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PROJECT TECHNICAL REPORT

TASK E-72C

PERFORMANCE VERIFICATION OF THE LUNAR DESCENT PROGRAM - P66 AUTO

NAS 9-8166

30 OCTOBER 1970

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

Prepared by

Guidance and Control Systems Department

Electronic Systems Laboratory

TRW

SYSTEMS GROUP

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1. INTRODUCTION

Based on the lunar descents of the Apollo 11 and 12 flights, it was deemed desirable to add a capability to the LM guidance and control system which would assist the crew during the last 100 feet of the lunar descent. A new P66 program was implemented which, in the Auto mode, was designed to null the horizontal velocity automatically while leaving the astronaut free to alter the rate of descent through the ROD switch. A description of the program change can be found in [1]* and a description of the new program can be found in [2]. Historical background of the factors inspiring the program change is contained in [3, 4]. Some pertinent details of the operation of P66 are given in [5]. A consolidated review of the new P66 Auto Program is given in [6].

The new P66 Program was introduced in a last minute remanufacture of the Apollo 13 flight software because of the overwhelmingly favorable response of the astronauts during preflight simulator tests with an unreleased version of the program. While there is no flight verification of its performance to this date (because of the flight problems encountered during the Apollo 13 mission and postponement of Apollo 14), this program has been subjected to considerable examination by Bellcomm [7], MSC [8, 9, 10], TRW [11], and MIT [12]. In these studies, simplifying assumptions of various degrees were made to effect analytical solutions or computer simulations were used to closely model the program. The general conclusion was that under certain conditions the system response could become undesirable and that the system needed some improvement. DPS engine throttle oscillations during the P66 Auto mode were identified as the main problem.

MIT discovered that the main cause of the throttle oscillations was the failure to account for the offset between the c.g. and the IMU location in the throttle command computations (PCN1052) [13]. It was also

* Brackets refer to References listed at the end of the report.

realized that the descent engine lag (THROTLAG) should have realistically been 0.08 sec. instead of the program value of 0.2 sec. Furthermore, an attempt to improve the performance by varying the gain (LAG/TAU) has resulted in its value being reduced from its previous value. These program changes required evaluation of the modified P66 performance.

The MSC 6 degrees-of-freedom powered descent (6DPD) functional simulator has long been used as an economical and efficient program which gives results consistent with those of the MIT Bit-by-Bit simulator. Incorporating the program changes mentioned above into the 6DPD simulation, it was deemed appropriate to also implement some updating simulator changes. To minimize the required simulation modifications, only those significant changes which directly affected guidance and control of the LM were implemented, instead of a complete update reflecting every change to the lunar landing programs. These modifications are:

(a) $\omega \times r$ correction (PCN 1052) [13]
(b) LR Update Cutoff at 50 feet (PCR 988) [1]
(c) The limit in LR Velocity Read test changed to 6000 fps (from 2000 fps)
(d) Incorporation of the new Two-Segment Altitude Weighting Functions (PCR 1028 and PCN 1039) [14, 15]
(e) THROTLAG changed to 0.08 (from 0.2), and LAG/TAU to 0.23 (from 0.4133)

The version of the 6DPD program used was the one incorporating all the revisions up to those described in [16] and the modifications listed above.

In order to evaluate the performance of P66, a set of seven runs was proposed [17] and made:

(a) A nominal run to provide a baseline for comparison,
(b) Four runs to stress the system by ROD exercise, velocity errors, and target redesignations, and

(c) Two runs to test the result of removing a certain nonlinearity in the throttle command computation under nominal conditions and subsequent ROD exercise.

This document presents a study of the results of these runs and attempts to evaluate the P66 performance under various stringent conditions. The criteria for evaluation are satisfactory transients in attitude and attitude rate errors and throttle oscillations, and acceptable increases in flight time and fuel consumption. The organization of the material in the rest of the document is as follows. Section 2 defines the runs made by specifying the conditions prevailing, options used, and maneuvers made. Section 3 consists of the presentation, analysis, comparison and discussion of the run results. Section 4 contains the conclusions. Finally, the references are listed.

2. DESCRIPTION OF THE RUNS

This section characterizes the seven runs made on the 6DPD Functional Simulator by specifying the initialization data, terminal conditions, options used, maneuvers made, etc.

Initialization Data

Total Weight = 33,500 lbs. at PDI

Center of gravity location:

$$\begin{bmatrix} CGX \\ CGY \\ CGZ \end{bmatrix} = \begin{bmatrix} 186.343 \\ -\ 0.124 \\ 0.388 \end{bmatrix} \quad \text{inches (LM coordinates)}$$

Inertia Matrix:

$$I = \begin{bmatrix} I_{XX} & I_{XY} & I_{XZ} \\ I_{YX} & I_{YY} & I_{YZ} \\ I_{ZX} & I_{ZY} & I_{ZZ} \end{bmatrix} = \begin{bmatrix} 19421.332 & -\ 108.805 & -\ 627.648 \\ -\ 109.805 & 22807.132 & 14.504 \\ -\ 666.880 & 10.486 & 22726.726 \end{bmatrix} \text{slug-ft}^2$$

Altit.de = 51110 ft.

Options Used

Fuel slosh effects are simulated.

All errors, misalignment, etc. are zero.

Terrain

Mission H2 Terrain Profile (Nominal Fra Mauro) is used.

Targets

Apollo 13 targets are used. These are as follows:

Target	Altitude rate (fps)	Altitude (ft)
High Gate	-165	7012
Low Gate	- 18	509
Touchdown	- 3	5

The Apollo 14 trajectory is almost identical to the Apollo 13 redesignated trajectory [20]. Essentially, the Apollo 14 trajectory approaches the landing site at a higher altitude and with a higher altitude rate as described below:

Target	Altitude rate (fps)	Altitude (ft)
High Gate	-153	7602
Low Gate	- 20	659
Touchdown	- 3	5

However, at the time of making these runs, Apollo 14 data were not available. It is anticipated that the differences between the two trajectories are not severe enough to alter the results qualitatively.

Comments About the Simulation

1. A window up maneuver is done in all the runs, which should have been deleted from the program. However, this should not affect the comparisons between the runs.
2. In this simulation, lunar descent is terminated when the altitude drops below 12 feet.
3. The granularity in the flight time is 2 seconds even though the time interval for the throttle command computation in P66 is one second. Hence, the altitude test is made every 2 seconds.

Specifications of the Runs

RUN 1 Nominal

RUN 2 ROD Exercise

+ 1 ROD pulse at T_o + 10 sec. (T_o = time of P66 entry)

+ 1 ROD pulse at T_o + 11 sec.

+1 ROD pulse at T_o + 12 sec.

-1 ROD pulse at T_o + 14 sec.

-1 ROD pulse at T_o + 15 sec.

-1 ROD pulse at T_o + 16 sec.

RUN 3 Velocity Errors

At T_o sec. a 2 fps error is introduced in each of the forward and lateral velocities.

At T_o + 3 sec., one + ROD pulse is commanded.

RUN 4 Up Range Redesignation

At T_o + 10 sec., the landing site is redesignated to be 100 ft. uprange, (i.e., ΔZ = -100 ft.)

RUN 5 Cross Range Redesignation

At T_o + 10 sec., the landing site is redesignated to be 100 ft. cross range, more specifically ΔY = 100 ft.

RUN 6 Nonlinearity Removal

In the Throttle Command Routine the nonlinear term in δf_p computation is dropped. More specifically, referring to the page 5.3-114 (Figure 3.4.7-1) of [18] the last term in δf_p equation is omitted.

RUN 7 Nonlinearity Removal: ROD Exercise

Same as Run 6 with ROD Exercise as in Run 2.

3. PERFORMANCE EVALUATION

This section presents the results of the Runs 1 through 7, and of a run which was made before the incorporation of the simulator modifications mentioned in the last section. That run will be designated as Run 0 Unmodified. (More will be mentioned about this run under the discussion of Run 1.) The presentation of the run results is accomplished by plots of some important variables and tables showing the values of a set of important variables at selected instants of time. The variables chosen for the plots are attitude and attitude rate errors, and environment thrust. To obtain a plot scale which clearly shows the thrust oscillations, a plot of the environment thrust in the last 100 seconds of the descent is given for each run. Such a plot is designated by the word "Enlarged". The presentation of data in the tables is as follows:

Table 1 - Key Variables

This table shows mass and altitude at initialization, P64 entry, P66 entry and termination. It also shows the flight time, and the RCS and DPS propellant consumption.

All the numbers are taken directly from the computer printout, except for the propellant consumptions in P66, which are obtained by linear extrapolation.

Table 2 - Terminal Quantities

This table shows the horizontal and vertical velocity at the end of the descent flight. These data are taken directly from the computer printout. It also shows the peak-to-peak amplitudes of the oscillations in attitude and attitude rate error, and environment thrust. These values are taken from the pertinent plots. Lastly, the flight time is also given for the sake of completeness.

TABLE 1 - KEY VARIABLES

DESCRIPTION		Run 0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
AT INITIALIZATION	Time in sec.	0	0	0	0	0	0	0	0
	Mass in lbs.	33,500	33,500	33,500	33,500	33,500	33,500	33,500	33,500
	Altitude in ft.	51,110	51,110	51,110	51,110	51,110	51,110	51,110	51,110
AT P64 ENTRY	Time in sec.	518	518	518	518	518	518	518	518
	Mass in lbs.	19,176	19,177	19,177	19,177	19,177	19,177	19,169	19,169
	Altitude in ft.	6,594	6,600	6,600	6,600	6,600	6,600	6,589	6,589
AT P66 ENTRY	Time in sec.	664	664	664	664	664	664	664	664
	Mass in lbs.	17,180	17,180	17,180	17,180	17,180	17,180	17,173	17,173
	Altitude in ft.	92.0	93.4	93.4	93.4	93.4	93.4	93.4	93.4
AT TERMINATION	Time in sec.	698	694	698	704	694	694	694	698
	Mass in lbs.	16,811	16,886	16,848	16,785	16,887	16,887	16,878	16,840
	Altitude in ft.	12.0	6.3	5.9	10.7	6.4	6.4	6.3	6.2
Flight time in sec		698	694	698	704	694	694	694	698
PROPELLANT CONSUMPTION IN LBS.	DPS Total	16,647.4	16,573.0	16,610.9	16,670.2	16,572.4	16,572.4	16,572.0	16,609.8
	RCS Total	41.6	41.0	41.1	44.8	40.6	40.6	50.0	50.2
	DPS in P66	366.5	291.8	329.7	389.0	291.2	291.[illegible]	291.6	329.4
	RCS in P66	2.5	2.2	2.3	6.0	1.8	1.8	3.4	3.6

TABLE 2 - TERMINAL QUANTITIES

DESCRIPTION		Run 0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
VELOCITY IN FPS	Vertical	-2.0	-3.1	-3.2	-2.2	-3.2	-3.2	-3.1	-3.1
	Horizontal	0.15	0.13	0.05	2.0	0.10	0.10	0.03	0.06
PEAK-TO-PEAK ATTITUDE ERROR IN DEG.	U-axis	0.6	0.6	0.5	0.6	0.6	0.5	0.6	0.6
	V-axis	0.4	0.6	0.4	0.5	0.8	0.8	0.6	0.6
PEAK-TO-PEAK ATTITUDE RATE ERROR IN DEG/SEC	U-axis	1.0	1.0	0.8	0.4	0.5	0.5	0.8	0.7
	V-axis	0.7	1.1	0.5	0.5	0.7	0.7	0.9	0.7
PEAK-TO-PEAK ENVIRONMENT THRUST OSCILLATION IN LBS.		179	143	170	54	58	58	108	63
FLIGHT TIME IN SEC.		698	694	698	704	694	694	694	698

Table 3 - Worst Transients in P66

All the data in this table are obtained from the pertinent plots. The peak to peak values of the oscillations in attitude and attitude rate error, and environment thrust are shown along with the time of occurrence (expressed as the elapsed time since the P66 entry).

The rest of this section is devoted to the discussion of the run results arranged serially by the run number, starting with one. First, the specification of the run is repeated (from Section 2), and the particular purpose of the run is mentioned. The pertinent plots are listed. The discussion draws heavily on the comparison presented in the tables.

3.1 Run 1 Nominal

The purpose of this run is twofold: (1) to check the modifications incorporated, and (2) to provide a baseline for comparison of the subsequent run results.

To check the modifications incorporated, this nominal run (1) is compared to an almost nominal run (0), which was made earlier on the 6DPD functional simulator and was satisfactorily compared to a run made on the MIT BBS simulator [19]. In Run 0, the only deviation from nominal conditions was that a ROD pulse was commanded at T_0 + 12 seconds.

The flight time in Run 1 (Table 1) is 4 seconds less than that in Run 0. Since the time of P66 entry in both the runs are equal, this 4 seconds difference is in the P66 program duration. As the following analysis shows, this difference is due to the reduced rate of descent in Run 0 caused by the ROD pulse commanded at T_0 + 12 seconds.

TABLE 3 - WORST TRANSIENTS IN P66

DESCRIPTION		Run 0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
PEAK-TO-PEAK ATTITUDE ERROR IN DEG.	U-axis	2.1	2.9	2.9	2.0	2.9	2.9	2.0	2.0
	Time of occurrence in sec.*	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 8$	$T_o + 5$	$T_o + 5$	$T_o + 6$	$T_o + 6$
	V-axis	1.7	3.0	3.0	1.2	3.0	3.0	2.8	2.8
	Time of occurrence in sec.	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 16$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 6$
PEAK-TO-PEAK ATTITUDE RATE ERROR IN DEG/SEC	U-axis	6.3	6.8	6.8	8.0	6.8	6.8	5.6	5.6
	Time of occurrence in sec.	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 4$
	V-axis	5.9	6.7	6.7	2.7	6.7	6.7	7.2	7.2
	Time of occurrence in sec.	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$
PEAK-TO-PEAK ENVIRONMENT THRUST OSCILLATION IN LBS.		636	609	1210	959	609	609	735	1183
Time of occurrence in sec.		$T_o + 6$	$T_o + 5$	$T_o + 14$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 5$	$T_o + 14$

* T_o = time of P66 entry = 664 secs. for all runs.

Estimation of P66 Duration

The simplifying assumptions made in the following analysis are as follows:

(a) At the time of P66 entry, the rate of descent is 3 fps. (This is substantiated by the data.)

(b) The ROD pulses effect the change in rate of descent instantaneously.

Run 0

T_0 = 664 sec.
1 ROD pulse commanded at T_0 + 12 sec.
Total height descended = 80 ft. (Table 1)

Height descended in 12 seconds during [664,676] @ 3 fps = 36 ft.
Time needed to descend the next 44 ft @ 2fps = 22 sec.
Total time required in P66 = 22 + 12 = 34 sec.
Actual time taken = 34 sec.

Run 1

No ROD pulse commanded.
Total height descended during P66 = 87.1 ft.
Time required @ 3fps = 29.03 sec.
Actual time taken = 30 sec.

Thus, the longer flight time in Run 0 is predicatable and valid.

Comparison of the propellant consumption indicates that the DPS propellant consumption in P66 of Run 1 is about 75 lbs less than that of Run 0. The primary causes are shorter duration of P66, and less thrust oscillations.

The plots for Run 0 are given in Figures 1 through 6, and those for Run 1 are given in Figures 7 through 12. A comparison of the corresponding plots in the two runs shows no difference up to time T_0 sec. (time of P66 entry).

The terminal quantities (Table 2) in the two runs are comparable except for the descent rates, which are different because of the ROD pulse, and the thrust oscillations, which are reduced 20% in Run 1 because of the P66 Auto Program modifications.

From Table 3 it appears that the P66 entrance transients reach their peaks in about 5 seconds. The maximum thrust transient in Run 1 is less than that in Run 0. The worst case attitude and attitude rate error transients in Run 1 are slightly greater than those in Run 0. However, the plots show them to be isolated instances not altering the average errors appreciably. The enlarged plots of the environment thrust (Figures 6 and 12) show that in Run 1 the oscillations progressively diminish in magnitude and reflect a definite decaying trend, unlike those in Run 0.

In summary, the performances in Run 0 and 1 are almost identical up to P64; in P66 the thrust performance in Run 1 is better than that in Run 0 with no degradation in spacecraft control performance.

3.2 Run 2 ROD Exercise

This run is characterized by a stringent ROD exercise; all other conditions are nominal. Before initiating the ROD command, a waiting period of 10 seconds after P66 entry was allowed to let the P66 entrance transients die down. The ROD commands exercised are described by:

1 ROD pulse at T_0 + 10 sec.
1 ROD pulse at T_0 + 11 sec.
1 ROD pulse at T_0 + 12 sec.
-1 ROD pulse at T_0 + 14 sec.
-1 ROD pulse at T_0 + 15 sec.
-1 ROD pulse at T_0 + 16 sec.

The three positive pulses (corresponding to a decrease of 3 fps in the descent rate) were intended to make the LM almost hover (for two seconds). Then, the three negative pulses restore the descent rate. This exercise, apart from stress testing, is expected to increase the flight time, as the following analysis shows.

Total height descended in P66 = 87.5 ft.

Height descended in 10 sec.	during $[T_0, T_0 + 10]$ @ 3 fps =	30 ft.
Height descended in 1 sec.	during $[T_0 + 10, T_0 + 11]$ @ 2fps =	2 ft.
Height descended in 1 sec.	during $[T_0 + 11, T_0 + 12]$ @ 1 fps =	1 ft.
Height descended in 2 sec.	during $[T_0 + 12, T_0 + 14]$ @ 0 fps =	0 ft.
Height descended in 1 sec.	during $[T_0 + 14, T_0 + 15]$ @ 1 fps =	1 ft.
Height descended in 1 sec.	during $[T_0 + 15, T_0 + 16]$ @ 2 fps =	2 ft.
Total 16 sec.		36 ft.

The next 51.5 ft @ 3 fps will take 17.16 seconds.
Thus, the theoretical total time needed in P66 = 33.16 seconds.
Actual time taken = 34 seconds.

Another significant difference is that the DPS propellant consumption in Run 2 is 38 lbs. more than that in Run 1. This difference is explained by the ROD exercise and the consequent longer flight time. The increase in RCS propellant consumption is negligible.

The terminal values of the velocity, and attitude and attitude rate errors compare well with the nominal if the longer flight time is taken into consideration.

The plots for this run are given in Figures 13 through 17. The attitude and attitude rate error plots (Figures 13 through 16) are nearly the same as those of the nominal (Figures 7 through 10).

The ROD exercise does not seem to cause any increase in the transients in attitude and attitude rate errors.

The (enlarged) environment thrust plot (Figure 17) shows the P66 entrance transient and ROD transient, distinctly. The amplitude of oscillations does decrease after these rather large transients but a definite decaying trend is not apparent.

In summary, the ROD exercise causes transients in thrust, an increase in DPS propellant consumption, and a change in the flight time of an accountable amount.

3.3 RUN 3 Velocity Errors

This run is intended to stress-test the P66 Program. Through this run and Run 4 and 5, an attempt is made to simulate the effect of (intentional) rotational errors since the simulation does not permit direct introduction of rotational errors.

At the time of P66 entry, a 2 fps error is introduced in each of the forward and lateral velocities, i.e., $\Delta V_Y = \Delta V_Z = 2$ fps at T_0. Three seconds later (i.e., at $T_0 + 3$ sec.) one positive ROD pulse is commanded. The velocity error injection is anticipated to stress-test the automatic horizontal velocity nulling feature of P66 Auto, and the ROD command is expected to reduce the descent rate, thereby increasing the flight time.

It may be noticed that before the P66 entry, this run is identical to Run 1 (nominal). Hence, the key variables are the attitude error transients, the attitude rate error transients, the flight time, propellant consumption, and thrust transients during the time interval between P66 entry and touchdown.

The flight time in this run is 10 seconds longer; all of the increase being in the P66 duration only. The following analysis shows that the entire amount of increase is accountable solely by the ROD exercise.

1 positive ROD pulse is applied at T_0 + 3 sec.
Total height descended during P66 = 82.7 ft.
Height descended in 3 seconds during $[T_0, T_0 + 3]$ @ 3 fps = 9 ft.
Time needed for the next 73.7 ft @ 2 fps = 36.85 sec.
Total theoretical time needed = 39.85 sec.
Actual time taken = 40 sec.

The breakdown of the propellant consumption in Table 1 indicates that all the increase occurred during P66. The increase in DPS propellant consumption is 97.2 pounds, which is explainable by the ROD command and the consequent increase in the flight time. The increase of 3.8 lbs. in RCS fuel consumption can be attributed to the injection of the velocity errors.

The plots for this run are given in Figures 18 through 23; the last plot shows the Y component of the (environment) velocity. The inclusion of this plot (Figure 23) is to show that the particular velocity error introduced at T_0 tends to reduce the load on the velocity nulling program. That is, the error reduced the Y-component of the velocity-to-be nulled. This factor may contribute to the reduction in the amplitude of some of the worst transients in P66 (Table 3); namely, attitude errors, and the V-axis attitude rate error. The increase in U-axis attitude rate error may be due to the appropriate sign of the error injected in the forward velocity. However, the conditional explanations remain unverified. A rerun with the errors established in a "worse" manner would confirm the explanation.

Except for what has been mentioned above, the plots of attitude and attitude rate errors compare well with the nominal. Among the terminal quantities (Table 2), the difference of 1 fps in vertical velocity is due to the ROD command; terminal horizontal velocity of 2 fps (in place of zero desirable) results from the injected velocity errors; and the much smaller amplitude of thrust oscillation is due to the extra 10 seconds of flight time during which the thrust oscillations were decaying. The decaying trend of the thrust transient, visible in Run 1 (Figure 12) but obscured in Run 2 (Figure 17), is most prominent in this Run (Figure [illegible]). Other terminal quantities compare well with those of the nominal.

The ROD pulse commanded before the extinction of the normal entrance transient causes the environment thrust oscillations to increase in amplitude (Table 3) in such a way that it appears as if the entrance transient has increased.

In summary, the performance of this run in the most part is explainable and acceptable. However, for some part of the performance, only a conditional explanation can be provided.

3.4 RUN 4 Up Range Redesignation

In this run the landing site is "redesignated" 100 ft. uprange, 10 sec. after P66 entry. The redesignation capability is not available in P66. However, by making a minor program change in the 6DPD Functional simulator, a pseudo-redesignation is made possible. The objective is to perturb the nominal performance of P66 Auto mode.

In order to make this run, a minor program change was made in the 6DPD Functional Simulator; namely, the Attitude Command Routine was allowed to function in P66 (as in P64). However, the Guidance coordinates which are fixed at the time of P66 entry, are not allowed to change. Thus, the redesignation is merely established to cause changes in the attitude and attitude rate, orientation of the window pointing vector and thrust vector. Henceforth, this redesignation will be referred to as pseudo-redesignation

The plots for this run are given in Figures 24 through 28. A comparison of these plots with the plots of the nominal run (Figures 7 through 12) indicates that the amplitude of oscillations (in attitude error, attitude rate error, and thrust) is less than nominal shortly after the pseudo-redesignation. However, this reduction is not constant with respect to time so that the decaying trend of the transients is affected; for example, the thrust oscillations (Figure 28) first decay and then increase to approximately the response noted in the nominal run.

