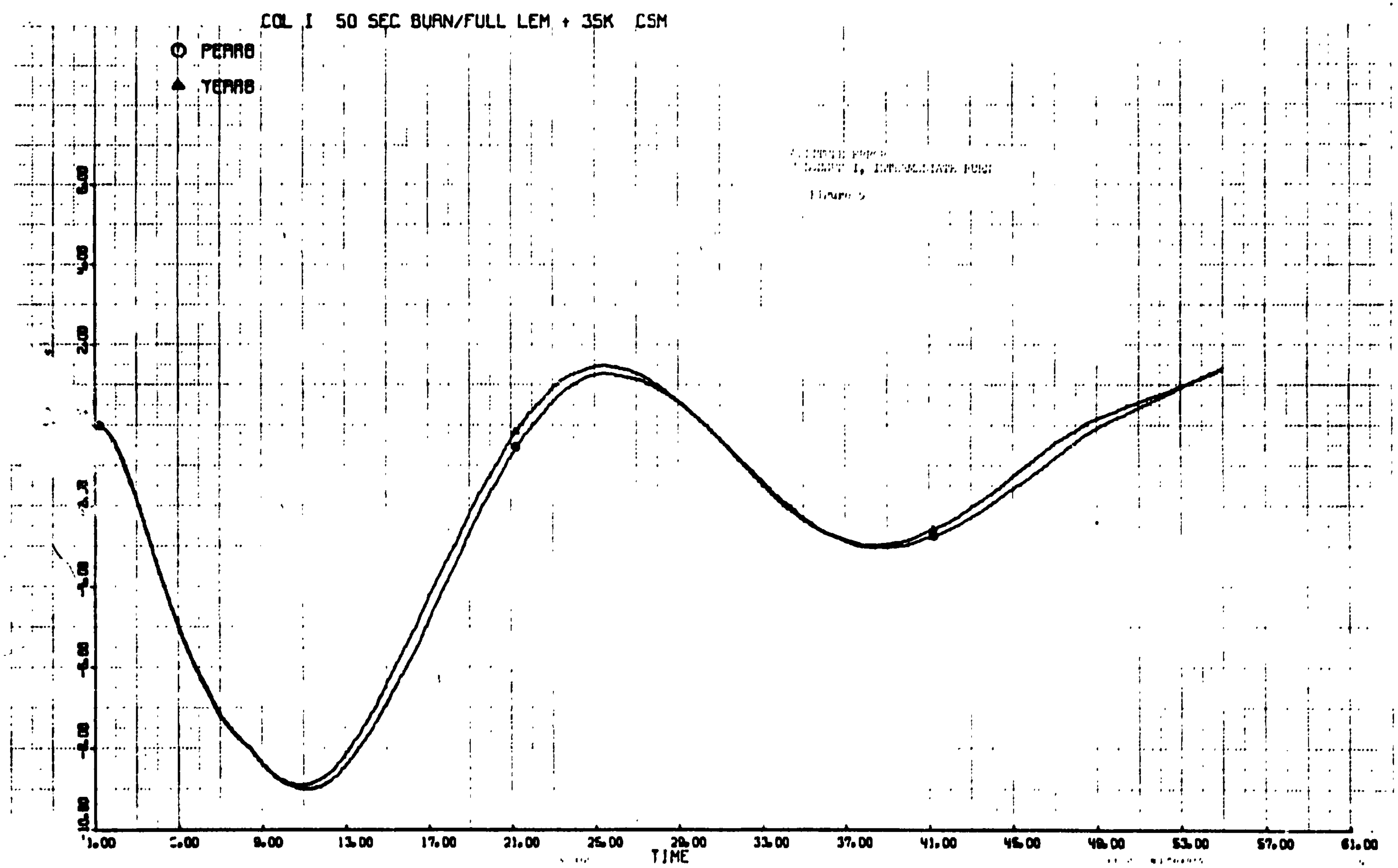
4. LEC (Lockheed Electronics Company) IC LEC/GC/32, Apollo Guidance Computer Functional Simulator Programmer User's Guide - Revision C., December 19, 1967.



