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THE SEA SWIFT EXPERIMENTS OCTOBER 1974.

PART I

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PART I

THE SEA SWIFT EXPERIMENTS,
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Claes Källström

1. INTRODUCTION

The purpose of the experiments was to investigate if an adaptive autopilot based on a self-tuning regulator could keep the ship on a straight course and perform suitable yaws in different weather conditions. Comparative experiments performed with Kockums' PID-regulator were also recorded. Extensive computer simulations had preceded the experiments. Some simulation results are reported in Aspernäs and Foisack (1975). Preliminary full scale experiments on a sistership, T/T Sea Scout, are described in Källström (1974).

The ship, T/T Sea Swift, is a 255 000 tdw oil tanker built for the Salén Group by Kockums Mekaniska Verkstads AB. It is 329 m long, has a beam of 52 m and has a cargo capacity of 339 000 m^3.

The experiments were performed during a voyage from Dubai via Jabal Dhanna (Abu Dhabi) and Kharg Island (Iran) to Cape Town between 1974-10-05 and 1974-10-24. When the tanker left Jabal Dhanna on 1974-10-08, the load was 105 000 long ton. At the departure from Kharg Island on 1974-10-10 the ship was fully loaded, which corresponds to 251 000 long ton. The trim of the ship was adjusted somewhat on 1974-10-14 and because of the decrease of bunker oil the draught was continuously changed about 2 cm per day. The wind varied from calm to strong gale during the voyage.

The adaptive autopilot was implemented as Fortran subroutines on the process computer Kongsberg SM 306, which is a standard equipment. A special paper tape punch was installed to record the experiments.

Forty-six experiments A1 - A45 of straight course keeping by the adaptive autopilot were performed. Notice that there are two experiments A39A and A39B. The number of experiments of yawing by the adaptive autopilot was fifteen (B1 - B15). However, it was not possible to read the paper tape from one of these experiments, namely B8. Three comparative straight course keeping experiments (C1 - C3) and two yawing experiments (D1 - D2) performed by Kockums' PID-regulator were also recorded. Finally four experiments E1 - E4 for identification of the model of the ship were performed. All the seventy experiments are described in Appendix C. The notations used in this report are explained in Appendix A.

2. MEASUREMENT EQUIPMENT

Several measurement signals are usually available in the computer, and no special equipment, besides the paper tape punch, had to be installed to carry through the experiments. Following measurement signals were recorded (the variable names used in the computer programs and in Appendix C are given in brackets):

- Rudder servo position δ_s (DELTAS), scan cycle 1 s.
- Rudder angle δ (DELTA), scan cycle 1 s.
- Pitch angular velocity q (PP), scan cycle 1 s, measured by a rate gyro manufactured by AB ATEW.
- Number of propeller revolutions n (AN), scan cycle 1 s.
- Forward velocity u (U), scan cycle 3 s, measured by a doppler log, type Ametek Straza, with an accuracy of 0.02 knots.
- Sway velocity of bow v_1 (V1), scan cycle 3 s, measured by the same kind of device and with the same accuracy as the forward velocity.
- Sway velocity of stern v_2 (V2), scan cycle 3 s, measured by the same device and with the same accuracy as the forward velocity.
- Yaw angular velocity r (R), scan cycle 1 s, measured with an accuracy of about 0.005 deg/s by a rate gyro manufactured by AB ATEW.
- Course Ψ (PSI), scan cycle 1/3 s, measured by a Sperry gyro compass, and transformed by a synchro-digital converter with an accuracy of about 0.02°.

The rudder servo was calibrated in such a way that +10 V corresponded to $+42^{\circ}$ and -10 V corresponded to -42°. The measurements of the rudder servo position δ_s were uncertain. During some of the experiments, the measurement signal of the pitch angular velocity was defect. The distance from the centre of mass to the forward doppler log transmitter is 146.3 m and to the aft doppler log transmitter 133.5 m. The distance from the forward perpendicular to the centre of mass is 155.2 m. The doppler log transmitters were adjusted a couple of times during the voyage. Sometimes the measurements of the forward and sway velocities were misleading due to air-bubbles below the doppler log transmitters.

In this report the convention of the sign of the rudder angle is chosen in such a way that a positive rudder angle (starboard rudder) gives a positive yaw rate (starboard yaw).

3. THE ADAPTIVE AUTOPILOT

The autopilot consists of two regulators, one to keep the ship on the demanded course Ψ_{ref} and one yaw regulator to perform suitable course changes. The yaw angular velocity is always used in the yaw regulator and may also be used in the straight course keeping regulator. The measured yaw angular velocity r is often a noisy signal, and therefore three different possibilities are available in the autopilot dependent on the assigned value of IRR. If IRR = 1, then the yaw angular velocity $\hat{r}$, which is used in the autopilot, is equal to the measured yaw angular velocity, i.e.

$$\hat{r}(t) = r(t)$$

If IRR = 2, then a filtered signal $\hat{r}$ is used in the autopilot:

$$\hat{r}(t+1) = \hat{r}(t) + \left(\frac{1 - \alpha}{t} + \alpha\right)\left(r(t) - \hat{r}(t)\right), \quad t = 1, 2, 3, \ldots$$

$$\hat{r}(1) = 0$$

If e.g. $\alpha = 0$, then $\hat{r}$ is the equally weighted arithmetical mean of the measurements of r. The latest measurement has the weight one and all previous measurements the weight zero if $\alpha = 1$. Finally, if IRR = 3, then

$$\hat{r}(t) = \frac{\Psi(t) - \Psi(t-h)}{h}$$

i.e. the heading measurement but not the yaw angular velocity measurement is used.

3.1 The Straight Course Keeping Regulator.

A simple self-tuning regulator based on least squares identification and minimum variance control is used to keep the ship on straight course. The basic self-tuning regulator is described in Wittenmark (1973).

The following model of the ship is used by the self-tuning regulator:

$$
\begin{aligned}
&\left(\Psi(t) - \Psi_{ref}\right) + a_1\left(\Psi(t-k-1) - \Psi_{ref}\right) + \ldots + \\
&\quad + a_{NA}\left(\Psi(t-k-NA) - \Psi_{ref}\right) = \\
&\quad = \nabla\delta_c(t-k-1) + b_1\nabla\delta_c(t-k-2) + \ldots + \\
&\quad + b_{NB}\nabla\delta_c(t-k-NB-1) + \\
&\quad + c_1\bar{r}(t-k-1) + c_2\bar{r}(t-k-2) + \ldots + c_{NC}\bar{r}(t-k-NC) + \\
&\quad + \varepsilon(t) \qquad (3.1)
\end{aligned}
$$

Then the minimum variance control is given by:

$$
\begin{aligned}
\nabla\delta_c(t) &= a_1\left(\Psi(t) - \Psi_{ref}\right) + \ldots + a_{NA}\left(\Psi(t-NA+1) - \Psi_{ref}\right) - \\
&\quad - b_1\nabla\delta_c(t-1) - \ldots - b_{NB}\nabla\delta_c(t-NB) - \\
&\quad - c_1\bar{r}(t) - \ldots - c_{NC}\bar{r}(t-NC+1) \qquad (3.2)
\end{aligned}
$$

where

$$\nabla\delta_c(t) = \delta_c(t) - \delta_c(t-1)$$

and δ_c is the rudder command. If the assigned value of IRDIF is equal to zero, then

$\bar{r}(t) = \hat{r}(t)$

but if IRDIF = 1, then

$\bar{r}(t) = \hat{r}(t) - \hat{r}(t-1)$

The value of NC may be zero, which means that no feedforward signal is used.

The executed rudder command δ_e is usually equal to δ_c. If, however, the rudder limit is active, then δ_e may be different from δ_c, which is indicated from another subroutine by putting IDELC = = -1.

A moving average $\bar{\delta}_e$ of the executed rudder command δ_e is computed during straight course keeping to be used in the yaw regulator:

$$\bar{\delta}_e(t+1) = \bar{\delta}_e(t) + \left(\frac{1-\beta}{t} + \beta\right)\left(\delta_e(t) - \bar{\delta}_e(t)\right), \quad t = 1, 2, 3, \ldots$$

$$\bar{\delta}_e(1) = 0$$

The value of β was equal to 0.05 during all the experiments.

Two different initial regulator parameter sets can be used, dependent on the actual number of propeller revolutions n. If n is greater than AN0 then high speed parameter values are provided, otherwise low speed parameter values are used.

3.2. The Yaw Regulator.

A yaw consists of three phases, namely the initial phase (phase 1), the phase of constant yaw rate (phase 2) and the terminating phase (phase 3). If, however, the demanded course change

$\Delta\Psi_{ref}$ is small, it may be suitable only to change the reference course Ψ_{ref} in the straight course keeping regulator and skip the yaw regulator. This is done in the autopilot if

$$\Delta\Psi_{ref} \leq \Psi_{max}$$

The purpose of the initial phase of the yaw is to reach the demanded yaw rate r_{ref}. In the yaw regulator this is performed by a modified P-regulator:

$$\delta_c(t) = - k_1\left(\hat{r}(t) - r_{ref}\right) + \bar{\delta}_e + c_1 r_{ref} \tag{3.3}$$

The phase of constant yaw rate is started when the difference between r_{ref} and $\hat{r}(t)$ is less than ε_1 or when the initial phase has been going on for more than T_1 s.

The same kind of self-tuning regulator, as is used in the straight course keeping regulator, performs the constant yaw rate keeping. The following model is used:

$$\begin{aligned}\left(\hat{r}(t) - r_{ref}\right) &+ a_1'\left(\hat{r}(t-k_y-1) - r_{ref}\right) + \ldots + \\ &+ a_{NAY}'\left(\hat{r}(t-k_y-NAY) - r_{ref}\right) = \\ &= \nabla\delta_c(t-k_y-1) + b_1'\nabla\delta_c(t-k_y-2) + \ldots + \\ &+ b_{NBY}'\nabla\delta_c(t-k_y-NBY-1) + \varepsilon(t)\end{aligned} \tag{3.4}$$

The minimum variance control is given by:

$$\begin{aligned}\nabla\delta_c(t) = a_1'\left(\hat{r}(t) - r_{ref}\right) + \ldots + a_{NAY}'\left(\hat{r}(t-NAY+1) - r_{ref}\right) - \\ - b_1'\nabla\delta_c(t-1) - \ldots - b_{NBY}'\nabla\delta_c(t-NBY)\end{aligned} \tag{3.5}$$

If, during the phase of constant yaw rate, the actual value of $\hat{r}(t)$ has a sign different from r_{ref} and if

$$|\hat{r}(t)| > \varepsilon_2$$

then the initial phase is started again.

The terminatting phase is always initialized when $\Psi(t) - \Psi_{ref}$ is less than zero and

$$-c_2\hat{r}(t) \leq \Psi(t) - \Psi_{ref}$$

or when $\Psi(t) - \Psi_{ref}$ is greater than zero and

$$-c_2\hat{r}(t) \geq \Psi(t) - \Psi_{ref}$$

The purpose of the terminating phase is to stop the yaw in such a way that the difference between the actual course $\Psi(t)$ and the demanded course Ψ_{ref} becomes as small as possible. This is performed by a modified PD-regulator:

$$\delta_c(t) = - k_2\left(\Psi(t) - \Psi_{ref}\right) - k_3\hat{r}(t) + \gamma \tag{3.6}$$

where $\gamma = \bar{\delta}_e$ if the phase of constant yaw rate has been going on for less than T_2 s, otherwise $\gamma = 0$.

The yaw is always terminated, irrespective of the phase, when

$$|\Psi(t) - \Psi_{ref}| \leq \Psi^*$$

If the terminating phase has continued for more than T_3 s, the yaw is also assumed to be over.

It is possible to change both Ψ_{ref} and r_{ref} during a yaw. Problems only arise when Ψ_{ref} is changed and the terminating phase is going on. In this case, if

$$|\Delta\Psi_{ref}| > \Psi^{**} \tag{3.7}$$

where $\Delta\Psi_{ref}$ is the new course change, the initial phase is started again. If the condition (3.7) is not true, no changes are made.

As in the straight course keeping regulator, there are two sets of yaw regulator parameters corresponding to high and low speed.

4. COMPUTER PROGRAMS

The adaptive autopilot was implemented as two Fortran subroutines AUTP1 and STURE in the standard real time task STEER, which is executed every second. See Fig. 4.1. Subroutine STURE contains the basic self-tuning regulator, and AUTP1 is the administration subroutine, which calls STURE. Listings of the two Fortran subroutines are given in Appendix B.

A program error in subroutine AUTP1 affected the experiments B1 - B7. The Fortran statement labelled 512 was during these experiments incorrectly

```
512   P(L)=0.
```

instead of

```
512   PY(L)=0.
```

The program error caused the off-diagonal elements of the covariance matrix P for the straight course regulator parameters to be put zero instead of the off-diagonal elements of PY for the yaw regulator parameters, when phase 2 of the yaw regulator was initiated. This error affected both the straight course keeping and the yawing, but only during experiments B1 - B7.

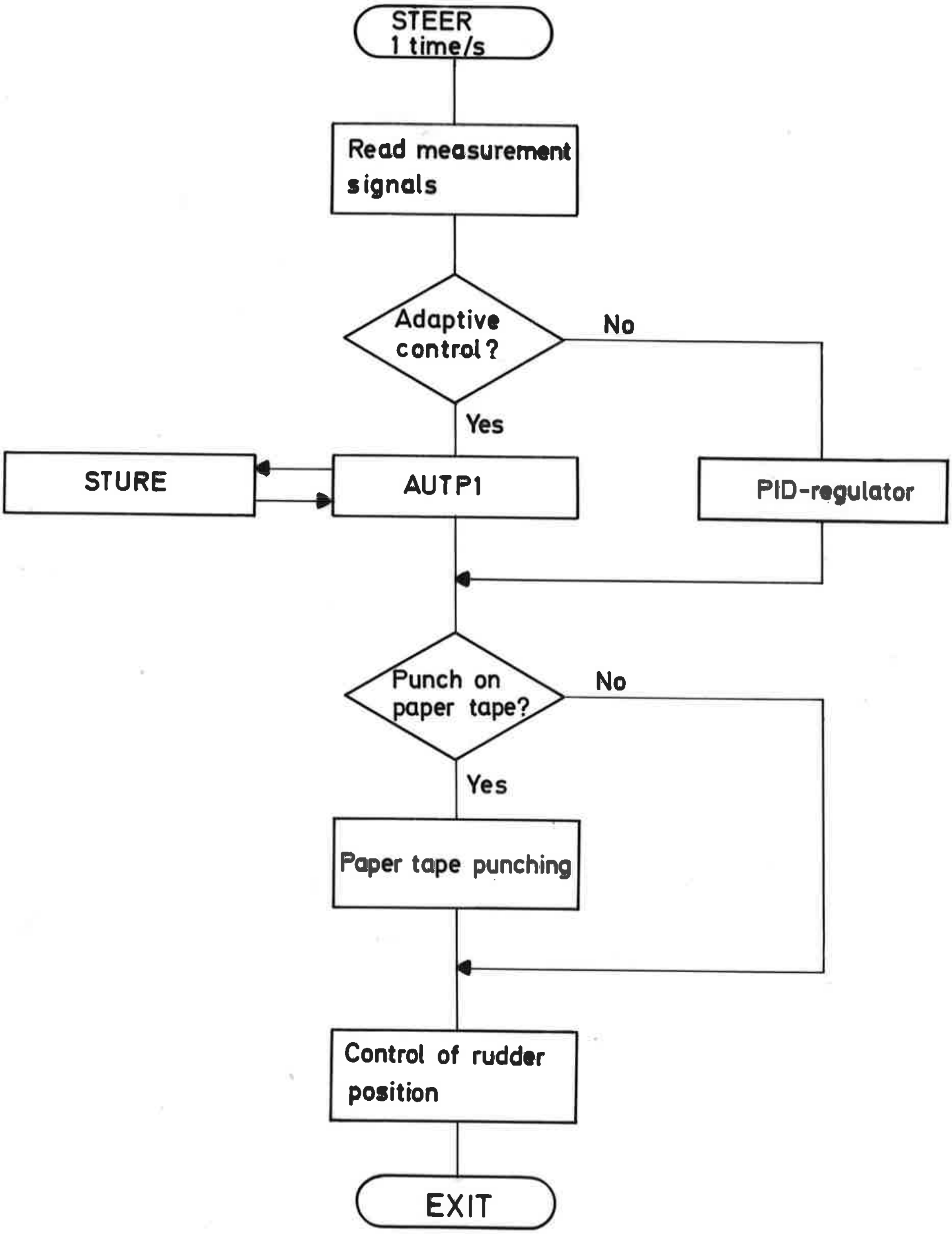

Fig. 4.1 - Flow chart of the real time program STEER.

5. DISCUSSION OF THE EXPERIMENTS

The experiments are described in Appendix C, where also plots of the measurements are shown. A summary of the experiments is given in the Tables C.1 - C.6 in the beginning of Appendix C.

During the comparative experiments, when the ship was controlled by Kockums' autopilot, the following discrete PID-regulator was used:

$$\delta_c(kT_s) = - k_P\left(\Psi(kT_s) - \Psi_{ref}\right) - k_D r(kT_s) - - k_I T_s \sum_{n=0}^{k} \left(\Psi(nT_s) - \Psi_{ref}\right) \qquad k = 0, 1, 2, \ldots \qquad (5.1)$$

The same regulator performed both straight course keeping and yawing, but the parameter values and the sampling interval T_s were changed.

5.1. The Straight Course Keeping Experiments.

To make it possible to compare the steering quality of different regulators, two performance indices are now being introduced:

$$V_1 = \frac{1}{\tau} \int_0^{\tau} \left[\left(\Psi(t) - \Psi_{ref}\right)^2 + \lambda \delta^2(t) \right] dt$$

$$(5.2)$$

$$V_2 = \frac{1}{\tau} \int_0^{\tau} \left[\left(\Psi(t) - \Psi_{ref}\right)^2 + \lambda \left(\delta(t) - \bar{\delta}\right)^2 \right] dt$$

where $\bar{\delta}$ is the mean value of $\delta(t)$ and where the weighting factor λ always is assigned the value 0.1. The duration of the experiment is denoted τ. Because only discrete measurements are considered, the two performance indices are approximated by:

$$V_1 = \frac{1}{N}\sum_{n=0}^{N-1}\left[\left(\Psi(nT_s) - \Psi_{ref}\right)^2 + \lambda\delta^2(nT_s)\right]$$

$$V_2 = \frac{1}{N}\sum_{n=0}^{N-1}\left[\left(\Psi(nT_s) - \Psi_{ref}\right)^2 + \lambda\left(\delta(nT_s) - \bar{\delta}\right)^2\right] \qquad (5.3)$$

where T_s is the sampling interval and $NT_s = \tau$. Notice the following relation between the two performance indices

$$V_1 = V_2 + \lambda\bar{\delta}^2 \qquad (5.4)$$

When the first performance index is used, the mean course error is weighted against the mean rudder angle. A regulator is usually required to keep the correct course in average as a constraint. A regulator without this constraint may achieve a less value of V_1, and this would not be desirable. The second performance index does not consider the mean rudder angle, which also is an advantage when steering experiments performed during different weather conditions are to be compared. When different experiments are regarded in the following, V_2 is considered more important than V_1, but also mean values and standard deviations of $\Psi - \Psi_{ref}$ and δ are used.

A systematic discussion of the experiments of straight course keeping by the adaptive autopilot will not be performed. The experiments are summarized in Tables C.1 and C.2. Two preliminary experiments A1 and A2 were carried through mainly to check the computer programs. The experiments A3 - A5 show the ability of the adaptive autopilot to perform a good steering in shallow water. See Table 5.1.

Experiment	Rel. wind direction	Wind velocity [m/s]	Regulator structure							δ		$\Psi - \Psi_{ref}$		V_1	V_2
			NA	NB	NC	k	T_s [s]	IRDIF	IRR	Mean value [deg]	Std. dev. [deg]	Mean value [deg]	Std. dev. [deg]		
A3	1	1-1.5	3	1	1	4	15	0	1	-0.04	1.03	0.071	0.182	0.144	0.144
A4	2	1-1.5	3	1	1	4	15	0	1	0.40	1.15	0.034	0.121	0.164	0.148
A5	-	0-0.5	3	1	1	4	20	0	1	-0.76	0.86	0.002	0.126	0.160	0.102

Table 5.1 - Straight course keeping by the adaptive autopilot in shallow water. An explanation of the relative wind direction is given in Appendix A. The water depths were 38 - 40 m (A3), 50 - 60 m (A4) and 60 - 70 m (A5). The exponential forgetting factor RL was equal to 0.98.

Different values of the number of pure time-delays k, the sampling interval T_s and the parameter IRDIF are tested in experiments A5 - A17. See Table 5.2. Notice that experiments A11 and A14 are omitted, the first one due to a main engine trip, which spoiled the experiment, and the second one since the experiment only lasted for 8 min.

From experiments A5 and A6 it can be concluded that a regulator with IRDIF = 0 is preferable compared to one with IRDIF = 1. Experiments A5 and A7 - A9 show that k = 4 is optimal when $T_s =$ $= 20$ s, i.e. a course error is expected to be eliminated after $(k+1)T_s = 100$ s. The wind speed was higher during experiment A7 when k = 3, which may indicate that k = 3 also is a good choice. From experiments A10, A12, A13 and A15 it can be concluded that k = 5 is optimal when $T_s = 15$ s, i.e. a course error is expected to be eliminated after 90 s. Notice, however, that the wind speed was lower during experiment A10 (k = 5) than during the other experiments. Experiments A16 and A17 show that k = 6 gives a higher steering quality than k = 8, when $T_s = 10$ s. If the optimal experiments when $T_s = 20$, 15, 10 s (A5, A10, A16) are compared, it can be concluded that $T_s = 15$ s (k = 5) is the best choice. Only two experiments with $T_s = 10$ s were performed, because such a short sampling interval wears the rudder machine and is not suitable by that reason. In the remaining experiments, with two exceptions, the values k = 5, $T_s = 15$, and IRDIF = 0 always will be used.

The experiments A18 - A27, where IRR, RL, NA, NB and NC are varied, are summarized in Table 5.3. Experiment A20 is omitted because of the bad initial performance of the adaptive autopilot.

Experiments A18 and A19 show that there is no use of filtering (IRR = 2) the yaw rate signal r. The performance of the adaptive autopilot does not change significantly when the exponential forgetting factor RL is varied, which can be concluded from experiments A21 - A23. When RL = 0.97, 0.98 or 0.99 the latest 20, 30 or 60 min., respectively, is remembered in the regulator. From the plot of the regulator parameters obtained during experiment

Experiment	Rel. wind direction	Wind velocity [m/s]	Regulator structure							δ		$\Psi - \Psi_{ref}$		V_1	V_2
			NA	NB	NC	k	T_s [s]	IRDIF	IRR	Mean value [deg]	Std. dev. [deg]	Mean value [deg]	Std. dev. [deg]		
A5	-	0-0.5	3	1	1	4	20	0	1	-0.76	0.86	0.002	0.126	0.160	0.102
A6	-	0-0.5	3	1	1	4	20	1	1	0.60	1.59	-0.036	0.200	0.330	0.294
A7	1	2-3.5	3	1	1	3	20	0	1	0.32	1.04	-0.025	0.200	0.159	0.149
A8	1	1-1.5	3	1	1	2	20	0	1	1.03	1.91	-0.062	0.292	0.560	0.454
A9	1	1-1.5	3	1	1	5	20	0	1	0.54	1.36	-0.080	0.206	0.263	0.234
A10	-	1-1.5	3	1	1	5	15	0	1	0.36	0.86	-0.028	0.101	0.098	0.085
A12	1	2-5.5	3	1	1	4	15	0	1	0.92	1.10	-0.017	0.168	0.234	0.150
A13	2	4-5.5	3	1	1	3	15	0	1	0.84	1.23	-0.069	0.173	0.257	0.186
A15	1	2-3.5	3	1	1	6	15	0	1	5.23	1.84	0.029	0.356	3.201	0.466
A16	1	1-1.5	3	1	1	6	10	0	1	1.46	1.41	-0.087	0.256	0.485	0.272
A17	1	1-1.5	3	1	1	8	10	0	1	1.21	1.98	-0.017	0.544	0.835	0.688

Table 5.2 - Straight course keeping by the adaptive autopilot. An explanation of the relative wind direction is given in Appendix A. The water was deep except during experiment A5, when the depth was 60 - 70 m. The exponential forgetting factor RL was equal to 0.98.

Experiment	Rel. wind direction	Wind velocity [m/s]	Regulator structure							δ		$\Psi - \Psi_{ref}$		V_1	V_2
			NA	NB	NC	k	T_s [s]	IRDIF	IRR	Mean value [deg]	Std. dev. [deg]	Mean value [deg]	Std. dev. [deg]		
A18	1	2-3.5	3	1	1	5	15	0	1	-1.06	1.87	-0.059	0.167	0.493	0.381
A19	1	2-3.5	3	1	1	5	15	0	2	-0.23	1.86	0.054	0.247	0.415	0.410
A21	1	2-3.5	3	1	1	5	15	0	1	-0.22	0.91	-0.122	0.207	0.145	0.141
A22	1	2-3.5	3	1	1	5	15	0	1	-0.17	0.85	-0.091	0.217	0.131	0.128
A23	1	2-3.5	3	1	1	5	15	0	1	-0.40	0.91	-0.034	0.167	0.128	0.112
A24	1	2-3.5	2	1	1	5	15	0	1	0.29	1.78	-0.510	0.555	0.893	0.885
A25	1	2-3.5	3	2	1	5	15	0	1	0.21	1.10	-0.003	0.171	0.155	0.150
A26	1	4-5.5	3	2	2	5	15	0	1	-0.34	0.89	-0.001	0.140	0.110	0.099
A27	1	2-5.5	4	1	1	5	15	0	1	0.17	0.74	0.005	0.153	0.081	0.078

Table 5.3 - Straight course keeping by the adaptive autopilot. An explanation of the relative wind direction is given in Appendix A. α was equal to 0.2 during experiment A19. The exponential forgetting factor RL was equal to 0.98, except during experiments A22 (RL = 0.97) and A23 (RL = 0.99).

A22 (RL = 0.97), it can be concluded that a time horizon of 20 min probably is too short. Further on RL will be chosen equal to 0.99 in the standard regulator. Experiments A21, A24 and A27 show that NA = 3 is preferable to NA = 2 and that NA = = 4 is slightly better than NA = 3. From experiments A21, A25 and A26 it can be concluded that a slightly better steering performance is obtained if NB and NC both are increased from 1 to 2. Too many regulator parameters, however, will give uncertain estimates and this has to be considered.

The yaw rate signal r is not used by the adaptive autopilot during experiments A28 - A36 (see Table 5.4).

From experiments A28, A29, A34 and A35 it can be concluded that a regulator with k = 4, T_s = 20 s is slightly better than one with k = 5, T_s = 15 s. However, during some not recorded experiments, the regulator with k = 4, T_s = 20 s behaved peculiarly now and then for a short period in such a way that large rudder angles were requested without any reason. Experiments A29, A30 and A31 show that NB = 2 is preferable to NB = 1 and that NA = 4 is slightly better than NA = 3. Use of the yaw rate estimate as a feedforward signal may decrease the value of V_2 according to experiments A32, A33 and A35.

Comparable experiments showing how much the steering quality is increased when the yaw rate r is used as a feedforward signal are difficult to find. If experiment A36 is compared to experiment A23 (Table 5.3), and the difference in wind speed is considered, the use of r as a feedforward signal does not seem to be particularly important. This fact is not surprising, since the regulator contains a model of the ship and the yaw rate r(t) is not that important to eliminate the course error at the time t + 90 s.

A standard regulator is now designed based on the preceding discussions: NA = 3, NB = 2, NC = 0, k = 5, T_s = 15 s, RL = = 0.99. This regulator was tested during varying weather conditions and in connection with the Sailmaster and the Course

Ex-peri-ment	Rel. wind direc-tion	Wind velo-city [m/s]	Regulator structure							δ		$\Psi - \Psi_{ref}$		V_1	V_2
			NA	NB	NC	k	T_s [s]	IRDIF	IRR	Mean value [deg]	Std. dev. [deg]	Mean value [deg]	Std. dev. [deg]		
A28	1	4-8	3	2	0	4	20	-	-	1.55	0.95	0.033	0.226	0.383	0.142
A29	8	4-8	3	2	0	5	15	-	-	1.48	1.03	0.001	0.260	0.393	0.174
A30	1	4-8	3	1	0	5	15	-	-	1.38	1.37	-0.024	0.253	0.443	0.252
A31	8	4-8	4	2	0	5	15	-	-	1.57	0.91	-0.063	0.171	0.363	0.116
A32	7	6-8	3	2	0	5	15	-	-	1.65	2.01	-0.003	0.405	0.840	0.568
A33	7	6-8	3	1	1	5	15	0	3	1.71	1.36	0.028	0.239	0.535	0.243
A34	7	6-8	3	2	0	4	20	-	-	1.89	1.54	-0.072	0.250	0.662	0.305
A35	7	6-8	3	2	0	5	15	-	-	1.75	1.66	0.001	0.283	0.662	0.356
A36	7	4-5.5	3	2	0	5	15	-	-	1.66	1.45	0.005	0.219	0.534	0.258

Table 5.4 - Straight course keeping by the adaptive autopilot. An explanation of the relative wind direction is given in Appendix A. h was equal to 5 during experiment A33. The exponential forgetting factor RL was equal to 0.98, except during experiments A32, A35 and A36 when RL was equal to 0.99. Only part 5 - 45 min of experiment A36 is considered.

correction (experiments A37 - A45, see Table C.1). The remarkably good steering quality during experiments A37, A38 and A39A, when the wind speed was 17 - 24 m/s (fresh to strong gale), should be pointed out. According to the captain of the ship, a conventional autopilot usually had to be switched off and replaced by manual control in such a bad weather. The resolution of the course measurement was only 1/6 deg during experiment A41. If this experiment is compared to experiment A40, it can be concluded that the decrease of steering quality is not significantly.

The standard regulator was used during experiments A35 - A45. Table C.2 shows that the parameter values of the adaptive autopilot vary remarkably, when the weather condition is changed. This effect was not discovered in the simulation study reported in Aspernäs and Foisack (1975).

Experiments of straight course keeping by Kockums' PID-regulator are summarized in Table C.4. Three of these experiments together with comparable adaptive autopilot experiments are shown in Table 5.5. Experiment A20 is omitted, since the initial performance of the adaptive autopilot was so bad that a comparison is impossible. Table 5.5 shows that the steering quality always is higher when the ship is controlled by the adaptive autopilot, if V_1 and V_2 are used to measure the quality. Notice that Kockums' PID-regulator uses the yaw rate signal r, which is not the case in the standard adaptive autopilot. The parameters of Kockums' PID-regulator were manually tuned before the experiments started. Conceivably a still more careful tuning of the parameters would increase the steering quality.

Ex-peri-ment	Rel. wind direc-tion	Wind velo-city [m/s.]	δ		$\Psi - \Psi_{ref}$		V_1	V_2
			Mean value [deg]	Stand. dev. [deg]	Mean value [deg]	Stand. dev. [deg]		
A29	8	4-8	1.48	1.03	0.001	0.260	0.393	0.174
C1	8	4-8	1.60	1.21	0.024	0.252	0.466	0.210
A35	7	6-8	1.75	1.66	0.001	0.283	0.662	0.356
C2	7	4-8	1.83	1.58	0.026	0.397	0.743	0.408
A36	7	4-5.5	1.66	1.45	0.005	0.219	0.534	0.258
A38	1	17-24	1.96	5.91	0.250	0.622	4.326	3.942
C3	1	17-24	1.31	6.11	0.203	1.510	6.226	6.055

Table 5.5 - Comparable straight course keeping experiments with Kockums' PID-regulator (C1, C2, C3) and the standard adaptive autopilot (A29, A35, A36, A38). Notice, however, that RL was equal to 0.98 during experiment A29. An explanation of the relative wind direction is given in Appendix A.

5.2. The Yawing Experiments.

Experiments of yawing by the adaptive autopilot are summarized in Table C.3. The preliminary experiments B1 - B7 were unfortunately disturbed by the program error in subroutin AUTP1. Experiments B9 and B10, where $k_y = 5$ and IRR = 1 (i.e. the measurements of the yaw rate were used), show that the yaw regulator has difficulties not to exceed the reference value r_{ref} too much. The estimated yaw rate (IRR = 3, h = 5) is used during experiments B11 - B15, since the standard straight course keeping regulator does not use the yaw rate measurements either. To keep the deviation from the reference value r_{ref} smaller, k_y was decreased to 3 during experiment B11. Since the reference value r_{ref} still was exceeded, k_y was assigned the value 2 during experiments B12 → B15. The parameters of the self-tuning regulator contained in the yaw regulator are tuned during experiments B12, B13 and B15.

If experiment B15 is compared to experiment D2 (see Table C.5), where the yaws are performed by Kockums' PID-regulator, it can be concluded that the course changes are not particularly smooth and the yaw rate still exceeds the reference value r_{ref} somewhat, when the adaptive autopilot is used. However, the terminating phase of Kockums' PID-regulator is not as good as would be desirable. Smaller course changes are performed during experiments B14 and D1 (see Table C.5), which may be compared. Both the adaptive autopilot and Kockums' PID-regulator performed well during these experiments.

5.3. The Experiments for Identification.

Three different kinds of identification experiments were performed, namely open loop experiments (E1, E4), closed loop experiment using additive rudder disturbances (E2) and closed loop experiment not using additive rudder disturbances but changing the gain of the feed-back (E3). The four recorded experiments E1-E4 are summarized in Table C.6. Fig. 5.1 explains the feed-back.

The rudder command δ_c is obtained as

$$\delta_c = - k_{id}(\Psi-\Psi_{ref}) + \delta_0$$

where δ_0 is the additive rudder disturbance signal, which may be assigned the values +DELAMP, -DELAMP and zero. An open loop experiment is now easily performed by setting $k_{id} = 0$. By assigning both k_{id} and DELAMP values different from zero, a closed loop experiment using additive rudder disturbances is obtained. Finally it is possible to skip the rudder disturbance signal if DELAMP = 0.

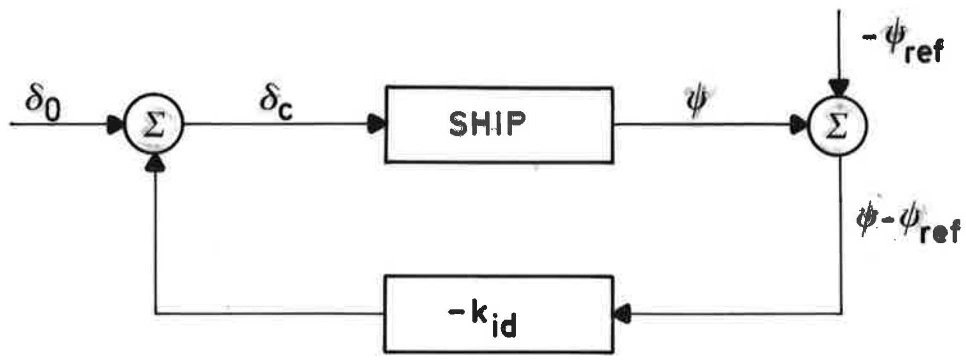

Fig. 5.1 - Proportional feedback from the course error used for identification experiments.

6. CONCLUSIONS

A standard adaptive straight course keeping regulator was designed after a number of experiments, where the regulator structure was varied systematically. The following standard regulator was chosen: NA = 3, NB = 2, NC = 0, k = 5, T_s = 15, RL = 0.99. If the yaw rate measurements are used as a feed-forward signal, the steering quality is slightly increased, but since it is a great advantage to be able to avoid a rate gyro, NC = 0 finally was chosen. The steering quality may also probably be increased by assigning NA the value 4. Another alternative, which may be considered, is to choose k = 4 and T_s = 20 s.

The standard regulator has proved to be able to perform a very good course keeping in different weather conditions. During some of the experiments, when the wind speed was 17 - 24 m/s (fresh to strong gale), the speed of the ship had to be decreased to about 5 knots, but still the steering quality of the standard regulator was very good. Comparative experiments have shown that the standard adaptive regulator is better than Kockums' PID-regulator, if the performance indices V_1 and V_2 are used to measure the steering quality. The great advantage of the adaptive regulator is, of course, that no manual tuning of the parameters has to be done. It was not possible to test the standard regulator in shallow water, but a slightly modified regulator proved to behave very good in such circumstances.

The adaptive yaw regulator has two unpleasant properties, namely that the reference value of the yaw rate usually is exceeded too much and that the course changes not are as smooth as desirable. Kockums' PID-regulator has proved to behave better in these two respects, and maybe a PID-regulator is to prefer during the phase of constant yaw rate in front of a self-tuning regulator.

During one experiment the adaptive autopilot proved to behave quite satisfactorily although the resolution of the course measurement only was 1/6 deg.

The adaptive autopilot was left behind on the tanker, and all assigned parameter values are shown in Table 6.1. The adaptive autopilot has been running for about half a year and according to the officers on board the behaviour is quite satisfactoring.

NA			3	a'_1		Initial values	-43.56
NB			2	a'_2			4.94
NC			0	a'_3			0.90
k	(K)		5	b'_1			1.30
T_s	(IREG)		15	b'_2			0.81
RL			0.99	PY(1,1)			500
IRDIF			0	PY(2,2)			500
IRR			3	PY(3,3)			500
α	(BR)		0.2	PY(4,4)			1
h	(IDPSI)		5	PY(5,5)			1
a_1		Initial values	-13.81	k_1	(AK1V)		40
a_2			21.69	k_2	(AK2V)		1.8
a_3			-8.54	k_3	(AK3V)		120
b_1			0.96	c_1	(C1V)		10
b_2			0.32	c_2	(C2V)		80
P(1,1)			10	ε_1	(EPS1V)		0.02
P(2,2)			25	ε_2	(EPS2V)		0.04
P(3,3)			10	Ψ^*	(PSISV)		0.15
P(4,4)			0.1	Ψ^{**}	(PSISSV)		1.5
P(5,5)			0.1	Ψ_{max}	(PSIMAV)		0.35
β	(BD)		0.05	T_1	(I1MV)		60
NAY			3	T_2	(I2MV)		300
NBY			2	T_3	(I3MV)		150
k_y	(KY)		2	ANO			30
IREGY			10	ISPM			600
RLY			0.95	INO			0

Table 6.1 - Final parameter values of the adaptive autopilot. The initial values of the off-diagonal elements of the covariance matrices P and PY are zero. The same values are used for high and low speed.

7. ACKNOWLEDGEMENTS

I would like to express my gratitude to the Salén Group for their willingness to allow experiments to be performed with their ship. I am particularly grateful to the captain of the Sea Swift, Mr. L. Sjöberg.

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8. REFERENCES

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APPENDIX A - NOTATIONS

Notations and variable names used in the computer programs (if twin symbols are used, this is indicated by the other symbol in brackets):

AKID	(k_{id})	parameter of P-regulator used for identification experiments
AK1V	(k_1)	yaw regulator parameter
AK2V	(k_2)	yaw regulator parameter
AK3V	(k_3)	yaw regulator parameter
AN	(n)	number of propeller revolutions
AN0		test value of the number of propeller revolutions to decide if low or high speed parameters are to be used
AVR		filtered yaw rate used if IRR = 2
a_i, i = 1, 2, ...		parameters of the self-tuning regulator for straight course keeping
a_i', i = 1, 2, ...		parameters of the self-tuning regulator for yawing
BD	(β)	parameter used when computing $\bar{\delta}_e$
BR	(α)	parameter used when computing the filtered yaw rate
b_i, i = 1, 2, ...		parameters of the self-tuning regulator for straight course keeping
b_i', i = 1, 2, ...		parameters of the self-tuning regulator for yawing
C1V	(c_1)	yaw regulator parameter
C2V	(c_2)	yaw regulator parameter
c_i, i = 1, 2, ...		parameters of the self-tuning regulator for straight course keeping

c_1	(C1V)	yaw regulator parameter
c_2	(C2V)	yaw regulator parameter
DELAMP		rudder amplitude used for identification experiments
DELCOC	(δ_c)	computed rudder command
DELCOM	(δ_e)	executed rudder command
DELTA	(δ)	rudder angle
DELTAS	(δ_s)	rudder servo position
DEL0	(δ_0)	additive rudder disturbance signal used for identification experiments
DEL1M	($\bar{\delta}_e$)	moving average value of δ_e
DPSIDT		yaw rate estimate used if IRR = 3
EPS1V	(ε_1)	yaw regulator parameter
EPS2V	(ε_2)	yaw regulator parameter
h	(IDPSI)	time increment used to compute DPSIDT
IDELC		variable to indicate if δ_c is limited
IDPSI	(h)	time increment used to compute DPSIDT
IN0		variable used in subroutine AUTP1
IRDIF		parameter of the straight course keeping regulator
IREG	(T_s)	sampling interval
IREGY		sampling interval of the yaw regulator
IRR		parameter of the adaptive autopilot to indicate if the yaw rate signal (IRR = 1), the filtered yaw rate (IRR = 2) or the estimated yaw rate (IRR = 3) is to be used
ISPM		variable used in subroutine AUTP1
I1MV	(T_1)	yaw regulator parameter
I2MV	(T_2)	yaw regulator parameter

I3MV	(T_3)	yaw regulator parameter
K	(k)	number of pure time-delays of the self-tuning regulator for straight course keeping
KY	(k_y)	number of pure time-delays of the self-tuning regulator for yawing
k	(K)	number of pure time-delays of the self-tuning regulator for straight course keeping
k_D		parameter of Kockums' PID-regulator
k_I		parameter of Kockums' PID-regulator
k_{id}	(AKID)	parameter of P-regulator used for identification experiments
k_P		parameter of Kockums' PID-regulator
k_y	(KY)	number of pure time-delays of the self-tuning regulator for yawing
k_1	(AK1V)	yaw regulator parameter
k_2	(AK2V)	yaw regulator parameter
k_3	(AK3V)	yaw regulator parameter
MODYAW		variable to indicate the phase of a yaw, initial phase (MODYAW = 1), phase of constant yaw rate (MODYAW = 2), terminating phase (MODYAW = 3) or if the straight course keeping regulator performs the yaw (MODYAW = = 4)
NA		number of a-parameters of the self-tuning regulator for straight course keeping
NAY		number of a'-parameters of the self-tuning regulator for yawing
NB		number of b-parameters of the self-tuning regulator for straight course keeping

NBY		number of b'-parameters of the self-tuning regulator for yawing
NC		number of c-parameters of the self-tuning regulator for straight course keeping
n	(AN)	number of propeller revolutions
P		covariance matrix of the self-tuning regulator for straight course keeping
PP	(q)	pitch angular velocity
PSI	(ψ)	course (heading angle)
PSIMAV	(ψ_{max})	yaw regulator parameter
PSIRFF	(ψ_{ref})	reference value of course
PSISSV	(ψ^{**})	yaw regulator parameter
PSISV	(ψ^{*})	yaw regulator parameter
PY		covariance matrix of the self-tuning regulator for yawing
q	(PP)	pitch angular velocity
R	(r)	yaw angular velocity (yaw rate)
RL		exponential forgetting factor of the self-tuning regulator for straight course keeping
RLY		exponential forgetting factor of the self-tuning regulator for yawing
RREF	(r_{ref})	reference value of yaw rate
r	(R)	yaw angular velocity (yaw rate)
$\hat{r}$		yaw angular velocity used by the adaptive autopilot
$\bar{r}$		feedforward signal used by the self-tuning regulator for straight course keeping
r_{ref}	(RREF)	reference value of yaw rate
T_s	(IREG)	sampling interval

T_1	(I1MV)	yaw regulator parameter
T_2	(I2MV)	yaw regulator parameter
T_3	(I3MV)	yaw regulator parameter
t		time
U	(u)	forward velocity
u	(U)	forward velocity
V1	(v_1)	sway velocity of bow
V2	(v_2)	sway velocity of stern
V_1		performance index
V_2		performance index
v_1	(V1)	sway velocity of bow
v_2	(V2)	sway velocity of stern
α	(BR)	parameter used when computing the filtered yaw rate
β	(BD)	parameter used when computing $\bar{\delta}_e$
δ	(DELTA)	rudder angle
$\bar{\delta}$		mean value of δ
δ_c	(DELCOC)	computed rudder command
δ_e	(DELCOM)	executed rudder command
$\bar{\delta}_e$	(DEL1M)	moving average value of δ_e
δ_s	(DELTAS)	rudder servo position
δ_0	(DEL0)	additive rudder disturbance signal used for identification experiments
ε		noise
ε_1	(EPS1V)	yaw regulator parameter
ε_2	(EPS2V)	yaw regulator parameter
λ		weighting factor of the performance indices V_1 and V_2

τ		experiment length
Ψ	(PSI)	course (heading angle)
ψ^*	(PSISV)	yaw regulator parameter
ψ^{**}	(PSISSV)	yaw regulator parameter
Ψ_{max}	(PSIMAV)	yaw regulator parameter
Ψ_{ref}	(PSIREF)	reference value of course

The wind direction related to the ship is explained in Fig. A.1.

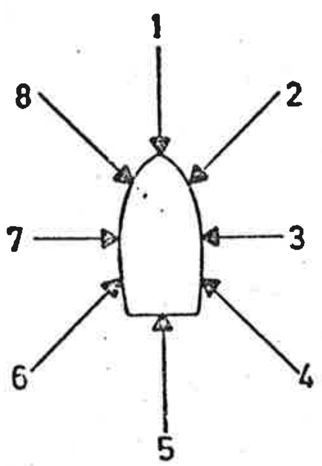


Fig. A.1 - Explanation of the relative wind direction.

APPENDIX B - PROGRAM LISTINGS

```
      SUBROUTINE AUTP1
C
C     AUTOPILOT FOR SHIP.
C
C     AUTHOR, C.KALLSTROM 1974-07-11.
C     REVISED, C.KALLSTROM 1974-10-01.
C
C     SUBROUTINE REQUIRED
C          STURE
C
      COMMON/DATA/ ITIME,IDELC,IYAW,MODYAW,ISTRD,IPORT,
     *   IFLAG,INAUT,IP,IPRINT,DELCOM,DELTAS,DELTA,V1,V2,
     *   R,PSI,U,DEL0,DELCOC,AVR,DPSIDT,PP,AN,RREF,PSIREF,
     *   TH(8),THY(6),THOL(8),POL(8),THOH(8),POH(8),
     *   THYOL(6),PYOL(6),THYOH(6),PYOH(6),
     *   AN0,BR,BD,B0,RL,AK1V(2),AK2V(2),AK3V(2),C1V(2),C2V(2),
     *   EPS1V(2),EPS2V(2),PSISV(2),PSISSV(2),PSIMAV(2),
     *   BOY,RLY,DELAMP,AKID,P(36),PY(21),DAT(35),DUM(8),
     *   STR,DEL1M,SL,SL1,STD,PSI0,PSIRF0,AK1,AK2,AK3,C1,C2,
     *   EPS1,EPS2,PSIS,PSISS,PSIMAX,RR,RREFF,DELY,DELY0,
     *   DELOLD,ROLD,DEL,
     *   ISPM,IN0,IDPSI,IDEXP,IRR,IREG,NA,NB,NC,K,IRDIF,
     *   I1MV(2),I2MV(2),I3MV(2),IREGY,NAY,NBY,KY,I4M,
     *   ISP,ISPP,ISPI,IDP,IR,IRY,I1,I2,I3,I4,I1M,I2M,I3M,
     *   NDAT,NN,NU1,NAB,NP,K1,NDAT1,N1,
     *   NDATY,NU1Y,NABY,NPY,K1Y,NDAT1Y,N1Y
C
C     COMPUTE ISPP.
C
      ISPP=2
      IF(AN-AN0) 2,3,3
2     ISPP=1
C
3     IF(INAUT) 7,4,7
C
4     IF(ISPP-ISP) 5,30,5
5     IF(ISPI-ISPM) 30,30,6
6     ISP=ISPP
      ISPI=-1
      IF(IN0) 16,16,10
C
7     MODYAW=0
      AVR=0.
      STR=1.-BR
      IDP=IDPSI
      PSI0=PSI
      DPSIDT=0.
      IRY=IREGY
      PSIRF0=PSIREF
      DELCOC=0.
      DEL1M=0.
      IDELC=1
      DELCOM=0.
      DEL=0.
      NU1Y=NAY+KY+2
      NABY=NAY+NBY
      NPY=NABY
      NDATY=NPY+3*KY+3
      K1Y=KY+1
      NDAT1Y=NDATY+1
      N1Y=NU1Y+KY
      IR=IREG
      NAB=NA+NB
```

```
      NP=NAB+NC
      K1=K+1
      NDAT=NP+3*K+3
      NN=NAB+2*K+3
      NU1=NA+K+2
      NDAT1=NDAT+1
      N1=NU1+K
      DELOLD=0.
      ROLD=0.
      STD=1.-BD
      ISTBD=0
      IPORT=0
      DEL0=0.
      I4=0
      ISPI=-1
      IF(INAUT) 8,8,9
8     IF(ISPP-ISP) 9,14,9
9     ISP=ISPP
C
C     INITIALIZE PARAMETERS TH.
C
10    DO 13 I=1,8
      IF(ISP-1) 11,11,12
11    TH(I)=THOL(I)
      GO TO 13
12    TH(I)=THOH(I)
13    CONTINUE
C
C     INITIALIZE VECTOR DAT.
C
14    SL=PSI-PSIREF
      IF(SL .LE. -180.) SL=SL+360.
      IF(SL .GT. 180.) SL=SL-360.
      J=NU1-1
      DO 600 I=1,J
600   DAT(I)=SL
      DO 15 I=NU1,35
15    DAT(I)=0.
C
C     INITIALIZE COVARIANCE MATRIX P.
C
16    DO 21 I=1,8
      DO 21 J=1,I
      L=I*(I-1)/2+J
      IF(I-J) 20,17,20
17    IF(ISP-1) 18,18,19
18    P(L)=POL(I)
      GO TO 21
19    P(L)=POH(I)
      GO TO 21
20    P(L)=0.
21    CONTINUE
C
      INAUT=0
C
30    IF(ISPI-ISPM) 31,31,32
31    ISPI=ISPI+1
C
32    IF(MODYAW .EQ. 4) MODYAW=0
C
C     COMPUTE AVERAGE VALUE OF R, AVR.
C
      AVR=AVR+(STR+BR)*(R-AVR)
      STR=(1.-BR)*STR/(1.-BR+STR)
```

```
C
C     COMPUTE DPSIDT.
C
      IF(IDP-IDPSI) 34,33,36
33    IDP=1
      SL=PSI-PSIO
      PSIO=PSI
      IF(SL .LE. -180.) SL=SL+360.
      IF(SL .GT. 180.) SL=SL-360.
      DPSIDI=SL/FLOAT(IDPSI)
      GO TO 36
34    IDP=IDP+1
C
C     IF IDEXP=1 OR 2, JUMP TO THE IDENTIFICATION EXPERIMENT PART.
C
36    IF(IDEXP) 40,40,140
C
C     YAW REGULATOR.
C
40    IF(IRY-IREGY) 130,41,140
41    IRY=1
      IF(IYAW) 44,140,42
C
42    I2=0
      AK1=AK1V(ISPP)
      AK2=AK2V(ISPP)
      AK3=AK3V(ISPP)
      C1=C1V(ISPP)
      C2=C2V(ISPP)
      EPS1=EPS1V(ISPP)
      EPS2=EPS2V(ISPP)
      I1M=I1MV(ISPP)
      I2M=I2MV(ISPP)
      I3M=I3MV(ISPP)
      PSIS=PSISV(ISPP)
      PSISS=PSISSV(ISPP)
      PSIMAX=PSIMAV(ISPP)
C
44    SL=PSIREF-PSIRFO
      PSIRFO=PSIREF
      IF(SL .LE. -180.) SL=SL+360.
      IF(SL .GT. 180.) SL=SL-360.
      IF(IYAW) 50,46,46
46    IF(ABS(SL) - PSIMAX) 48,48,50
48    MODYAW=4
      IYAW=0
      GO TO 140
C
50    SL1=PSI-PSIREF
      IF(SL1 .LE. -180.) SL1=SL1+360.
      IF(SL1 .GT. 180.) SL1=SL1-360.
      IF(ABS(SL1) - PSIS) 51,51,52
51    IF(IYAW) 127,129,129
C
52    IF(IRR-2) 54,56,58
54    RR=R
      GO TO 60
56    RR=AVR
      GO TO 60
58    RR=DPSIDT
C
60    IF(IYAW) 62,66,66
62    IF(MODYAW-3) 66,64,66
64    IF(ABS(SL)-PSISS) 122,122,65
```

```
65    IYAW=1
C
66    IF(SL1) 68,70,70
68    IF(SL1+C2*RR) 72,120,120
70    IF(SL1+C2*RR) 120,120,74
C
72    RREFF=RREF
      GO TO 75
74    RREFF=-RREF
C
75    IF(IYAW) 76,80,80
76    IF(MODYAW-2) 86,77,122
C
77    IF(SL1) 78,79,79
78    IF(SL1*(RR+EPS2)) 114,114,80
79    IF(SL1*(RR-EPS2)) 114,114,80
C
C     PHASE 1.
C
80    MODYAW=1
      IYAW=-1
      I1=-1
86    I1=I1+1
      IF(RREFF) 96,94,94
94    IF(RR-RREFF+EPS1) 98,110,110
96    IF(RR-RREFF-EPS1) 110,110,98
98    IF(I1*IREGY-I1M) 100,110,110
100   DELCOC=-AK1*(RR-RREFF)+DEL1M+C1*RREFF
      GO TO 126
C
C     PHASE 2.
C
110   MODYAW=2
      IYAW=-1
      I2=-1
      DELY=DELCOM
      DELYO=DELCOM
      DO 111 I=1,35
111   DAT(I)=0.
C
      DO 504 I=1,6
      IF(ISPP-1) 500,500,502
500   THY(I)=THYOL(I)
      GO TO 504
502   THY(I)=THYOH(I)
504   CONTINUE
C
      DO 514 I=1,6
      DO 514 J=1,I
      L=I*(I-1)/2+J
      IF(I-J) 512,506,512
506   IF(ISPP-1) 508,508,510
508   PY(L)=PYOL(I)
      GO TO 514
510   PY(L)=PYOH(I)
      GO TO 514
512   PY(L)=0.
514   CONTINUE
C
114   DAT(1)=RR-RREFF
      I2=I2+1
      IF(IDELC+1) 118,116,118
116   DELY=DELCOM
      DAT(NU1Y)=(DELY-DELYO)*BOY
```

```
C
118    CALL STURE(DAT,THY,PY,DUM,RLY,NAY,NABY,NPY,K1Y,
     *    NDATY,NDAT1Y,NU1Y,N1Y)
C
       DELCOC=DAT(NU1Y)/BOY+DELY
       DELYO=DELY
       DELY=DELCOC
       GO TO 126
C
C      PHASE 3.
C
120    MODYAW=3
       IYAW=-1
       I3=-1
122    I3=I3+1
       IF(I3*IREGY-I3M) 124,127,127
C
124    DELCOC=-AK2*SL1-AK3*RR
       IF(I2*IREGY - I2M) 125,125,126
125    DELCOC=DELCOC+DEL1M
C
126    DELCOM=DELCOC
       IDELC=1
       GO TO 140
C
127    J=NU1-1
       DO 700 I=1,J
700    DAT(I)=SL1
       DO 128 I=NU1,35
128    DAT(I)=0.
       DELOLD=DELCOM
       DEL=DELCOM
       ROLD=RR
       DELCOC=DELCOM
       IDELC=1
129    MODYAW=0
       IYAW=0
       GO TO 140
C
130    IRY=IRY+1
C
C      STRAIGHT COURSE REGULATOR.
C
140    IF(IR-IREG) 210,142,999
142    IR=1
       SL=PSI-PSIREF
       IF(SL .LE. -180.) SL=SL+360.
       IF(SL .GT. 180.) SL=SL-360.
       IF(IDEXP) 144,144,180
144    IF(IYAW) 999,146,999
146    IF(IRR-2) 148,150,152
148    RR=R
       GO TO 154
150    RR=AVR
       GO TO 154
152    RR=DPSIDT
C
154    DAT(1)=SL
       IF(NC) 168,168,162
162    IF(IRDIF) 166,166,164
164    DAT(NN)=RR-ROLD
       ROLD=RR
       GO TO 168
166    DAT(NN)=RR
```

```
168     IF(IDELC+1) 172,170,172
170     DEL=DELCOM
        DAT(NU1)=(DEL-DELOLD)*B0
C
172     CALL STORE(DAT,TH,P,DUM,RL,NA,NAB,NP,K1,NDAT,
       *   NDAT1,NU1,N1)
C
        DELCOC=DAT(NU1)/B0+DEL
        DELOLD=DEL
        DEL1M=DEL1M+(STD+BD)*(DEL-DEL1M)
        STD=(1.-BD)*STD/(1.-BD+STD)
        DEL=DELCOC
        GO TO 200
C
C       IDENTIFICATION EXPERIMENT PART.
C
180     IF(IDEXP-1) 181,181,192
181     IF(ISTBD+IPORT-1) 190,182,188
182     IF(ISTBD) 186,186,184
184     DEL0=DELAMP
        GO TO 190
C
186     DEL0=-DELAMP
        GO TO 190
188     DEL0=0.
190     ISTBD=0
        IPORT=0
C
        DELCOC=DEL0-AKID*SL
        GO TO 200
C
192     IF(I4-I4M) 194,196,198
194     I4=I4+1
        DELCOC=0.
        GO TO 200
C
196     DELCOC=DELAMP
        I4=I4+1
        GO TO 200
C
198     DELCOC=-DELCOC
C
200     DELCOM=DELCOC
        IDELC=1
        GO TO 999
C
210     IR=IR+1
C
999     RETURN
        END
```

```
      SUBROUTINE STURE(DAT,TH,P,DUM,RL,NA,NAB,NP,K1,NDAT,NDAT1,NU1,N1)
C
C     SELFTUNING REGULATOR BASED ON LEAST SQUARES IDENTIFICATION
C     AND MINIMUM VARIANCE CONTROL, ADMITS FEEDFORWARD AND
C     EXPLOITS SYMMETRY OF P.
C
C     AUTHOR, C.KALLSTROM 1974-07-04.
C     REVISED, C.KALLSTROM 1974-09-23.
C
C     THE ALGORITHM IS BASED ON THE MODEL
C
C     Y(T)+A(1)*Y(T-K-1)+...+A(NA)*Y(T-K-NA)=
C          B0*(U(T-K-1)+B(1)*U(T-K-2)+...+B(NB)*U(T-K-NB-1))+
C          C(1)*V(T-K-1)+C(2)*V(T-K-2)+...+C(NC)*V(T-K-NC)+EPS(T)
C
C     AT EACH STEP THE LEAST SQUARES ESTIMATES OF THE PARAMETERS
C     OF THE MODEL ARE COMPUTED. THE CONTROL VARIABLE U(T) TO
C     BE APPLIED AT TIME T IS THEN COMPUTED FROM
C
C     US(T)= AE(1)*Y(T)+...+AE(NA)*Y(T-NA+1)
C             -BE(1)*US(T-1)-...-BE(NB)*US(T-NB)
C             -CE(1)*V(T)-...-CE(NC)*V(T-NC+1)
C
C     WHERE AE,BE AND CE ARE THE PARAMETER ESTIMATES
C     AND US THE SCALED CONTROL SIGNAL I.E. US=B0*U
C
C     WHEN USING THE ALGORITHM THE PROCESS OUTPUT Y(T) AND THE
C     FEEDFORWARD SIGNAL V(T) ARE READ AT TIME T AND THE CONTROL
C     SIGNAL U(T) TO BE APPLIED AT TIME T IS THEN COMPUTED
C
C     DAT- VECTOR OF DIMENSION NA+NB+NC+3*K+3 CONTAINING
C         PROCESS OUTPUTS Y, SCALED CONTROL VARIABLES U
C         AND FEED FORWARD SIGNALS V ORGANIZED AS FOLLOWS
C     DAT(1)=Y(T)                            RETURNED AS Y(T)
C     DAT(2)=Y(T-1)                          RETURNED AS Y(T)
C     DAT(3)=Y(T-2)                          RETURNED AS Y(T-1)
C     .
C     DAT(NA+K+1)=Y(T-K-NA)                  RETURNED AS Y(T-K-NA+1)
C     DAT(NA+K+2)=US(T-1)                    RETURNED AS US(T)
C     DAT(NA+K+3)=US(T-2)                    RETURNED AS US(T-1)
C     .
C     DAT(NA+NB+2*K+2)=US(T-K-NB-1)          RETURNED AS US(T-K-NB)
C     DAT(NA+NB+2*K+3)=V(T)                  RETURNED AS US(T-K-NB-1)
C     DAT(NA+NB+2*K+4)=V(T-1)                RETURNED AS V(T)
C     .
C     DAT(NA+NB+NC+3*K+3)=V(T-K-NC)          RETURNED AS V(T-K-NC+1)
C
C
C     TH- VECTOR OF DIMENSION NP=NA+NB+NC CONTAINING THE PARAMETER
C        ESTIMATES ORGANIZED AS FOLLOWS
C     TH(1)=-AE(1)
C     TH(2)=-AE(2)
C     .
C     TH(NA)=-AE(NA)
C     TH(NA+1)=BE(1)
C     TH(NA+2)=BE(2)
C     .
C     TH(NA+NB)=BE(NB)
C     TH(NA+NB+1)=CE(1)
C     TH(NA+NB+2)=CE(2)
C     .
C     TH(NA+NB+NC)=CE(NC)
C
```

```
C
C       P- COVARIANCE MATRIX STORED AS FOLLOWS
C       P(1)=P(1,1)
C       P(2)=P(2,1)
C       P(3)=P(2,2)
C       .
C       P(I*(I-1)/2+J)=P(I,J)
C       .
C       P(NP*(NP+1)/2)=P(NP,NP)
C
C
C       DUM- DUMMY VECTOR OF DIMENSION NP
C       RL- BASE OF EXPONENTIAL WEIGHTING FACTOR
C       NA- NUMBER OF A-PARAMETERS  (MAX 8, MIN 0)
C          NB- NUMBER OF B-PARAMETERS  (MAX 8, MIN 0)
C          NC- NUMBER OF C-PARAMETERS  (MAX 8, MIN 0)
C          K -NUMBER OF TIME DELAYS IN THE MODEL  (MAX (32-NA-NB-NC)/3,
C               MIN 0)
C       NAB- NA+NB
C       NP- NA+NB+NC (MAX 8, MIN 1)
C       K1- K+1
C       NDAT- NP+3*K+3
C       NDAT1- NDAT+1
C       NU1- NA+K+2
C       N1- NU1+K
C
C       SUBROUTINE REQUIRED
C            NONE
C
        DIMENSION DAT(35),TH(8),P(36),DUM(8)
C
        RES=DAT(1)-DAT(N1)
        DENOM=1.
        DO 12 I=1,NP
        R=0.
        DO 10 J=1,NP
        L=I*(I-1)/2+J
        IF (J.GT.I) L=J*(J-1)/2+I
        M=K1+J
        IF (J.GT.NA) M=M+K1
        IF (J.GT.NAB) M=M+K1
10      R=R+P(L)*DAT(M)
        DUM(I)=R
        M=K1+I
        IF (I.GT.NA) M=M+K1
        IF (I.GT.NAB) M=M+K1
        DENOM=DENOM+R*DAT(M)
12      RES=RES-DAT(M)*TH(I)
C
        DO 20 I=1,NP
        R=DUM(I)/DENOM
        TH(I)=TH(I)+R*RES
        DO 20 J=1,I
        L=I*(I-1)/2+J
20      P(L)=(P(L)-R*DUM(J))/RL
C
        R=0.
        DO 30 I=1,NP
        L=I
        IF (I.GT.NA) L=L+K1
        IF (I.GT.NAB) L=L+K1
30      R=R-TH(I)*DAT(L)
C
        DO 32 I=2,NDAT
```

```
      L=NDAT1-I
32    DAT(L+1)=DAT(L)
      DAT(NU1)=R
C
      RETURN
      END
```

APPENDIX C - EXPERIMENTS

Plots from all the experiments are shown in this appendix. Experiments of straight course keeping by the adaptive autopilot are summarized in Tables C.1 and C.2. Yawing experiments performed by the same autopilot are shown in Table C.3. Notice that course changes also were performed during experiments A37 and A40 - A45. Experiments of straight course keeping and yawing by Kockums' PID-regulator are summarized in Tables C.4 and C.5, respectively. Notice that the ship was controlled by Kockums' PID-regulator during the first part of experiment A20, too. Finally Table C.6 shows the experiments for identification.

Experiment	Duration [min]	Draught Forward [m]	Draught Aft [m]	Rel. wind dir.	Wind velocity [m/s]	Regulator structure NA	NB	NC	K	IREG	IRDIF	IRR	DELTA Mean value [deg]	DELTA Std. dev. [deg]	PSI - PSIREF Mean value [deg]	PSI - PSIREF Std. dev. [deg]	Mean value of AN [rpm]	Mean value of U [knots]	V_1	V_2	Remarks
A1	20	10.9	10.9	1	1-3.5	3	1	1	4	15	0	3	2.35	1.86	-0.213	0.501	80.55	17.37	1.195	0.642	Depth 70 m.
A2	54	10.9	10.9	1	4-5.5	3	1	1	4	20	0	3	0.66	2.58	0.082	0.454	80.82	17.08	0.922	0.878	Depth 50-65 m Rudd.lim ±10°
A3	29	20.1	20.4	1	1-1.5	3	1	1	4	15	0	1	-0.04	1.03	0.071	0.182	80.19	14.00	0.144	0.144	Depth 38-40 m
A4	62	20.1	20.4	2	1-1.5	3	1	1	4	15	0	1	0.40	1.15	0.034	0.121	80.98	14.37	0.164	0.148	Depth 50-60 m
A5	46	20.1	20.4	-	0-0.5	3	1	1	4	20	0	1	-0.76	0.86	0.002	0.126	81.95	17.88	0.160	0.102	Depth 60-70 m
A6	40	20.1	20.4	-	0-0.5	3	1	1	4	20	1	1	0.60	1.59	-0.036	0.200	85.78	16.53	0.330	0.294	
A7	41	20.1	20.4	1	2-3.5	3	1	1	3	20	0	1	0.32	1.04	-0.025	0.200	85.80	16.59	0.159	0.149	
A8	39	20.1	20.4	1	1-1.5	3	1	1	2	20	0	1	1.03	1.91	-0.062	0.292	85.89	15.87	0.560	0.454	
A9	34	20.1	20.4	1	1-1.5	3	1	1	5	20	0	1	0.54	1.36	-0.080	0.206	86.16	16.06	0.263	0.234	
A10	32	20.2	20.2	-	1-1.5	3	1	1	5	15	0	1	0.36	0.86	-0.028	0.101	85.88	15.04	0.098	0.085	
A11	31	20.2	20.2	-	1-1.5	3	1	1	4	20	0	1	0.83	3.82	-0.076	0.600	72.24	14.61	1.894	1.825	Rudd.lim ±10° Trip.
A12	30	20.2	20.2	1	2-5.5	3	1	1	4	15	0	1	0.92	1.10	-0.017	0.168	85.75	15.63	0.234	0.150	
A13	34	20.2	20.2	2	4-5.5	3	1	1	3	15	0	1	0.84	1.23	-0.069	0.173	85.71	15.32	0.257	0.186	
A14	8	20.2	20.2	1	2-3.5	3	1	1	6	15	0	1	2.80	1.56	-0.066	0.190	85.44	14.40	1.068	0.284	
A15	41	20.2	20.2	1	2-3.5	3	1	1	6	15	0	1	5.23	1.84	0.029	0.356	85.50	14.55	3.201	0.466	
A16	31	20.2	20.2	1	1-1.5	3	1	1	6	10	0	1	1.46	1.41	-0.087	0.256	85.79	15.50	0.485	0.272	
A17	27	20.2	20.2	1	1-1.5	3	1	1	8	10	0	1	1.21	1.98	-0.017	0.544	85.65	15.29	0.835	0.688	
A18	27	20.2	20.2	1	2-3.5	3	1	1	5	15	0	1	-1.06	1.87	-0.059	0.167	86.13	16.20	0.493	0.381	
A19	30	20.2	20.2	1	2-3.5	3	1	1	5	15	0	2	-0.23	1.86	0.054	0.247	85.78	16.17	0.415	0.410	BR = 0.2
A20	32	20.2	20.2	1	2-3.5	3	1	1	5	15	0	1	-0.01	2.61	0.509	0.771	85.87	16.40	1.535	1.535	Rudd.lim ±10° Part 15-32 min

Table C.1a - Summary of experiments of straight course keeping by the adaptive autopilot. An explanation of the relative wind direction is given in Appendix A. If nothing else is remarked, it can be assumed that the water is "deep", the rudder limit is not active and RL is equal to 0.98. IDPSI is equal to 5, when IRR = 3. During the first part of experiment A20 the ship was controlled by Kockums' PID-regulator. Course changes were performed during experiments A37, A40, A41 and A42. Small course changes were performed during experiments A40 - A45 due to the Sailmaster or the Course correction. During experiment A41 the resolution of the course measurement only was 1/6 deg. Data were recorded only every second min. during experiment A42. The table is continued on next page.

Experiment	Duration [min]	Draught: Forward [m]	Draught: Aft [m]	Rel. wind dir.	Wind velocity [m/s]	Regulator structure: NA	NB	NC	K	IREG	IRDIF	IRR	DELTA: Mean value [deg]	DELTA: Std. dev. [deg]	PSI - PSIREF: Mean value [deg]	PSI - PSIREF: Std. dev. [deg]	Mean value of AN [rpm]	Mean value of U [knots]	V_1	V_2	Remarks
A41	104	20.2	20.2	1	6-8	3	2	0	5	15	-	-	1.64	3.47	0.002	0.322	81.61	17.40	1.577	1.308	Rudd.lim act. RL = 0.99 Part 0-50 min
A42	380	20.0	20.0	4-5	4-8	3	2	0	5	15	-	-	-0.10	1.62	-0.019	0.186	85.55	16.29	0.298	0.297	RL = 0.99 Part 200-380min
A43	62	20.0	20.0	5	4-8	3	2	0	5	15	-	-	1.21	1.58	0.003	0.152	85.57	15.12	0.419	0.273	RL = 0.99 Part 20-62 min
A44	92	20.0	20.0	5	6-8	3	2	0	5	15	-	-	1.28	1.67	0.002	0.159	85.25	15.43	0.468	0.304	RL = 0.99
A45	78	20.0	20.0	8	6-10.5	3	2	0	5	15	-	-	0.86	1.54	0.023	0.208	85.13	15.43	0.355	0.281	RL = 0.99

Table C.1c

Experiment	a_1	a_2	a_3	a_4	b_1	b_2	c_1	c_2	Σa_i	Remarks
A1	-13.207	17.540	-5.014	-	0.635	-	-59.363	-	-0.681	
A2	-9.847	14.845	-5.577	-	0.493	-	-13.298	-	-0.579	
A3	-12.373	21.422	-9.450	-	0.307	-	44.214	-	-0.401	
A4	-8.730	18.286	-11.470	-	0.517	-	144.576	-	-1.914	
A5	-8.829	14.382	-7.214	-	0.811	-	131.639	-	-1.661	
A6	-11.287	15.643	-5.025	-	1.091	-	17.224	-	-0.669	
A7	-12.597	18.895	-6.873	-	0.928	-	3.236	-	-0.575	
A8	-11.997	17.190	-5.861	-	0.929	-	25.157	-	-0.668	
A9	-12.968	18.223	-5.855	-	0.937	-	17.697	-	-0.600	
A10	-17.208	28.241	-11.576	-	1.003	-	2.784	-	-0.543	
A11	-9.087	14.512	-7.024	-	0.800	-	129.841	-	-1.599	Main engine trip
A12	-13.471	22.748	-9.121	-	0.864	-	1.252	-	0.156	
A13	-14.802	25.104	-10.707	-	0.835	-	5.044	-	-0.405	
A14	-14.237	22.677	-9.210	-	0.873	-	-3.642	-	-0.770	
A15	-12.105	19.258	-7.655	-	0.830	-	-2.543	-	-0.502	
A16	-17.867	30.324	-13.044	-	0.668	-	5.747	-	-0.587	
A17	-15.448	25.557	-9.928	-	0.845	-	-3.271	-	0.181	
A18	-16.325	26.380	-10.022	-	1.034	-	-1.195	-	0.033	
A19	-17.159	28.051	-10.999	-	1.036	-	-0.560	-	-0.107	
A20	-14.171	20.518	-7.202	-	0.837	-	-11.302	-	-0.855	Part 15-32 min.
A21	-10.640	15.967	-5.930	-	0.679	-	16.434	-	-0.603	
A22	-12.708	19.647	-7.066	-	0.670	-	3.836	-	-0.127	
A23	-13.563	20.540	-7.076	-	0.662	-	2.719	-	-0.099	
A24	-4.554	4.147	-	-	0.888	-	30.925	-	-0.407	
A25	-14.112	21.221	-7.715	-	0.654	0.025	-0.588	-	-0.606	

Table C.2a - Final parameter values of the adaptive autopilot for straight course keeping experiments. See also Table C.1.

Experiment	a_1	a_2	a_3	a_4	b_1	b_2	c_1	c_2	Σa_i	Remarks
A26	-13.790	21.190	-7.316	-	0.686	0.018	-2.277	0.112	0.084	
A27	-12.034	17.518	-4.728	-1.337	0.467	-	-3.039	-	-0.581	
A28	-5.815	8.792	-2.997	-	0.480	0.162	-	-	-0.020	
A29	-9.280	13.473	-4.185	-	0.966	0.562	-	-	0.008	
A30	-12.381	18.843	-6.589	-	1.079	-	-	-	-0.127	
A31	-11.335	14.571	-3.058	-0.575	0.961	0.549	-	-	-0.397	
A32	-13.014	20.353	-7.757	-	0.645	0.327	-	-	-0.418	
A33	-10.302	16.913	-6.688	-	0.367	-	3.424	-	-0.077	
A34	-9.729	13.809	-4.053	-	0.828	0.667	-	-	0.027	
A35	-11.569	15.763	-4.783	-	0.894	0.568	-	-	-0.589	
A36	-11.357	16.107	-4.851	-	0.902	0.576	-	-	-0.101	
A37	-22.296	31.504	-9.285	-	0.349	0.316	-	-	-0.077	
A38	-22.712	34.185	-11.401	-	0.136	0.187	-	-	0.072	
A39A	-24.797	39.146	-14.606	-	0.015	0.096	-	-	-0.257	
A39B	-22.693	34.380	-11.816	-	0.757	0.210	-	-	-0.129	
A40	-20.825	32.393	-12.147	-	0.719	0.198	-	-	-0.579	
A41	-20.736	32.124	-12.391	-	0.695	0.176	-	-	-1.003	
A42	-17.942	28.377	-10.738	-	0.830	0.159	-	-	-0.303	
A43	-18.071	29.138	-11.124	-	0.802	0.129	-	-	-0.057	
A44	-17.867	29.214	-11.686	-	0.776	0.109	-	-	-0.339	
A45	-17.858	29.931	-12.077	-	0.757	0.097	-	-	-0.004	

Table C.2b

Experiment	Duration [min]	Water depth [m]	Draught		Rel. wind direction	Wind velocity [m/s]	PSIREF [deg]	RREF [deg/s]	Rudder limit [deg]	DEL1M at termination [deg]	Approx. mean value of AN [rpm]	Approx. mean value of U [knots]	Remarks
			Forward [m]	Aft [m]									
B1	36	20-22	10.9	10.9	7	1-3.5	52-71	0.07,0.14	±6 - ±12	-1.91	78.5	16.3	Program errors
B2	83	22-25	10.9	10.9	7,8,1	1-3.5	350-76	0.07	±5 - ±10	-1.15	78.0	16.5	Program errors
B3	14	40	20.1	20.4	1	1-1.5	115-157	0.14	±15	-	64.5	9.2	Program errors
B4	31	70	20.1	20.4	2	1-1.5	119-157	0.07	Not active	0.10	82.0	14.9	Program errors
B5	7	40	20.1	20.4	2	1-1.5	119-135	0.07	±15 - ±20	2.90	80.5	14.6	Program errors
B6	25	90	20.1	20.4	-	0-0.5	97-110	0.07	Not active	0.24	82.5	14.8	Program errors
B7	26	100	20.1	20.4	-	0-0.5	71-97	0.07	±4 - ±10	0.82	75.0	15.0	Trip. Program errors
B9	21	deep	20.1	20.4	-	0-0.5	171-203	0.07	Not active	0.71	85.5	16.3	
B10	99	deep	20.2	20.2	6	4-5.5	180-225	0.07	Not active	0.04	85.5	17.9	
B11	46	deep	20.2	20.2	5,6	4-5.5	180-225	0.07	Not active	-	85.5	17.7	
B12	41	deep	20.2	20.2	5,6	4-5.5	180-225	0.07,0.14	Not active	-	85.5	17.8	
B13	69	deep	20.2	20.2	5,6	4-5.5	180-225	0.07,0.21	Not active	-	85.5	17.7	
B14	68	deep	20.2	20.2	4	4-8	202-212	0.07	Not active	-0.99	85.5	17.0	
B15	59	deep	20.2	20.2	4,5	4-8	180-225	0.07,0.14	Not active	-0.57	85.0	17.1	

Table C.3 - Summary of experiments of yawing by the adaptive autopilot. An explanation of the relative wind direction is given in Appendix A. It was not possible to read the paper tape from experiment B8.

Experiment	Duration [min]	Rel. wind direction	Wind velocity [m/s]	k_P	k_D [s]	DELTA Mean value [deg]	DELTA Std. dev. [deg]	PSI - PSIREF Mean value [deg]	PSI - PSIREF Std. dev. [deg]	Mean value of AN [rpm]	Mean value of U [knots]	V_1	V_2	Remarks
A20	32	1	2-3.5	1.0	123	0.32	0.63	0.033	0.140	85.87	16.46	0.071	0.060	Part 0-15 min.
C1	33	8	4-8	0.5	135	1.60	1.21	0.024	0.252	85.65	19.25	0.466	0.210	Misleading meas. of U
C2	37	7	4-8	1.3	105	1.83	1.58	0.026	0.397	85.97	16.52	0.743	0.408	
C3	87	1	17-24	{1.9, 1.6}	{150, 105}	1.31	6.11	0.203	1.510	48.75	4.55	6.226	6.055	

Table C.4 - Summary of experiments of straight course keeping by Kockums' PID-regulator. An explanation of the relative wind direction is given in Appendix A. During all the experiments the water was "deep", the forward and aft draught was 20.2 m and the rudder limit was not active. The regulator parameter k_I was always equal to $1/k_D$ s^{-1} and the sampling interval T_s was equal to 15 s. Notice that the ship was controlled by Kockums' PID-regulator during the first part of experiment A20. The regulator parameters were changed several times during experiment C3. The initial and final parameter values of this experiment are given in the table.