The flight time is not changed but the propellant consumption is slightly reduced (0.4 lb. in DPS, 0.6 lb. in RCS). The terminal quantities, and the worst transients in P66 are acceptable.

An explanation of the performance of this run can be provided by the projected effects of the program change made. The Attitude Command Routine attempts to redefine the window pointing vector. The FINDCDUW Routine commands the attitude rates and the desired attitude based on the thrust pointing vector and the window pointing vector. However, the direction of the thrust vector is redefined in P66 Auto by its horizontal velocity nulling feature. This sequence of events, initiated at the beginning of P66, is repeated every cycle.

The deviations from the nominal are noticeable only after the pseudo-redesignation. The reason is that the change in the window pointing vector is very small during $[T_0, T_0 + 10]$. Noticeable deviations from the nominal first occur a few seconds after the pseudo-redesignation. It is likely that an appreciable change in the window pointing vector takes place. Examination of the LM position at the time of the attempted redesignation indicates that the amount of redesignation locates 'the landing site far below the bottom of the window edge'. This condition invokes a limiting process in which the window vector is pointed in the direction of the Z-axis of the guidance frame to avoid excessive spacecraft reorientations (pages 5.3-95 and 5.3-102 of [16]). The change in the desired window pointing direction is sufficient to affect the spacecraft response. Moreover, the timing and direction of the desired change cause a disruption in the thrust oscillations and the angular response observed in the nominal run. The disruption in the thrust oscillations momentarily reduces their amplitude.

In summary, the pseudo-redesignation produces deviations from the nominal in attitude errors, attitude rate errors, and thrust. But the amount of deviation is small.

3.5 RUN 5 Cross Range Redesignation

In this run the pseudo-redesignation is in the cross range direction. The amount of redesignation is 100 ft. in the +Y direction and it is initiated at T_0 + 10 sec. The program change mentioned in Section 3.4 is applicable to this run also.

The performance of this run is identical to that of Run 4 because of the magnitude of the pseudo-redesignation. The conditions of this run just prior to the pseudo-redesignation are identical to those in Run 4. The cross range pseudo-redesignation exceeded the limit and the window pointing vector is set in the direction of the Z-axis of the guidance frame. Hence, the target direction is identical to that of Run 4 and the runs exhibit identical results. Therefore, the evaluation of Run 4 is directly pertinent to this run and no plots for Run 5 are included.

3.6 RUN 6 Nonlinearity Removal

This run is characterized by the removal of the nonlinear term in the δf_p computation in the Throttle Command Routine. Theoretical analyses of the P66 performance have often used this step as a simplifying assumption. The objective of this run is to investigate the effects of this assumption.

∘ It may be noted that the change in the Throttle Command Routine affects the entire powered descent flight; consequently, the comparison of this run with the nominal cannot be confined to P66 alone.

From Table 1 it is seen that in this run the times of P64 entry, P66 entry, and run termination are identical to the nominal. However, the mass and the altitude at these instances are slightly different. The consumption of DPS propellant is 1 lb. less than nominal whereas the consumption of RCS propellant is up by 9 lbs. Excess consumption of RCS propellant in P66, however, is up by only 1.2 lbs. The terminal quantities (Table 2) are comparable except for the peak-to-peak amplitude of the thrust oscillation, which is about 24% less than nominal. The worst transients in P66 (Table 3) are almost comparable.

The plots for this run are given in Figures 29 through 34. The overall comparison of the plots with the nominal in attitude errors and attitude rate errors is good. So far as the thrust oscillations are concerned, the peak-to-peak amplitude of the worst transient is up by 4%. This, in conjunction with the 24% reduction in the peak-to-peak amplitude of the terminal thrust oscillations, indicates a faster rate of decay of the thrust oscillations in P66. It appears that if the nonlinearity is removed only from P66, then a more desirable thrust behavior will result without an appreciable increase in consumption of RCS propellant. This conclusion is based, however, on the assumption that the differences in the P66 initialization with and without the nonlinearity removal during earlier phases of the descent (P63 and P64) do not influence the results.

In summary, the performance of this run is acceptable. The assumption of neglecting the nonlinear term seems justifiable in P66 under normal conditions.

3.7 RUN 7 Nonlinearity Removal: ROD Exercise

This Run is the same as Run 6 except for an ROD exercise in P66 which is identical to that of Run 2. The objective of this run is to determine the effects of the nonlinearity removal assumption under a stringent ROD exercise. Additionally, the purpose is also to investigate whether this simplification can withstand a stringent ROD exercise.

From Table 1, it is seen that this run takes 4 seconds longer than Run 6. By an analysis similar to that in Section 3.2 it can be shown that the increase of 4 seconds in flight time is expected for the particular ROD exercise. Another observation is that the additional expenditure of DPS propellant due to the ROD exercise is 37.8 lbs. which compares well with 37.9 lbs. for the same ROD exercise in the nominal case (Run 2, Section 3.2, and Table 1).

This run can be analyzed from two different points of view: effects of ROD exercise with the nonlinearity removal (comparison of Runs 7 and 6), and the effects of the nonlinearity removal on the ROD exercise (comparison of Runs 7 and 2). Plots for this run are given in Figures 35 through 39.

A comparison of Runs 7 and 6 reveals that the ROD exercise with the nonlinearity removal causes an expected additional expenditure of DPS propellant; makes an expected increase of 4 seconds in the flight time; and produces transients in the thrust oscillations. However, this does not cause any appreciable difference in the attitude errors and the attitude rate errors. The thrust oscillations in P66 do have a decaying trend, and this, in conjunction with the longer flight time, causes the peak-to-peak amplitude of the terminal thrust oscillations in Run 7 to be 42% lower than that of Run 6. Other terminal conditions (Table 2) in Run 7 compare very well with those of Run 6.

A comparison of Runs 7 and 2 brings out the effects of the nonlinearity removal under identical ROD exercise conditions. The peak-to-peak amplitude of the worst thrust oscillations in P66 in Run 7 is over 2% less than that in Run 2. Moreover, the thrust oscillations in Run 7 are almost monotonically decreasing (unlike those in Run 2). The peak-to-peak amplitude of the terminal thrust oscillations in Run 7 is 63% lower than that in Run 2. This makes the behavior of the P66 thrust oscillations in Run 7 far better than that in Run 2.

These inter-related comparisons suggest that the removal of the nonlinearity from the Throttle Command Computation greatly improves the transient behavior of the thrust oscillations in P66. The significant differences in thrust oscillations between this run and Run 2 (with the nonlinear term intact), indicate that the theoretical results obtained by dropping the nonlinear term would be poor approximations of the real response for the ROD exercise.

In summary, the performance of this run in P66 is much better than that in Run 2. In view of the conclusion reached in Run 6, it appears that if the nonlinearity removal is effected only in P66, then a better transient behavior of thrust oscillations, even under ROD exercise, can be achieved at the cost of the RCS propellant consumption of about a pound. However, this conclusion is again subject to the reasonable assumption that the small differences in the P66 initialization caused by the nonlinearity removal in the earlier phases (P63 and P64) do not alter the results. This conclusion can be verified by making an additional run.

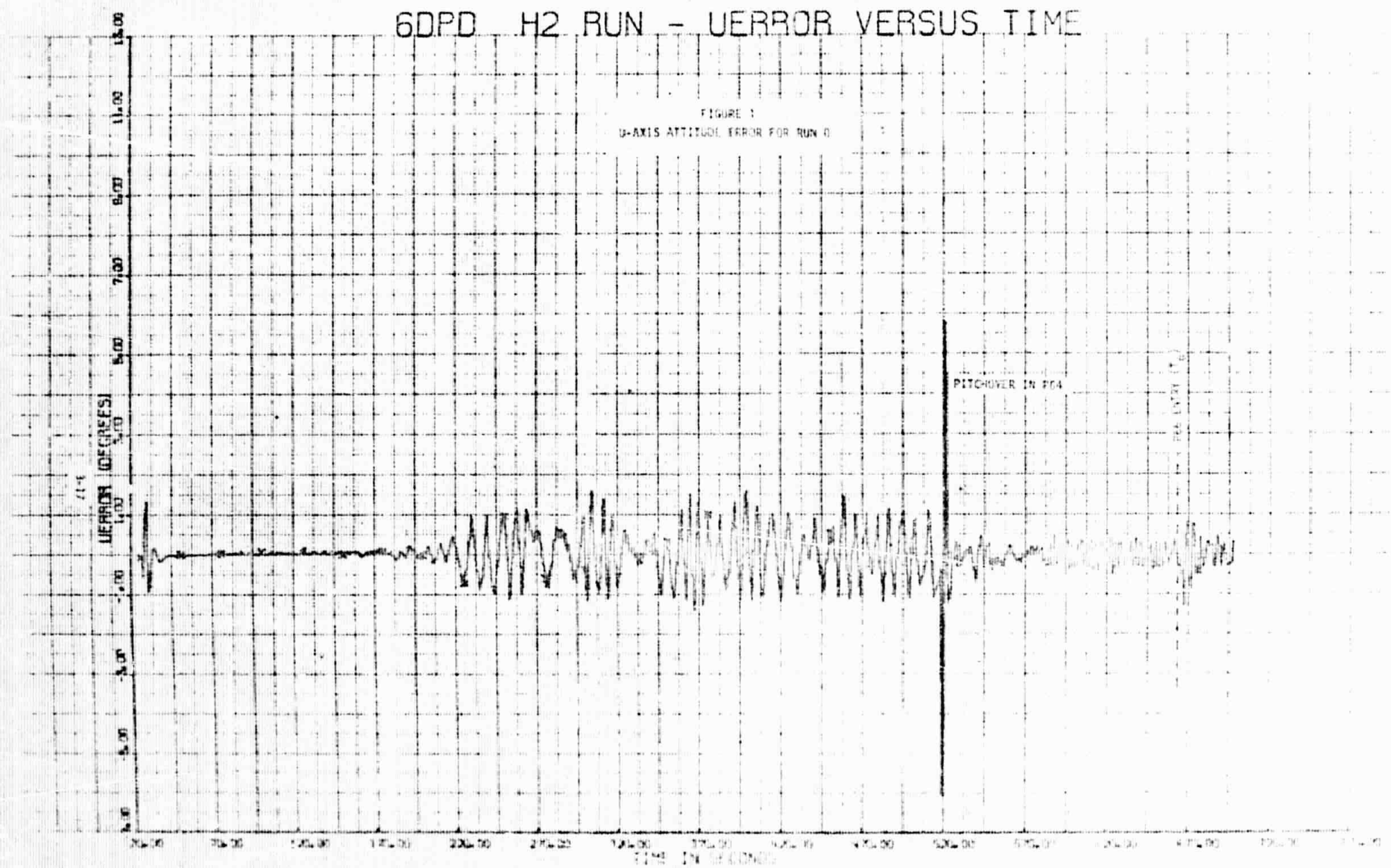


FIGURE 1
U-AXIS ATTITUDE ERROR FOR RUN 0

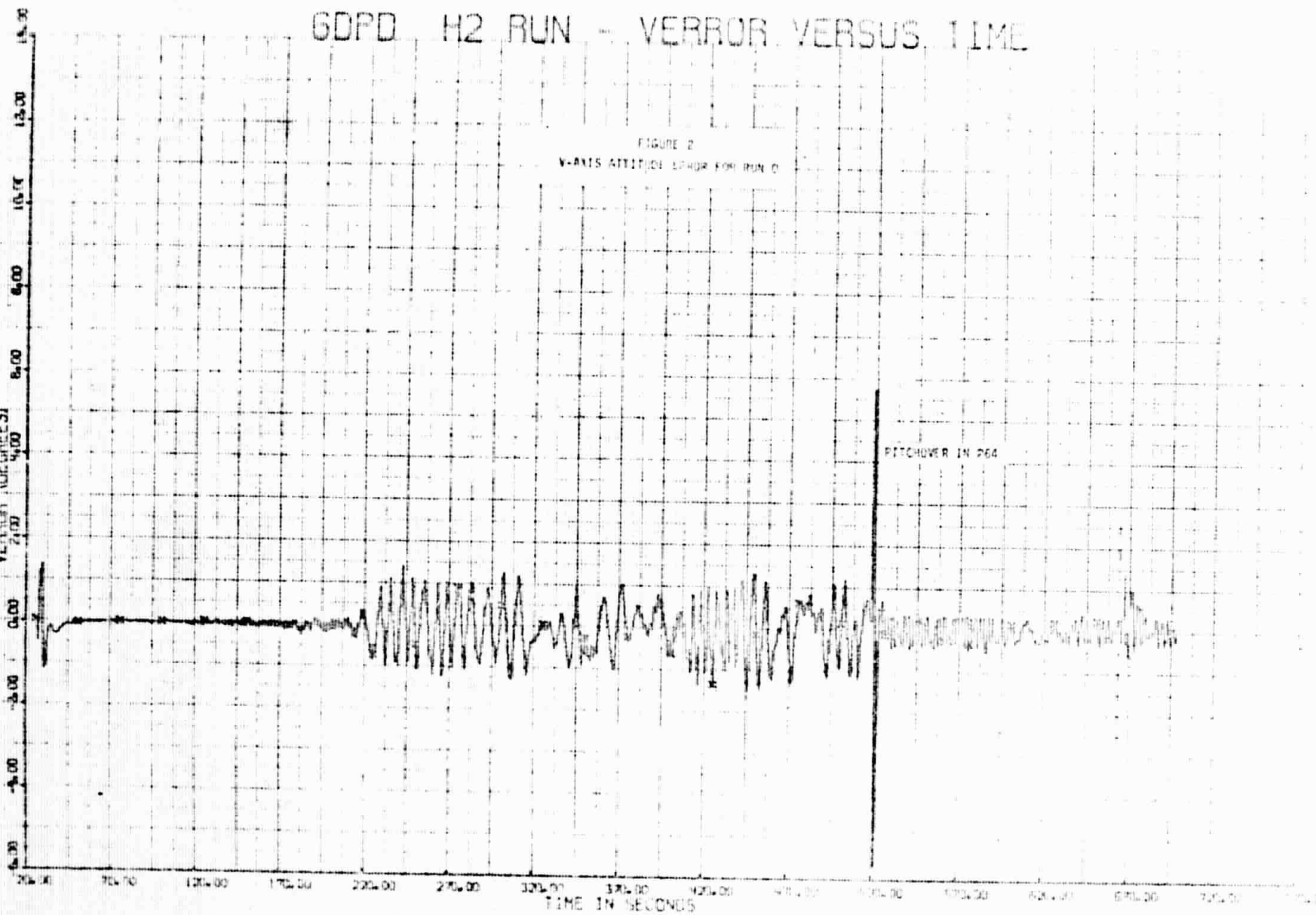
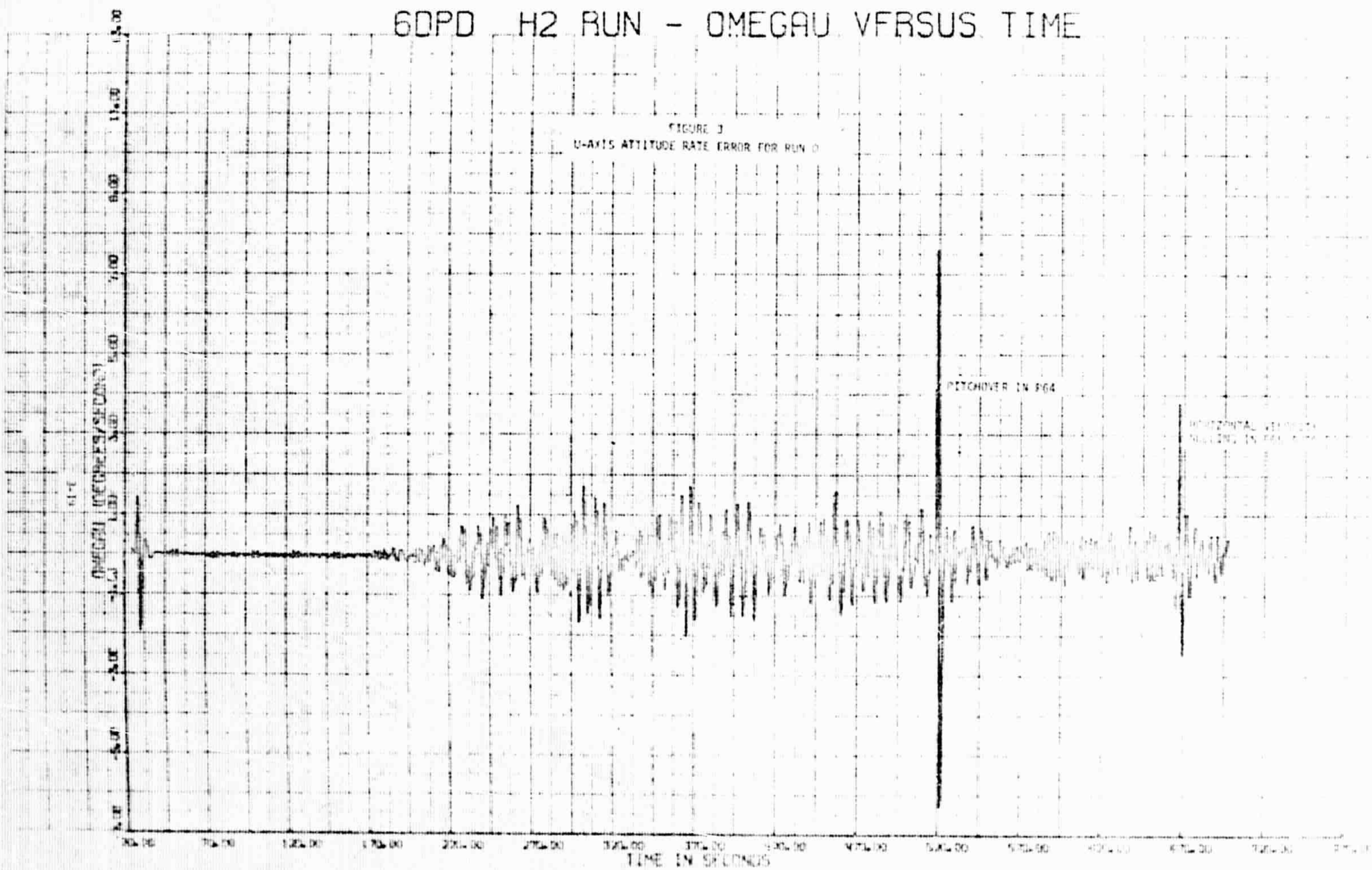
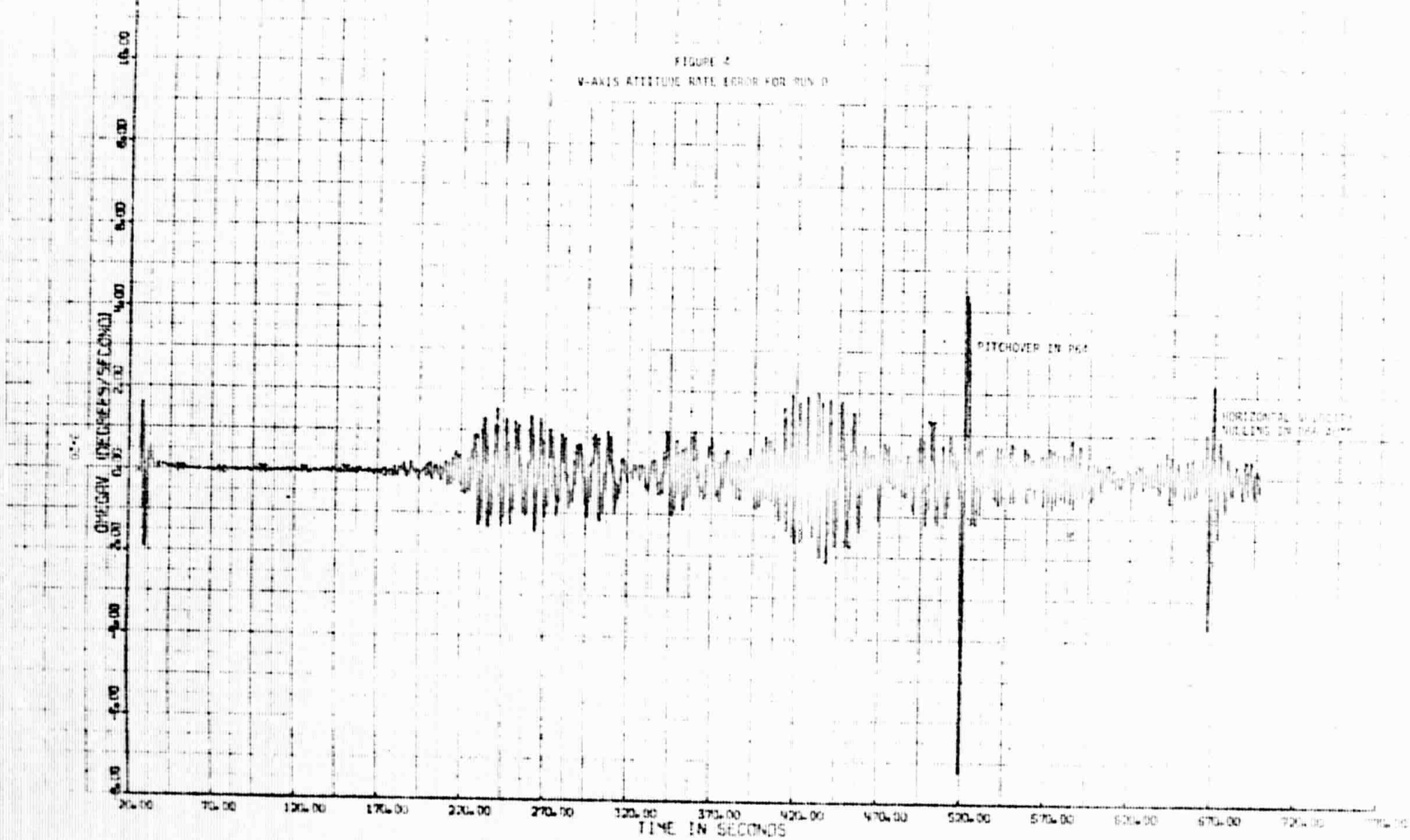


FIGURE 2
V-AXIS ATTITUDE ERROR FOR RUN D


6DPD H2 RUN - OMEGAU VERSUS TIME
FIGURE 3
U-AXIS ATTITUDE RATE ERROR FOR RUN 0
PITCHOVER IN P64
OMEGAU (DEGREES/SECOND)
TIME IN SECONDS