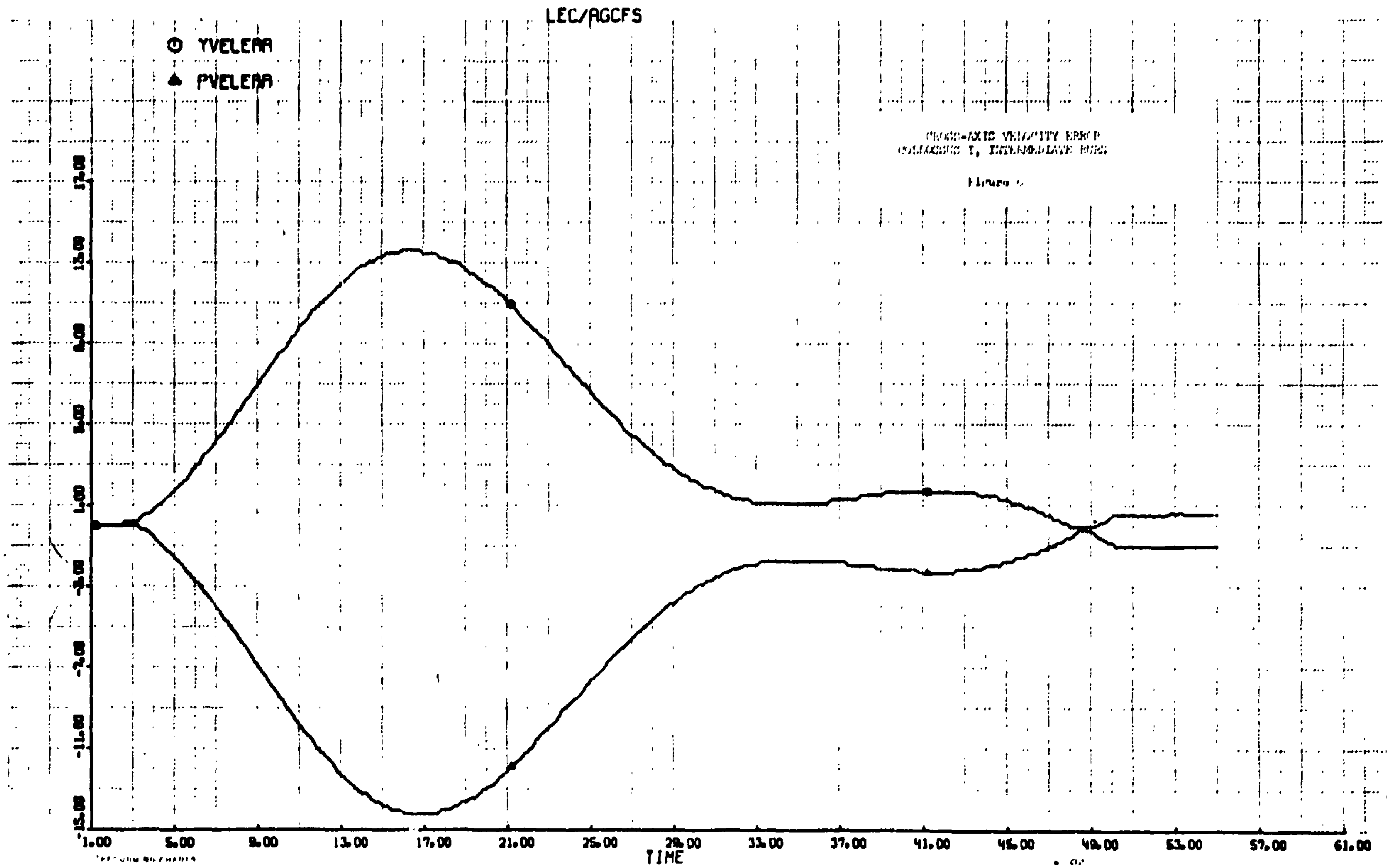
ATTITUDE ERROR
COLOSSUS I, SHORT BURN

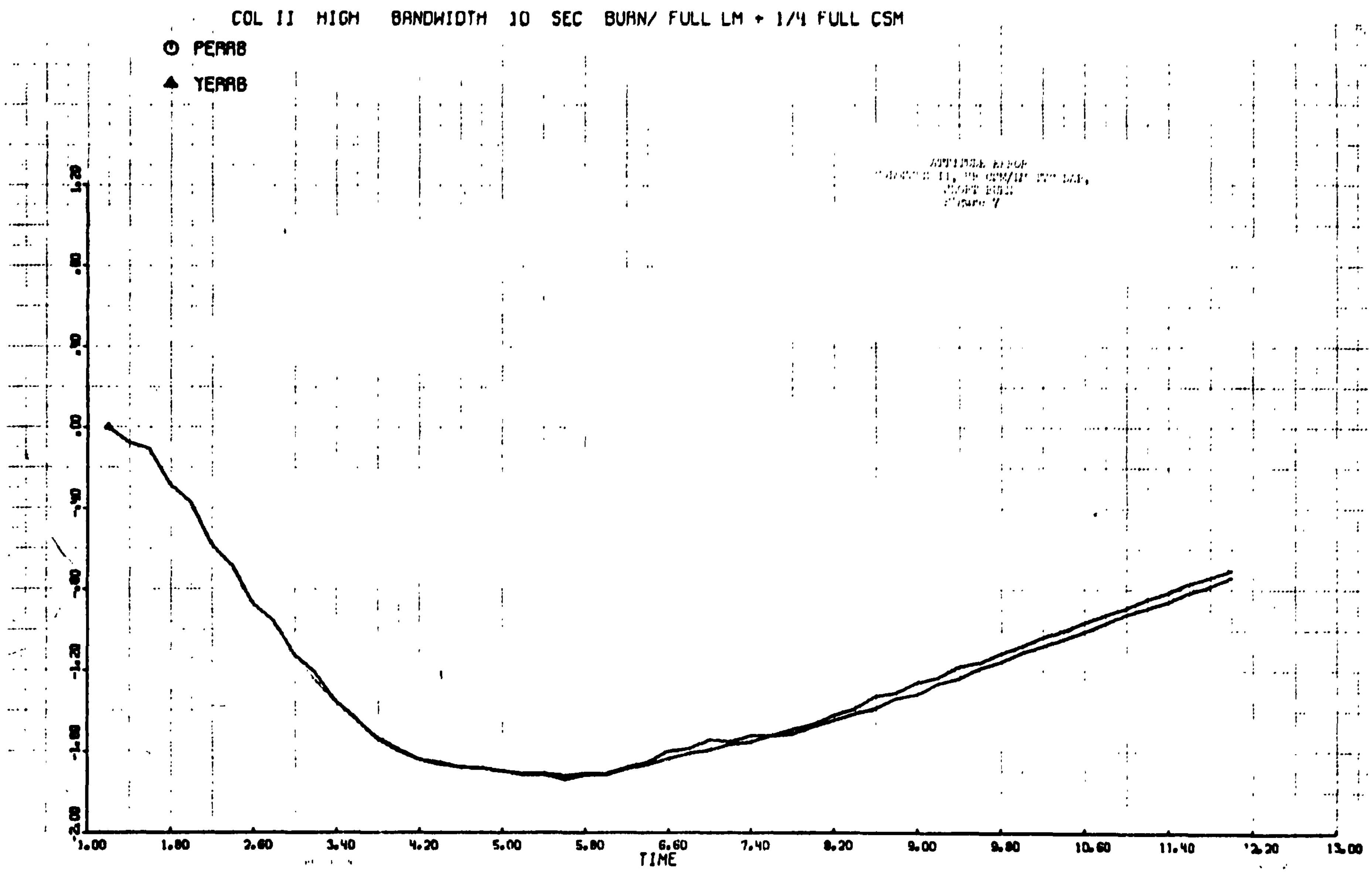
Figure 3

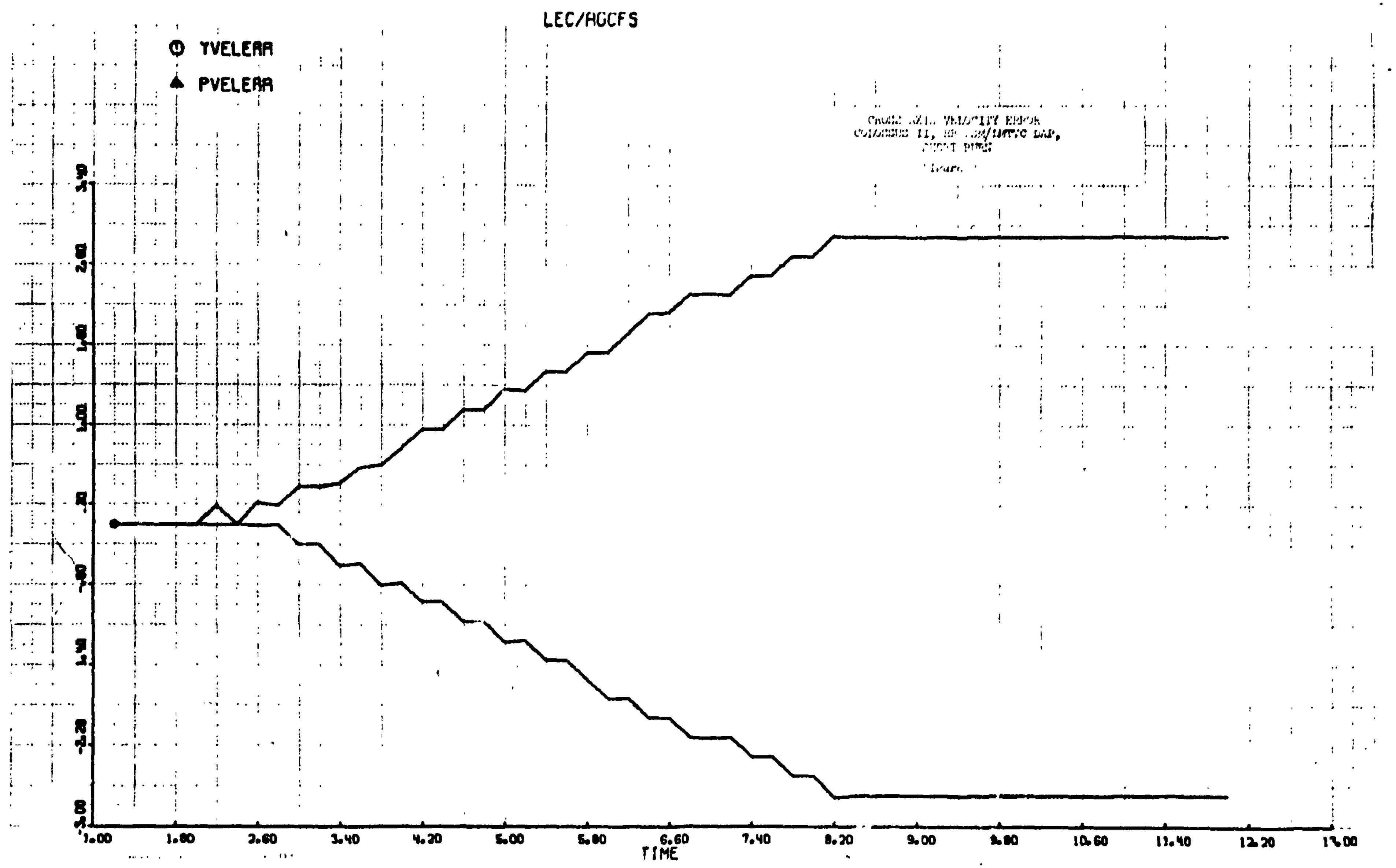

LEC/AGCFS
TVELERR
PVELERR
FT/SEC
TIME
Figure 4

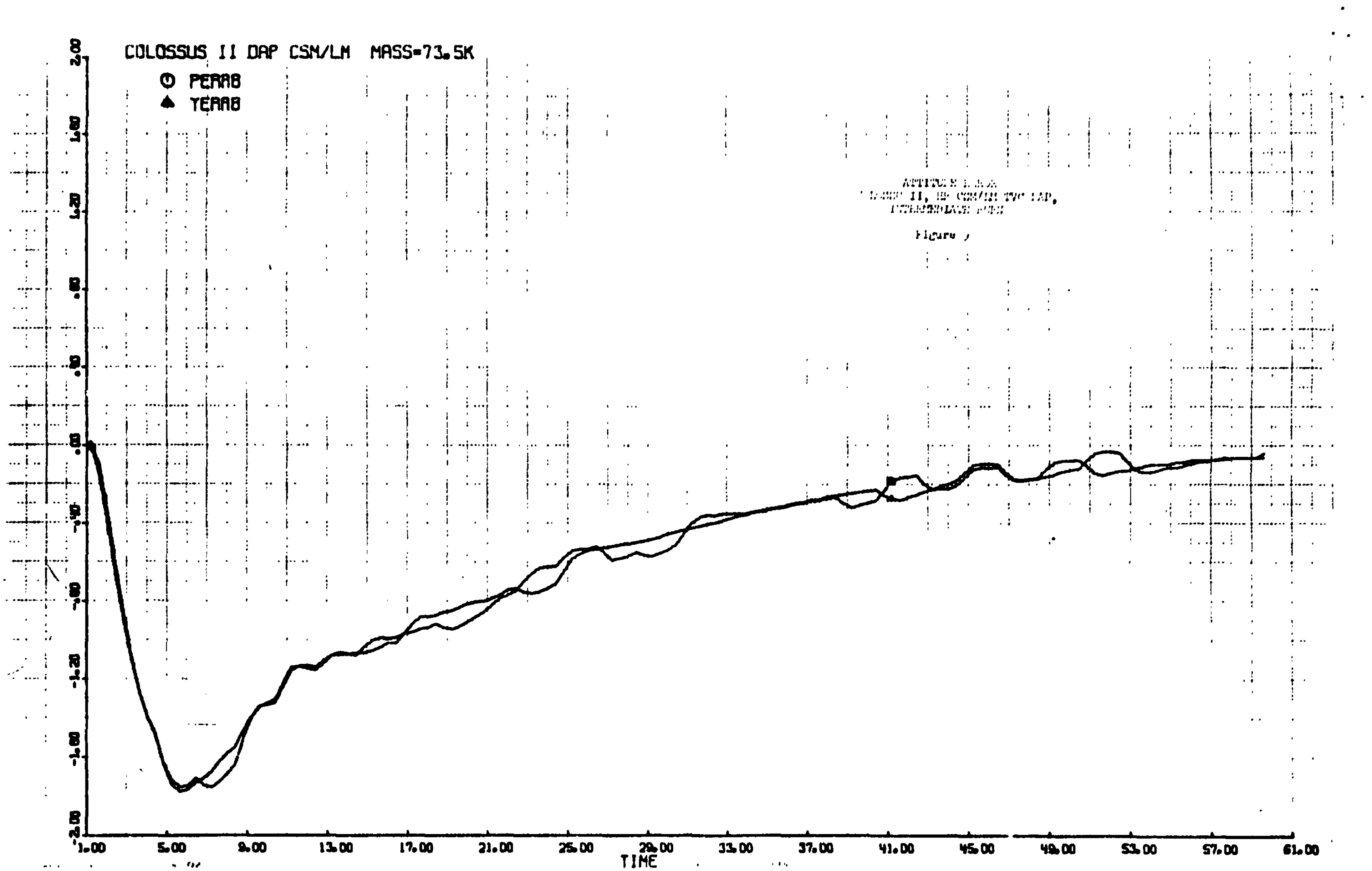