Experiment	Duration [min]	Draught Forward [m]	Draught Aft [m]	Rel. wind dir.	Wind velocity [m/s]	Regulator structure NA	NB	NC	K	IREG	IRDIF	IRR	DELTA Mean value [deg]	DELTA Std. dev. [deg]	PSI - PSIREF Mean value [deg]	PSI - PSIREF Std. dev. [deg]	Mean value of AN [rpm]	Mean value of U [knots]	V_1	V_2	Remarks
A21	40	20.2	20.2	1	2-3.5	3	1	1	5	15	0	1	-0.22	0.91	-0.122	0.207	85.81	16.04	0.145	0.141	
A22	36	20.2	20.2	1	2-3.5	3	1	1	5	15	0	1	-0.17	0.85	-0.091	0.217	85.86	16.29	0.131	0.128	RL = 0.97
A23	17	20.2	20.2	1	2-3.5	3	1	1	5	15	0	1	-0.40	0.91	-0.034	0.167	85.84	16.33	0.128	0.112	RL = 0.99
A24	30	20.2	20.2	1	2-3.5	2	1	1	5	15	0	1	0.29	1.78	-0.510	0.555	85.59	16.14	0.893	0.885	
A25	26	20.2	20.2	1	2-3.5	3	2	1	5	15	0	1	0.21	1.10	-0.003	0.171	85.55	16.30	0.155	0.150	
A26	26	20.2	20.2	1	4-5.5	3	2	2	5	15	0	1	-0.34	0.89	-0.001	0.140	85.55	16.32	0.110	0.099	
A27	33	20.2	20.2	1	2-5.5	4	1	1	5	15	0	1	0.17	0.74	0.005	0.153	85.52	15.92	0.081	0.078	
A28	21	20.2	20.2	1	4-8	3	2	0	4	20	-	-	1.55	0.95	0.033	0.226	85.60	15.67	0.383	0.142	
A29	32	20.2	20.2	8	4-8	3	2	0	5	15	-	-	1.48	1.03	0.001	0.260	85.62	6.36	0.393	0.174	Misleading meas. of U
A30	31	20.2	20.2	1	4-8	3	1	0	5	15	-	-	1.38	1.37	-0.024	0.253	85.67	20.24	0.443	0.252	
A31	31	20.2	20.2	8	4-8	4	2	0	5	15	-	-	1.57	0.91	-0.063	0.171	85.65	18.64	0.363	0.116	
A32	20	20.2	20.2	7	6-8	3	2	0	5	15	-	-	1.65	2.01	-0.003	0.405	85.99	7.89	0.840	0.568	RL = 0.99
A33	30	20.2	20.2	7	6-8	3	1	1	5	15	0	3	1.71	1.36	0.028	0.239	86.11	10.77	0.535	0.243	
A34	33	20.2	20.2	7	6-8	3	2	0	4	20	-	-	1.89	1.54	-0.072	0.250	86.05	16.91	0.662	0.305	
A35	28	20.2	20.2	7	6-8	3	2	0	5	15	-	-	1.75	1.66	0.001	0.283	86.14	17.01	0.662	0.356	RL = 0.99
A36	45	20.2	20.2	7	4-5.5	3	2	0	5	15	-	-	1.66	1.45	0.005	0.219	86.05	16.55	0.534	0.258	RL = 0.99 Part 5-45 min
A37	92	20.2	20.2	1	17-24	3	2	0	5	15	-	-	3.93	7.09	0.158	0.847	54.02	4.82	7.314	5.769	RL = 0.99 Part 10-92 min
A38	71	20.2	20.2	1	17-24	3	2	0	5	15	-	-	1.96	5.91	0.250	0.622	49.30	5.24	4.326	3.942	RL = 0.99
A39A	22	20.2	20.2	1	17-24	3	2	0	5	15	-	-	-1.51	10.98	0.522	1.089	48.53	4.32	13.742	13.514	Rudd.lim ±25° RL = 0.99
A39B	48	20.2	20.2	1	6-10.5	3	2	0	5	15	-	-	2.09	2.62	0.015	0.240	64.07	12.64	1.181	0.744	RL = 0.99
A40	140	20.2	20.2	1	6-10.5	3	2	0	5	15	-	-	1.10	3.04	0.183	0.555	78.98	15.51	1.387	1.266	Rudd.lim act. RL = 0.99 Part 0-120 min

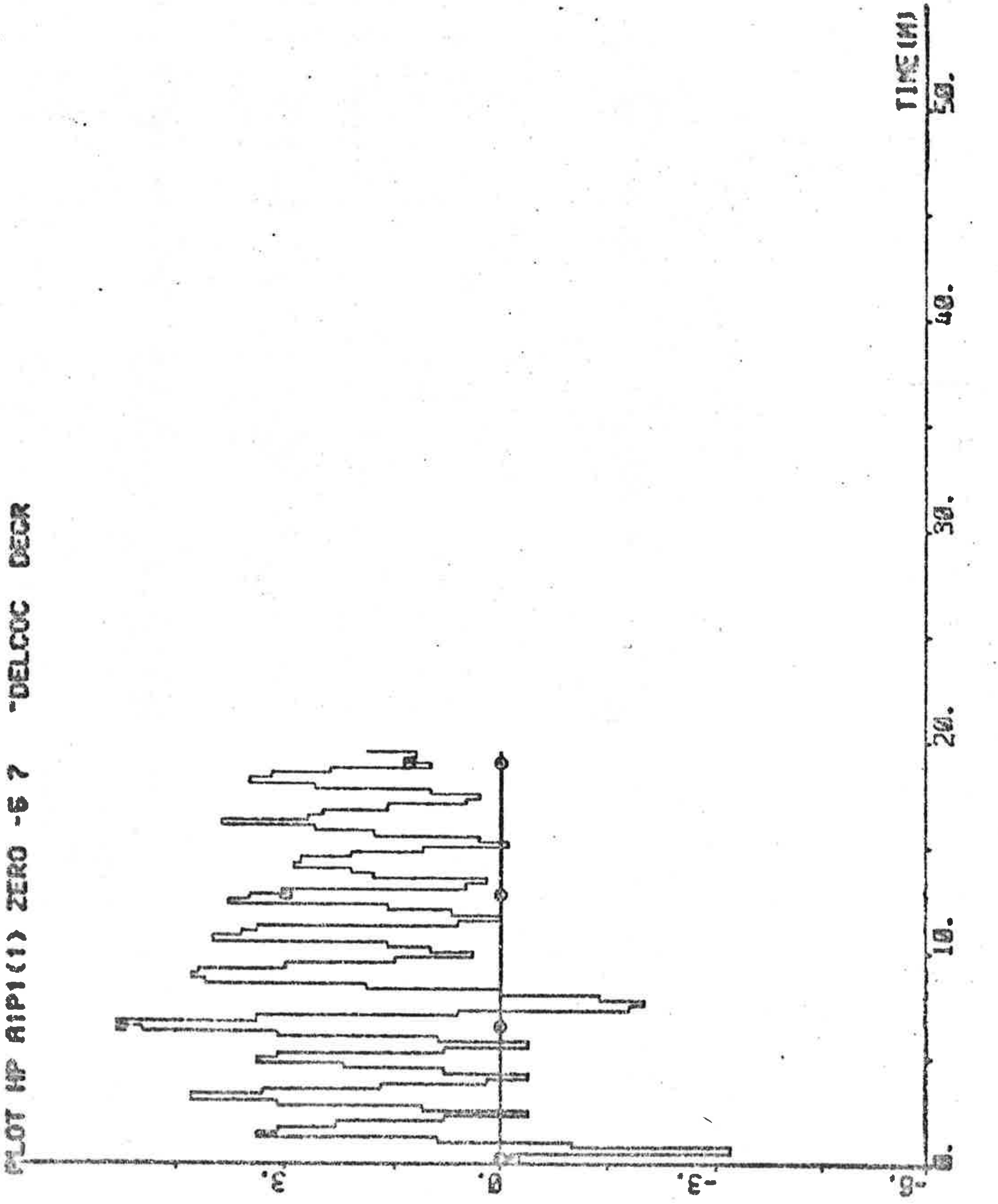
Table C.1b

Experiment	Duration [min]	Water depth [m]	Draught		Rel. wind direction	Wind velocity [m/s]	PSIREF [deg]	RREF [deg/s]	Rudder limit [deg]	Approx. mean value of AN [rpm]	Approx. mean value of U [knots]
			Forward [m]	Aft [m]							
D1	62	deep	20.2	20.2	4,5	4-8	180-225	0.07	Not active	85.5	18.0
D2	66	deep	20.2	20.2	4,5	4-5.5	180-225	0.07,0.14	Not active	85.5	17.2

<u>Table C.5</u> - Summary of experiments of yawing by Kockums' PID-regulator. An explanation of the relative wind direction is given in Appendix A.

Experiment	Duration [min]	Water depth [m]	Draught		Rel. wind direction	Wind velocity [m/s]	Rudder limit [deg]	DELAMP [deg]	AKID	IREG [s]
			Forward [m]	Aft [m]						
E1	78	deep	20.2	20.2	8	2-3.5	Not active	3,5	0	10
E2	59	deep	20.2	20.2	8	2-3.5	±10	5	2	10
E3	36	deep	20.2	20.2	8	2-3.5	±10	0	0.5,3	10
E4	61	deep	20.2	20.2	6,7	2-3.5	Not active	3	0	10

Table C.6 - Summary of experiments for identification. An explanation of the relative wind direction is given in Appendix A.


PLOT HP AIP1(1) ZERO -6 7 "DELCOC DEGR
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

EXPERIMENT A1.

Date	1974-10-08
Time	17.30
Duration	20 min
Position	N 26° 12' E 53° 08'
Water depth	70 m
Forward draught	10.9 m
Aft draught	10.9 m
Wind direction	NW (1; see Appendix A)
Wind velocity	1-2 Beaufort (1-3.5 m/s, light air to light breeze)
Wave height	0.5 - 1.0 m
PSIREF	309°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 4	
IREG = 15	IRDIF = 0	RL = 0.98	IRR = 3	IDPSI = 5

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -13.207 \\ 17.540 \\ -5.014 \\ 0.635 \\ -59.363 \end{bmatrix}$$

P unknown

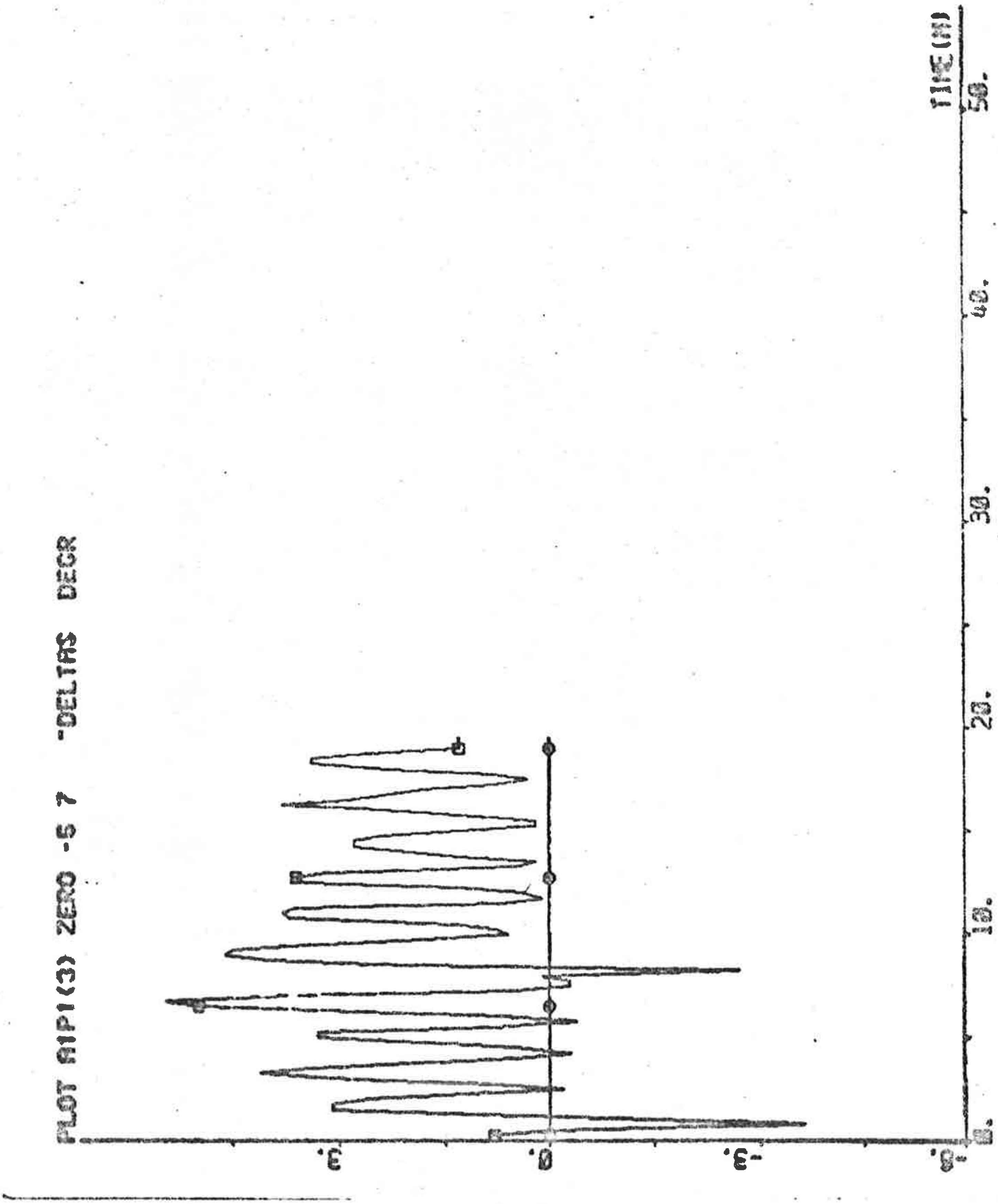
$$a_1 + a_2 + a_3 = -0.681$$

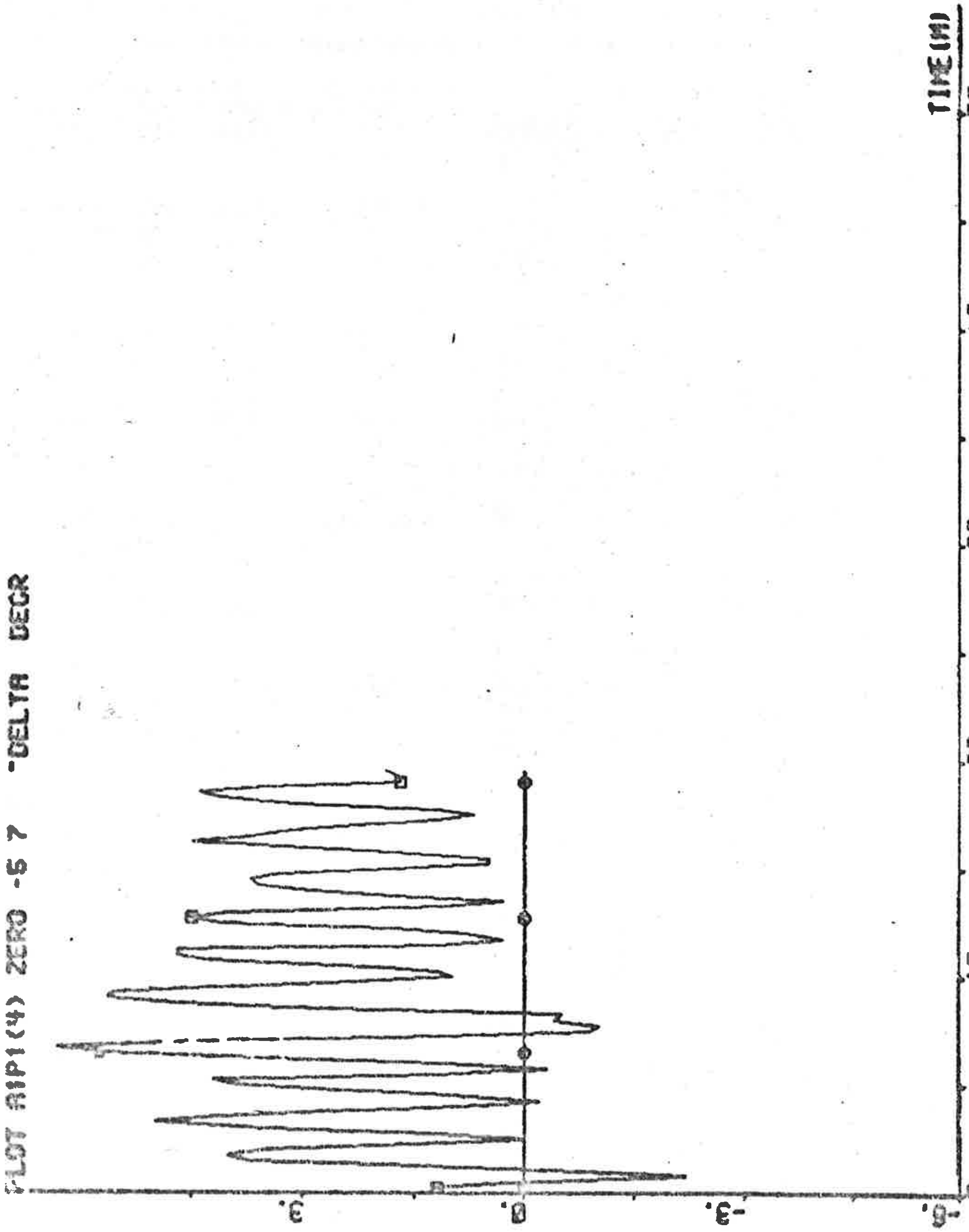
Statistics (mean value and standard deviation)

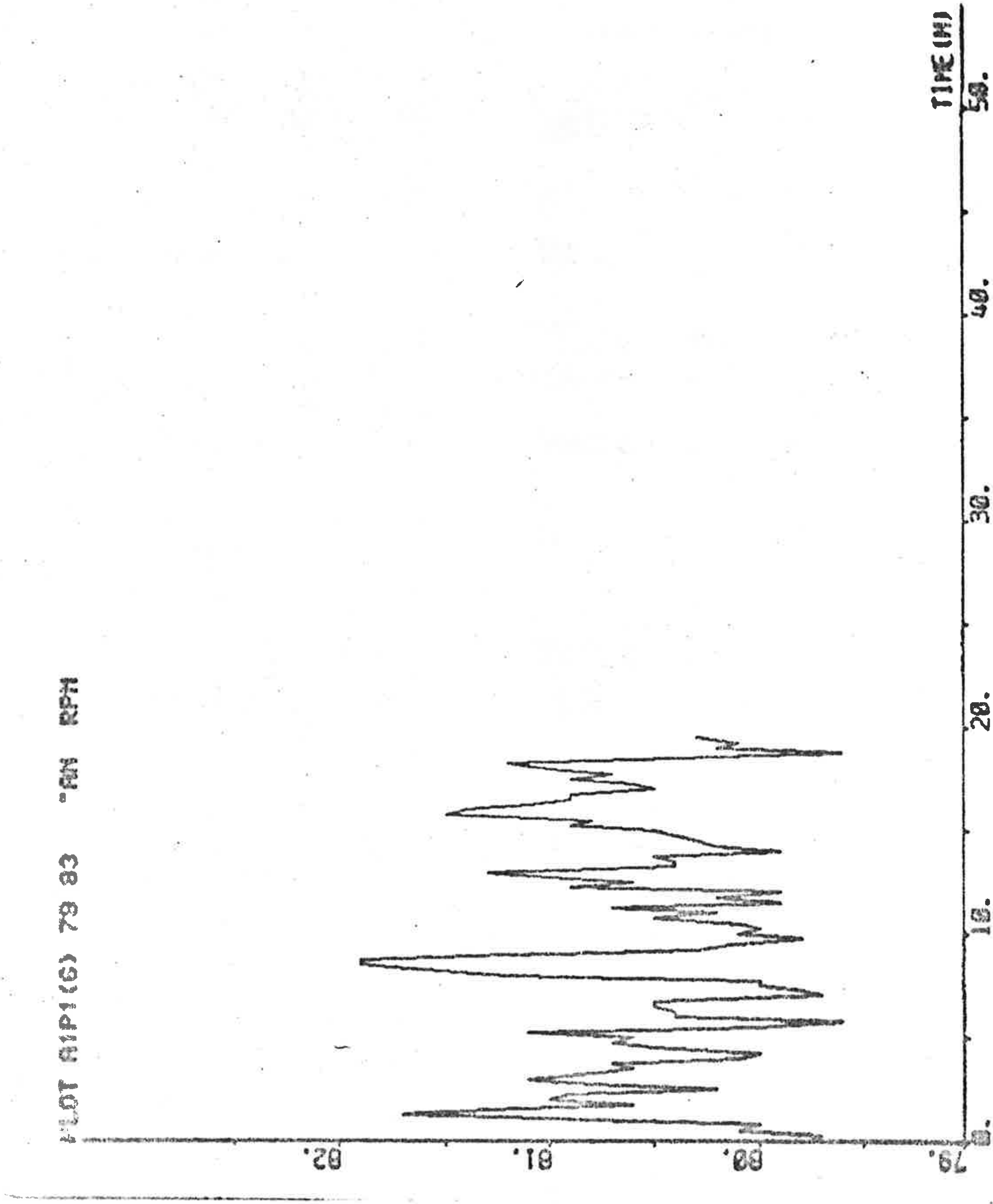
DELTA	2.35 ± 1.86 deg
PSI - PSIREF	-0.213 ± 0.501 deg
AN	80.55 ± 0.53 rpm
U	17.37 ± 0.22 knots

$V_1 = 1.195$

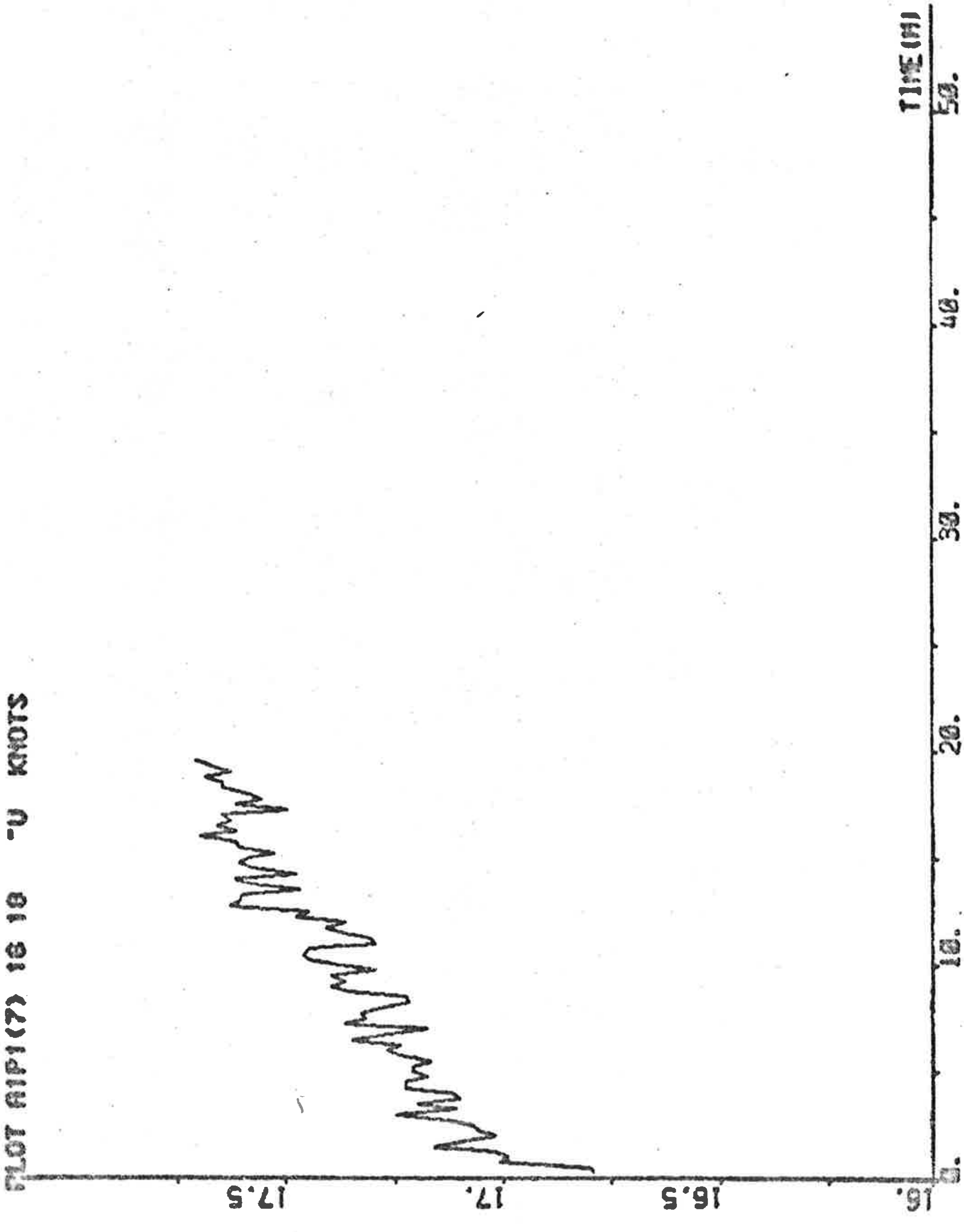
$V_2 = 0.642$

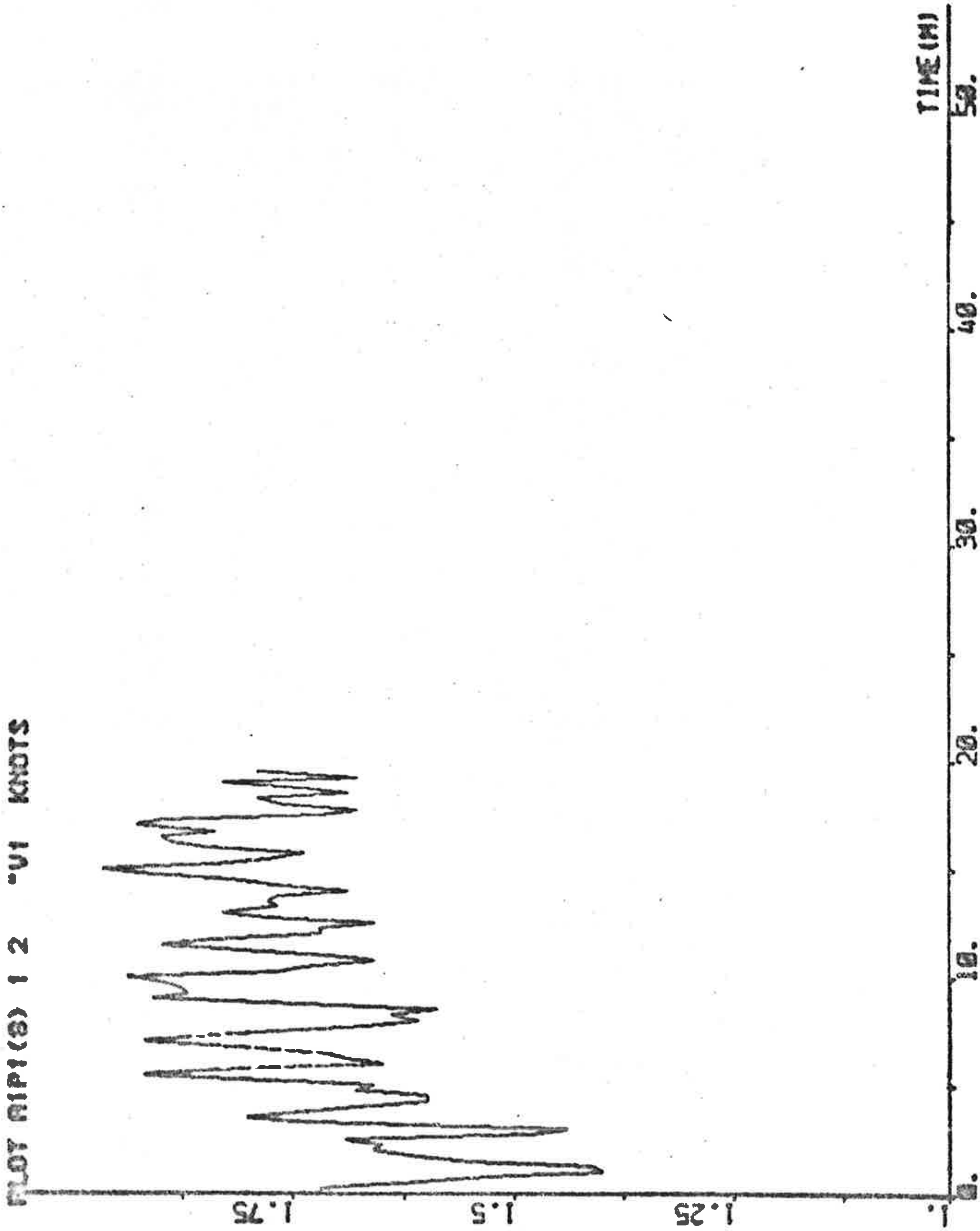

PLOT A1P1(3) ZERO -5 7 -DELTAS DECR
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

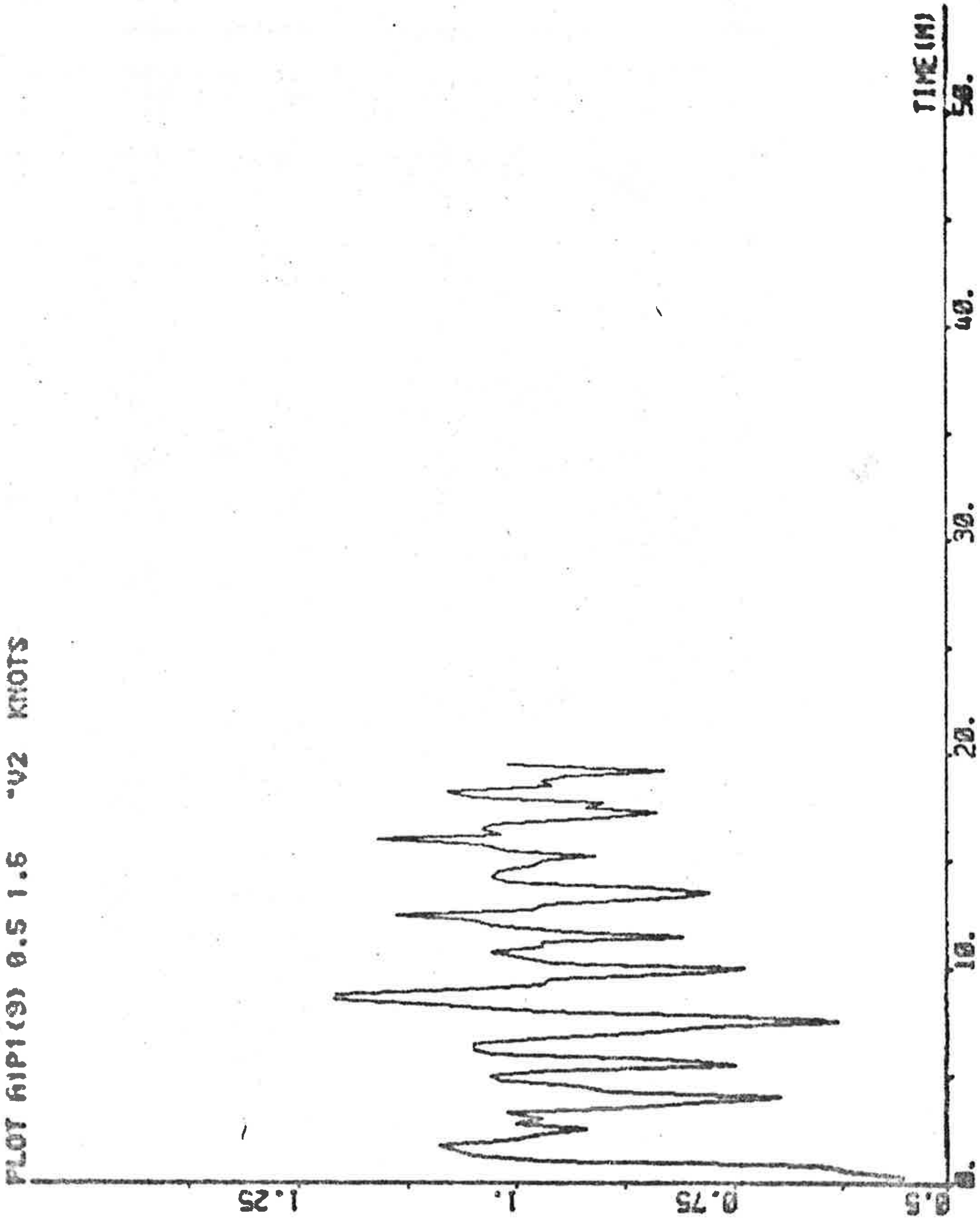

PLOT A1P1(4) ZERO -5 7 -DELTA DECR
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

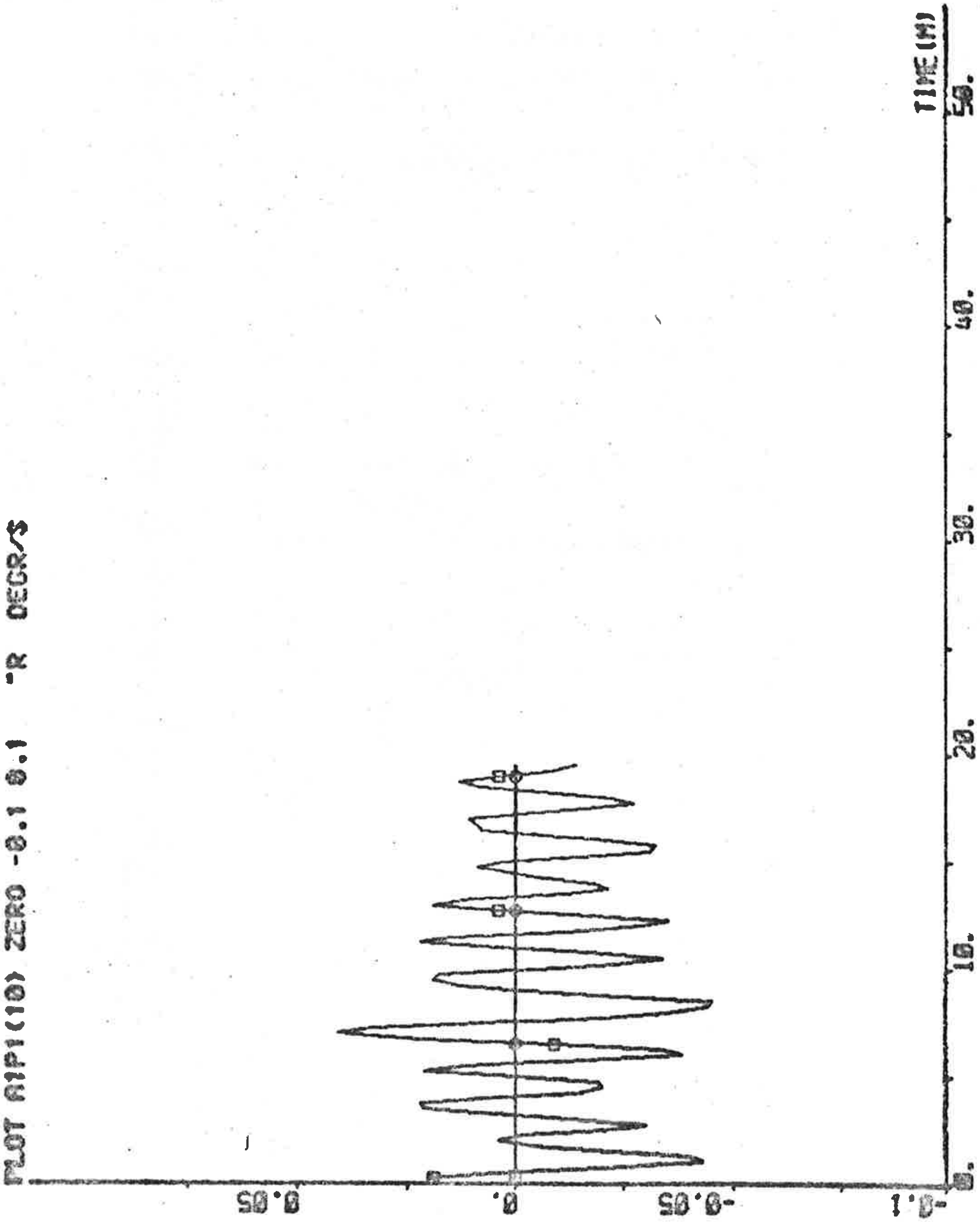


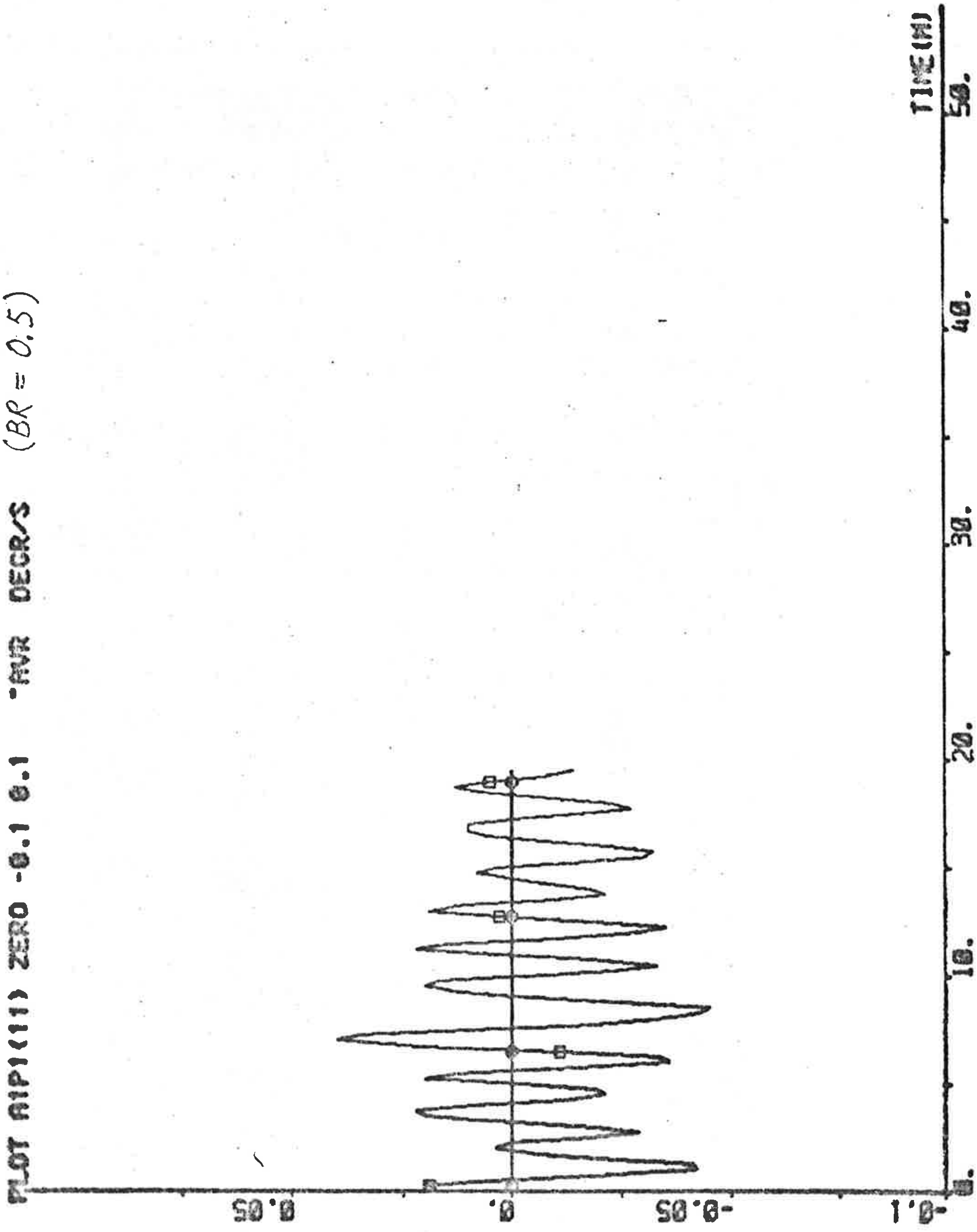
A1P1(G) 79 83
RPM
TIME(M)
0.
10.
20.
30.
40.
50.
79.
80.
81.
82.

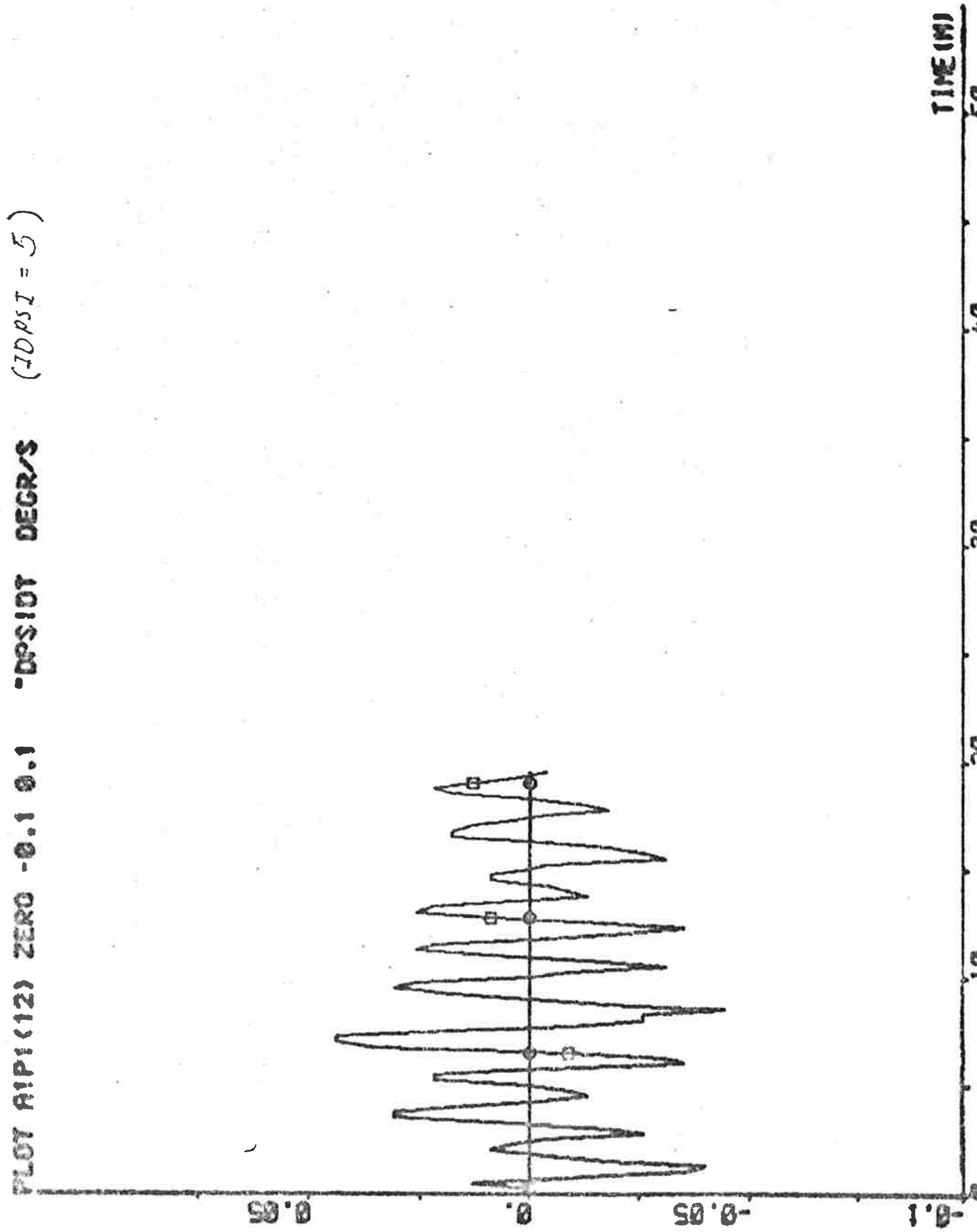

PLOT A1P1(7) 10 10 -U KNOTS
17.5
17.
16.5
16.
0.
10.
20.
30.
40.
50.
TIME (H)

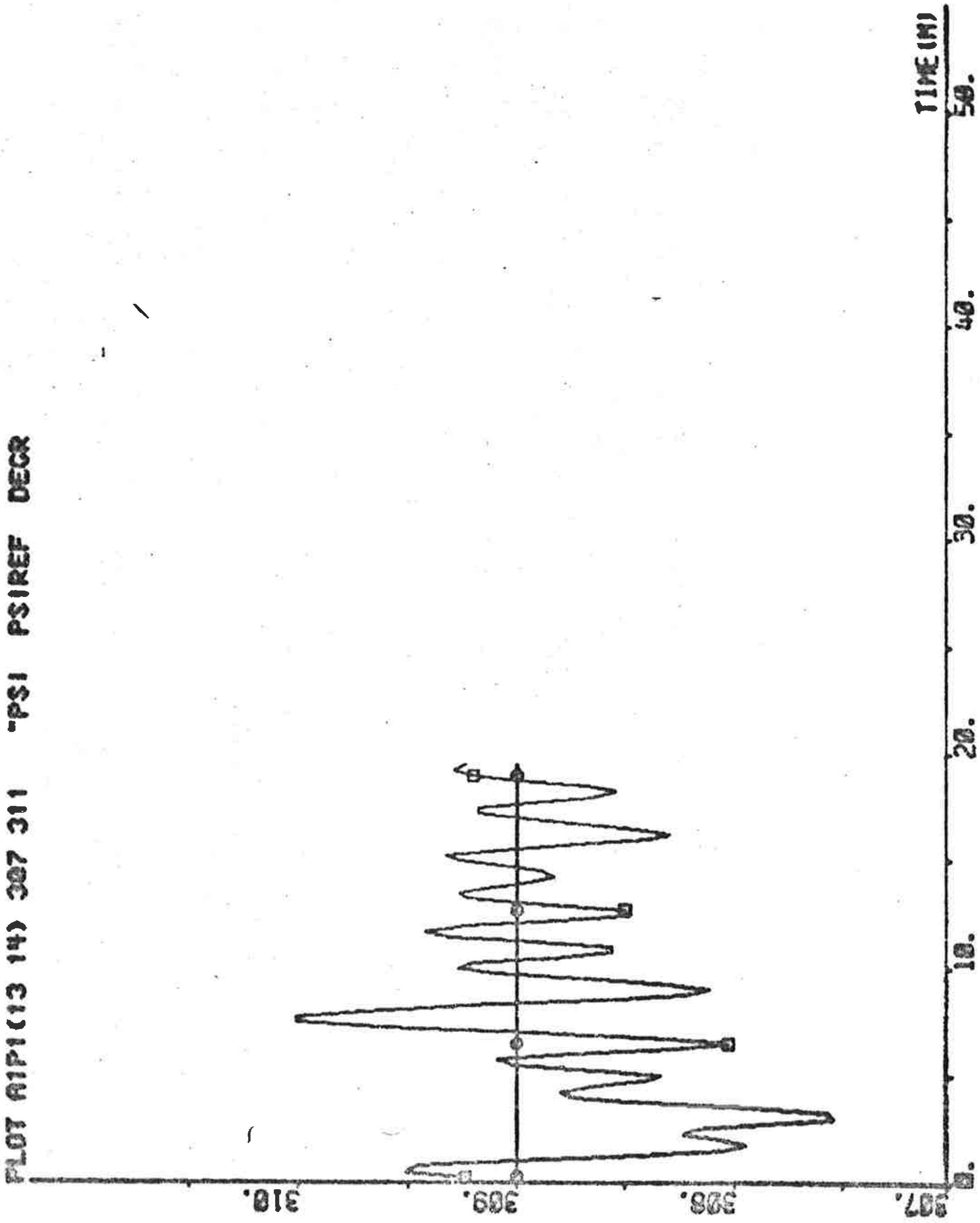

PLOT RIP1(S) 1 2 *V1 KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
1.
1.25
1.5
1.75

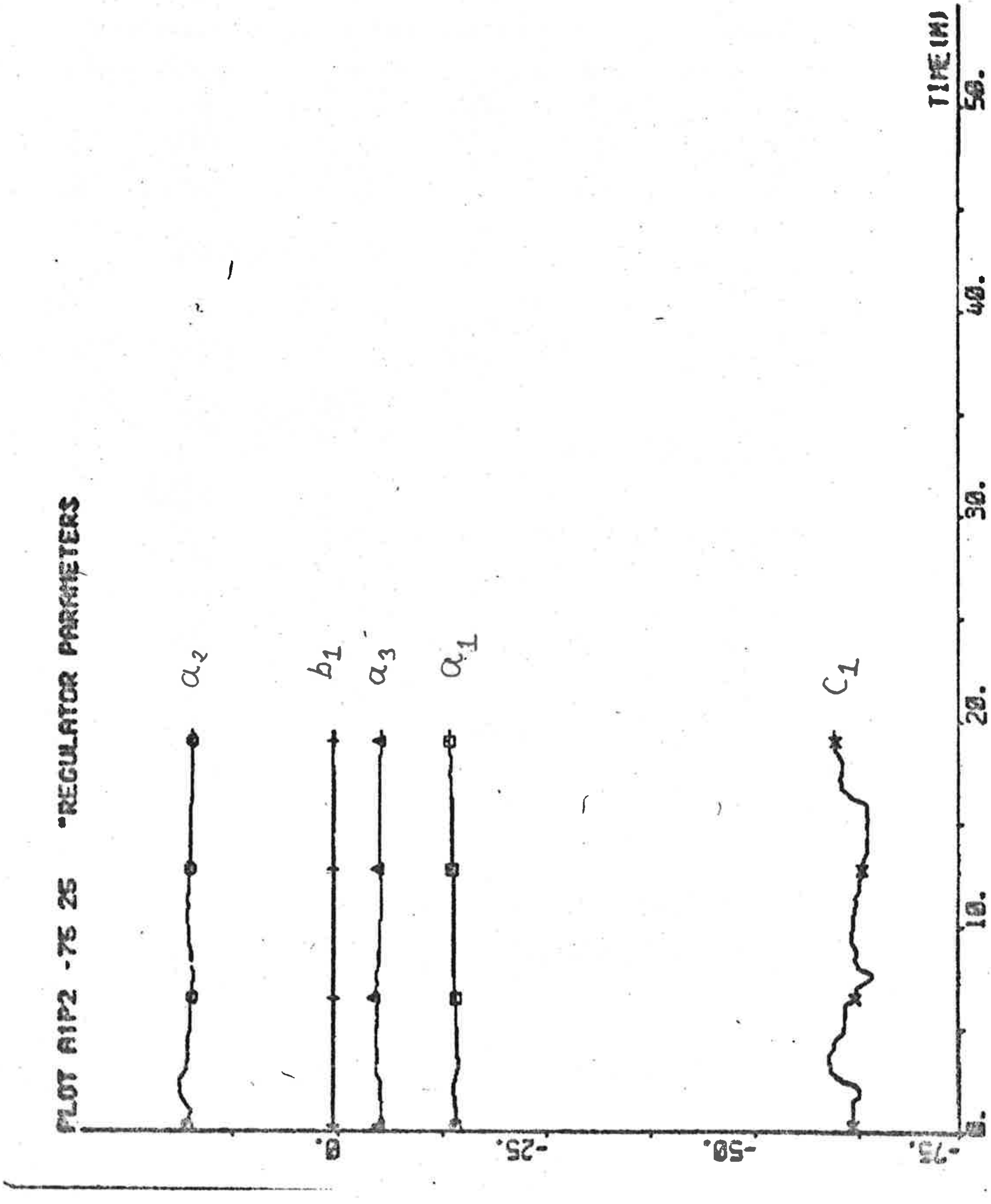

PLOT RIP1(3) 0.5 1.5 'V2 KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
0.5
0.75
1.
1.25


PLOT A1P1(10) ZERO -0.1 0.1 'R DEGR/S
TIME(M)
0.
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1


PLOT A1P1(11) ZERO -0.1 0.1 *AVR DECR/S
(BR = 0.5)
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(H)


PLOT R!P!(12) ZERO -0.1 0.1 -DPSIDT DEGR/S
(IDPSI = 5)
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A1P1(13 14) 307 311
-PSI PSIREF DEGR
TIME (M)
10.
20.
30.
40.
50.
307.
308.
309.
310.


PLOT A1P2 -75 25 'REGULATOR PARAMETERS
0.
-25.
-50.
-75.
10.
20.
30.
40.
50.
TIME (M)
a_2
b_1
a_3
a_1
C_1

EXPERIMENT A2.

Date	1974-10-08
Time	22.01
Duration	54 min
Position	N 27° 00' E 51° 51'
Water depth	50 - 65 m
Forward draught	10.9 m
Aft draught	10.9 m
Wind direction	NW (1; see Appendix A)
Wind velocity	3 Beaufort (4-5.5 m/s, gentle breeze)
Wave height	1 - 2 m
PSIREF	319°
Rudder limit	±10°

Regulator structure

NA = 3	NB = 1	NC = 1	K = 4	
IREG = 20	IRDIF = 0	RL = 0.98	IRR = 3	IDPSI = 5

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -9.847 \\ 14.845 \\ -5.577 \\ 0.493 \\ -13.298 \end{bmatrix}$$

P unknown

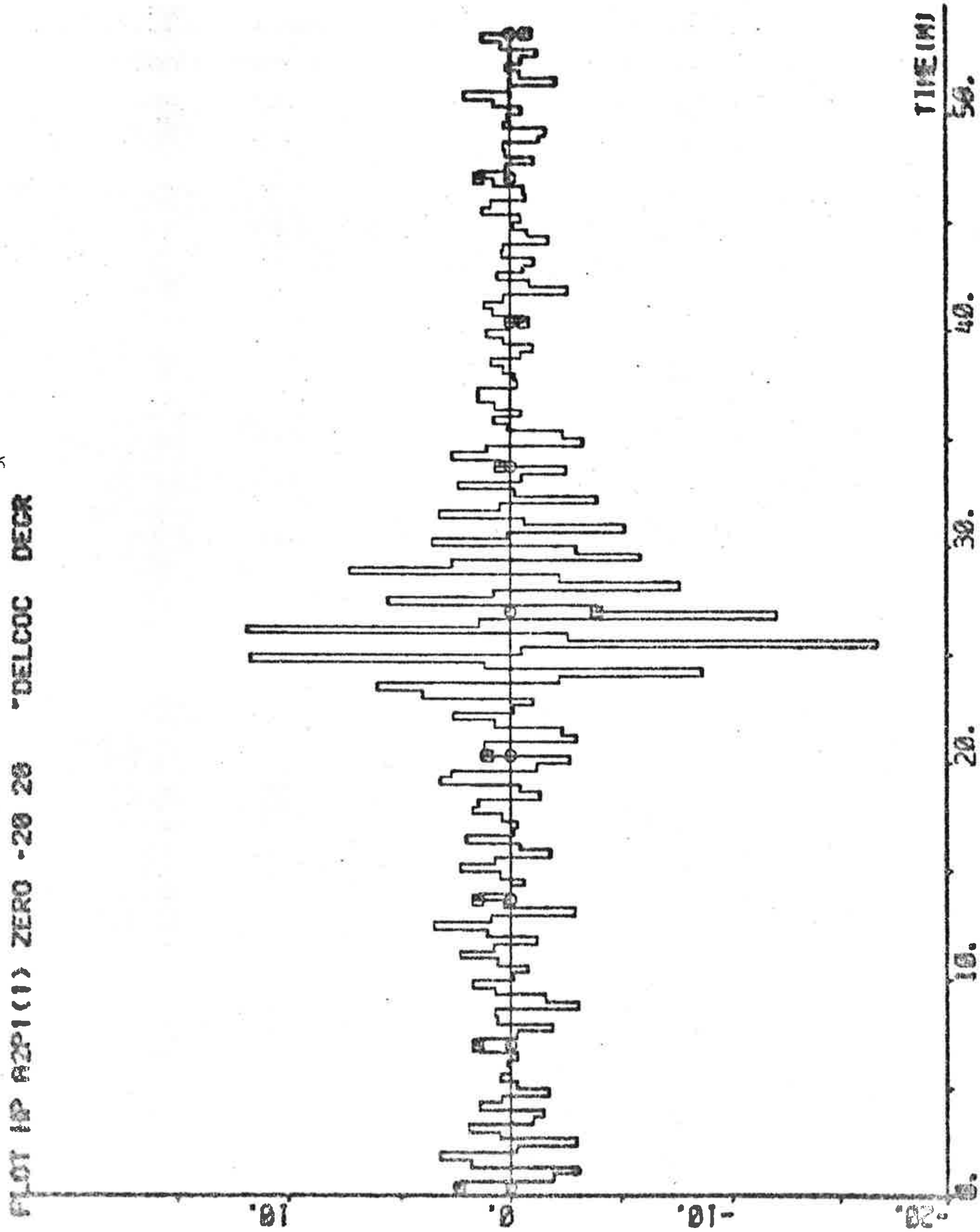
$a_1 + a_2 + a_3 = -0.579$

<u>Statistics</u> (mean value and standard deviation)

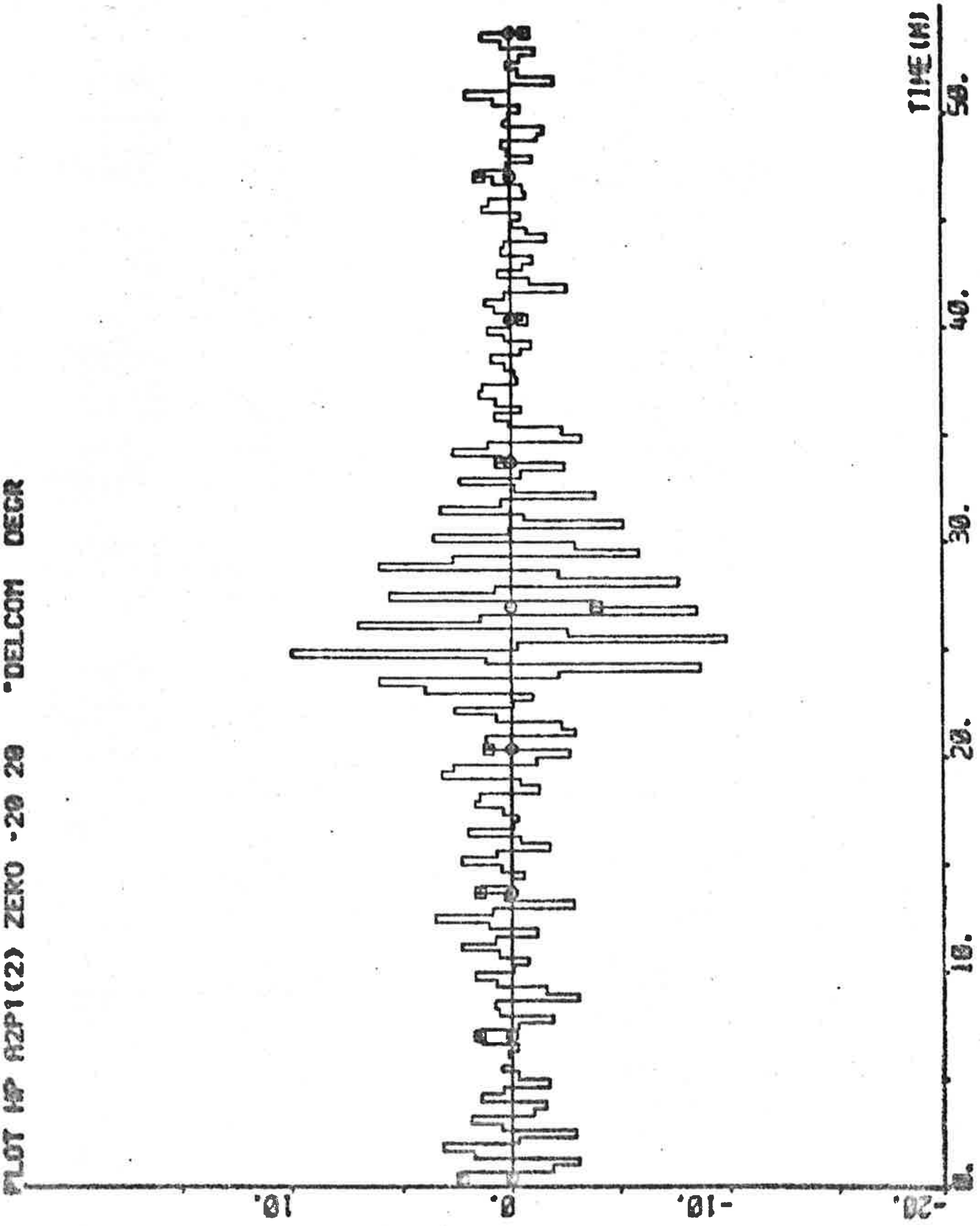
DELTA	0.66 ± 2.58 deg
PSI - PSIREF	0.082 ± 0.454 deg
AN	80.82 ± 0.49 rpm
U	17.08 ± 0.10 knots

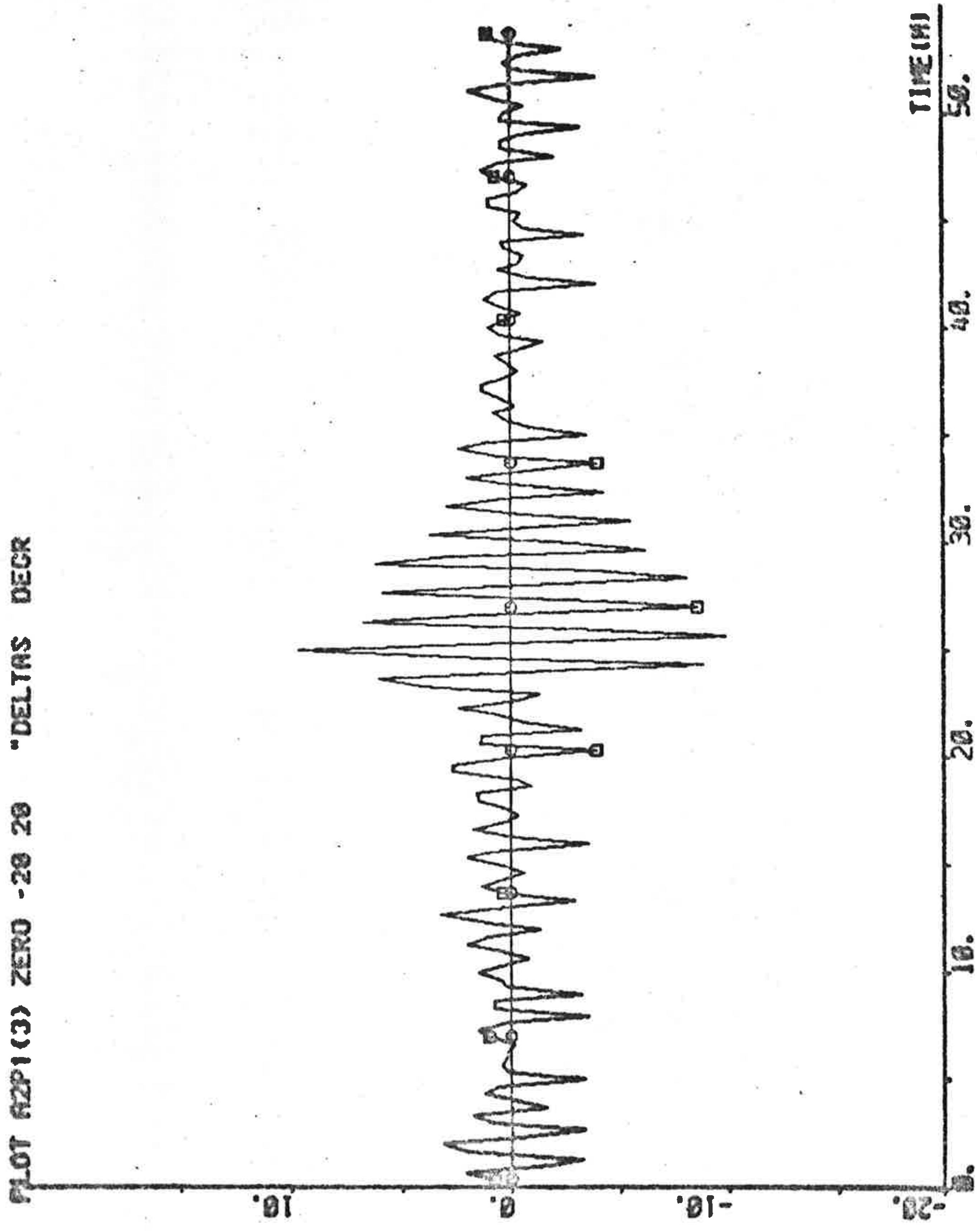
$V_1 = 0.922$

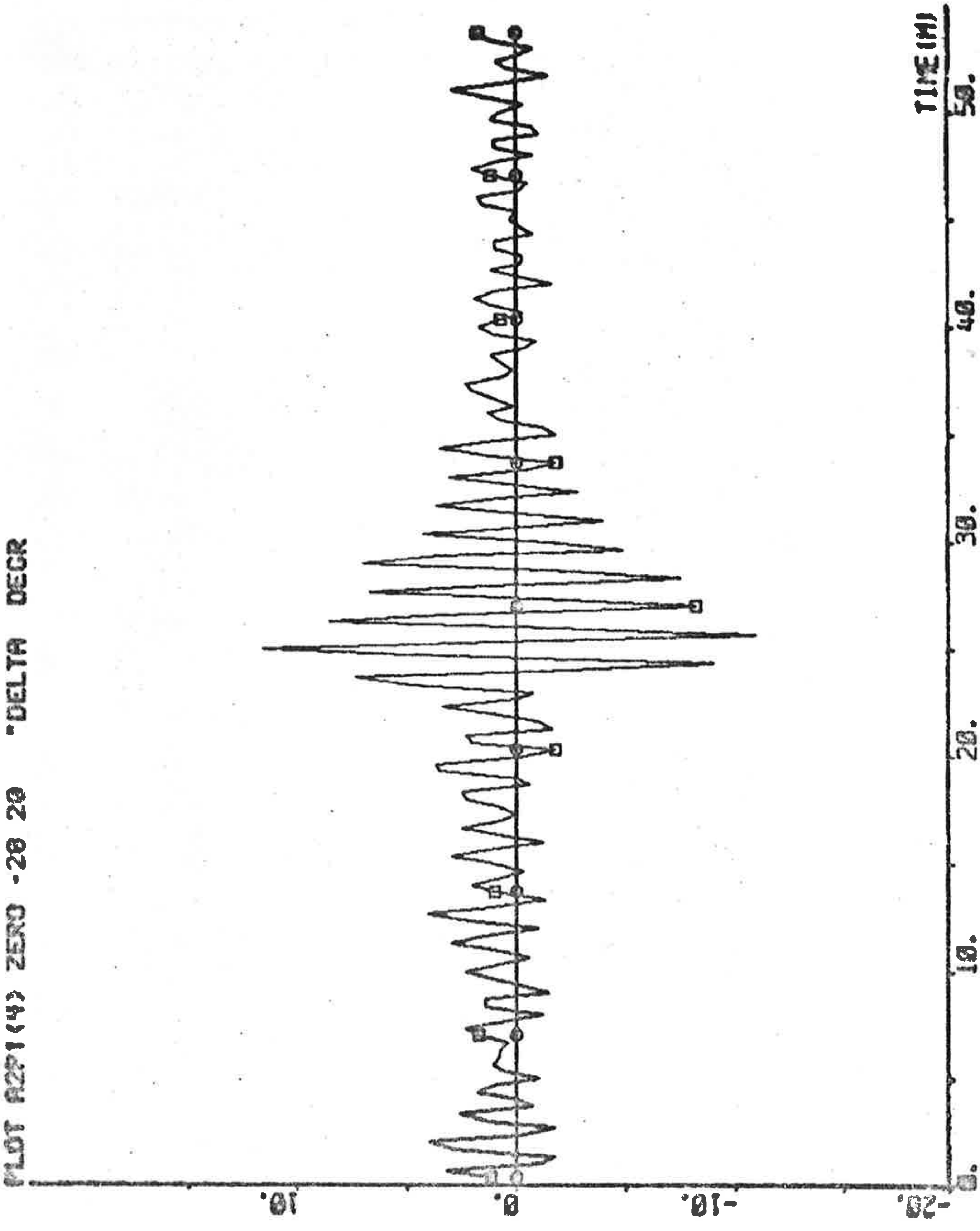
$V_2 = 0.878$

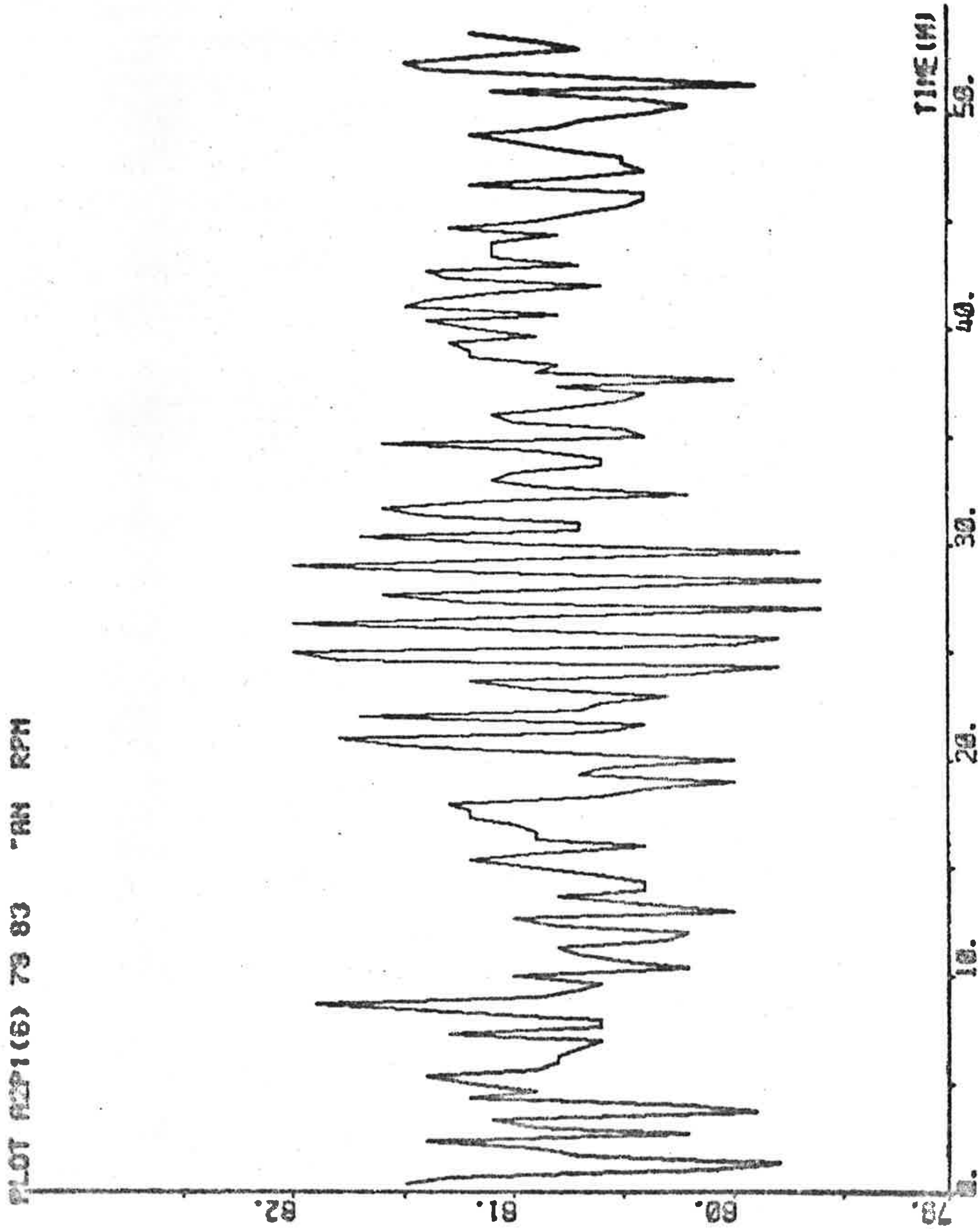


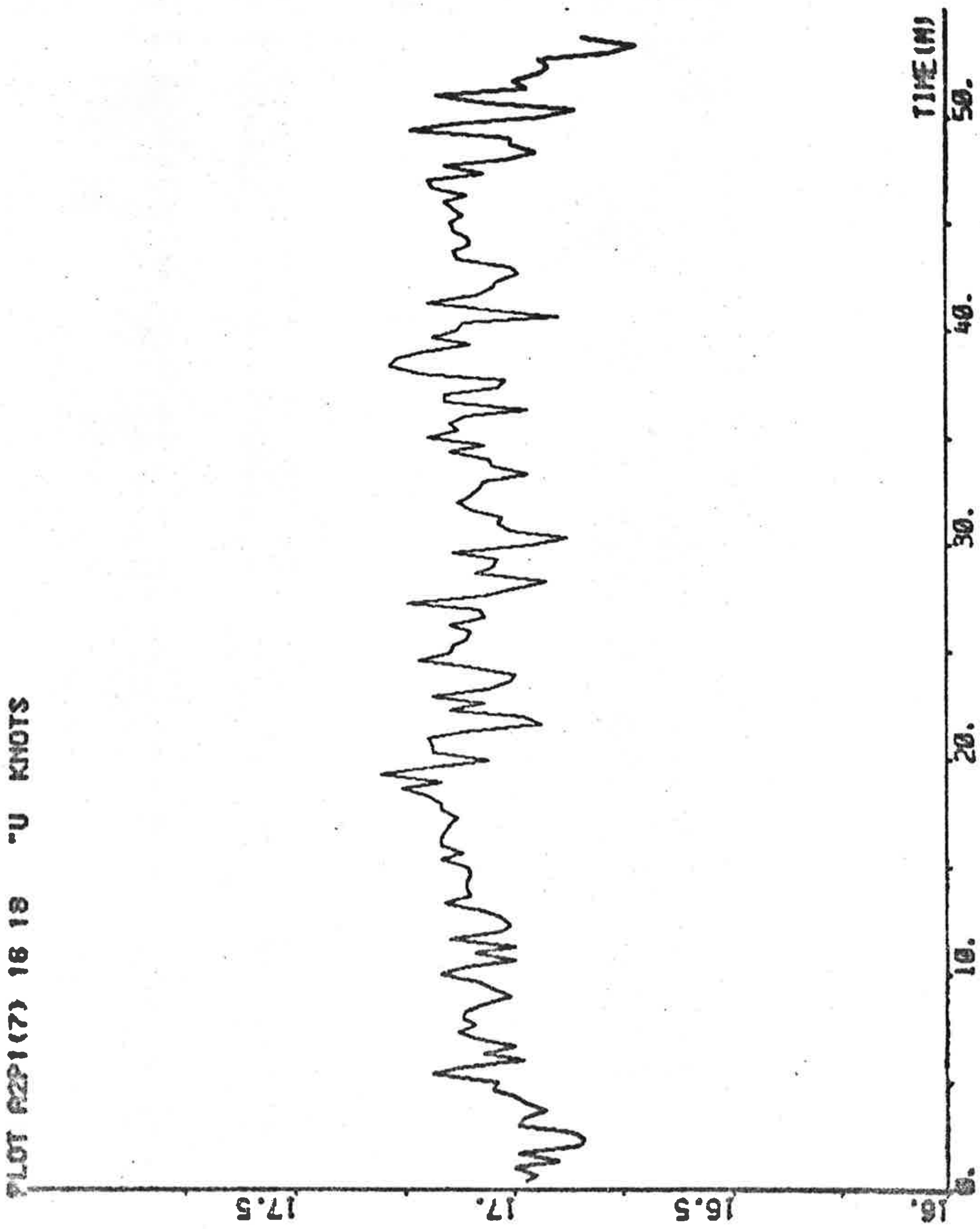
PLOT IP R2P1(I) ZERO -20 20 "DELCOC DEGR
TIME(H)
0.
10.
20.
30.
40.
50.
10.
0.
-10.
-20.

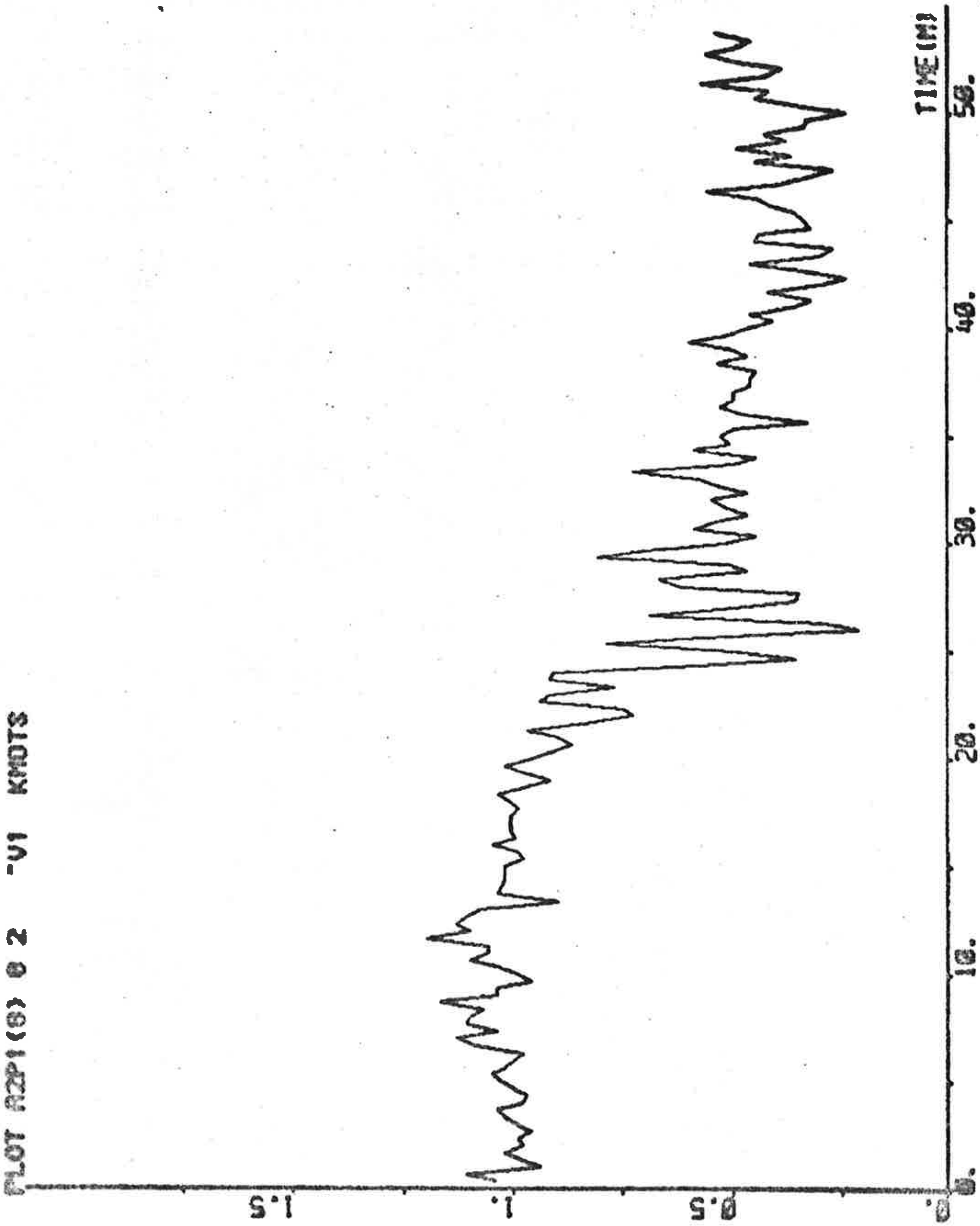

PLOT HP A2P1(2) ZERO -20 20 'DELCOM DEGR
TIME(M)
0.
10.
20.
30.
40.
50.
10.
0.
-10.
-20.