6DPD H2 RUN - OMEGAV VERSUS TIME



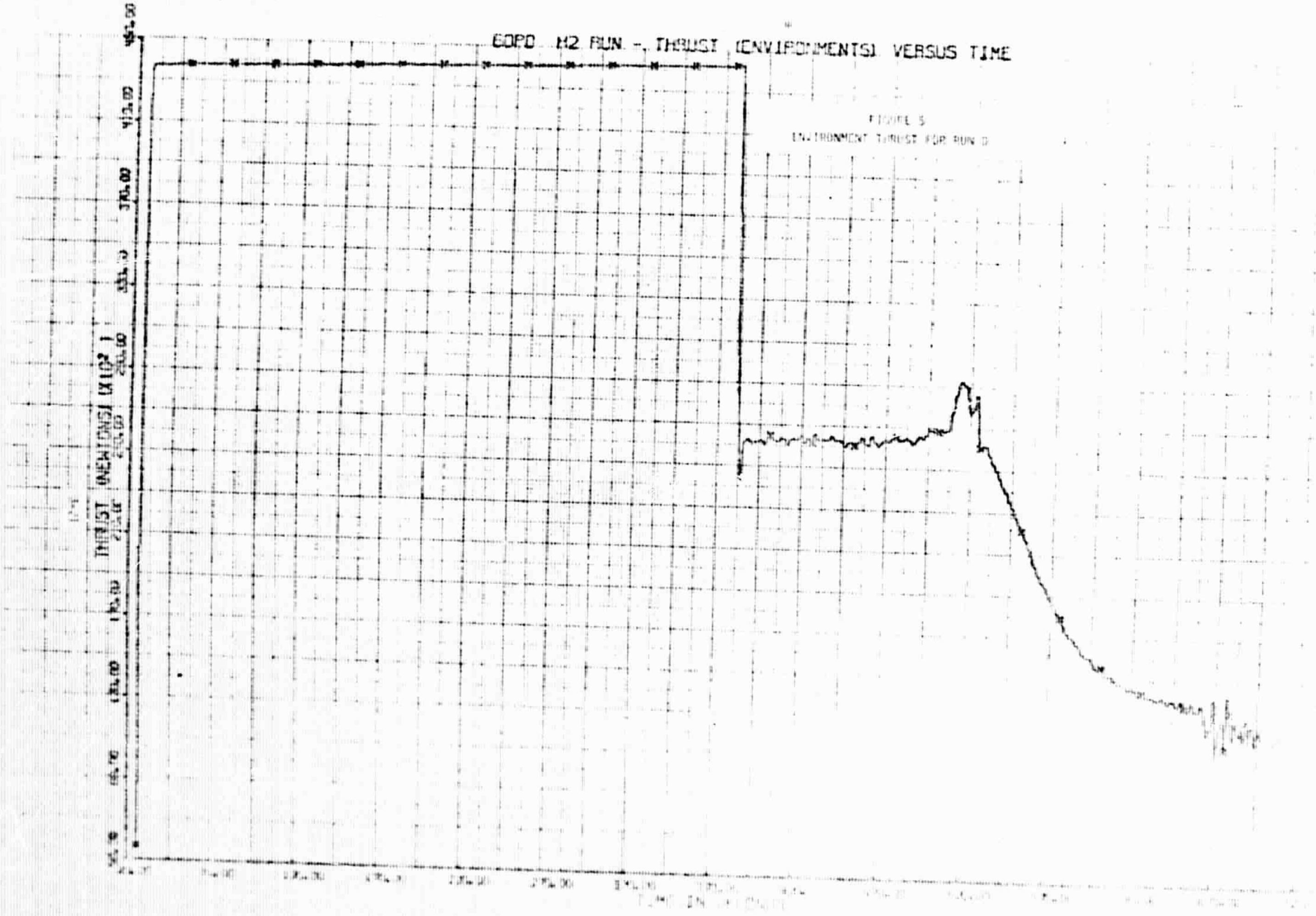


FIGURE 5
ENVIRONMENT THRUST FOR RUN D

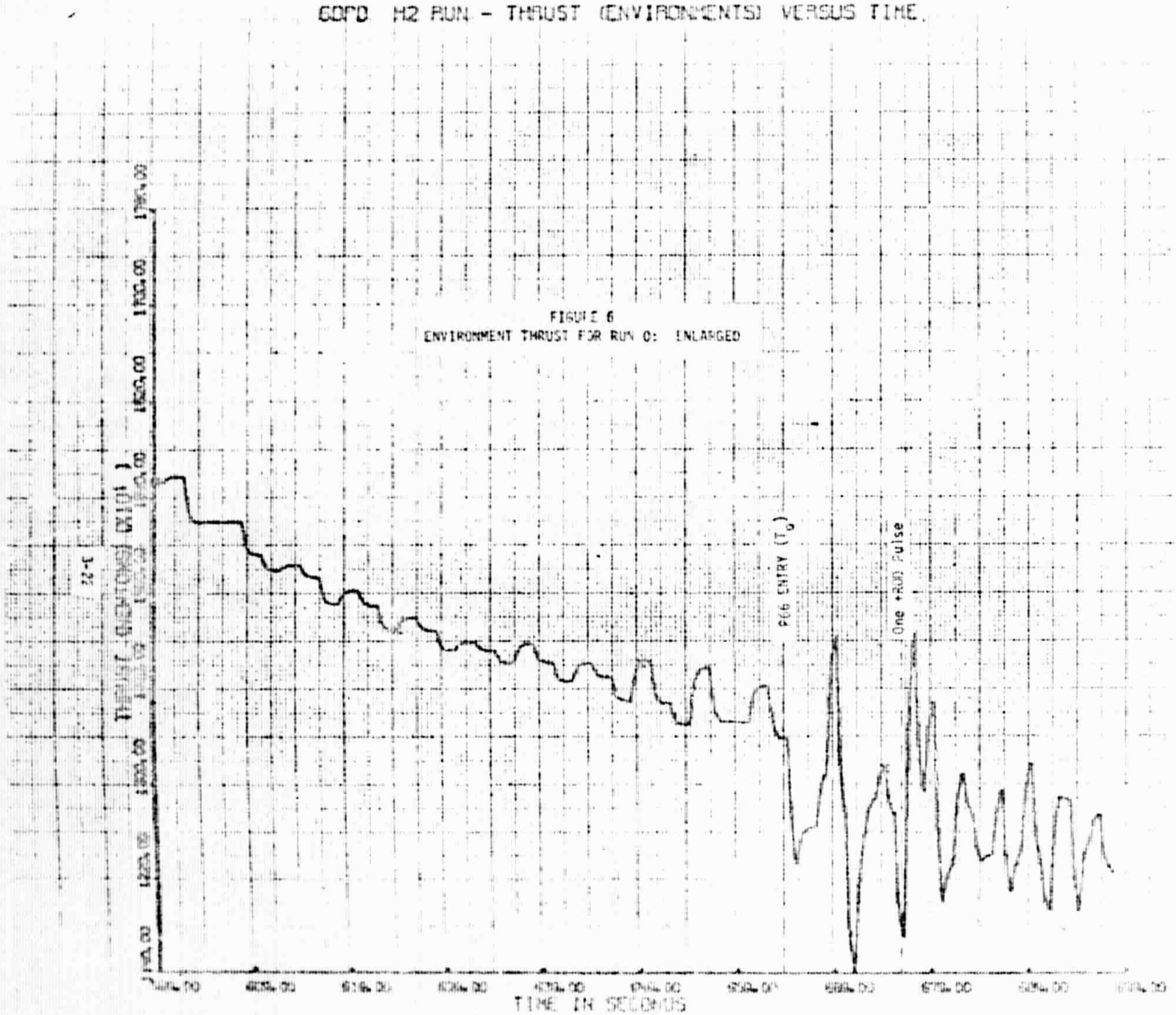
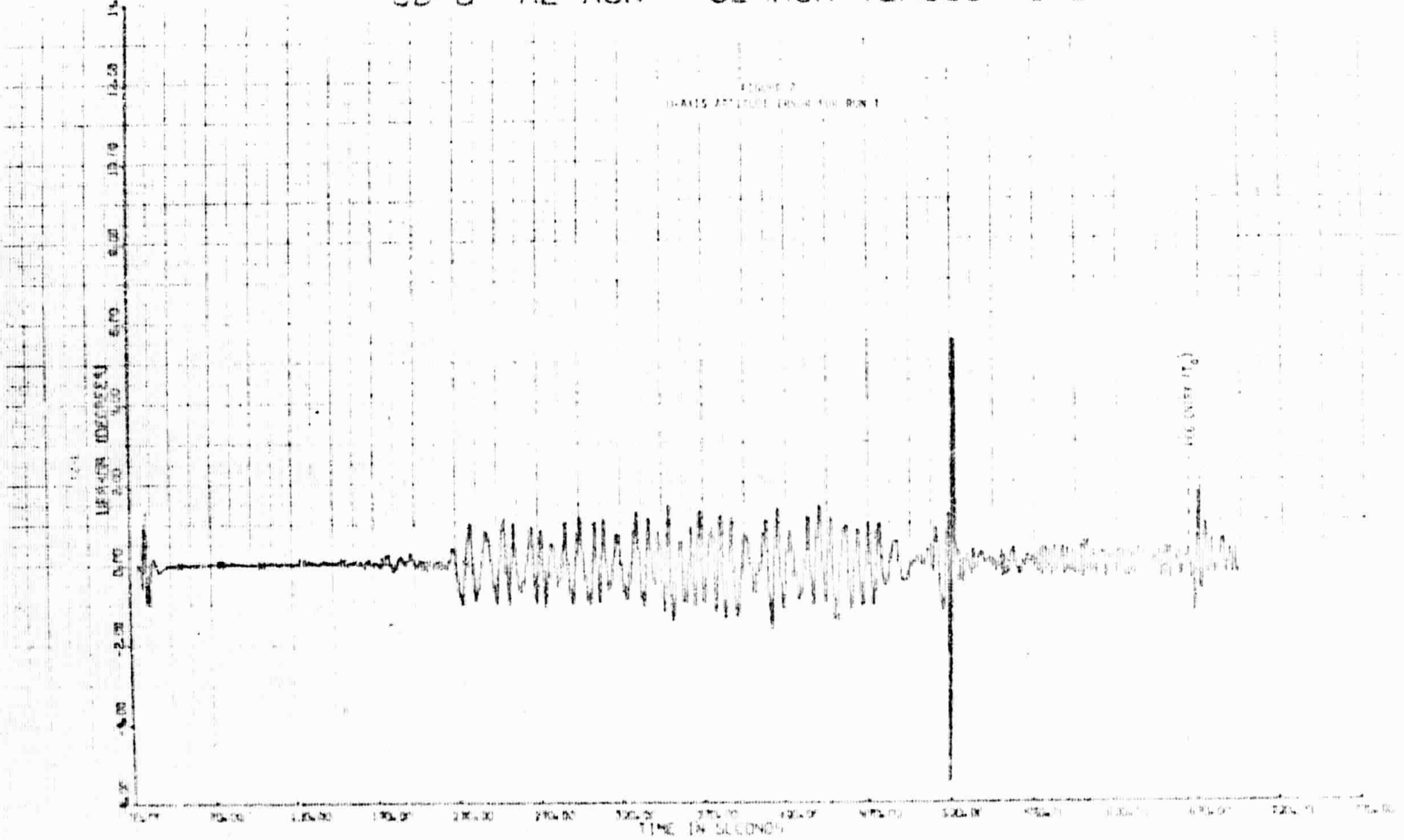
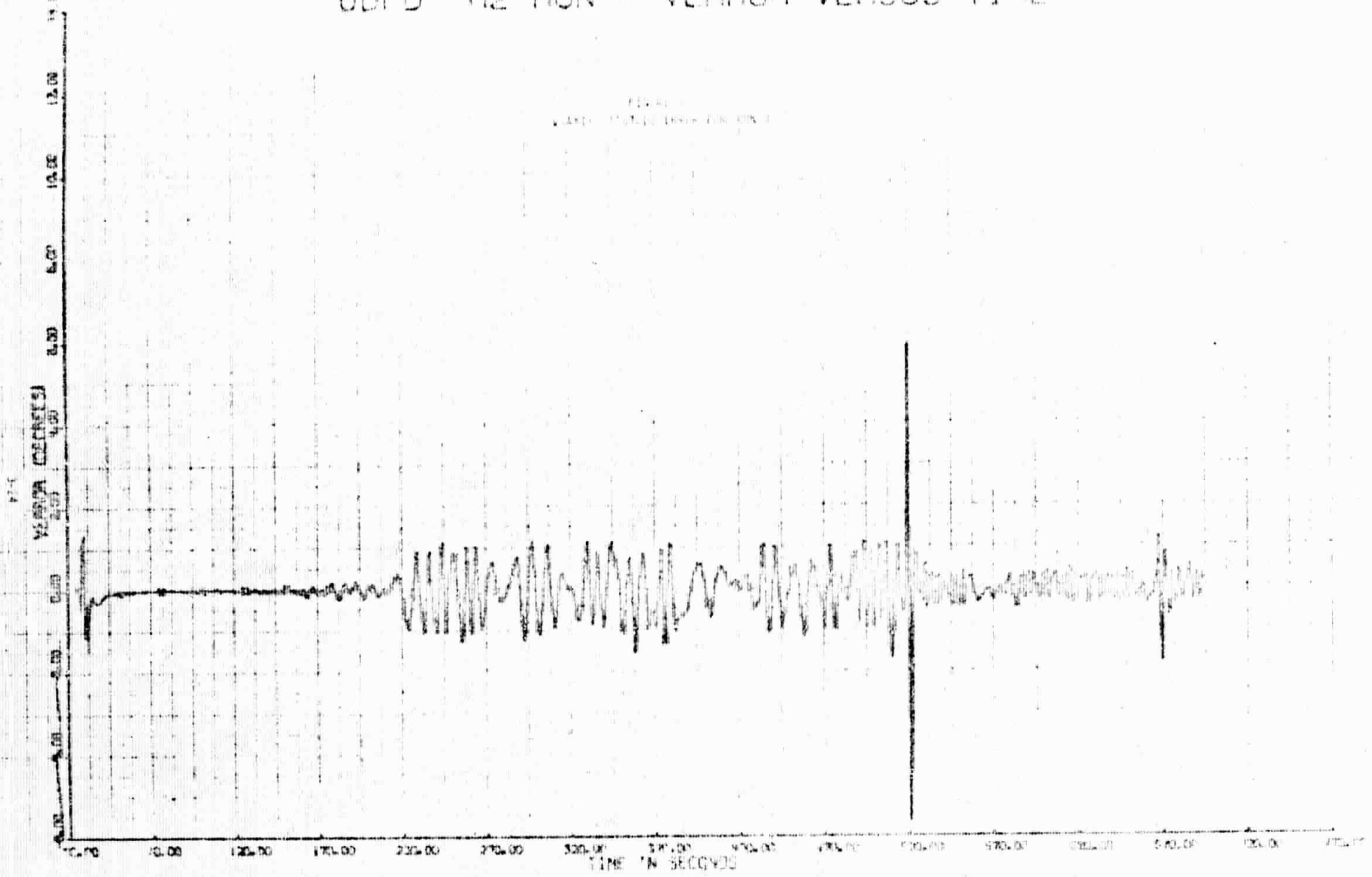


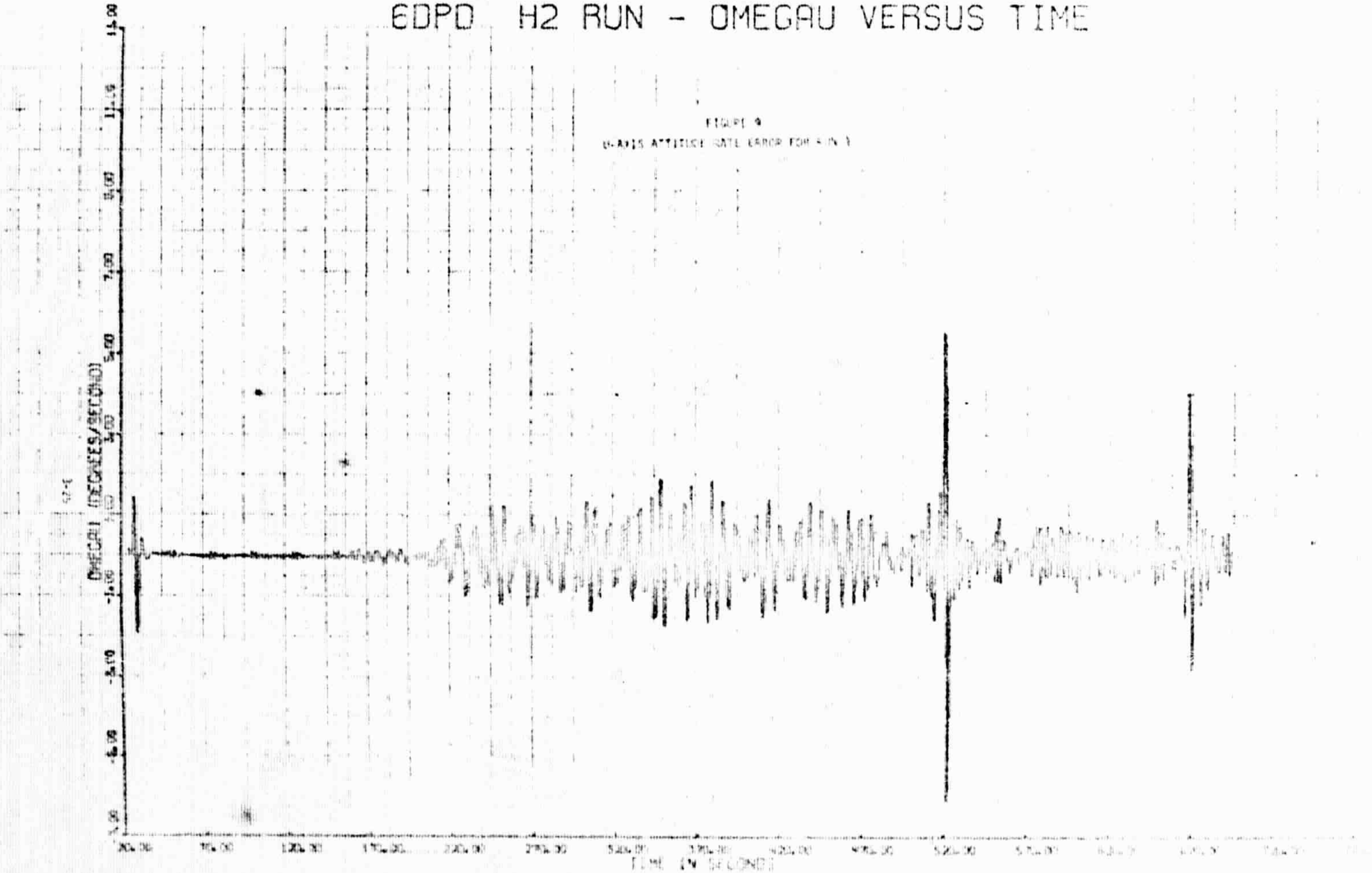
FIGURE 6
ENVIRONMENT THRUST FOR RUN O: ENLARGED