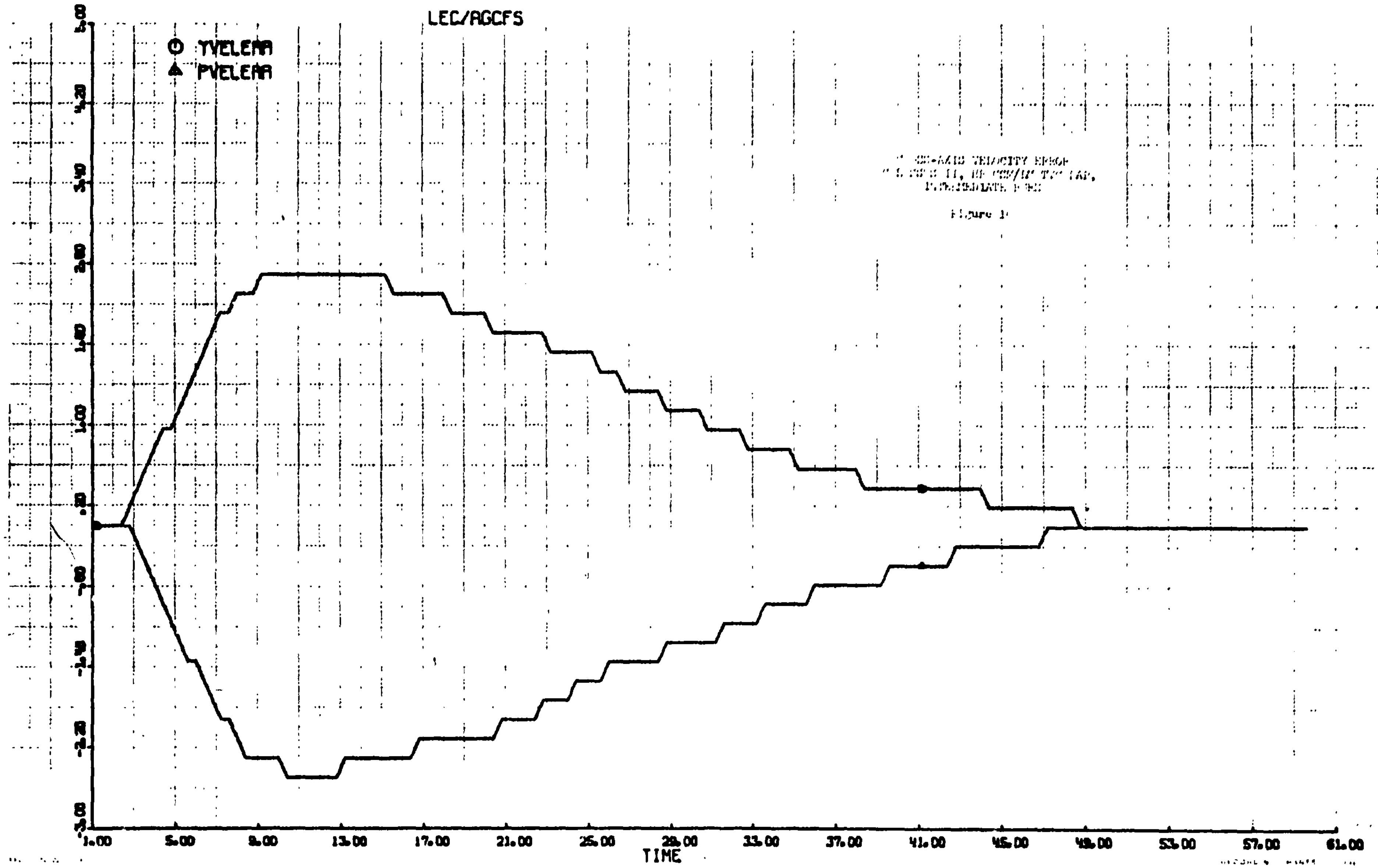
COL I 50 SEC BURN/FULL LEM + 35K CSM
PERR8
YERR8
TIME

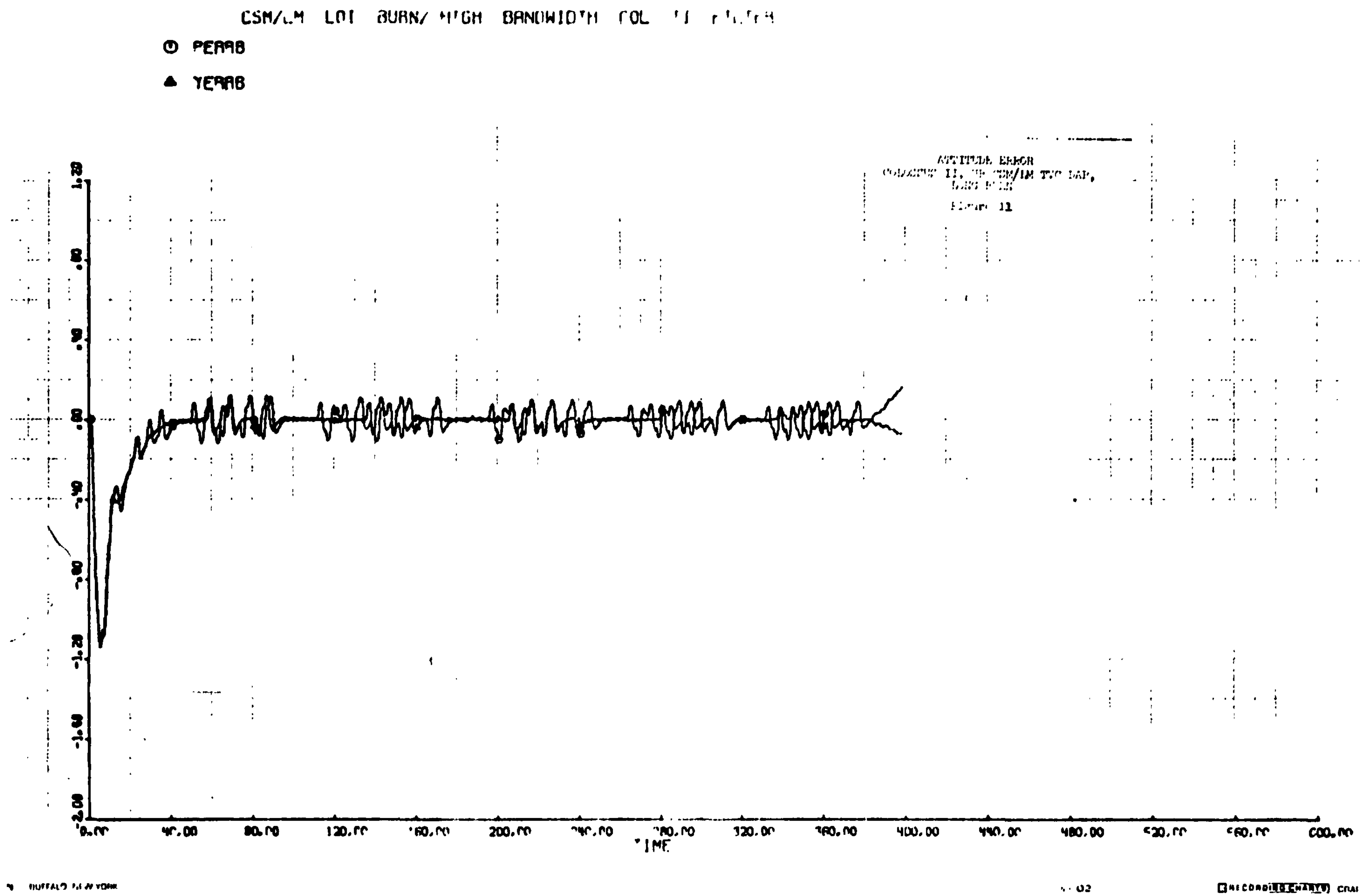

LEC/AGCFS
YVELERR
PVELERR
TIME
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
45.00
49.00
53.00
57.00
61.00