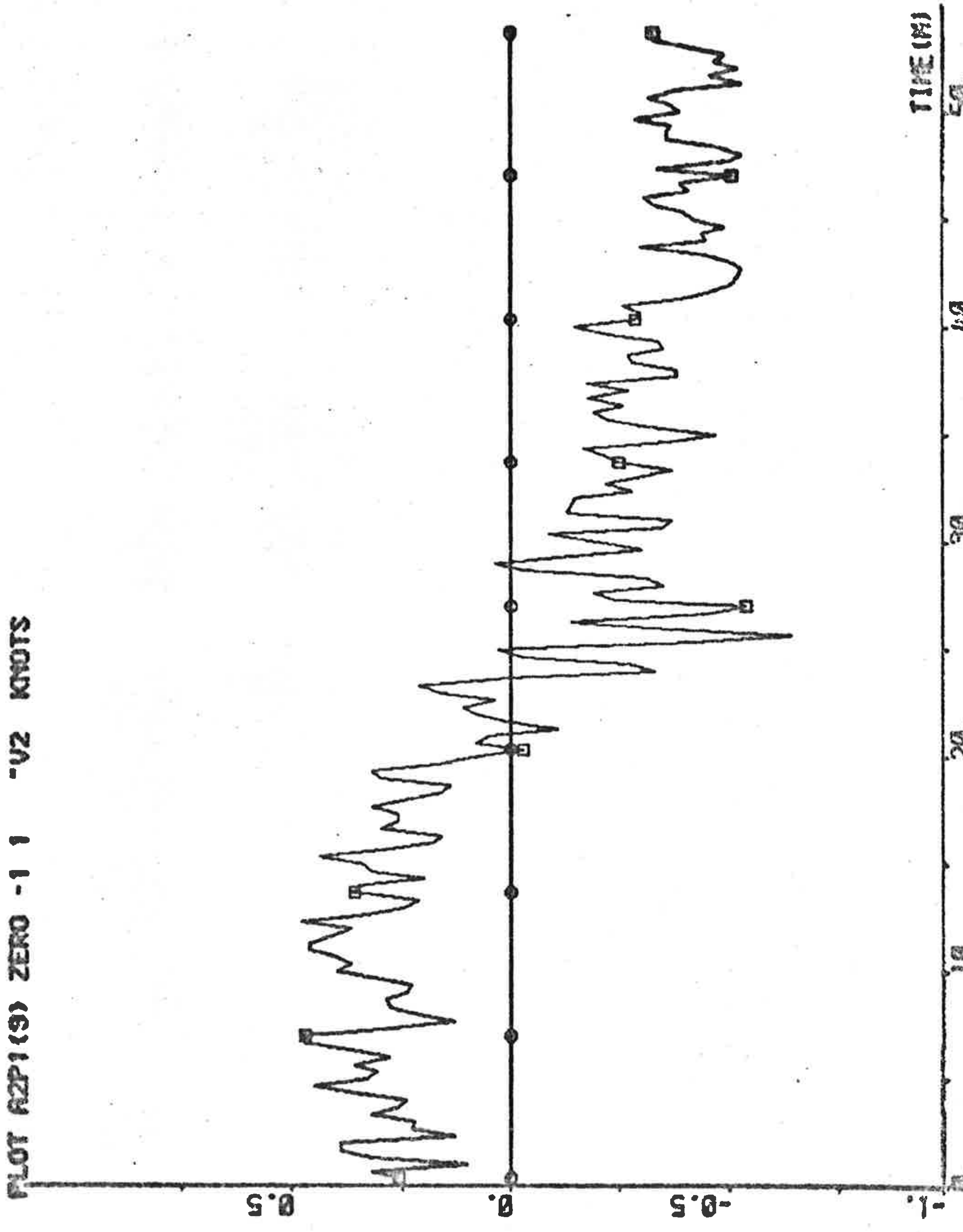

PLOT AZP1(3) ZERO -20 20 "DELTAS DECR
TIME(M)
0.
10.
20.
30.
40.
50.
10.
0.
-10.
-20.

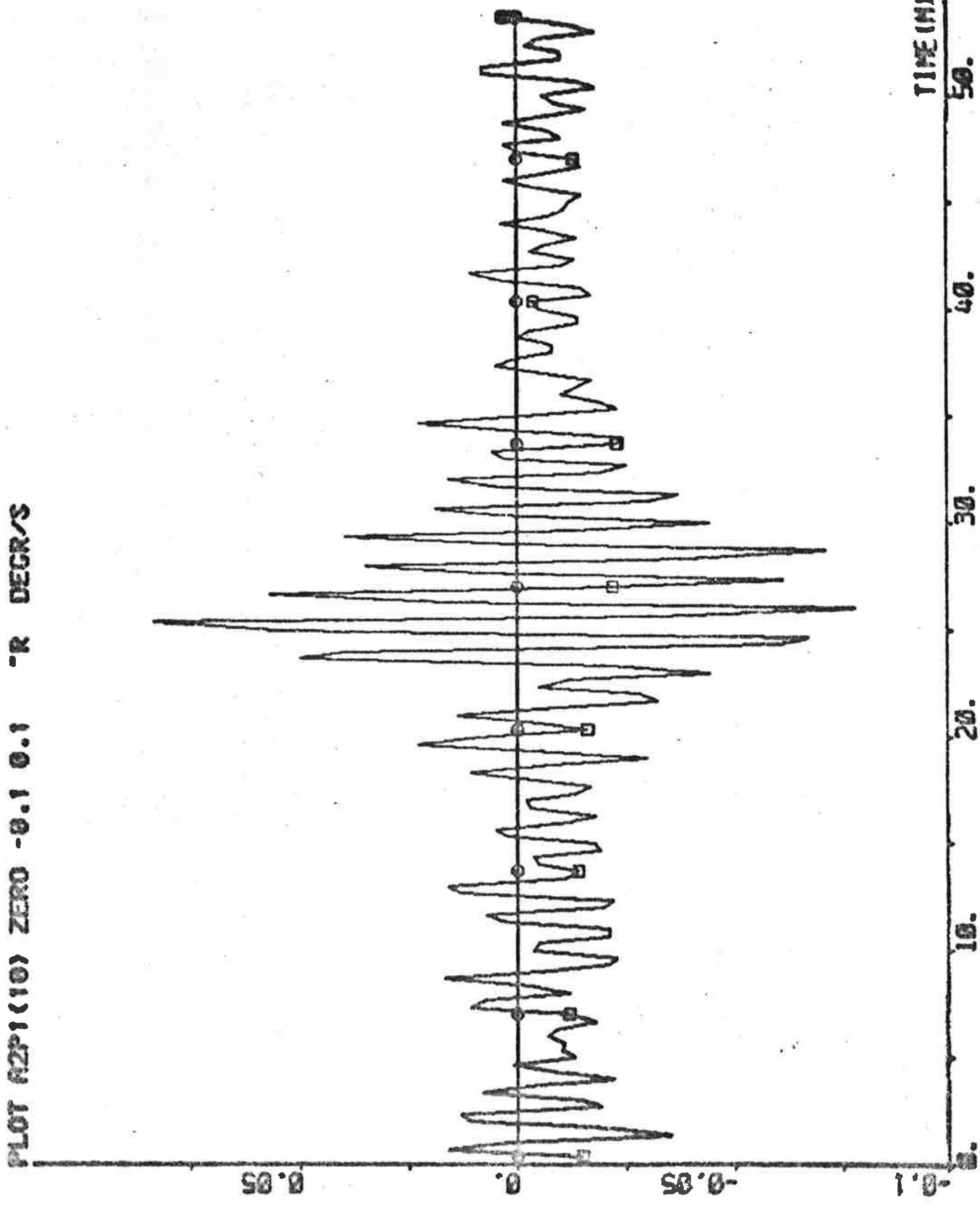

PLOT A2P1(4) ZERO -20 20 *DELTA DECR
10.
0.
-10.
-20.
0.
10.
20.
30.
40.
50.
TIME(M)

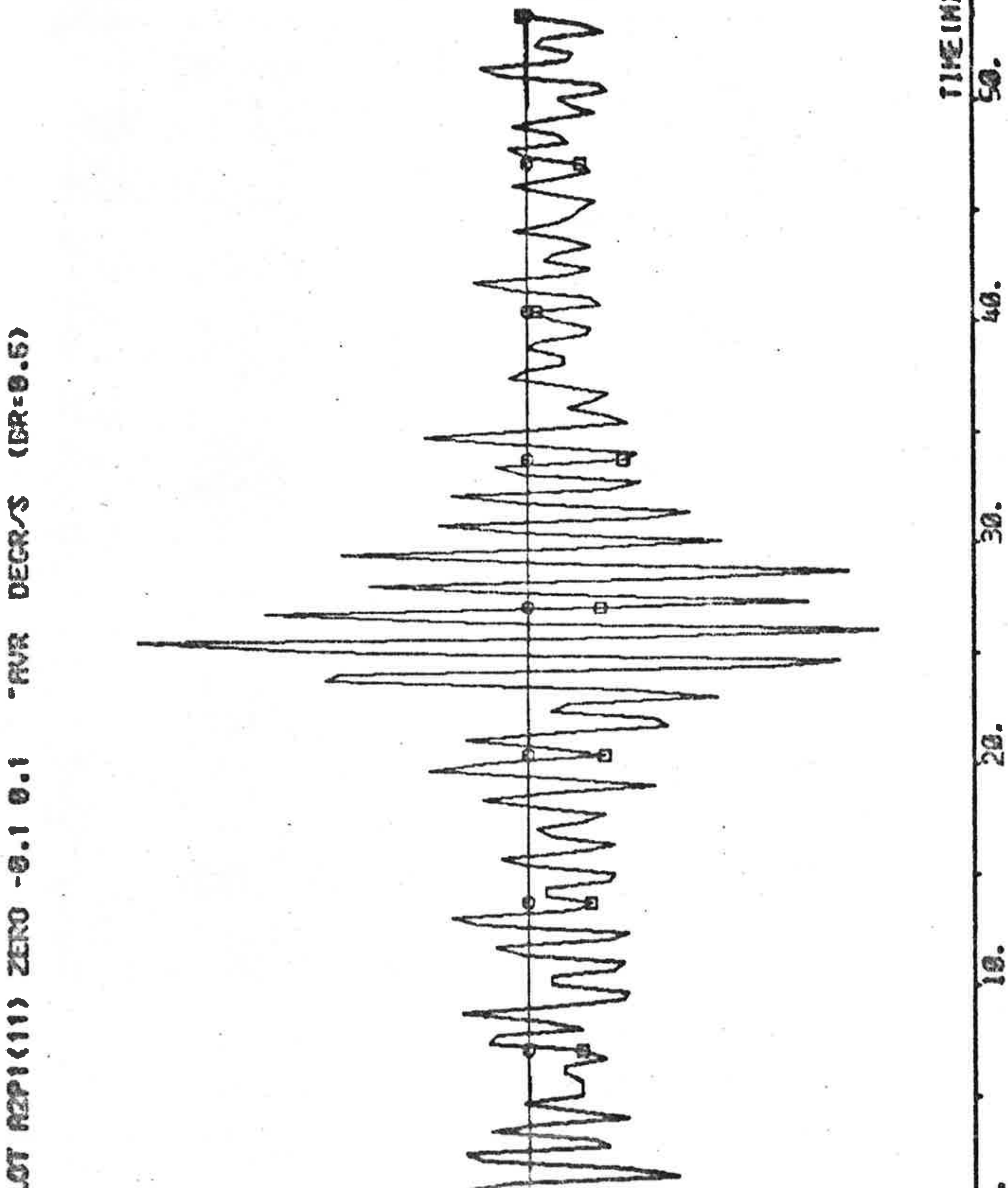

TIME(M)
10.
20.
30.
40.
50.
78.
80.
81.
82.

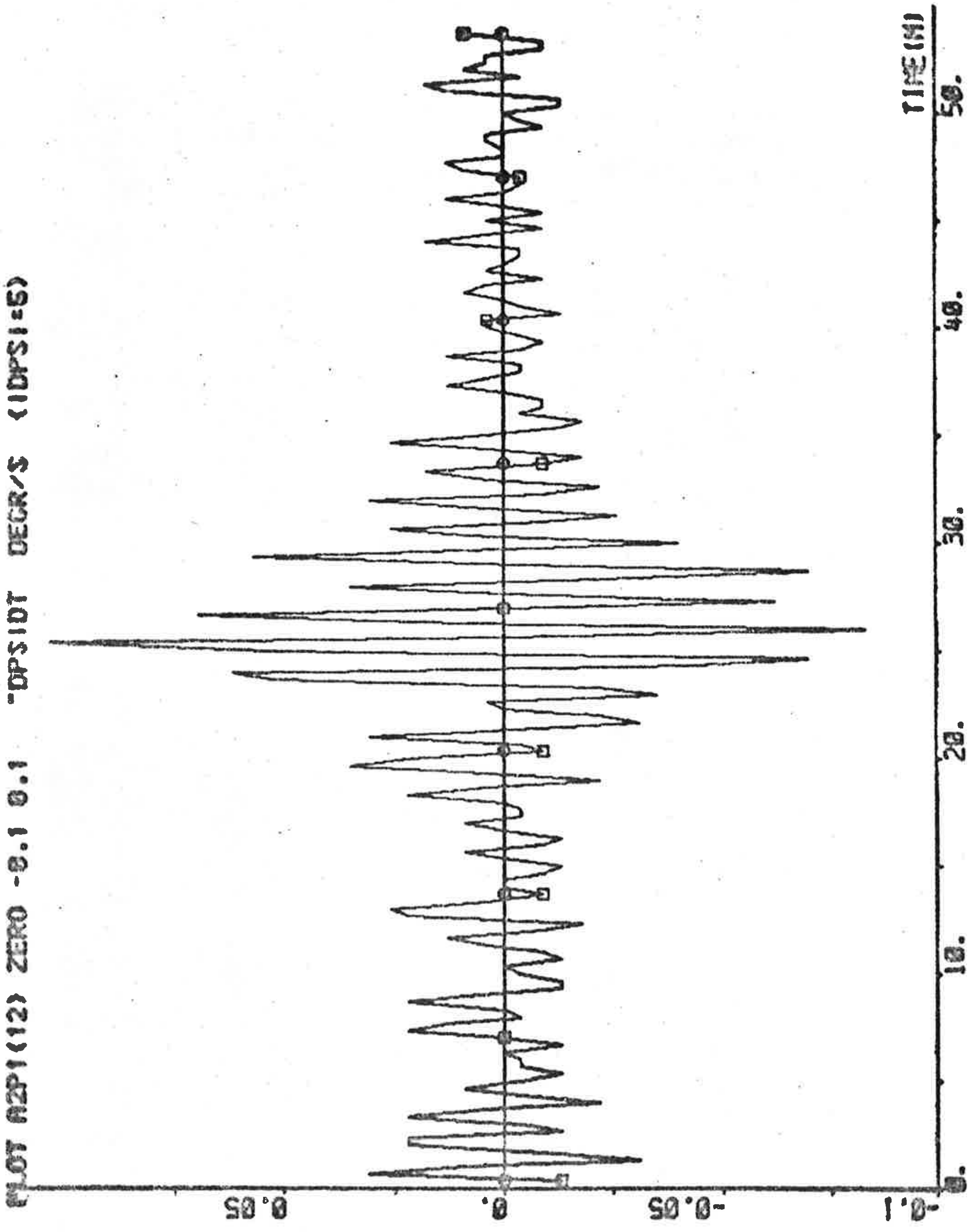

PLOT R2P1(7) 18 18 "U KNOTS
TIME(M)
0.
10.
20.
30.
40.
50.
16.
16.5
17.
17.5

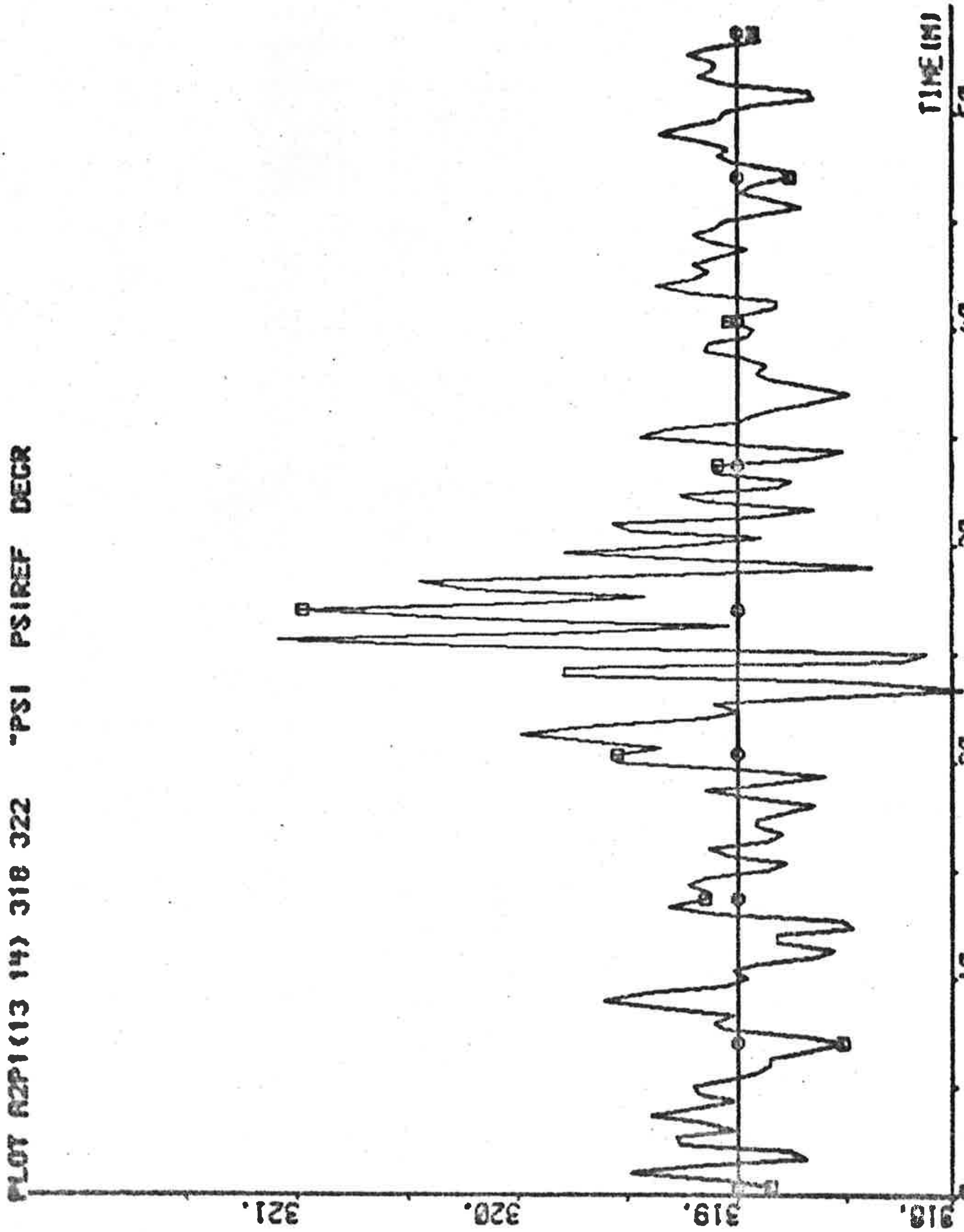

PLOT A2P1(S) 0 2 -V1 KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
0.5
1.
1.5

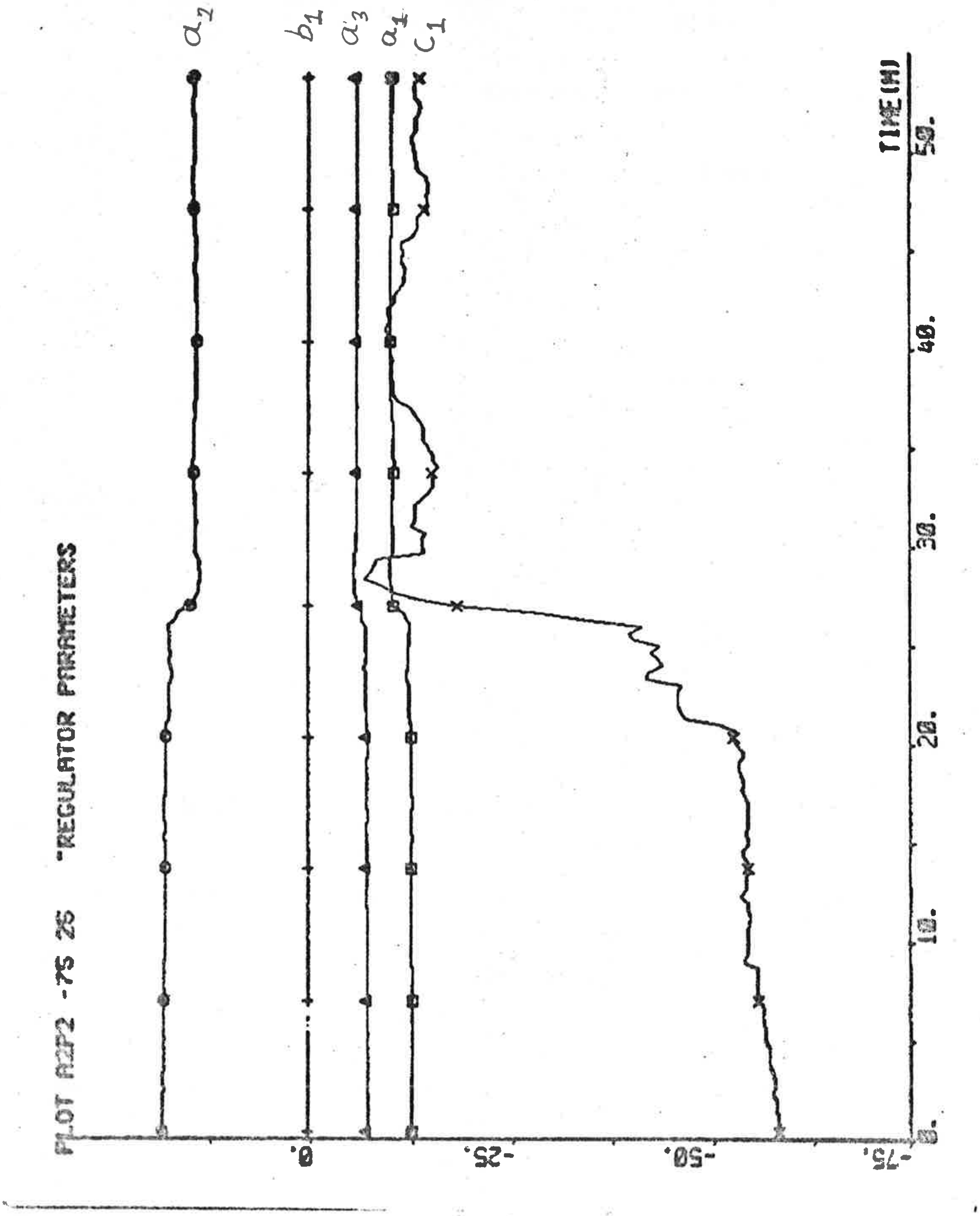

PLOT A2P1(3) ZERO -1 1 -V2 KNOTS
TIME(M)
0.5
0.
-0.5
-1.
0.
10.
20.
30.
40.
50.


PLOT R2P1(10) ZERO -0.1 0.1 "R DEGR/S
TIME(M)
0.
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1


PLOT A2P1(11) ZERO -0.1 0.1 °AVR DEGR/S (GR:0.5)
TIME(M)
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1


PLOT A2P1(12) ZERO -0.1 0.1 "DPSIDT DEGR/S (IDPSI=5)
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A2P1(13 14) 318 322 "PSI PSIREF DEGR
321.
320.
319.
318.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A2P2 -75 25 "REGULATOR PARAMETERS
TIME(H)
0.
10.
20.
30.
40.
50.
0.
-25.
-50.
-75.
a_2
b_1
a_3
a_1
c_1

EXPERIMENT A3.

Date	1974-10-10
Time	13.13
Duration	29 min
Position	N 28° 49' E 50° 35'
Water depth	38 - 40 m
Forward draught	20.1 m
Aft draught	20.4 m
Wind direction	SE (1; see Appendix A)
Wind velocity	1 Beaufort (1-1.5 m/s, light air)
Wave height	0.5 m
PSIREF	157°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 4
IREG = 15	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -12.373 \\ 21.422 \\ -9.450 \\ 0.307 \\ 44.214 \end{bmatrix}$$

P unknown

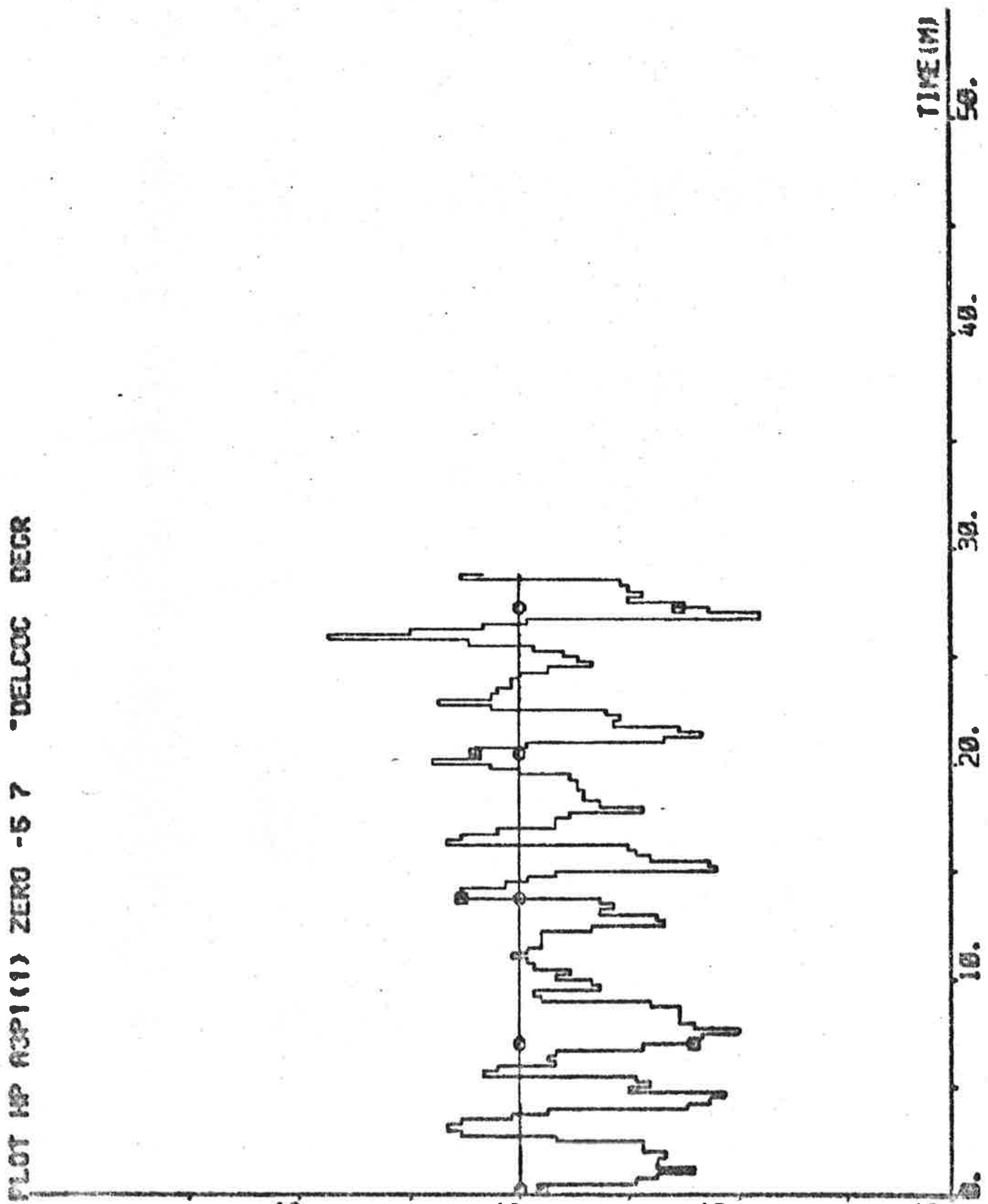
$a_1 + a_2 + a_3 = -\ 0.401$

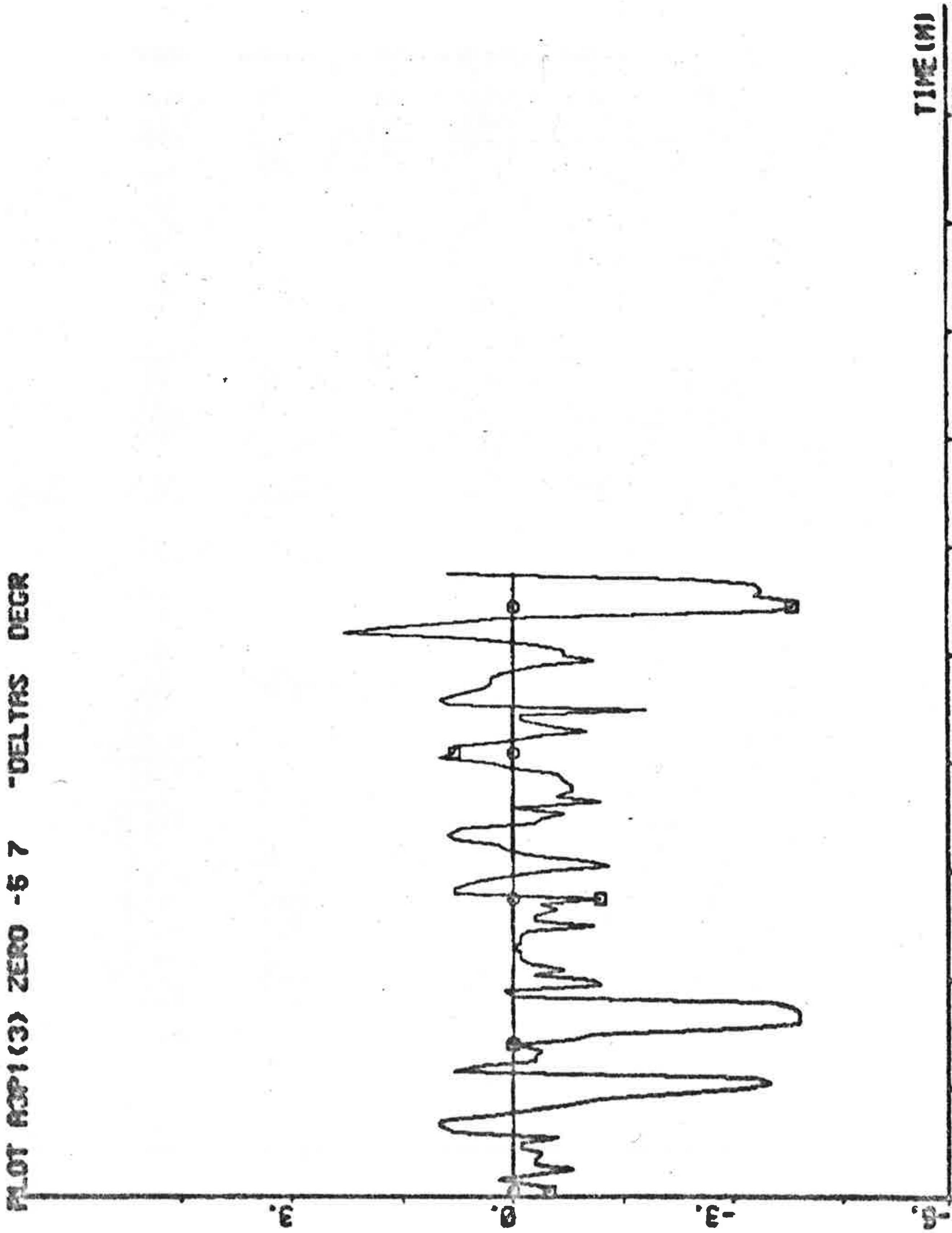
<u>Statistics</u> (mean value and standard deviation)

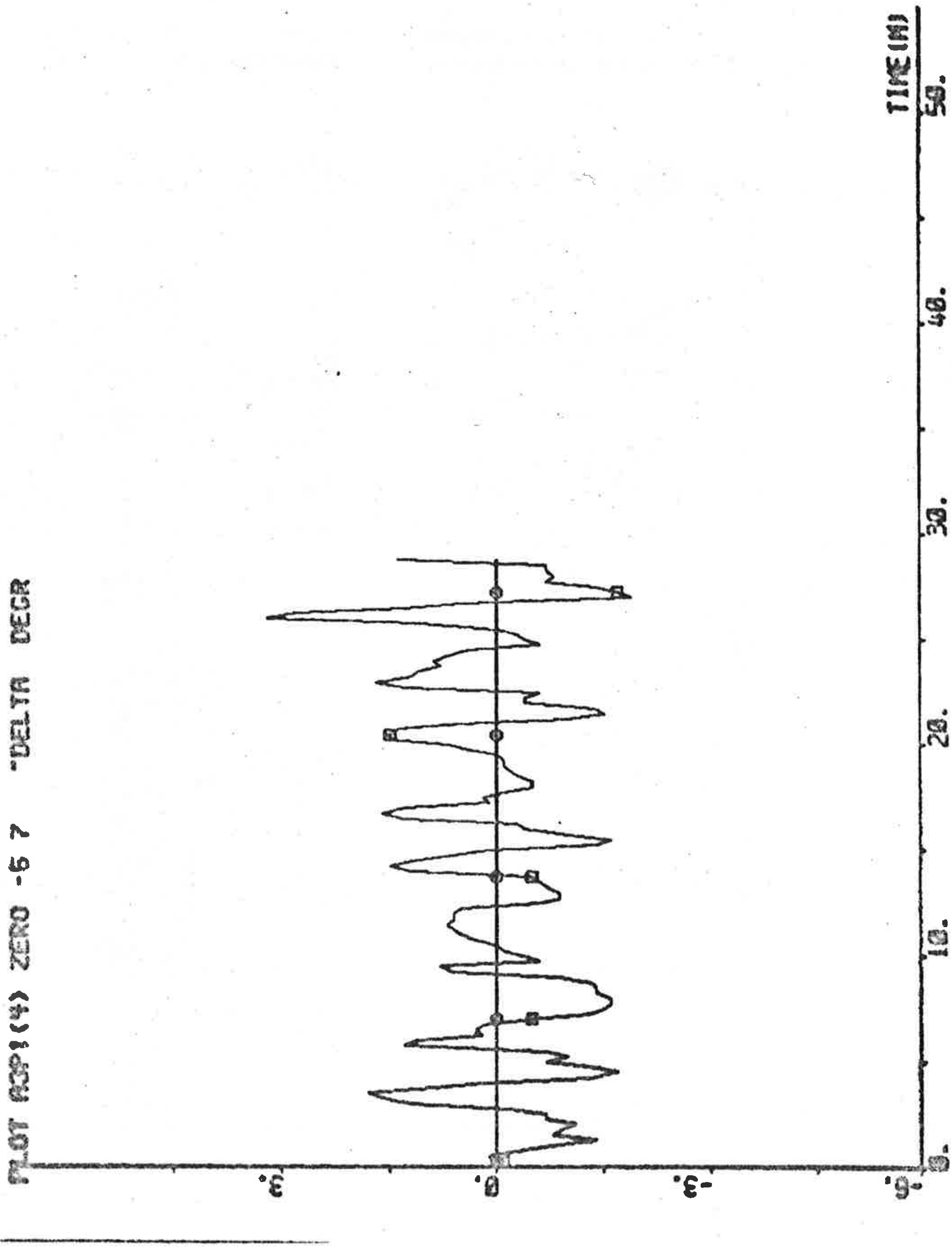
DELTA	-0.04 ± 1.03 deg
PSI - PSIREF	0.071 ± 0.182 deg
AN	80.19 ± 0.31 rpm
U	14.00 ± 0.08 knots

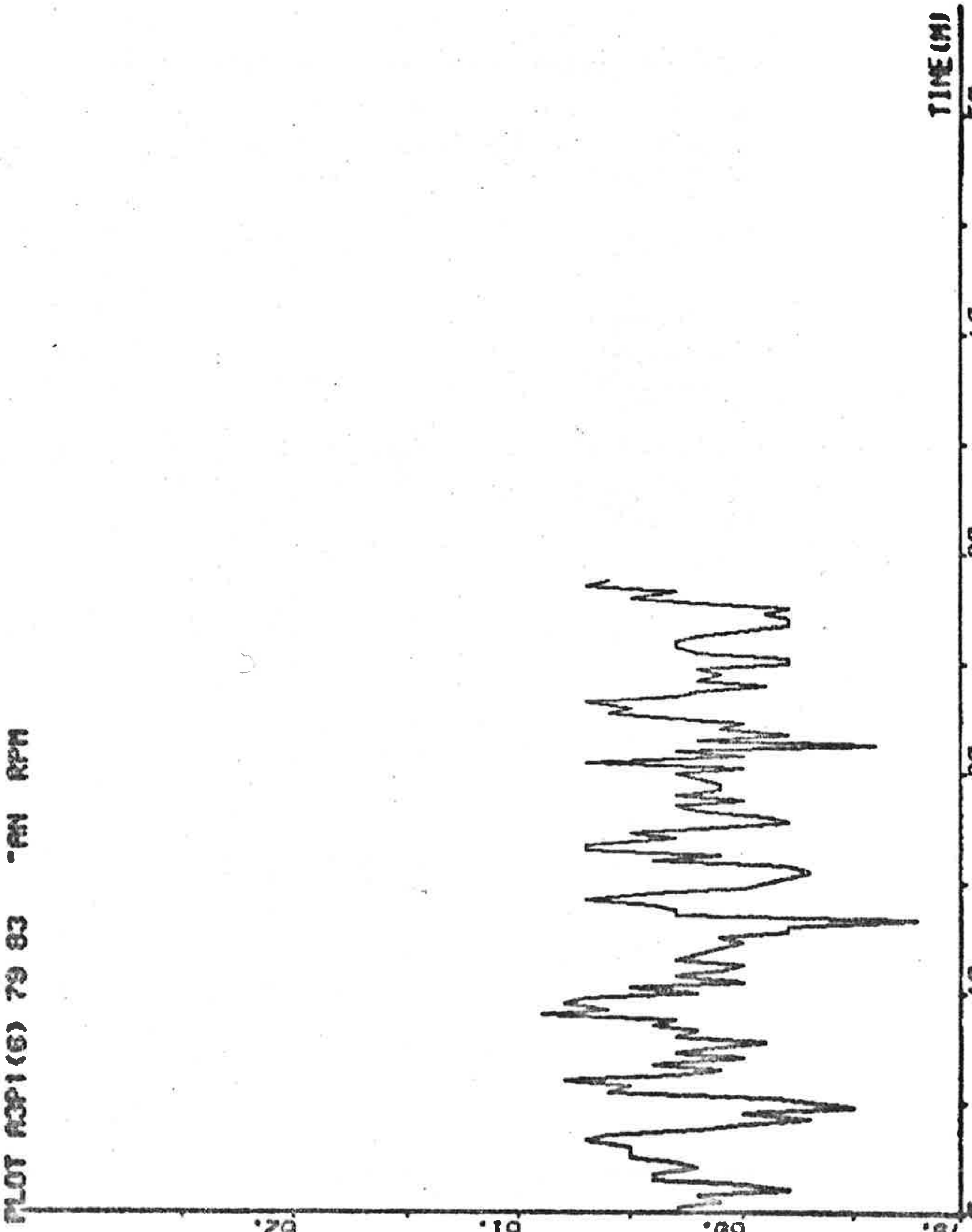
$V_1 = 0.144$

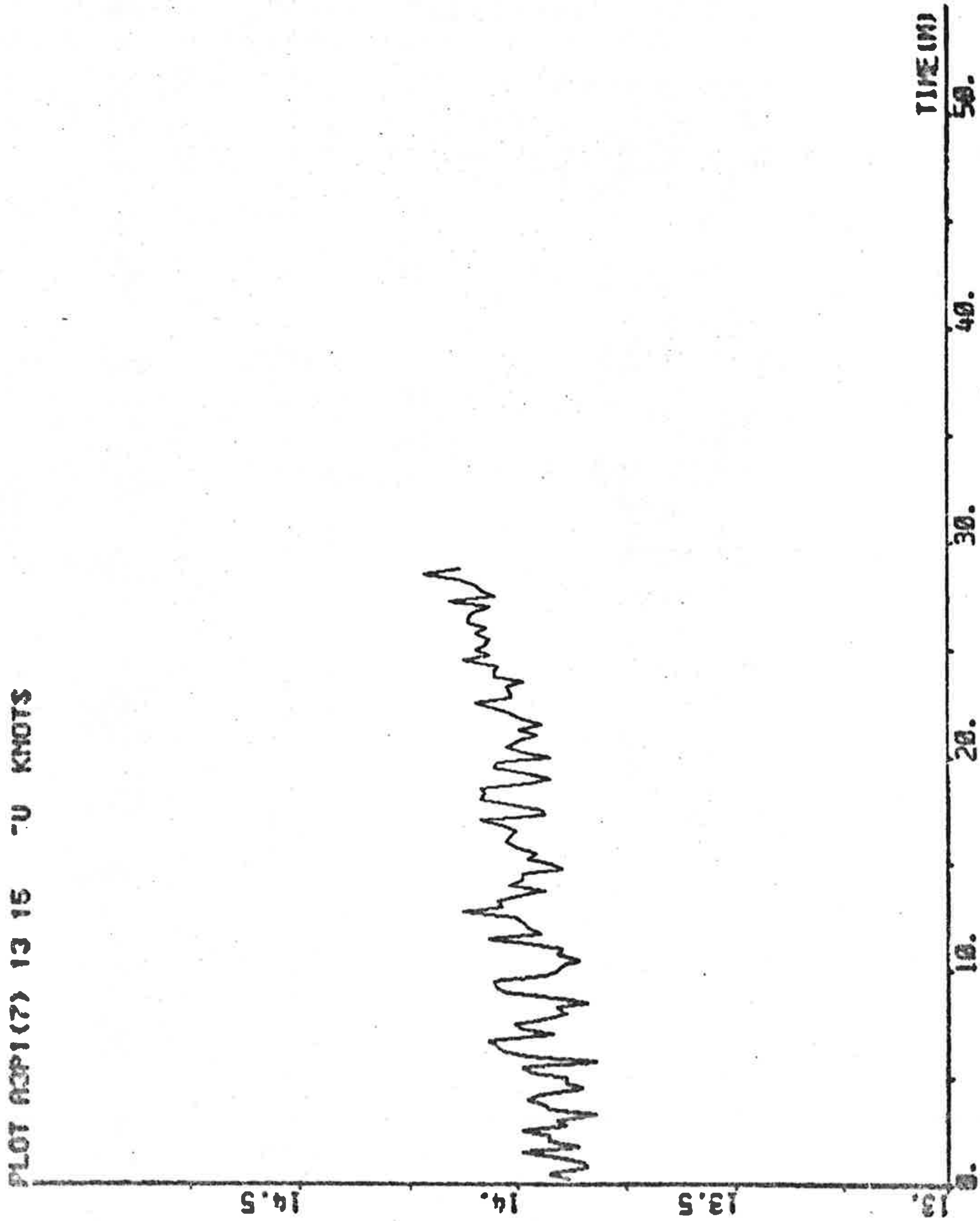
$V_2 = 0.144$

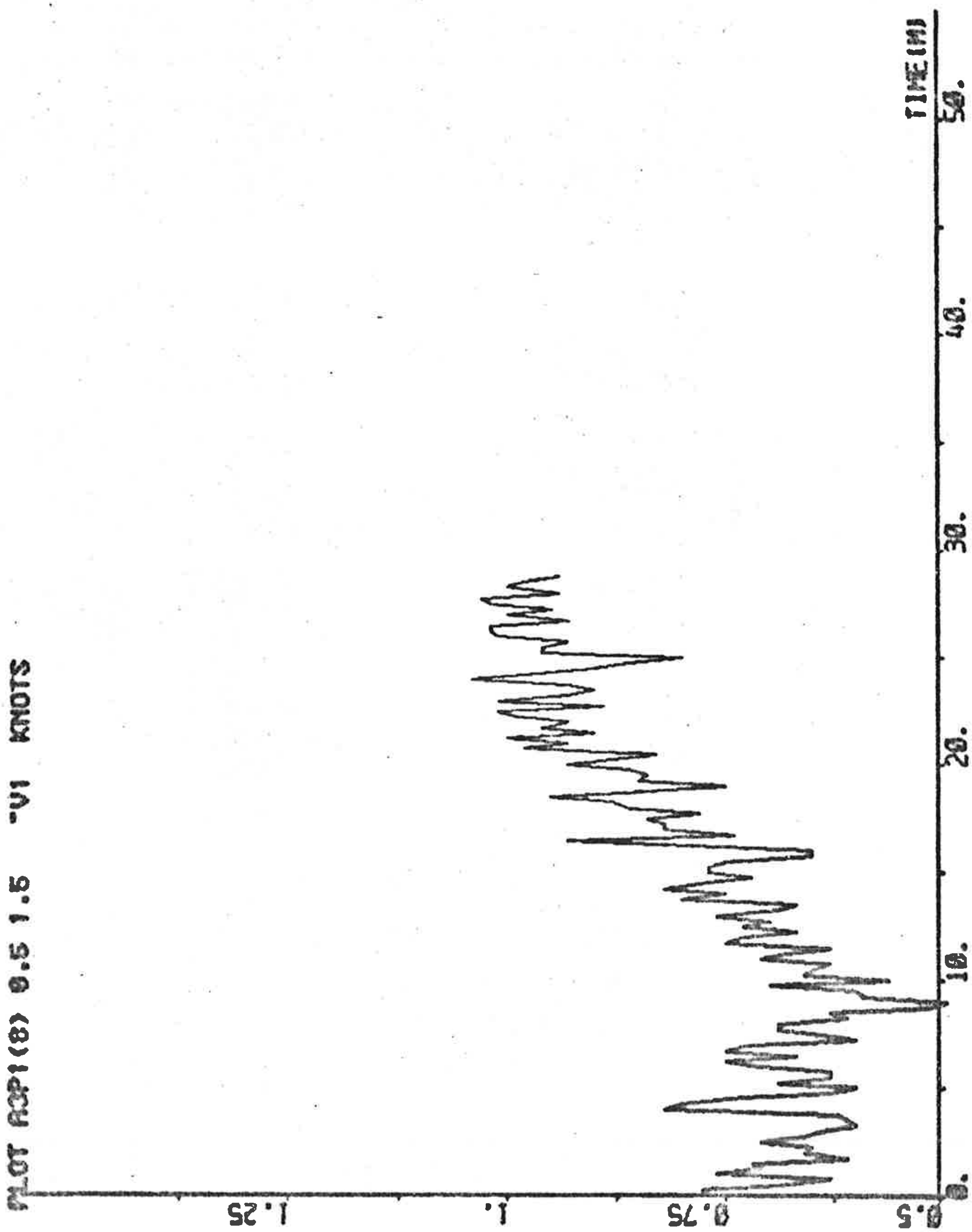

PLOT HP A3P1(1) ZERO -5 7 "DELCOC DEGR
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

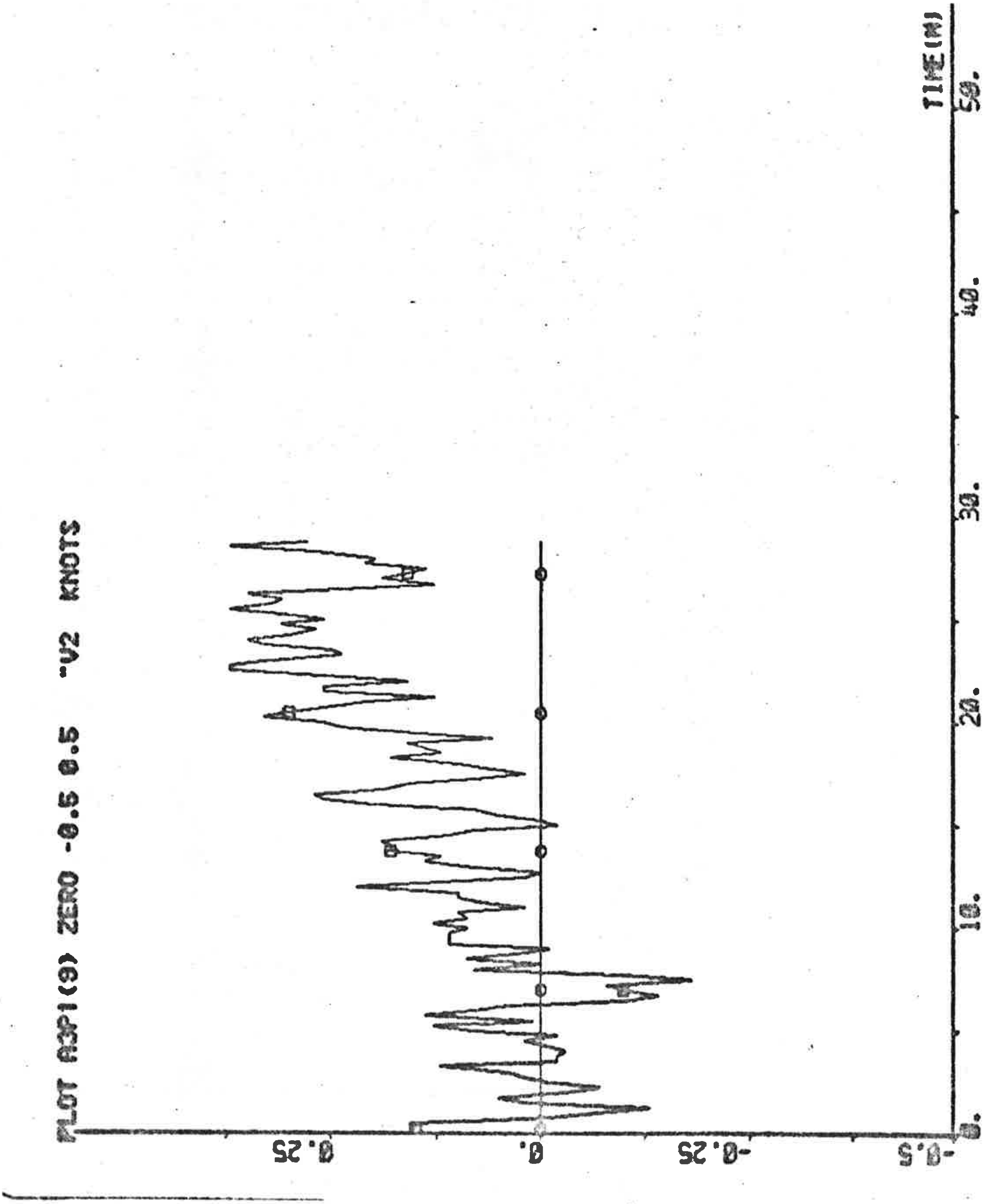

-DELTRS DEGR
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.

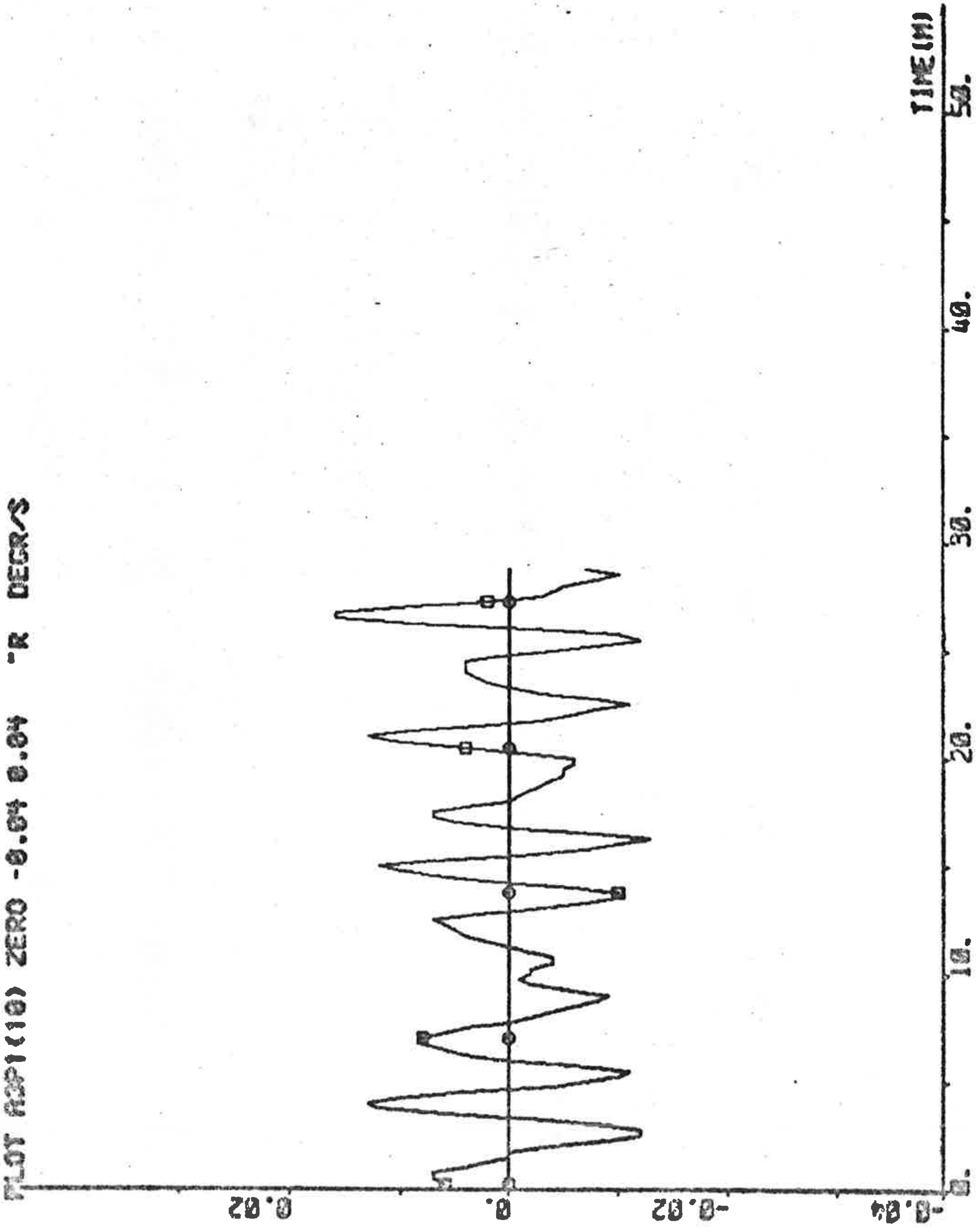

PLOT ASP1(4) ZERO -6 7 "DELTA DEGR
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

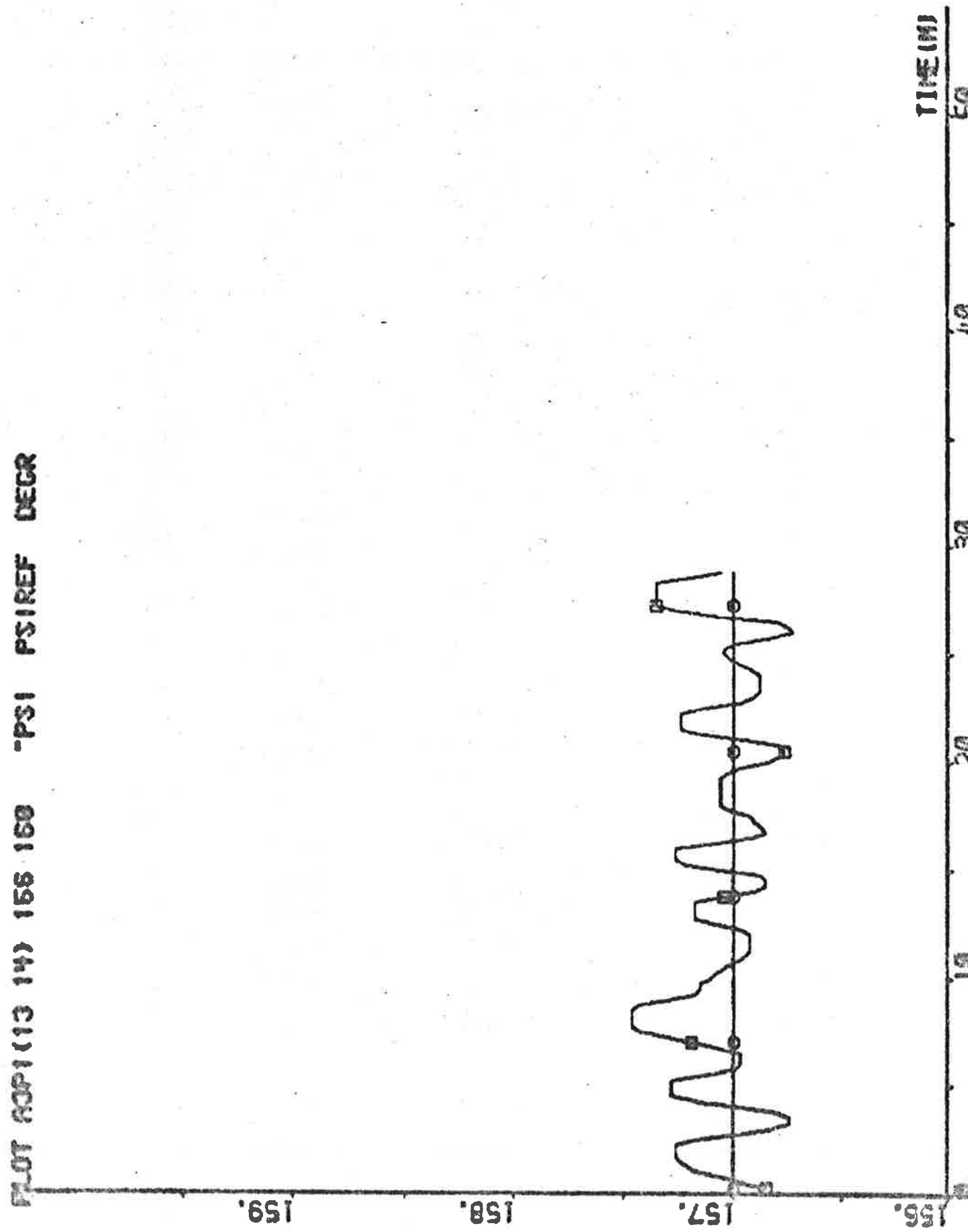

RPM
TIME(M)
0.
10.
20.
30.
40.
50.
79.
80.
81.
82.

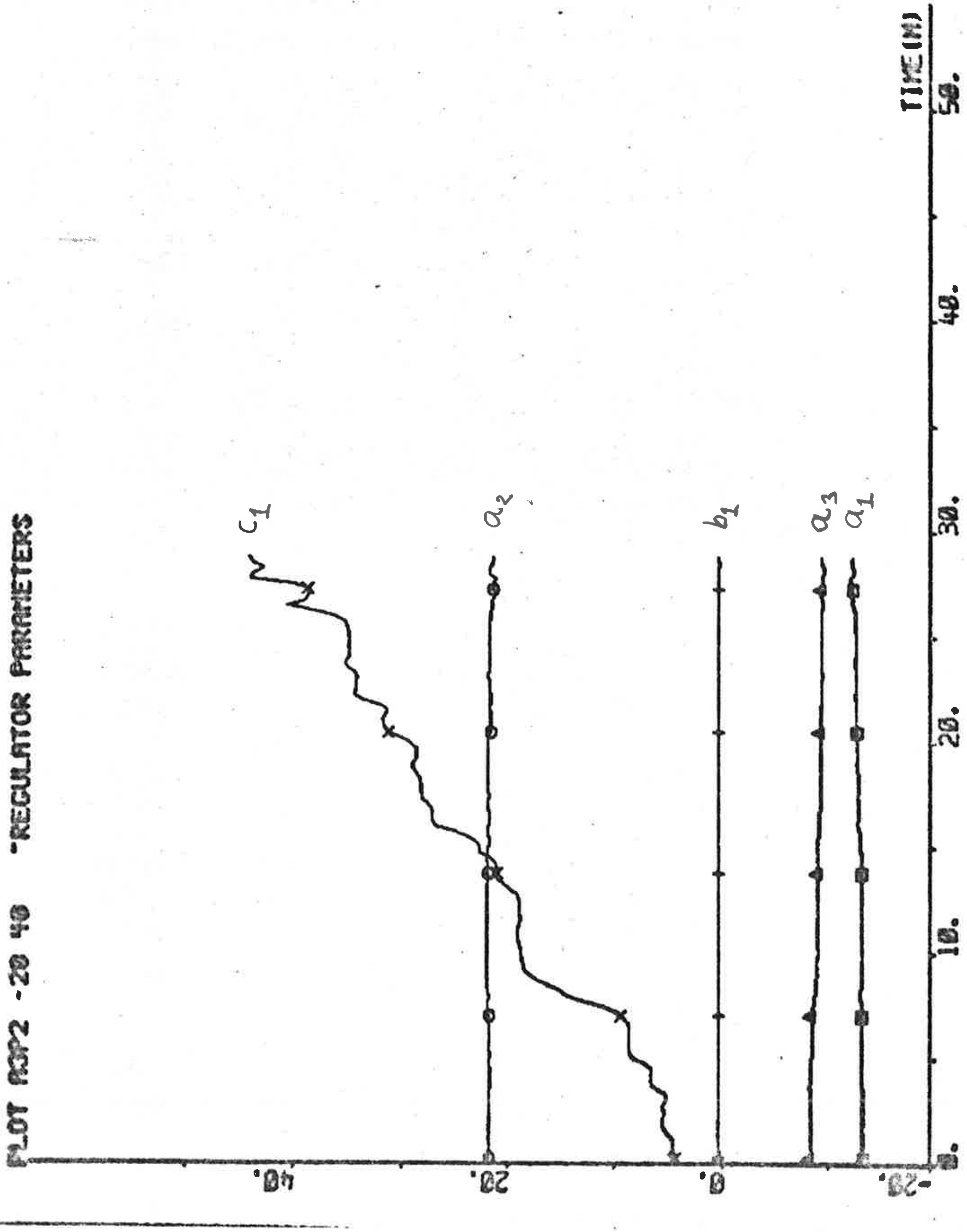

PLOT ACP1(2) 13 15 "U KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
13.
13.5
14.
14.5


PLOT RCP1(8) 0.5 1.5 "V1 KNOTS
TIME(M)
0.
10.
20.
30.
40.
50.
0.5
0.75
1.
1.25


PLOT A3P1(9) ZERO -0.5 0.5 "V2 KNOTS
0.25
0.
-0.25
-0.5
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A3P1(10) ZERO -0.04 0.04 R DEGR/S
TIME(M)
0.
10.
20.
30.
40.
50.
0.02
0.
-0.02
-0.04


PLOT ROPI(13 14) 156 160 -PSI PSIREF DEGR
TIME(M)
0.
10.
20.
30.
40.
50.
156.
157.
158.
159.


PLOT ASP2 -20 40
"REGULATOR PARAMETERS
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME(H)
c_1
a_2
b_1
a_3
a_1

EXPERIMENT A4

Date	1974-10-10
Time	15.46
Duration	62 min
Position	N 28° 25' E 50° 47'
Water depth	50 - 60 m
Forward draught	20.1 m
Aft draught	20.4 m
Wind direction	S (2; see Appendix A)
Wind velocity	1 Beaufort (1-1.5 m/s, light air)
Wave height	0.5 m
PSIREF	157°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 4
IREG = 15	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -8.730 \\ 18.286 \\ -11.470 \\ 0.517 \\ 144.576 \end{bmatrix} \qquad P = \begin{bmatrix} 12.082 & & & & \\ -19.048 & 38.190 & & & \\ 7.095 & -17.204 & 11.188 & & \\ 0.080 & -0.410 & 0.306 & 0.038 & \\ 85.698 & -199.703 & 79.430 & 5.299 & 2036.391 \end{bmatrix}$$

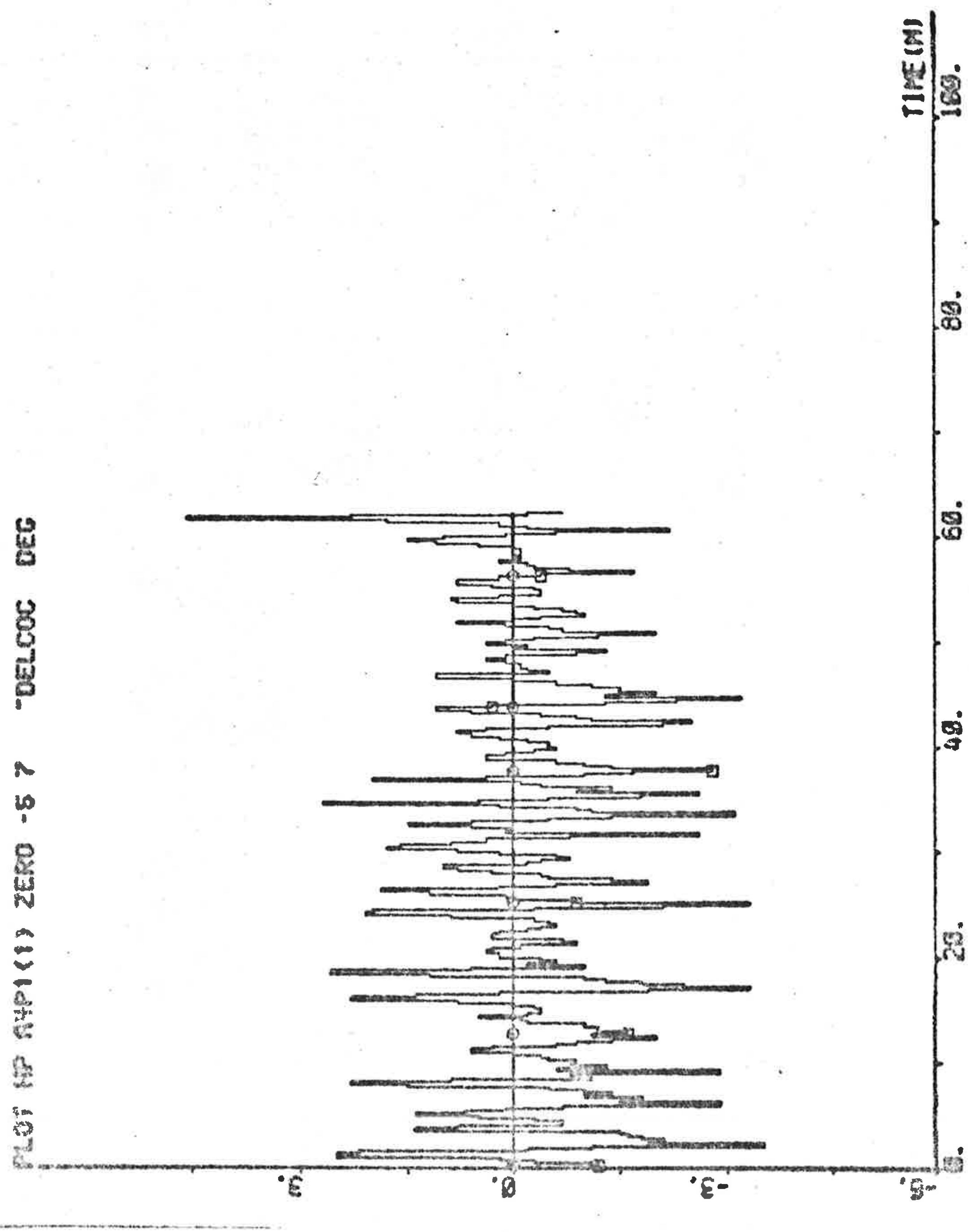
$a_1 + a_2 + a_3 = -1.914$

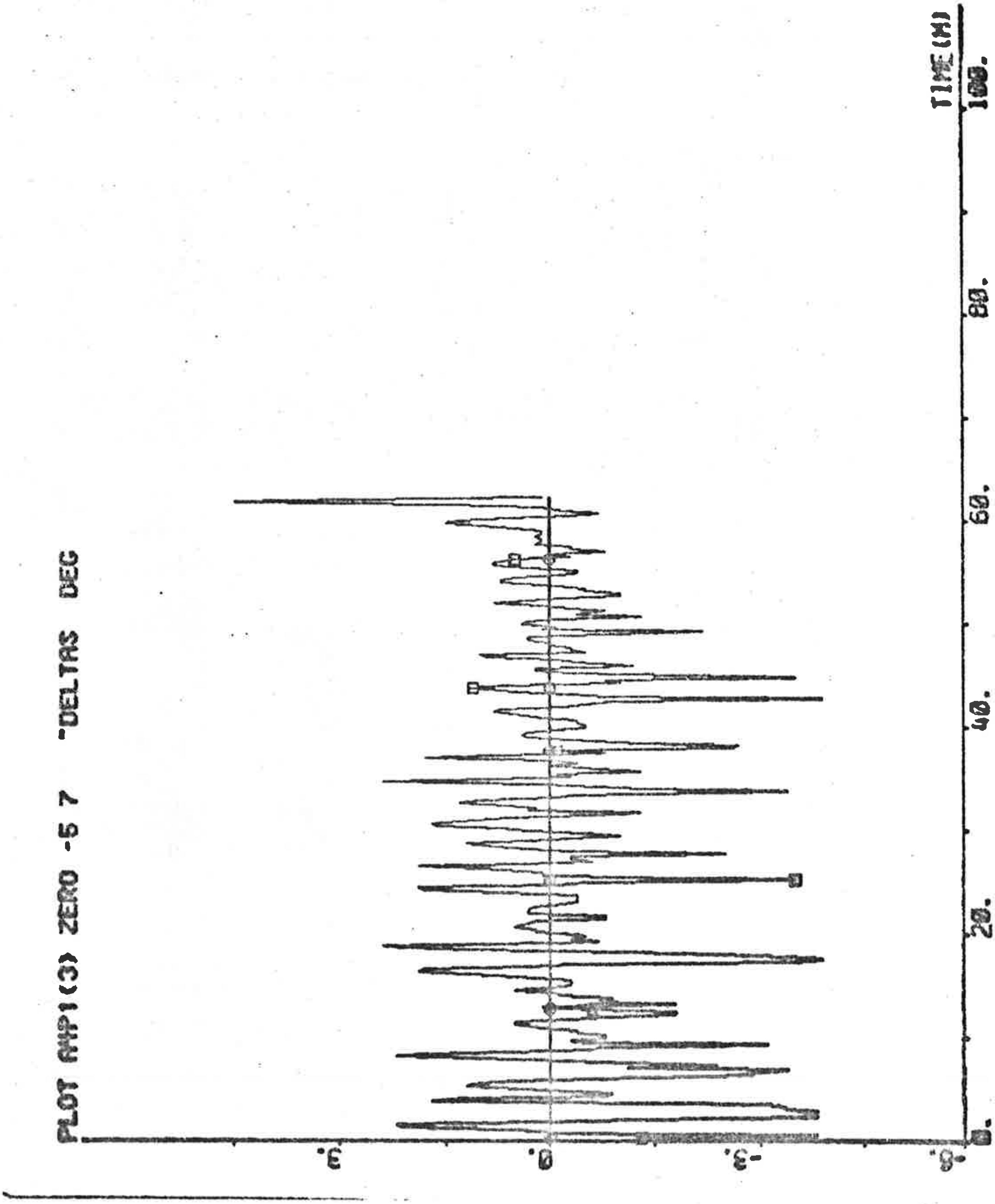
<u>Statistics</u> (mean value and standard deviation)

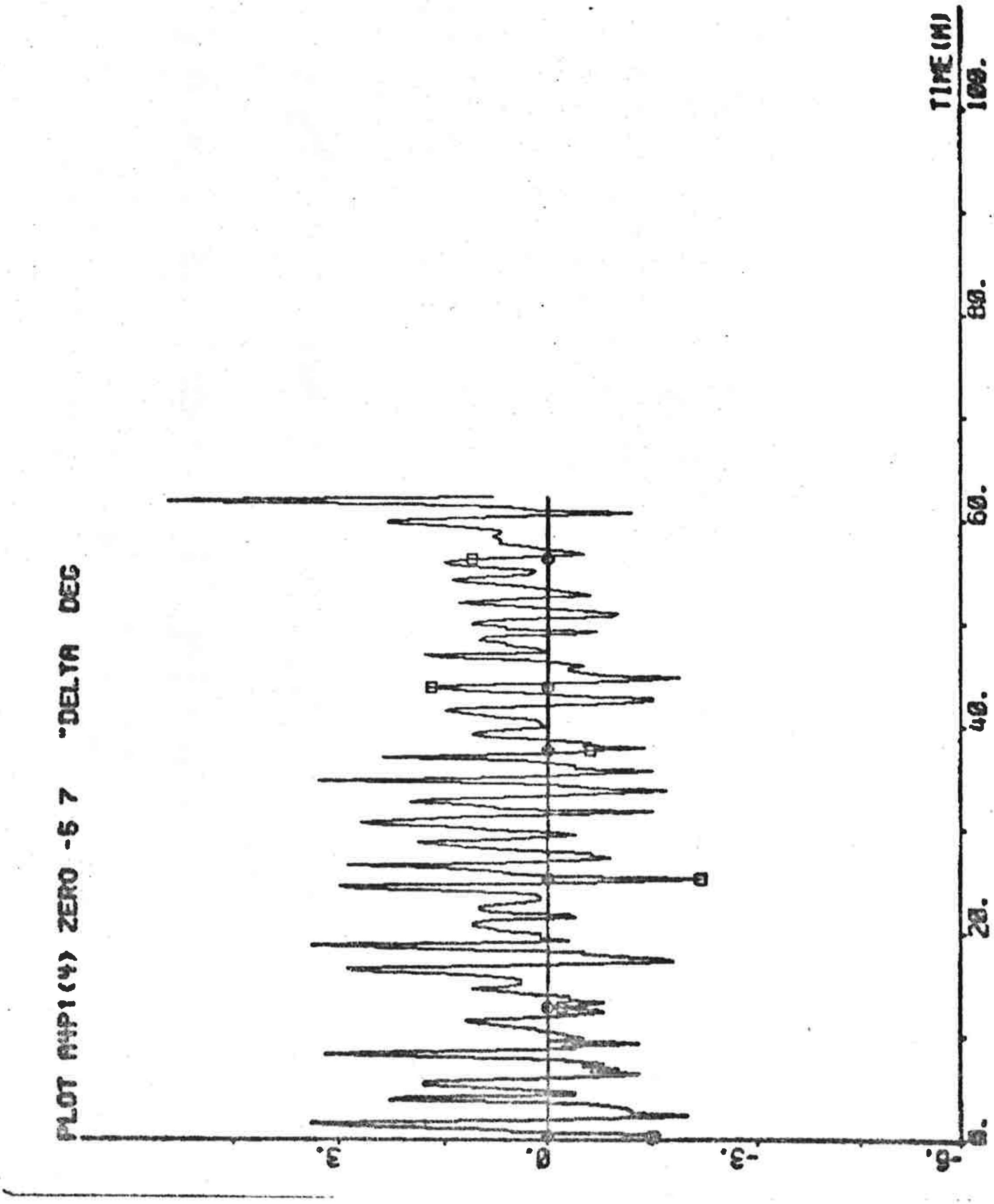
DELTA	0.40 ± 1.15 deg
PSI-PSIREF	0.034 ± 0.121 deg
AN	80.98 ± 0.36 rpm
U	14.37 ± 0.11 knots

$V_1 = 0.164$

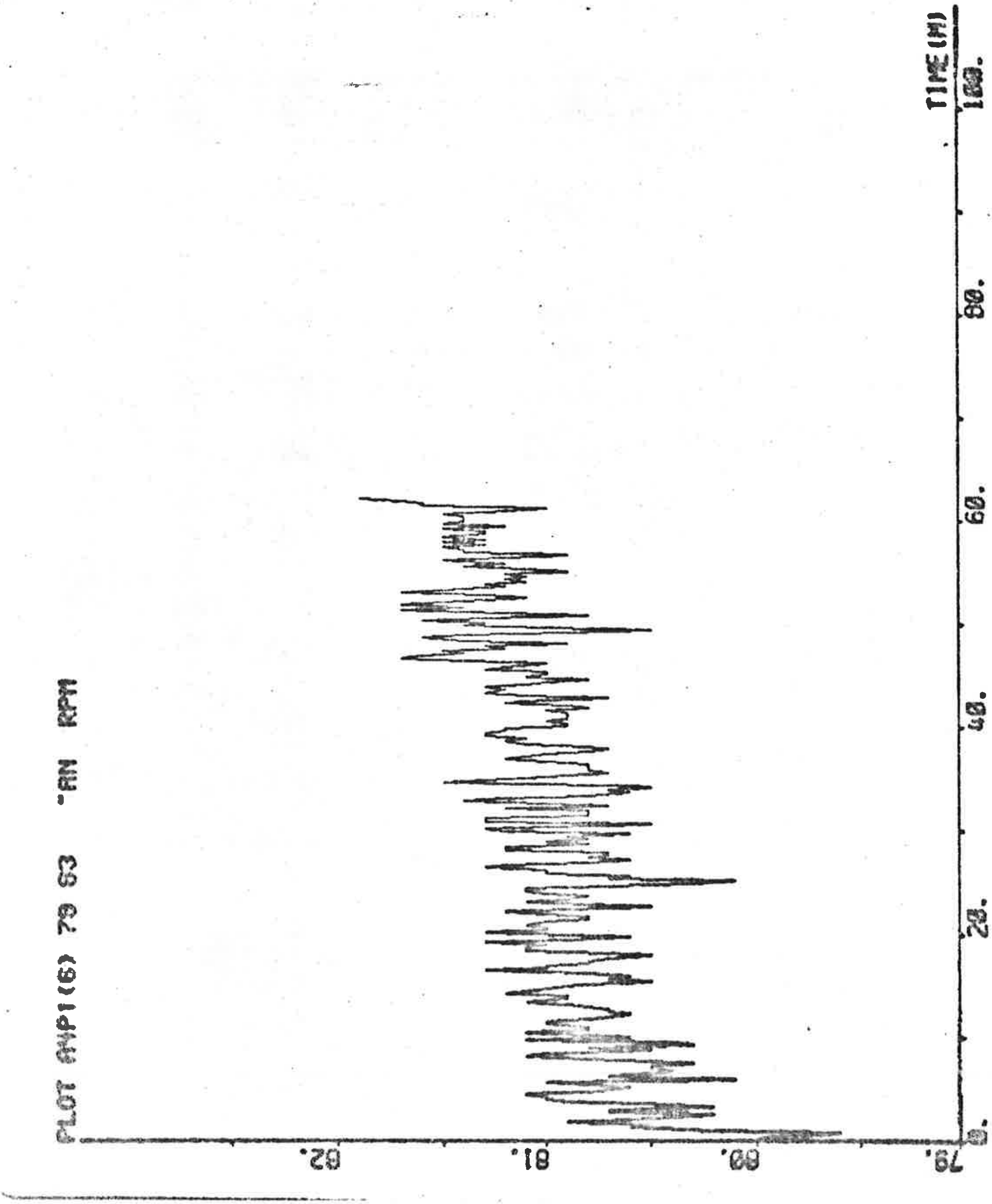
$V_2 = 0.148$

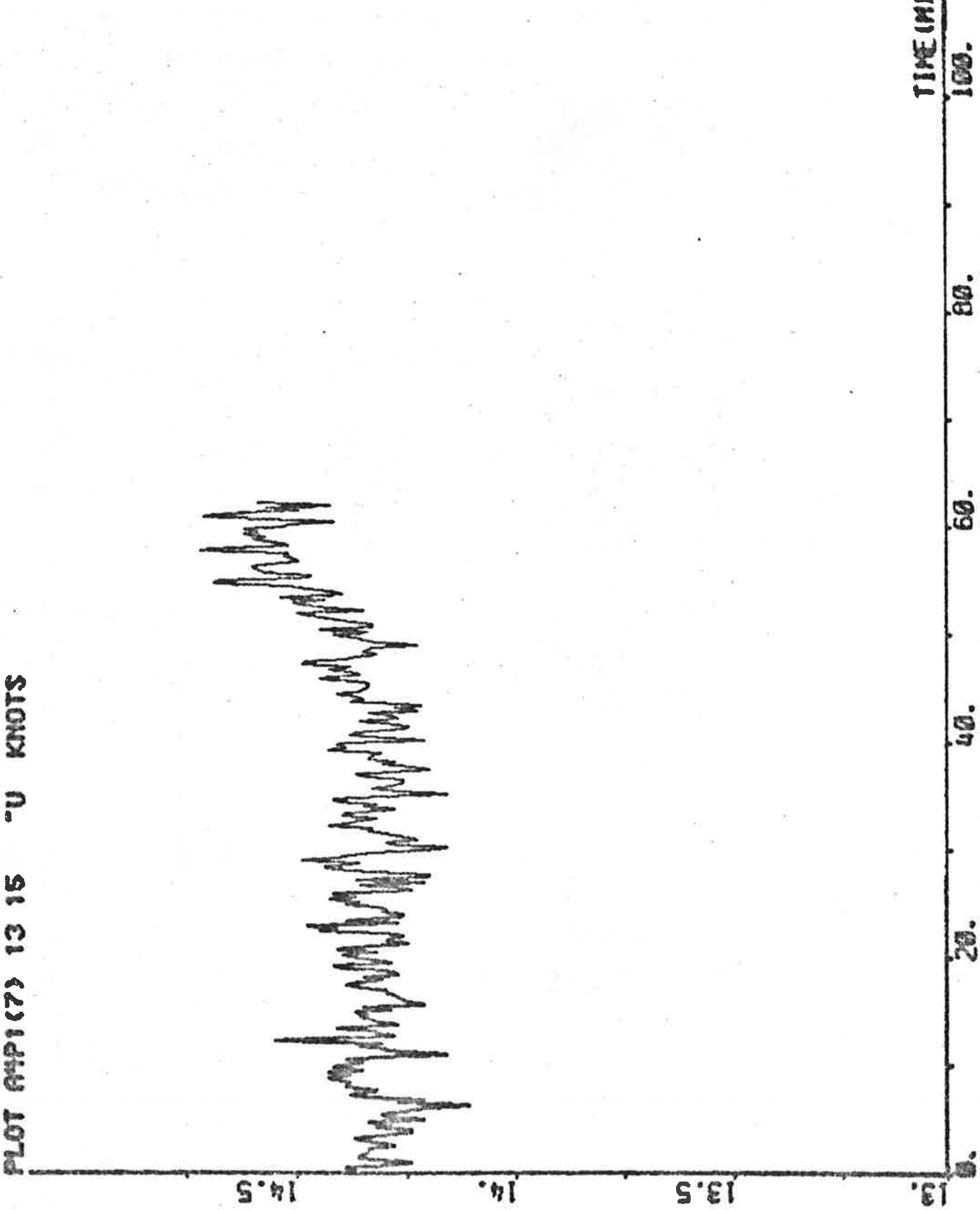

PLOT HP AYP1(1) ZERO -5 7 'DELCOC DEG
TIME(M)
0.
20.
40.
60.
80.
100.
3.
0.
-3.