6DPD H2 RUN - UERROR VERSUS TIME



6DPD H2 RUN - VERROR VERSUS TIME




EDPD H2 RUN - OMEGAU VERSUS TIME
FIGURE 9
U-AXIS ATTITUDE RATE ERROR FOR RUN 1
OMEGAU (DEGREES/SECOND)
TIME IN SECONDS

6DPD H2 RUN - OMEGAV VERSUS TIME

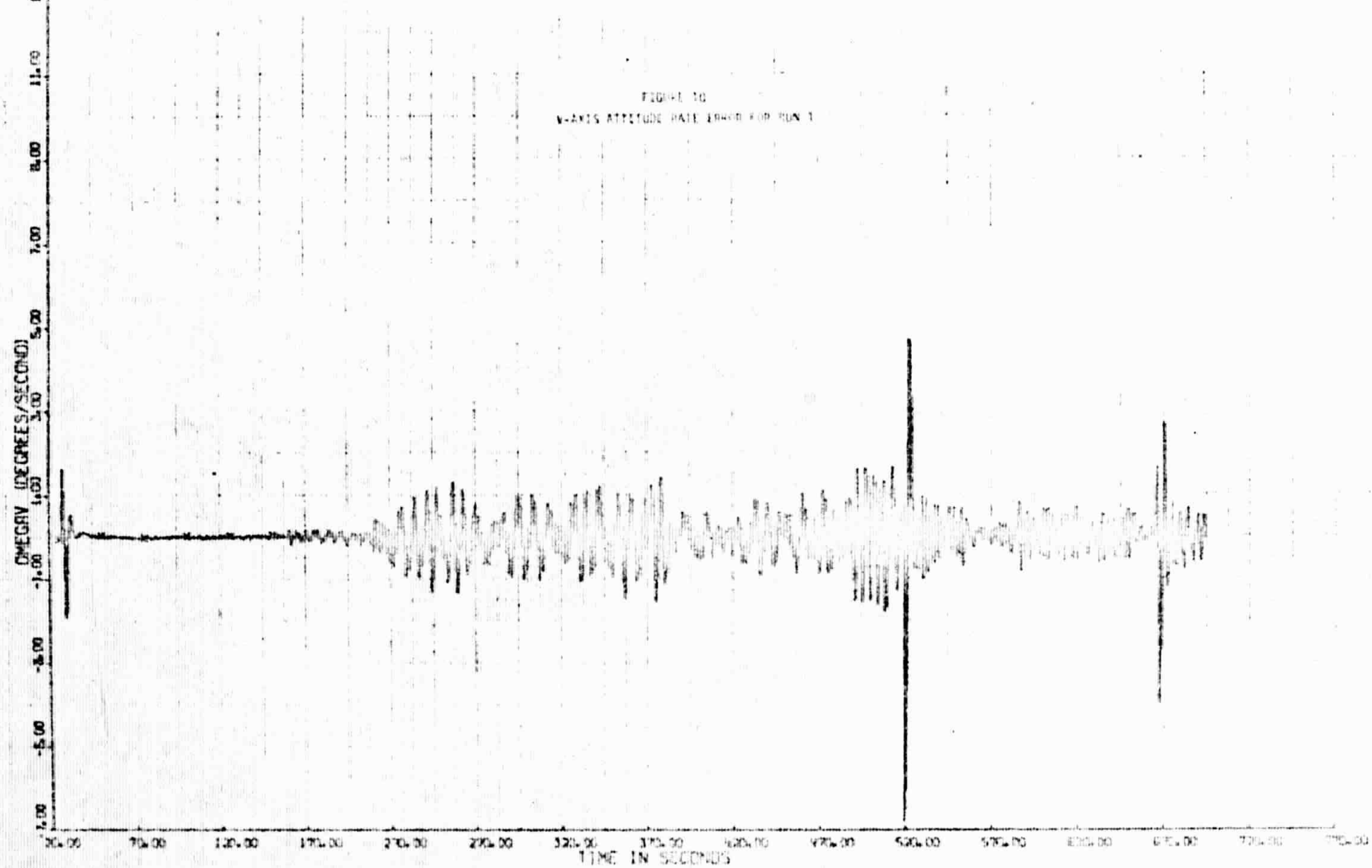


FIGURE 10
V-AXIS ATTITUDE RATE ERROR FOR RUN 1

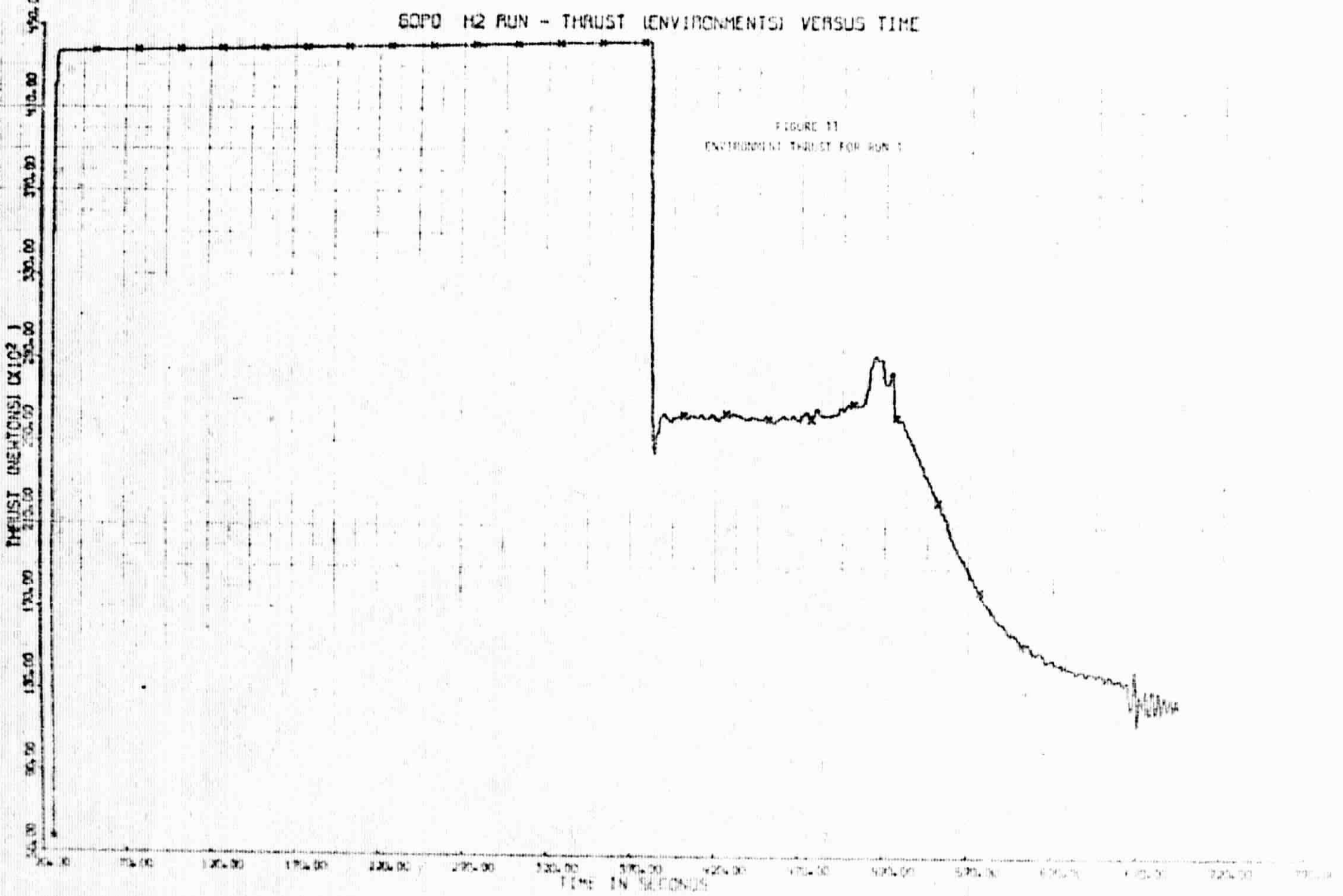


FIGURE 11
ENVIRONMENT THRUST FOR RUN 1

SDPO H2 RUN - THRUST (ENVIRONMENTS) VERSUS TIME

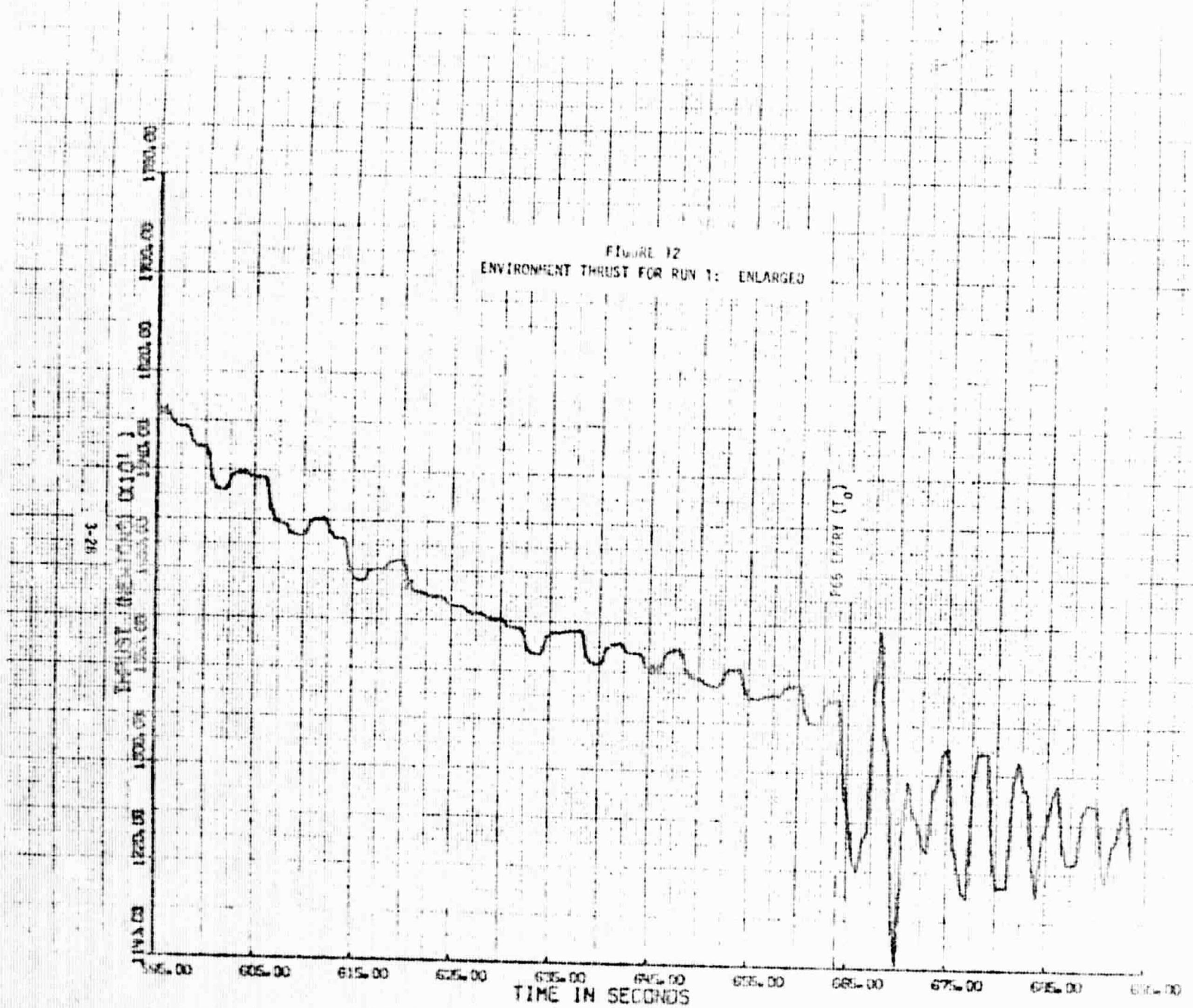


FIGURE 12
ENVIRONMENT THRUST FOR RUN 1: ENLARGED

GDPD H2 RUN - UERROR VERSUS TIME

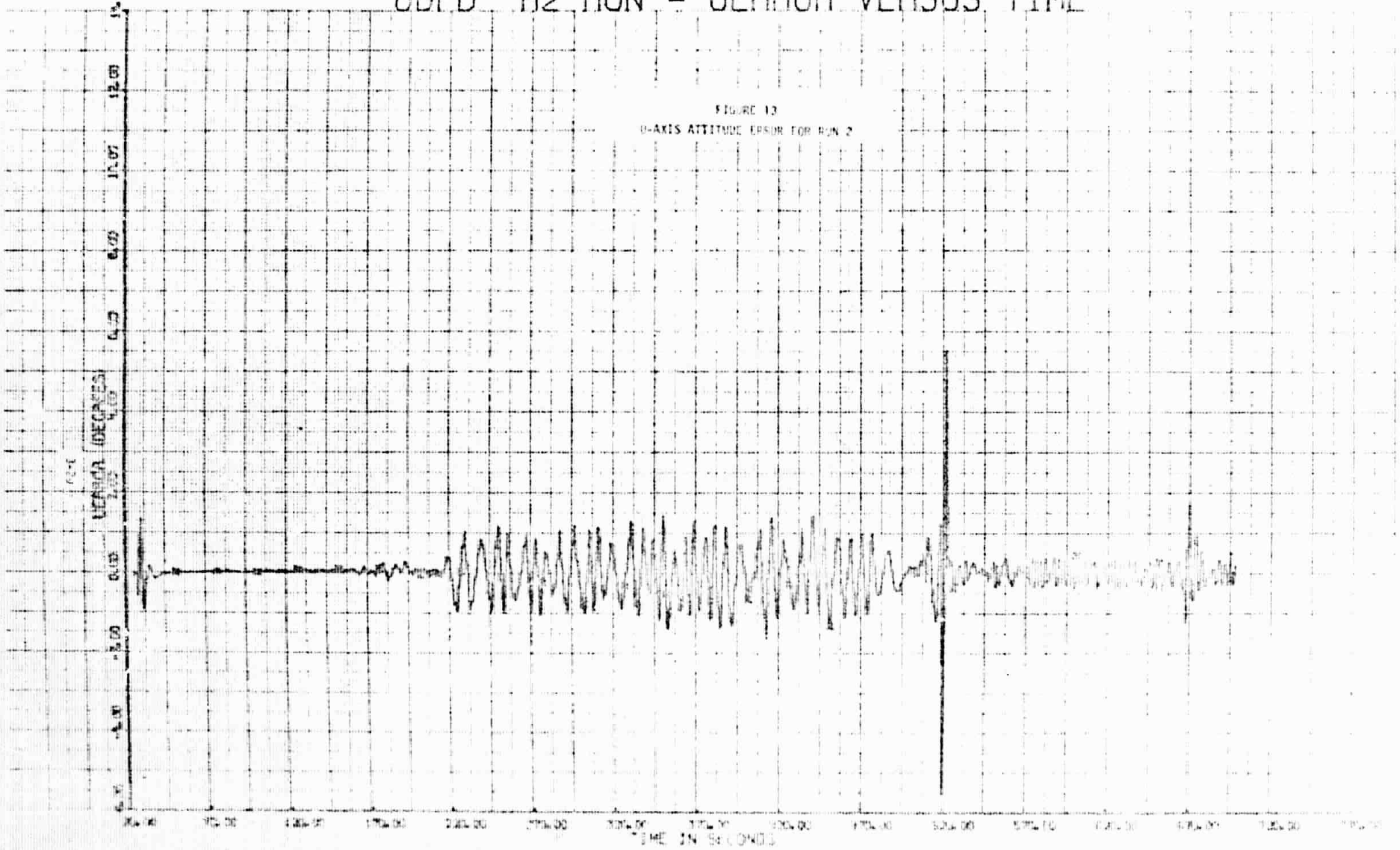


FIGURE 13
U-AXIS ATTITUDE ERROR FOR RUN 2

6DPD H2 RUN - VERROR VERSUS TIME

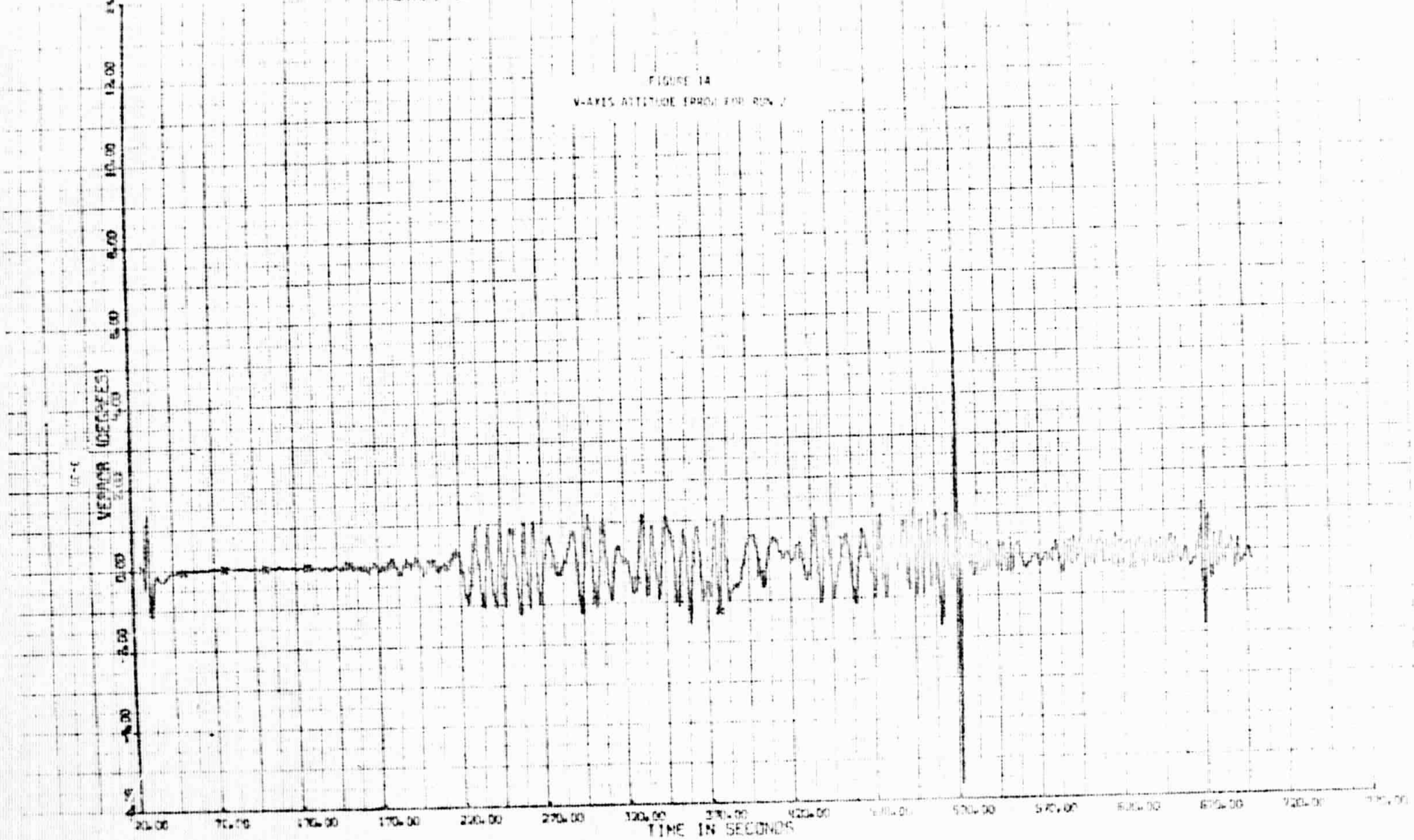


FIGURE 14
V-AXIS ATTITUDE ERROR FOR RUN 2

6DPD H2 RUN - OMEGAU VERSUS TIME

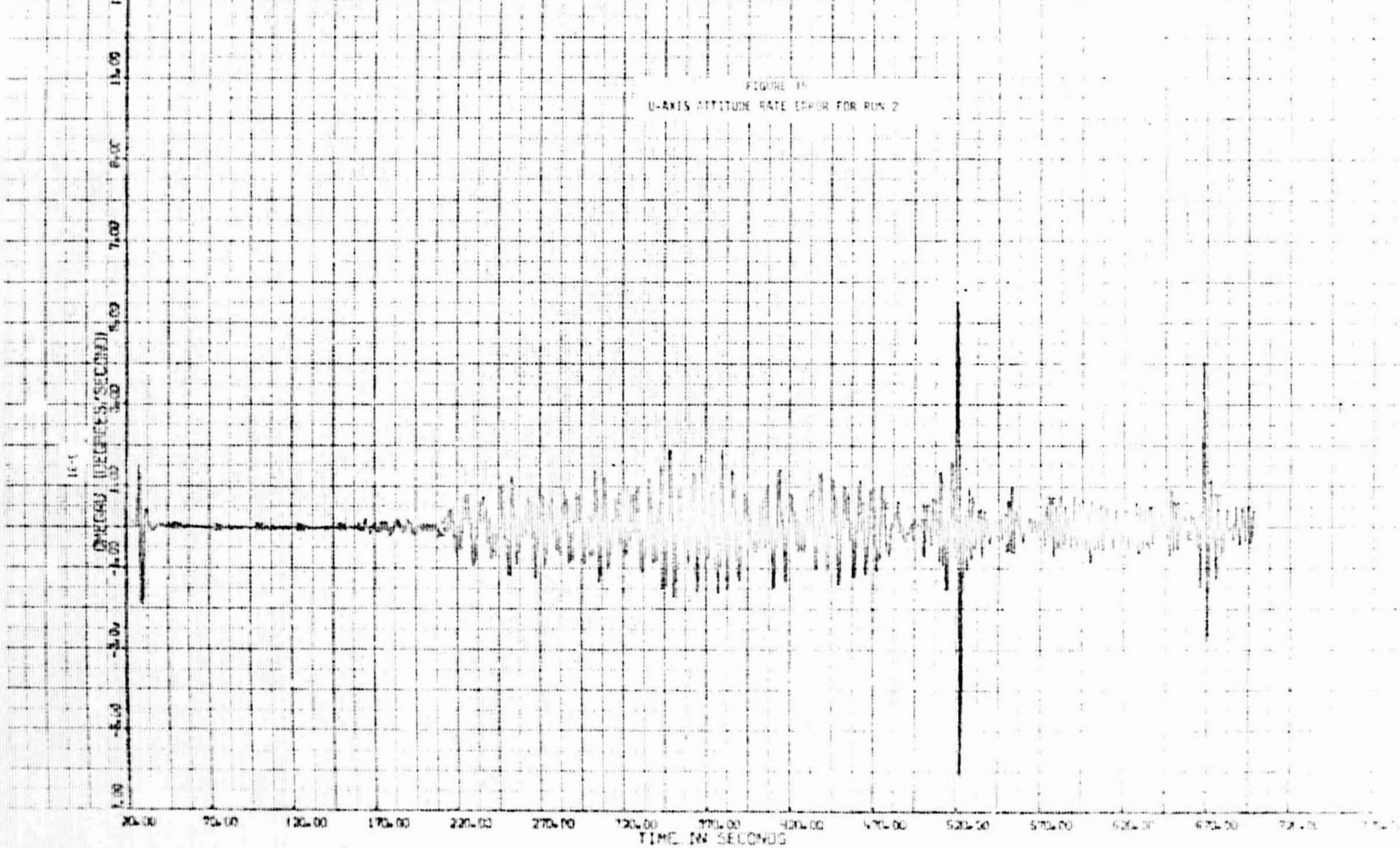
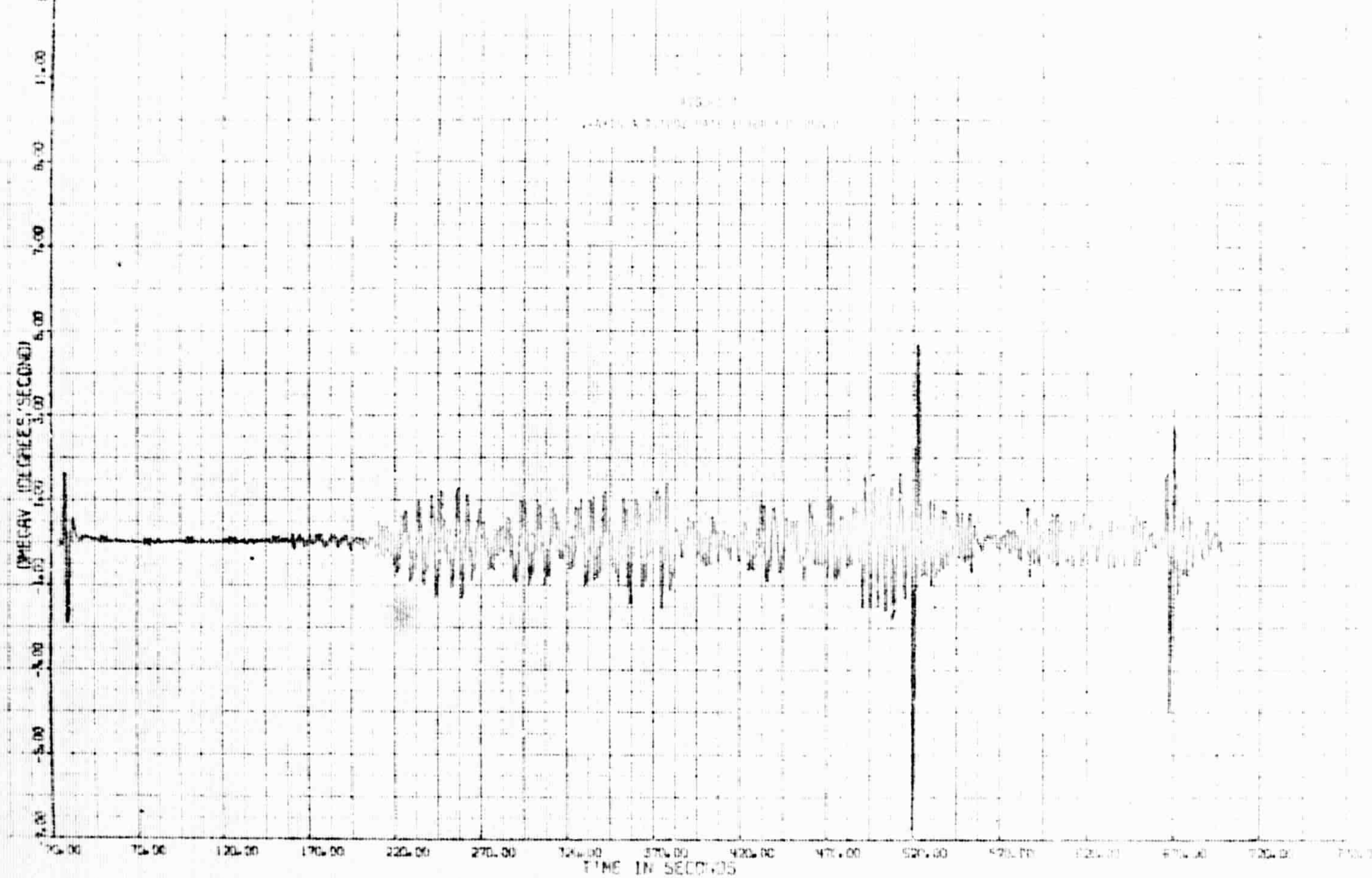