COL II HIGH BANDWIDTH 10 SEC BURN/ FULL LM + 1/4 FULL CSM
PERRB
YERRB
1.20
.80
.40
.00
-.40
-.80
-1.20
-1.60
-2.00
1.00
1.80
2.60
3.40
4.20
5.00
5.80
6.60
7.40
8.20
9.00
9.80
10.60
11.40
12.20
13.00
TIME

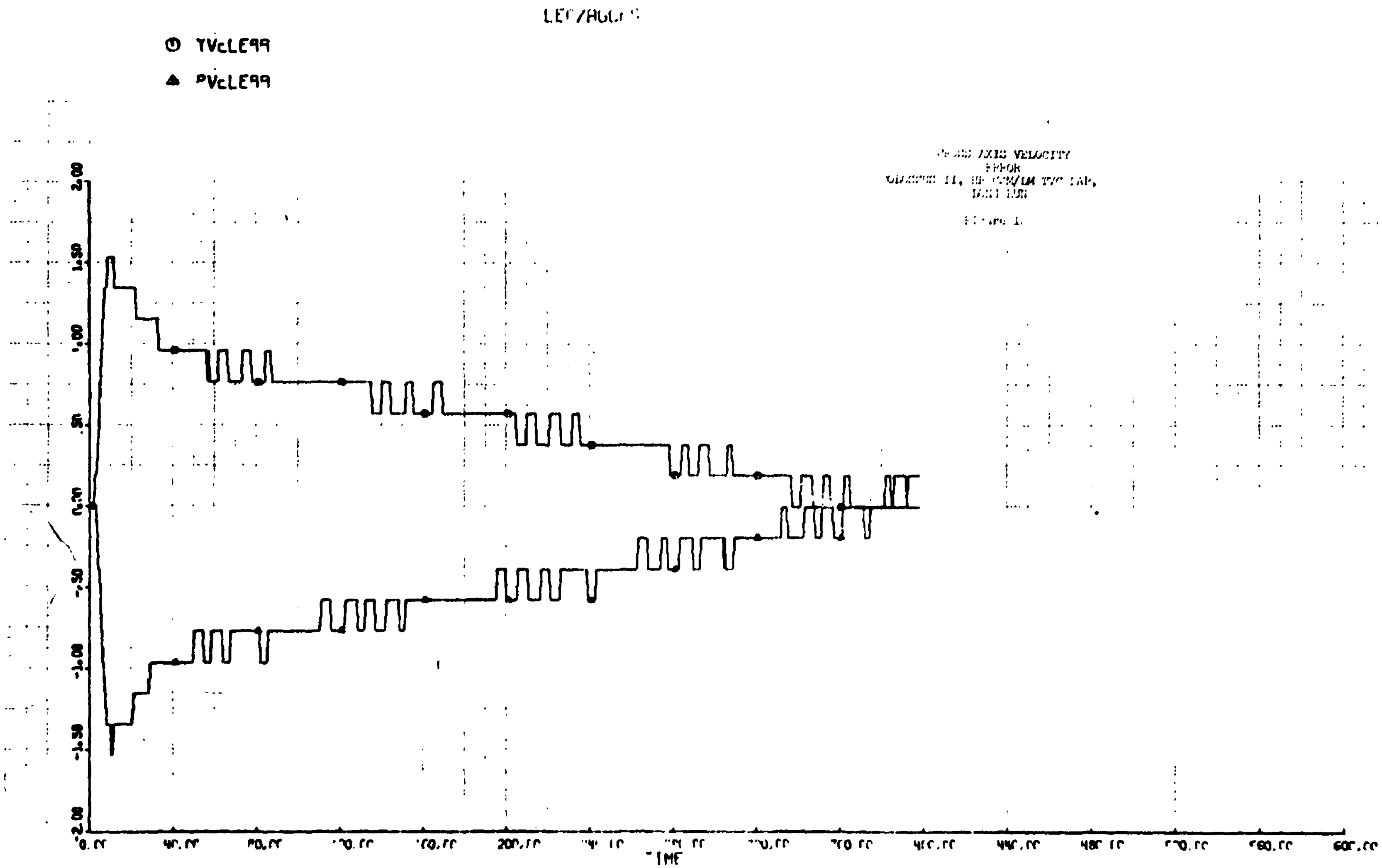

LEC/AGCFS
TVELERR
PVELERR
1.00
1.80
2.60
3.40
4.20
5.00
5.80
6.60
7.40
8.20
9.00
9.80
10.60
11.40
12.20
13.00
TIME

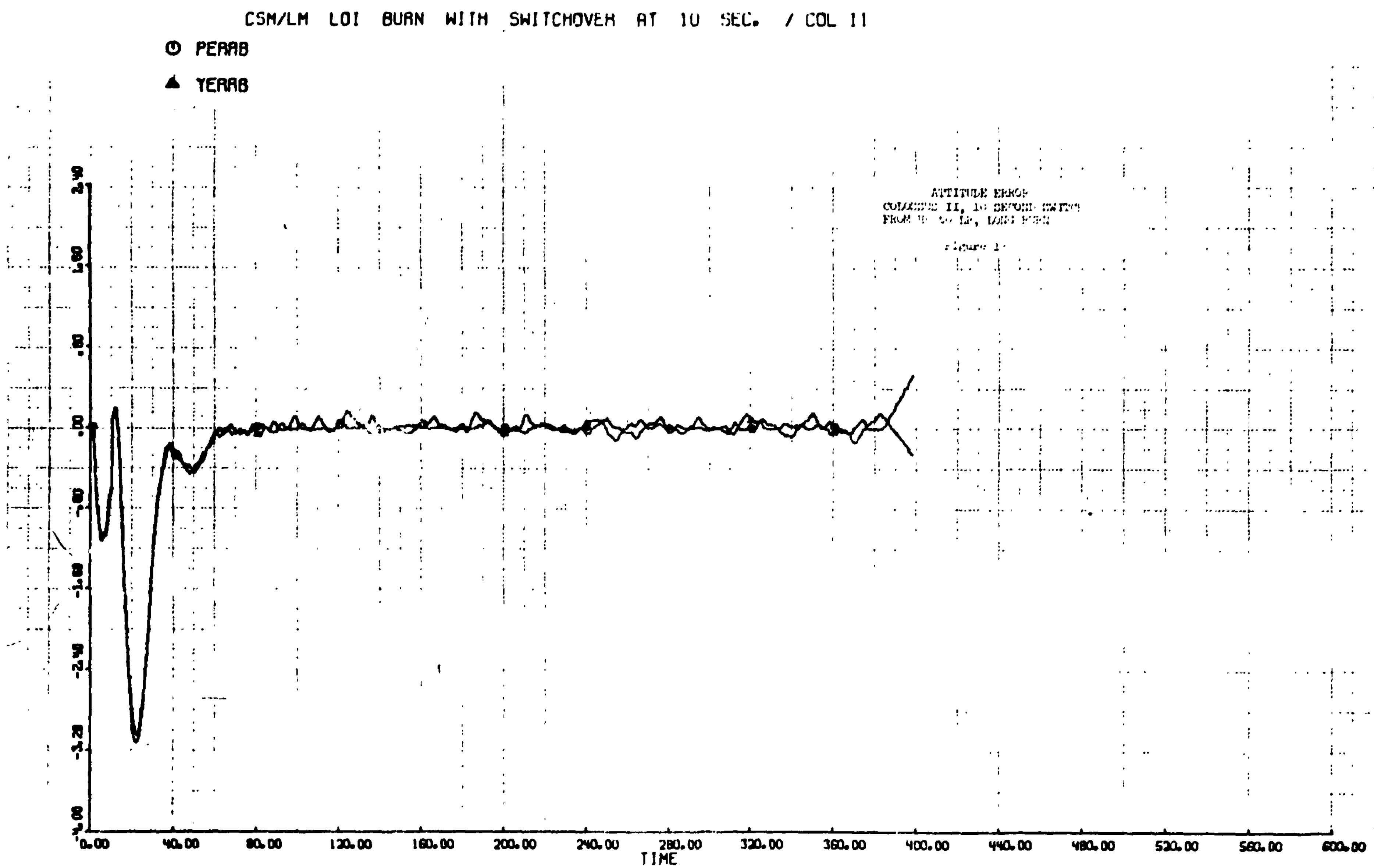

COLOSSUS II DAP CSM/LM MASS=73.5K
PERRB
TERRB
2.00
1.60
1.20
.80
.40
.00
-.40
-.80
-1.20
-1.60
-2.00
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
45.00
49.00
53.00
57.00
61.00
TIME


LEC/AGCFS
TYVELERA
PVELERA
TIME
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
45.00
49.00
53.00
57.00
61.00