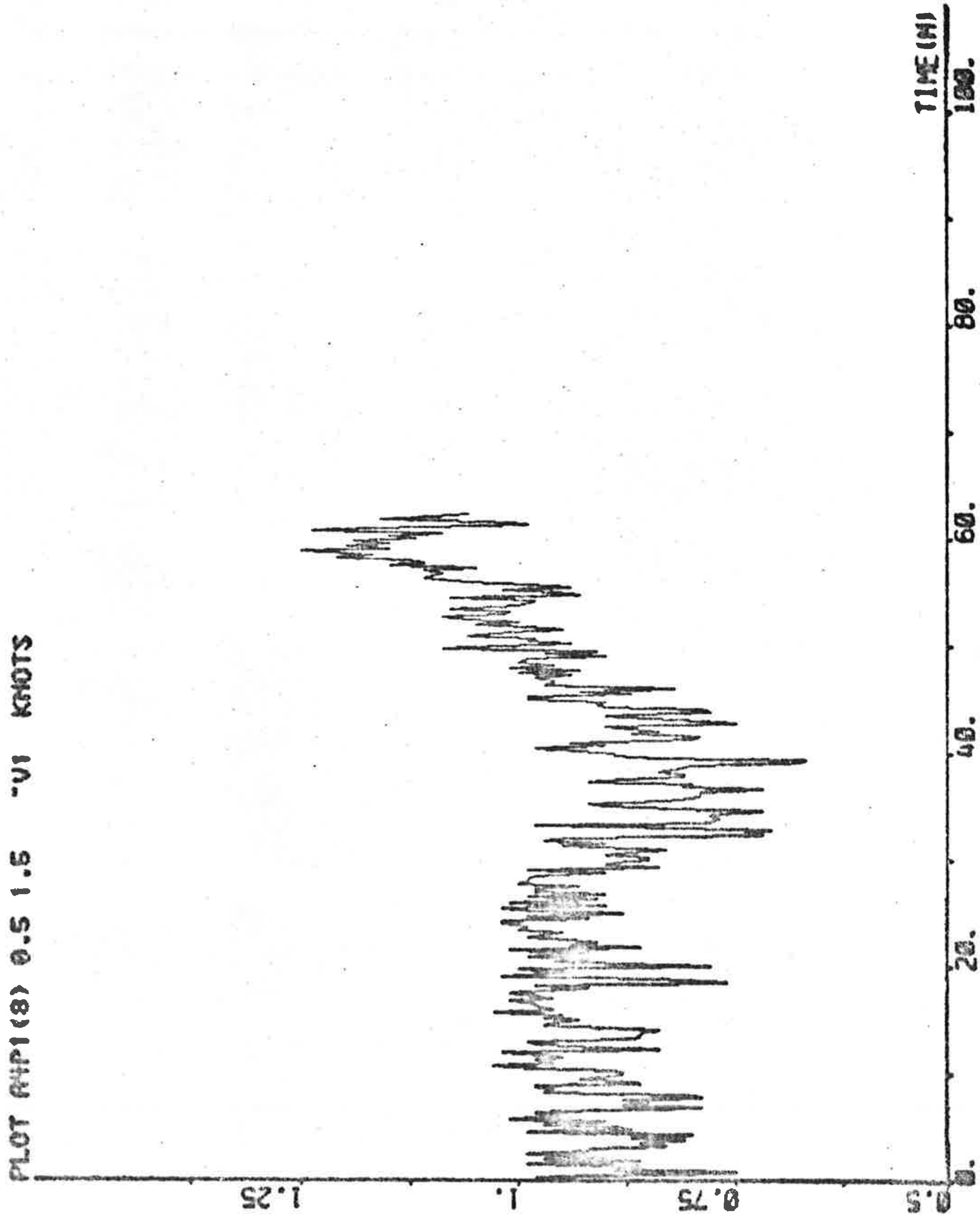

PLOT AMP1(3) ZERO -5 7 "DELTAS DEG
3.
0.
-3.
-6.
0.
20.
40.
60.
80.
100.
TIME(M)

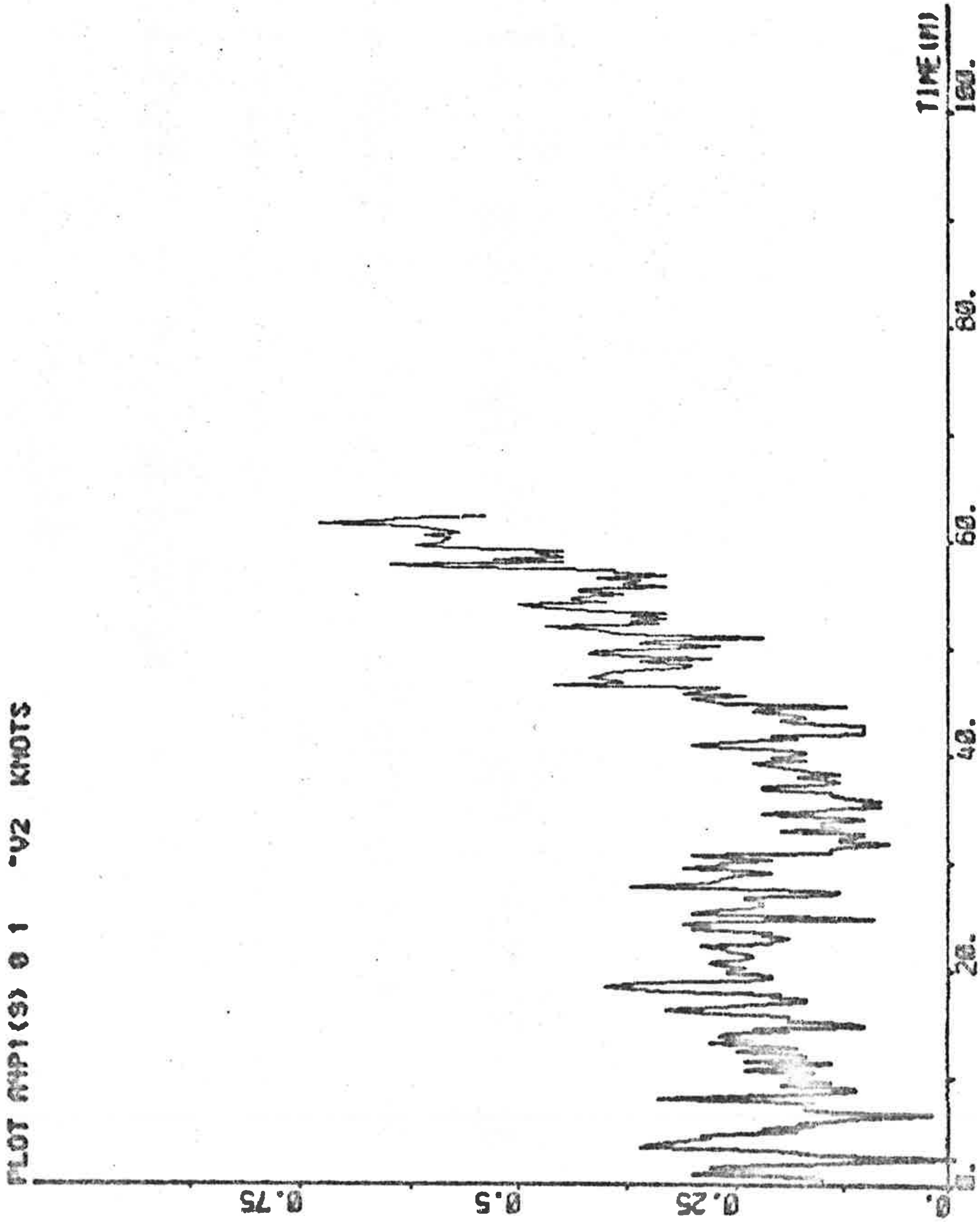


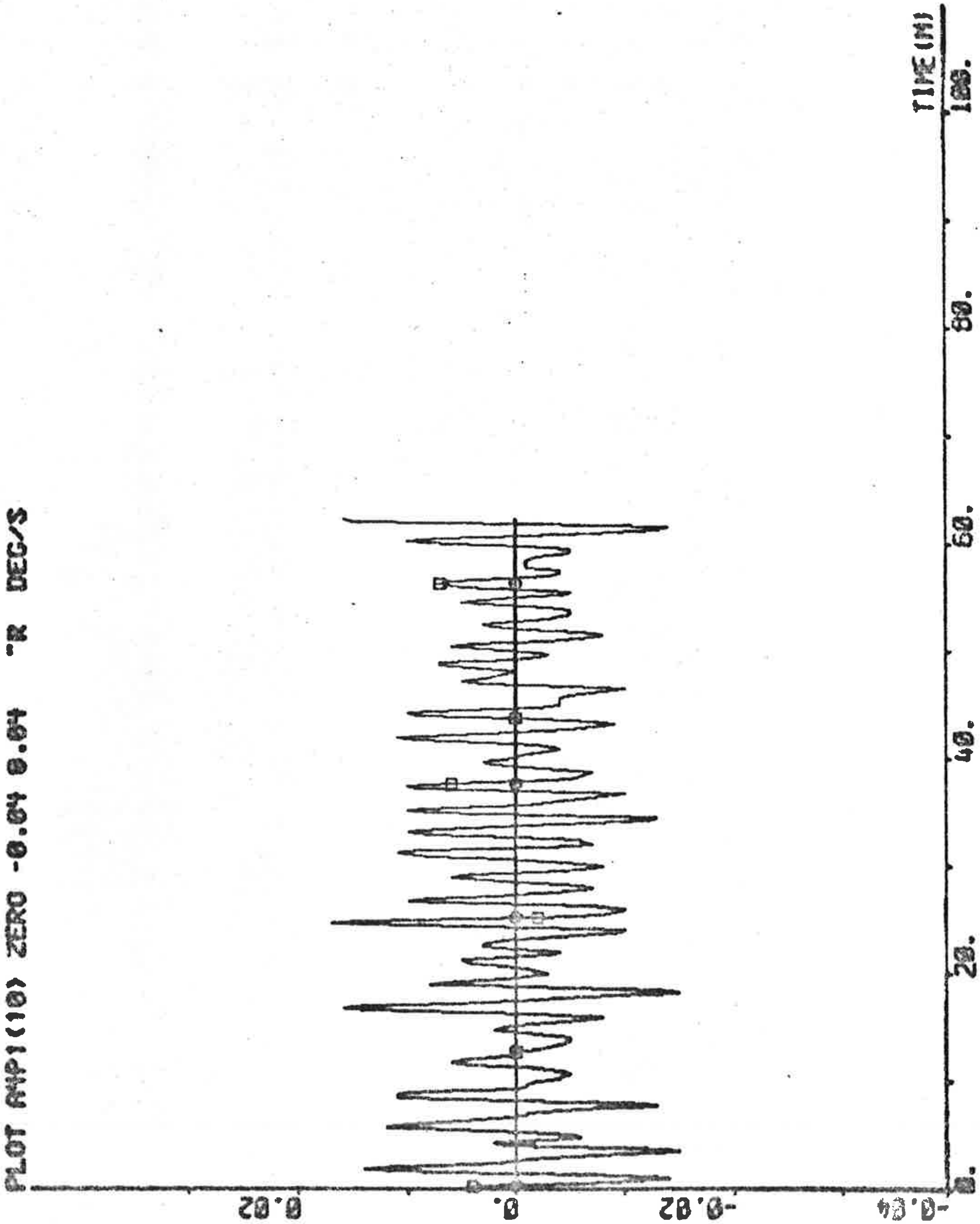
PLOT AMP1(4) ZERO -5 7 "DELTA DEG
TIME(M)
0.
20.
40.
60.
80.
100.
3.
0.
-3.
-6.


PLOT AMP1(6) 79 83 'RN RPM
79.
80.
81.
82.
0.
20.
40.
60.
80.
100.
TIME (M)

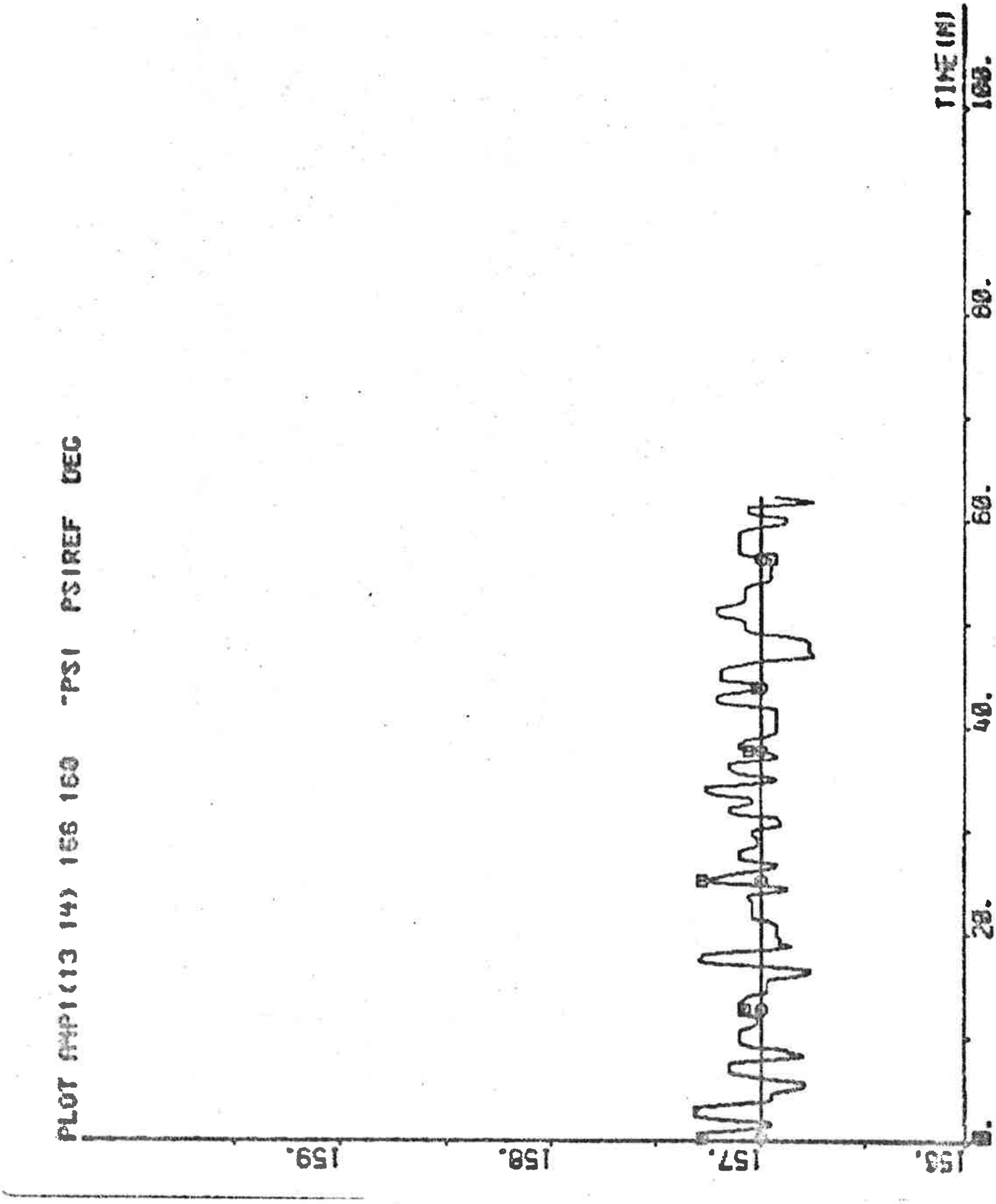

PLOT AMP1(7) 13 15 "U KNOTS
TIME(M)
0.
20.
40.
60.
80.
100.
13.
13.5
14.
14.5

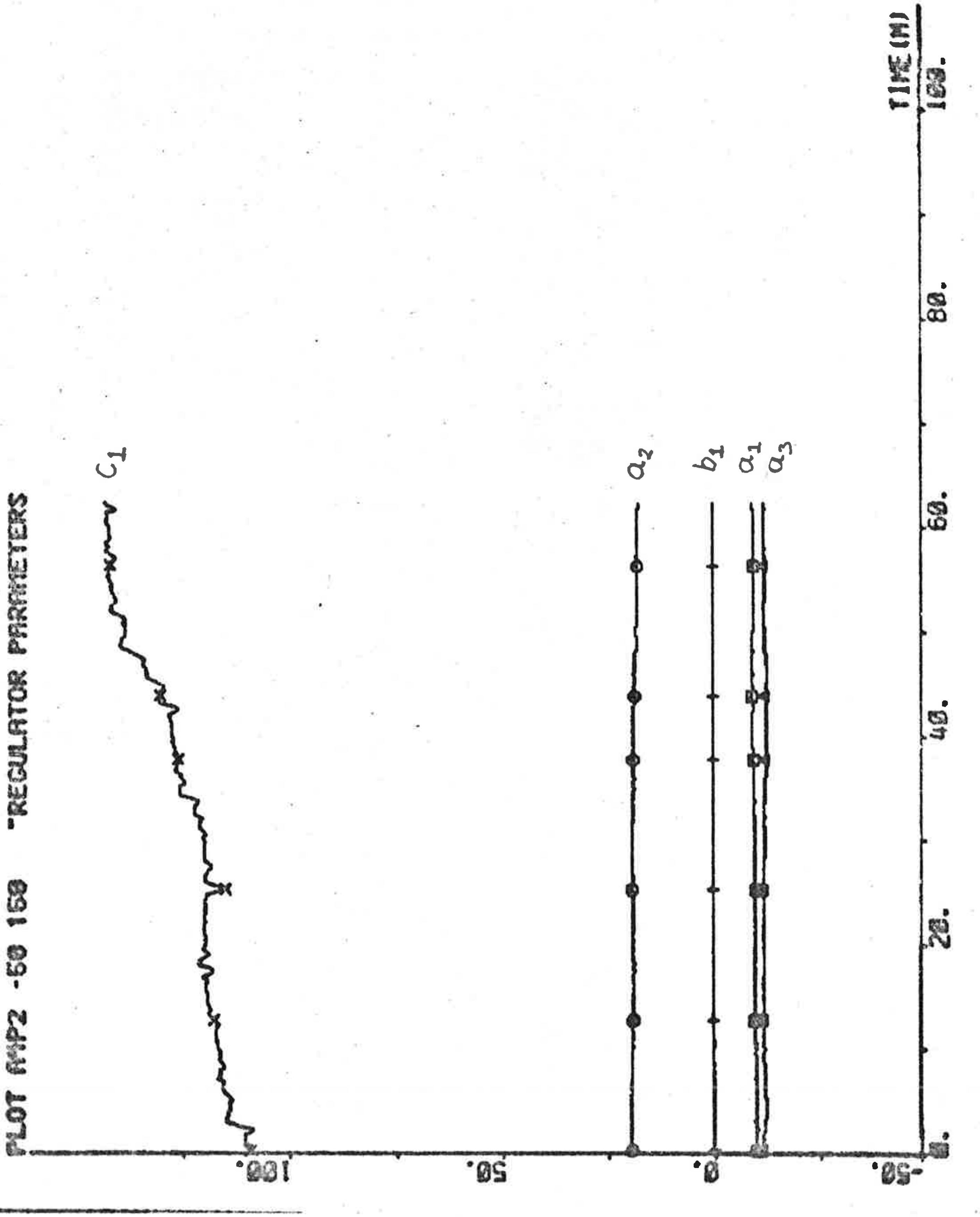

PLOT A+P1(8) 0.5 1.5 "V1 KNOTS
1.25
1.
0.75
0.5
0.
20.
40.
60.
80.
100.
TIME(H)


PLOT AMP1(S) 0 1 -V2 KNOTS
0.
0.25
0.5
0.75
20.
40.
60.
80.
100.
TIME(M)



PLOT ANP1(10) ZERO -0.04 0.04 "R DEG/S
TIME(M)
0.
20.
40.
60.
80.
100.
0.02
0.
-0.02
-0.04


PSIREF DEG
157.
158.
159.
20.
40.
TIME(M)


PLOT AMP2 -50 150 "REGULATOR PARAMETERS
TIME (M)
0.
20.
40.
60.
80.
100.
-50.
0.
50.
100.
C1
a2
b1
a1
a3

EXPERIMENT A5

Date	1974-10-10
Time	23.22
Duration	46 min
Position	N 27° 06' E 52° 05'
Water depth	60 - 70 m
Forward draught	20.1 m
Aft draught	20.4 m
Wind direction	-
Wind velocity	0 Beaufort (0-0.5 m/s, calm)
Wave height	0 m
PSIREF	117°
Rudder limit	Not active

<u>Regulator structure</u>

NA = 3	NB = 1	NC = 1	K = 4
IREG = 20	IRDIF = 0	RL = 0.98	IRR = 1

<u>Final values</u>

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -8.829 \\ 14.382 \\ -7.214 \\ 0.811 \\ 131.639 \end{bmatrix} \qquad P = \begin{bmatrix} 59.091 & & & & \\ -83.116 & 120.612 & & & \\ 24.364 & -38.351 & 16.762 & & \\ -1.385 & 1.754 & -0.363 & 0.097 & \\ 694.849 & -984.399 & 244.258 & -10.380 & 11216.128 \end{bmatrix}$$

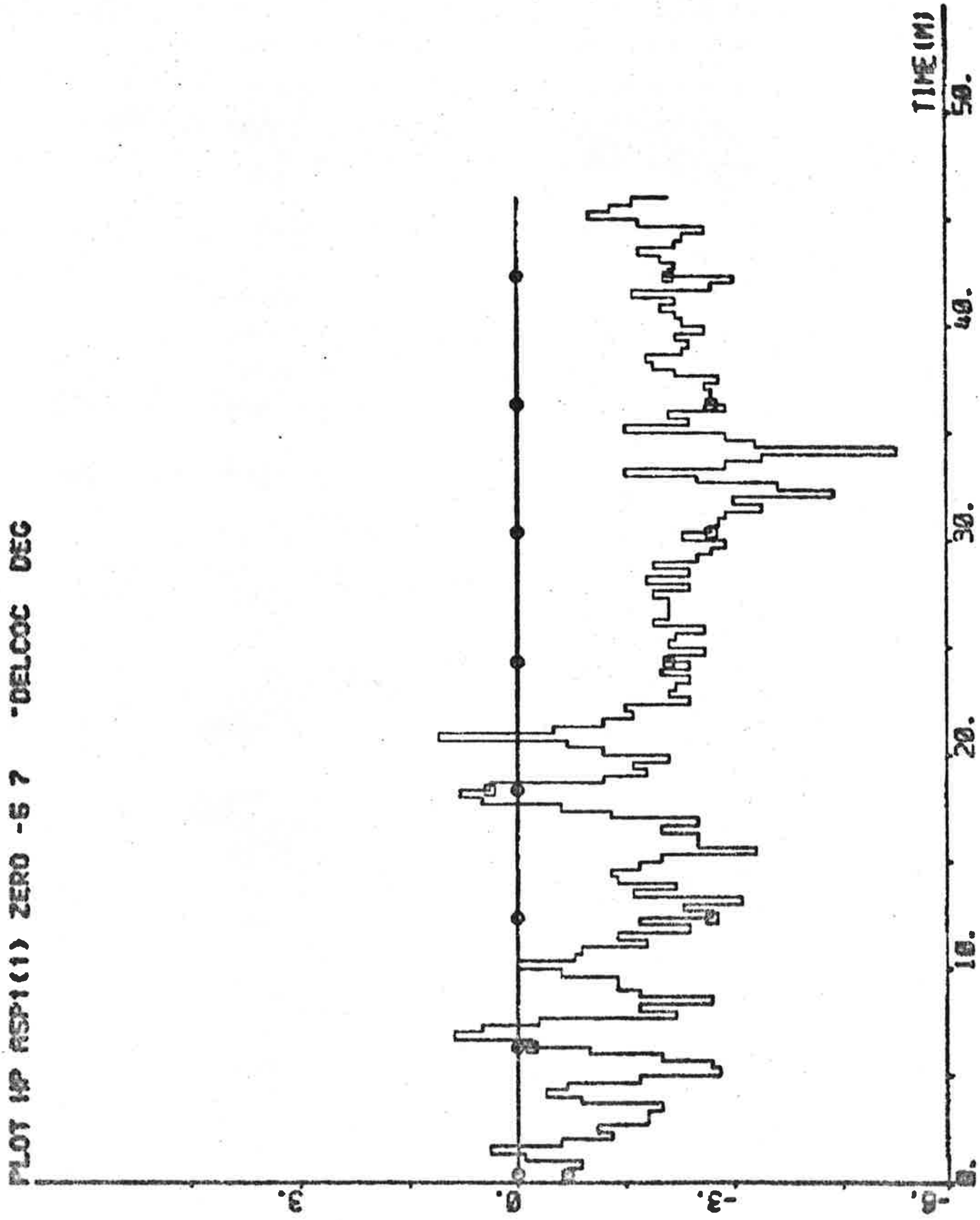
$$a_1 + a_2 + a_3 = -1.661$$

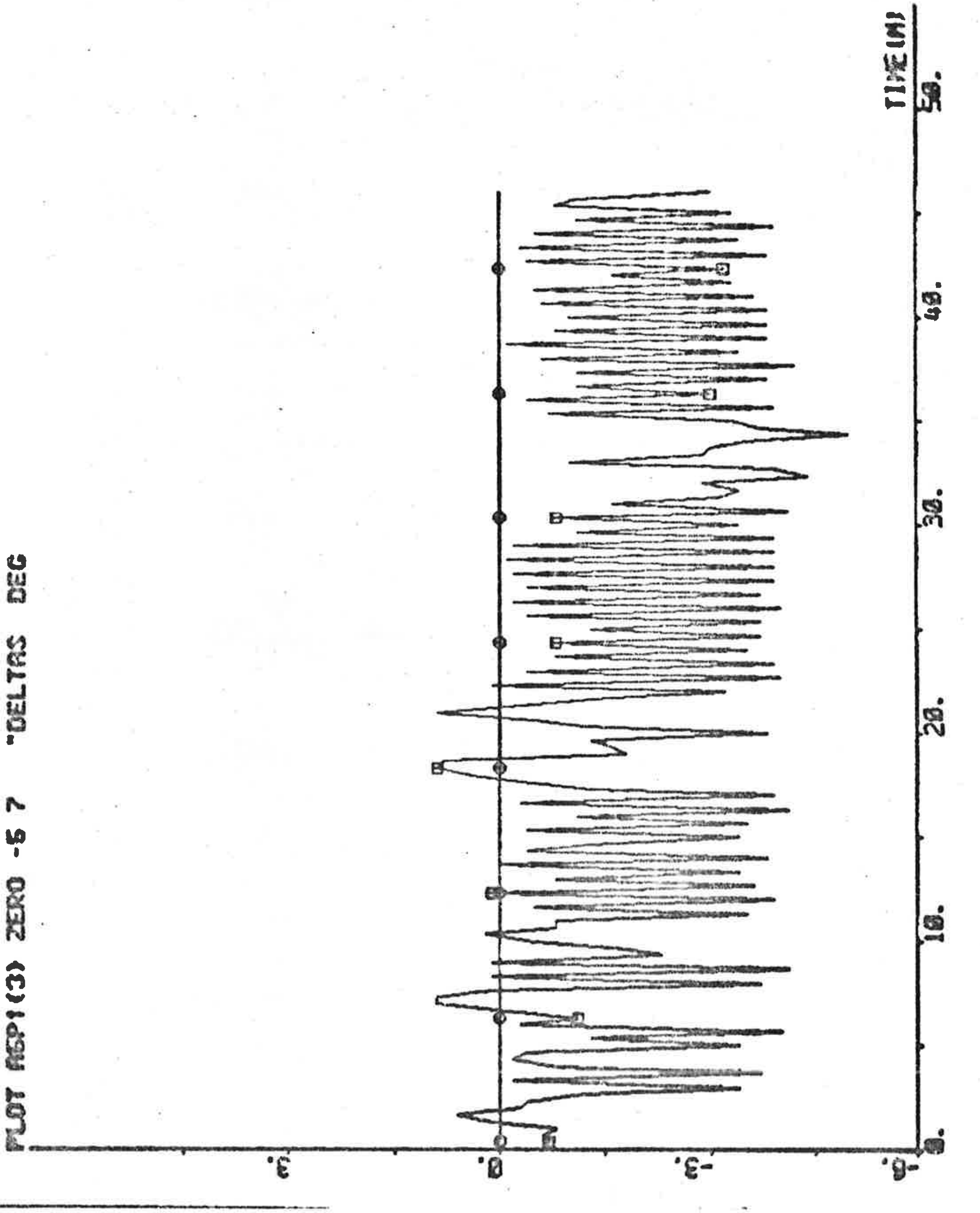
<u>Statistics</u> (mean value and standard deviation)

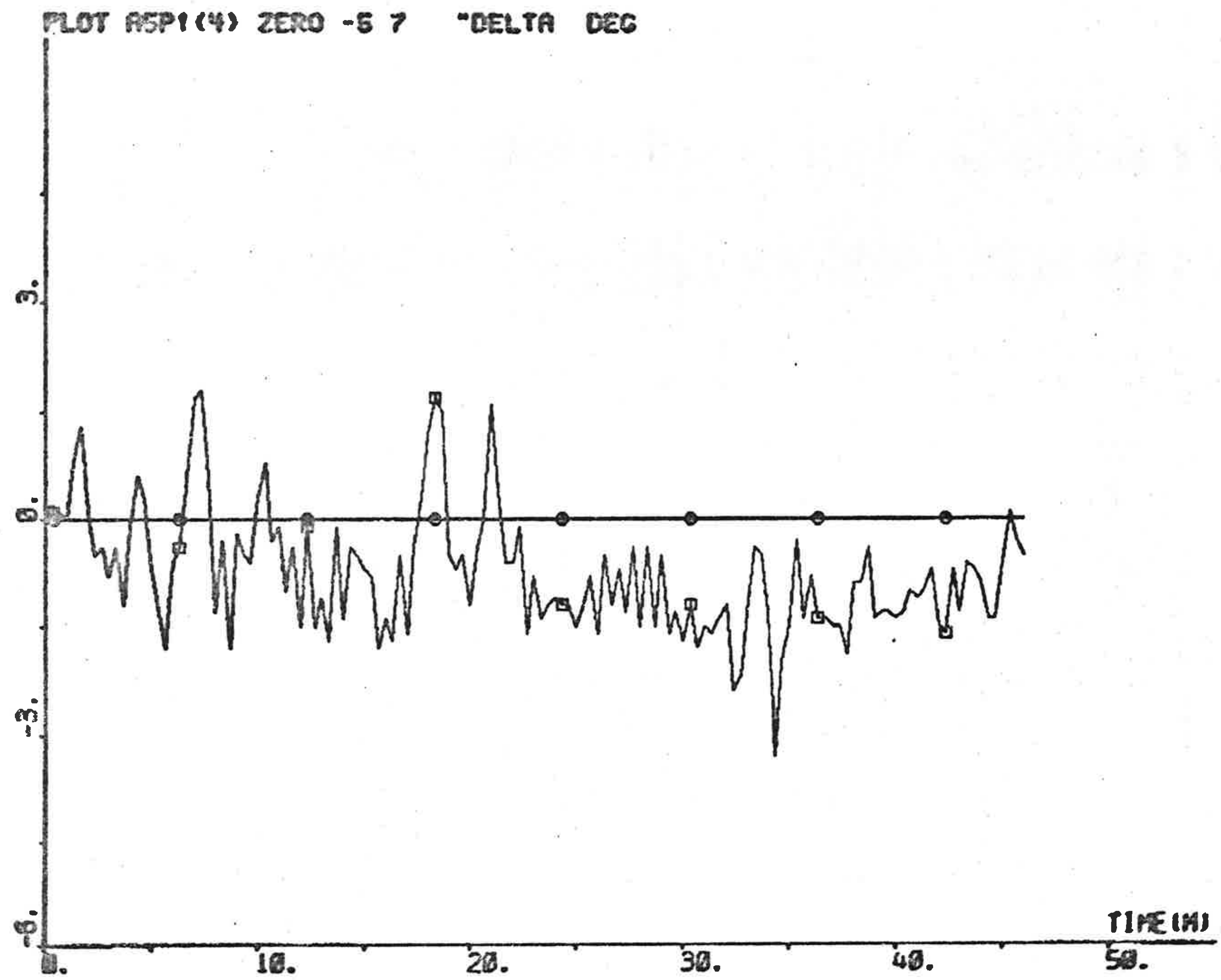
DELTA	−0.76 ± 0.86 deg
PSI − PSIREF	0.002 ± 0.126 deg
AN	81.95 ± 0.22 rpm
U	17.88 ± 0.22 knots

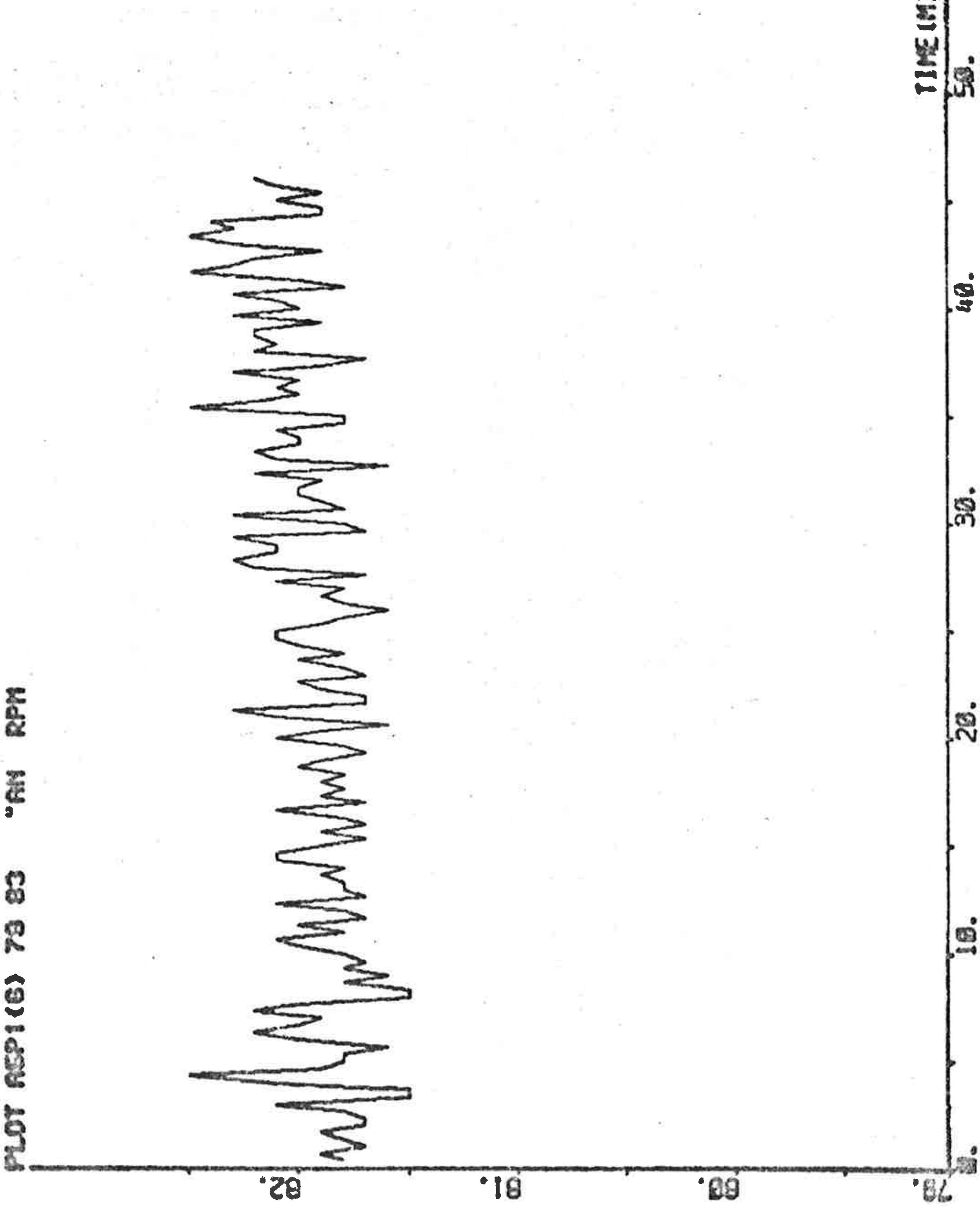
$V_1 = 0.160$

$V_2 = 0.102$

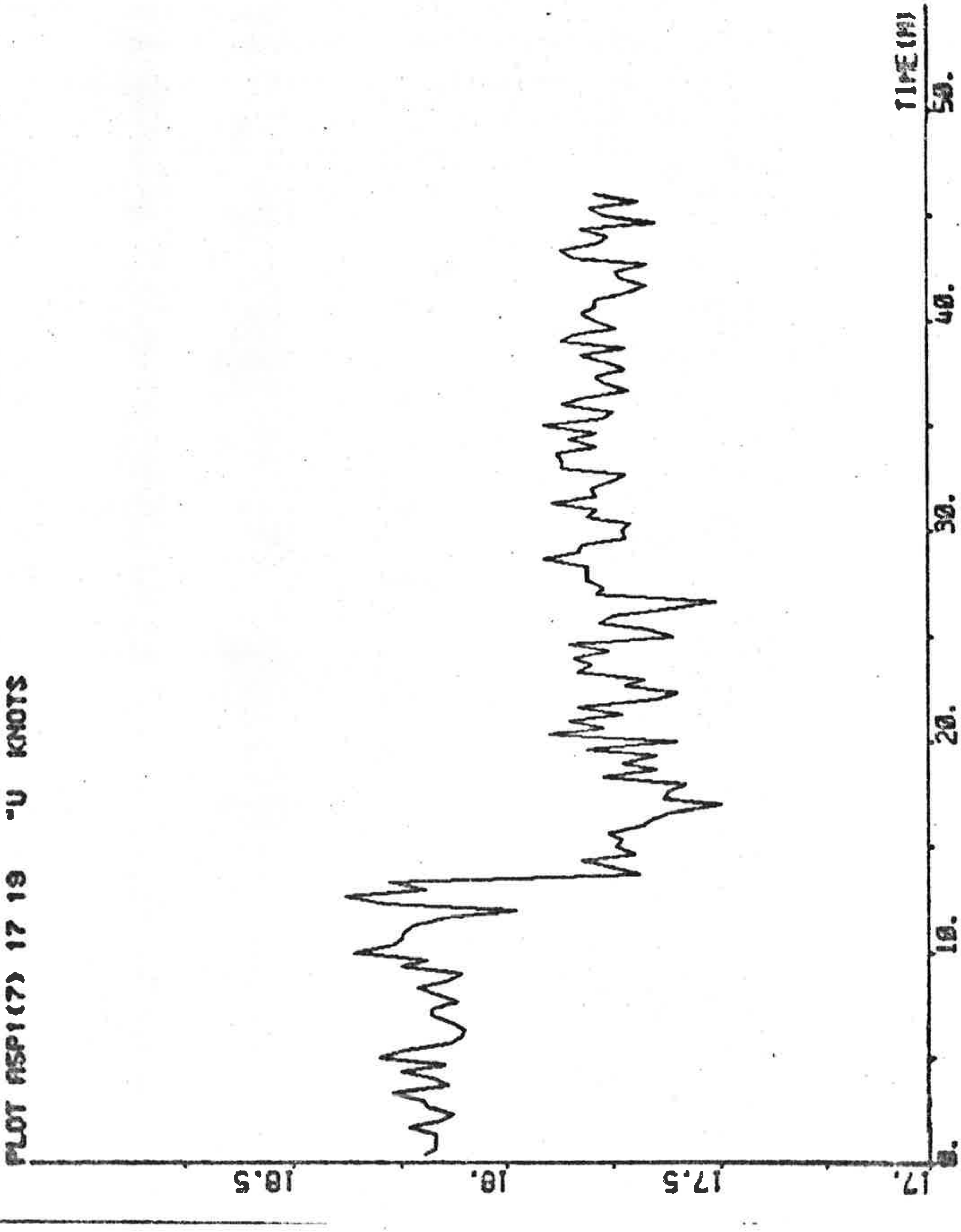

PLOT HP RSP1(1) ZERO -5 7 'DELDOC DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

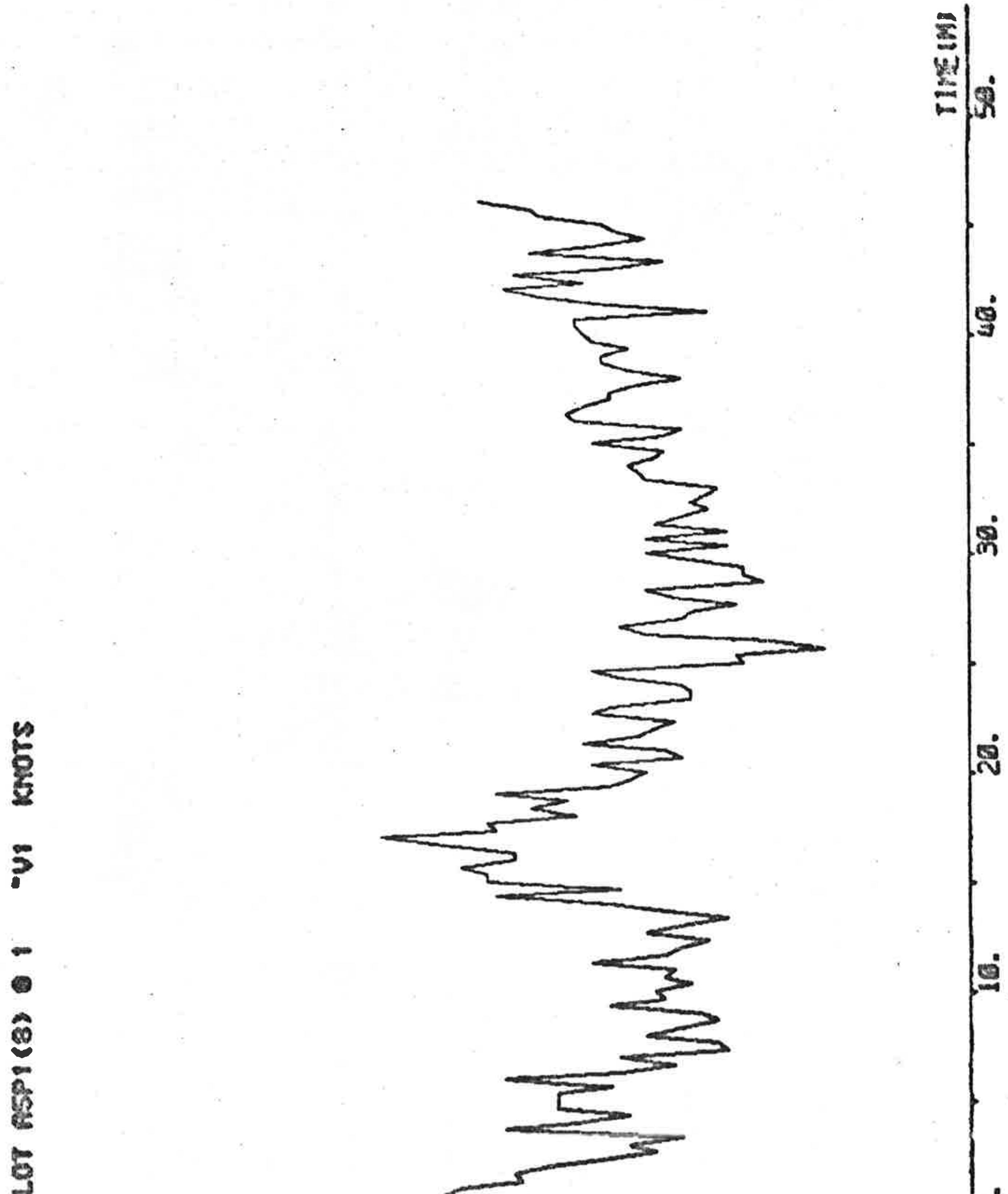

PLOT AEP1(3) ZERO -5 7 "DELTAS DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

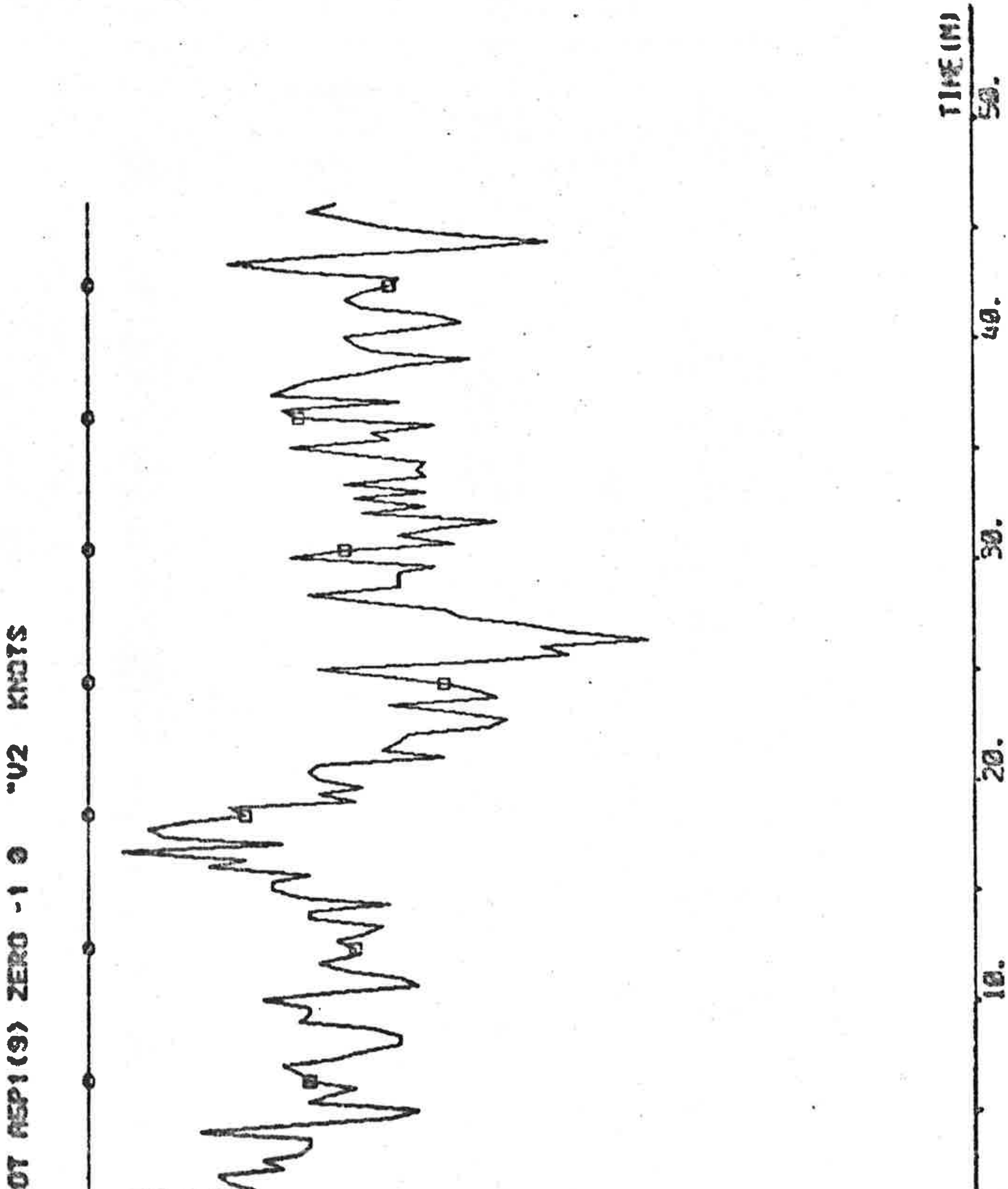

PLOT ASP1(4) ZERO -5 7 "DELTA DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(H)

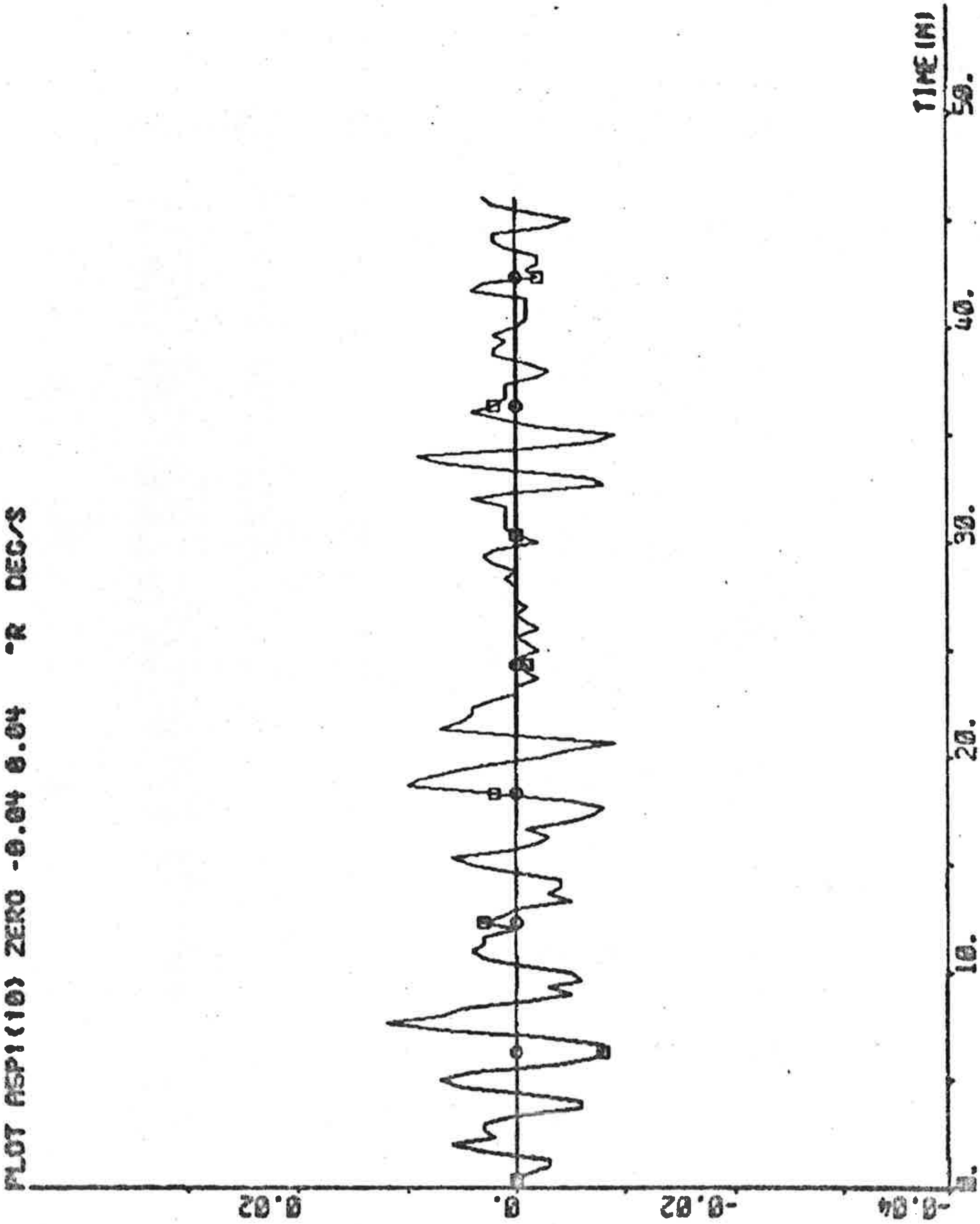


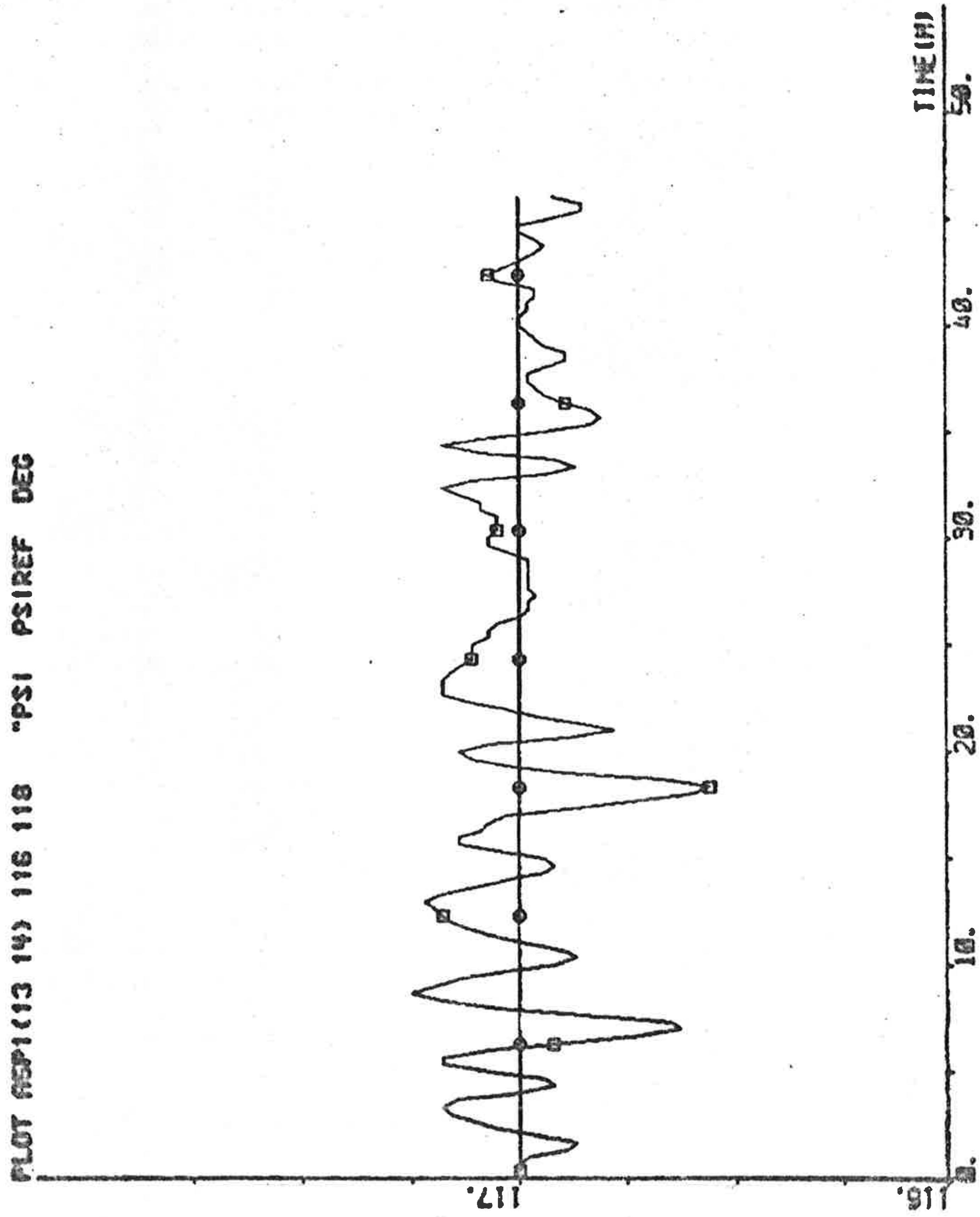
PLOT RESP1(6) 78 83 "AN RPM
82.
81.
80.
79.
0.
10.
20.
30.
40.
50.
TIME (M)

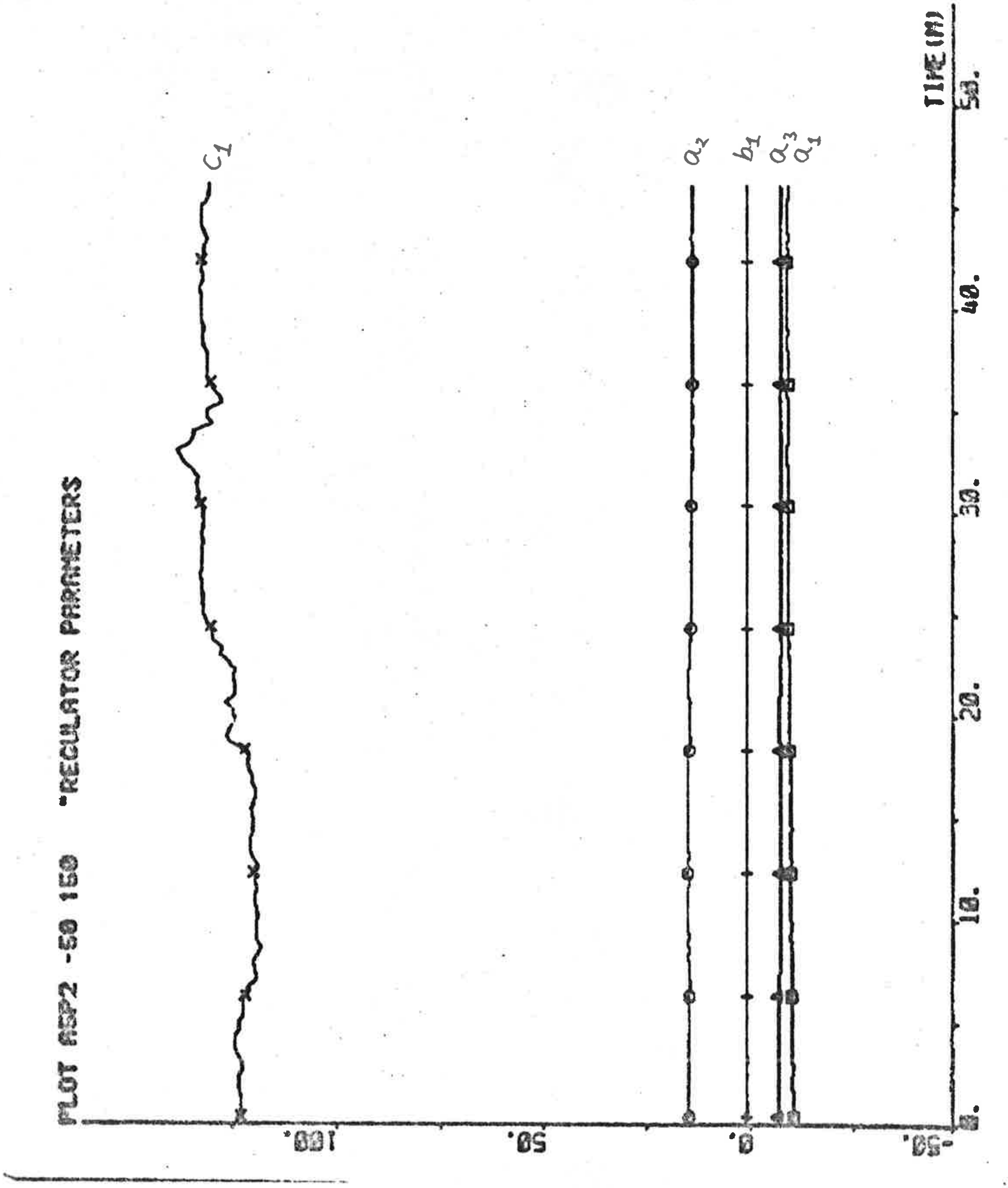

PLOT ASP1(7) 17 19 "U KNOTS
18.5
18.
17.5
17.
0.
10.
20.
30.
40.
50.


PLOT RSP1(3) @ 1 "V1 KNOTS
0.
0.25
0.5
0.75
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT RESP1(9) ZERO -1 0 "V2 KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
-0.25
-0.5
-0.75
-1.


PLOT ASP1(10) ZERO -0.04 0.04 °R DEG/S
0.02
0.
-0.02
-0.04
0.
10.
20.
30.
40.
50.
TIME(M)


PSI PSIREF DEG
117.
116.
10.
20.
30.
40.
50.
TIME(M)


PLOT ASP2 -50 150 *REGULATOR PARAMETERS
100.
50.
0.
-50.
0.
10.
20.
30.
40.
50.
TIME (M)
c_1
a_2
b_1
a_3
a_1

EXPERIMENT A6

Date	1974-10-12
Time	14.38
Duration	40 min
Position	N 21° 12' E 59° 35'
Water depth	deep
Forward draught	20.1 m
Aft draught	20.4 m
Wind direction	-
Wind velocity	0 Beaufort (0-0.5 m/s, calm)
Wave height	0 m
PSIREF	203°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 4
IREG = 20	IRDIF = 1	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -11.287 \\ 15.643 \\ -5.025 \\ 1.091 \\ 17.224 \end{bmatrix} \qquad P = \begin{bmatrix} 2.044 & & & & \\ -2.649 & 4.876 & & & \\ 1.166 & -2.636 & 1.986 & & \\ -0.041 & 0.058 & -0.023 & 0.003 & \\ 4.396 & -11.495 & 6.991 & -0.181 & 138.289 \end{bmatrix}$$

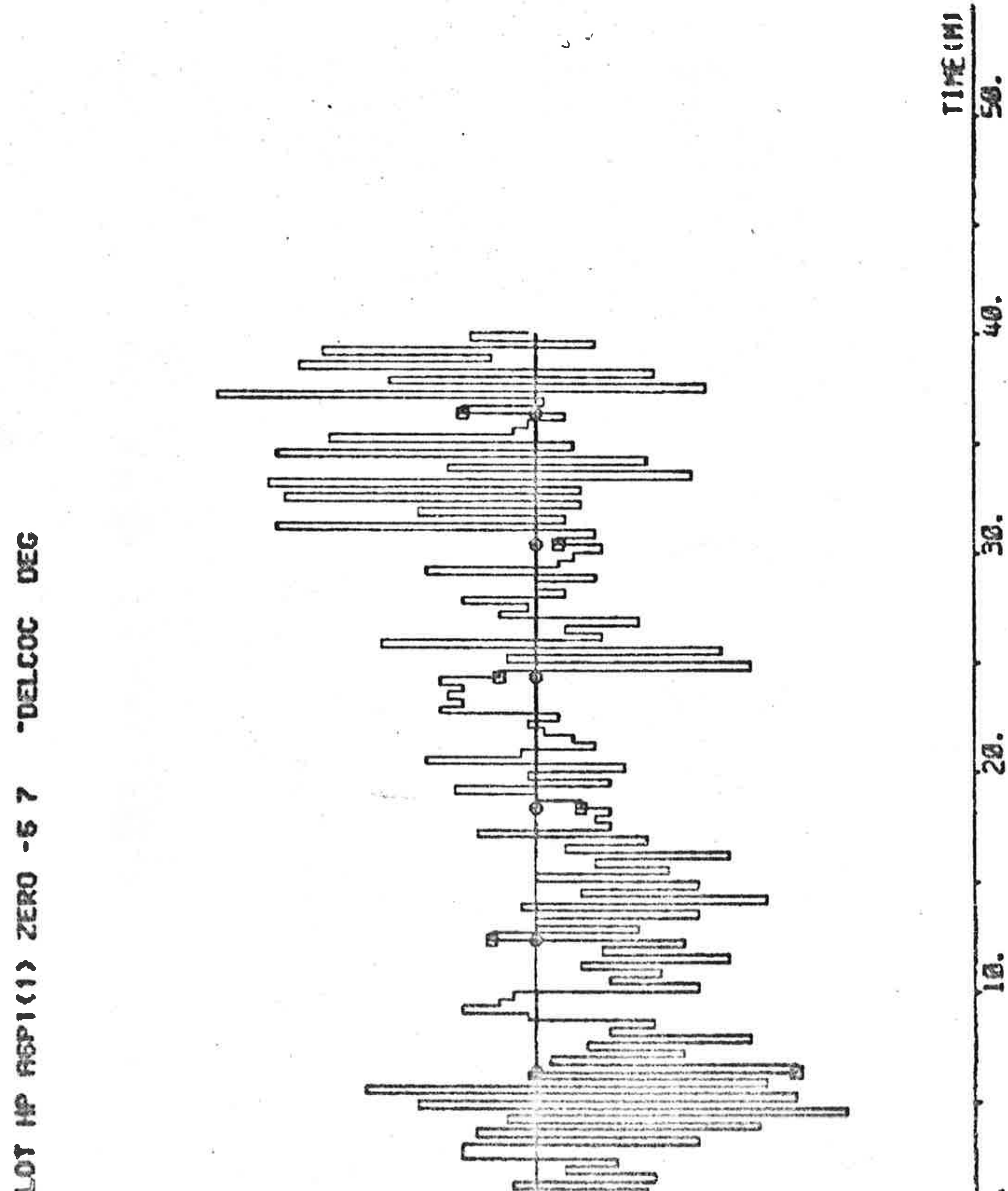
$a_1 + a_2 + a_3 = -0.669$

<u>Statistics</u> (mean value and standard deviation)

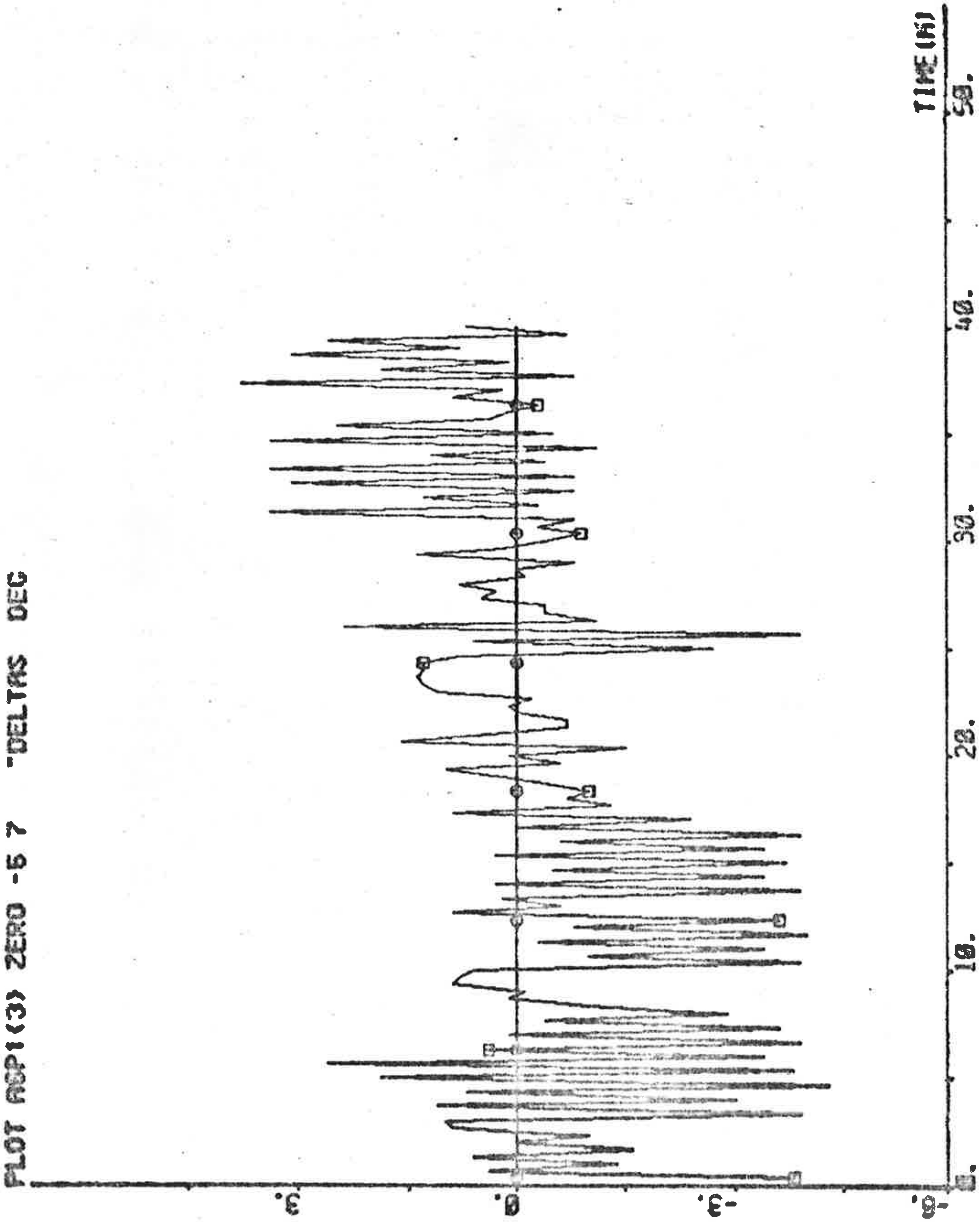
DELTA	0.60 ± 1.59 deg
PSI - PSIREF	-0.036 ± 0.200 deg
AN	85.78 ± 0.40 rpm
U	16.53 ± 0.12 knots