FIGURE 15
U-AXIS ATTITUDE RATE ERROR FOR RUN 2

GLPD H2 RUN - OMEGAV VERSUS TIME



GDPD H2 RUN - THRUST (ENVIRONMENTS) VERSUS TIME

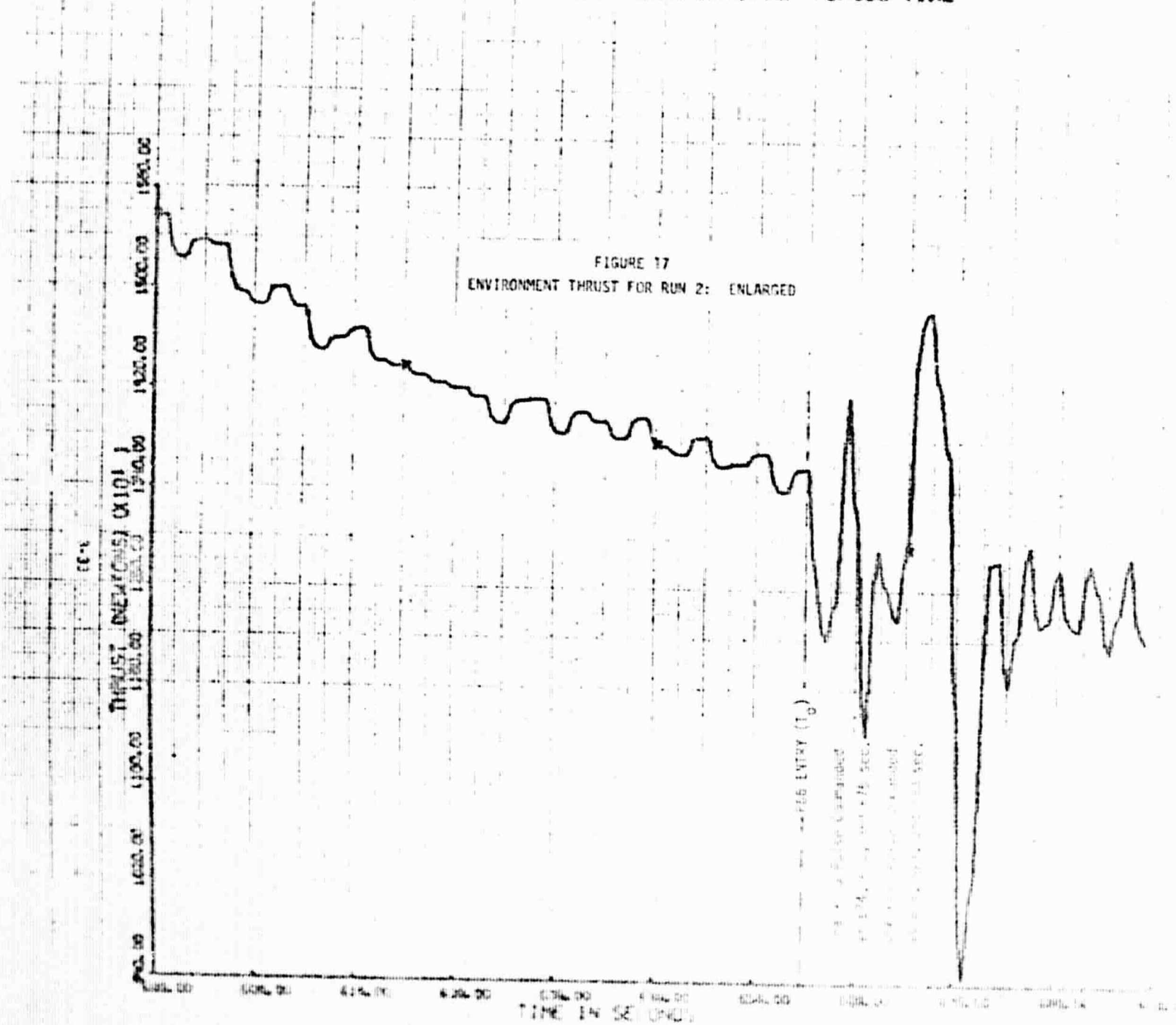


FIGURE 17
ENVIRONMENT THRUST FOR RUN 2: ENLARGED

6DPD H2 RUN - UERROR VERSUS TIME

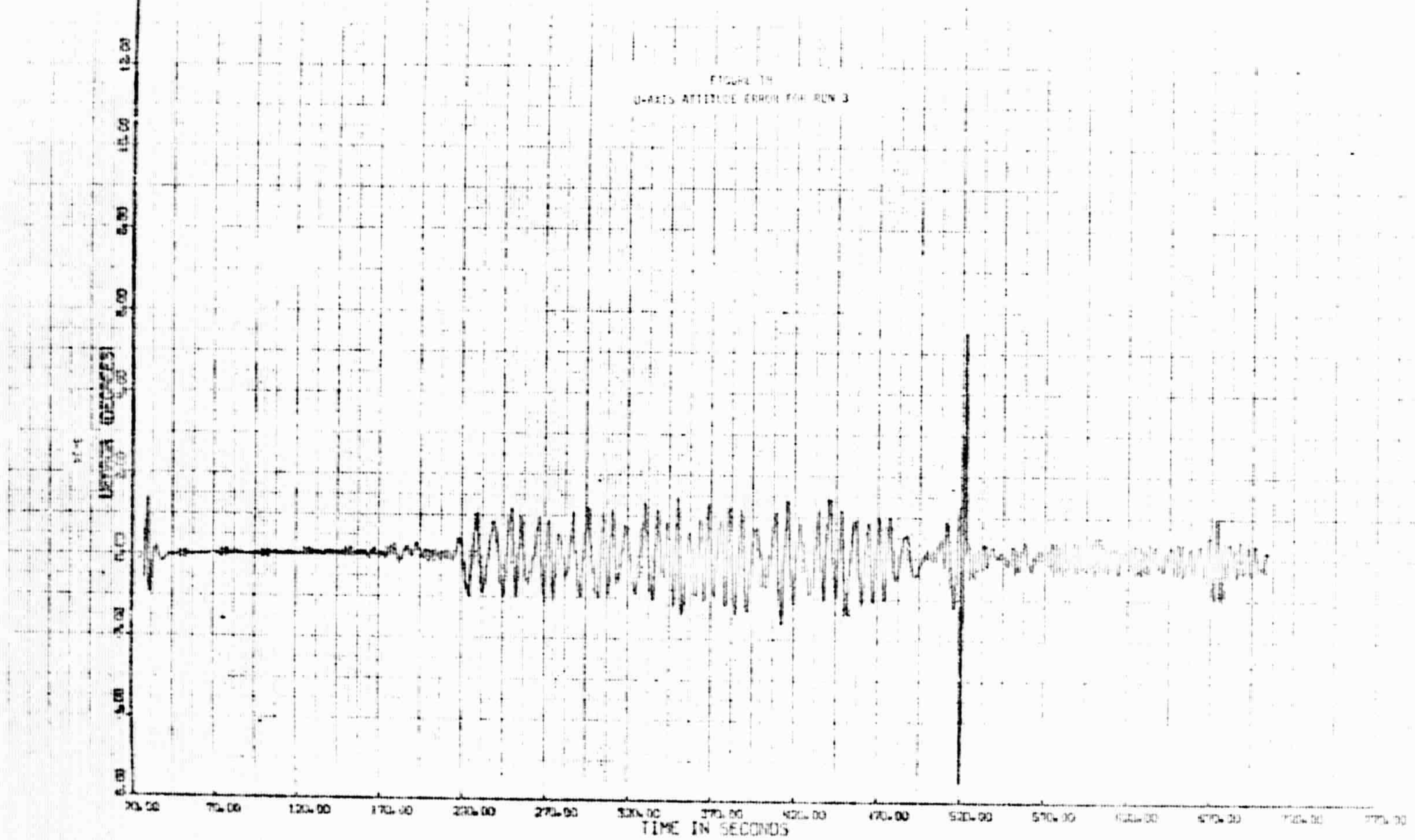
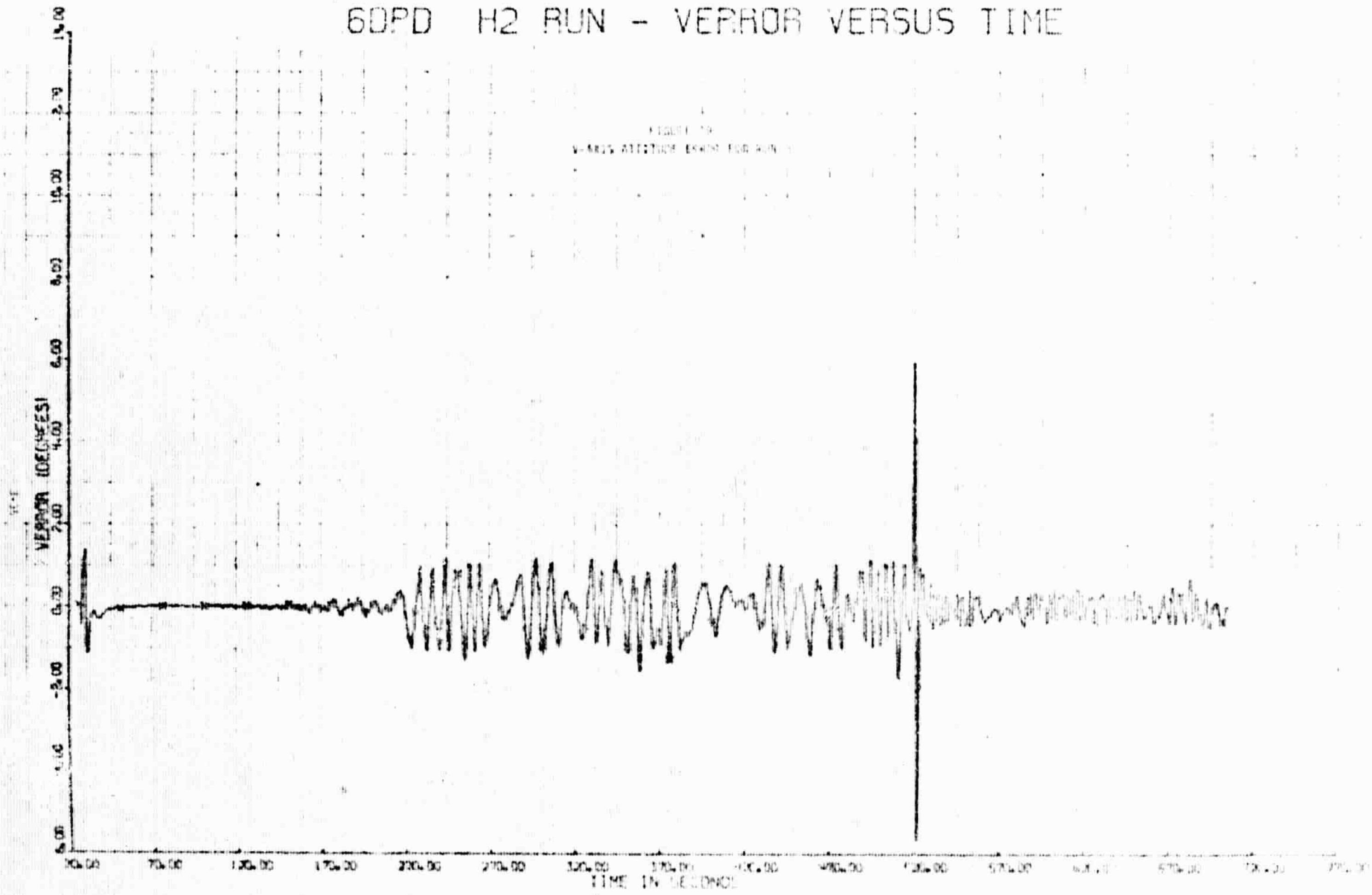
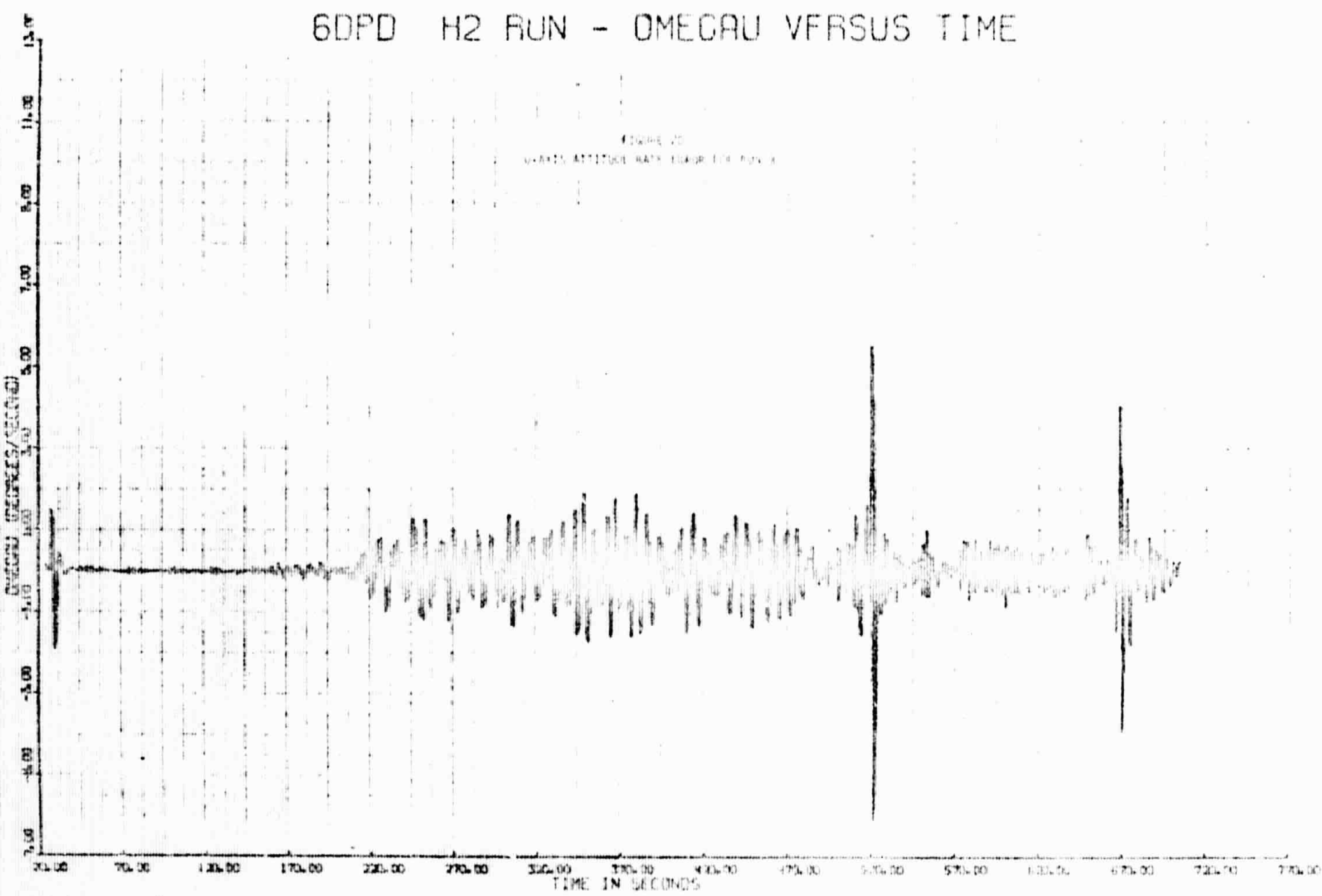