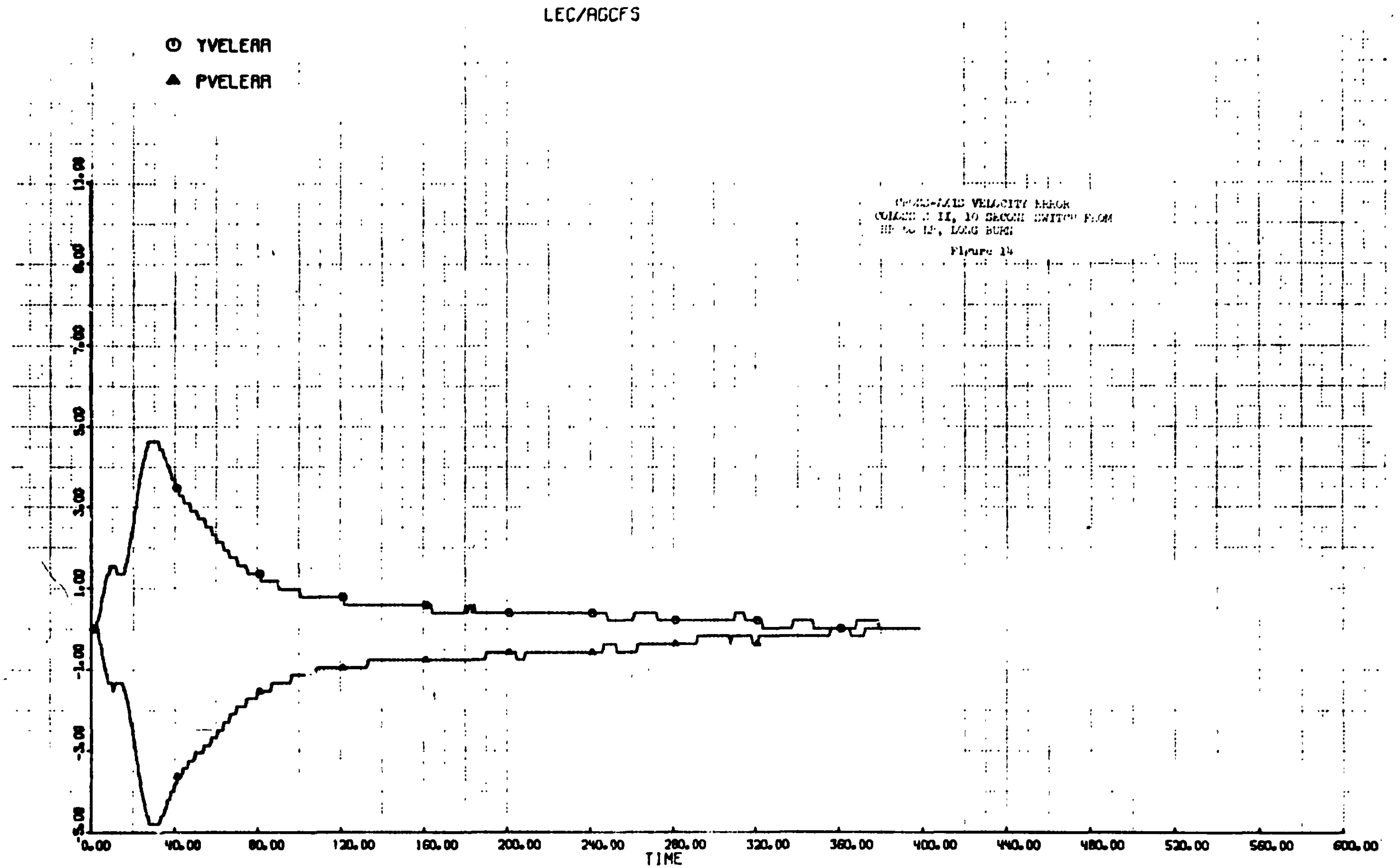


CSM/LM LOI BURN/ HIGH BANDWIDTH
PERRB
YERRB
ATTITUDE ERROR
Figure 11
1.20
.80
.40
.00
-.40
-.80
-1.20
-1.60
-2.00
0.00
40.00
80.00
120.00
200.00
320.00
400.00
480.00
600.00
TIME


TVcLERR
PVcLERR
AXIS VELOCITY
ERROR
2.00
1.50
1.00
.50
0.00
-.50
-1.00
-1.50
-2.00
0.00
40.00
80.00
200.00
440.00
480.00
600.00
TIME