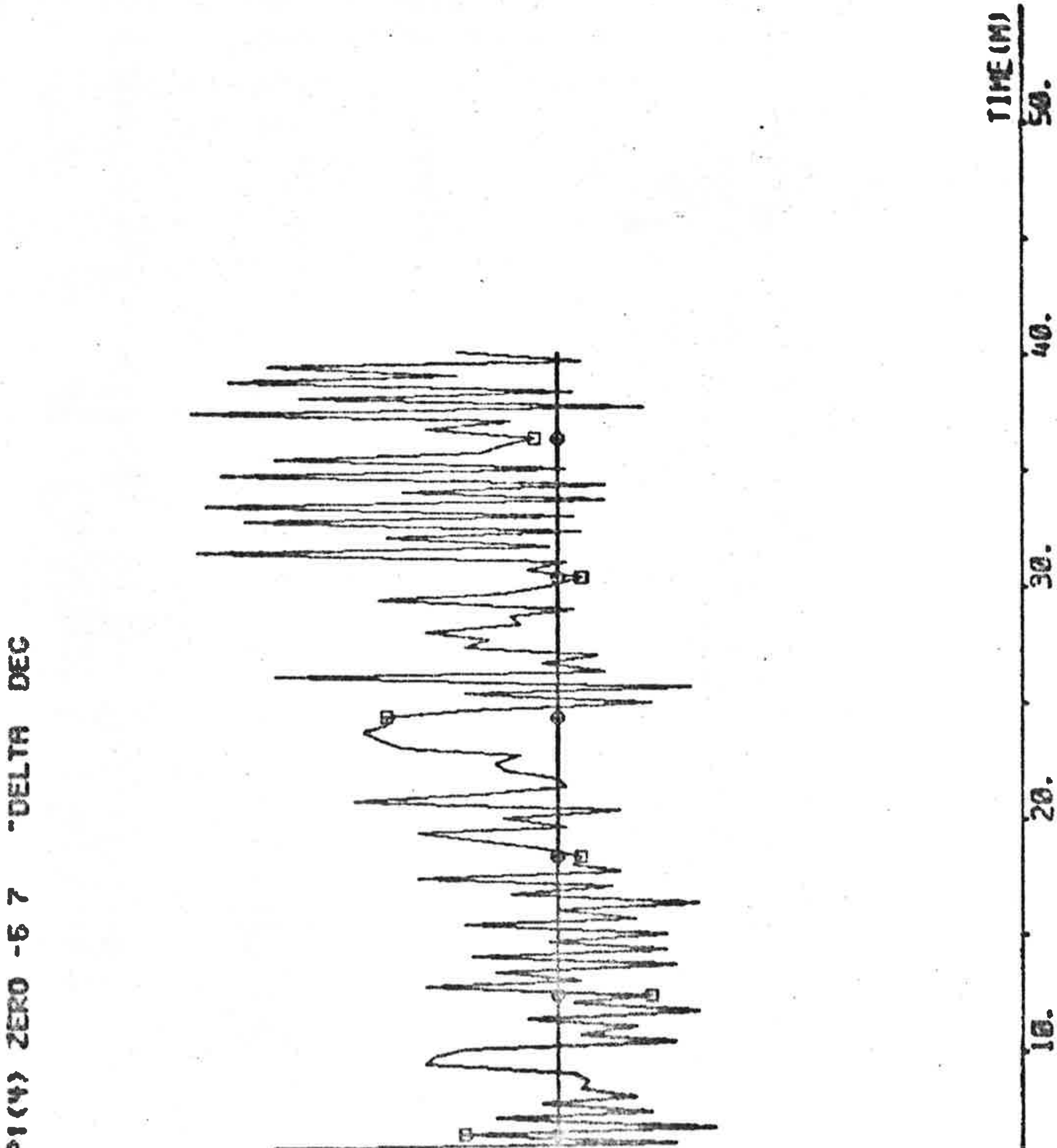
$V_1 = 0.330$

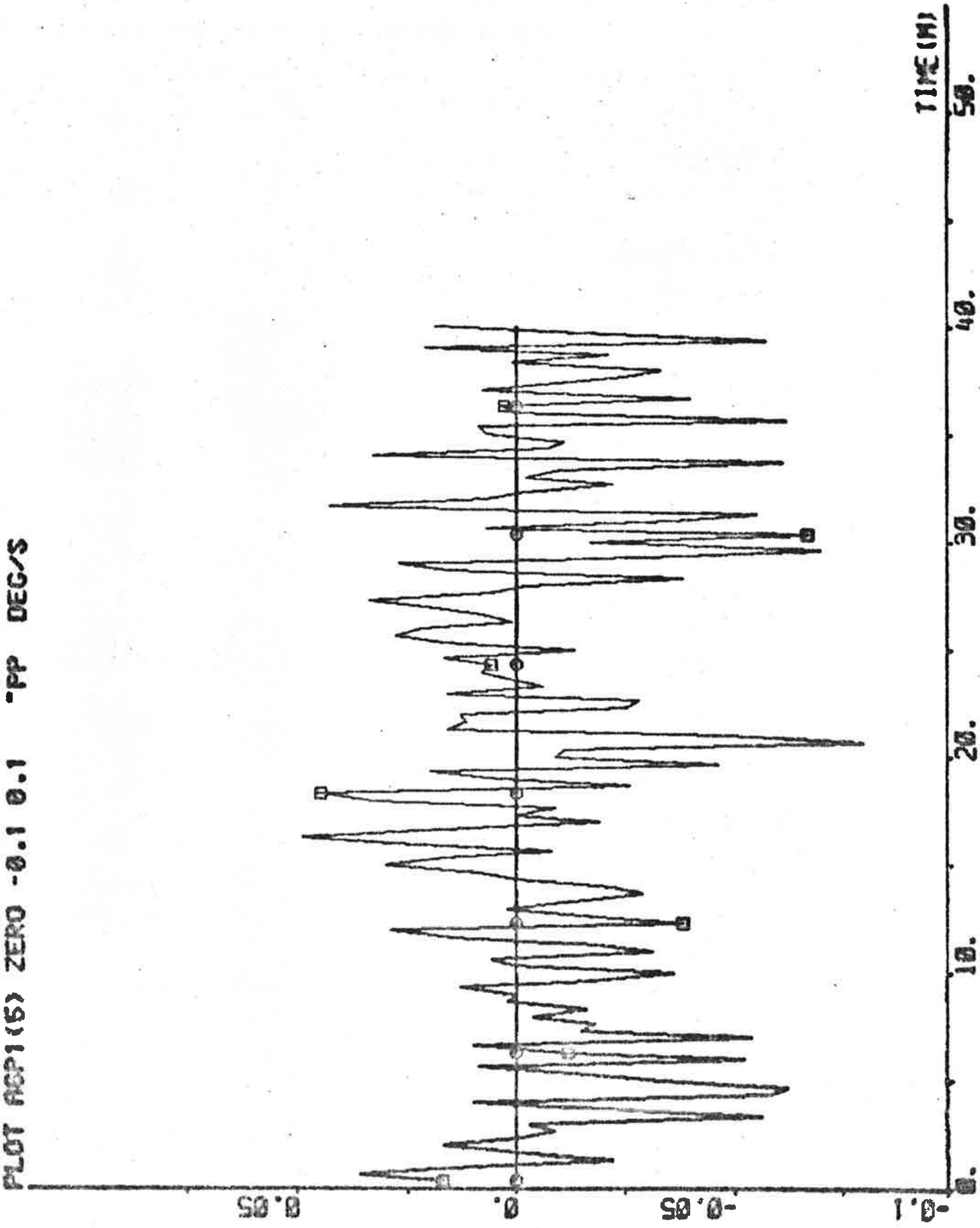
$V_2 = 0.294$

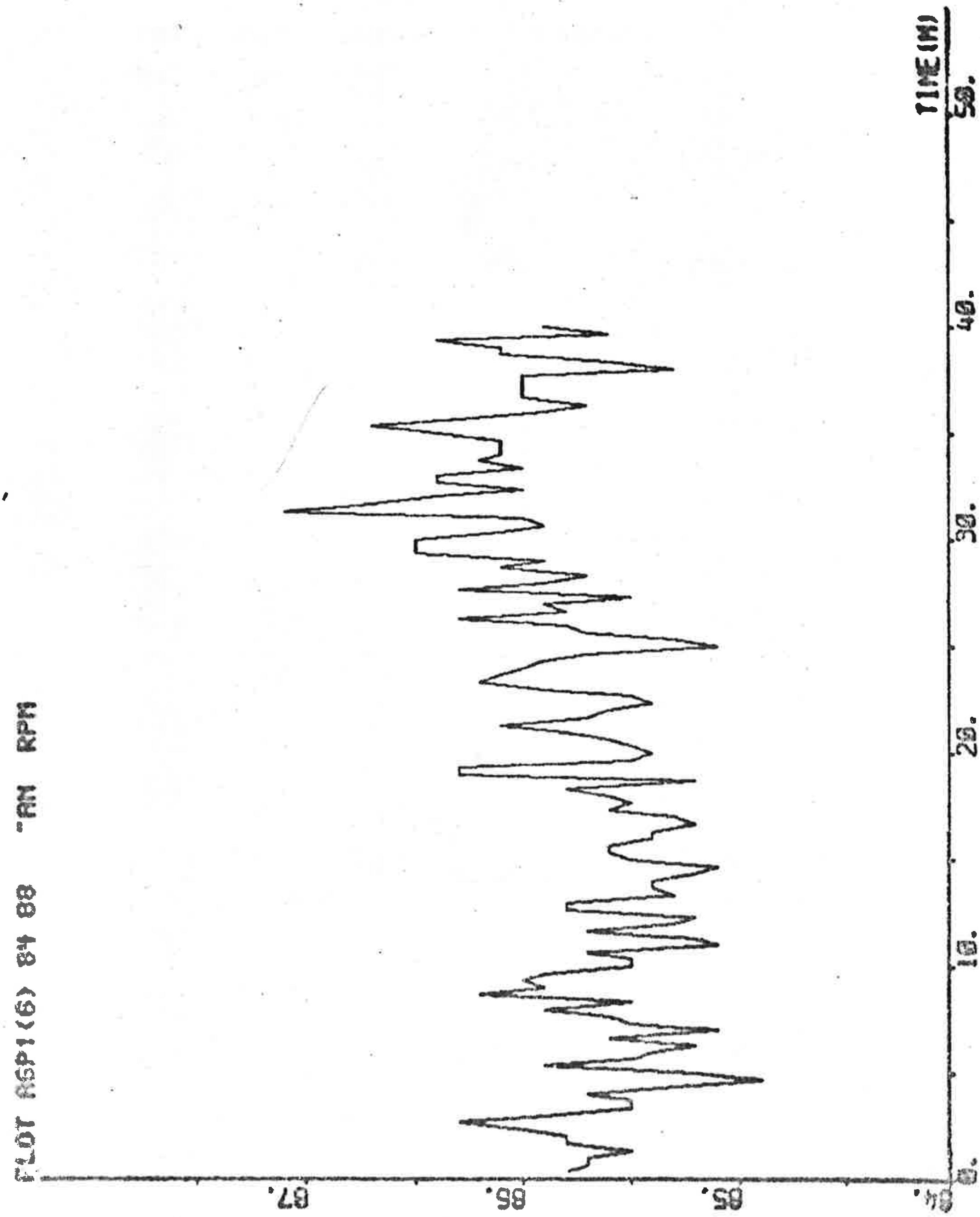


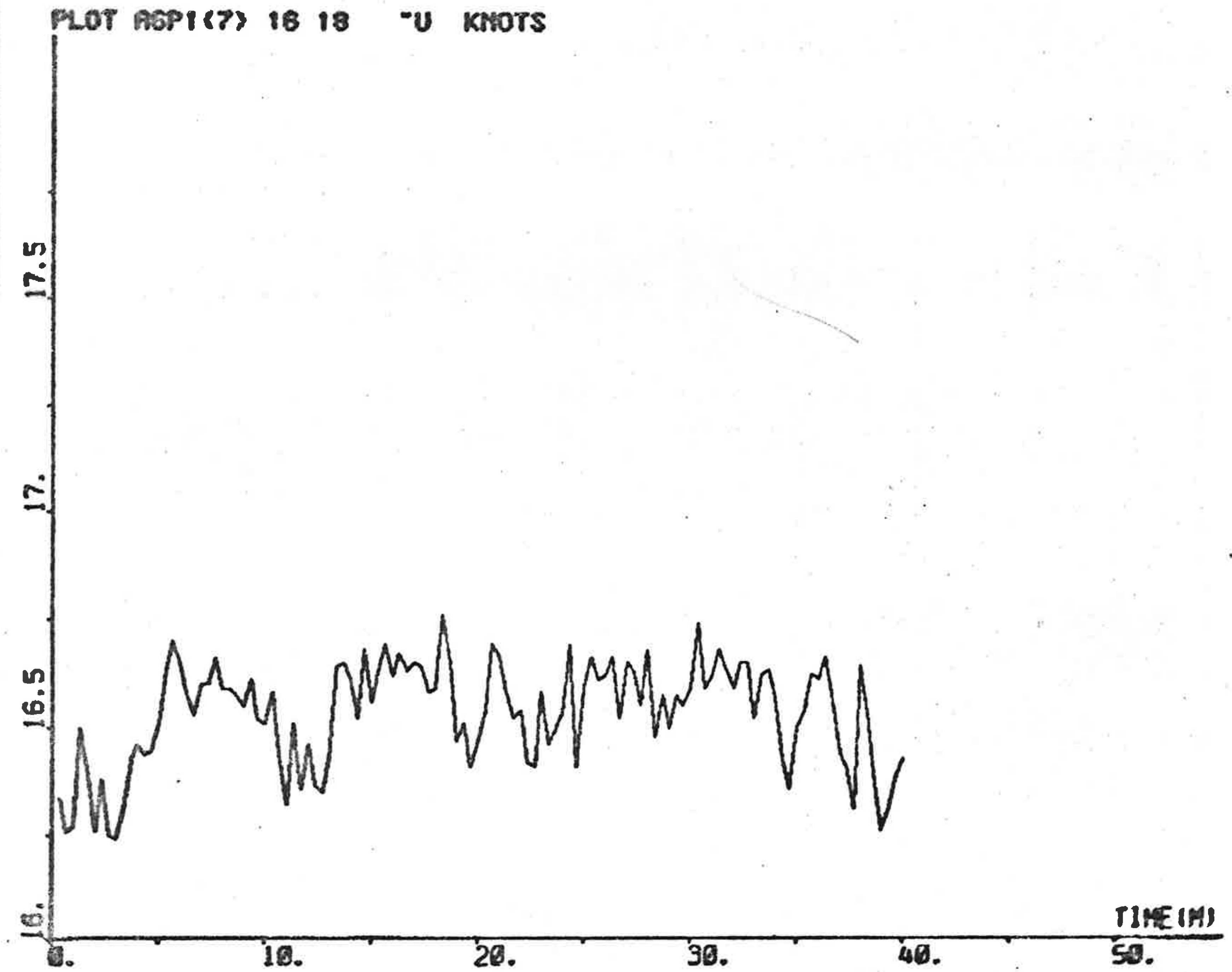
PLOT HP ASPI(1) ZERO -5 7 -DELCOC DEG
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

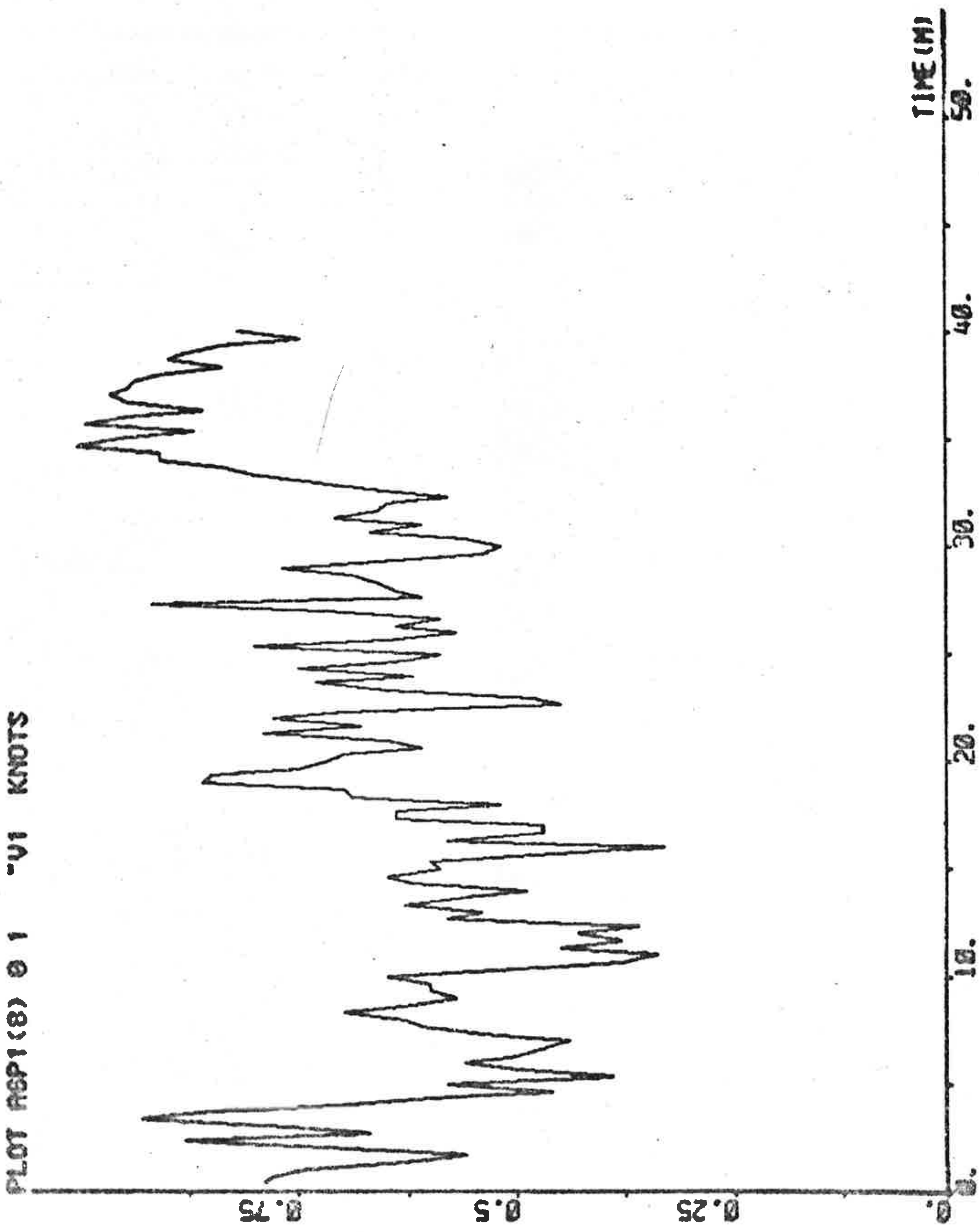

PLOT ADP1(3) ZERO -5 7 "DELTAS DEG
3.
0.
-3.
-6.
10.
20.
30.
40.
50.
TIME (H)

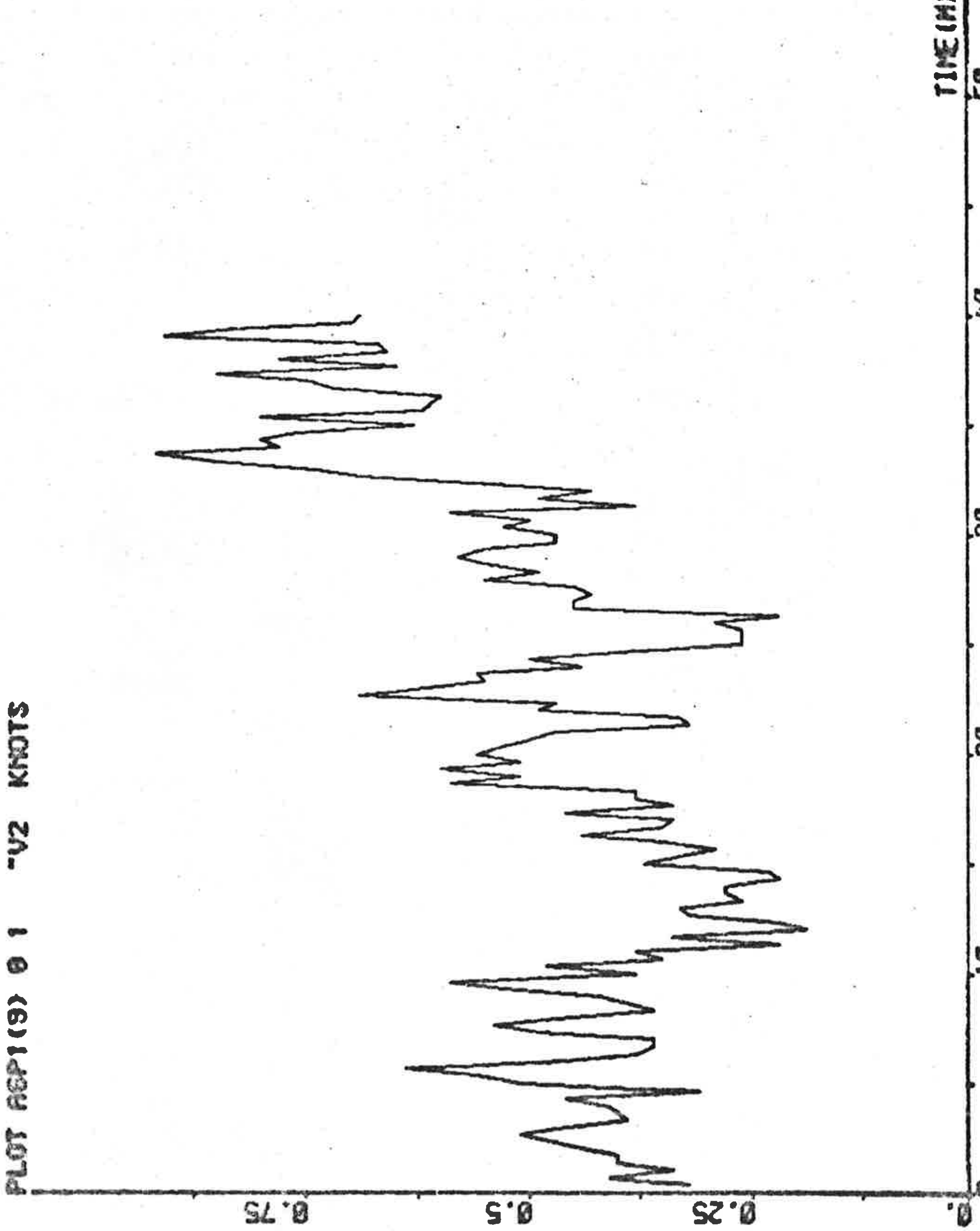

PLOT ASPI(4) ZERO -6 7 "DELTA DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

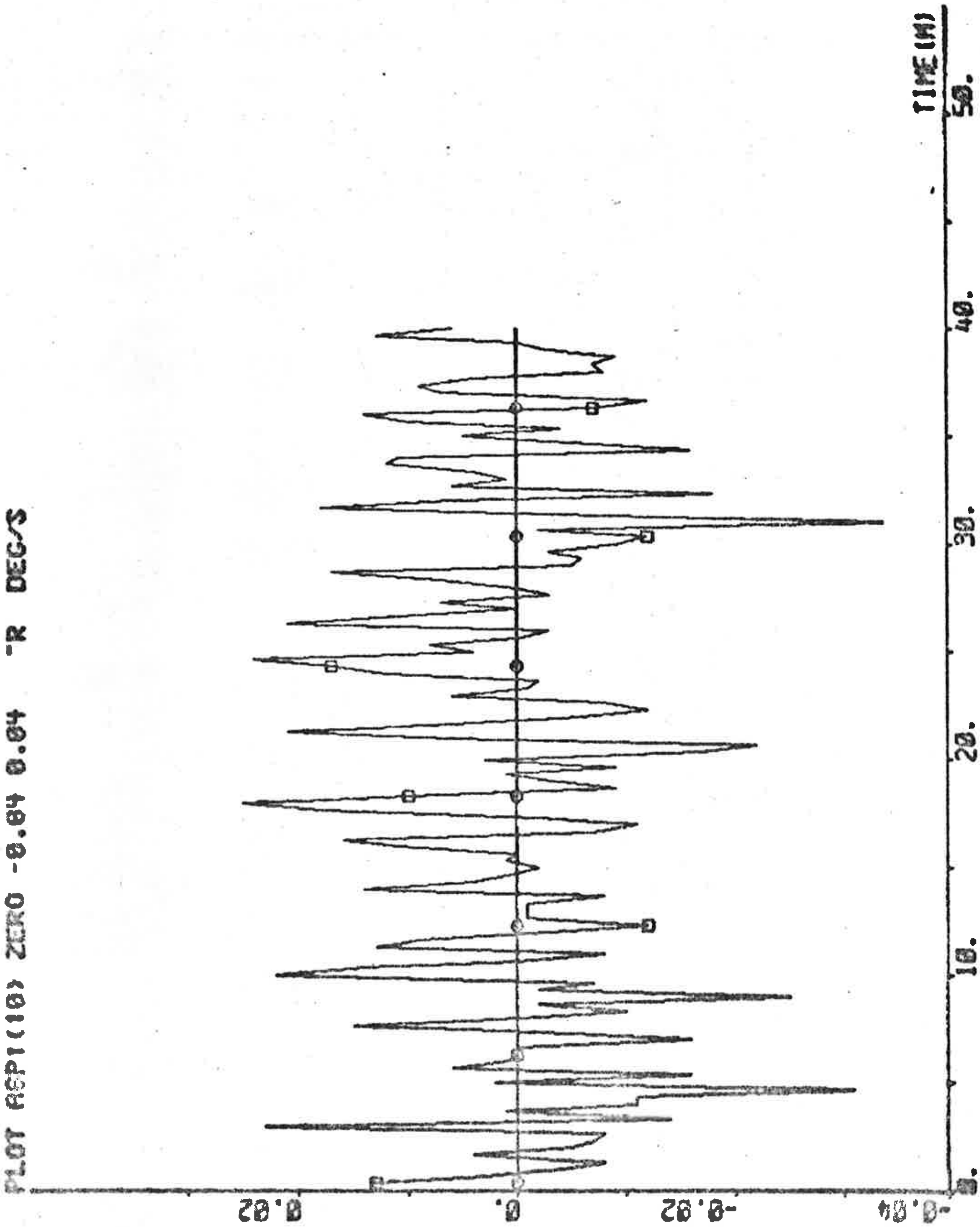

PLOT AGP1(5) ZERO -0.1 0.1 "PP DEG/S
0.05
0.
-0.05
-0.1
10.
20.
30.
40.
50.
TIME(M)

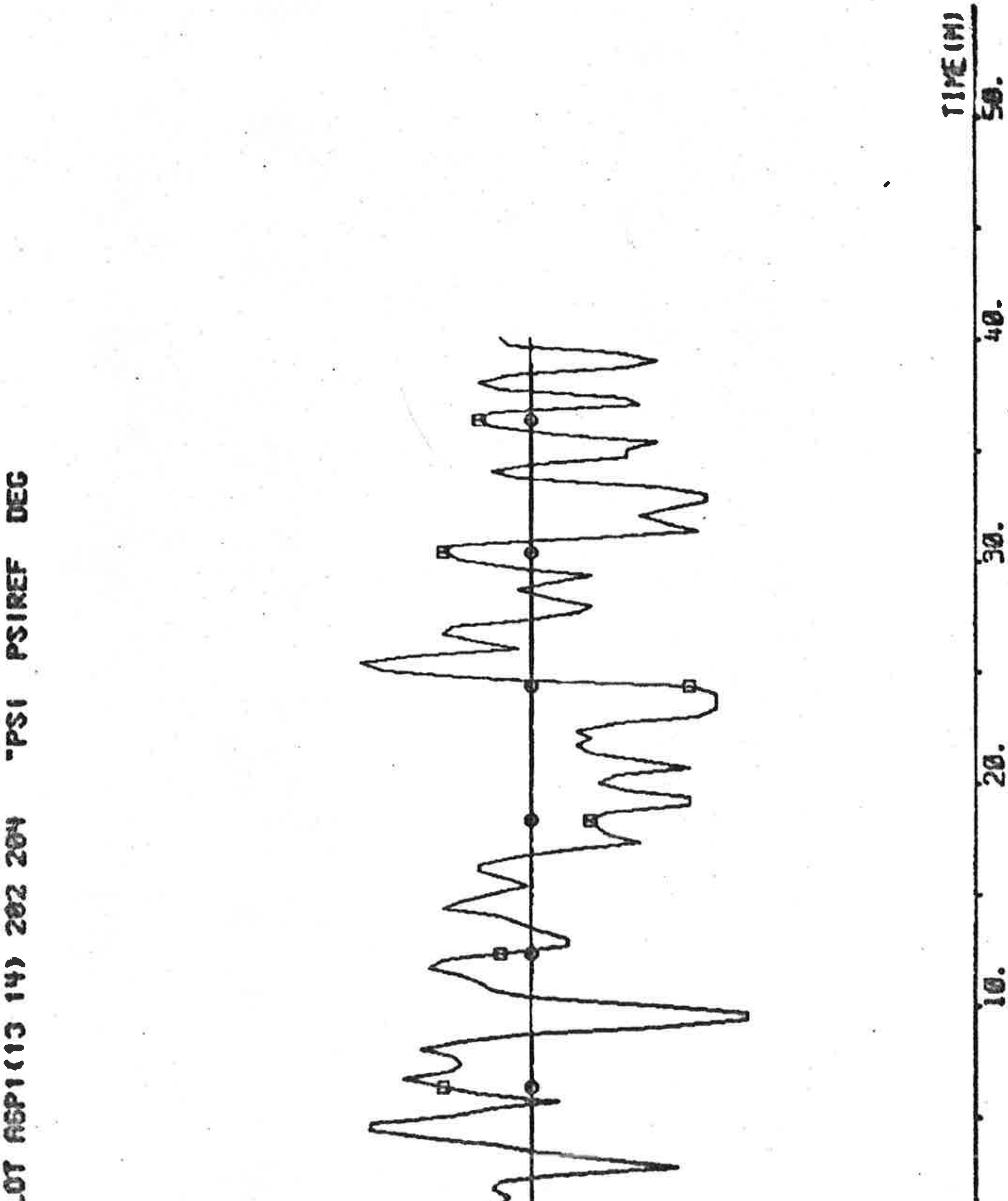

PLOT RSP1(6) 84 88
RPM
84.
85.
86.
87.
0.
10.
20.
30.
40.
50.
TIME(M)

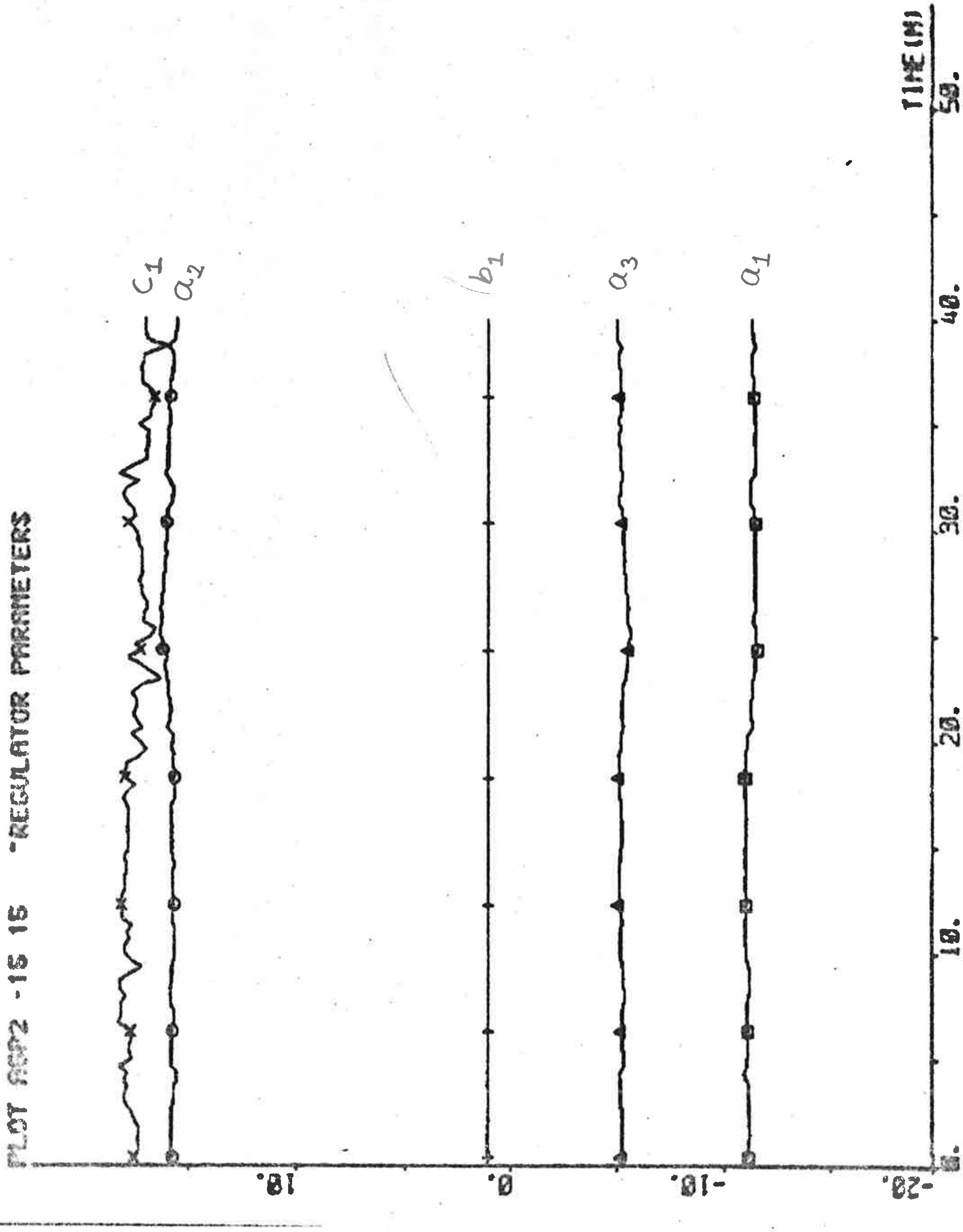

PLOT AGPI(7) 16 18 "U KNOTS
17.5
17.
16.5
16.
TIME(M)
0.
10.
20.
30.
40.
50.


PLOT ASP1(8) @ 1 "V1 KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
0.
0.25
0.5
0.75


PLOT AGP1(9) @ 1 -V2 KNOTS
TIME (H)
0.
10.
20.
30.
40.
50.
0.25
0.5
0.75


PLOT ASP1(10) ZERO -0.04 0.04 -R DEG/S
TIME (M)
0.
10.
20.
30.
40.
50.
0.02
0.
-0.02
-0.04


PLOT ASP1(13 14) 202 204 "PSI PSIREF DEG
TIME (M)
0.
10.
20.
30.
40.
50.
202.
203.


PLOT RSP2 -15 15 'REGULATOR PARAMETERS
TIME (M)
0.
10.
20.
30.
40.
50.
10.
0.
-10.
-20.
c1
a2
b1
a3
a1

EXPERIMENT A7

Date	1974-10-13
Time	10.03
Duration	41 min
Position	N 16° 31' E 57° 20'
Water depth	deep
Forward draught	20.1 m
Aft draught	20.4 m
Wind direction	SSW (1; see Appendix A)
Wind velocity	2 Beaufort (2-3.5 m/s, light breeze)
Wave height	2 m
PSIREF	205°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 3
IREG = 20	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -12.597 \\ 18.895 \\ -6.873 \\ 0.928 \\ 3.236 \end{bmatrix} \qquad P = \begin{bmatrix} 5.230 & & & & \\ -6.555 & 10.367 & & & \\ 2.330 & -4.621 & 3.277 & & \\ -0.144 & 0.131 & 0.010 & 0.022 & \\ 21.860 & -32.898 & 10.045 & -0.115 & 353.779 \end{bmatrix}$$

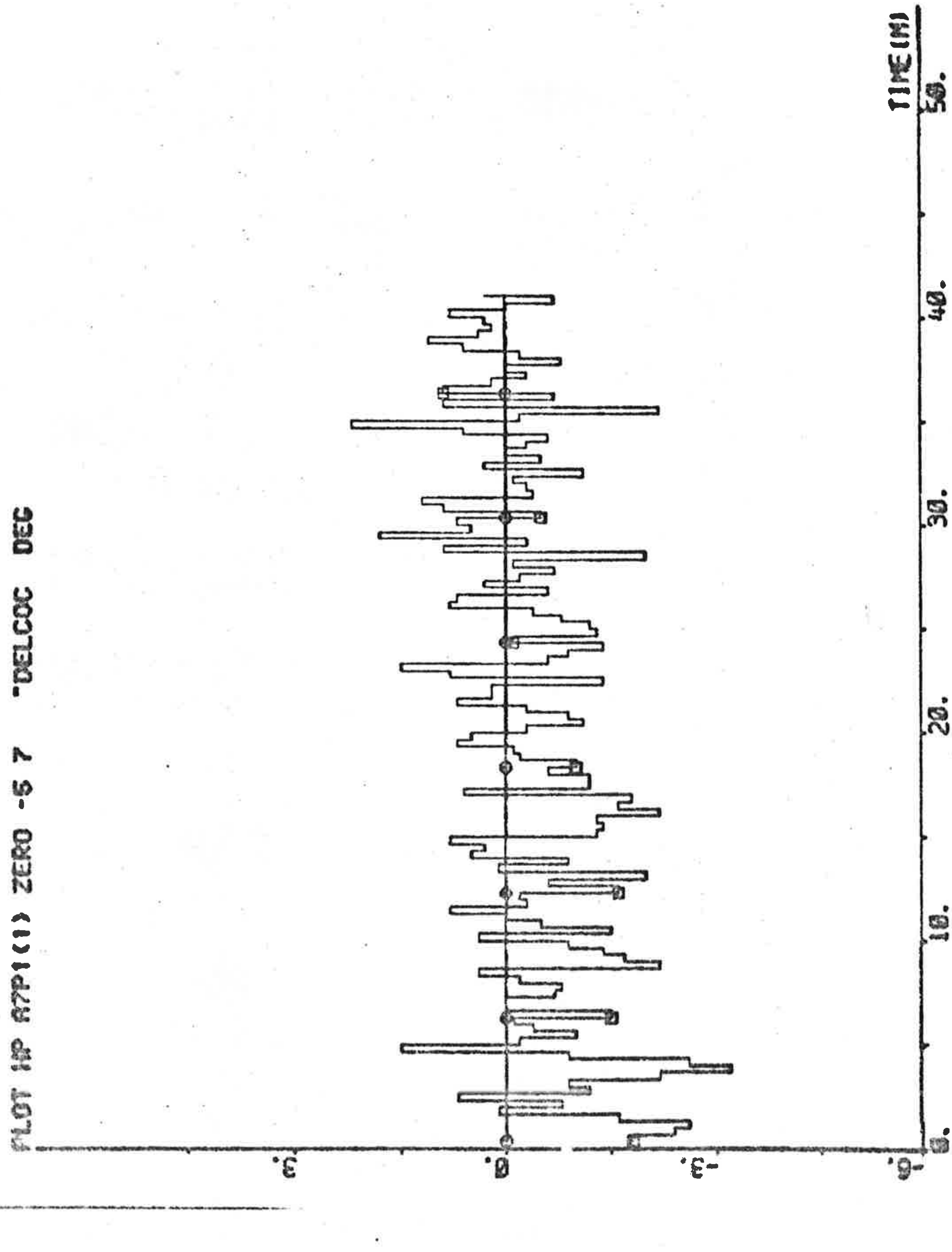
$$a_1 + a_2 + a_3 = -0.575$$

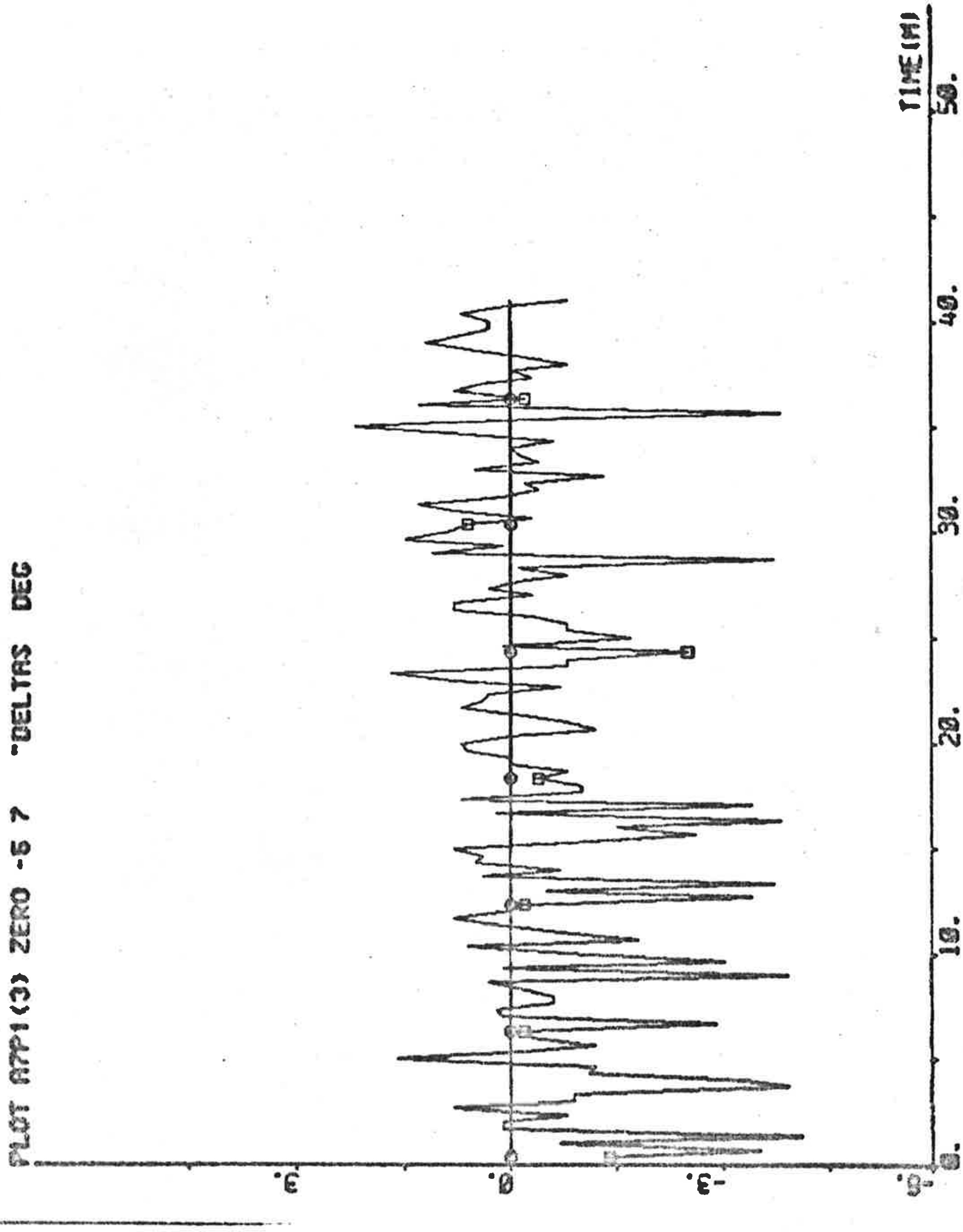
<u>Statistics</u> (mean value and standard deviation)

DELTA	0.32 ± 1.04 deg
PSI - PSIREF	-0.025 ± 0.200 deg
AN	85.80 ± 0.30 rpm
U	16.59 ± 0.15 knots

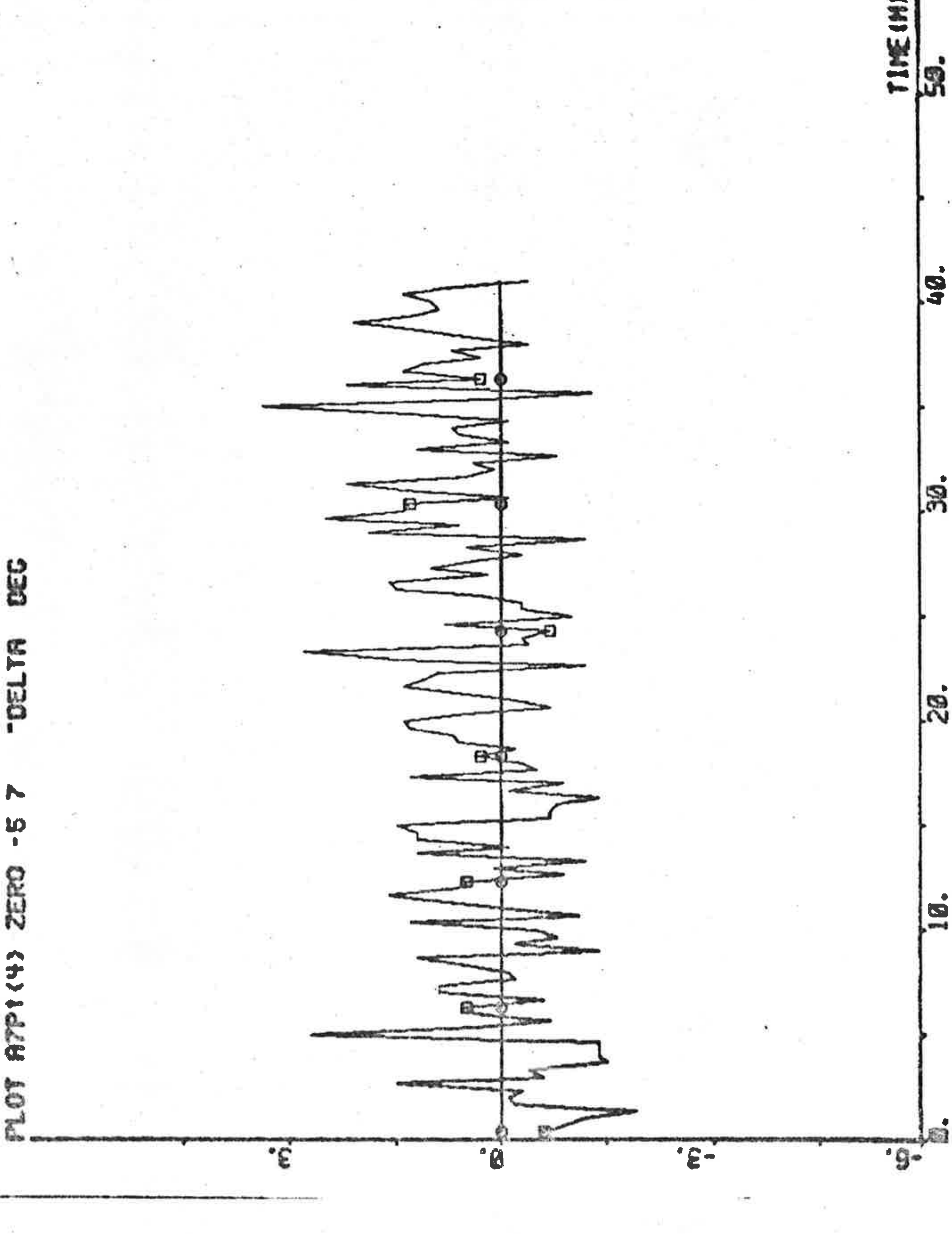
$V_1 = 0.159$

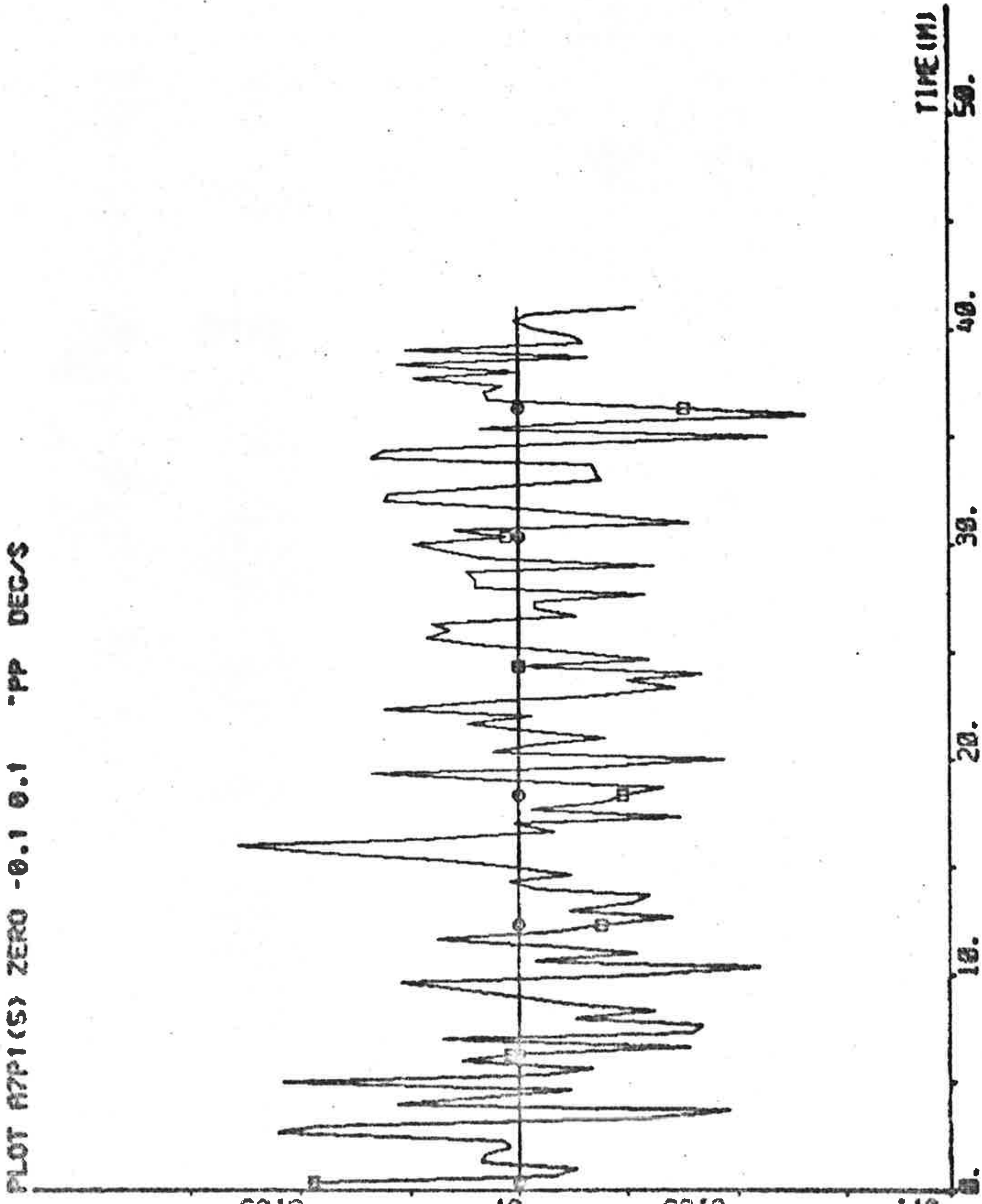
$V_2 = 0.149$

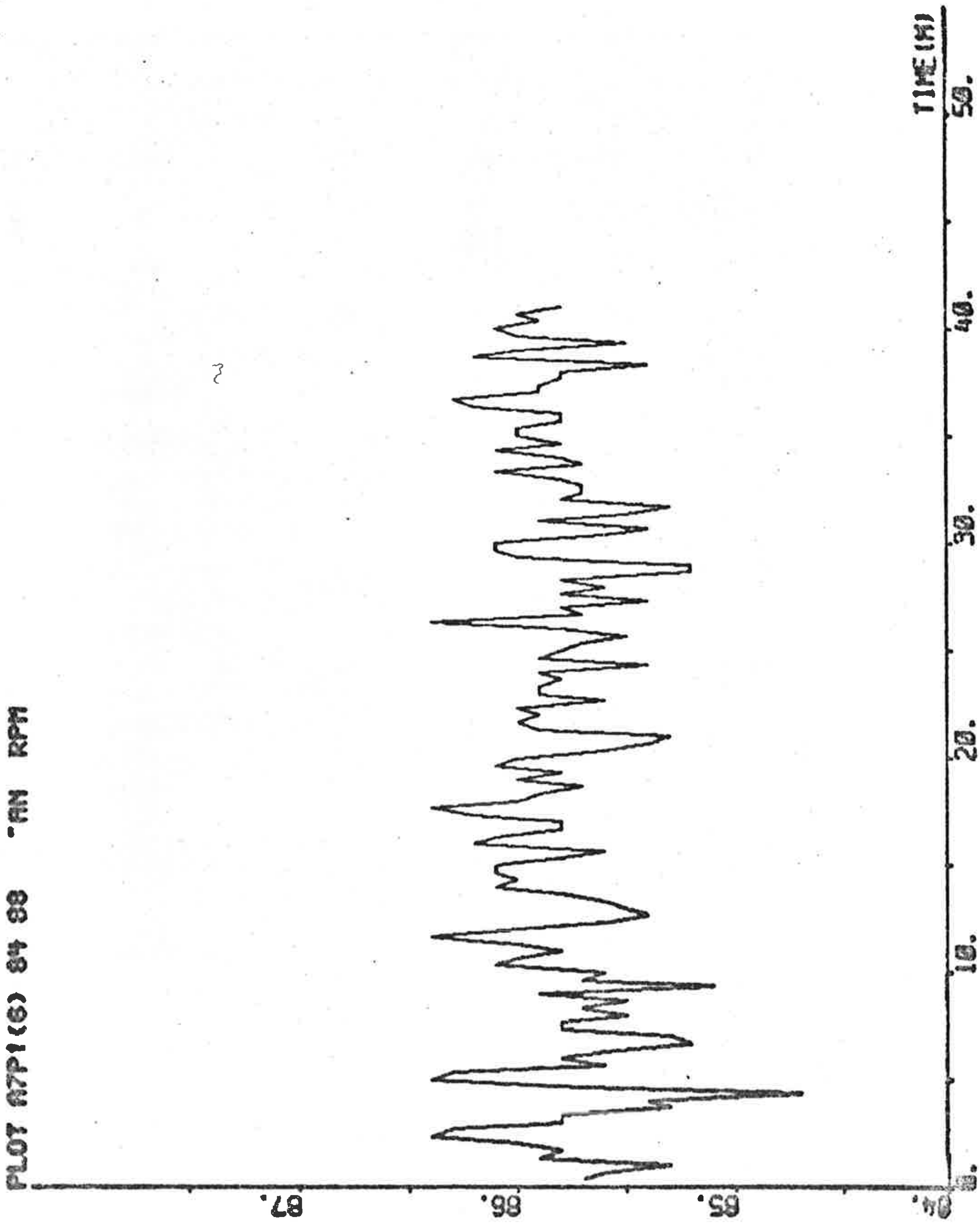

PLOT HP A7P1(1) ZERO -5 7 "DELCOC DEG
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

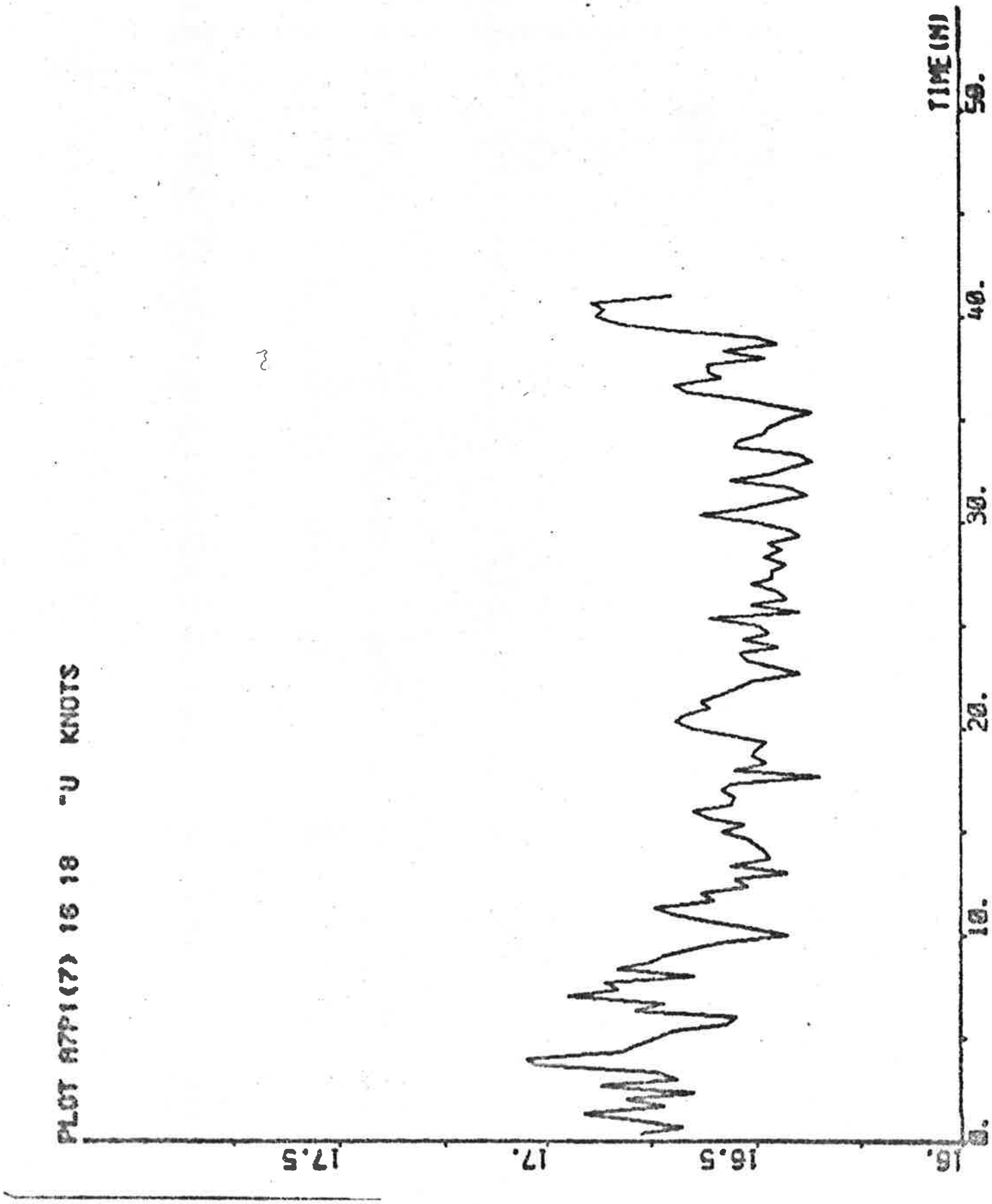


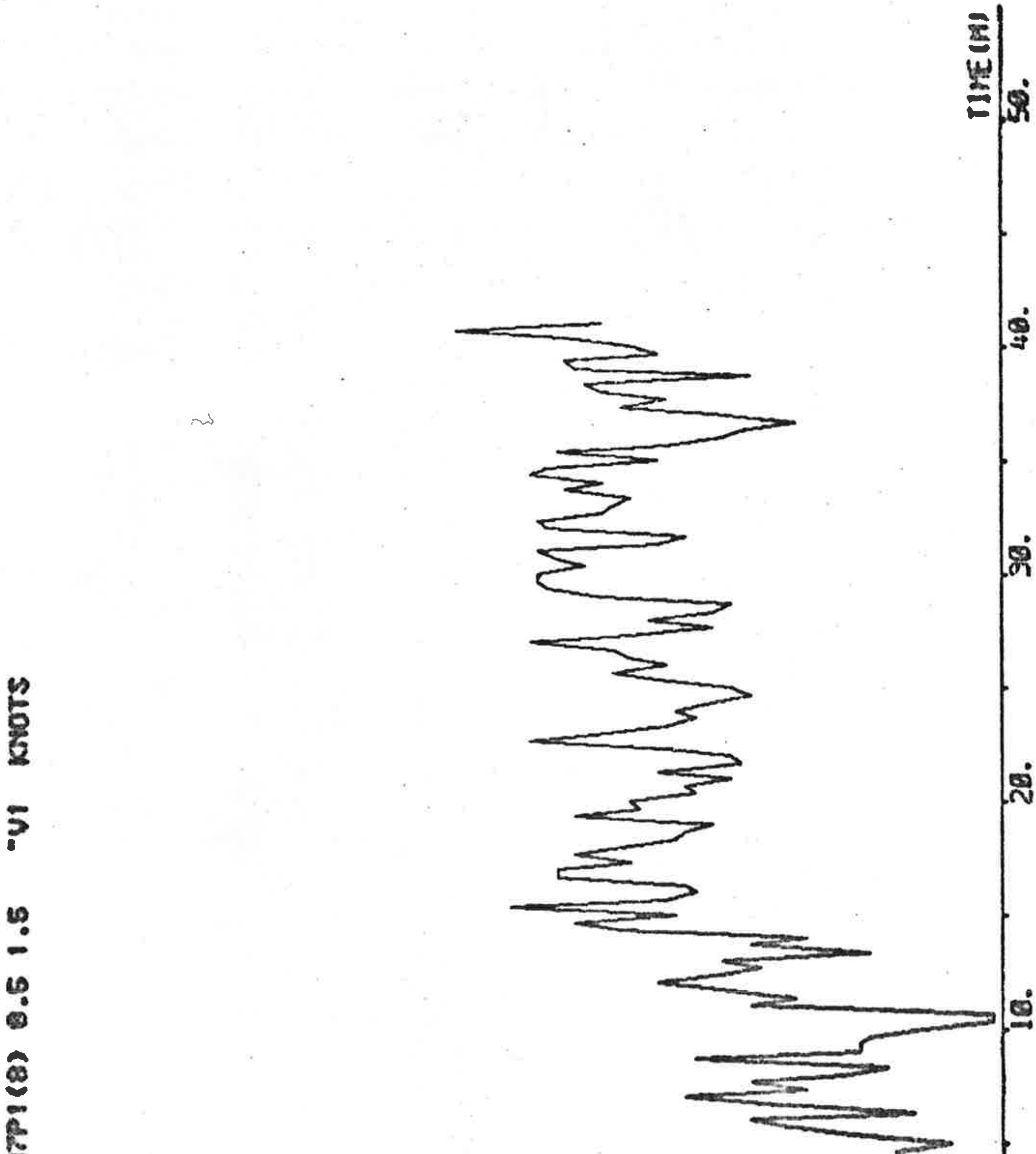
PLOT A7P1(3) ZERO -5 7 "DELTAS DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

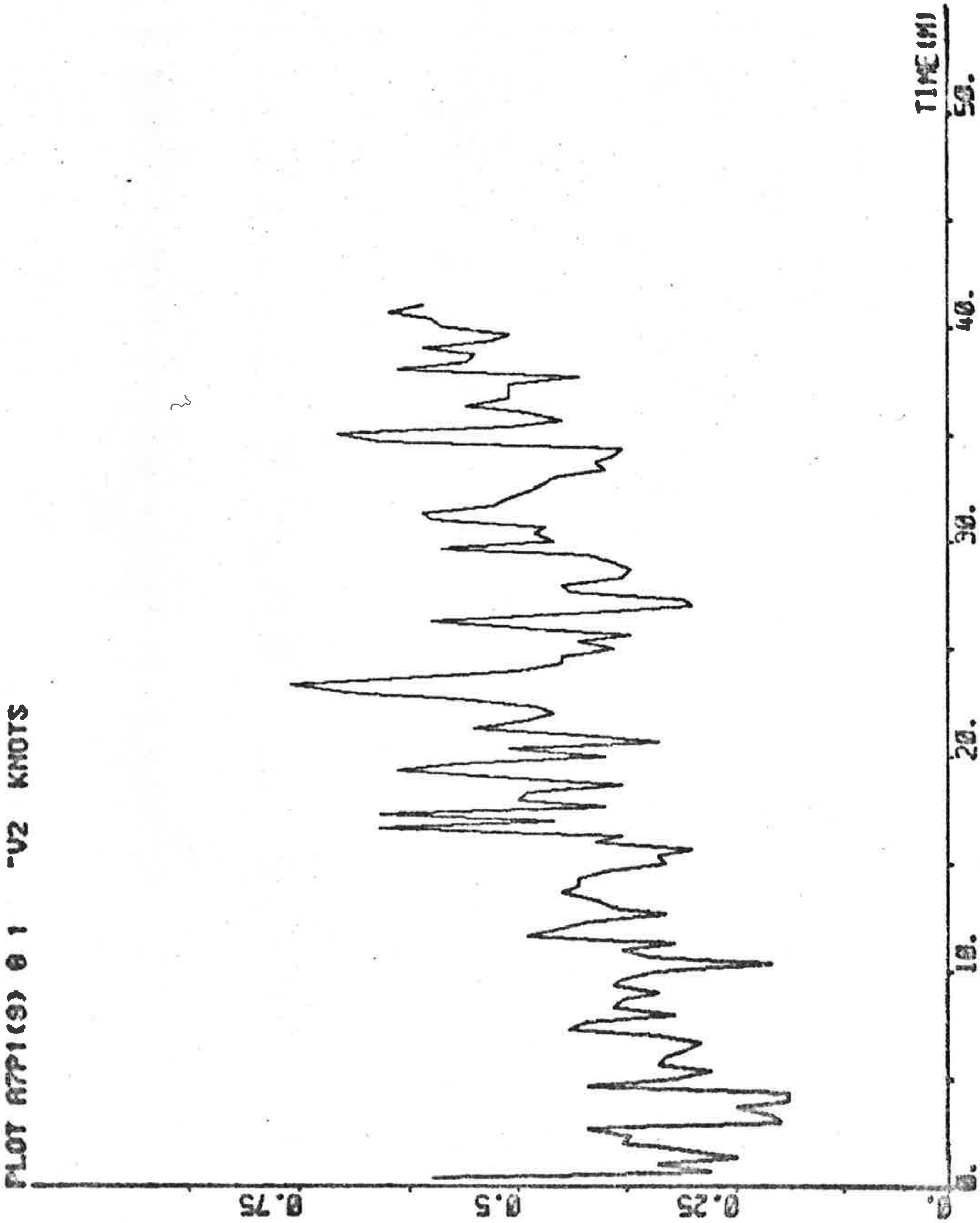

PLOT A7P1(4) ZERO -5 7 "DELTA DEG
3.
0.
-3.
-6.
10.
20.
30.
40.
50.
TIME(H)


PLOT A7P1(5) ZERO -0.1 0.1 'PP DEG/S
TIME(M)
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1

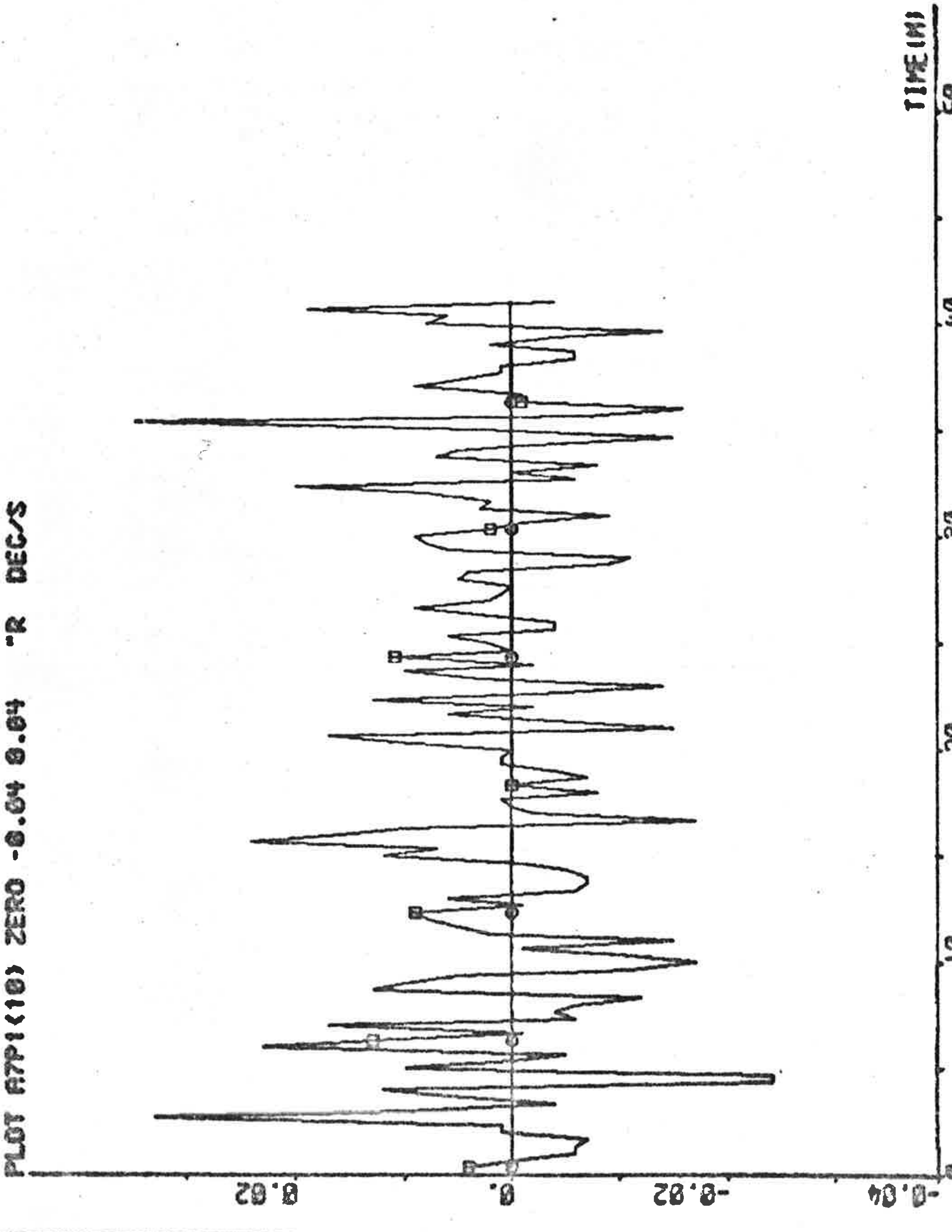

PLOT A7P1(6) 84 88 'AN RPM
87.
86.
85.
84.
0.
10.
20.
30.
40.
50.
TIME(M)

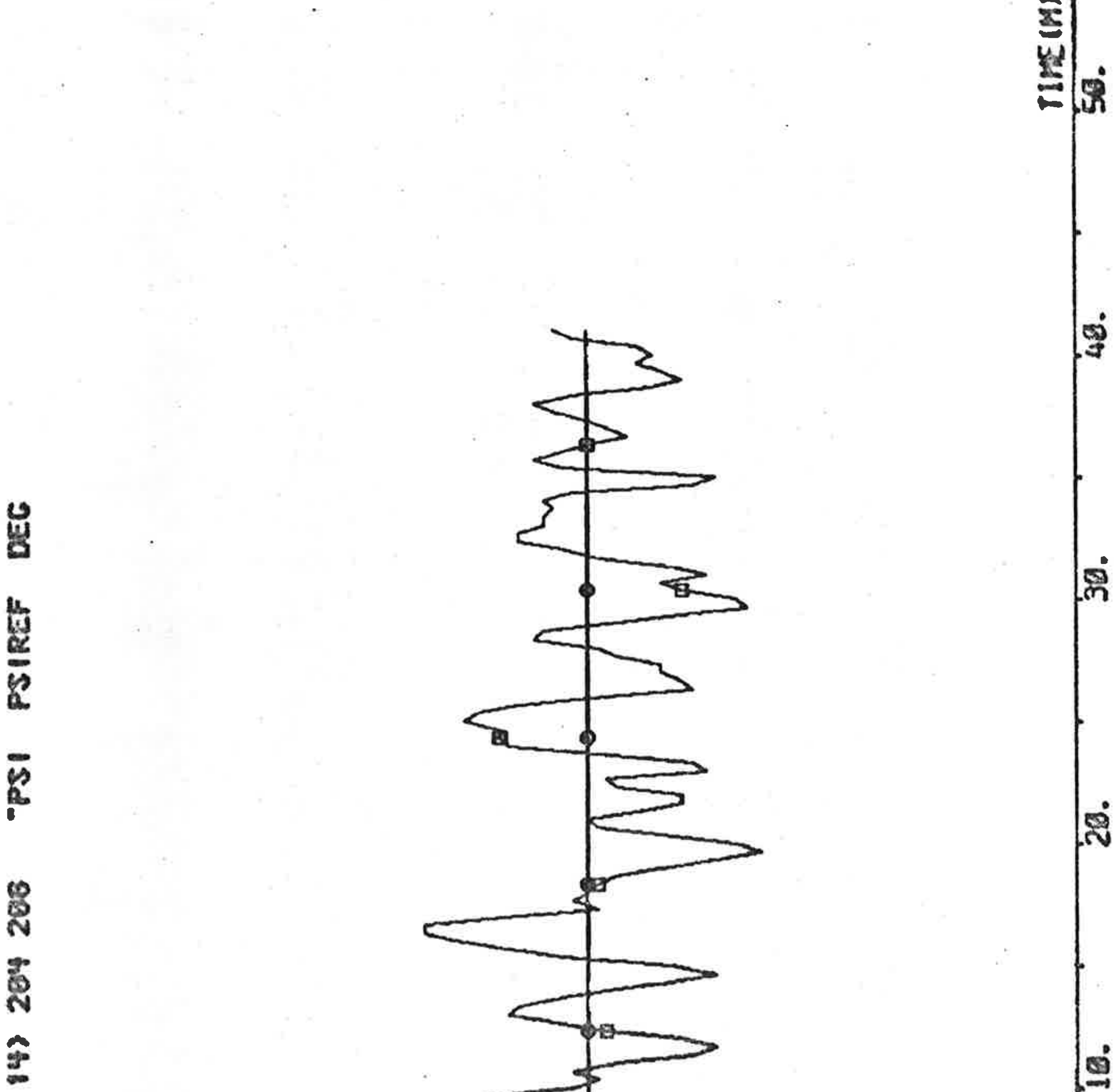

PLOT A7P1(7) 16 18 "U KNOTS
17.5
17.
16.5
16.
0.
10.
20.
30.
40.
50.
TIME(M)

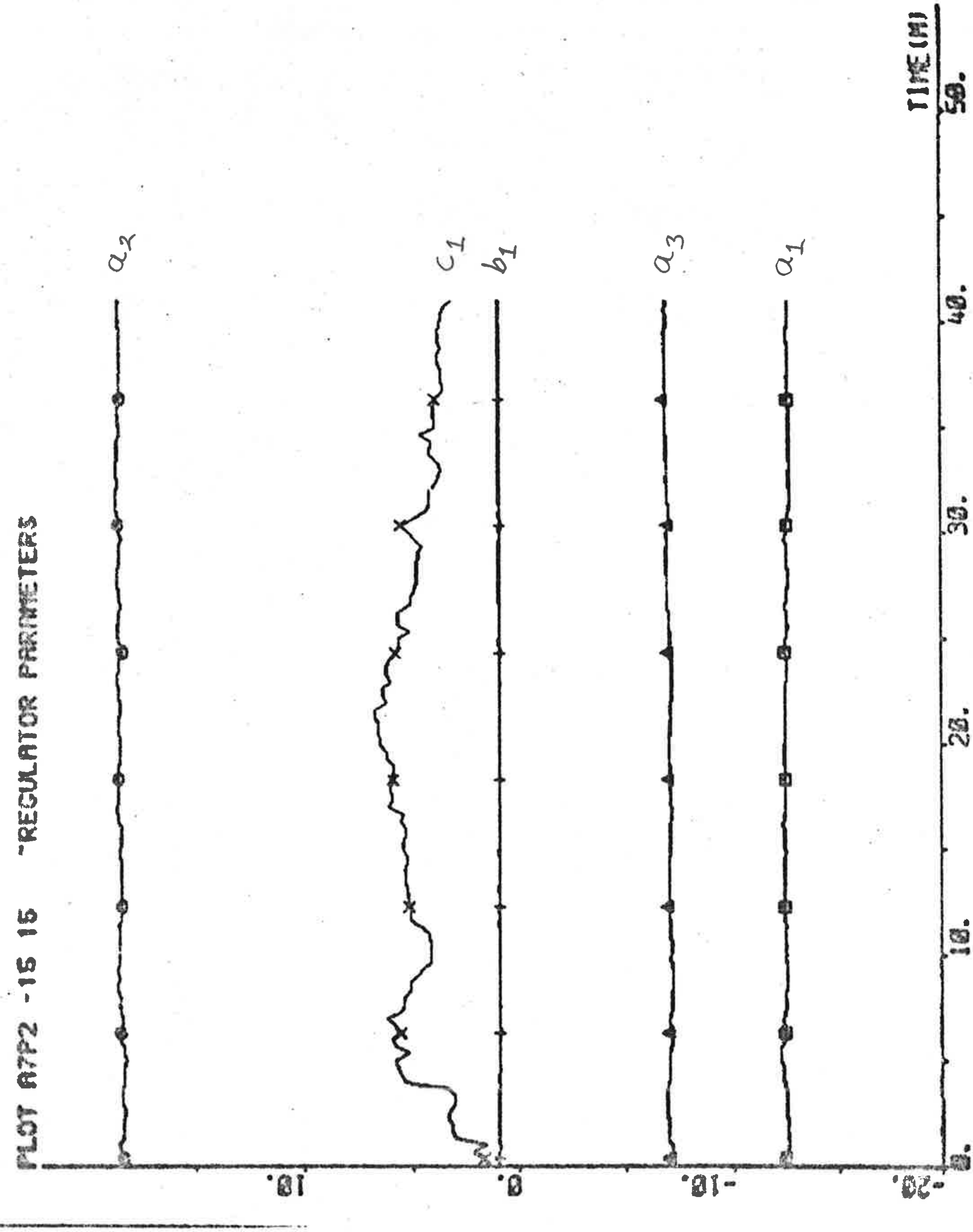

PLOT A7P1(8) Ø.5 1.5 -V1 KNOTS
Ø.5
Ø.75
1.
1.25
Ø.
1Ø.
2Ø.
3Ø.
4Ø.
5Ø.
TIME(M)



PLOT A7P1(9) 0 1 -V2 KNOTS
0.75
0.5
0.25
0.
TIME (H)
0.
10.
20.
30.
40.
50.


PLOT A7P1(10) ZERO -0.04 0.04 "R DEG/S
0.
10.
20.
30.
40.
50.
TIME(M)
0.02
0.
-0.02
-0.04


PLOT A7P1(13 14) 204 206 "PSI PSIREF DEG
TIME(M)
0.
10.
20.
30.
40.
50.
204.
205.