FIGURE 19
U-AXIS ATTITUDE ERROR FOR RUN 3

6DPD H2 RUN - VERROR VERSUS TIME




6DPD H2 RUN - OMEGAU VERSUS TIME
OMEGAU (DEGREES/SECOND)
TIME IN SECONDS

6DPD H2 RUN - OMEGAV VERSUS TIME

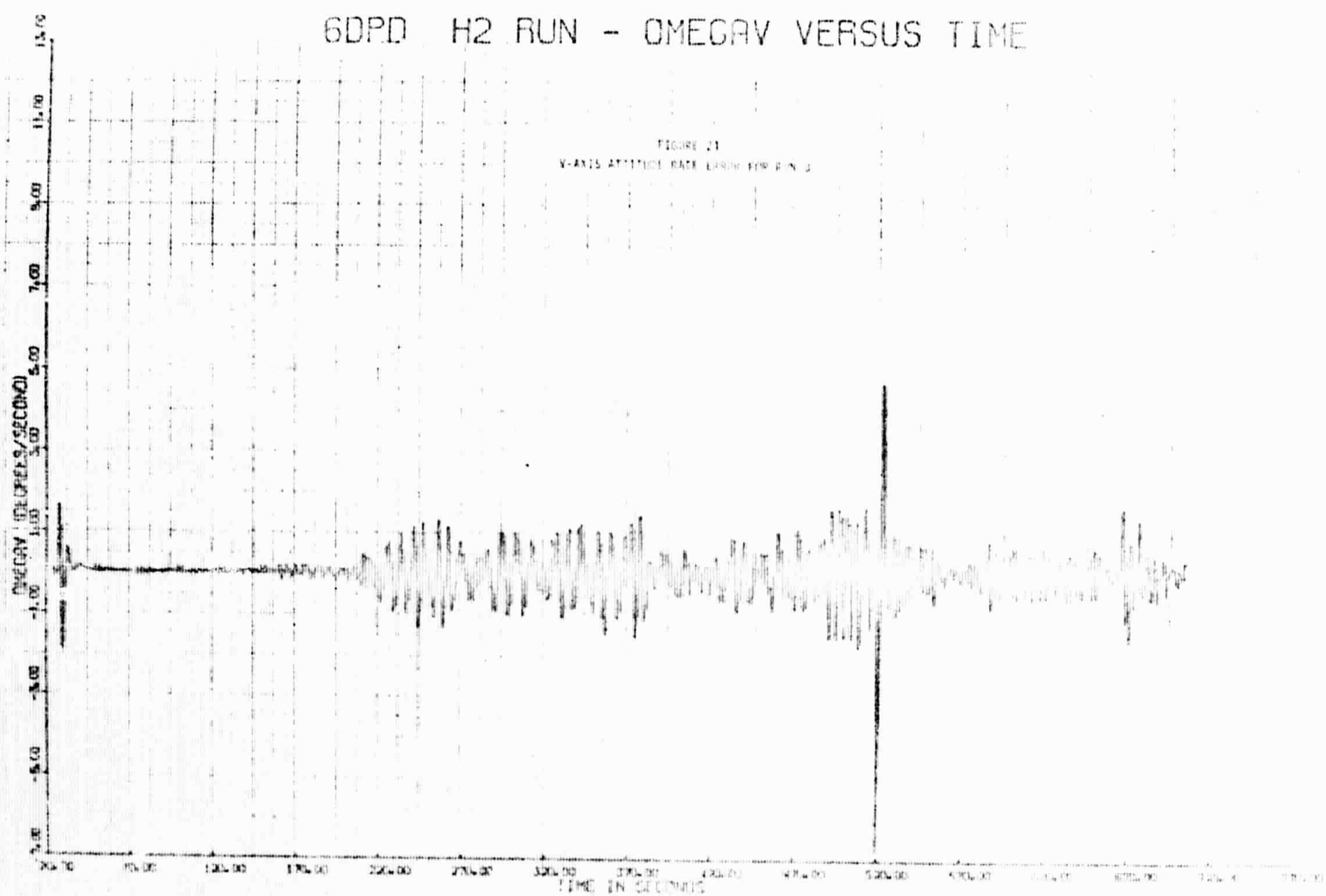


FIGURE 21
Y-AXIS ATTITUDE RATE ERROR FOR RUN 2

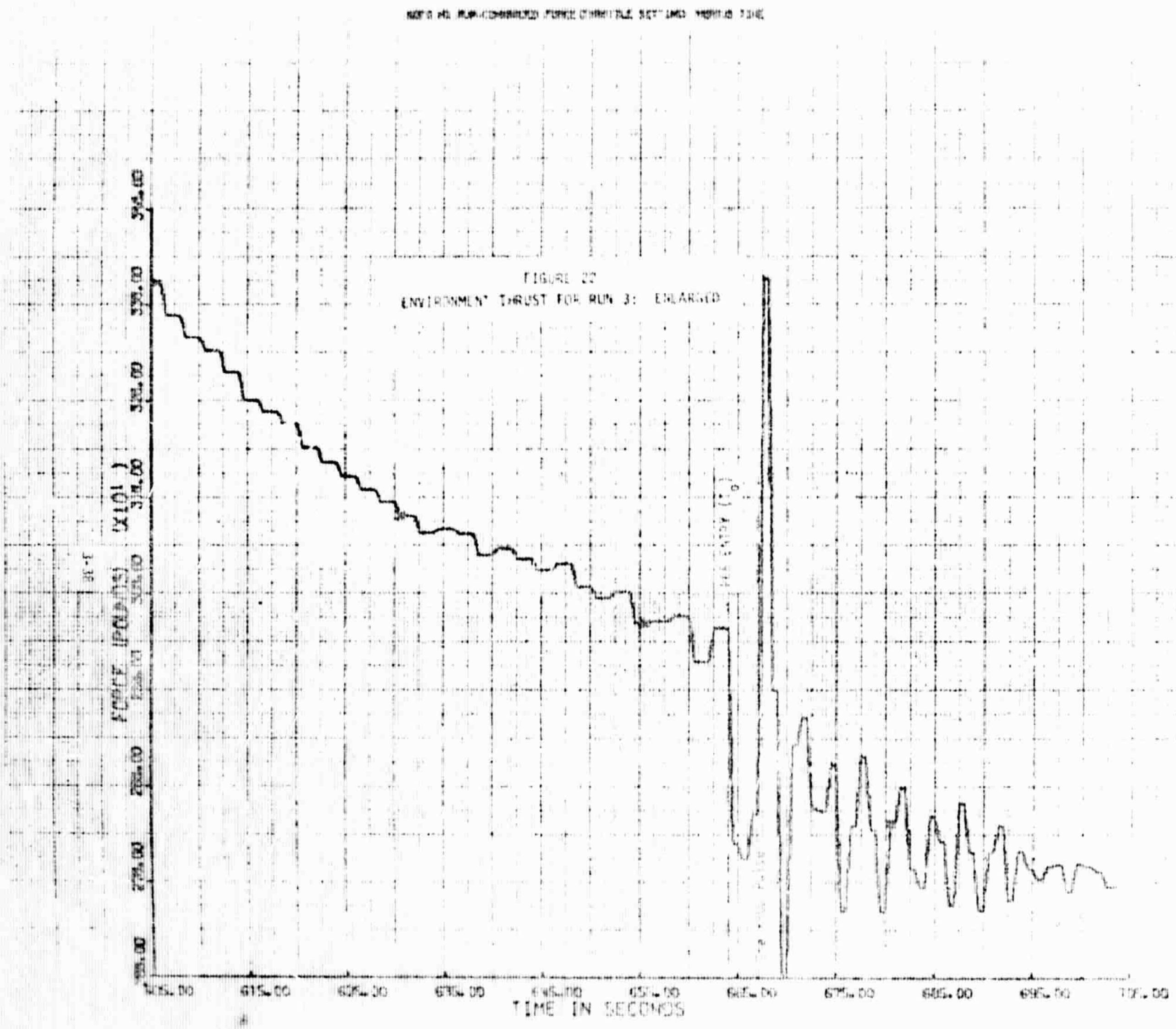


FIGURE 22
ENVIRONMENT THRUST FOR RUN 3: ENLARGED

GDPD H2 RUN - VELOCITY (ENV) Y-COMP

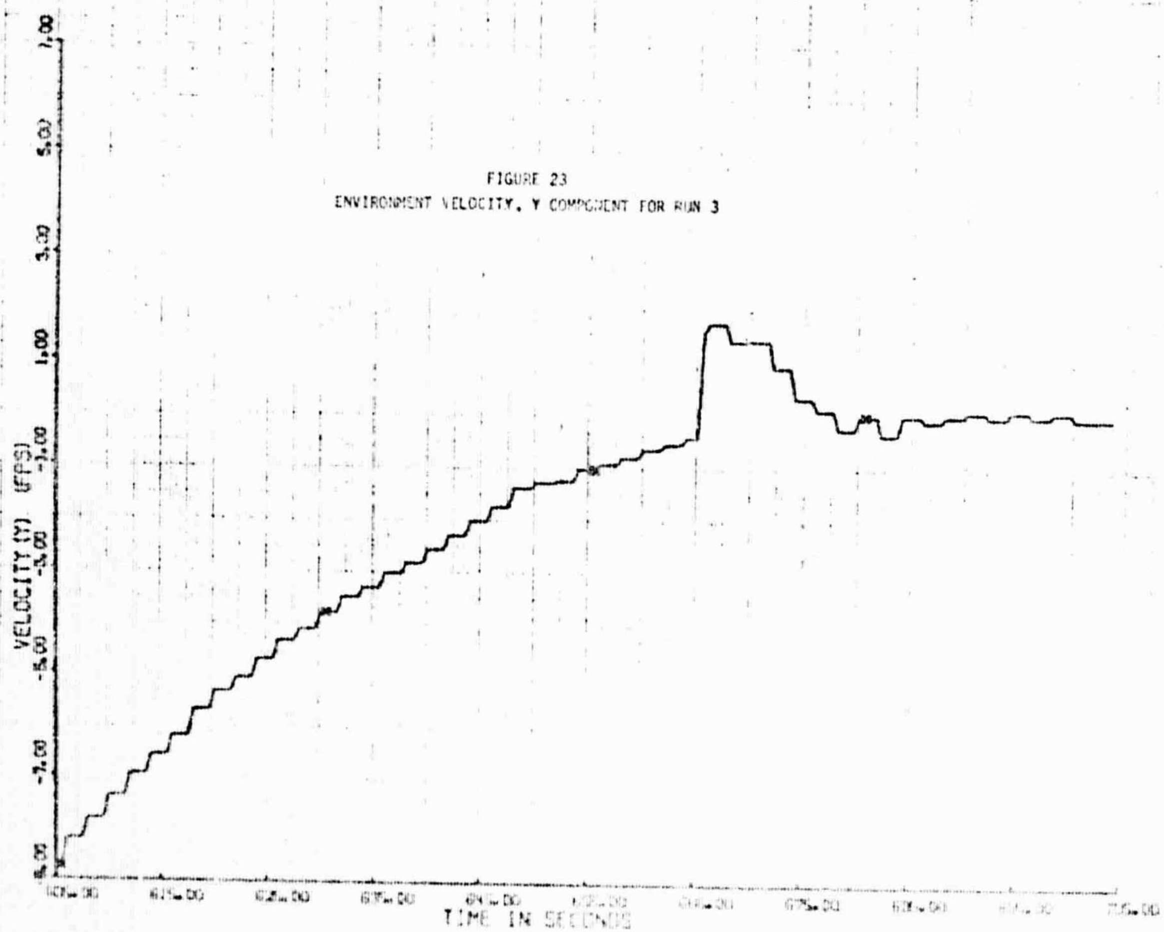


FIGURE 23
ENVIRONMENT VELOCITY, Y COMPONENT FOR RUN 3

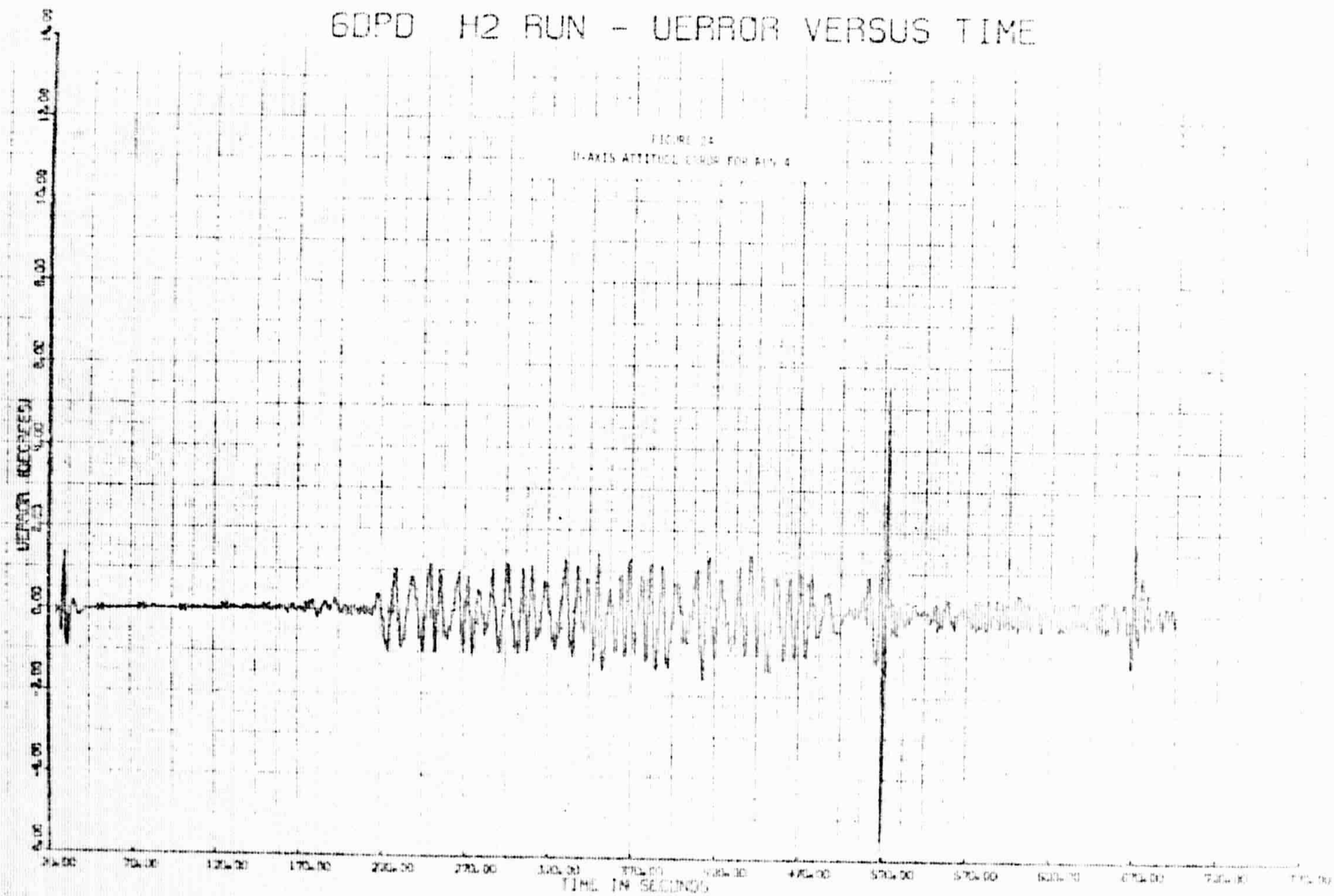


FIGURE 24
U-AXIS ATTITUDE ERROR FOR RUN 4

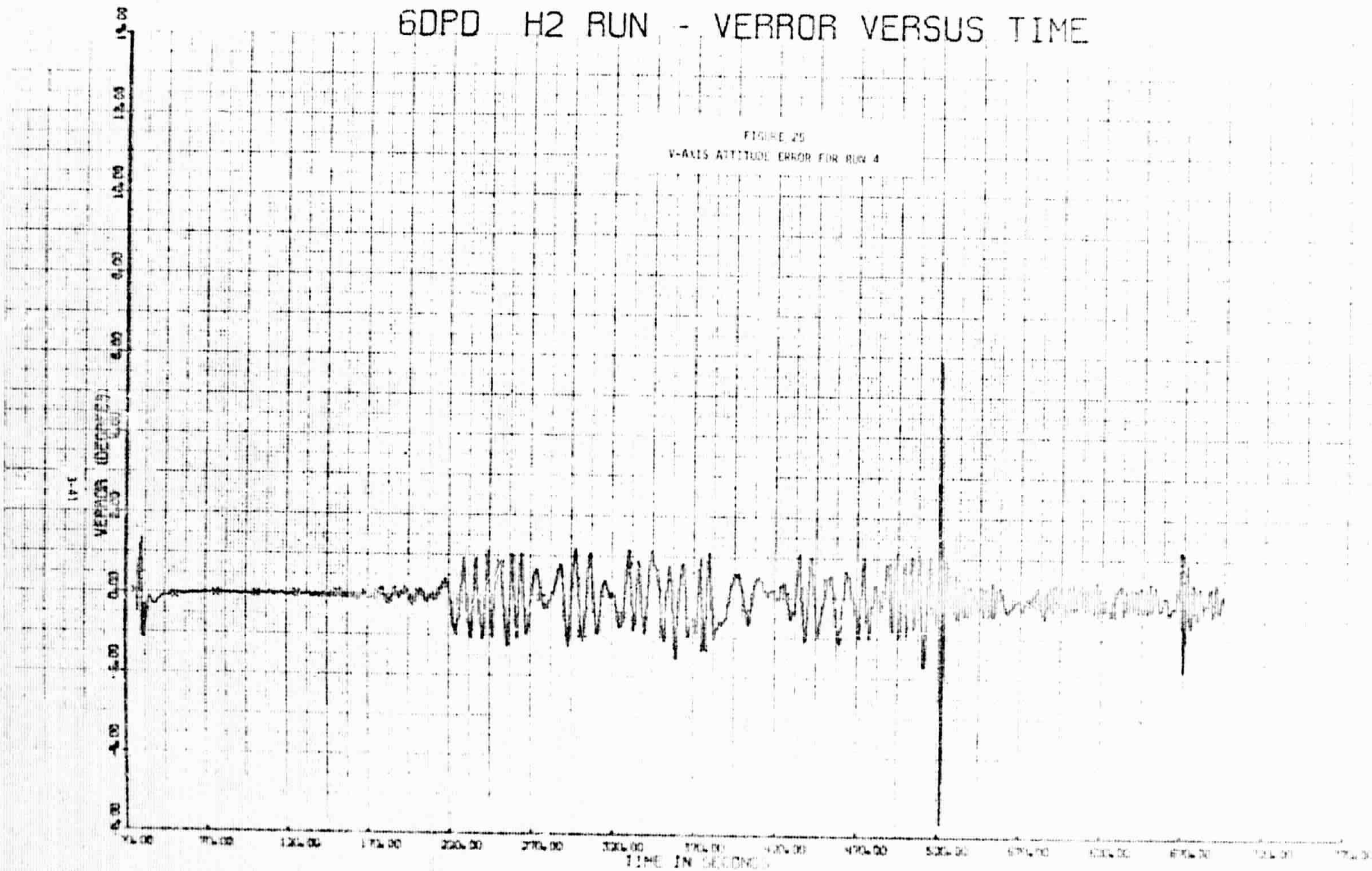
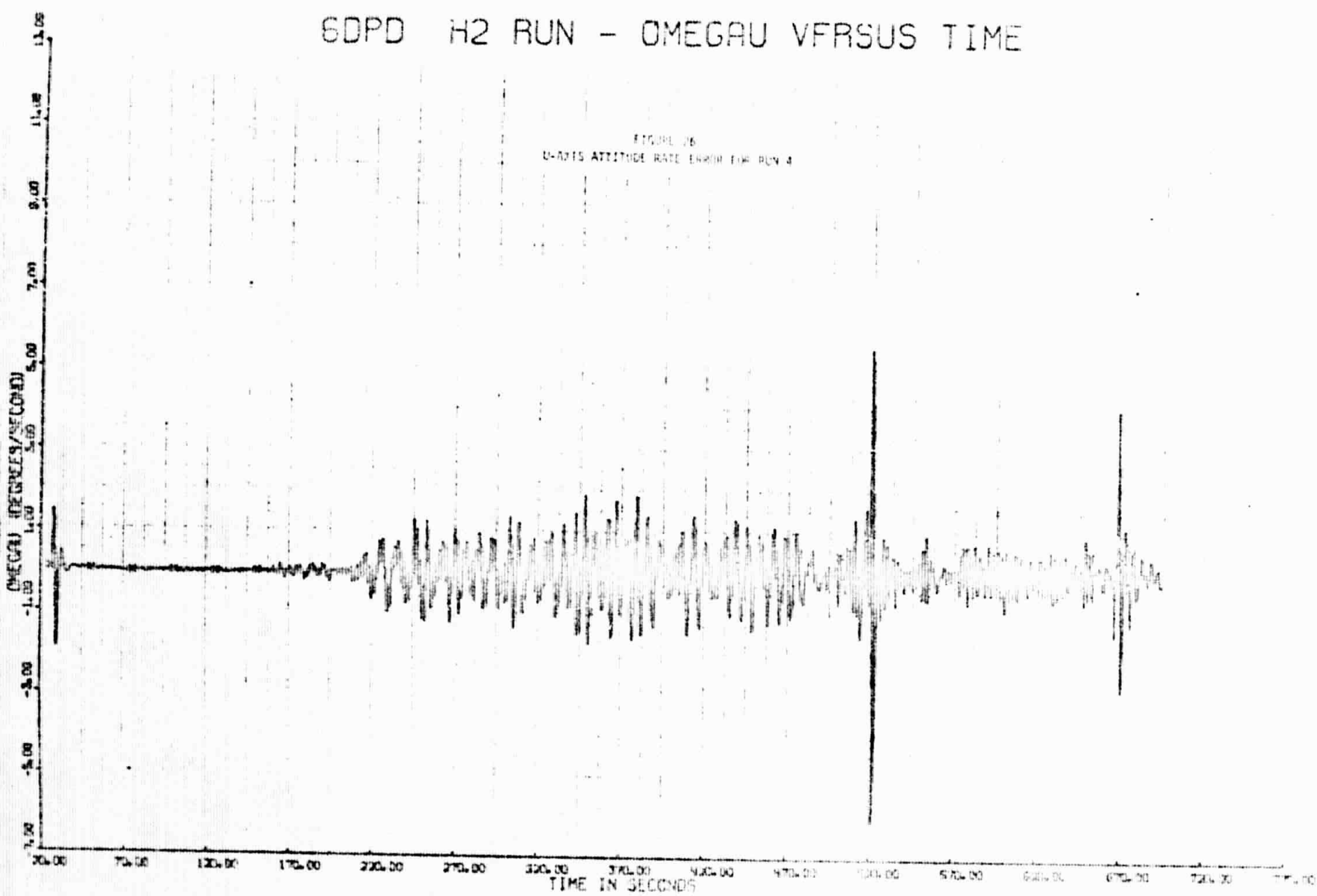


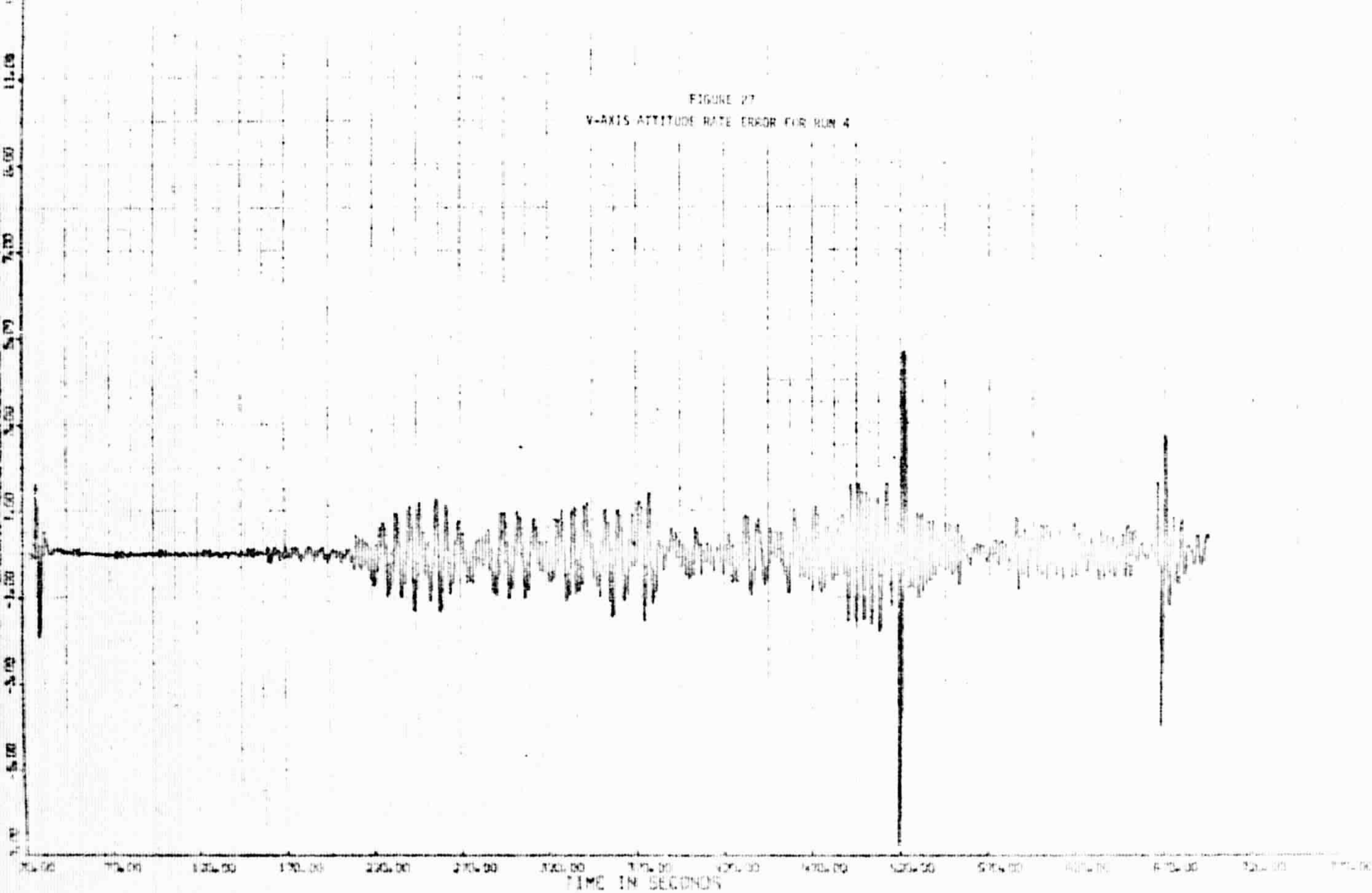
FIGURE 25
V-AXIS ATTITUDE ERROR FOR RUN 4