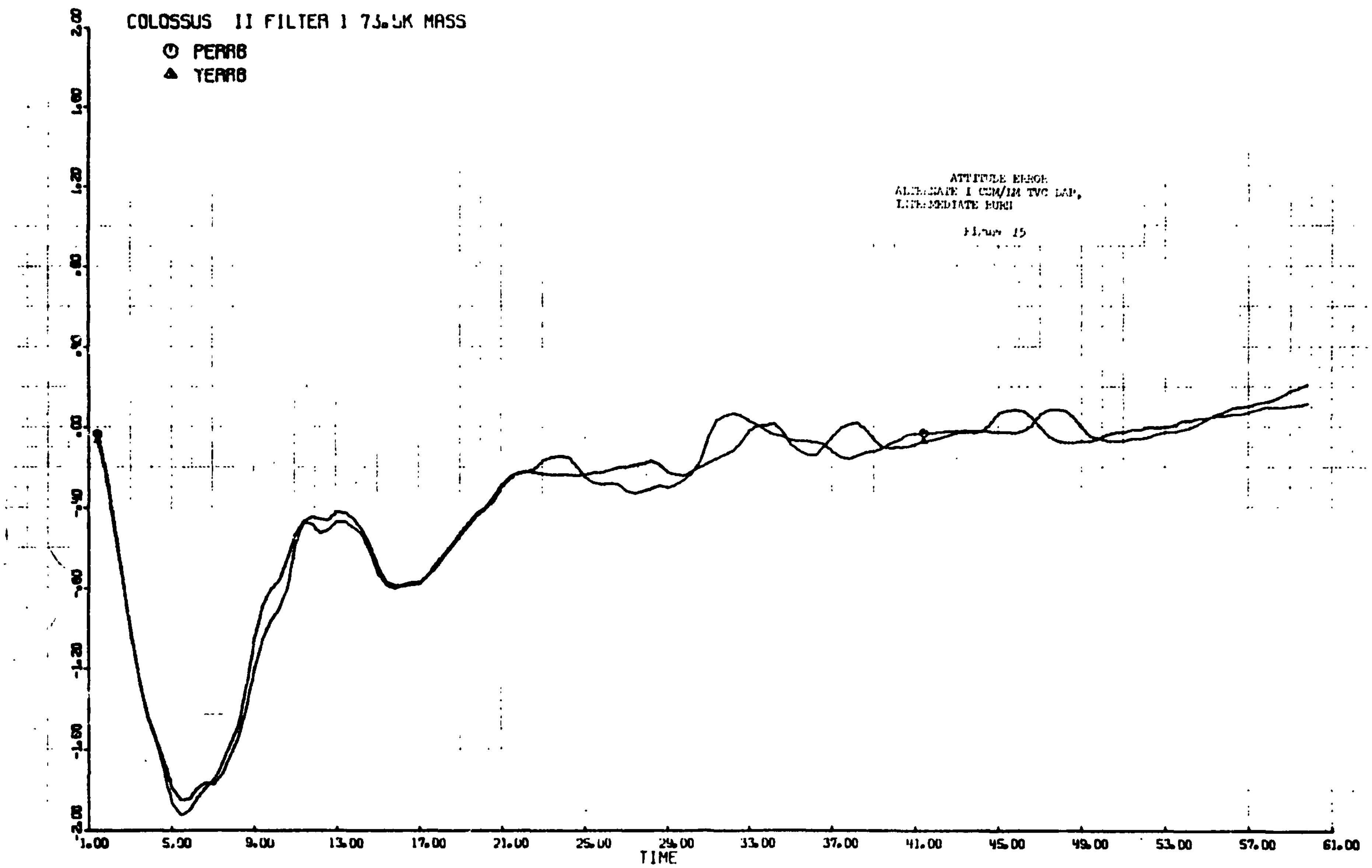


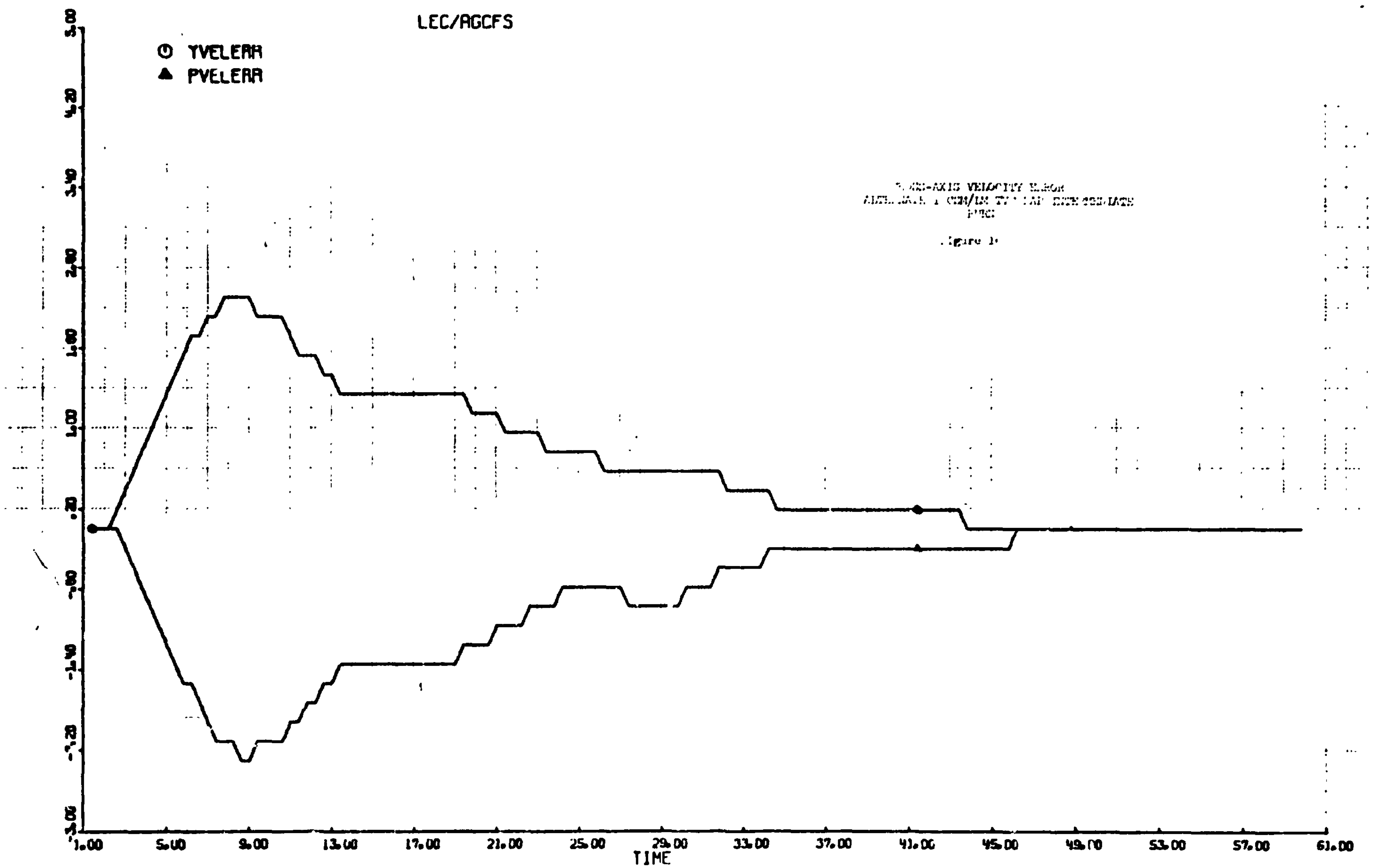
CSM/LM LOI BURN WITH SWITCHOVER AT 10 SEC. / COL II
PERRB
YERRB
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
400.00
440.00
480.00
520.00
560.00
600.00
TIME



CROSS-AXIS VELOCITY ERROR
GUIDANCE II, 10 SECOND SWITCH FROM
HP to LP, LONG BURN

Figure 14


COLOSSUS II FILTER I 73.5K MASS
PERRB
YERRB
ATTITUDE ERROR
ALTERNATE I CSM/LM TVC DAP,
INTERMEDIATE BURN
Figure 15
2.00
1.60
1.20
.80
.40
.00
-.40
-.80
-1.20
-1.60
-2.00
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
45.00
49.00
53.00
57.00
61.00
TIME



LEC/AGCFS
TVELERR
PVELERR
5.00
4.20
3.40
2.60
1.80
1.00
.20
-.60
-1.40
-2.20
-3.00
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
45.00
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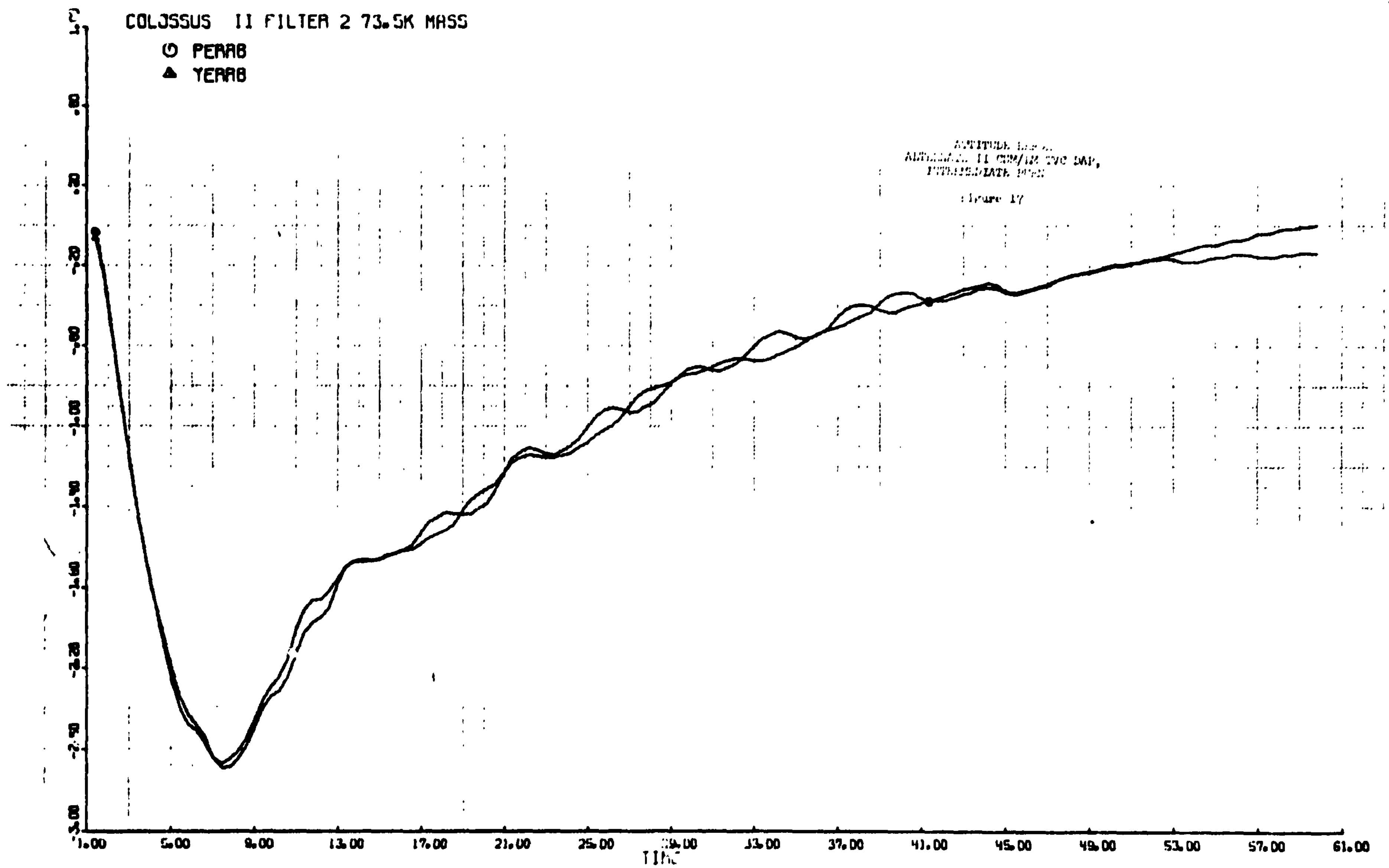
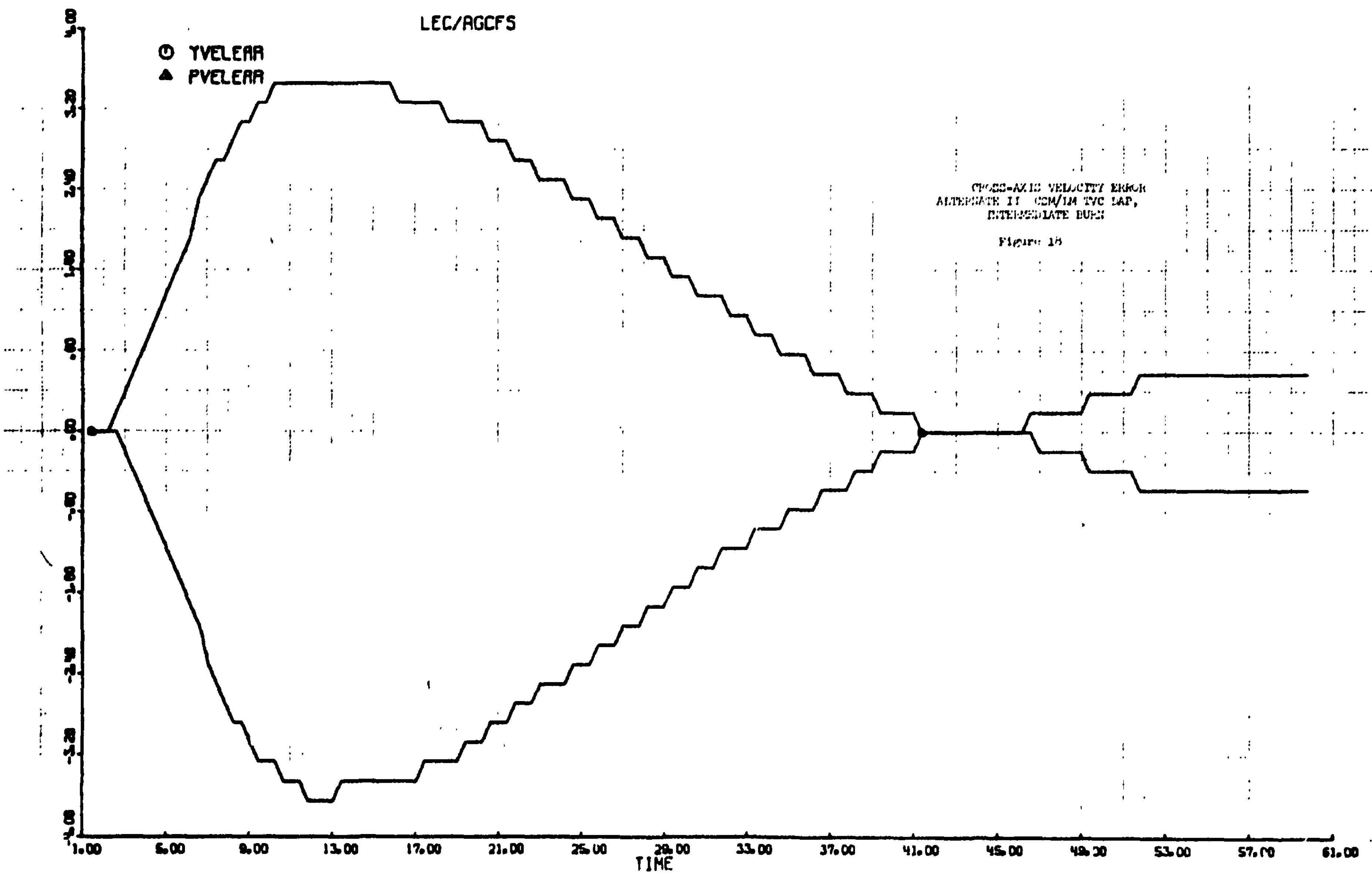
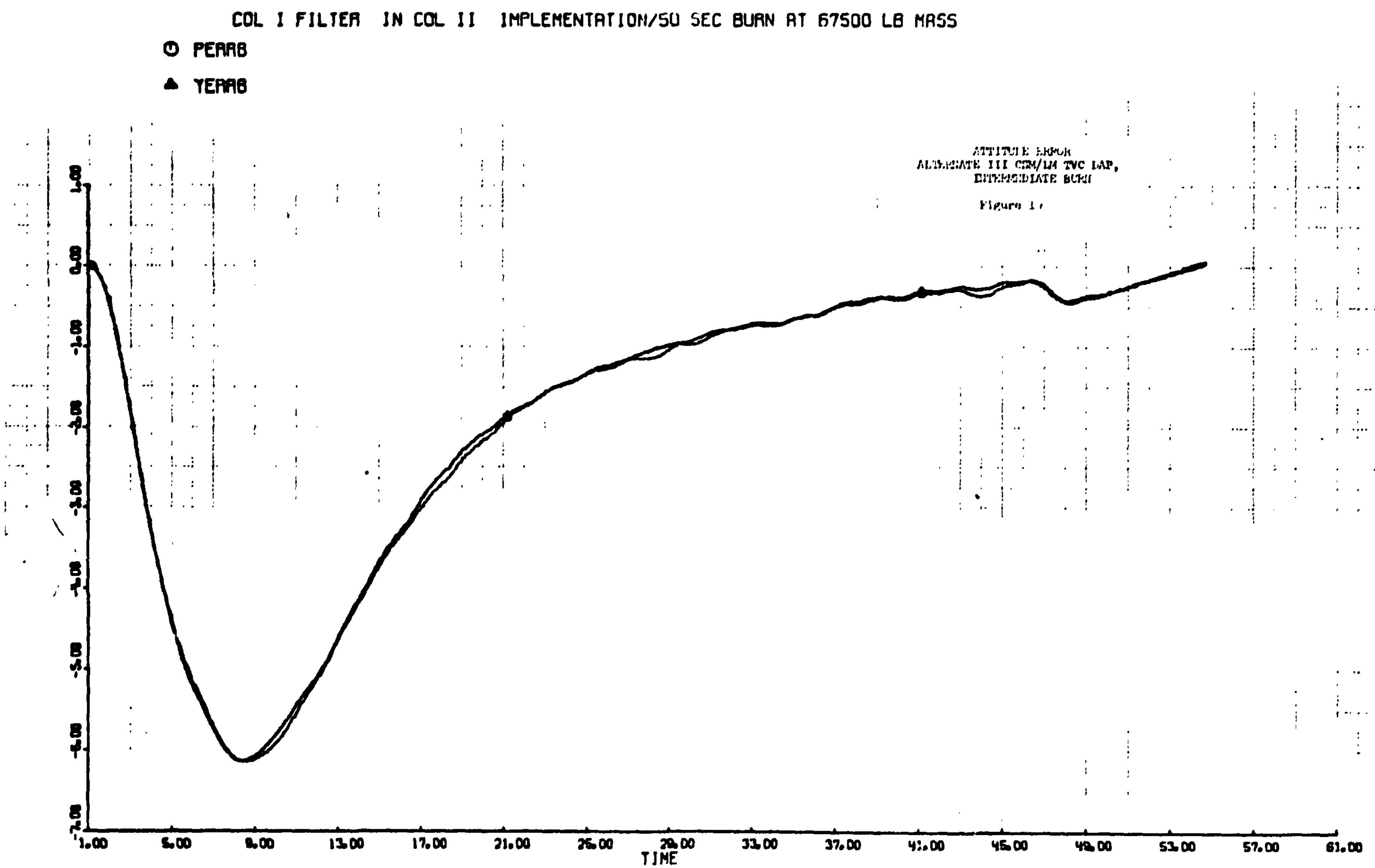
53.00
57.00
61.00
TIME