PLOT A7P2 -15 15 'REGULATOR PARAMETERS
a_2
c_1
b_1
a_3
a_1
10.
0.
-10.
-20.
0.
10.
20.
30.
40.
50.
TIME (M)

EXPERIMENT A8

Date	1974-10-13
Time	12.58
Duration	39 min
Position	N 15^{o} 55' E 57^{o} 06'
Water depth	deep
Forward draught	20.1 m
Aft draught	20.4 m
Wind direction	SSW (1; see Appendix A)
Wind velocity	1 Beaufort (1-1.5 m/s, light air)
Wave height	0.5 m
PSIREF	205^{o}
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 2
IREG = 20	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -11.997 \\ 17.190 \\ -5.861 \\ 0.929 \\ 25.157 \end{bmatrix} \qquad P = \begin{bmatrix} 2.660 & & & & \\ -3.257 & 4.959 & & & \\ 1.299 & -2.255 & 1.533 & & \\ -0.063 & 0.050 & 0.015 & 0.011 & \\ 12.669 & -19.684 & 7.110 & 0.042 & 182.636 \end{bmatrix}$$

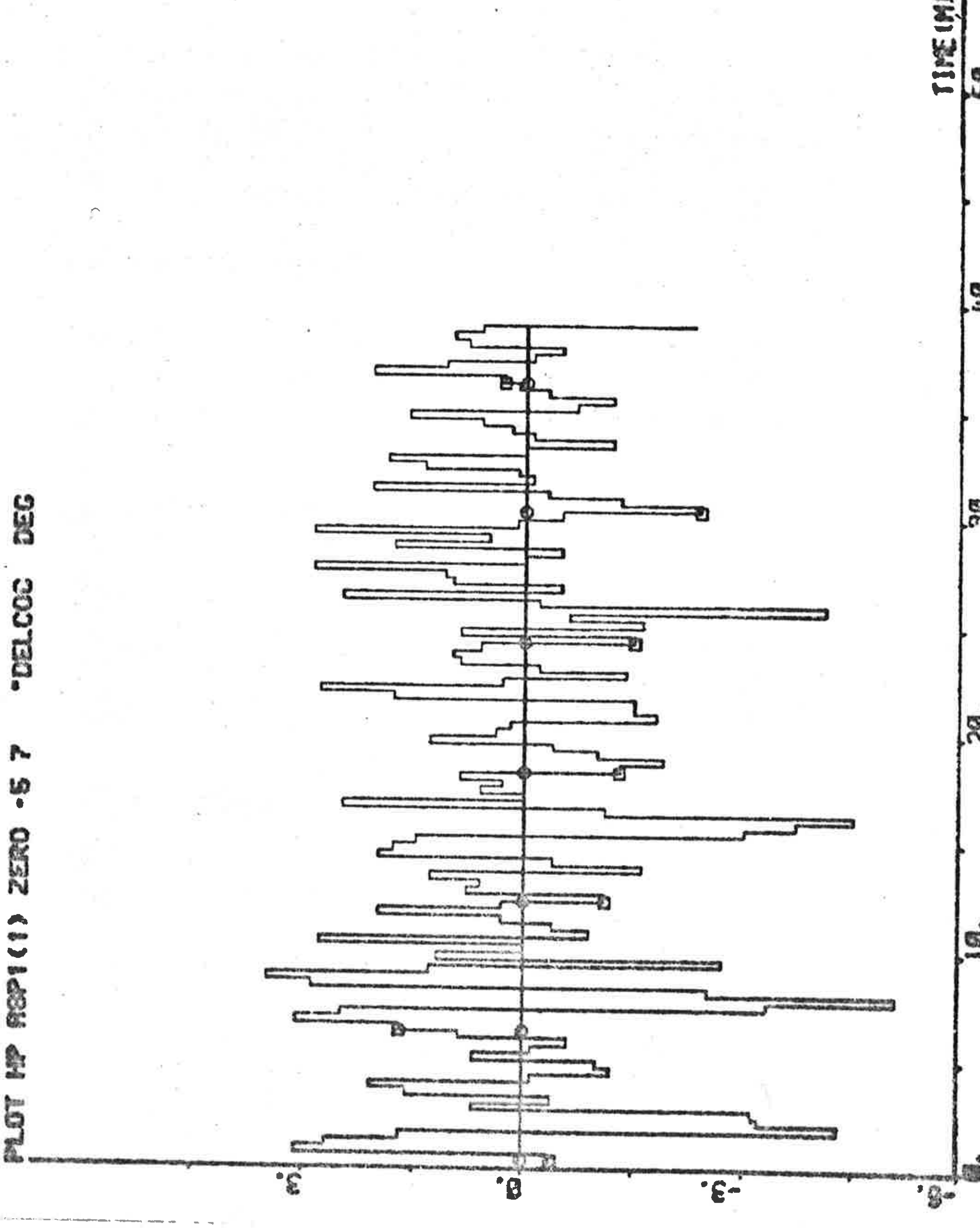
$$a_1 + a_2 + a_3 = -0.668$$

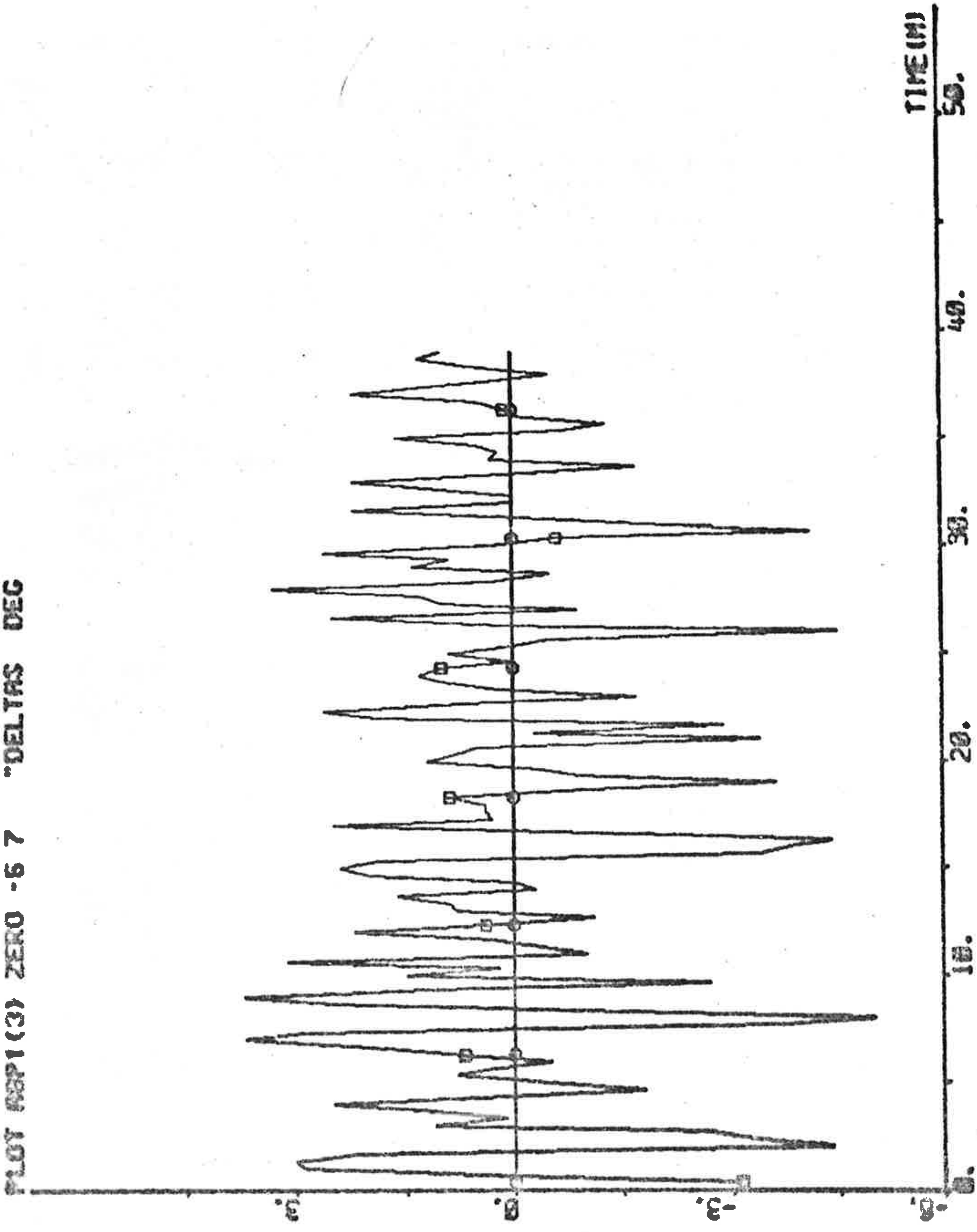
<u>Statistics</u> (mean value and standard deviation)

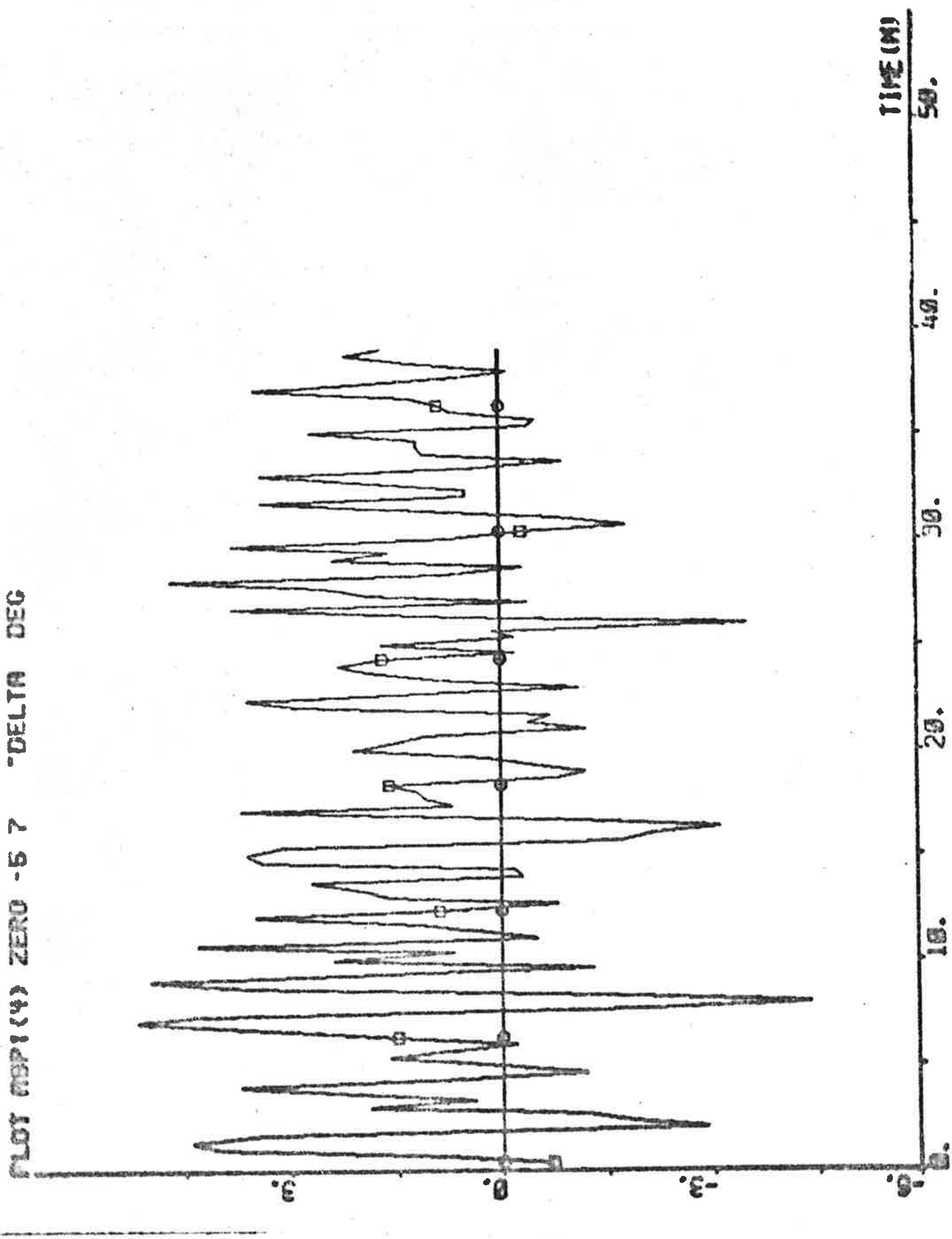
DELTA	1.03 ± 1.91 deg
PSI - PSIREF	-0.062 ± 0.292 deg
AN	85.89 ± 0.37 rpm
U	15.87 ± 0.15 knots

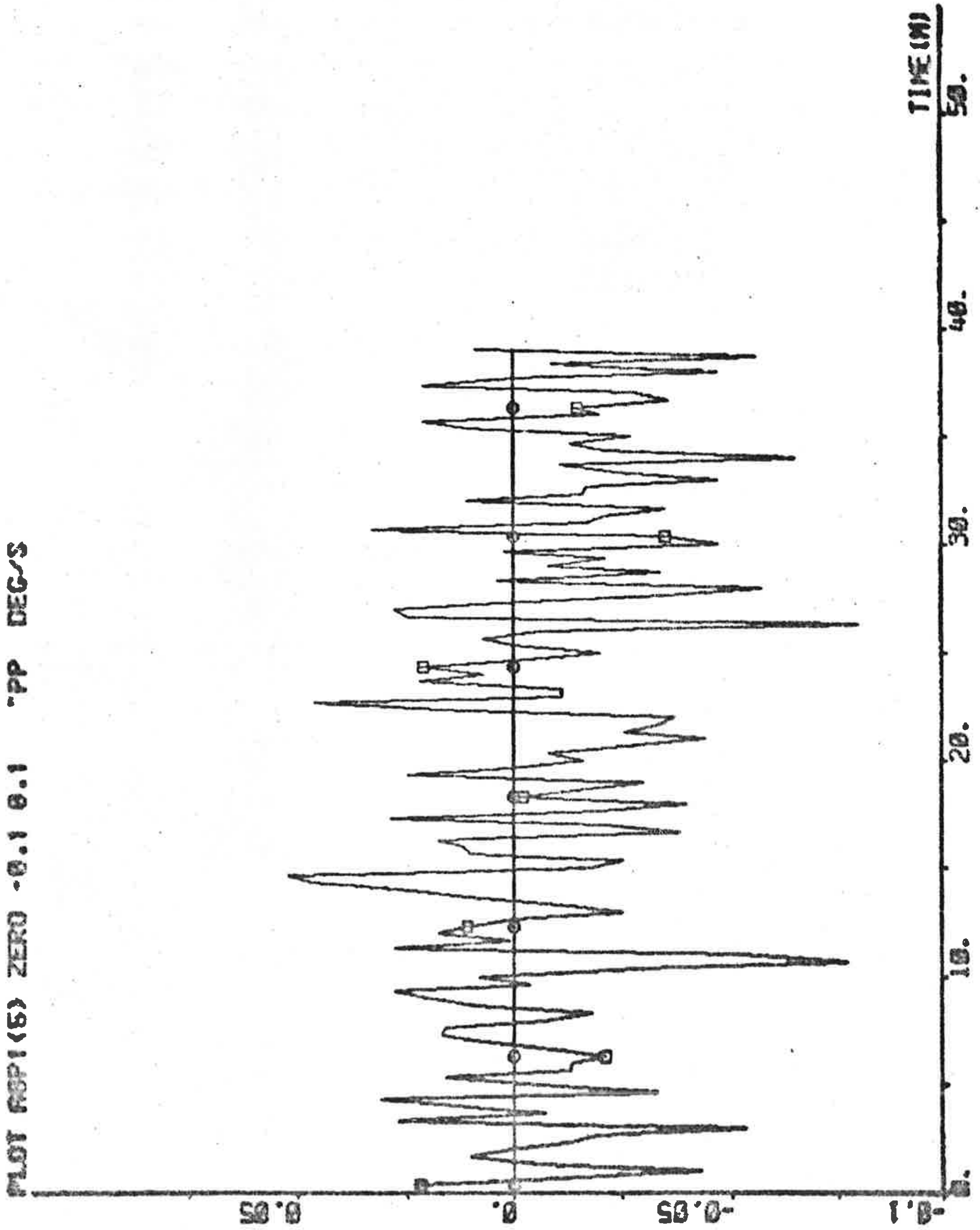
$V_1 = 0.560$

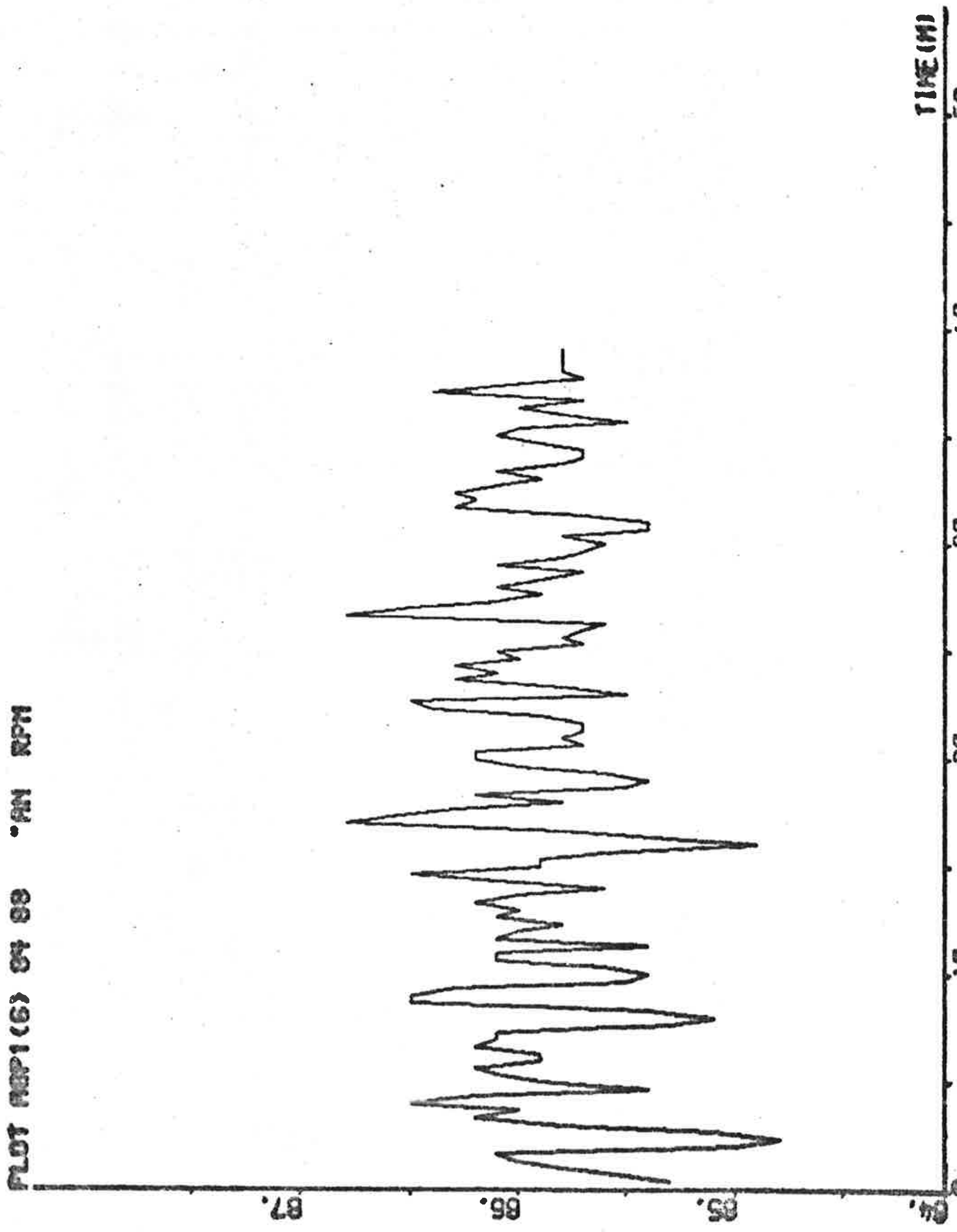
$V_2 = 0.454$

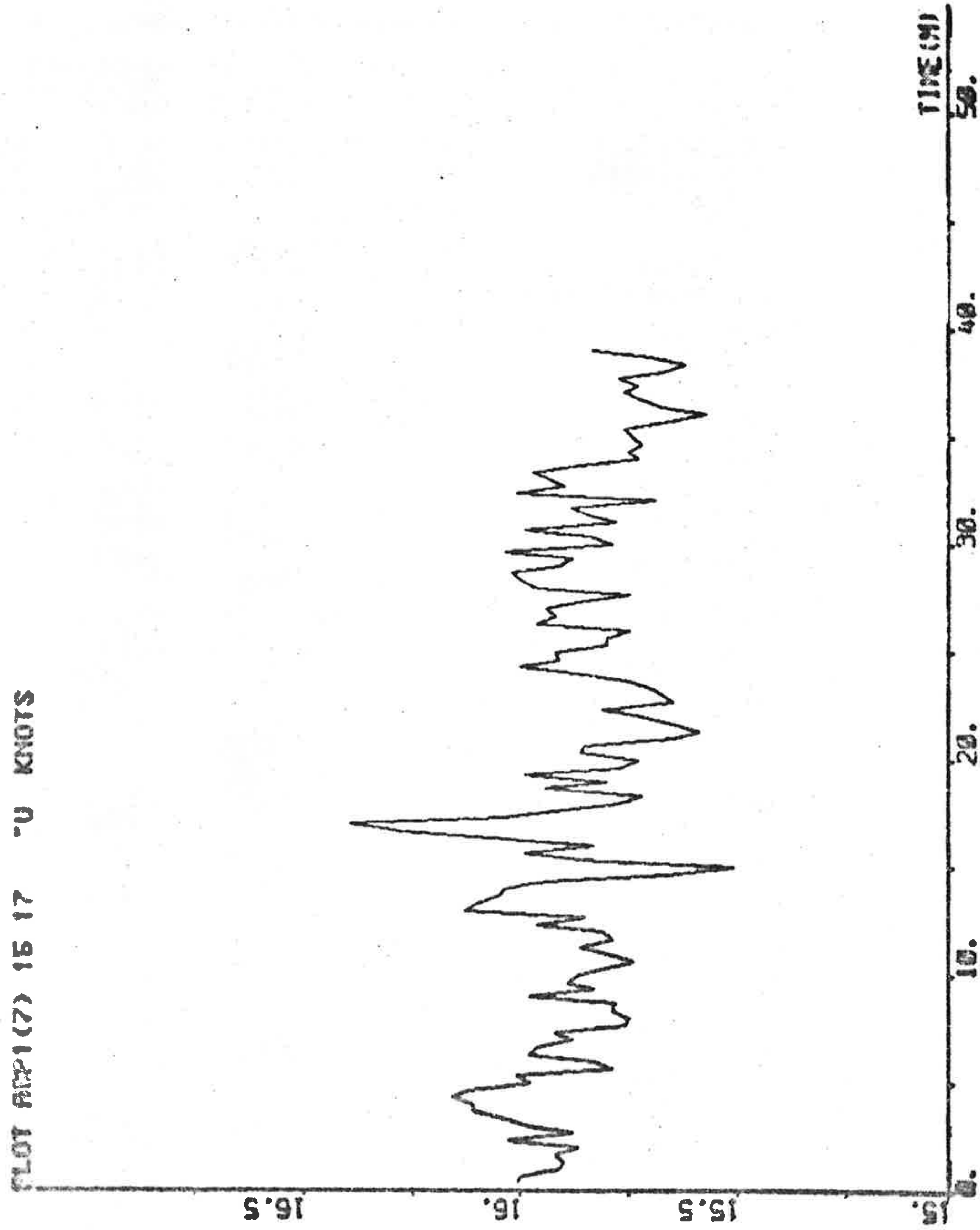

PLOT HP ABP1(1) ZERO .5 7 'DELCOC DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

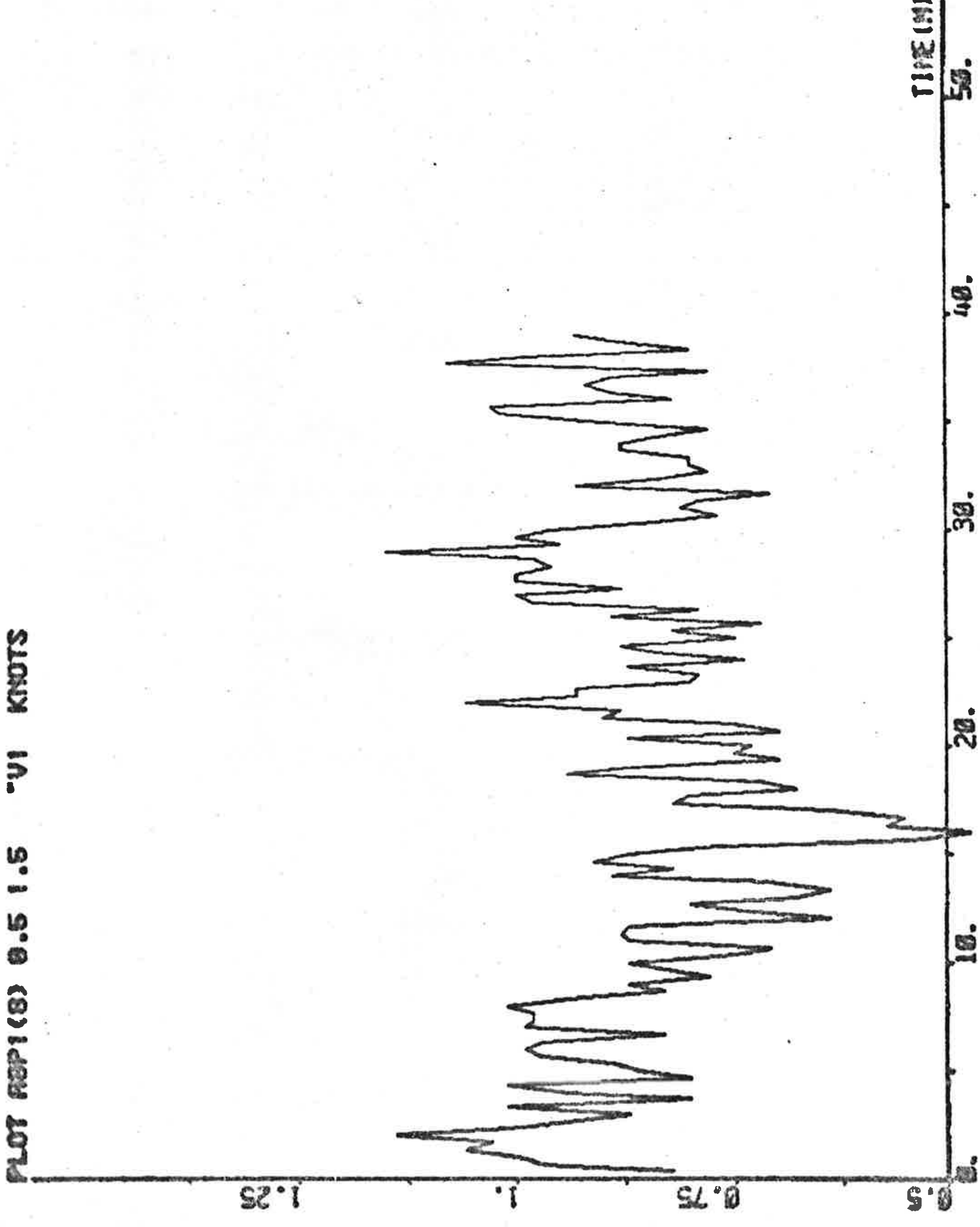

PLOT RRP1(3) ZERO -6 7 "DELTAS DEG
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.


PLOT ABP(4) ZERO -5 7 "DELTA DEG
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

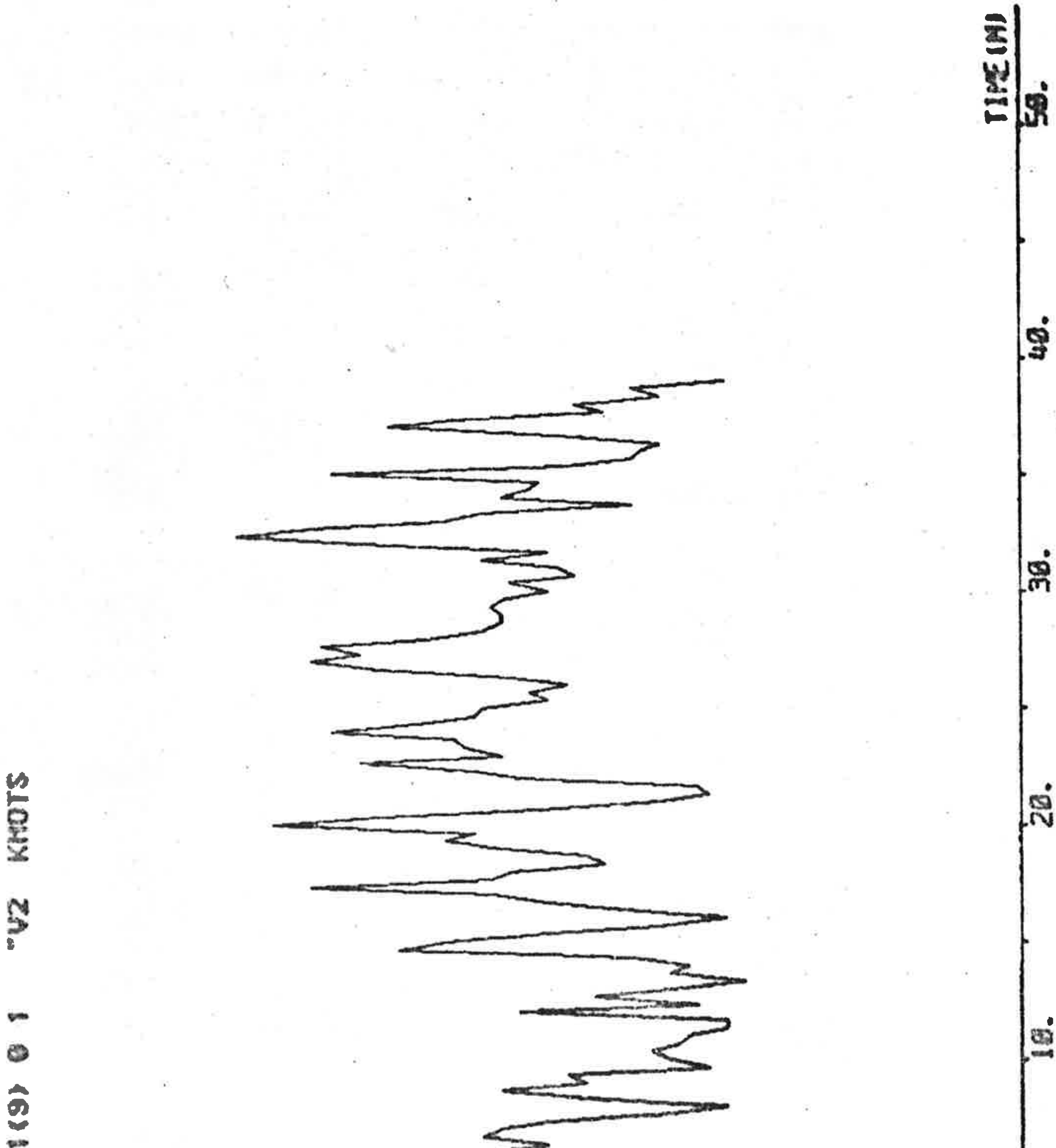

PLOT RSP1(5) ZERO -0.1 0.1 "PP DEG/S
TIME(M)
0.
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1

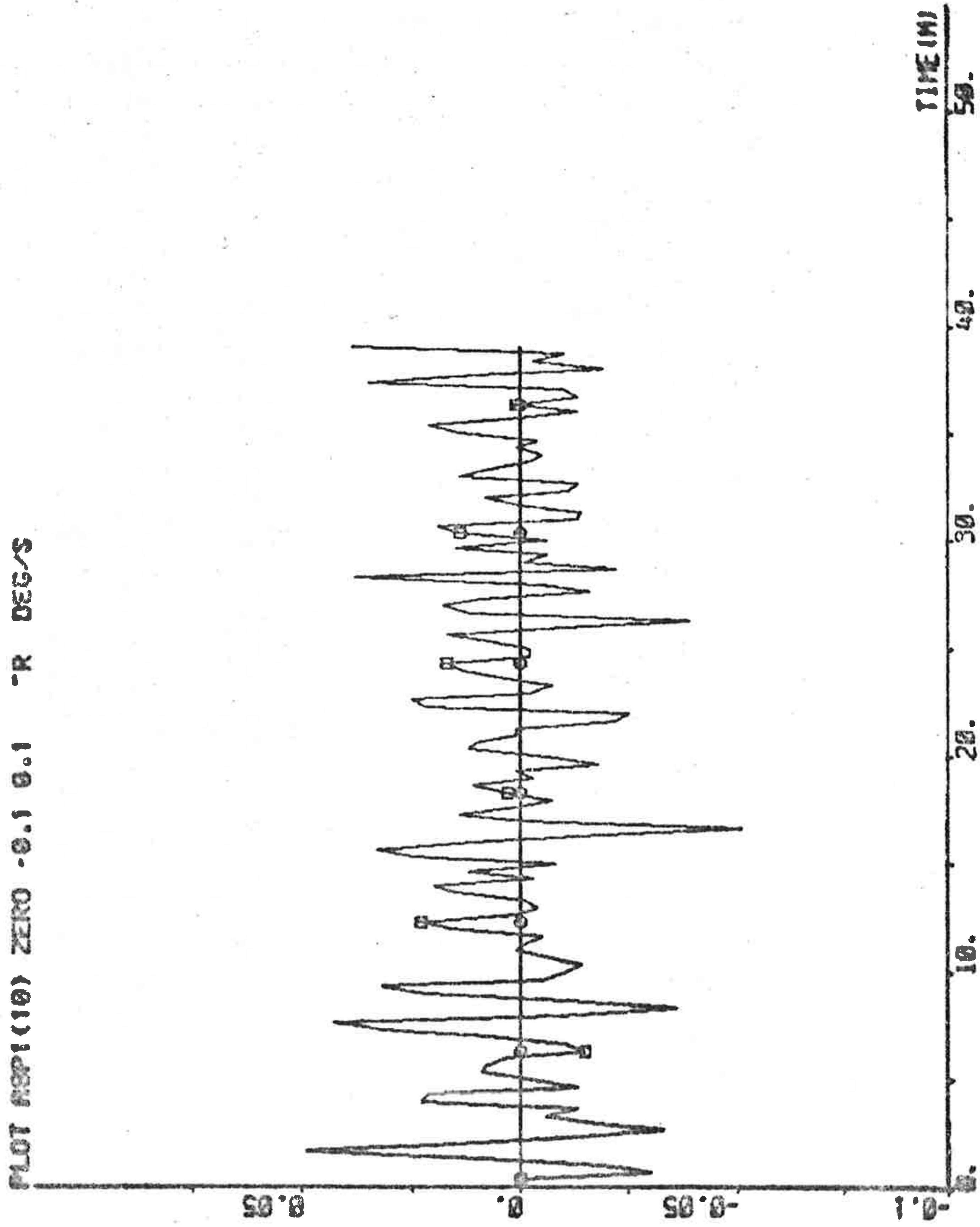

PLOT
RPM
87.
86.
85.
84.
0.
10.
20.
30.
40.
50.
TIME (M)

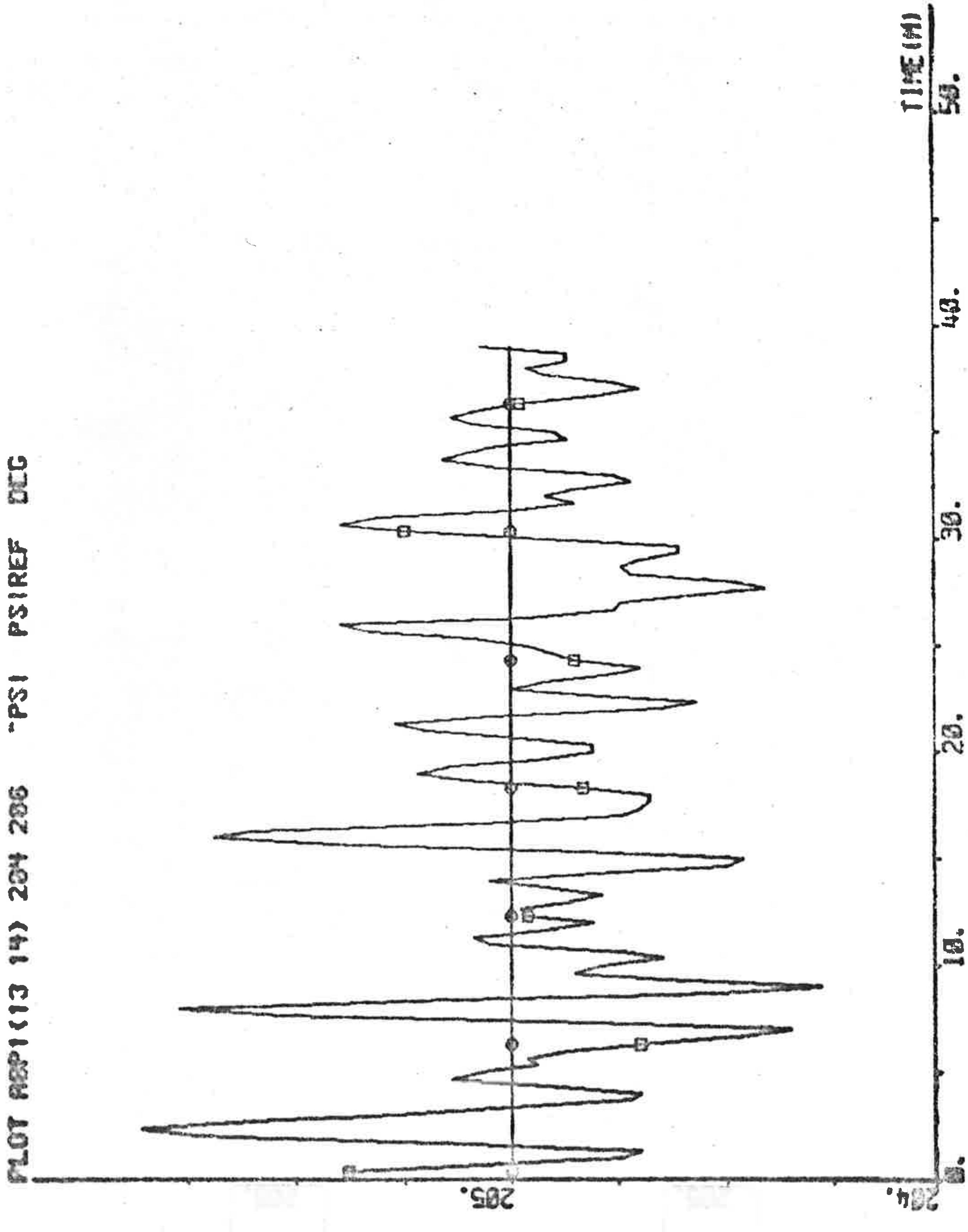

PLOT
(7) 15 17
"U KNOTS
TIME(M)
0.
10.
20.
30.
40.
50.
15.
15.5
16.
16.5

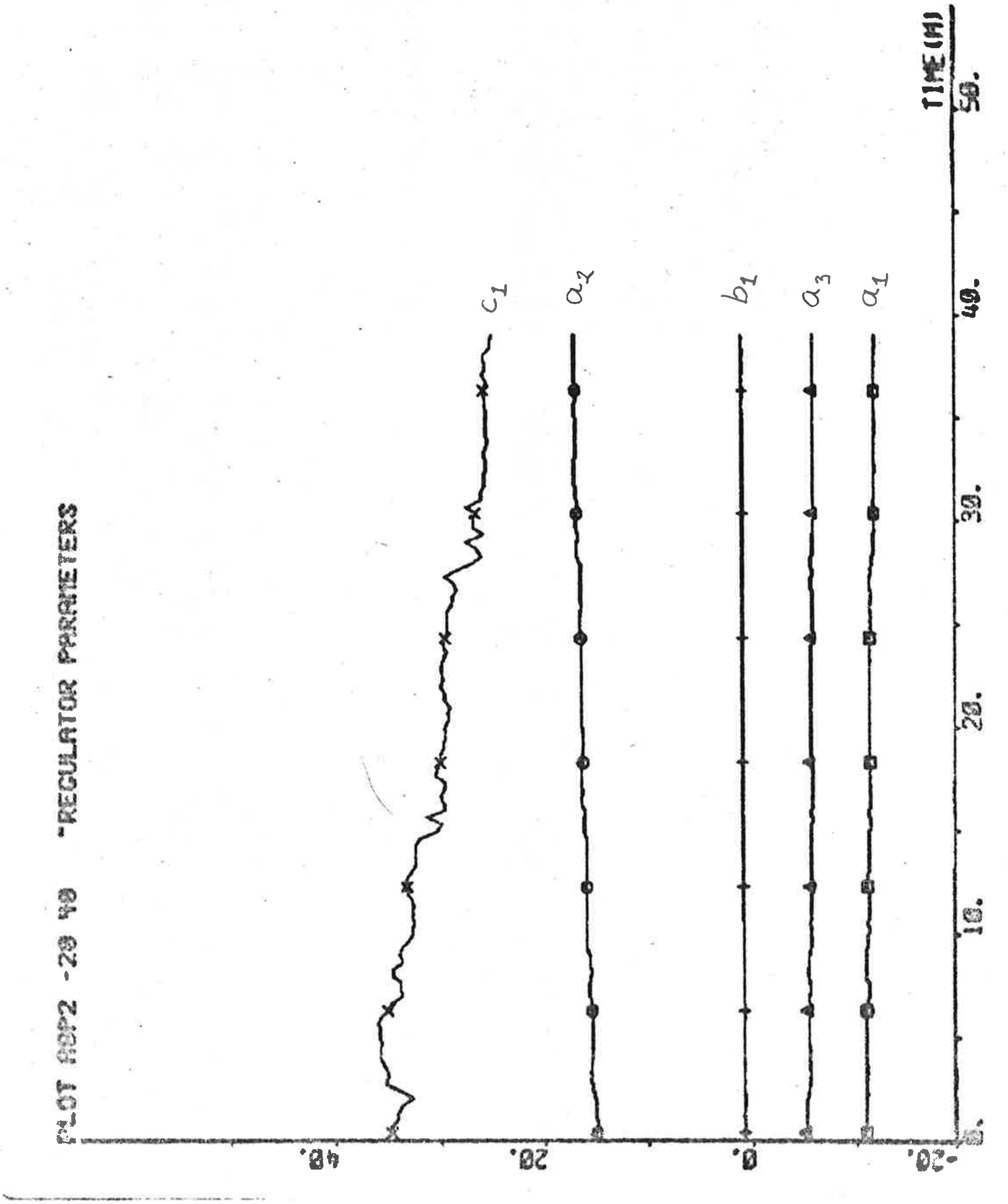


PLOT ABP1(B) 0.5 1.5 "V1 KNOTS
0.5
0.75
1.
1.25
0.
10.
20.
30.
40.
50.
TIME (M)


PLOT ABP(9) 0 1 "V2 KNOTS
0.
0.25
0.5
0.75
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT RSP1(10) ZERO -0.1 0.1 'R DEG/S
TIME(M)
0.
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1


PLOT RBP1(13 14) 204 206 "PSI PSIREF DEG
TIME(M)
0.
10.
20.
30.
40.
50.
204.
205.


PLOT ROP2 -20 40 'REGULATOR PARAMETERS
c1
a2
b1
a3
a1
TIME (H)
0.
10.
20.
30.
40.
50.
40.
20.
0.
-20.

EXPERIMENT A9

Date	1974-10-13
Time	14.49
Duration	34 min
Position	N 15° 28' E 56° 53'
Water depth	deep
Forward draught	20.1 m
Aft draught	20.4 m
Wind direction	SSW (1; see Appendix A)
Wind velocity	1 Beaufort (1-1.5 m/s, light air)
Wave height	0.5 m
PSIREF	205°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 5
IREG = 20	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -12.968 \\ 18.223 \\ -5.855 \\ 0.937 \\ 17.697 \end{bmatrix} \qquad P = \begin{bmatrix} 2.935 & & & & \\ -3.365 & 4.935 & & & \\ 1.048 & -2.050 & 1.616 & & \\ -0.151 & 0.134 & 0.015 & 0.021 & \\ 9.833 & -15.631 & 4.520 & -0.201 & 219.730 \end{bmatrix}$$

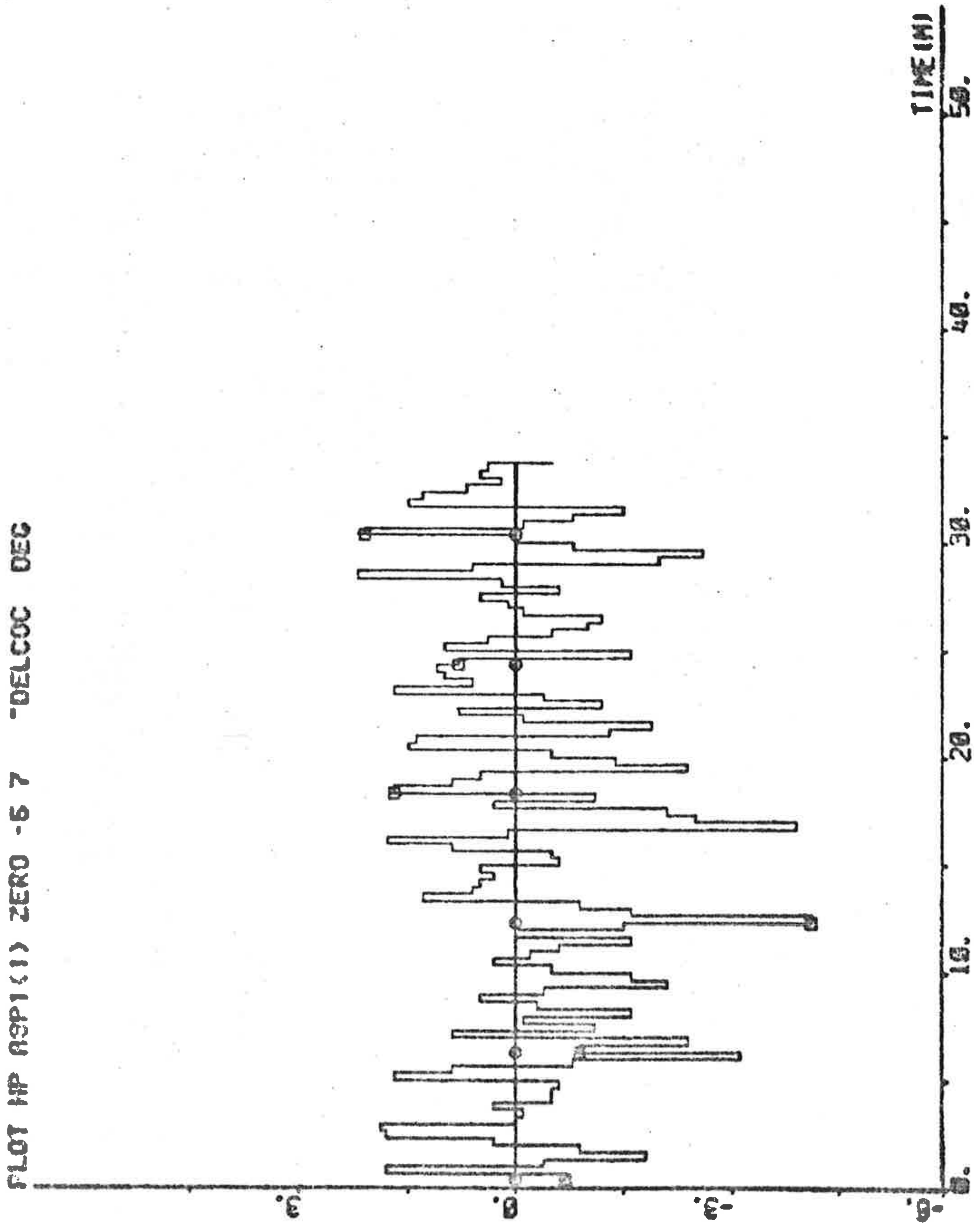
$$a_1 + a_2 + a_3 = -0.600$$

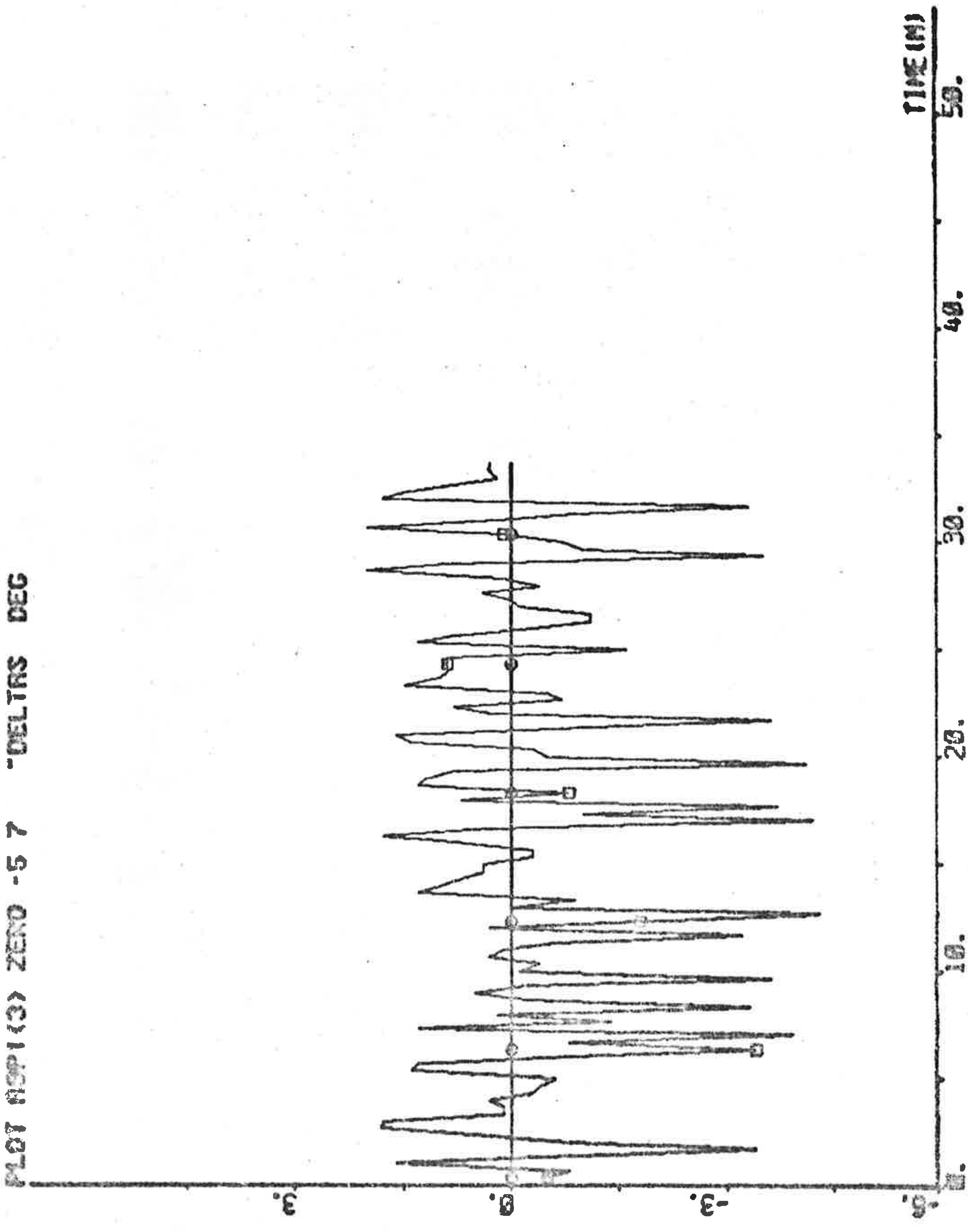
<u>Statistics</u> (mean value and standard deviation)

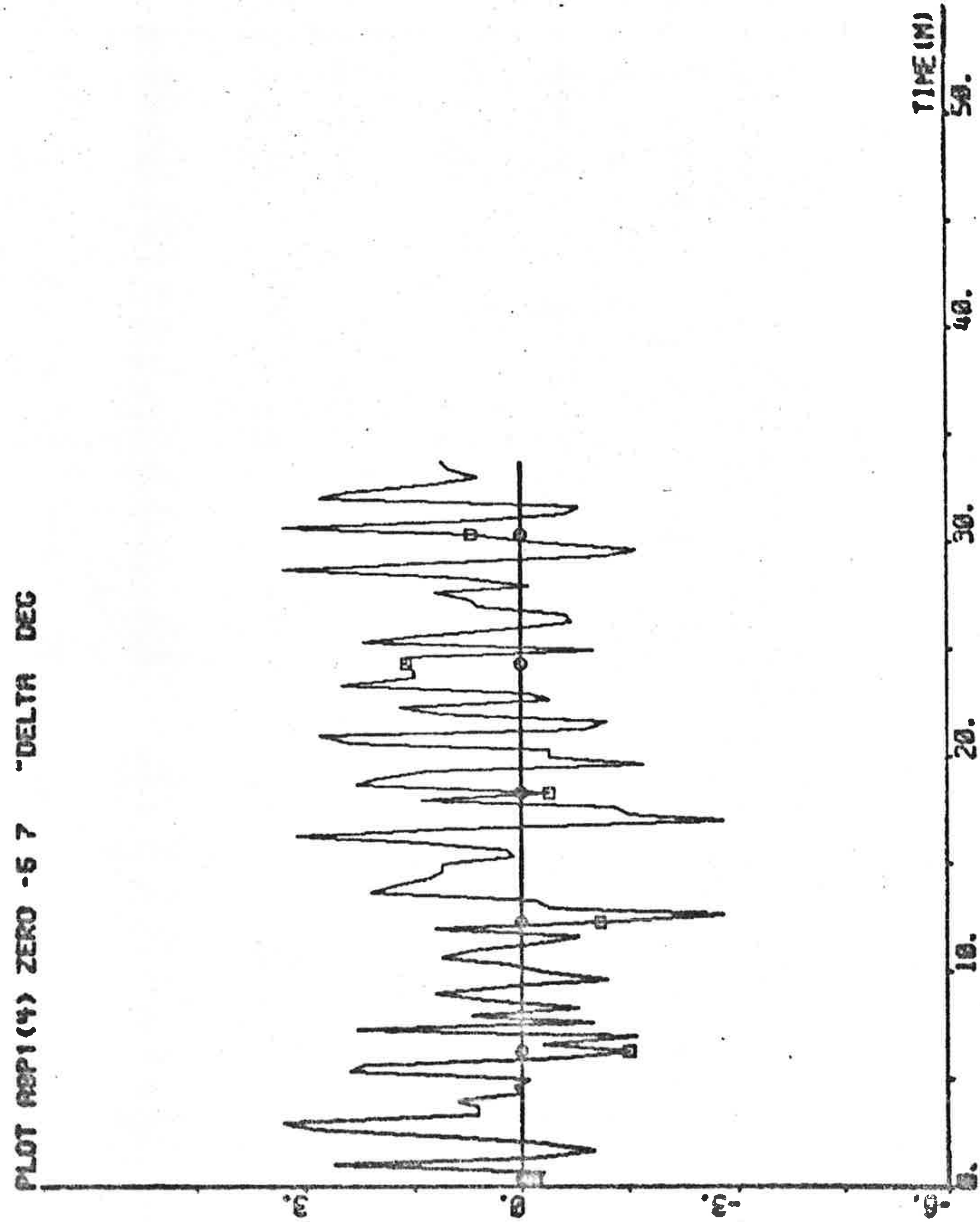
DELTA	0.54 ± 1.36 deg
PSI - PSIREF	-0.080 ± 0.206 deg
AN	86.16 ± 0.30 rpm
U	16.06 ± 0.10 knots

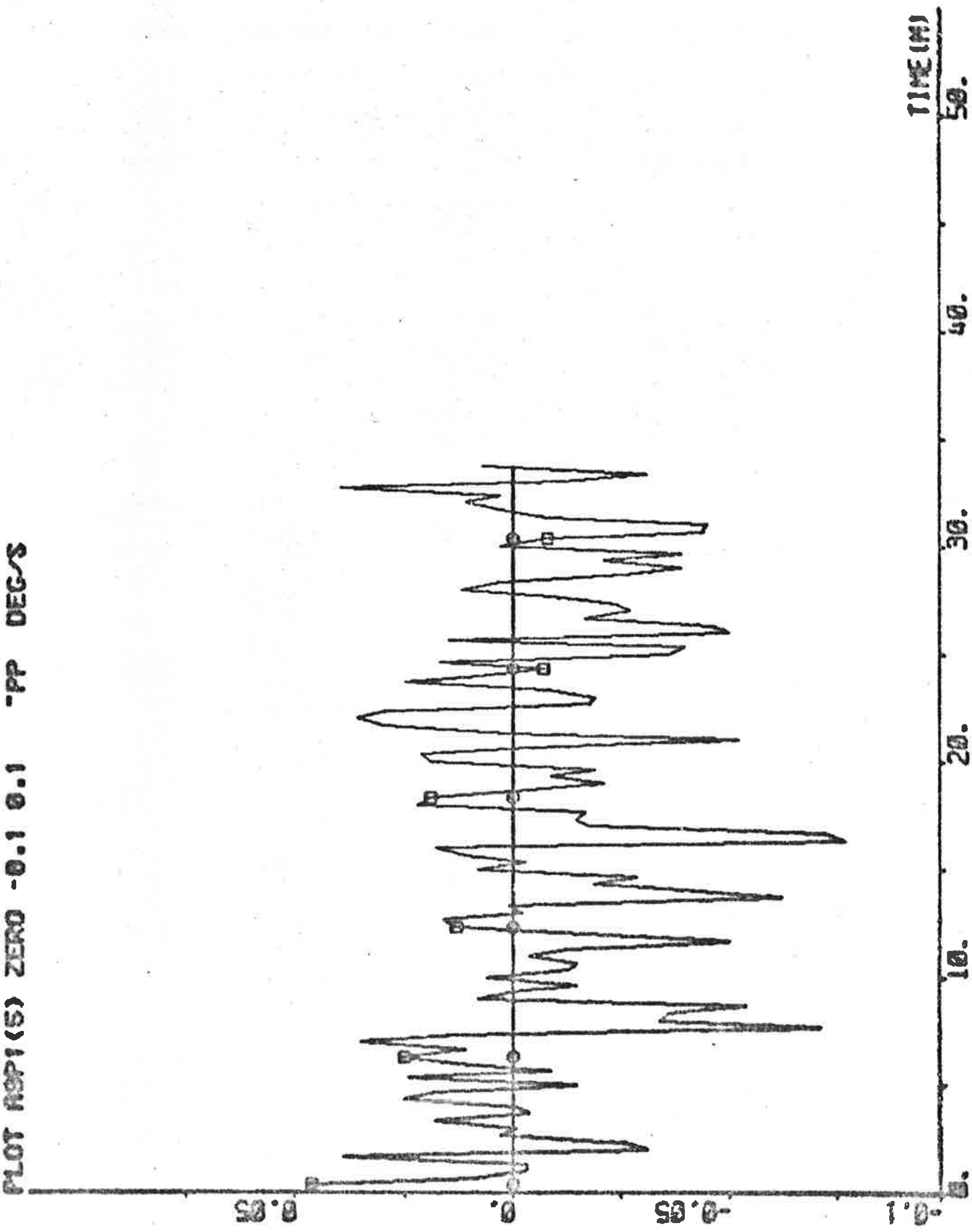
$V_1 = 0.263$

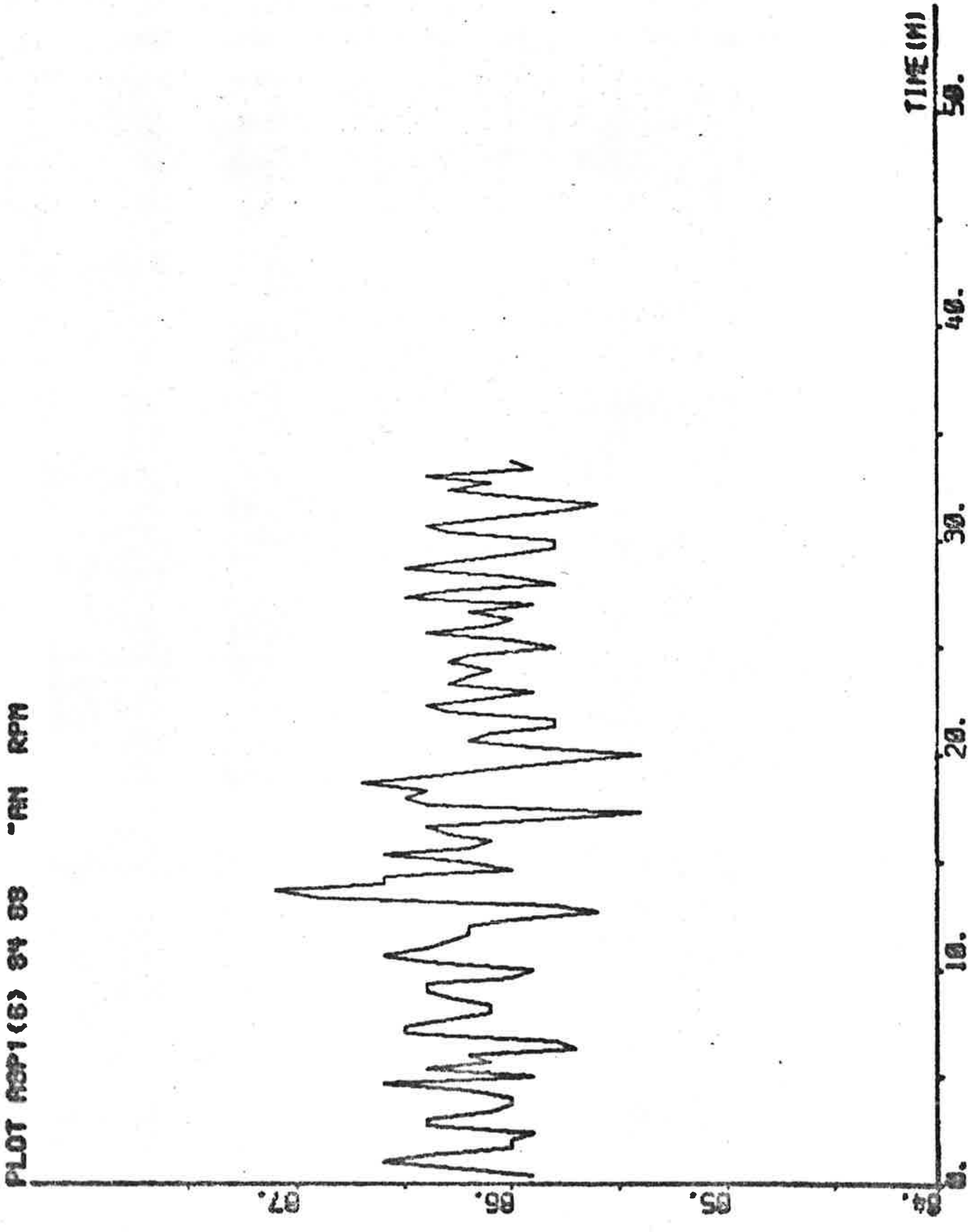
$V_2 = 0.234$


PLOT HP ASP1(1) ZERO -6 7 -DELCOC DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(H)

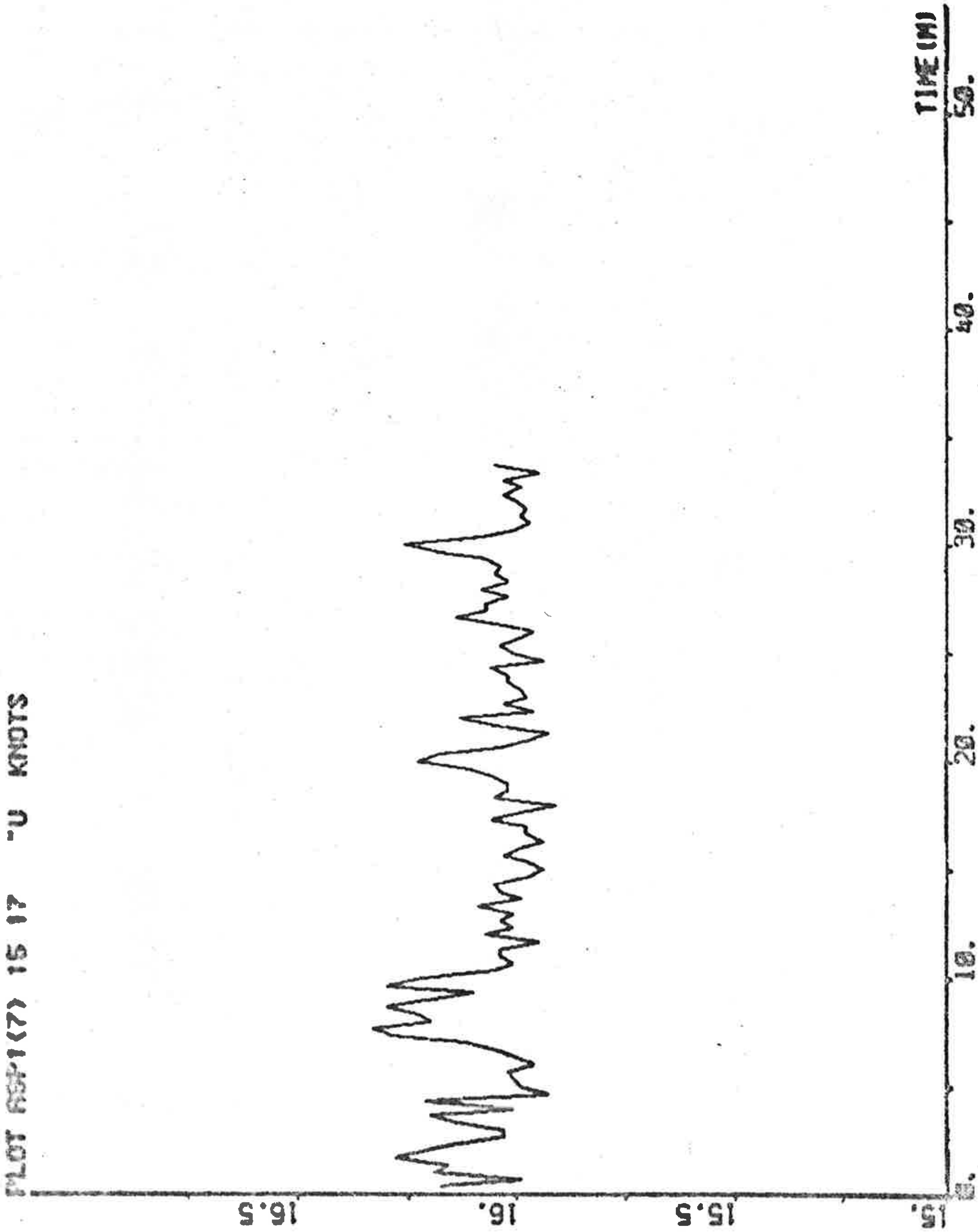

PLOT RSP1(3) ZERO -5 7 "DELTRS DEG
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

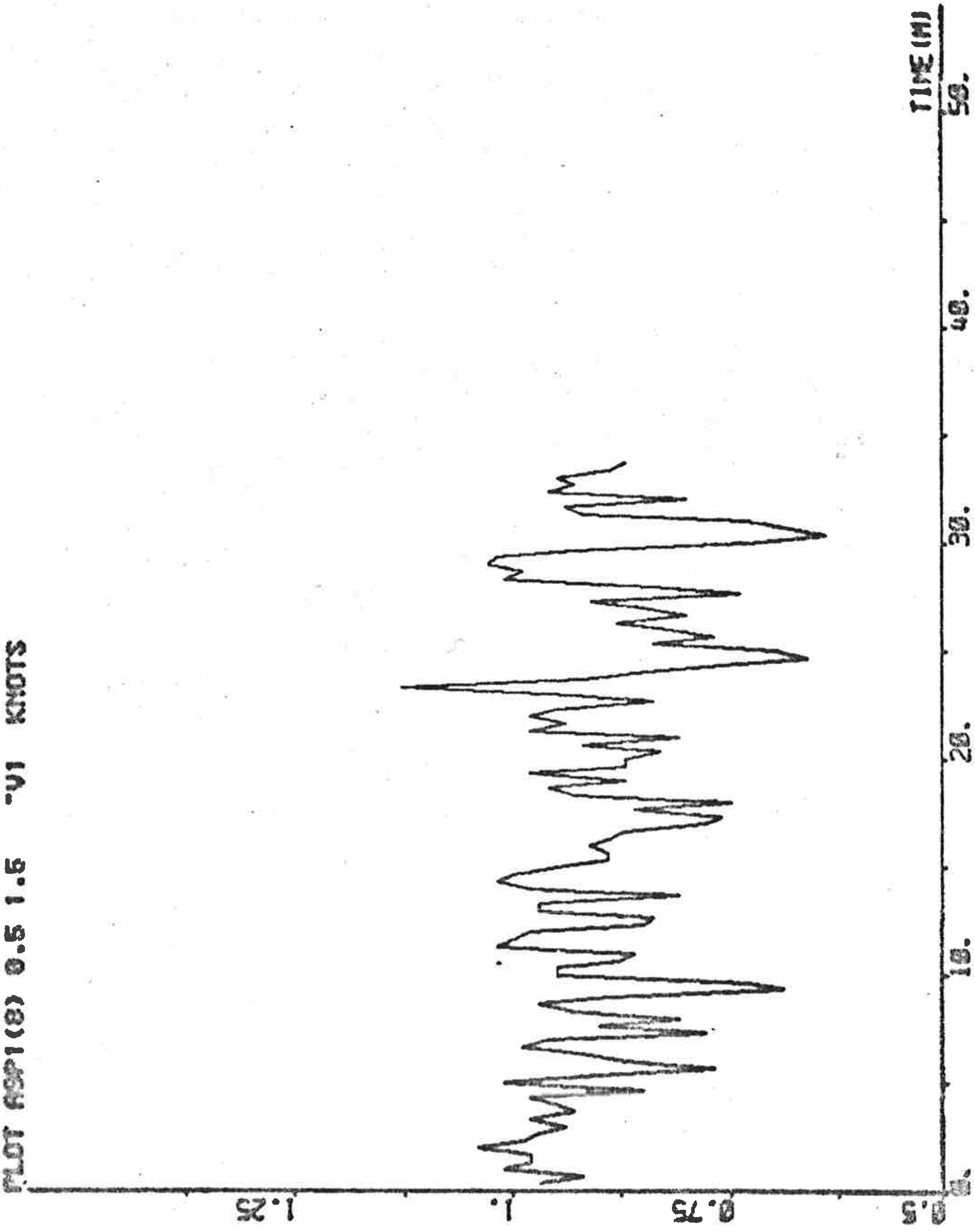

PLOT ADP1(4) ZERO -5 7 "DELTA DEG
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

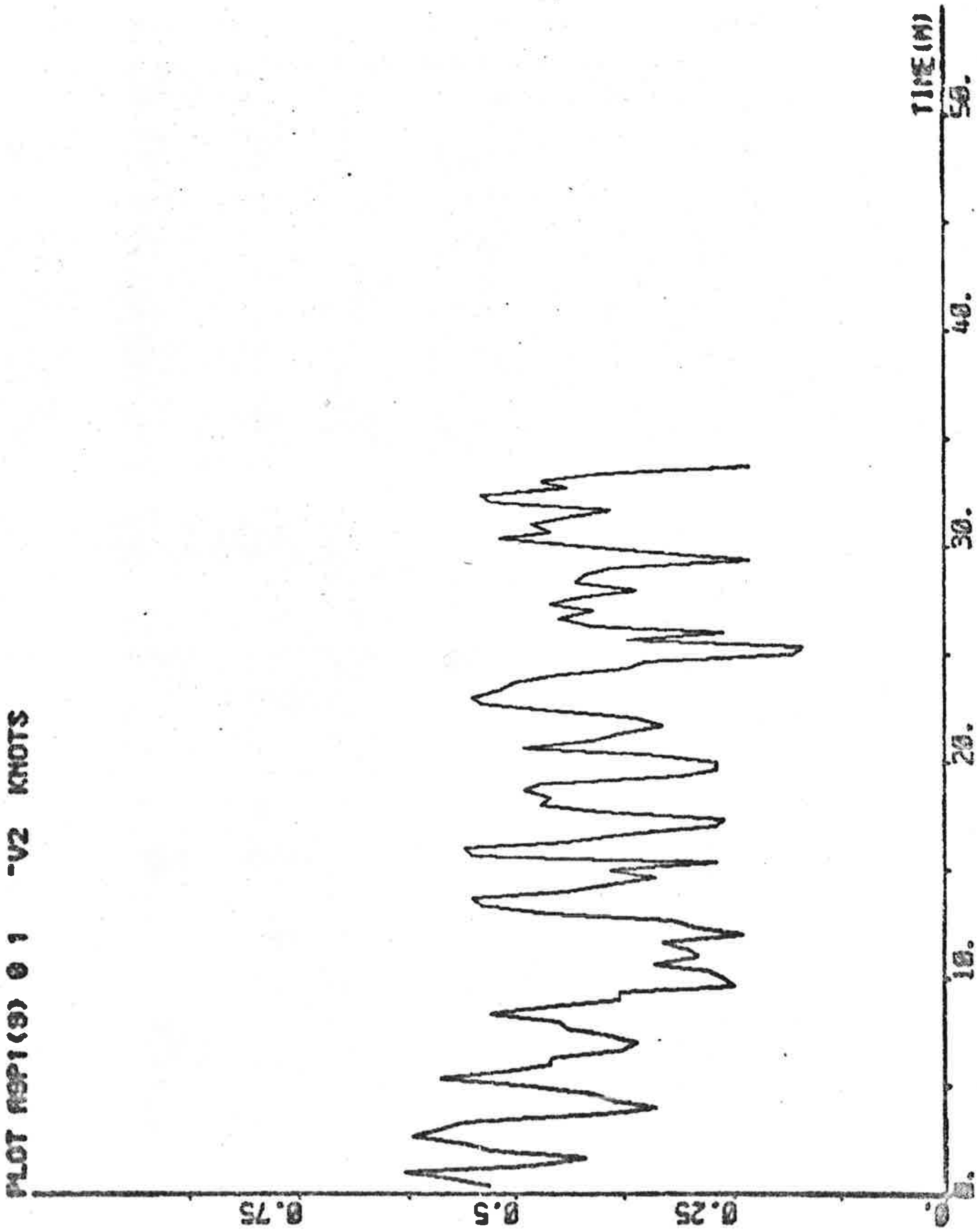

PLOT RSP1(5) ZERO -0.1 0.1 'PP DEG/S
TIME (M)
0.
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1

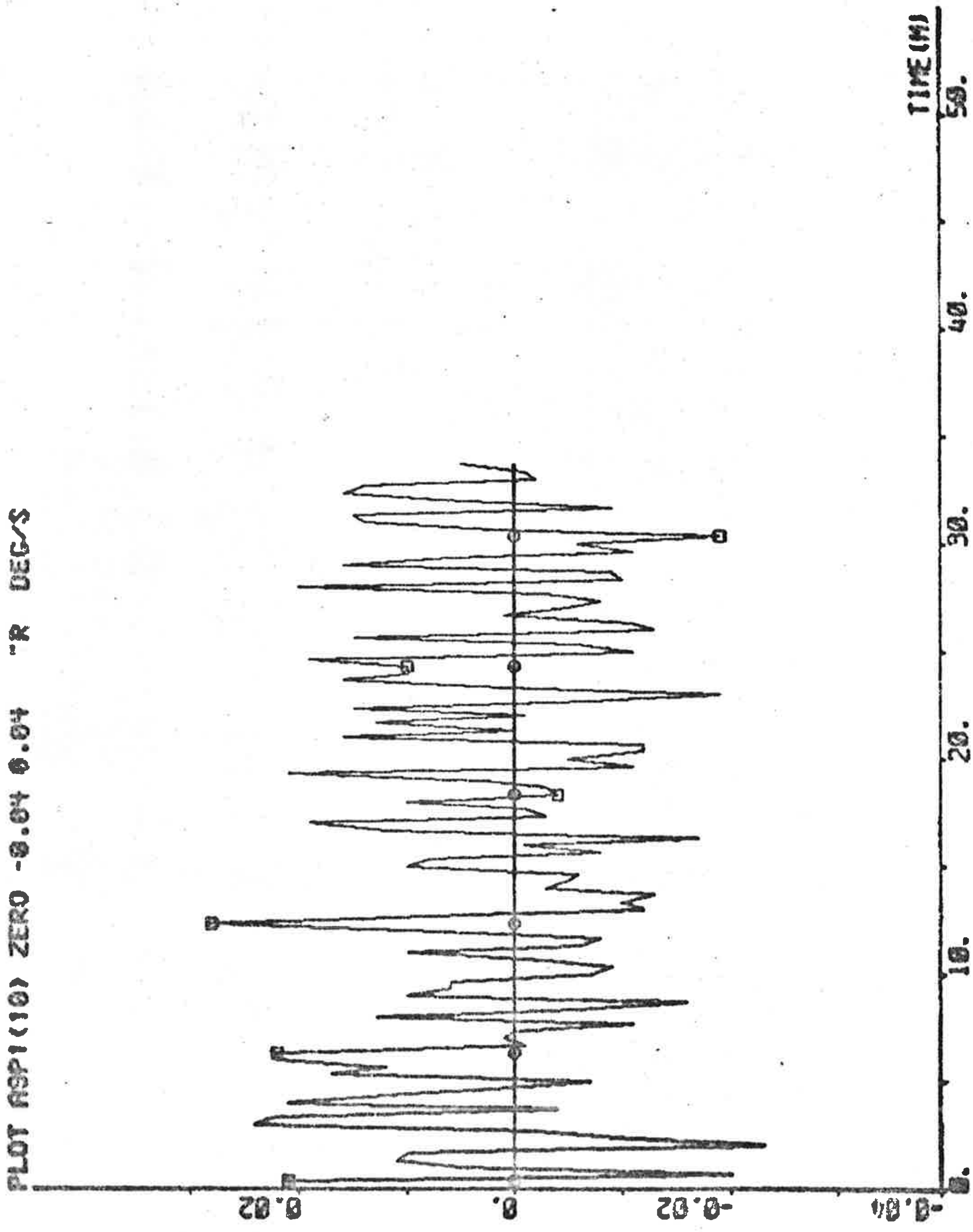


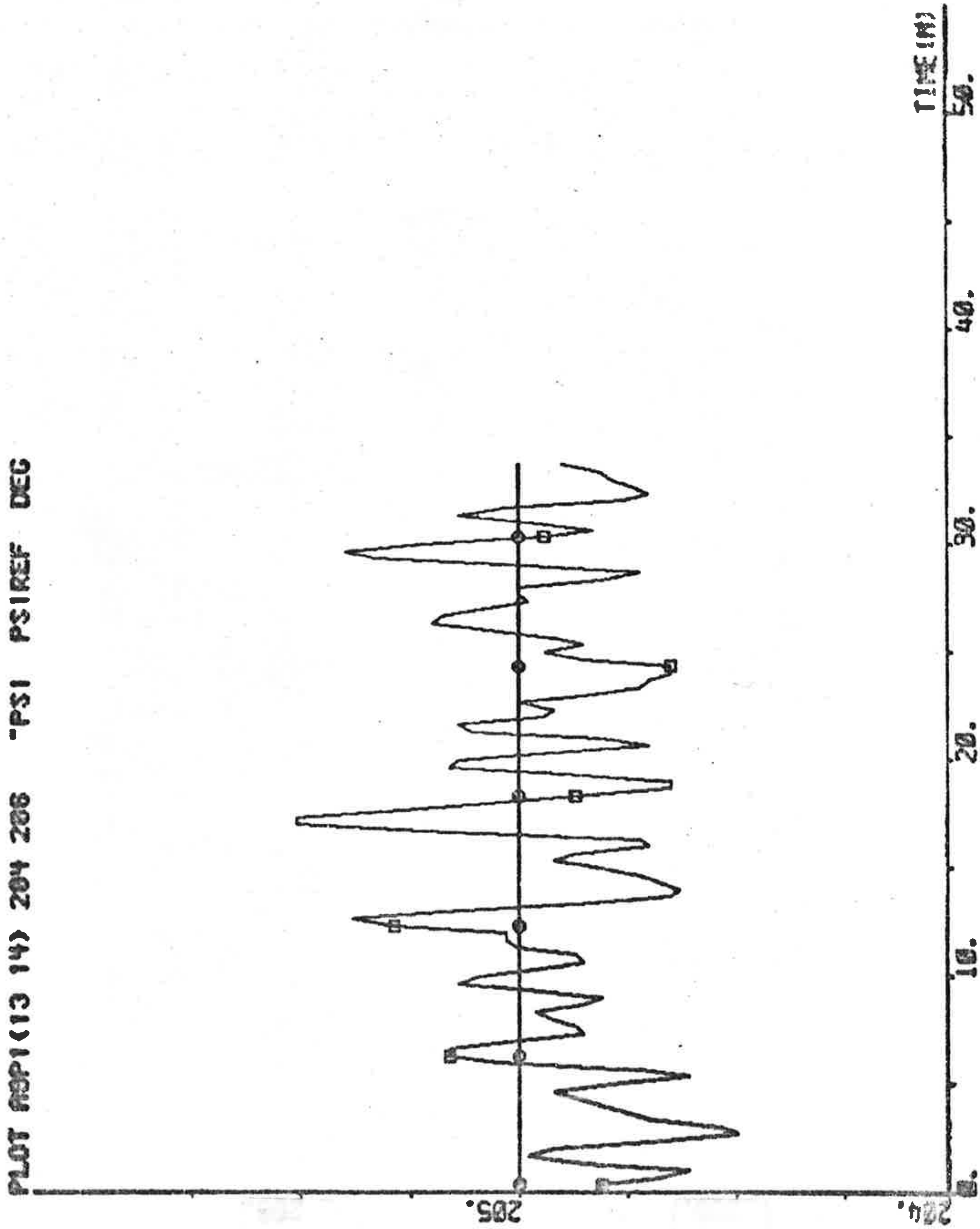
PLOT
RPM
TIME(M)
0.
10.
20.
30.
40.
50.
84.
85.
86.
87.