6DPD H2 RUN - OMEGAU VFRSUS TIME

FIGURE 26
U-AXIS ATTITUDE RATE ERROR FOR RUN 4



6DPD H2 RUN - OMEGAV VERSUS TIME



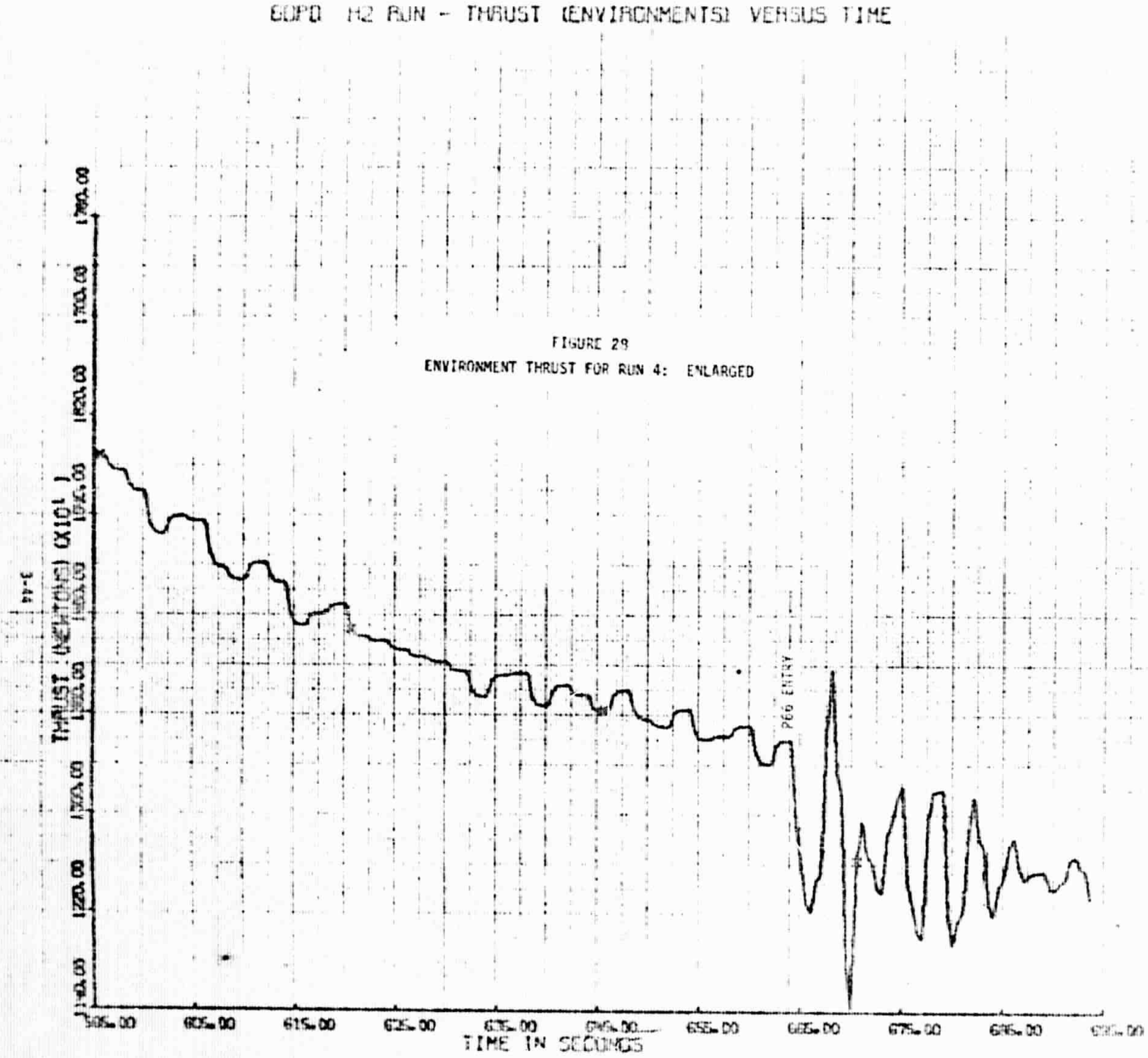


FIGURE 29
ENVIRONMENT THRUST FOR RUN 4: ENLARGED

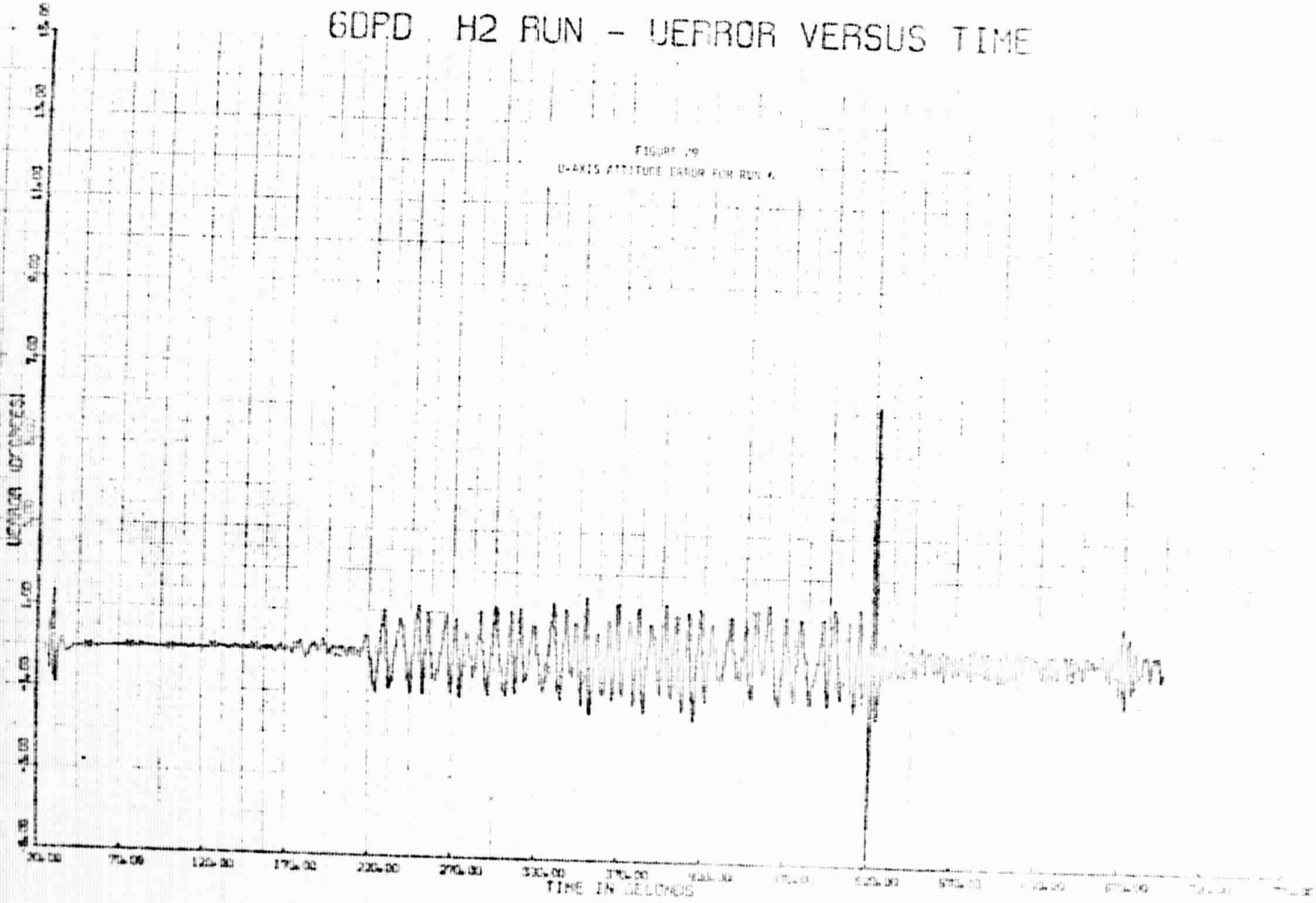
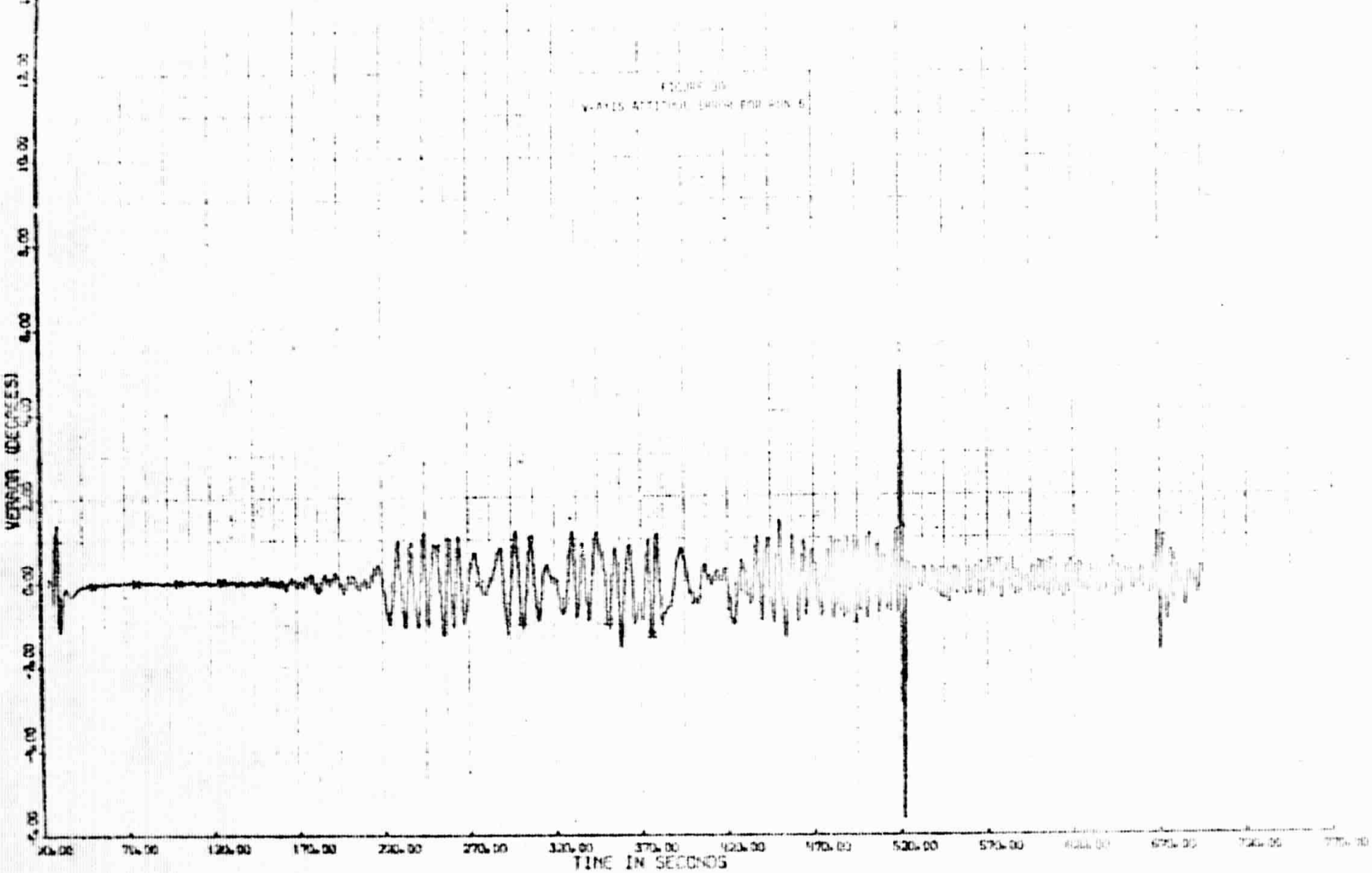


FIGURE 29
U-AXIS ATTITUDE ERROR FOR RUN 4.