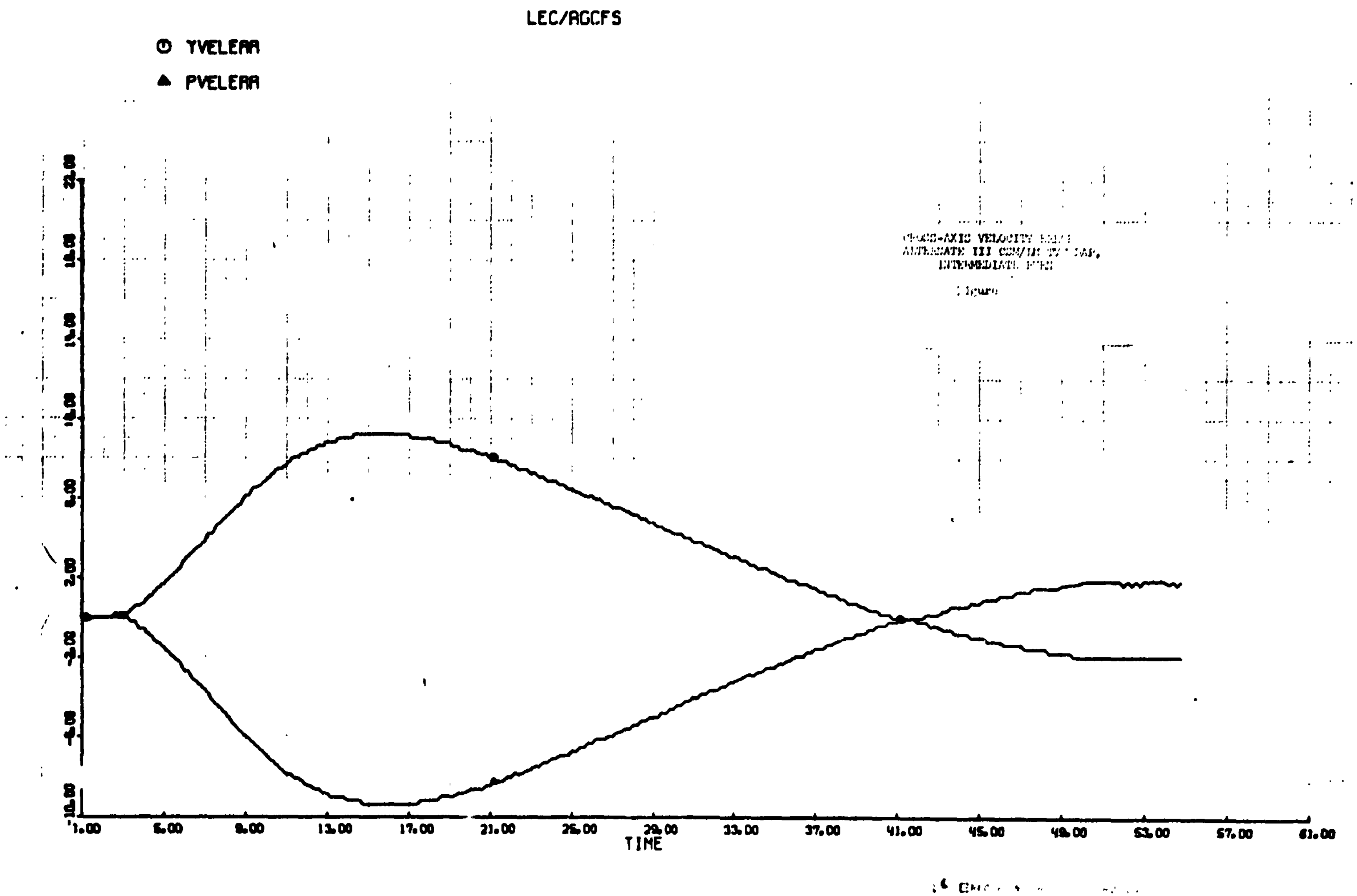

COLOSSUS II FILTER 2 73.5K MASS
PERRB
YERRB
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
45.00
49.00
53.00
57.00
61.00
TIME