PLOT RSP1(7) 15 17 "U KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
15.
15.5
16.
16.5

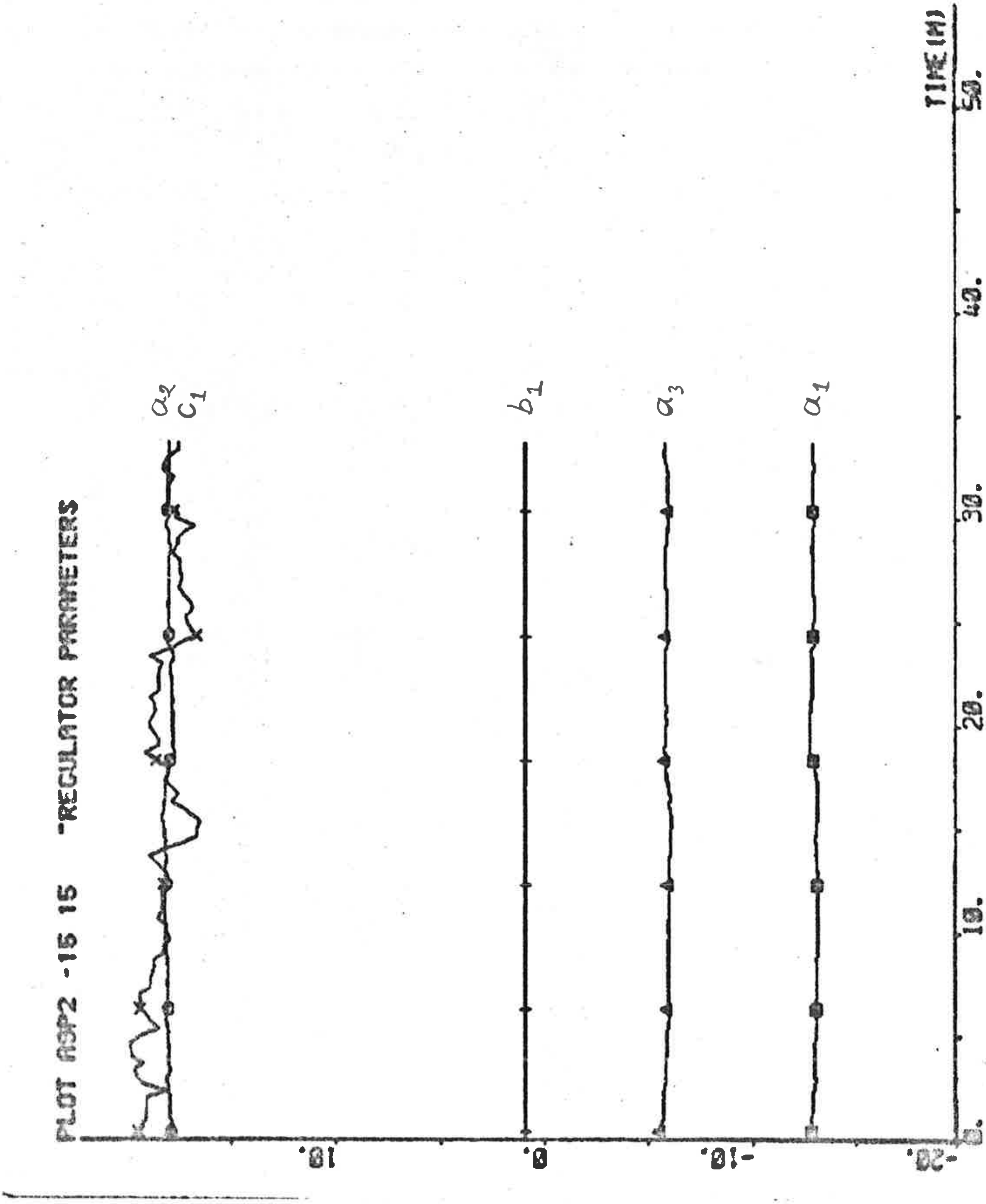

PLOT ASP1(8) 0.5 1.5 "V1 KNOTS
TIME (H)
10.
20.
30.
40.
50.
0.5
0.75
1.
1.25


PLOT ABP1(S) @ 1 -V2 KNOTS
TIME (H)
0.75
0.5
0.25
0.
10.
20.
30.
40.
50.


PLOT ASP1(10) ZERO -0.04 0.04 'R DEG/S
TIME(M)
0.
10.
20.
30.
40.
50.
0.02
0.
-0.02
-0.04



PLOT ABP1(13 14) 204 206 "PSI PSIREF DEG
TIME (M)
0.
10.
20.
30.
40.
50.
204.
205.



PLOT ASP2 -15 15 "REGULATOR PARAMETERS
TIME (M)
0.
10.
20.
30.
40.
50.
10.
0.
-10.
-20.
a_2
c_1
b_1
a_3
a_1

EXPERIMENT A10

Date	1974-10-14
Time	8.29
Duration	32 min
Position	N 11° 16' E 55° 05'
Water depth	deep
Forward draught	20.2 m
Aft draught	20.2 m
Wind direction	-
Wind velocity	1 Beaufort (1-1.5 m/s, light air)
Wave height	1 m
PSIREF	208°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 5
IREG = 15	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -17.208 \\ 28.241 \\ -11.576 \\ 1.003 \\ 2.784 \end{bmatrix}$$

P unknown

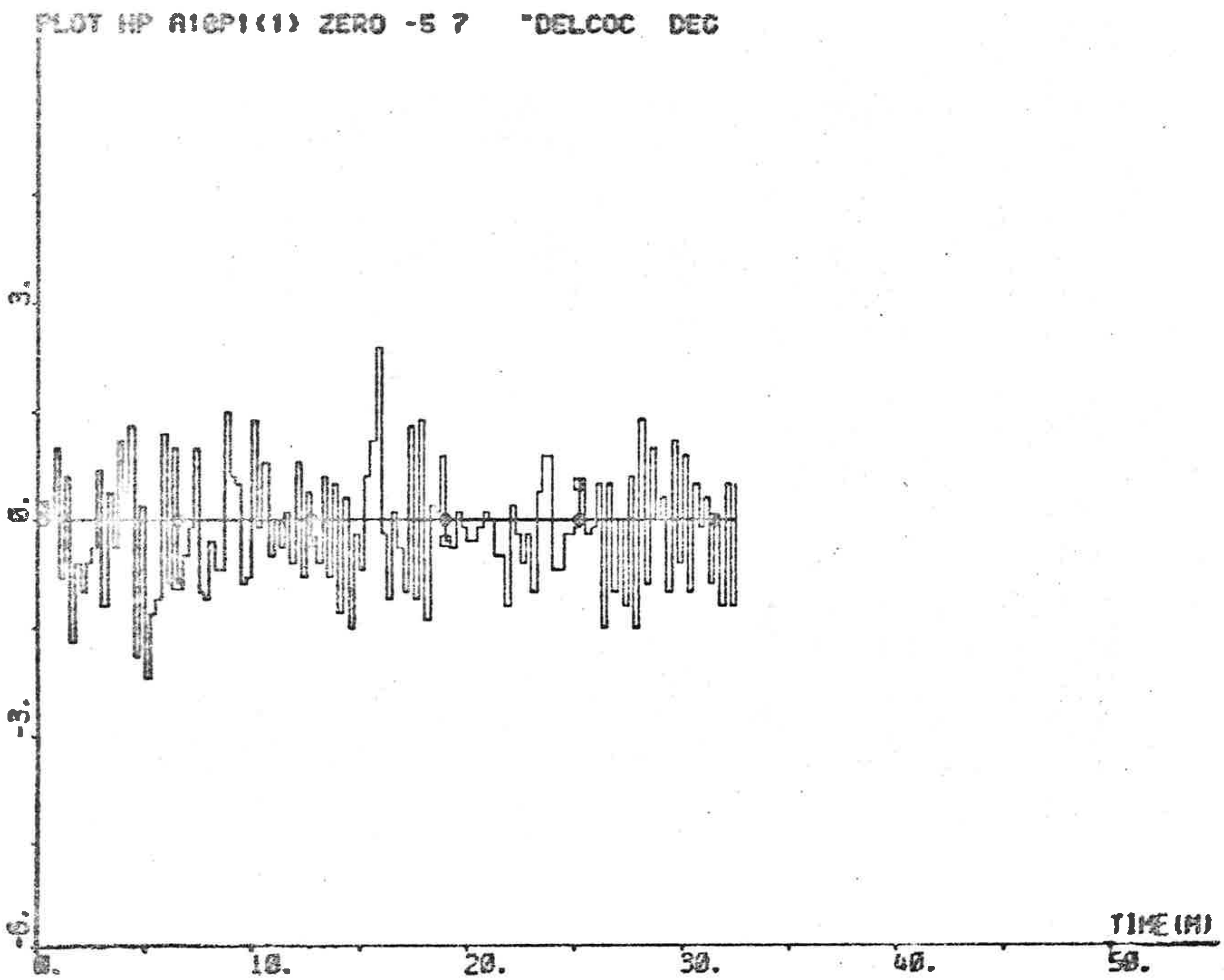
$a_1 + a_2 + a_3 = - 0.543$

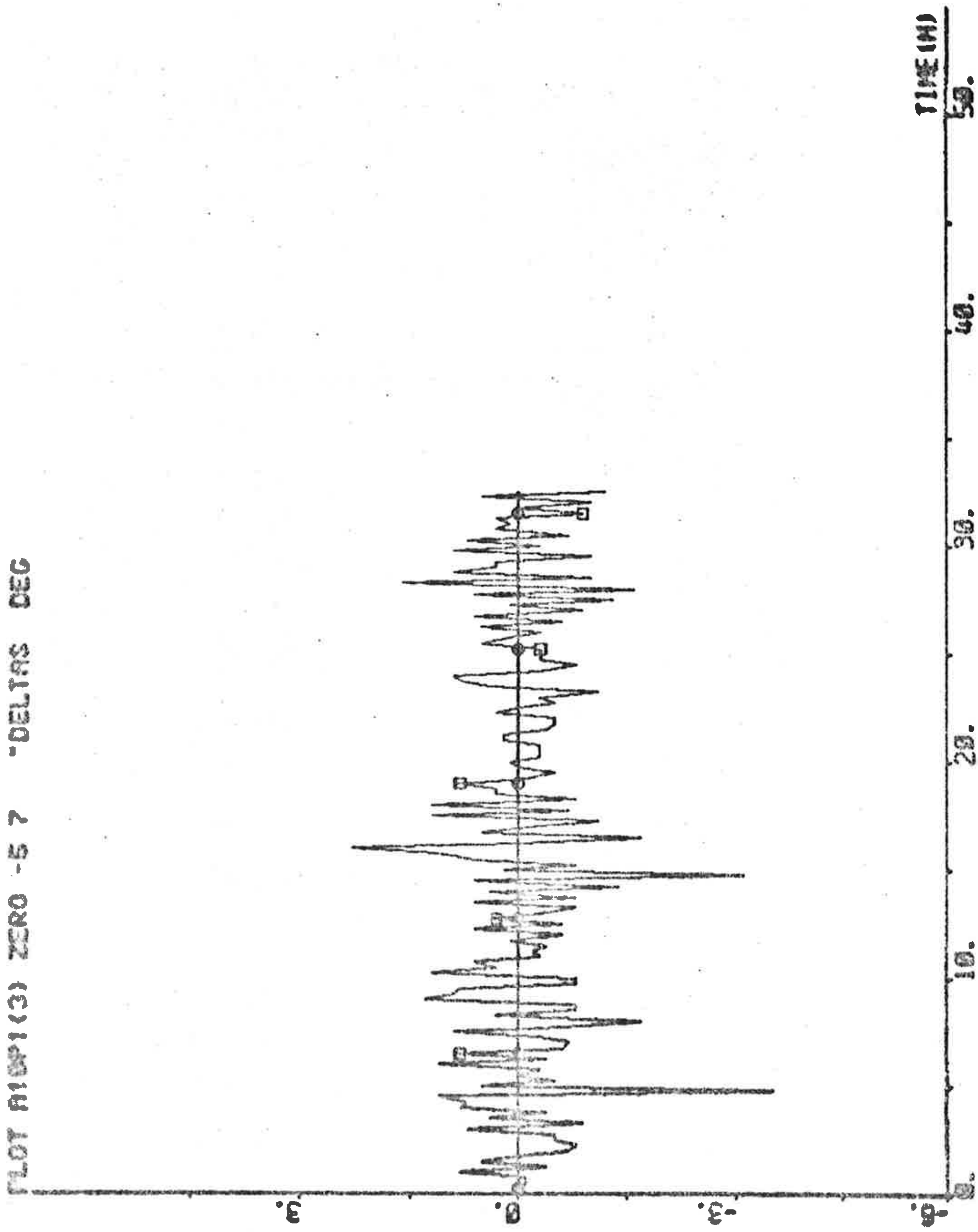
<u>Statistics</u> (mean value and standard deviation)

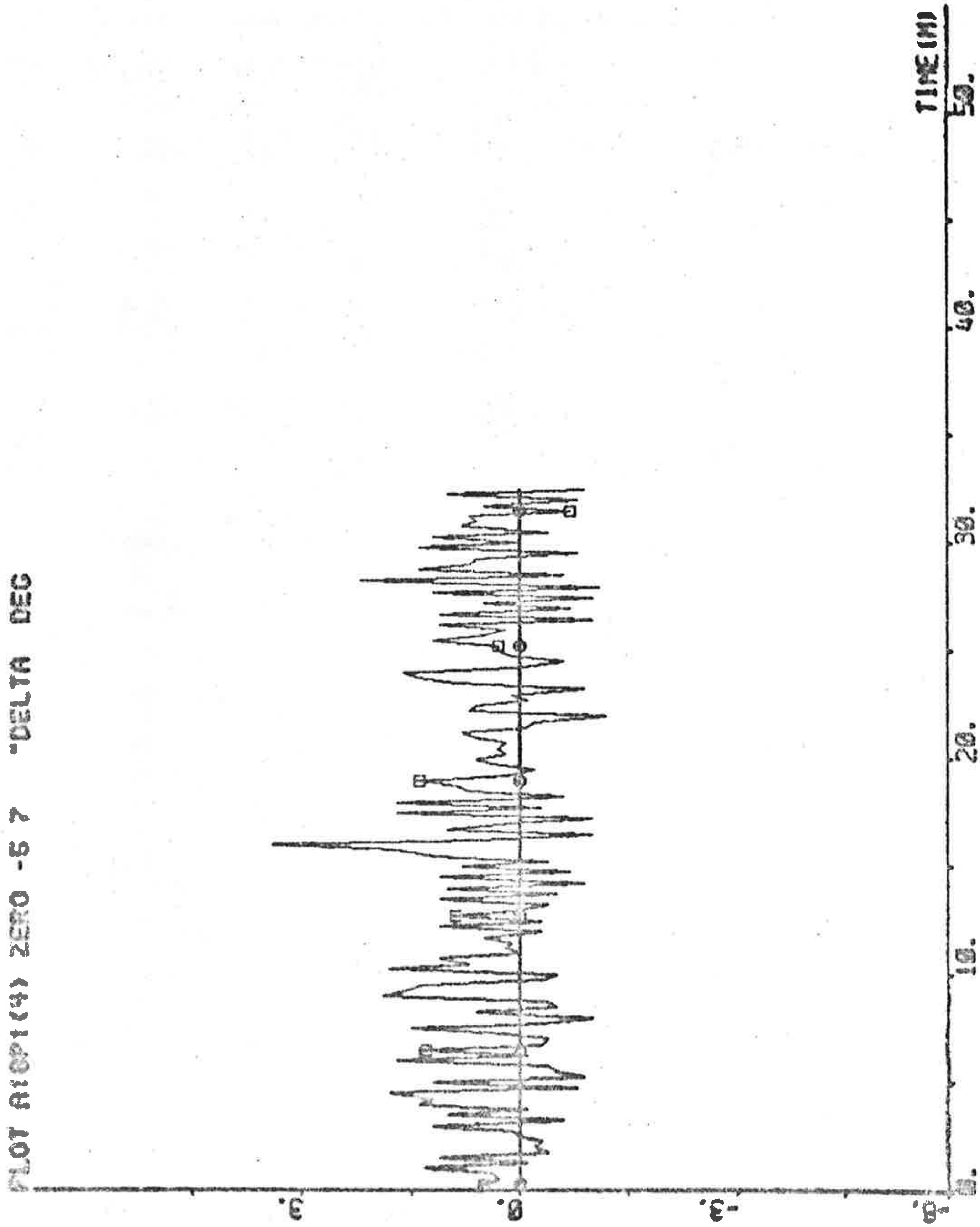
DELTA	0.36 ± 0.86 deg
PSI-PSIREF	-0.028 ± 0.101 deg
AN	85.88 ± 0.30 rpm
U	15.04 ± 0.25 knots

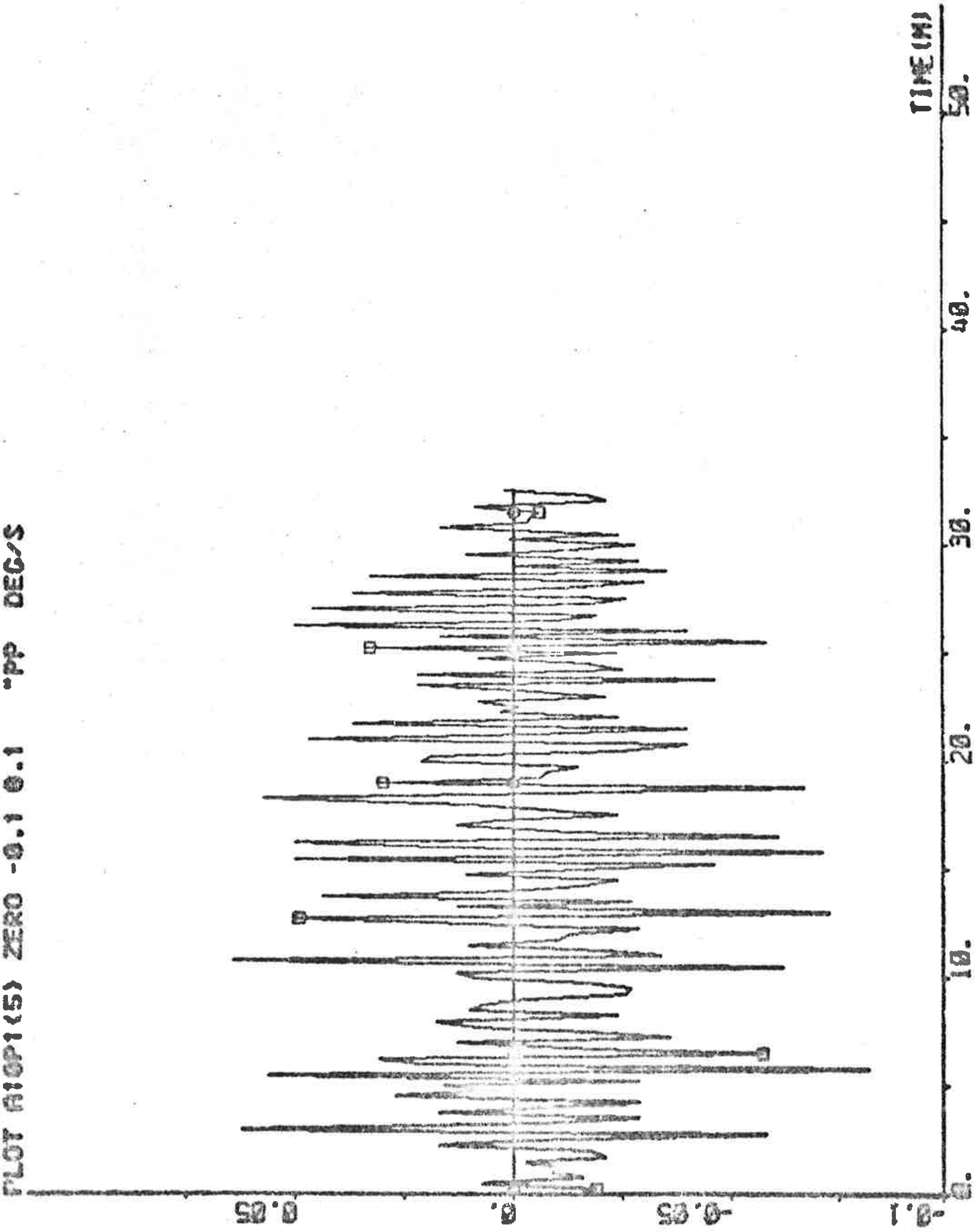
$V_1 = 0.098$

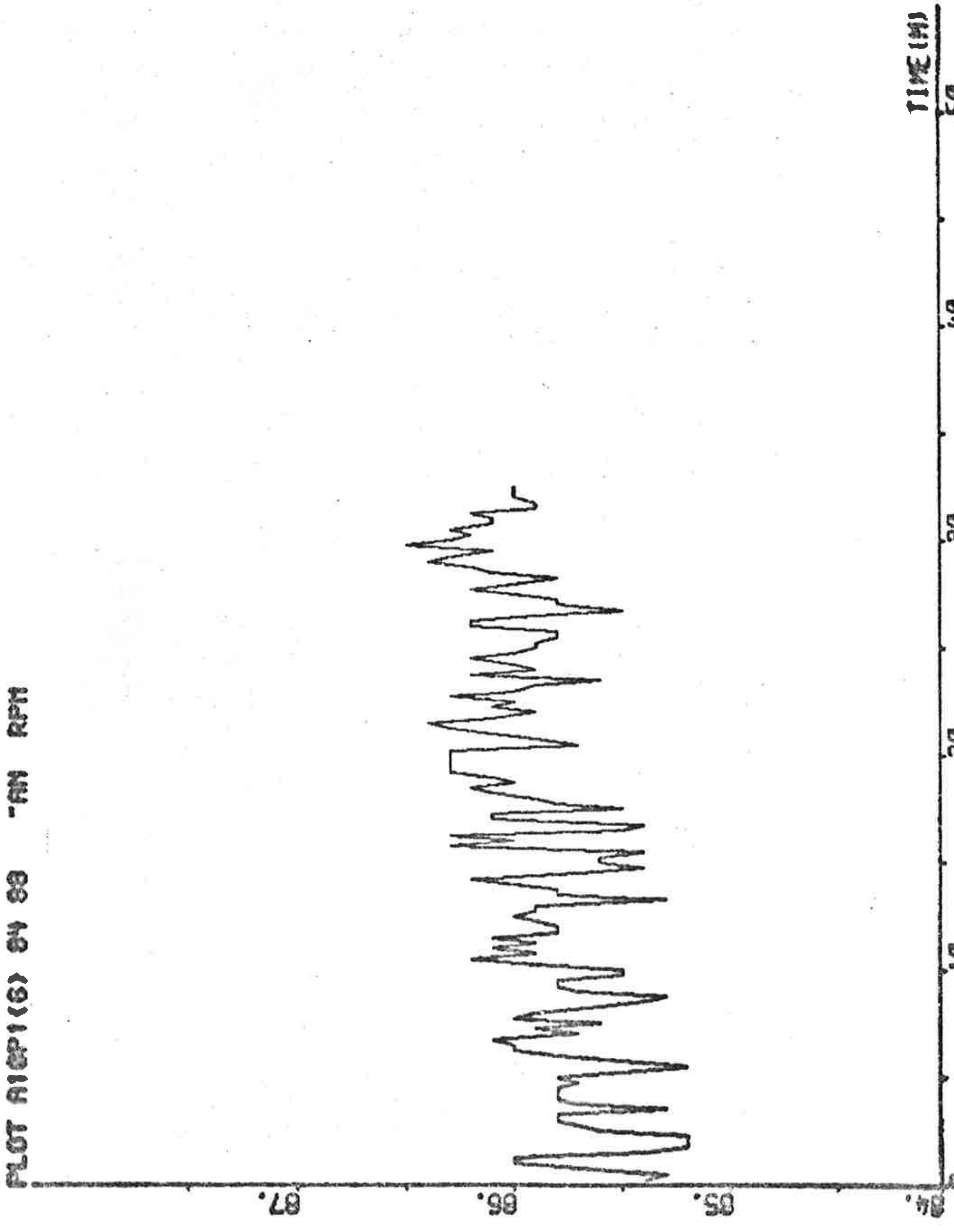
$V_2 = 0.085$

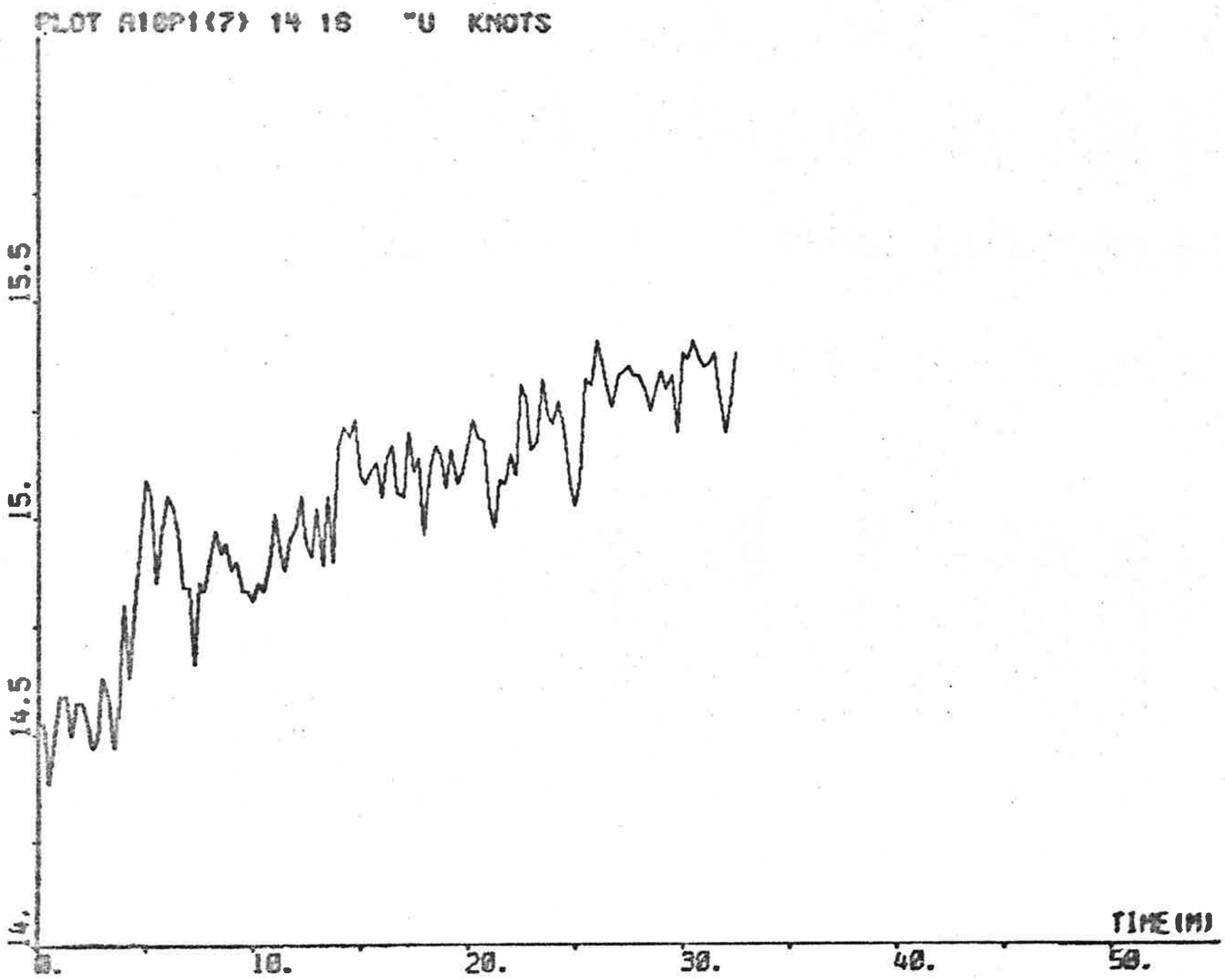

PLOT HP A1GP1(1) ZERO -5 7 "DELCOC DEC
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(H)

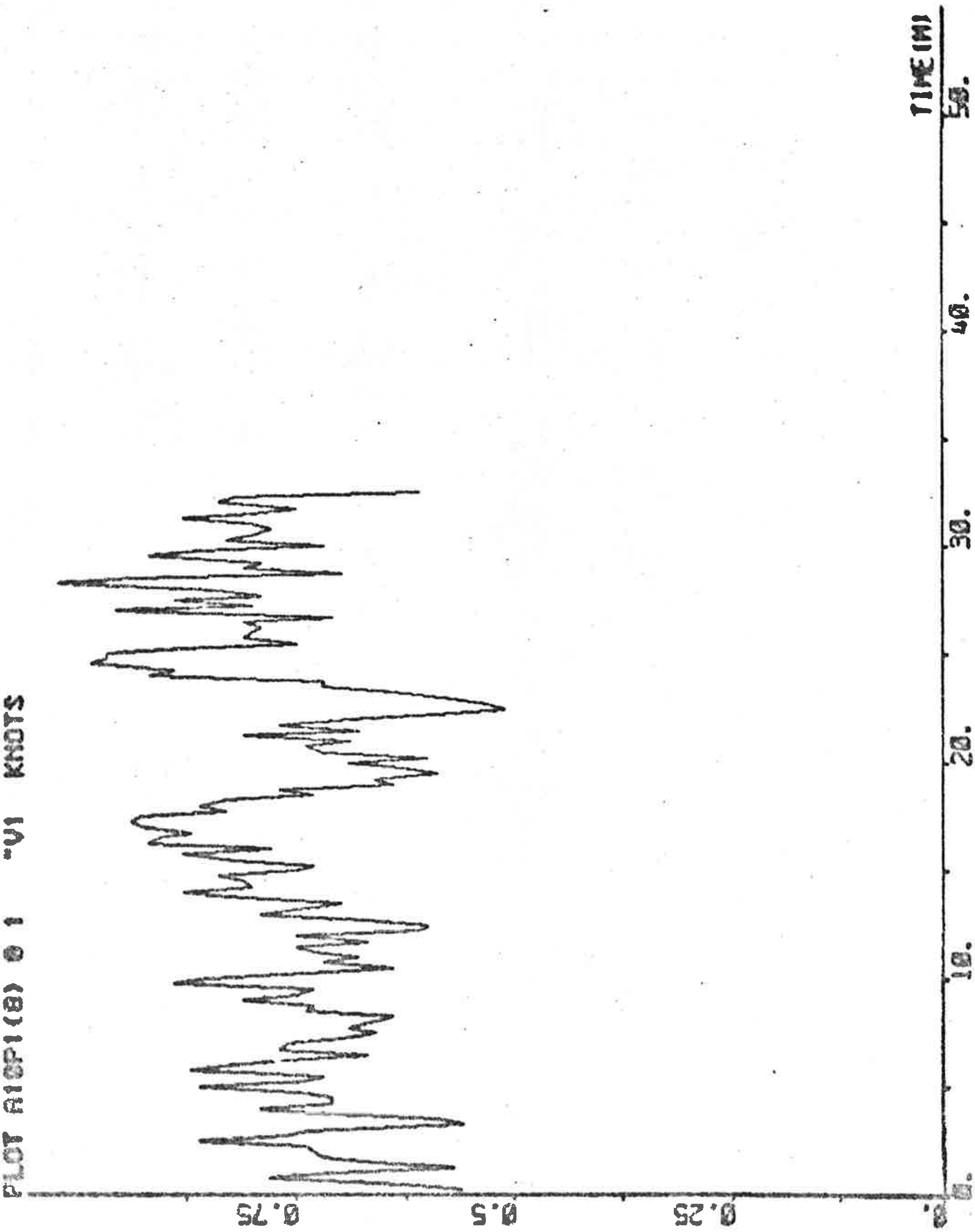

PLOT A10P1(3) ZERO -5 7 'DELTRS DEG
TIME (H)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

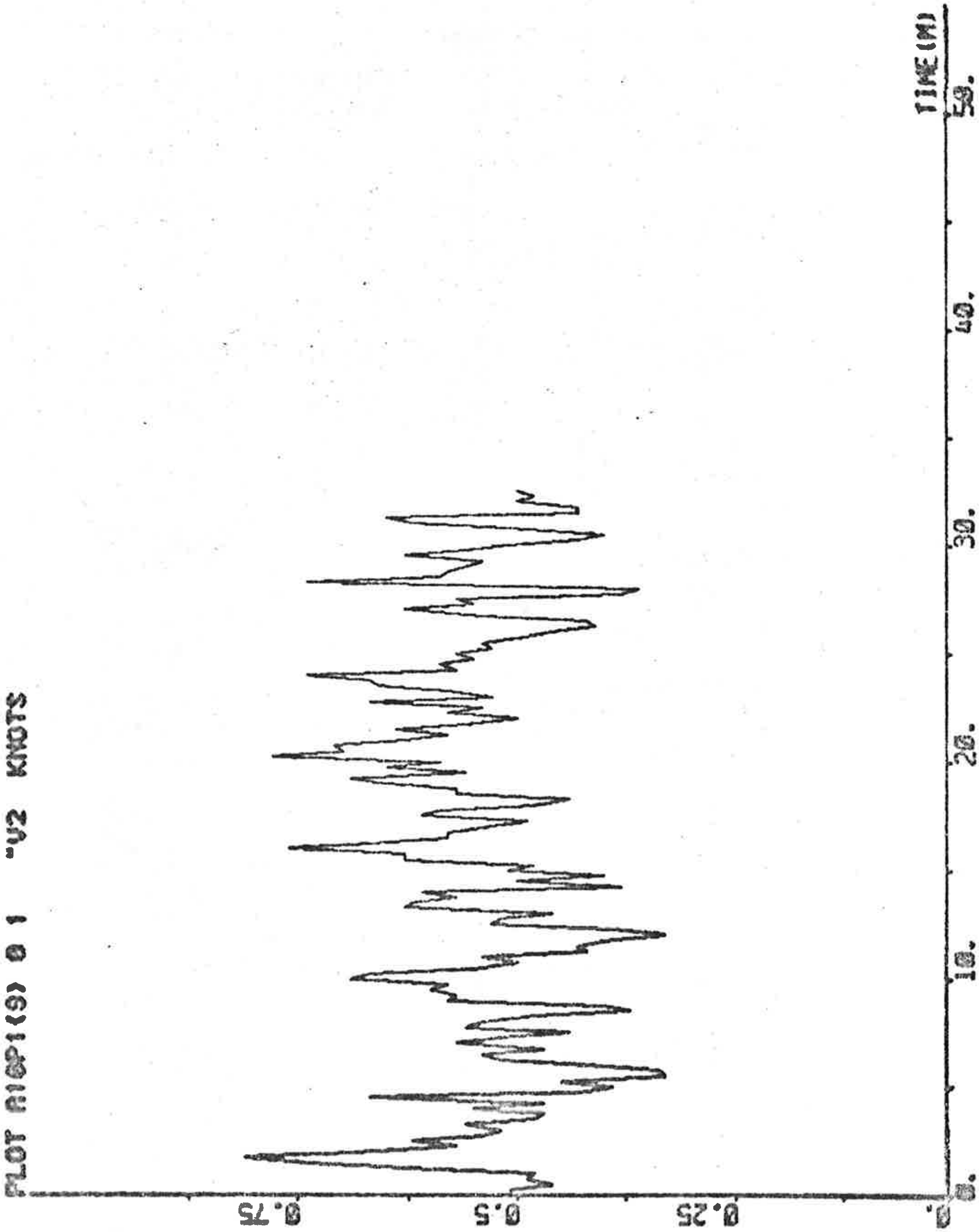

PLOT A(GP1(4) ZERO -5 7 "DELTA DEG
TIME (H)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.


PLOT A10P1(5) ZERO -0.1 0.1 *PP DEG/S
TIME (M)
0.
10.
20.
30.
40.
50.
0.05
0.
-0.05
-0.1

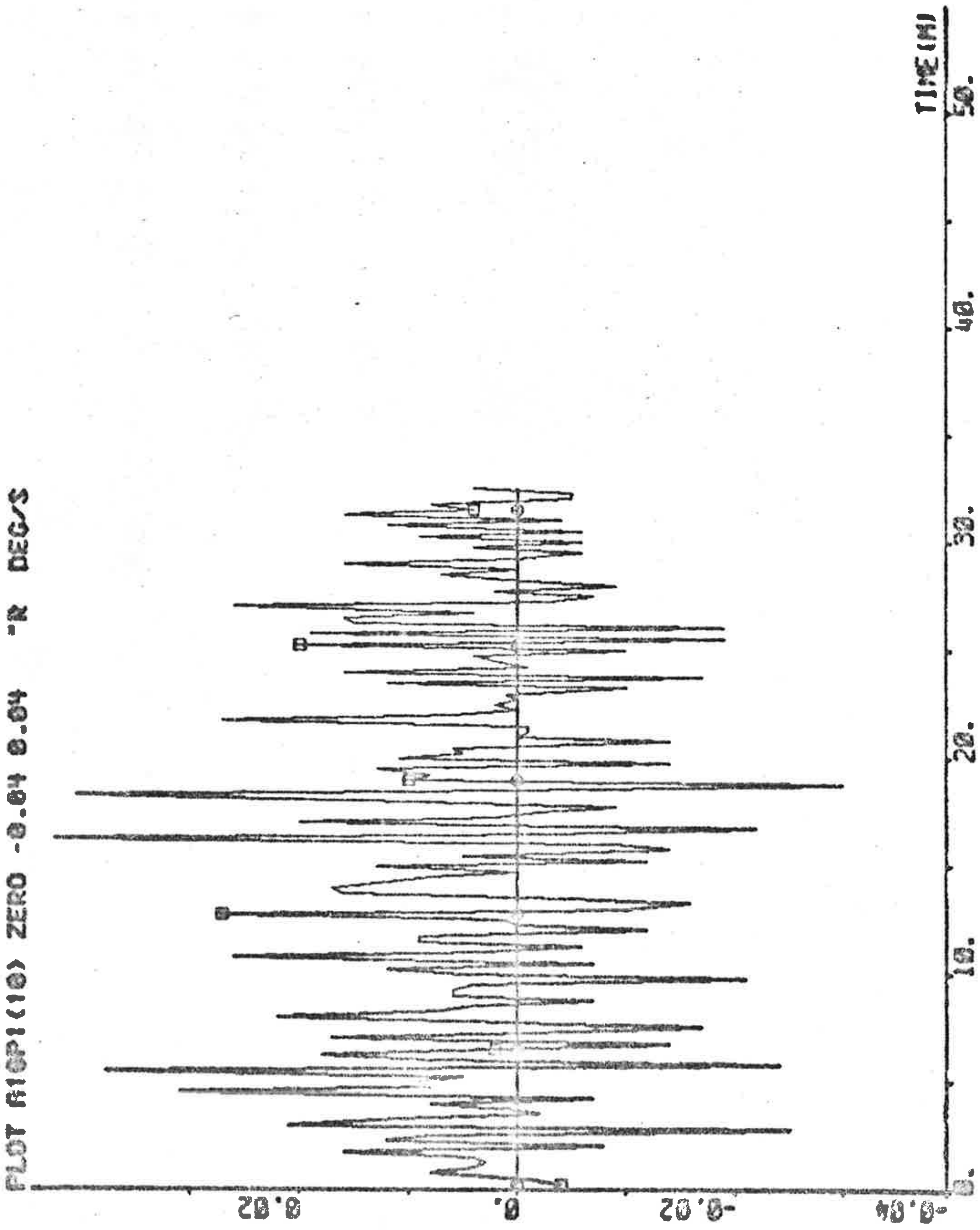

TIME (M)
0.
10.
20.
30.
40.
50.
84.
85.
86.
87.


PLOT A10P1(7) 14 1S "U KNOTS
15.5
15.
14.5
14.
0.
10.
20.
30.
40.
50.
TIME(M)

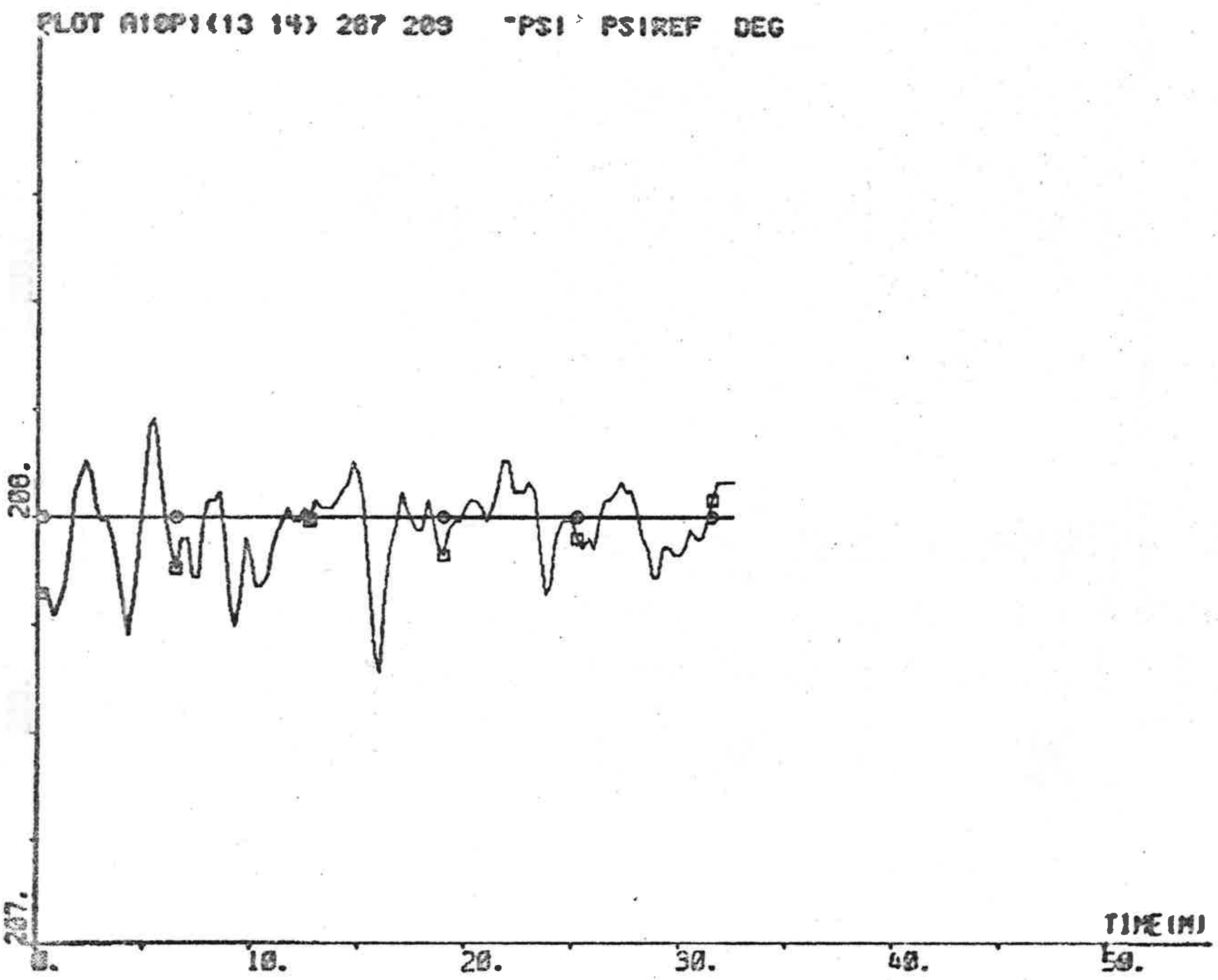

PLOT A10P1(B) @ 1 "V1 KNOTS
0.75
0.5
0.25
0.
0.
10.
20.
30.
40.
50.
TIME(M)

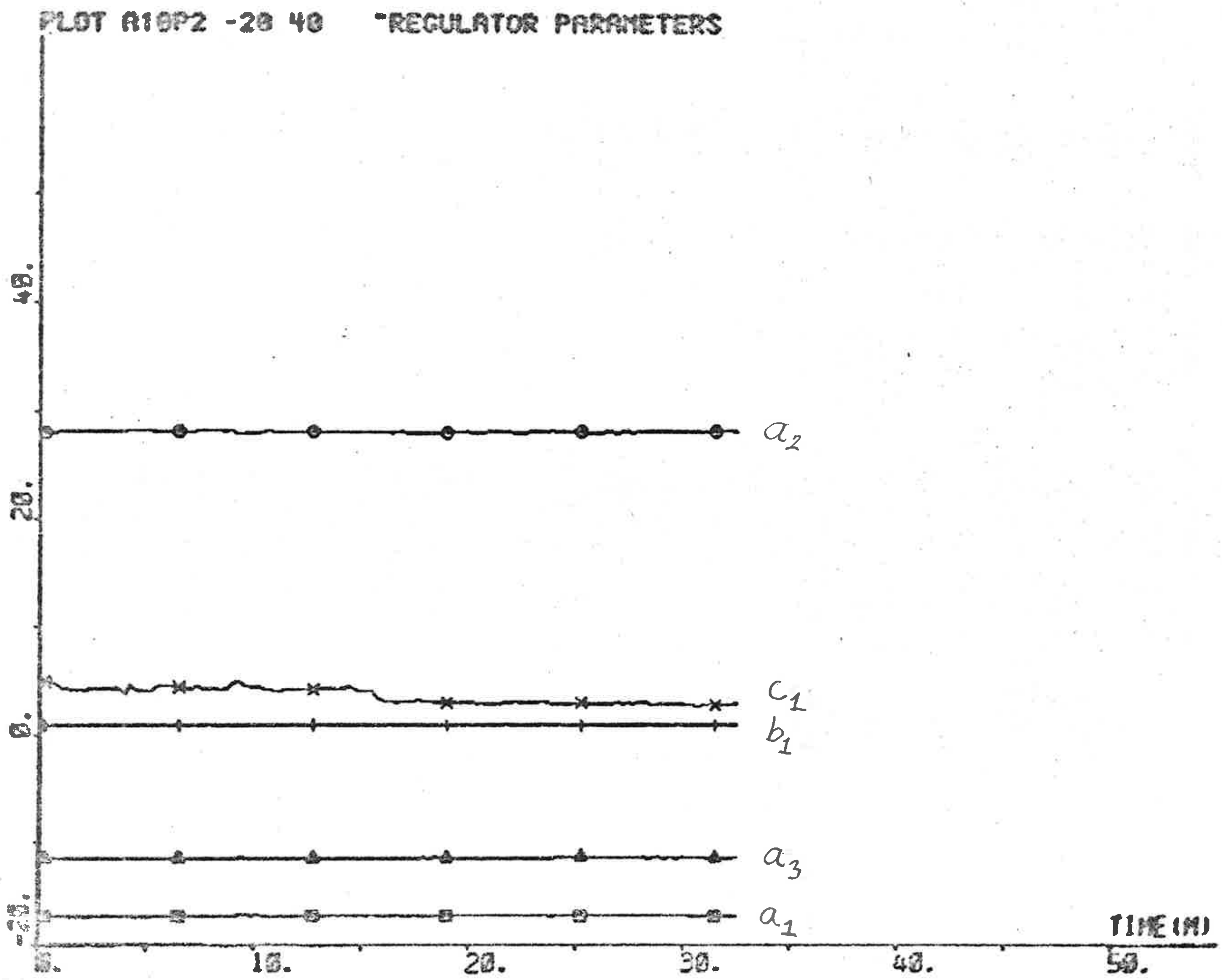


PLOT R10P1(S) 0 1 "V2 KNOTS
0.75
0.5
0.25
0.
0.
10.
20.
30.
40.
50.
TIME(M)



PLOT R1GP1(10) ZERO -0.04 0.04 "R DEG/S
TIME(H)
0.
10.
20.
30.
40.
50.
0.02
0.
-0.02
-0.04


PLOT A1OP1(13 14) 207 209 -PSI PSIREF DEG
200.
207.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A10P2 -20 40 "REGULATOR PARAMETERS
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME (M)
a_2
c_1
b_1
a_3
a_1

EXPERIMENT A11

Date	1974-10-14
Time	10.09
Duration	31 min
Position	N 10° 52' E 54° 30'
Water depth	deep
Forward draught	20.2 m
Aft draught	20.2 m
Wind direction	-
Wind velocity	1 Beaufort (1-1.5 m/s, light air)
Wave height	0.5 m (rollings)
PSIREF	208°
Rudder limit	±10°

The main engine tripped during the experiment

Regulator structure

NA = 3	NB = 1	NC = 1	K = 4
IREG = 20	IRDIF = 0	RL = 0.98	IRR = 1
ISPM = 600	INO = 1	ANO = 45	

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -9.087 \\ 14.512 \\ -7.024 \\ 0.800 \\ 129.841 \end{bmatrix}$$

P unknown

$a_1 + a_2 + a_3 = -1.599$

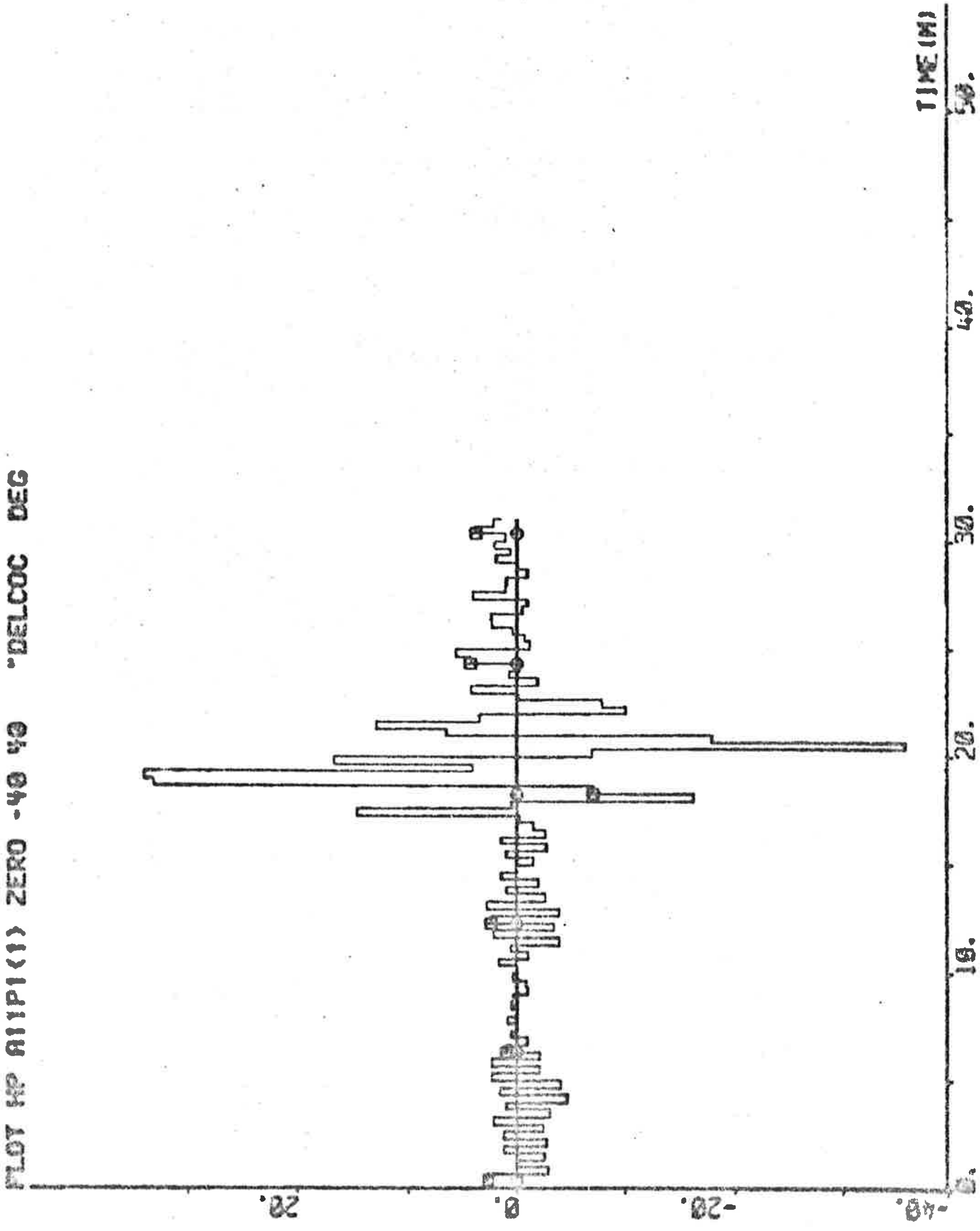
Regulator parameter values for low speed were used after 16.5 min. of the experiment, but initial high speed parameter values were introduced again after 26.5 min.

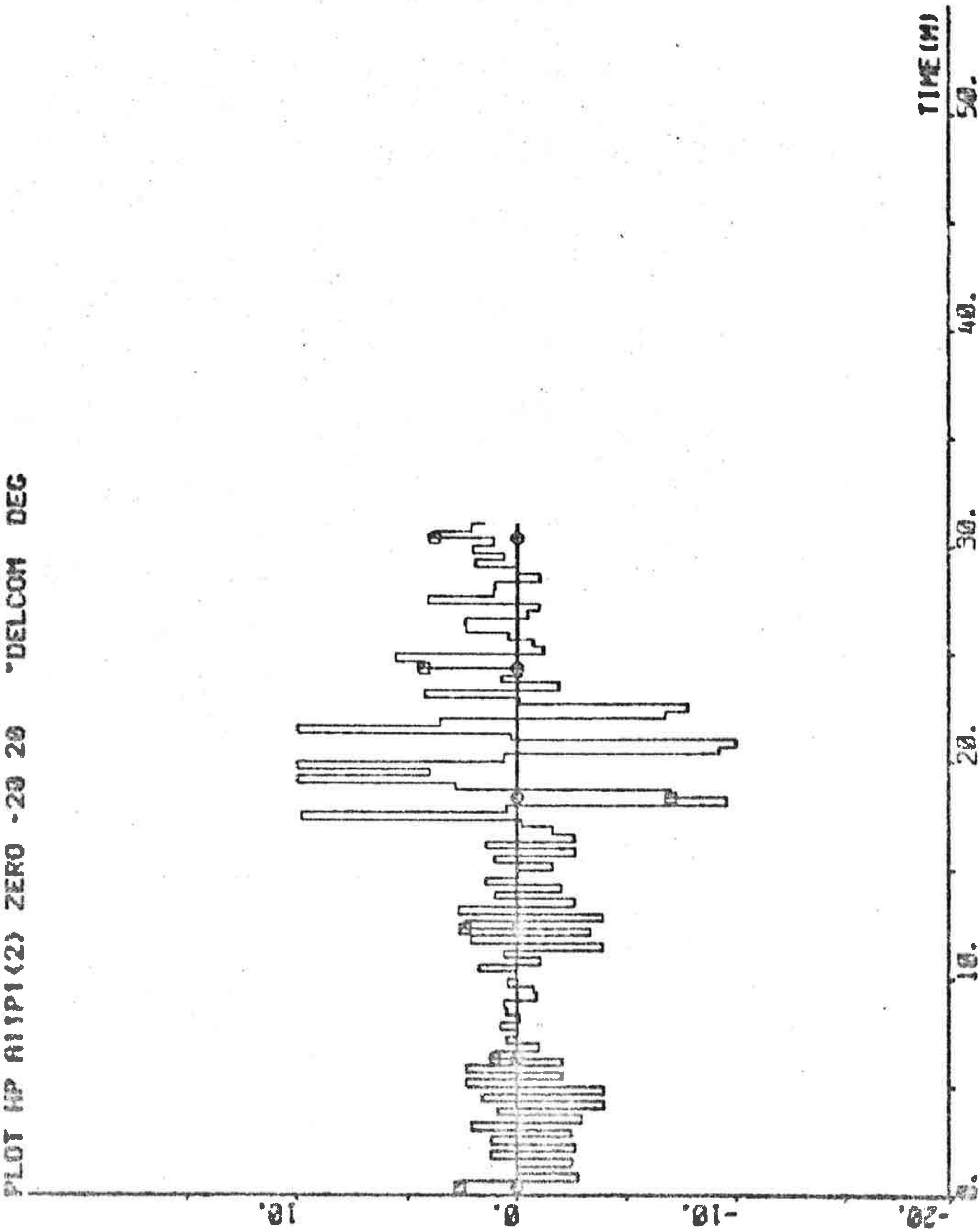
Statistics (mean value and standard deviation)

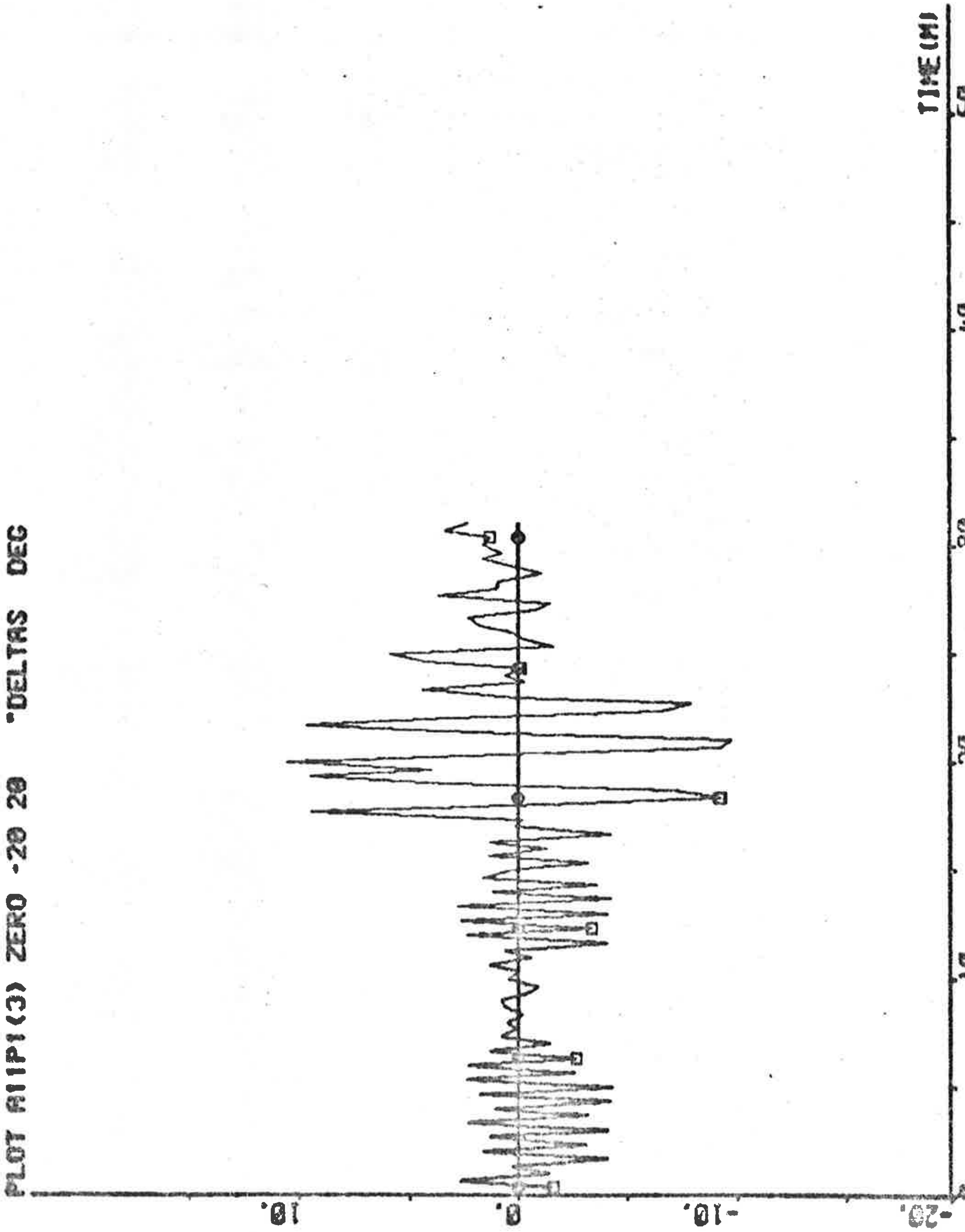
DELTA	0.83 ± 3.82 deg
PSI - PSIREF	-0.076 ± 0.600 deg
AN	72.24 ± 14.98 rpm
U	14.61 ± 1.48 knots

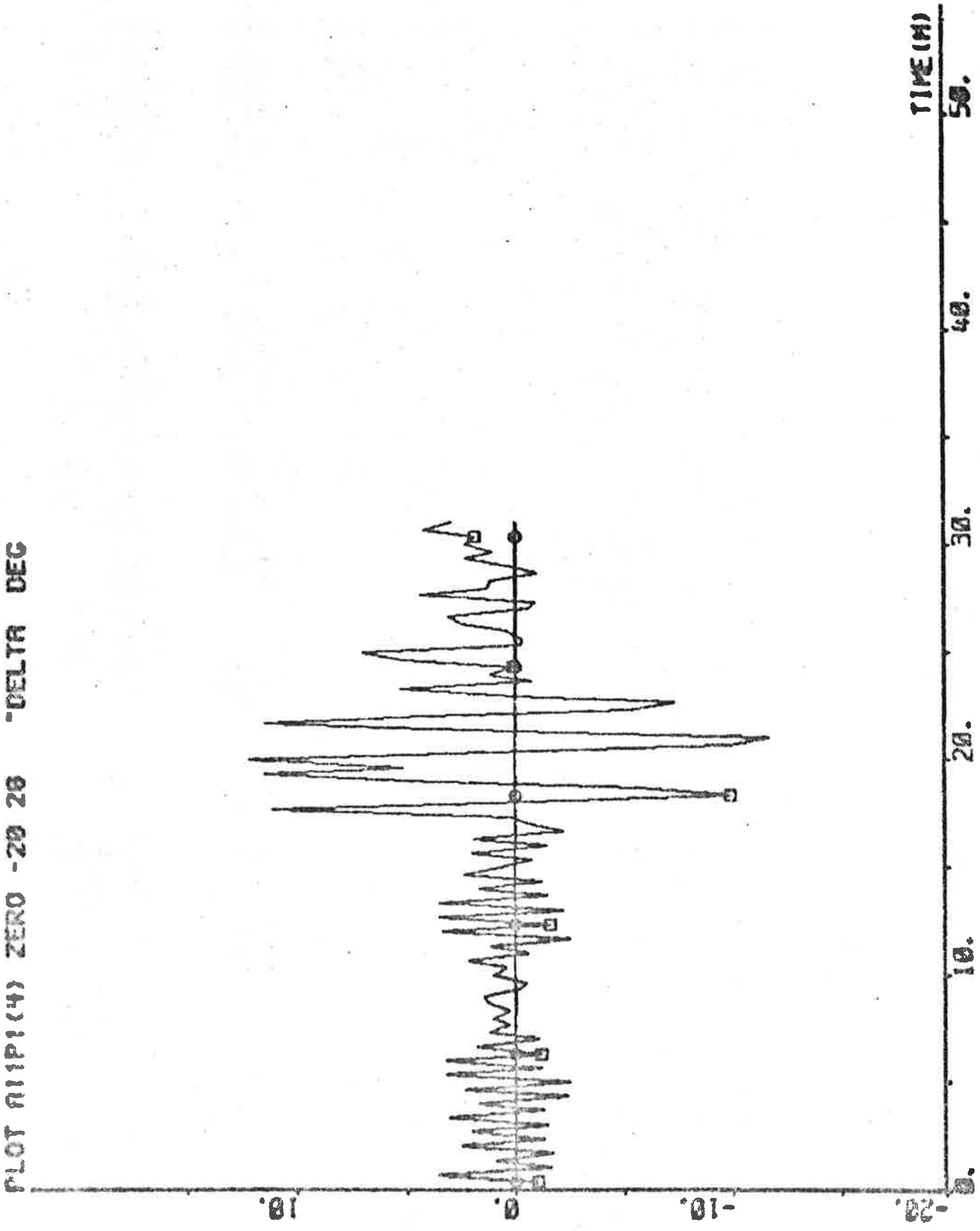
$V_1 = 1.894$

$V_2 = 1.825$

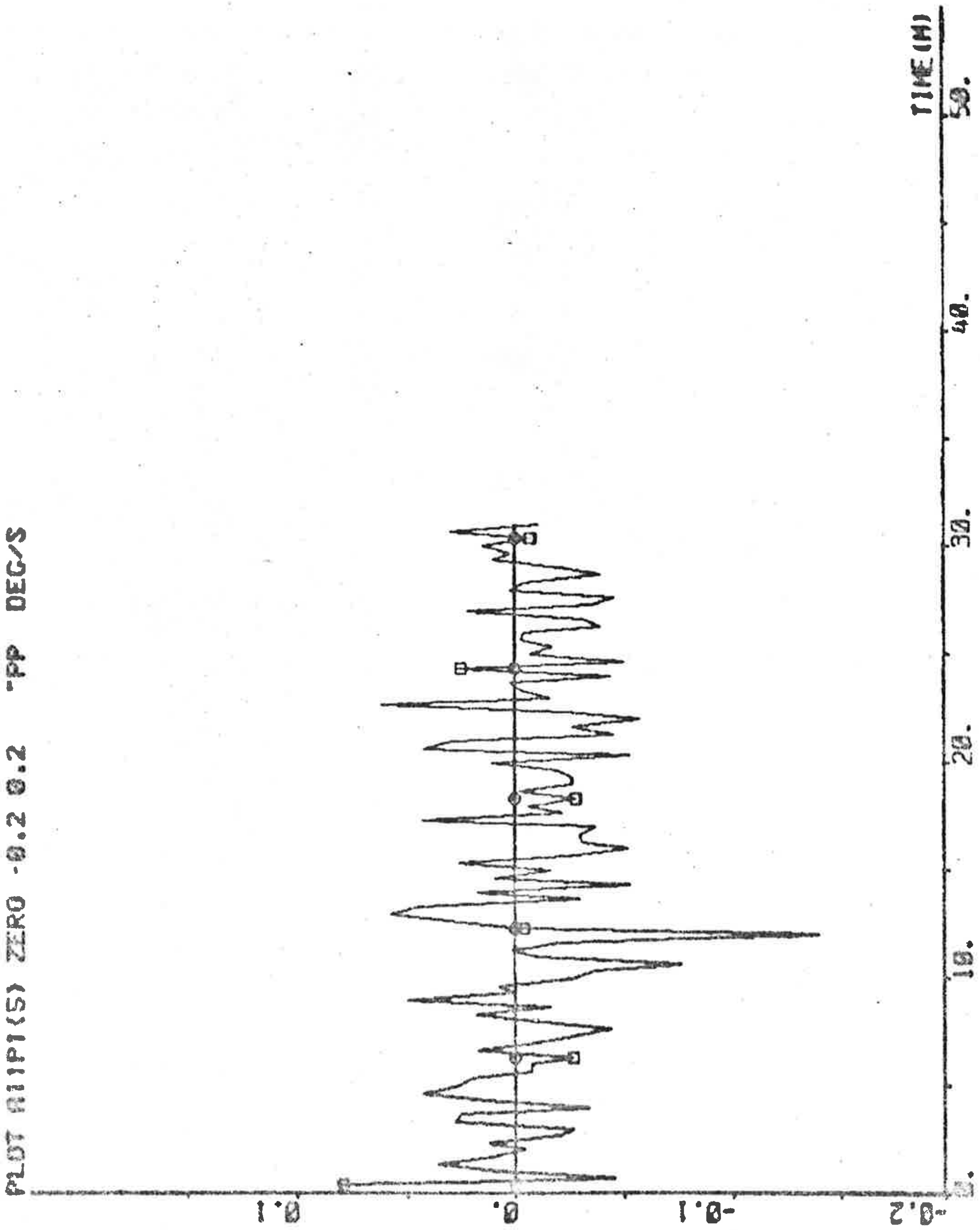

PLOT HP ALLPI(1) ZERO -40 40 "DELCOC DEG
20.
0.
-20.
-40.
0.
10.
20.
30.
40.
50.
TIME (M)

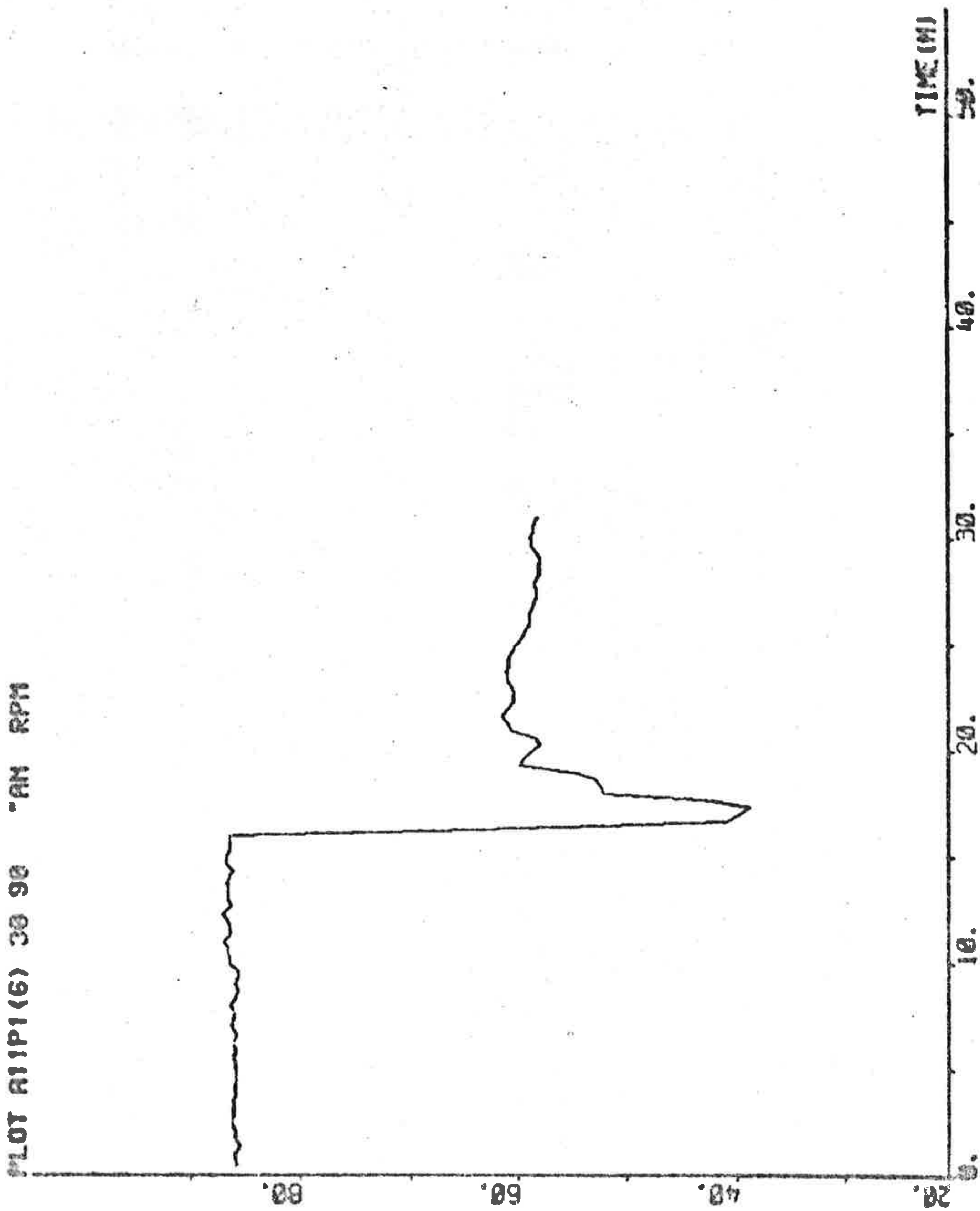

PLOT HP A11P1(2) ZERO -20 20 "DELCOM DEG
TIME(M)
0.
10.
20.
30.
40.
50.
10.
0.
-10.
-20.

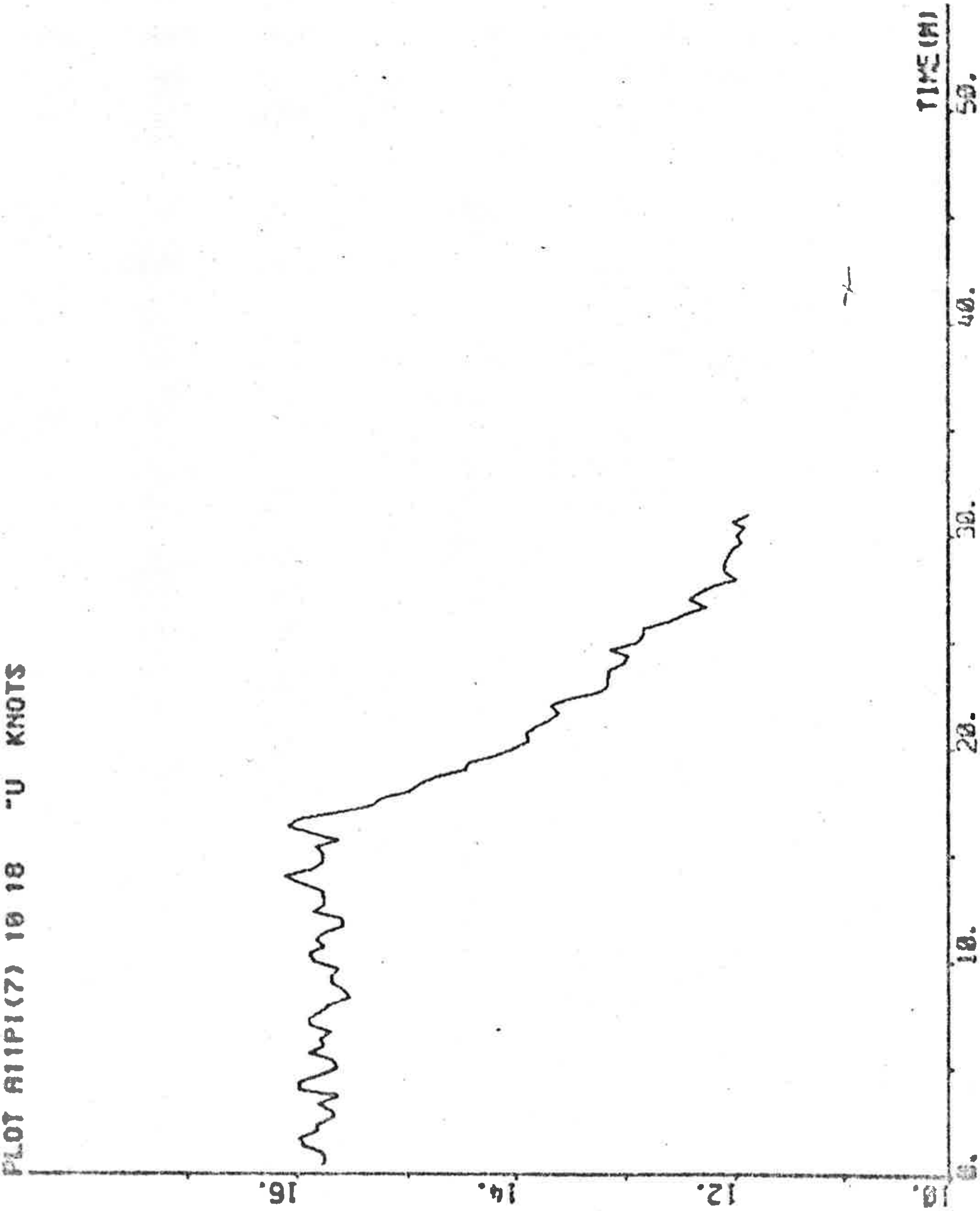

PLOT A11P1(3) ZERO -20 20 *DELTAS DEG
10.
0.
-10.
-20.
0.
10.
20.
30.
40.
50.
TIME(M)

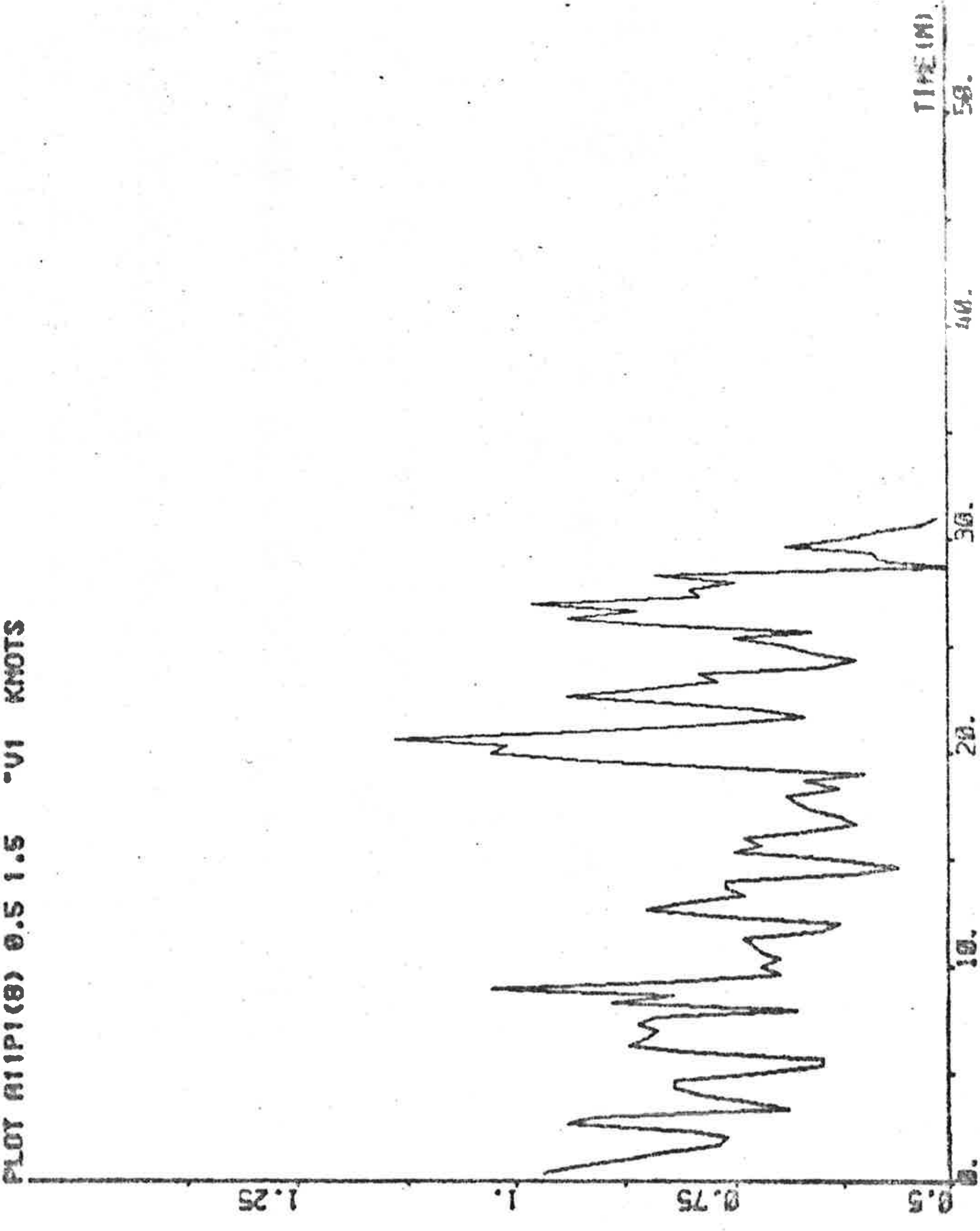


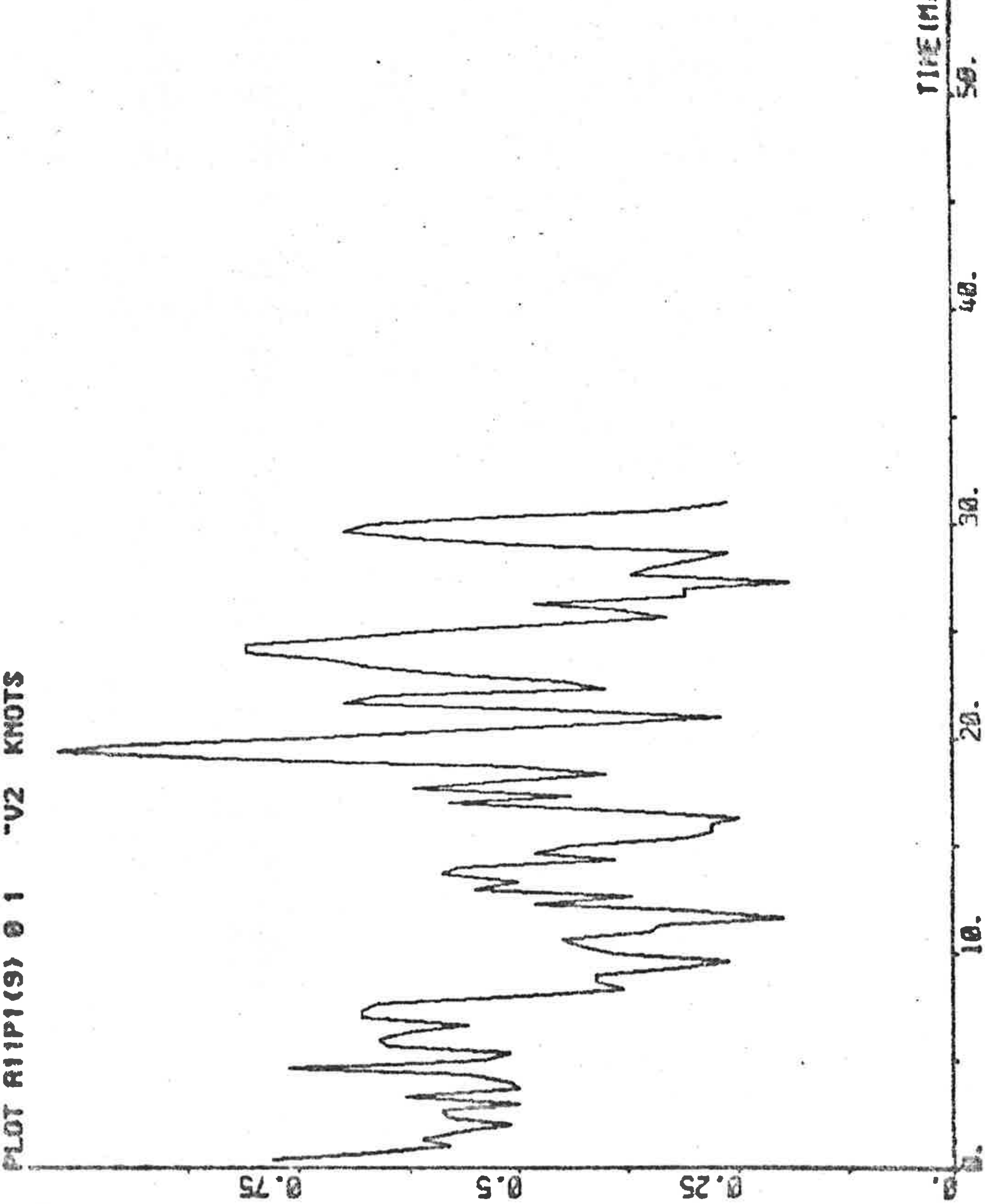
PLOT A11P1(4) ZERO -20 20 "DELTA DEG
TIME(M)
0.
10.
20.
30.
40.
50.
10.
0.
-10.
-20.