6DPD H2 RUN - VERROR VERSUS TIME



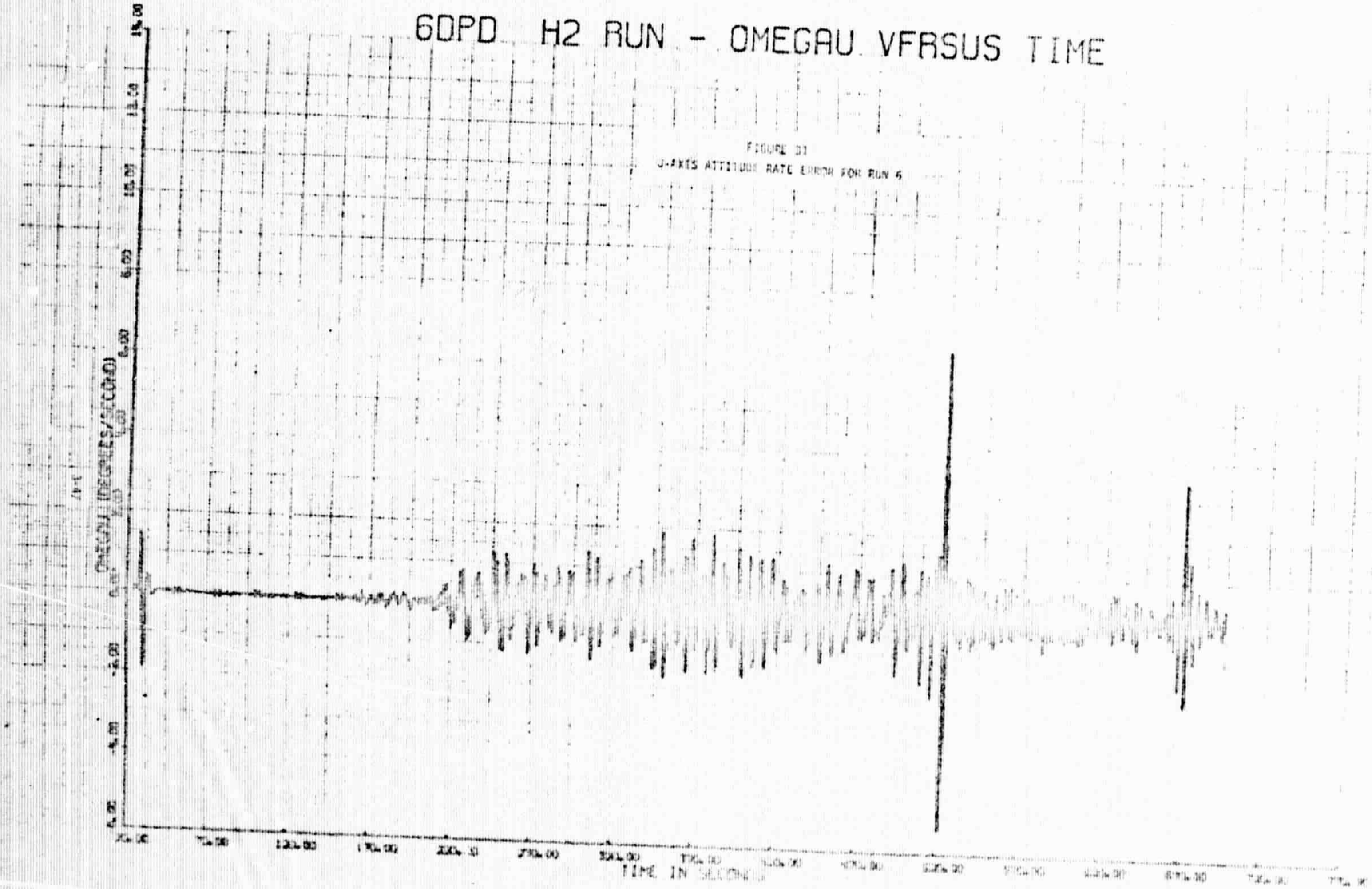


FIGURE 31
U-AXIS ATTITUDE RATE ERROR FOR RUN 6

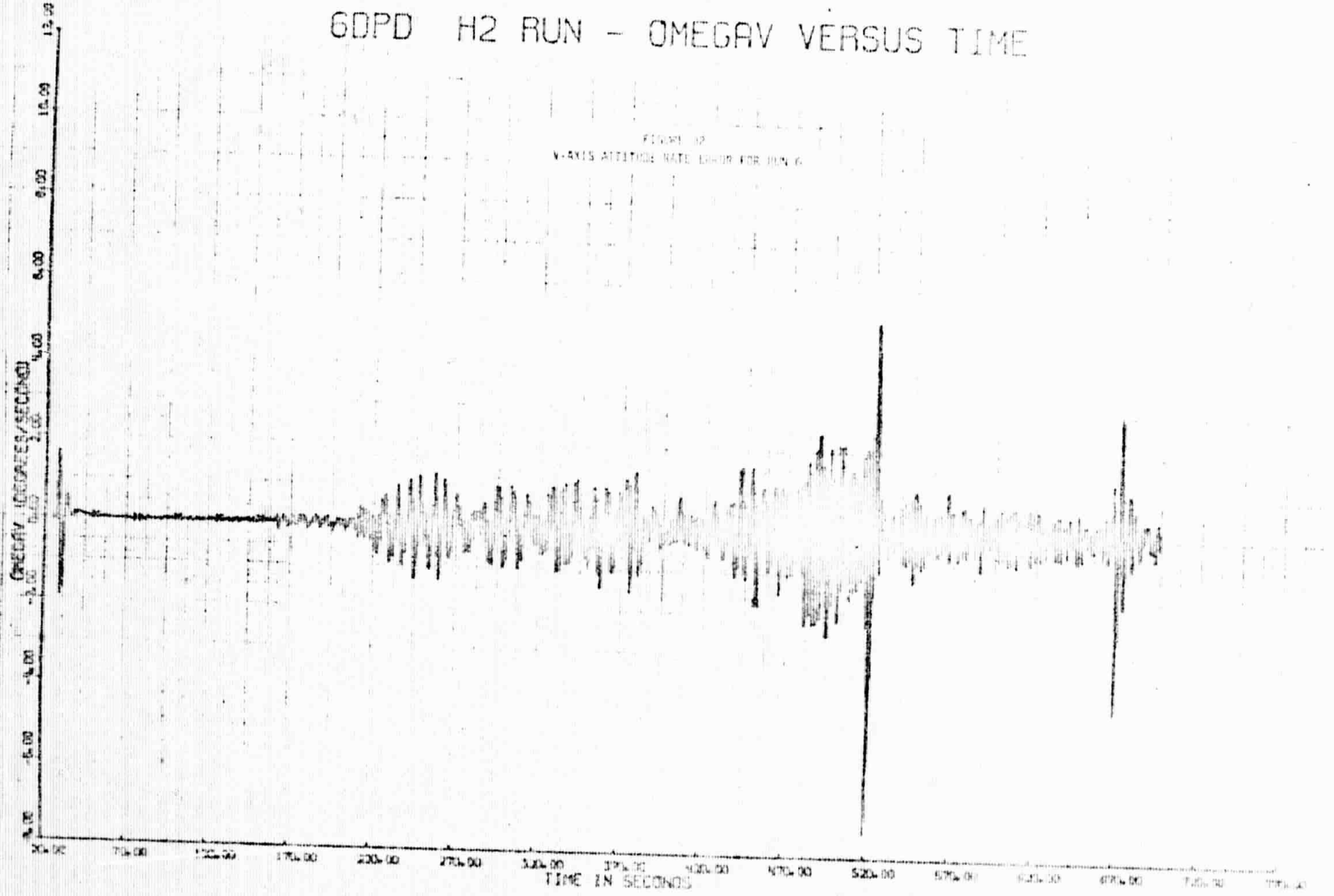


FIGURE 12
V-AXIS ATTITUDE RATE ERROR FOR RUN 6

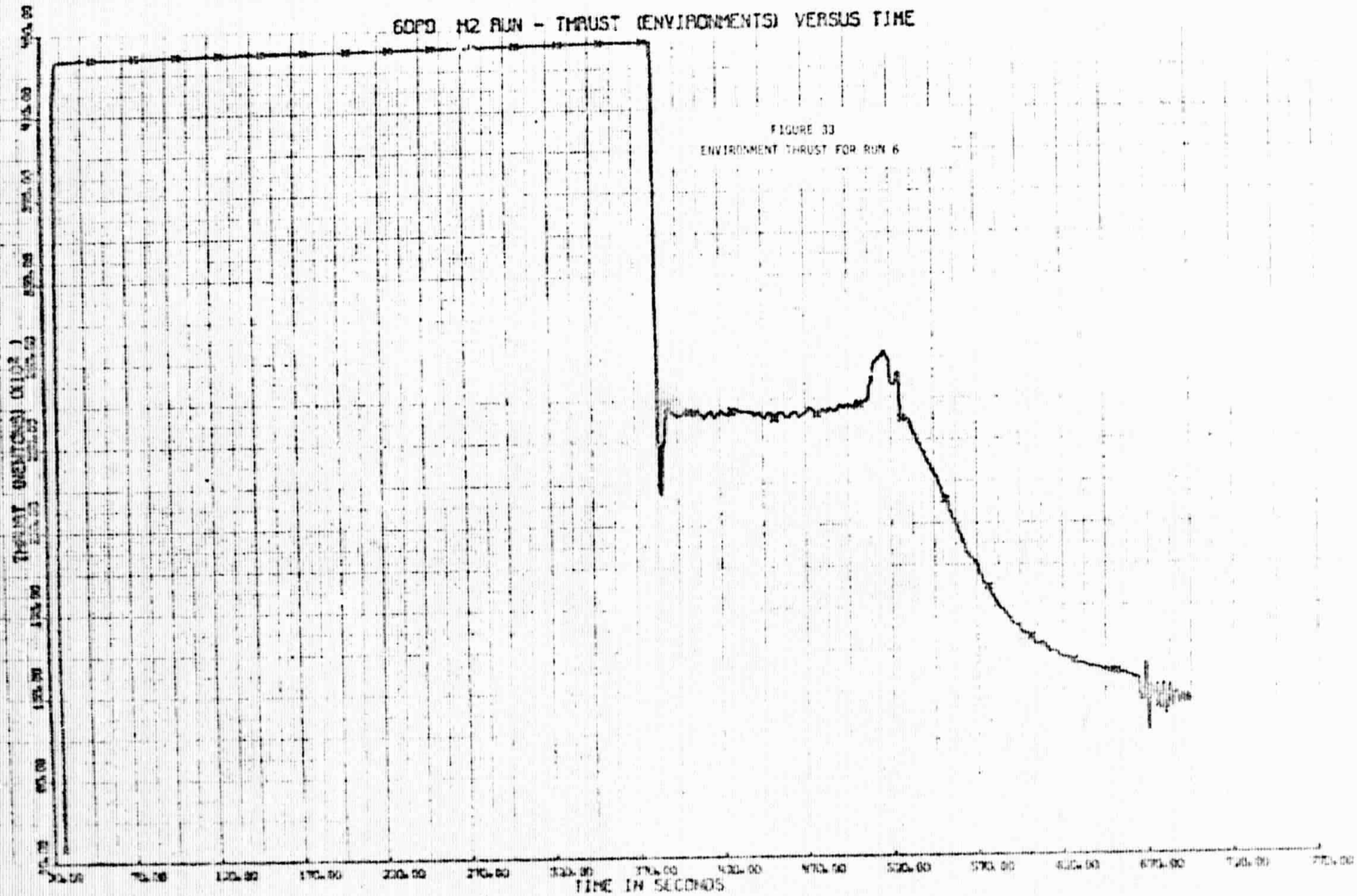


FIGURE 33
ENVIRONMENT THRUST FOR RUN 6

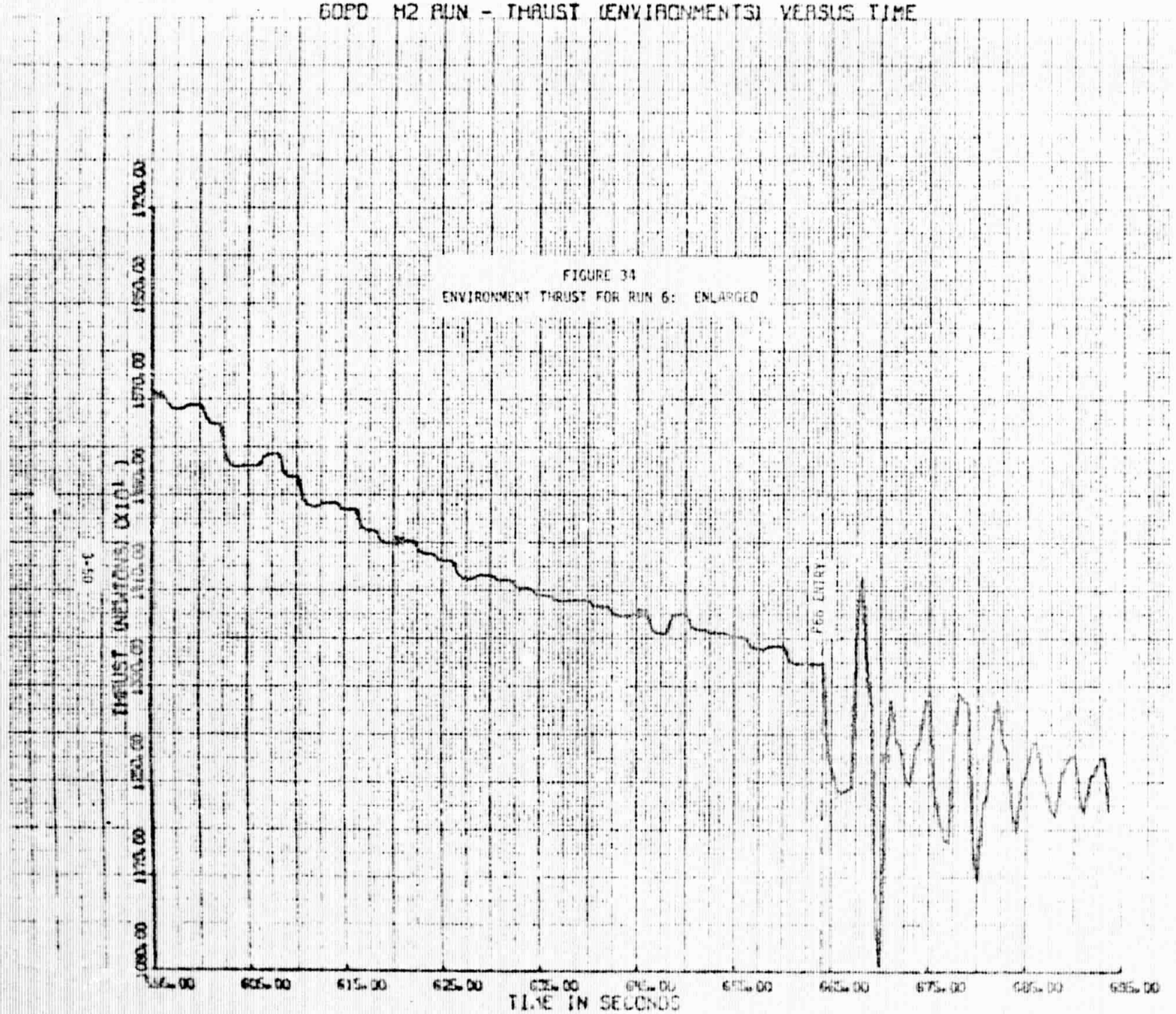


FIGURE 34
ENVIRONMENT THRUST FOR RUN 6: ENLARGED

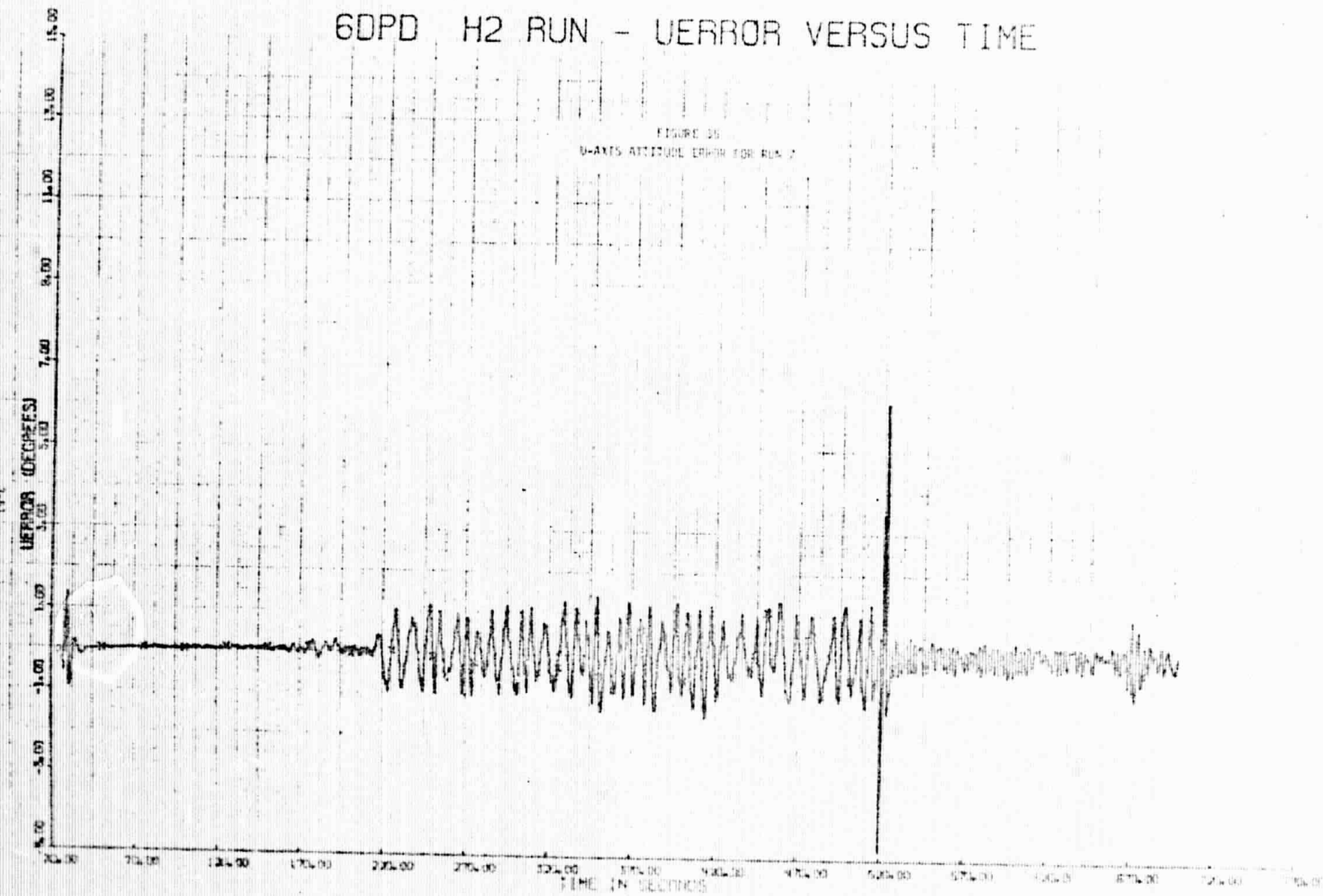


FIGURE 35
U-AXIS ATTITUDE ERROR FOR RUN 2

6DPD H2 RUN - VERROR VERSUS TIME

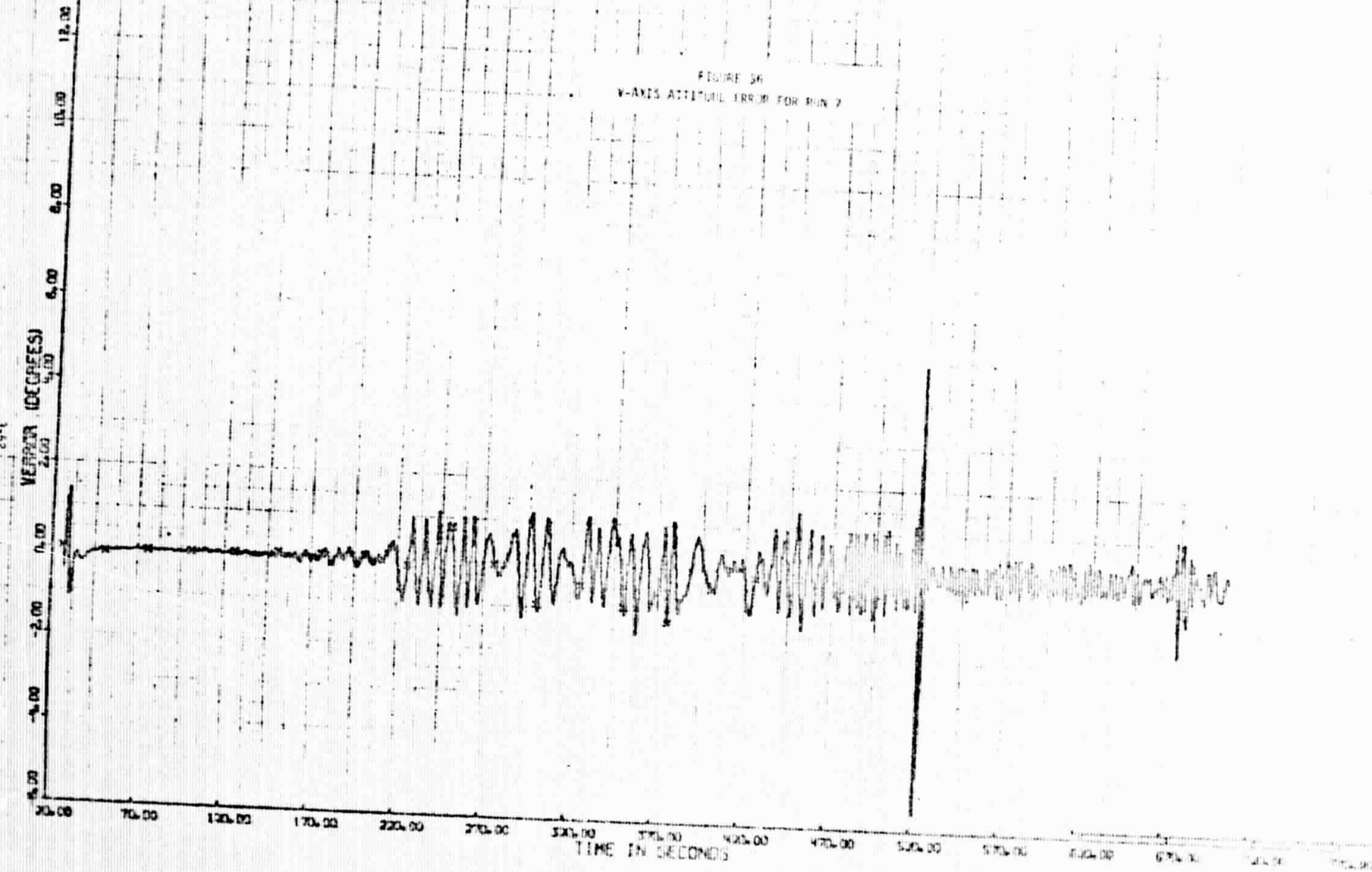


FIGURE 56
V-AXIS ATTITUDE ERROR FOR RUN 7

6DPD H2 RUN - OMEGAU VFRSUS TIME

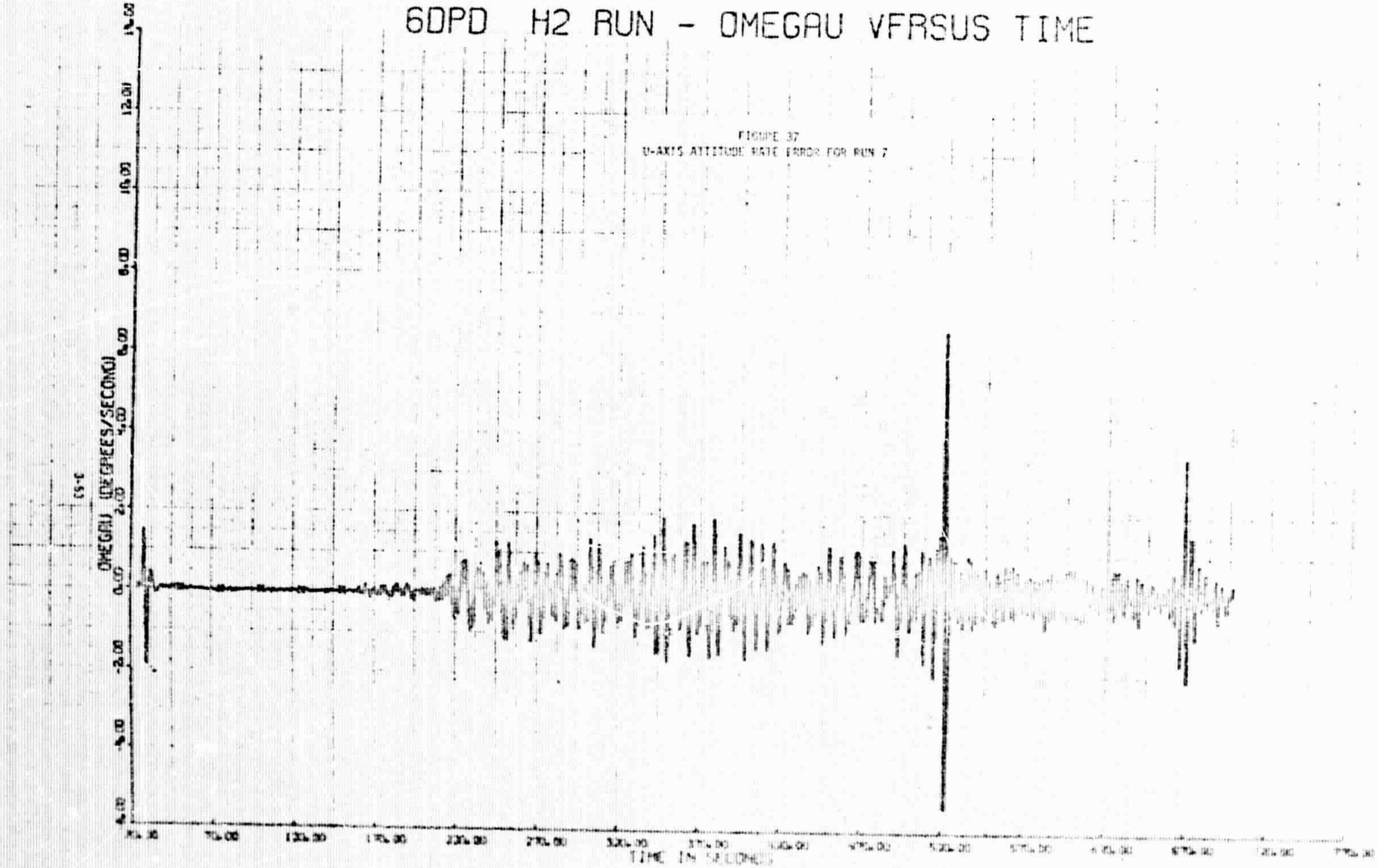


FIGURE 37
U-AXIS ATTITUDE RATE ERROR FOR RUN 7

6DPD H2 RUN - OMEGAV VERSUS TIME

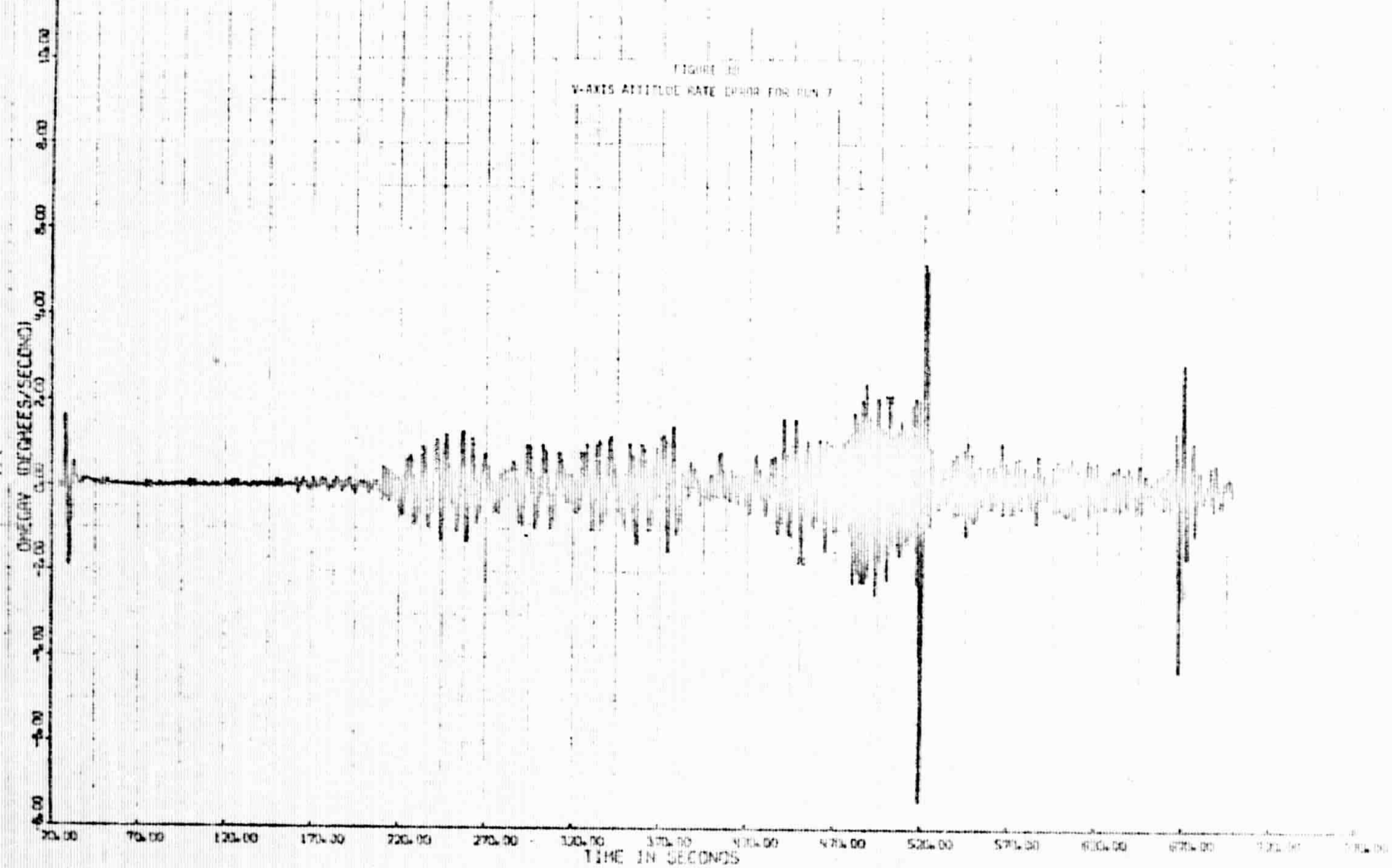


FIGURE 30
V-AXIS ATTITUDE RATE ERROR FOR RUN 7

SDPD H2 RUN - THRUST (ENVIRONMENTS) VERSUS TIME

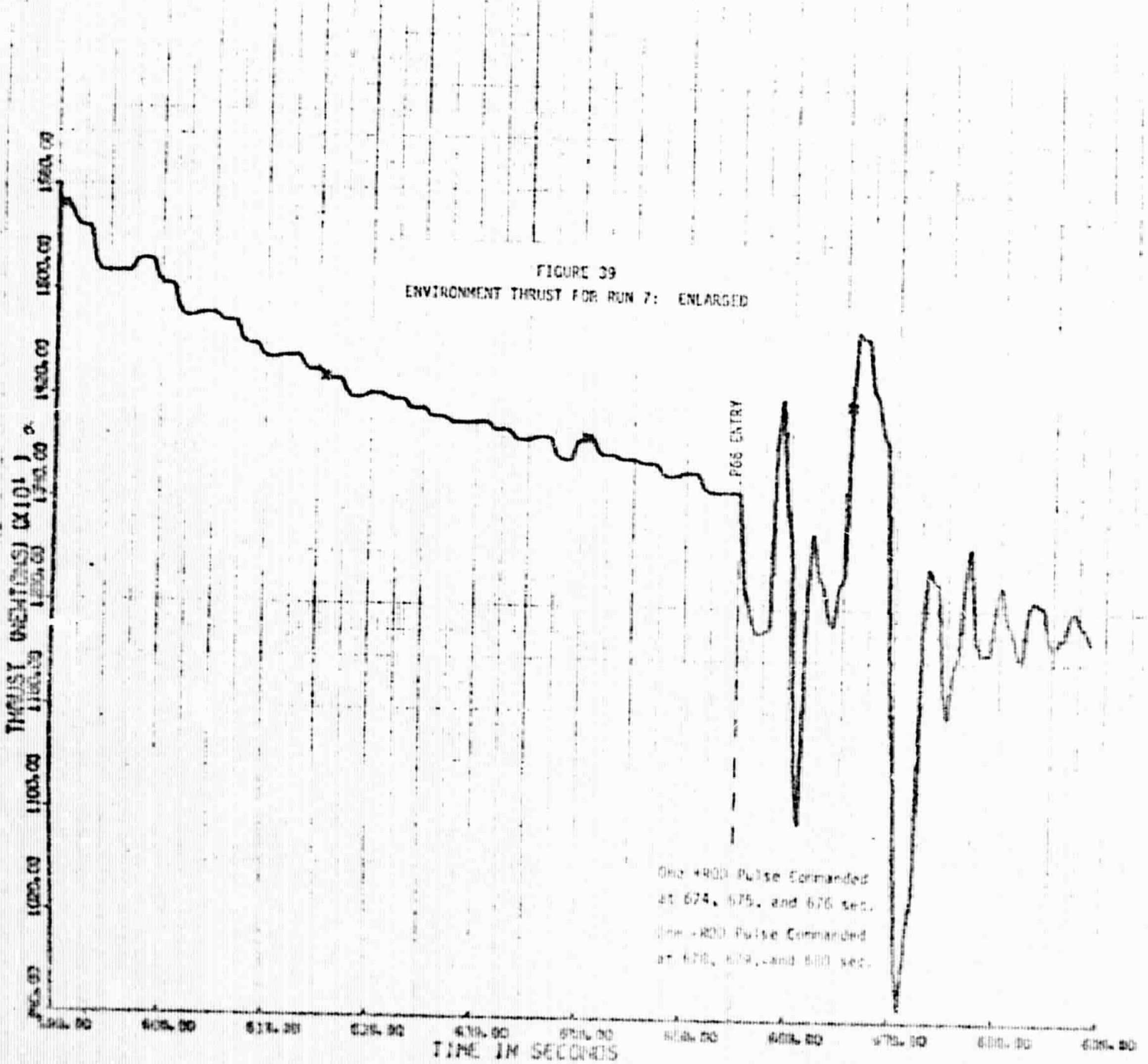


FIGURE 39
ENVIRONMENT THRUST FOR RUN 7: ENLARGED

4. CONCLUSIONS

On the basis of the simulation results the following conclusions can be drawn:

(a) The modifications introduced in the GDPD functional simulator update and improve the program. In particular, the transient behavior of the thrust oscillation under nominal conditions in P66 is slightly improved. No unacceptable control/guidance/slosh interactions result from the program modifications under the test conditions.

(b) A stringent ROD exercise in P66 under otherwise nominal conditions causes large oscillations in thrust. The thrust oscillations do not exhibit a monotonic decay.

(c) The removal of nonlinearity from the Throttle Command Computation, if effected only during P66, has been shown to improve the thrust oscillations problem even under a stringent ROD exercise. However, the improvement costs about a pound of RCS propellant.

Assuming that the small difference between the lunar descent trajectories of Apollo 13 and Apollo 14 [20] does not affect the results qualitatively, it appears that the thrust oscillations in P66 still remain a problem. The last conclusion seems to offer a promising means of attenuating the severity of the thrust oscillation.
It should be emphasized that to effect the improvement suggested by this conclusion, the program change required in the Throttle Command Routine is quite simple.

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4. H. W. Tindall, Jr., "Status Report on 'P66' Fix," MSC Memorandum No. 70-PA-T-13, 10 Feburary 1970.

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7. J. A. Sorensen, "Linear Stability Analysis of LM Rate-of-Descent Guidance Equations, Case 310," Bellcomm Inc. Memorandum No. B70-06074, 25 June 1970.

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