CROSS-AXIS VELOCITY ERROR
ALTERNATE II CSM/LM TVC DAP,
INTERMEDIATE BURN

Figure 18


COL I FILTER IN COL II IMPLEMENTATION/50 SEC BURN AT 67500 LB MASS
PERRB
YERRB
ATTITUDE ERROR
ALTERNATE III CSM/LM TVC DAP,
INTERMEDIATE BURN
Figure 1
TIME
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
45.00
49.00
53.00
57.00
61.00


LEC/AGCFS
TVELERR
PVELERR
TIME
1.00
5.00
9.00
13.00
17.00
21.00
25.00
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33.00
37.00
41.00
45.00
49.00
53.00
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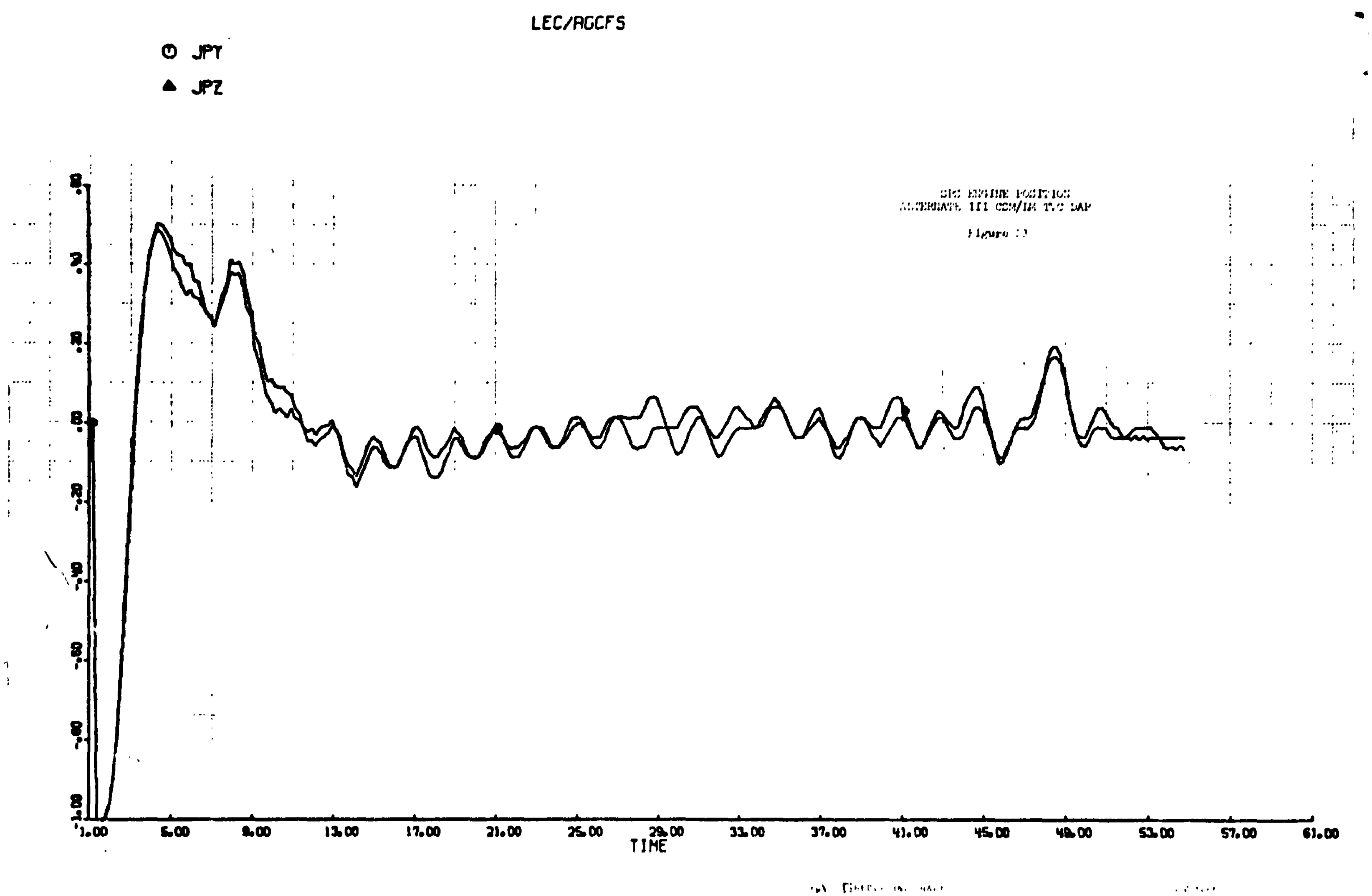
14.00
18.00
22.00


LEC/AGCFS
JPY
JPZ
SPS ENGINE POSITION
ALTERNATE III CSM/LM TVC DAP
1.00
5.00
9.00
13.00
17.00
21.00
25.00
29.00
33.00
37.00
41.00
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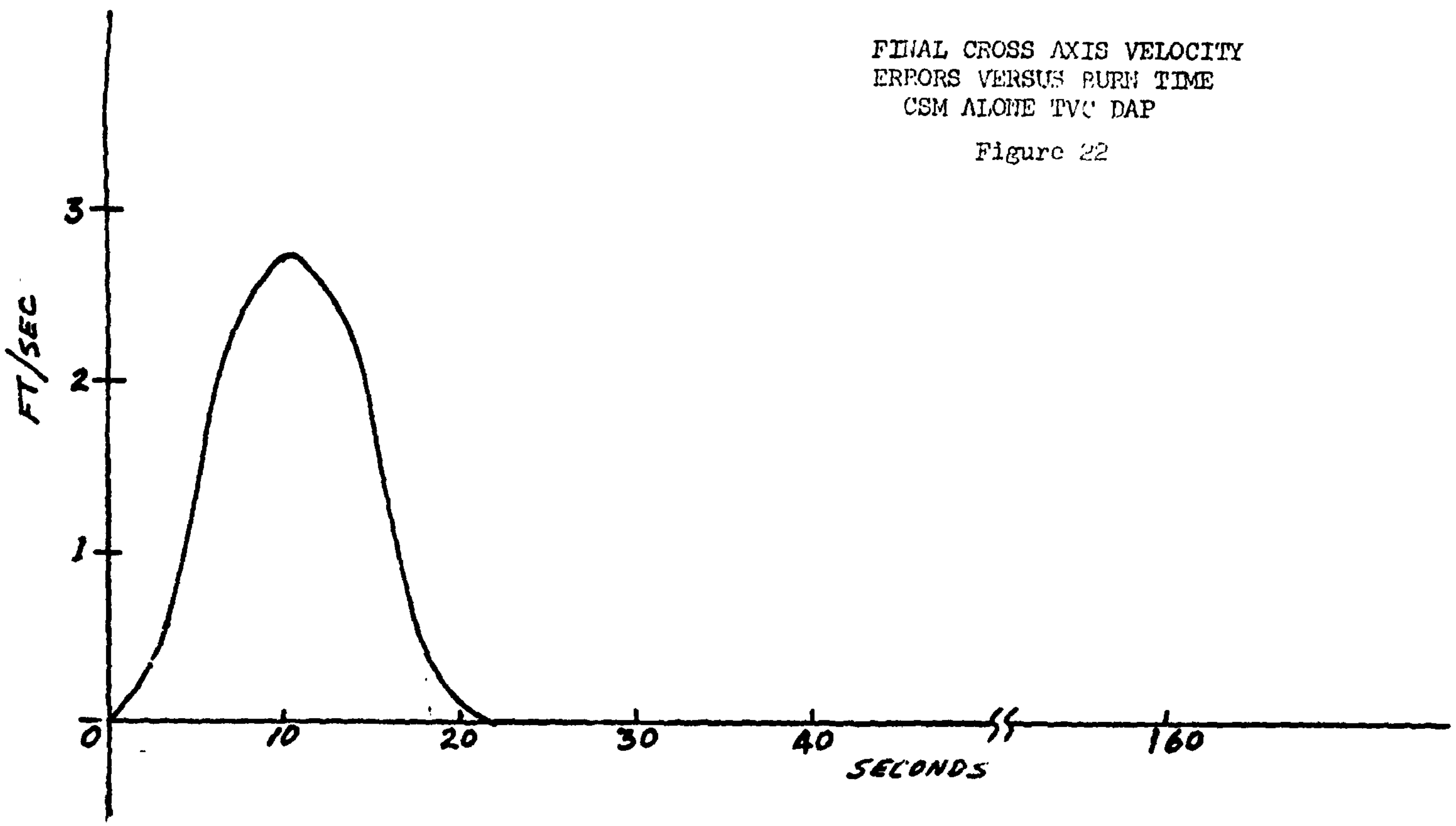
57.00
61.00
TIME



FINAL CROSS AXIS VELOCITY
ERRORS VERSUS BURN TIME
CSM ALONE TVC DAP

Figure 22