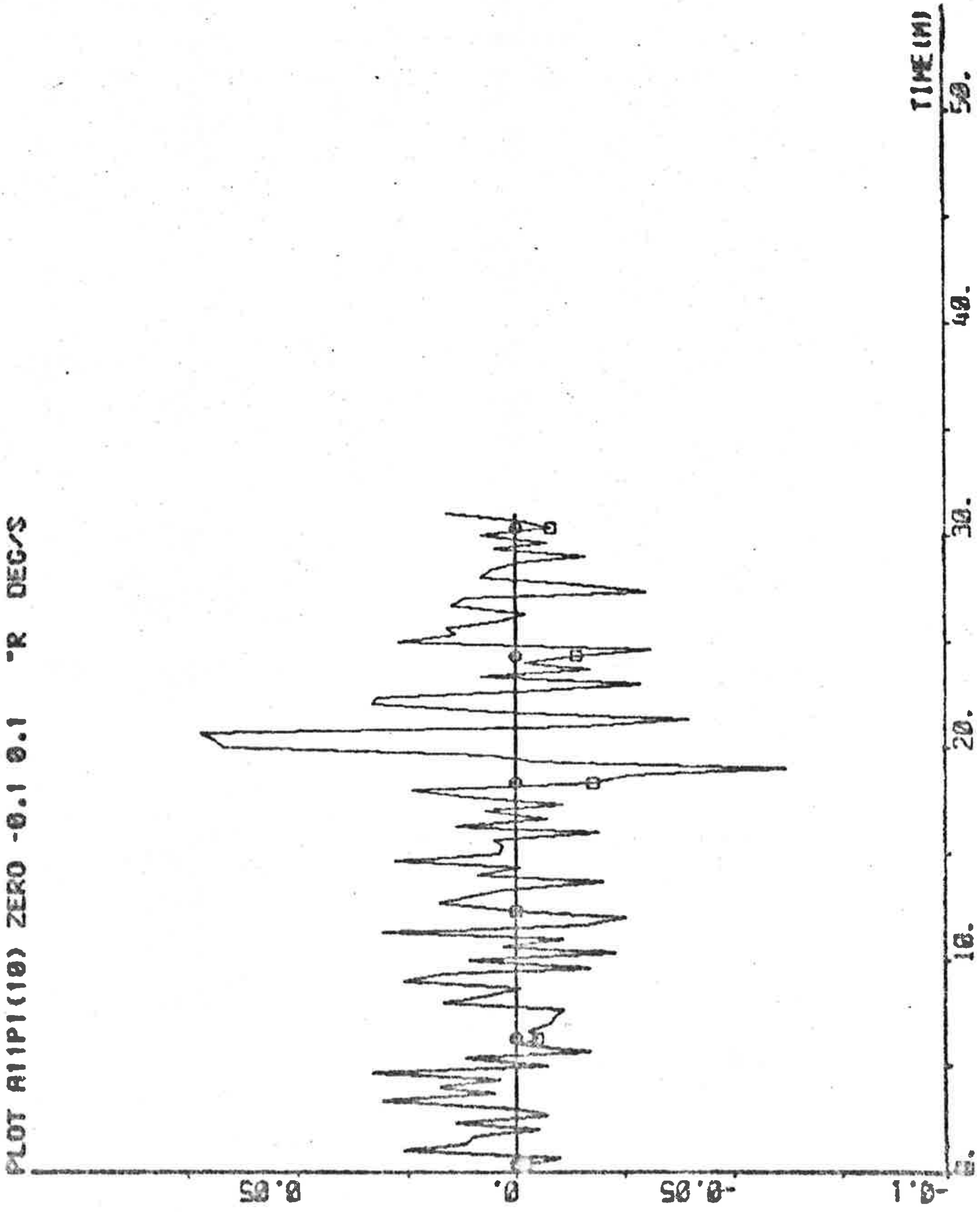

PLOT A11P1(S) ZERO -0.2 0.2 'PP DEG/S
0.1
0.
-0.1
-0.2
10.
20.
30.
40.
50.
TIME (M)

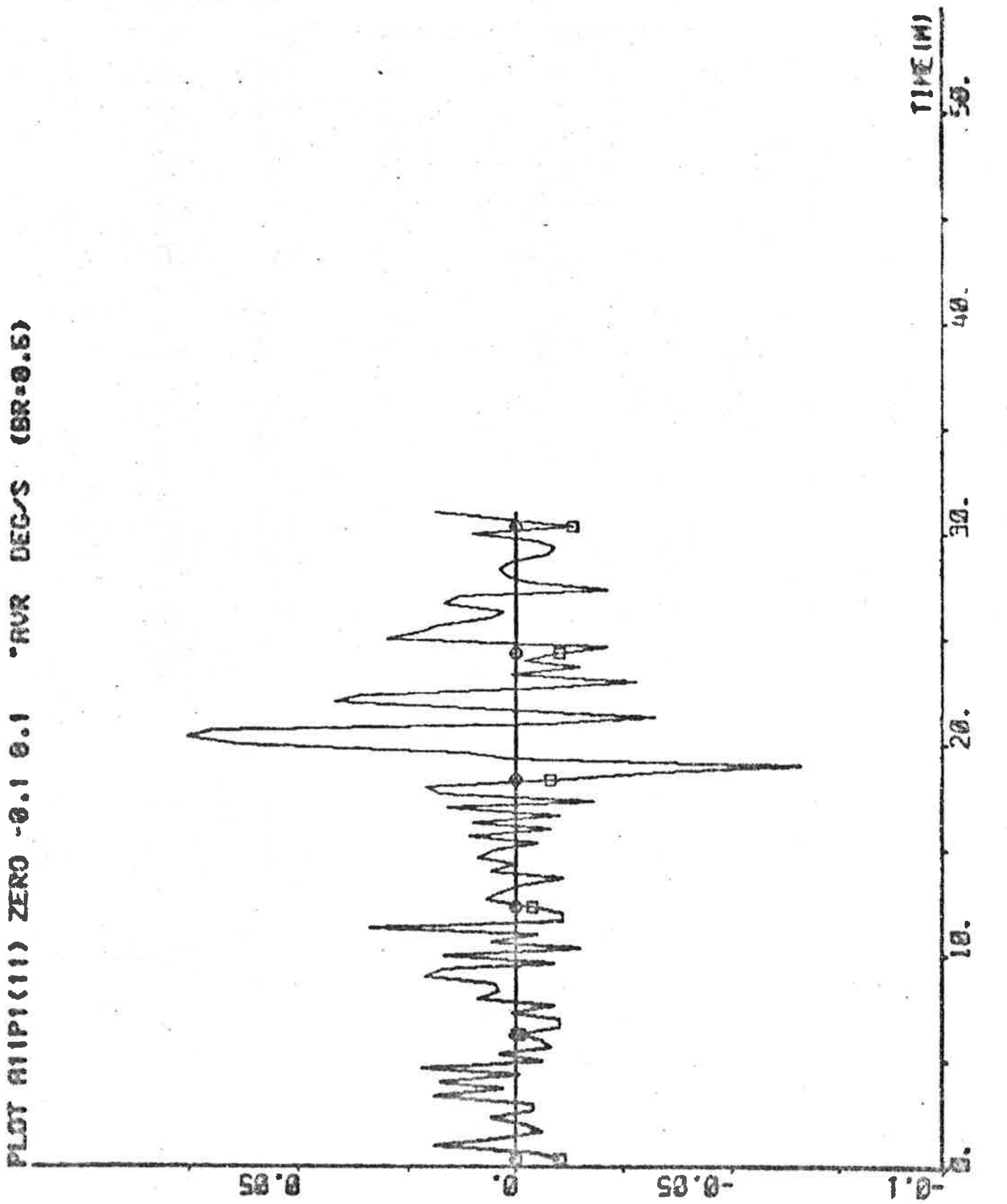

PLOT A11P1(6) 30 90 'AN RPM
TIME (M)
0.
10.
20.
30.
40.
50.
20.
40.
60.
80.

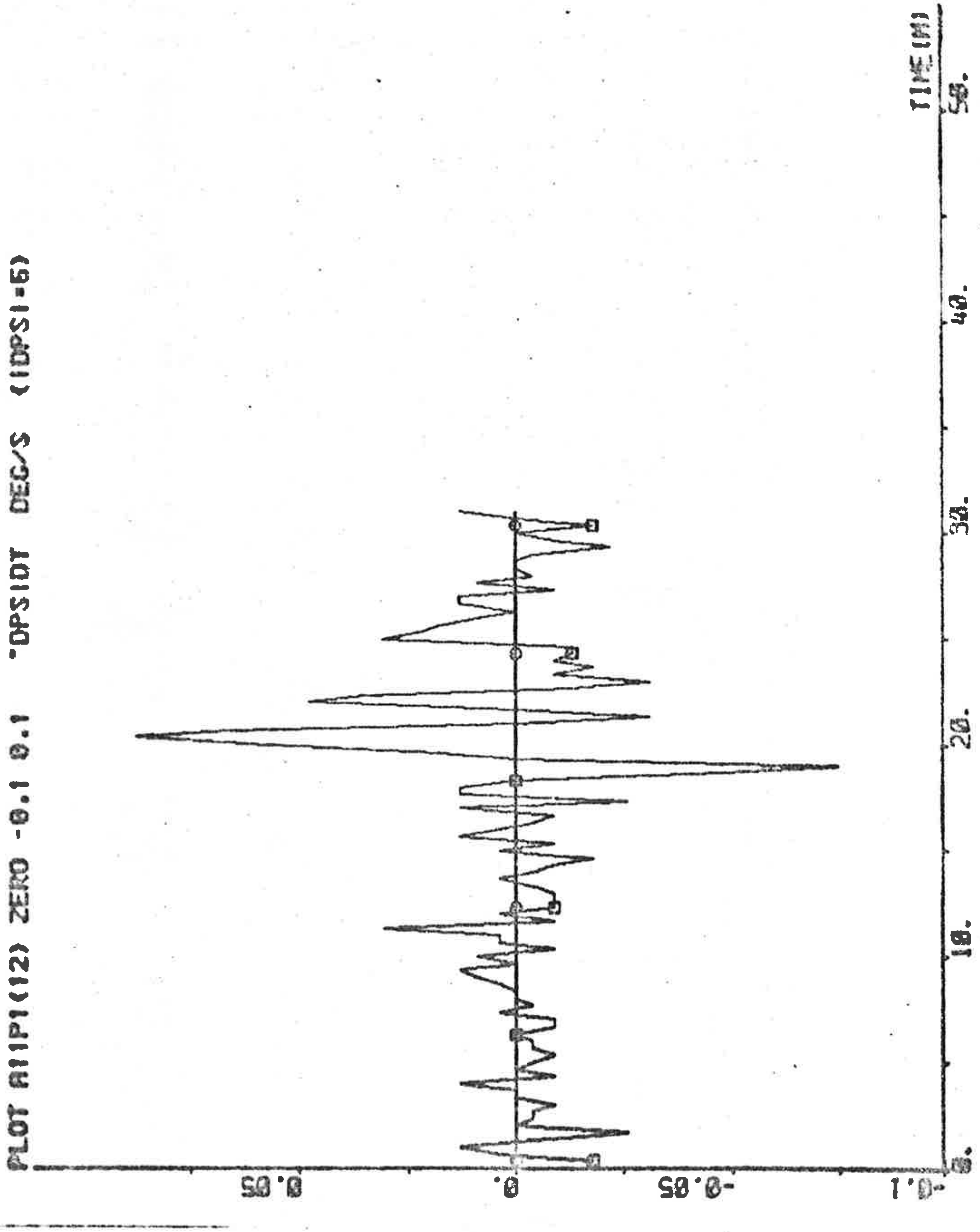

PLOT A11P1(7) 10 18 "U KNOTS
16.
14.
12.
10.
0.
10.
20.
30.
40.
50.
TIME (M)

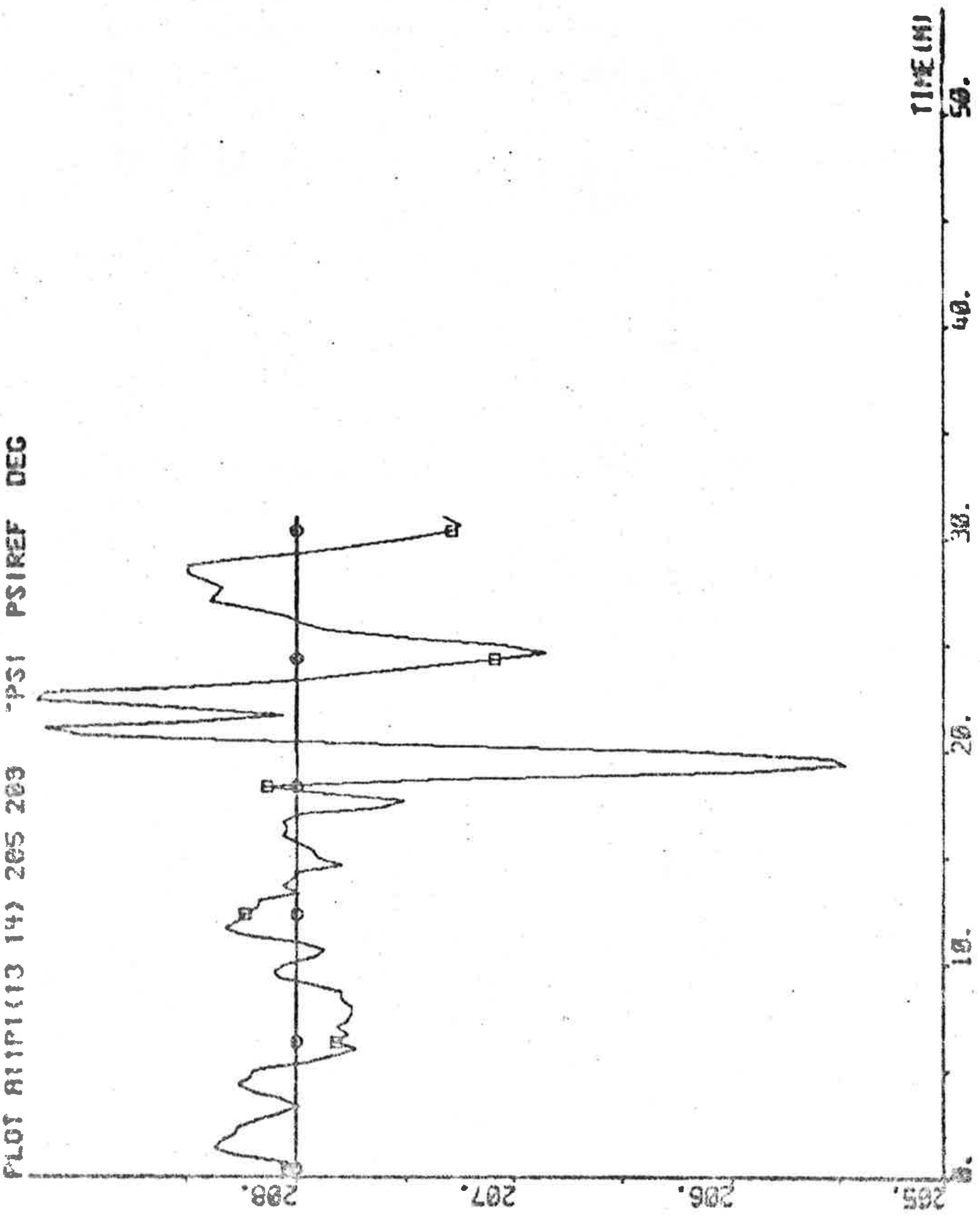

PLOT A11P1(B) 0.5 1.5 "V1 KNOTS
1.25
1.
0.75
0.5
0.
10.
20.
30.
40.
50.
TIME (M)


PLOT R11P1(9) @ 1 "V2 KNOTS
0.75
0.5
0.25
0.
TIME(M)
0.
10.
20.
30.
40.
50.

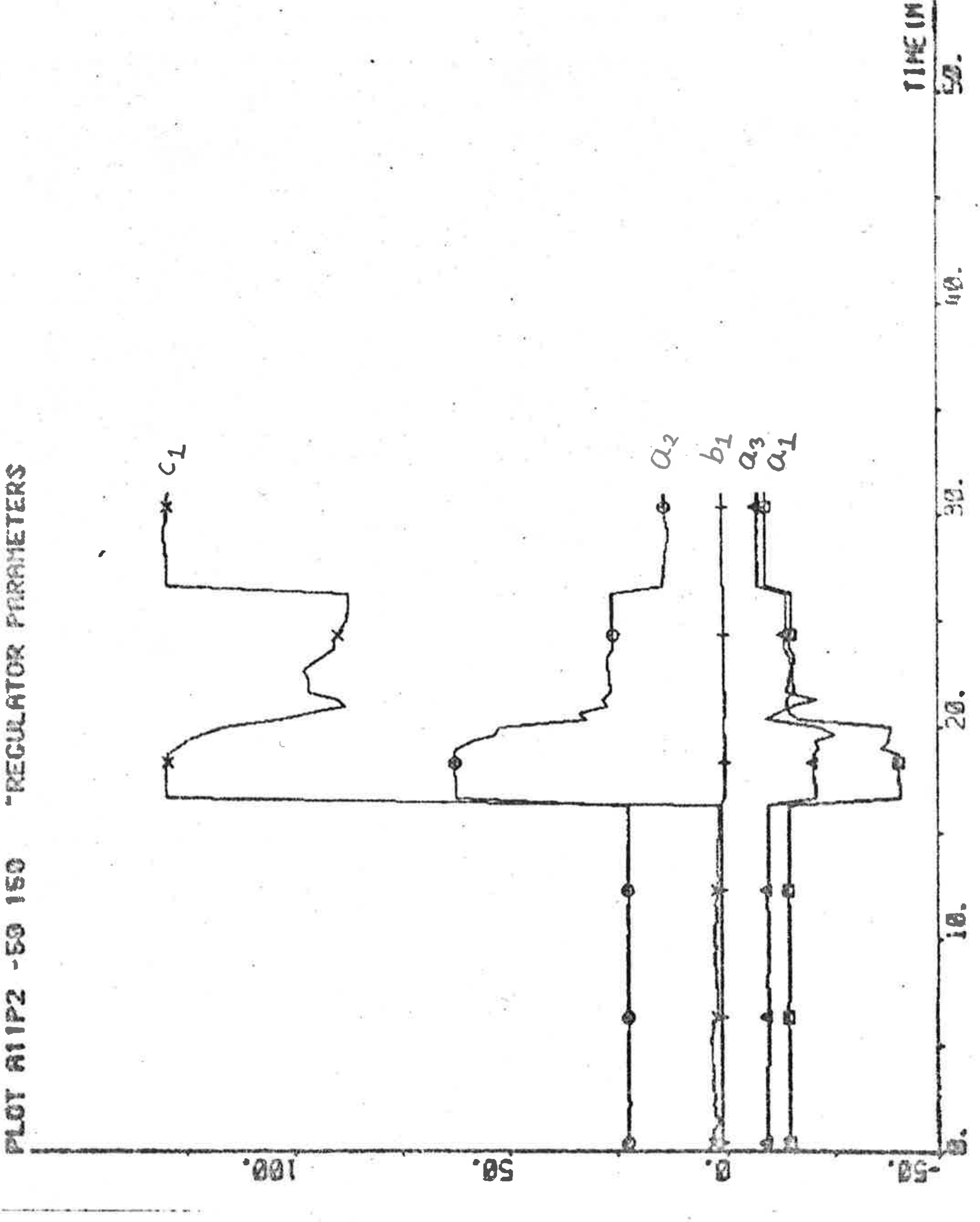

PLOT A11P1(10) ZERO -0.1 0.1 'R DEG/S
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A11P1(11) ZERO -0.1 0.1 *AVR DEG/S (BR=0.5)
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A11P1(12) ZERO -0.1 0.1 "DPSIDT DEG/S (IDPSI=6)
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(M)



PSI PSIREF DEG
TIME (M)
0.
10.
20.
30.
40.
50.
205.
206.
207.
208.


PLOT A11P2 -50 150 "REGULATOR PARAMETERS
100.
50.
0.
-50.
0.
10.
20.
30.
40.
50.
TIME (M)
c_1
a_2
b_1
a_3
a_1

EXPERIMENT A12

Date	1974-10-14
Time	13.10
Duration	30 min
Position	N 10° 16' E 54° 22'
Water depth	deep
Forward draught	20.2 m
Aft draught	20.2 m
Wind direction	SW (1; see Appendix A)
Wind velocity	2-3 Beaufort (2-5.5 m/s, light to gentle breeze)
Wave height	1 m (light sea from SW, rollings)
PSIREF	208°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 4
IREG = 15	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -13.471 \\ 22.748 \\ -9.121 \\ 0.864 \\ 1.252 \end{bmatrix} \qquad P = \begin{bmatrix} 5.578 & & & & \\ -7.679 & 12.873 & & & \\ 3.457 & -6.612 & 4.689 & & \\ -0.101 & 0.107 & 0.008 & 0.019 & \\ 9.784 & -16.046 & 1.969 & 0.038 & 207.770 \end{bmatrix}$$

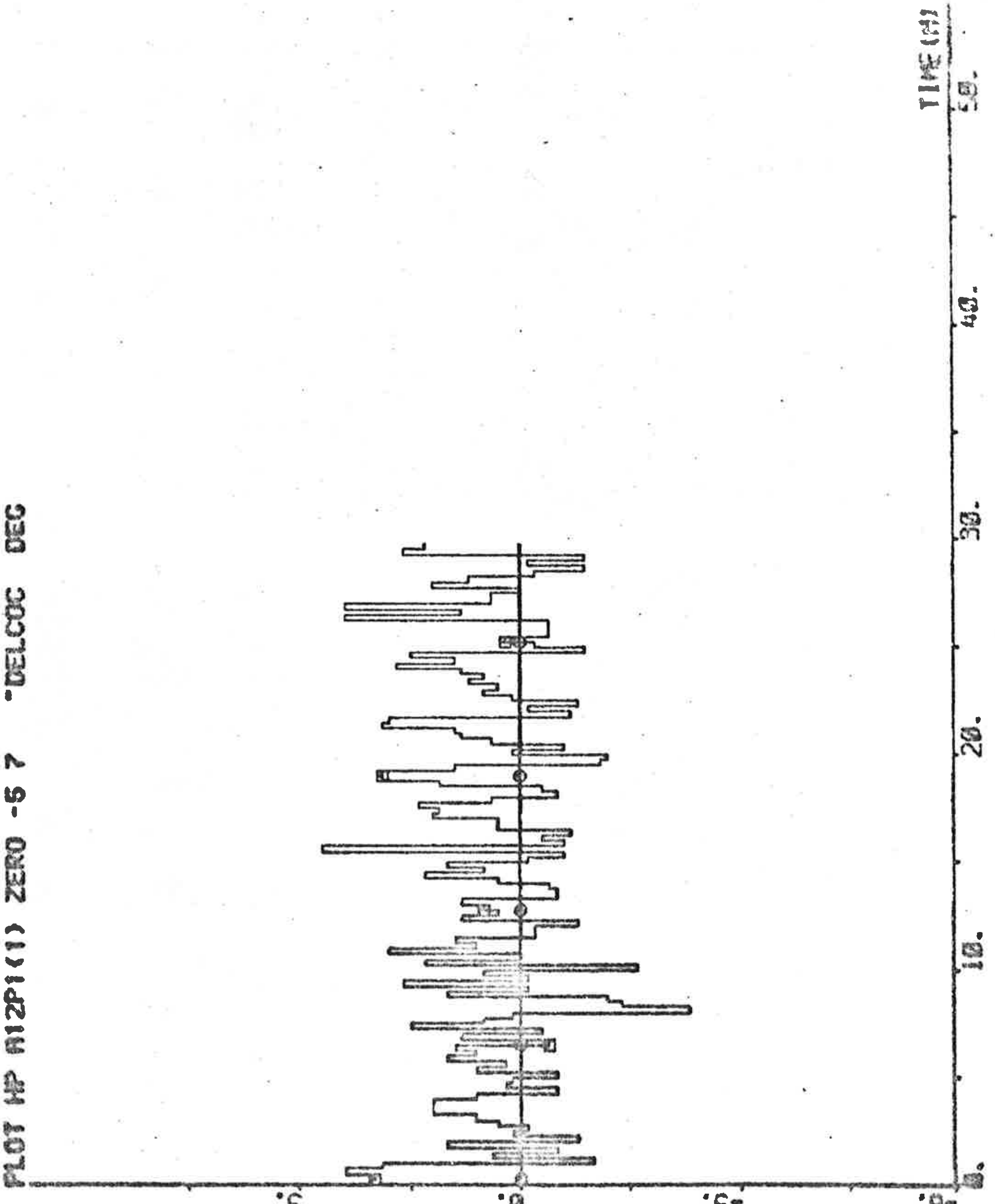
$$a_1 + a_2 + a_3 = 0.156$$

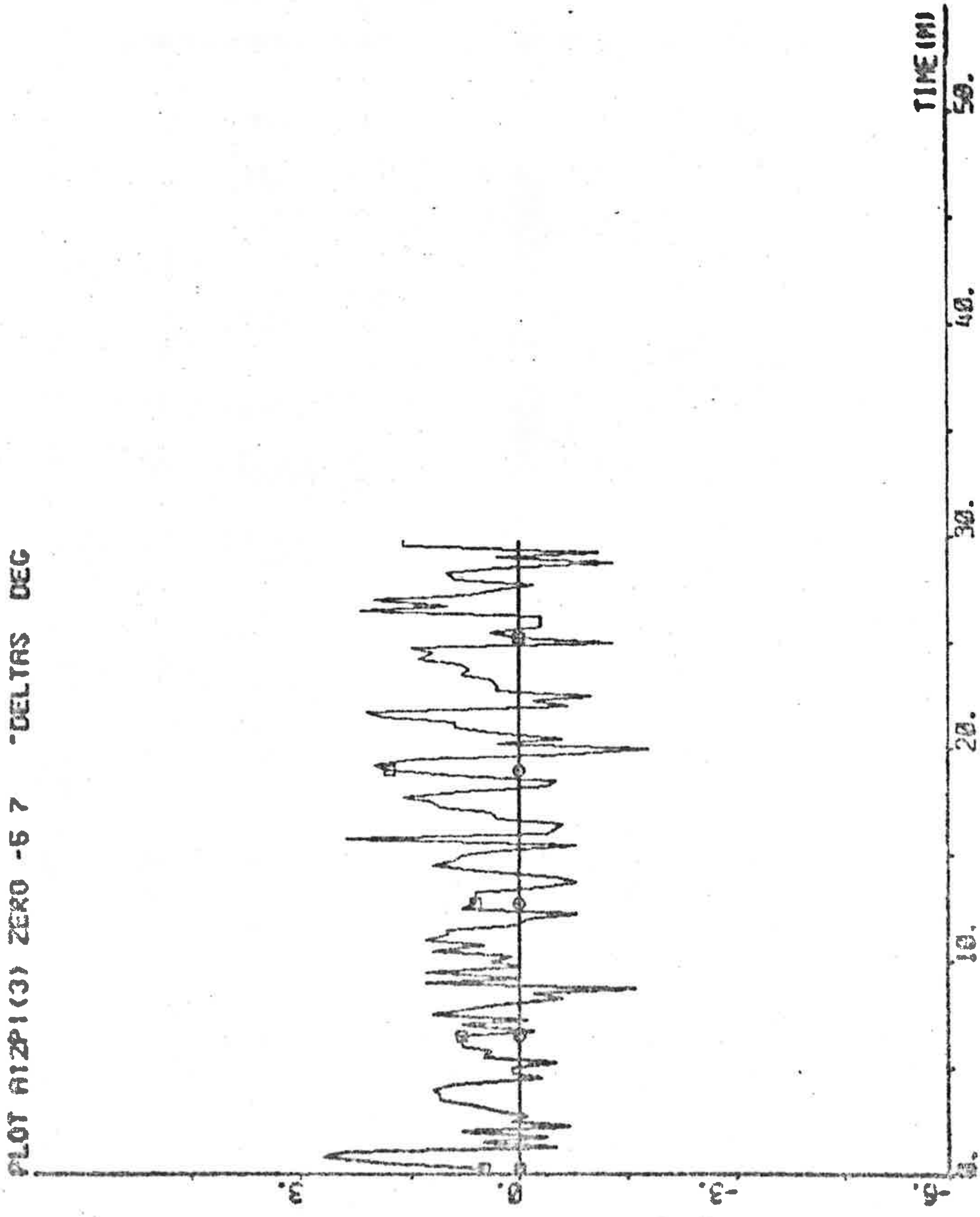
<u>Statistics</u> (mean value and standard deviation)

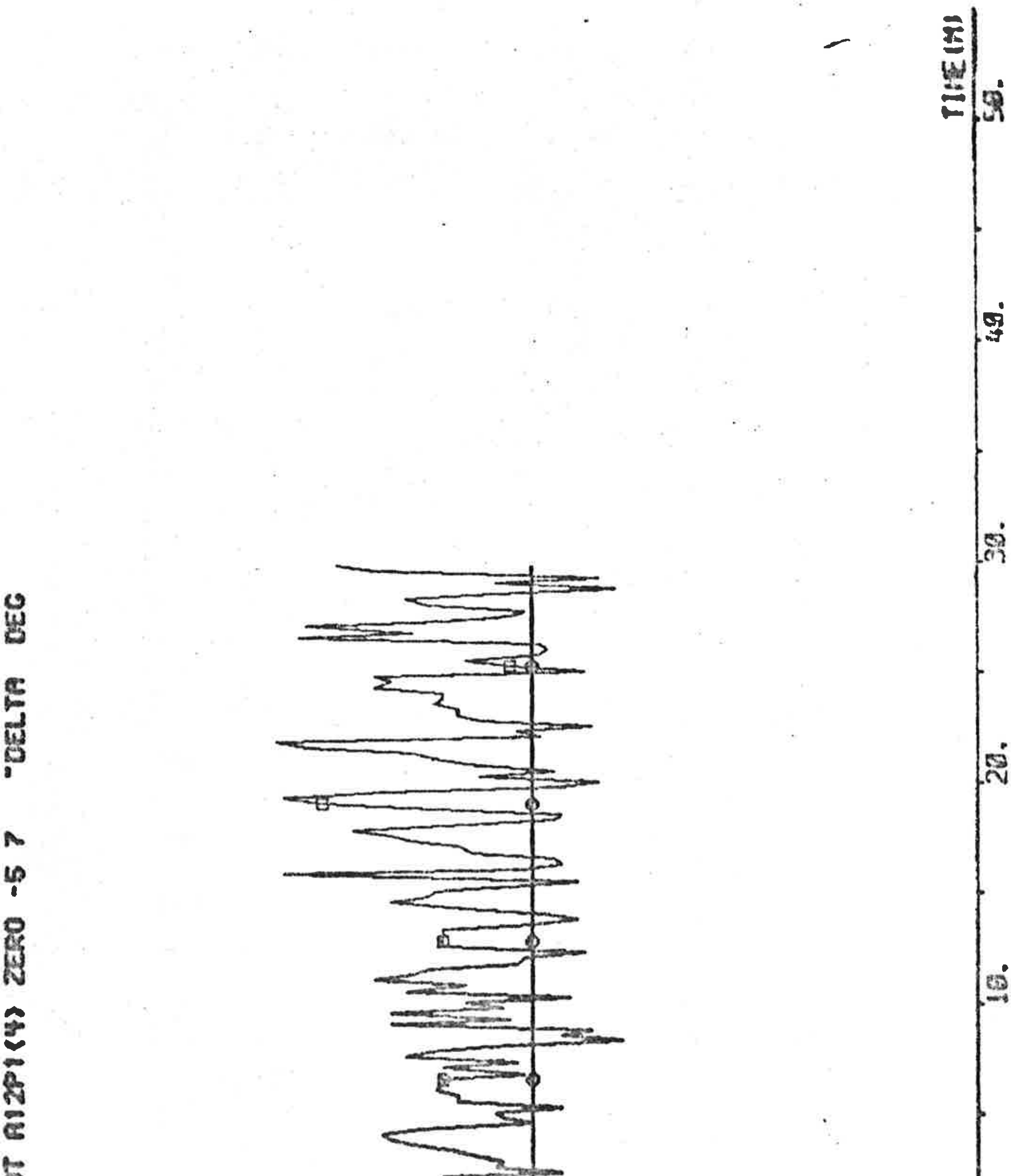
DELTA	0.92 ± 1.10 deg
PSI - PSIREF	-0.017 ± 0.168 deg
AN	85.75 ± 0.34 rpm
U	15.63 ± 0.18 knots

$V_1 = 0.234$

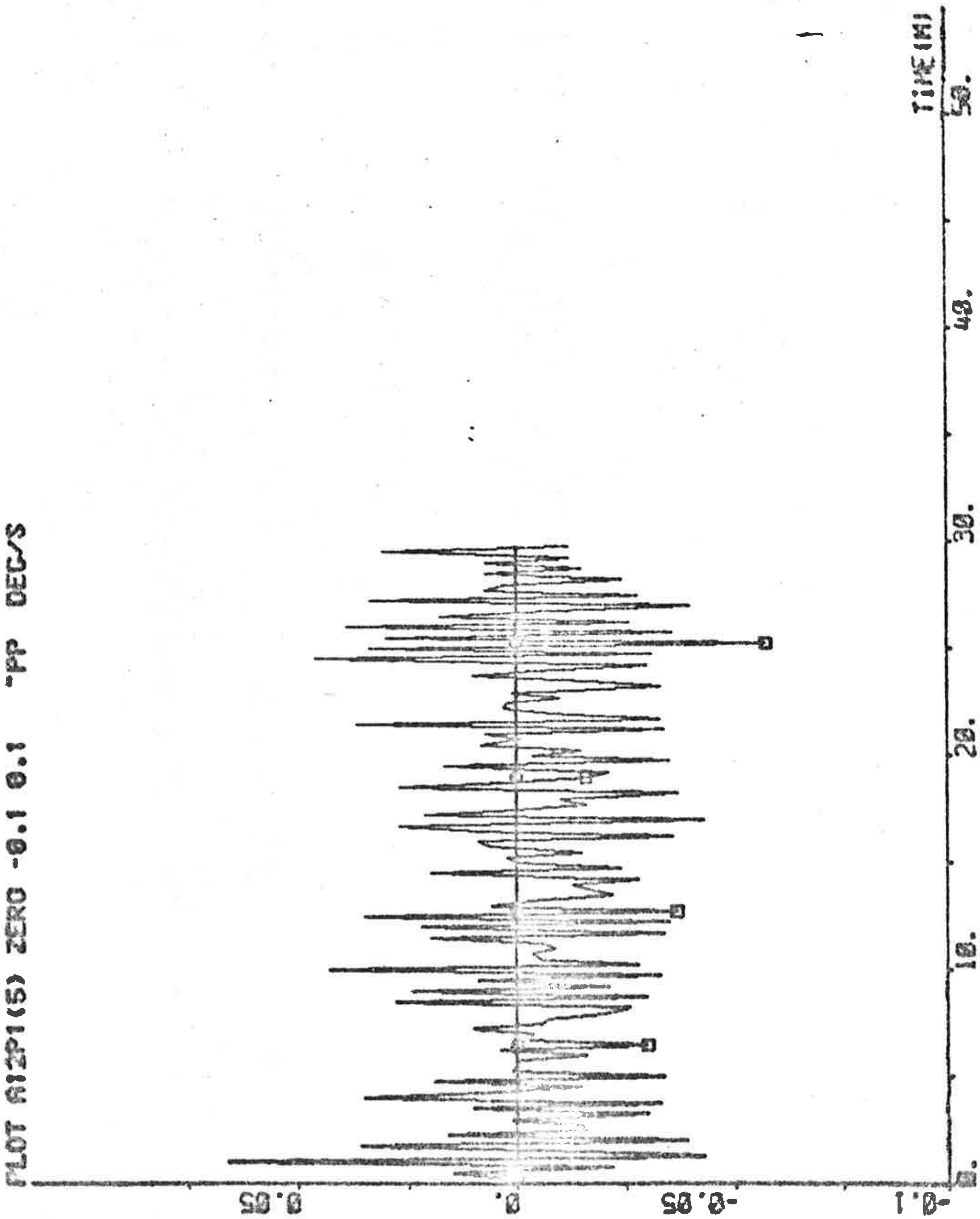
$V_2 = 0.150$

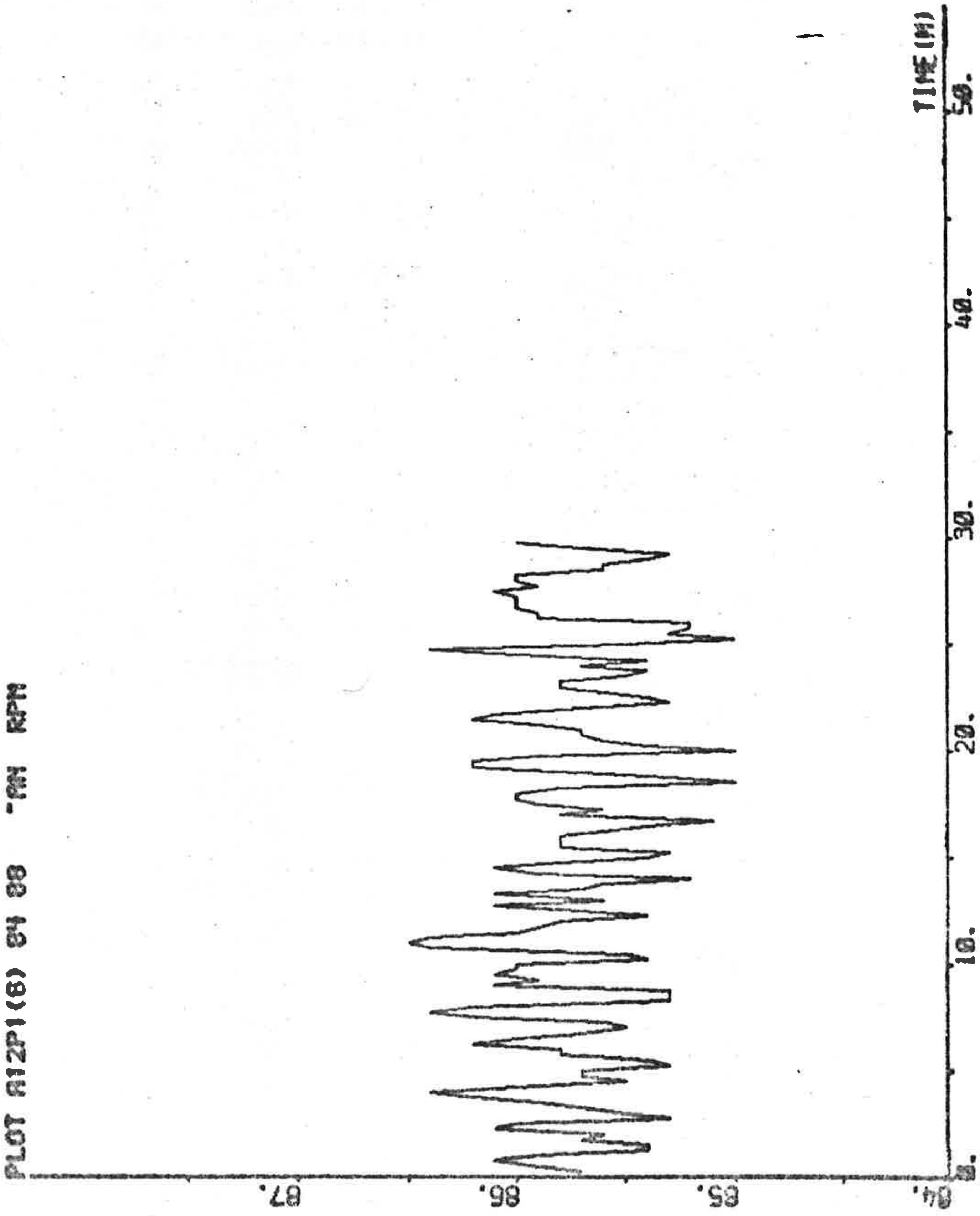

PLOT HP A12P1(1) ZERO -5 7 'DELCOC DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME (H)

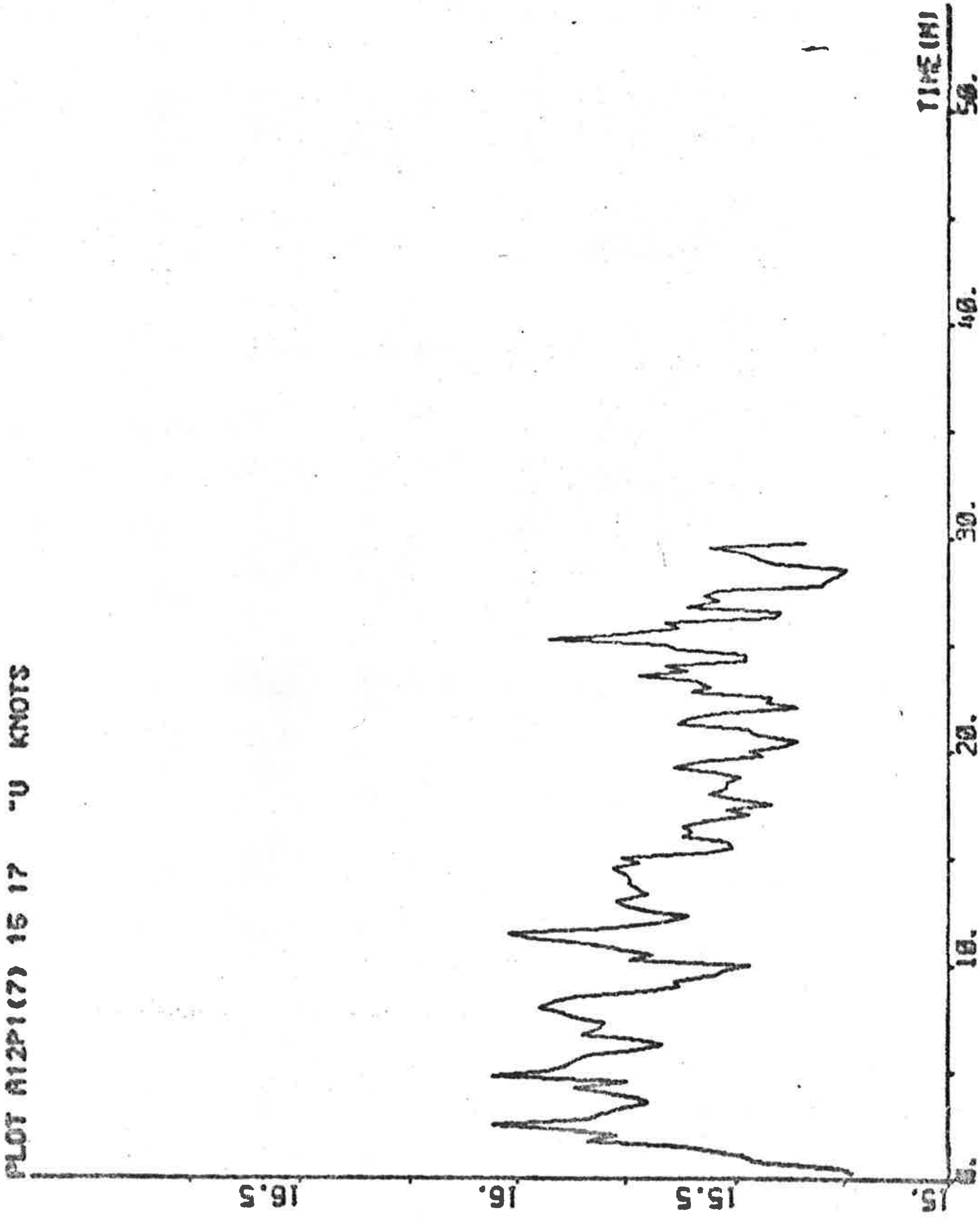

PLOT A12P1(3) ZERO -5 7 -DELTAS DEG
TIME(M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

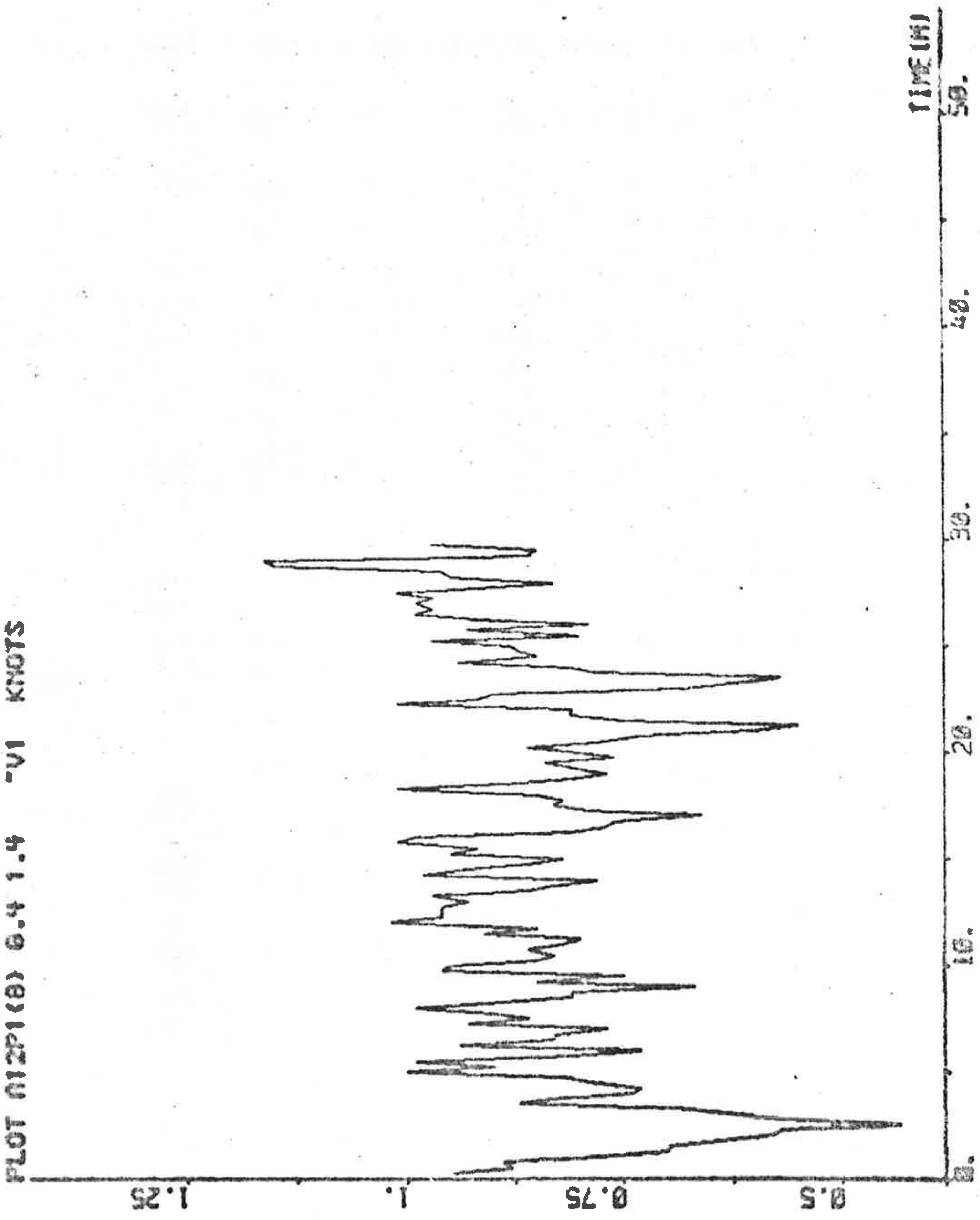


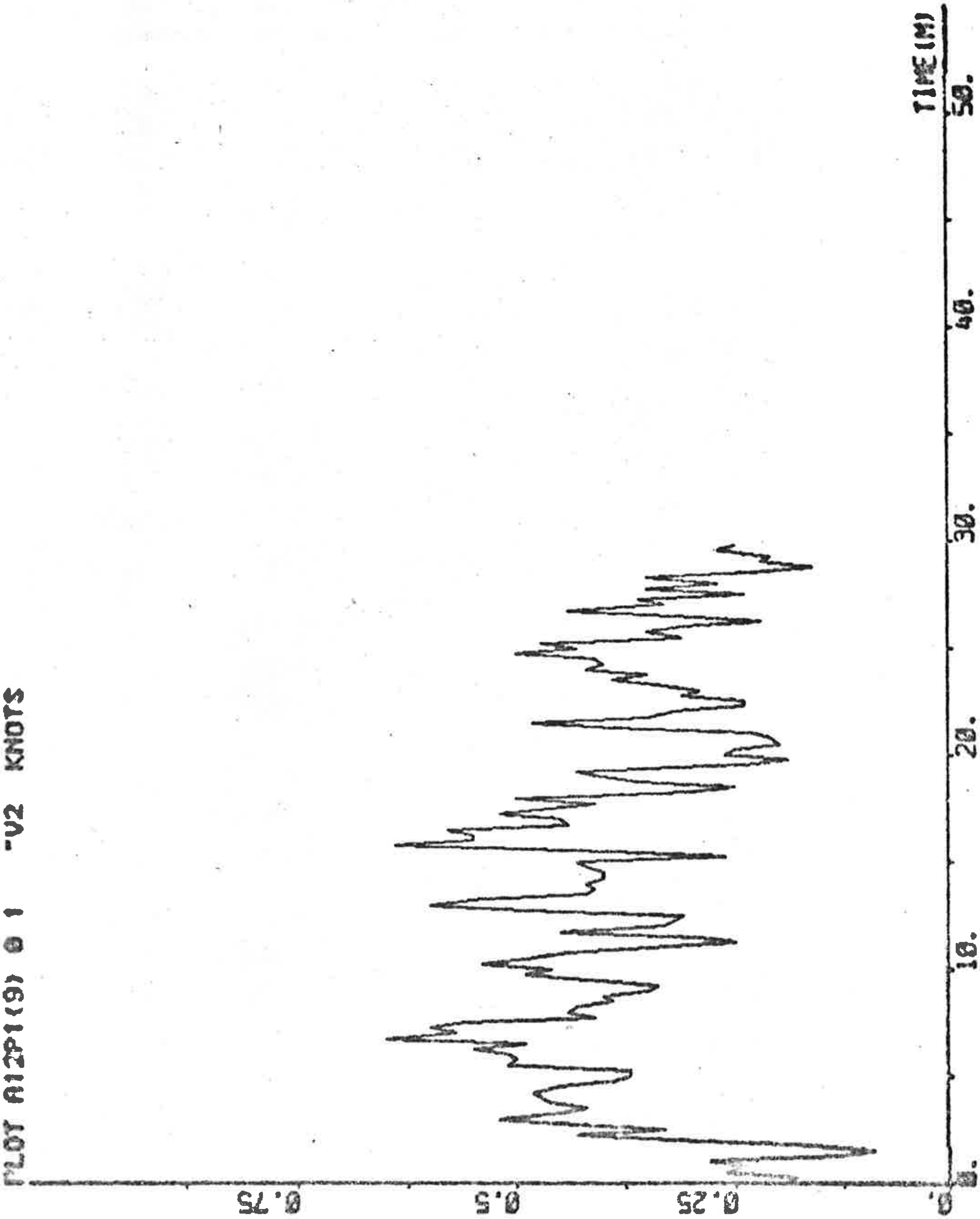
PLOT A12P1(4) ZERO -5 7 'DELTA DEG
TIME (H)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

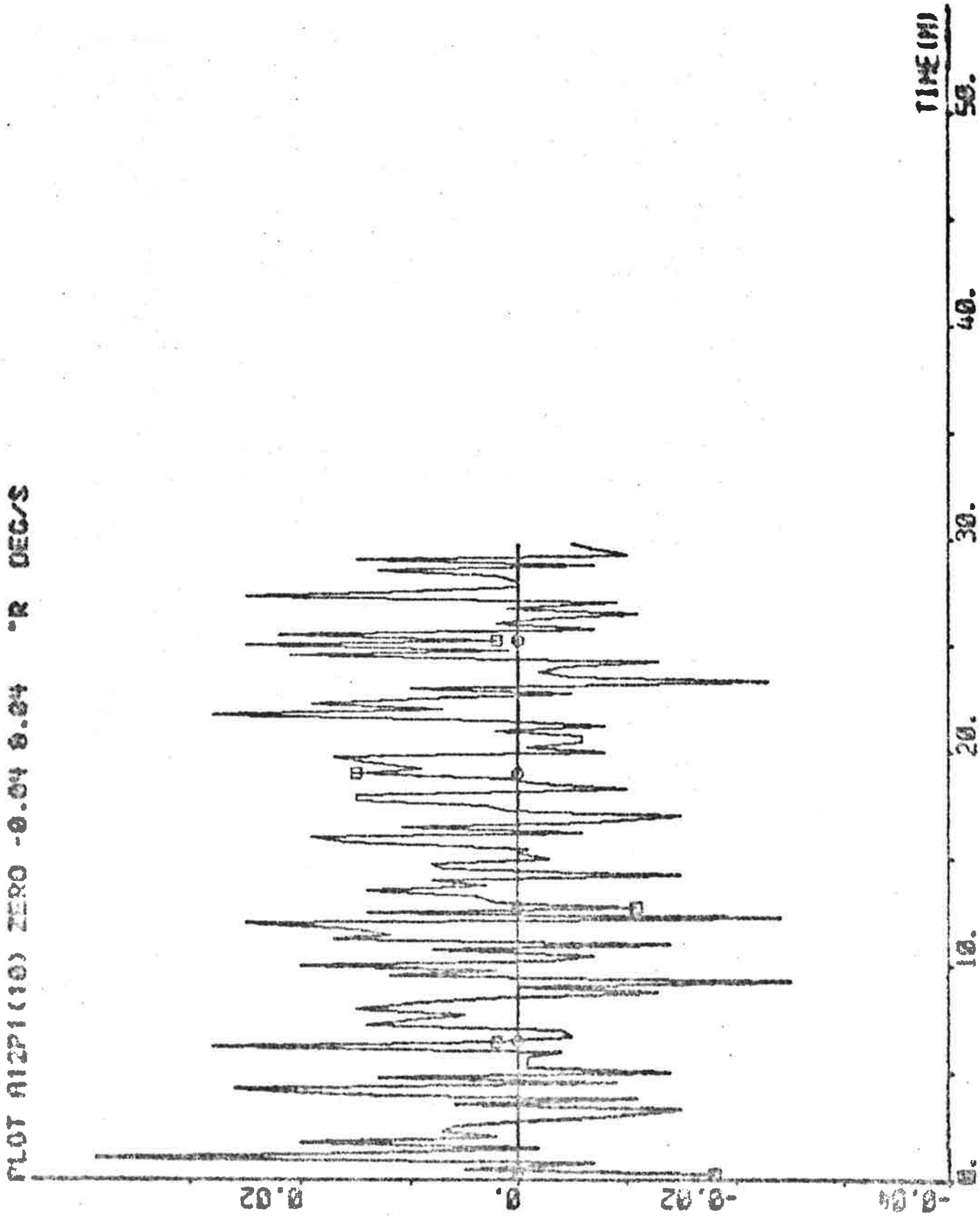

PLOT A12P1(5) ZERO -0.1 0.1 "PP DEG/S
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(M)

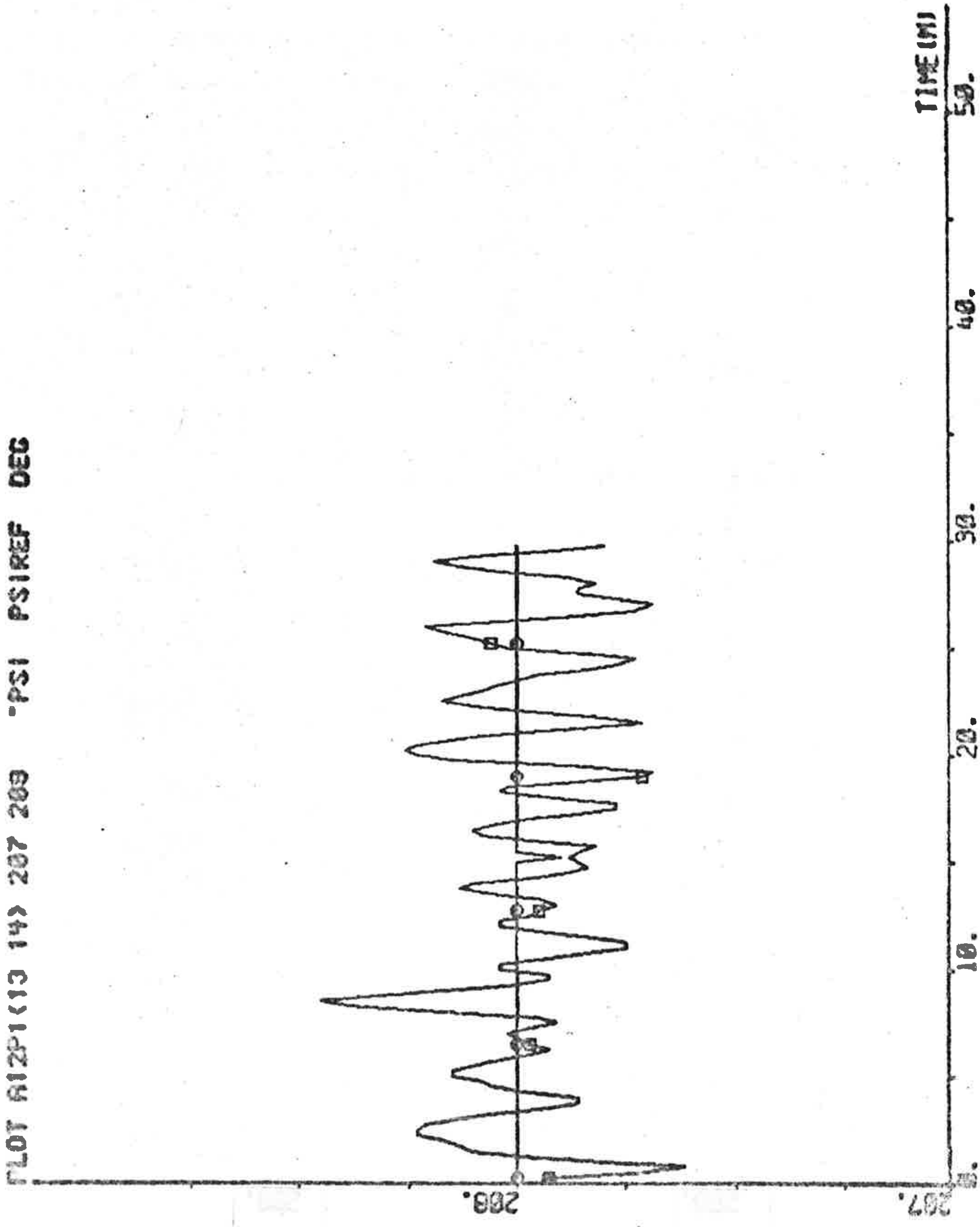

PLOT A12P1(8)
RPM
TIME(M)
0.
10.
20.
30.
40.
50.
84.
85.
86.
87.

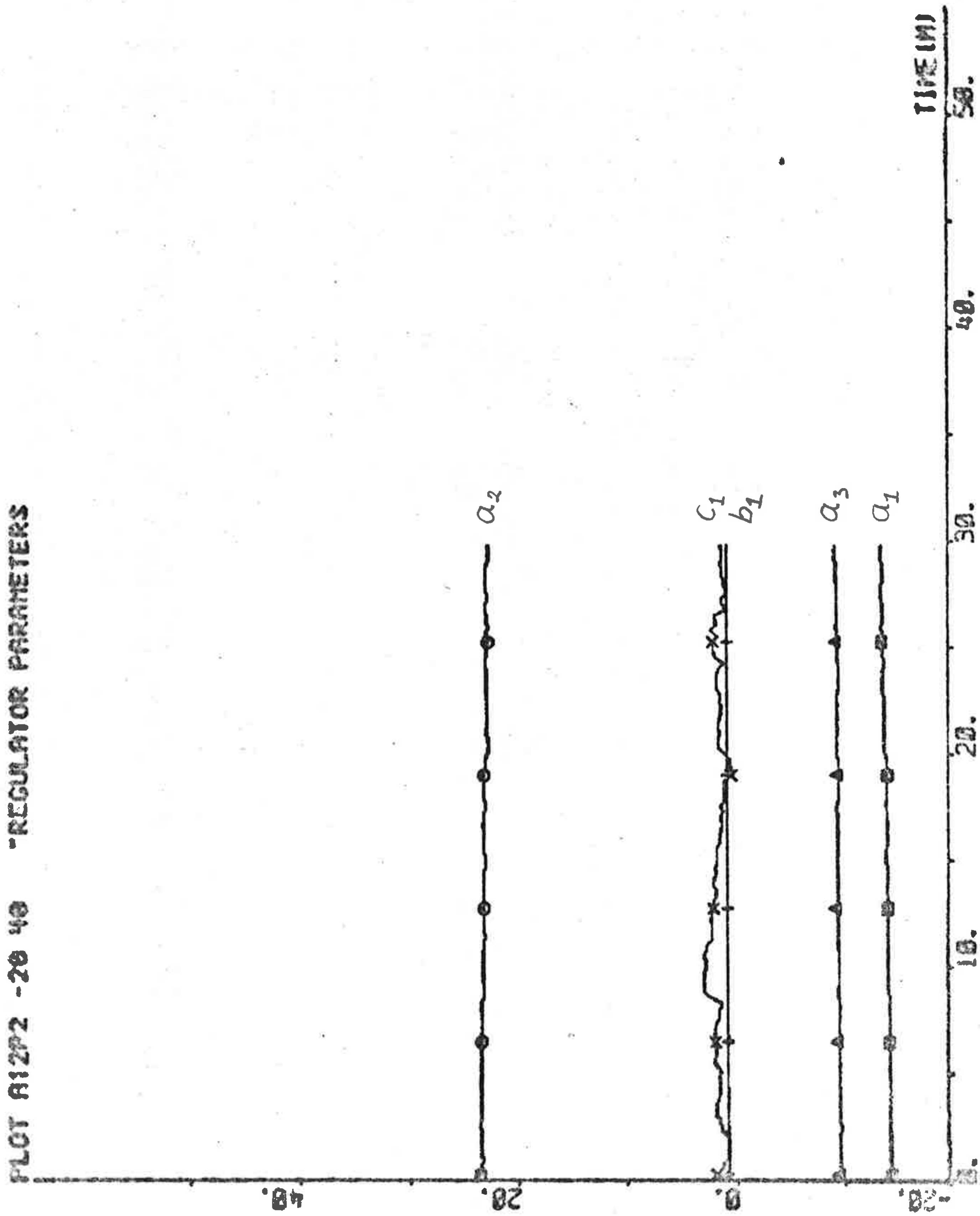

PLOT R12P1(7) 15 17 "U KNOTS
15.
15.5
16.
16.5
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A12P1(8) 0.4 1.4 -V1 KNOTS
1.25
1.
0.75
0.5
0.
10.
20.
30.
40.
50.
TIME (H)


PLOT A12P1(9) @ 1 -V2 KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
0.25
0.5
0.75


PLOT A12P1(10) ZERO -0.04 0.04 'R DEG/S
TIME (M)
0.
10.
20.
30.
40.
50.
0.02
0.
-0.02
-0.04


PLOT A12P1(13 14) 207 209 -PSI PSIREF DEG
TIME(M)
0.
10.
20.
30.
40.
50.
208.
207.


PLOT A12P2 -20 40 'REGULATOR PARAMETERS
TIME (M)
0.
10.
20.
30.
40.
50.
-20.
0.
20.
40.
a_2
c_1
b_1
a_3
a_1

EXPERIMENT A13

Date	1974-10-14
Time	14.15
Duration	34 min
Position	N 10° 04' E 54° 12'
Water depth	deep
Forward draught	20.2 m
Aft draught	20.2 m
Wind direction	WSW (2; see Appendix A)
Wind velocity	3 Beaufort (4-5.5 m/s, gentle breeze)
Wave height	1 m (light see from SW, rollings)
PSIREF	208°
Rudder limit	Not active

Regulator structure

NA = 3	NB = 1	NC = 1	K = 3
IREG = 15	IRDIF = 0	RL = 0.98	IRR = 1

Final values

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} -14.802 \\ 25.104 \\ -10.707 \\ 0.835 \\ 5.044 \end{bmatrix} \qquad P = \begin{bmatrix} 5.896 & & & & \\ -8.441 & 14.508 & & & \\ 3.607 & -7.385 & 5.168 & & \\ -0.049 & 0.040 & 0.023 & 0.012 & \\ 11.465 & -13.139 & -1.036 & -0.117 & 198.940 \end{bmatrix}$$

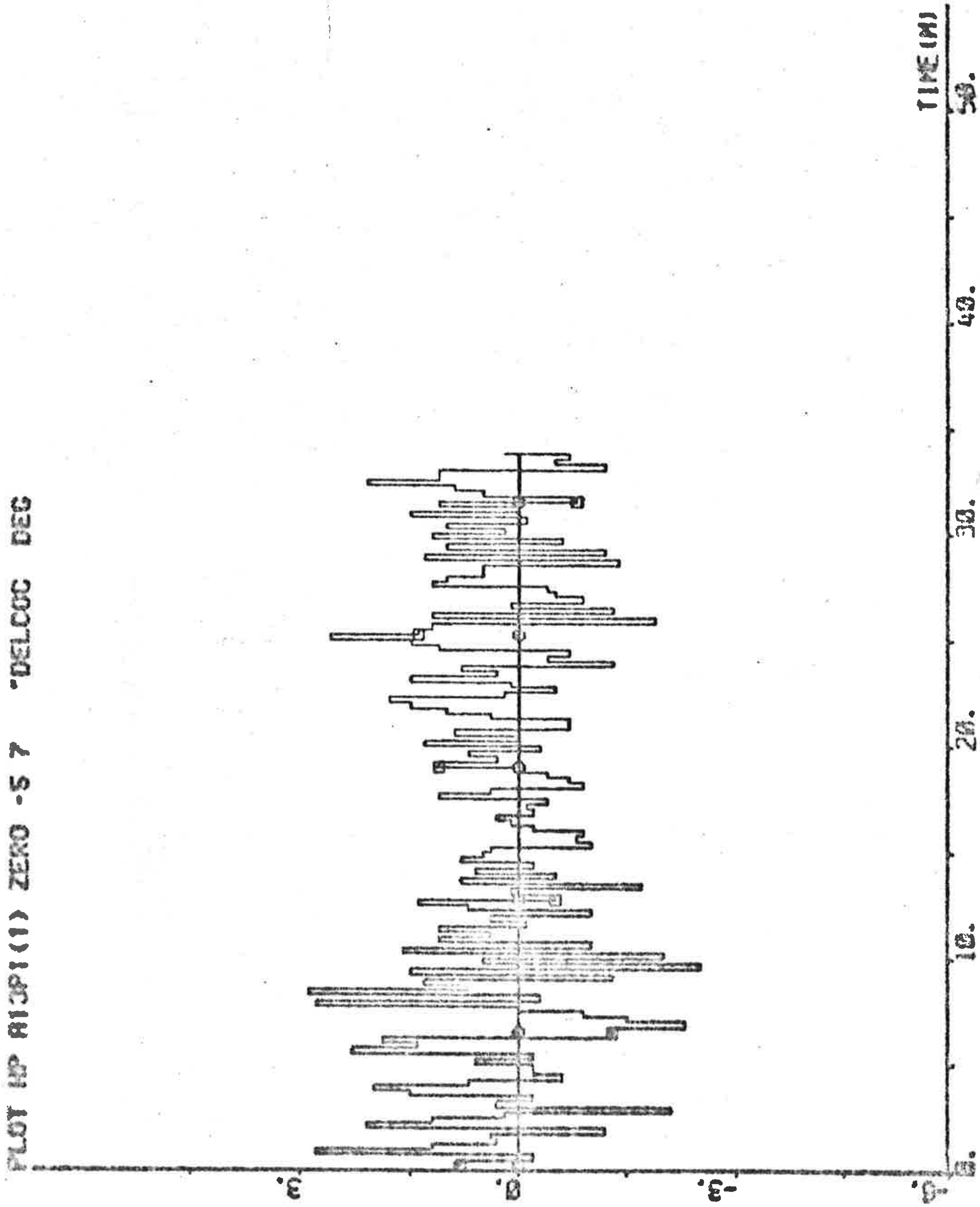
$$a_1 + a_2 + a_3 = -0.405$$

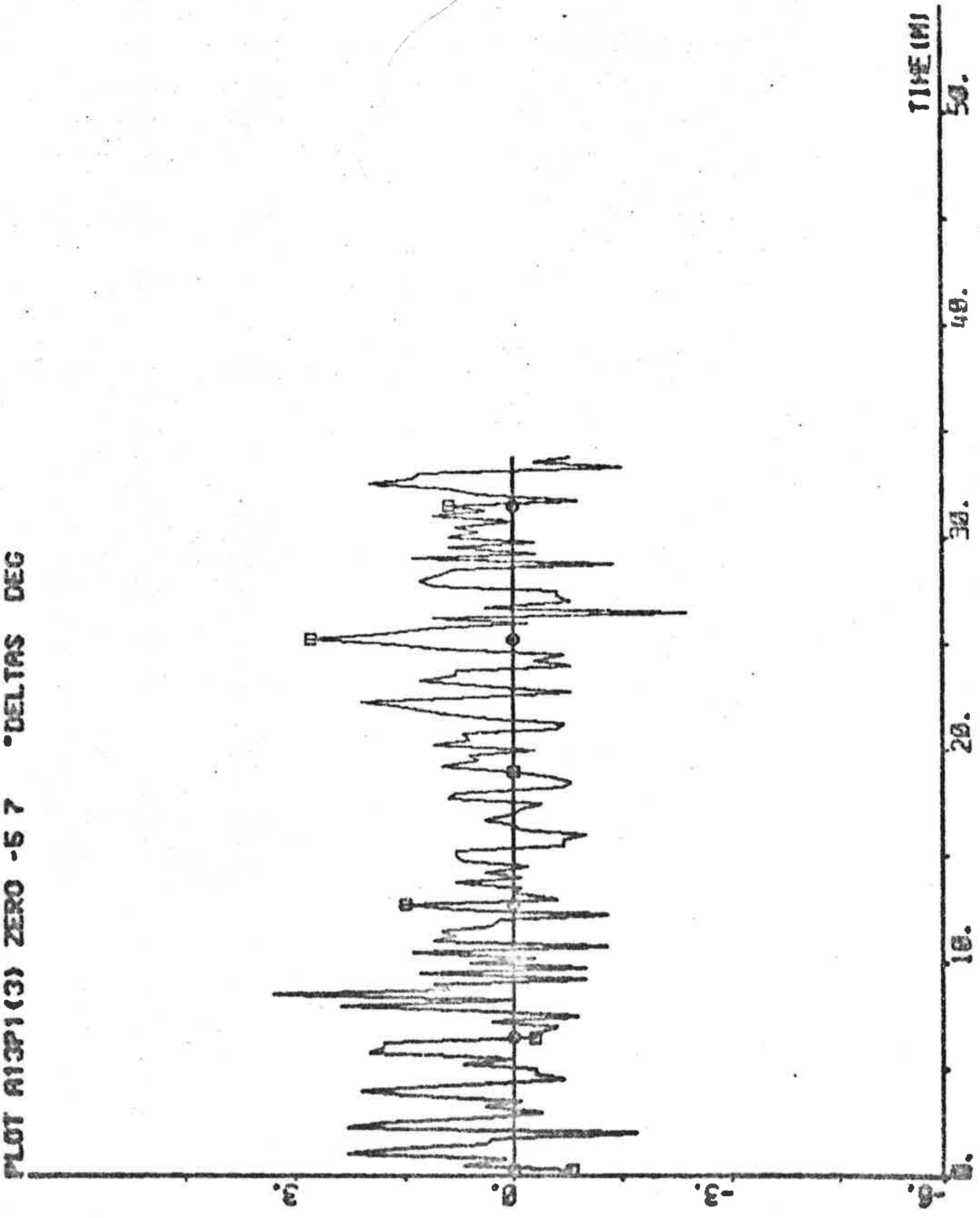
<u>Statistics</u> (mean value and standard deviation)

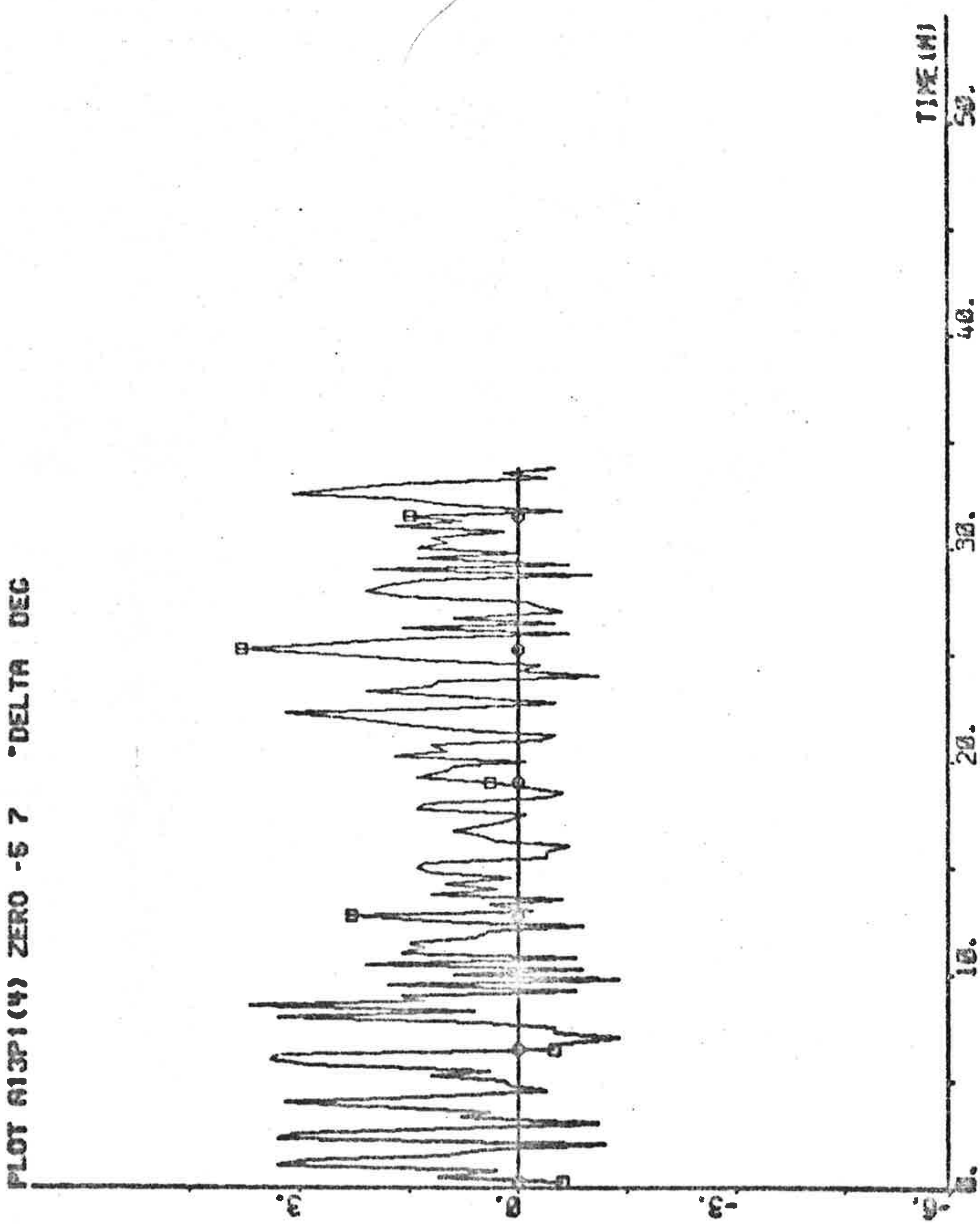
DELTA	0.84 ± 1.23 deg
PSI-PSIREF	-0.069 ± 0.173 deg
AN	85.71 ± 0.29 rpm
U	15.32 ± 0.16 knots

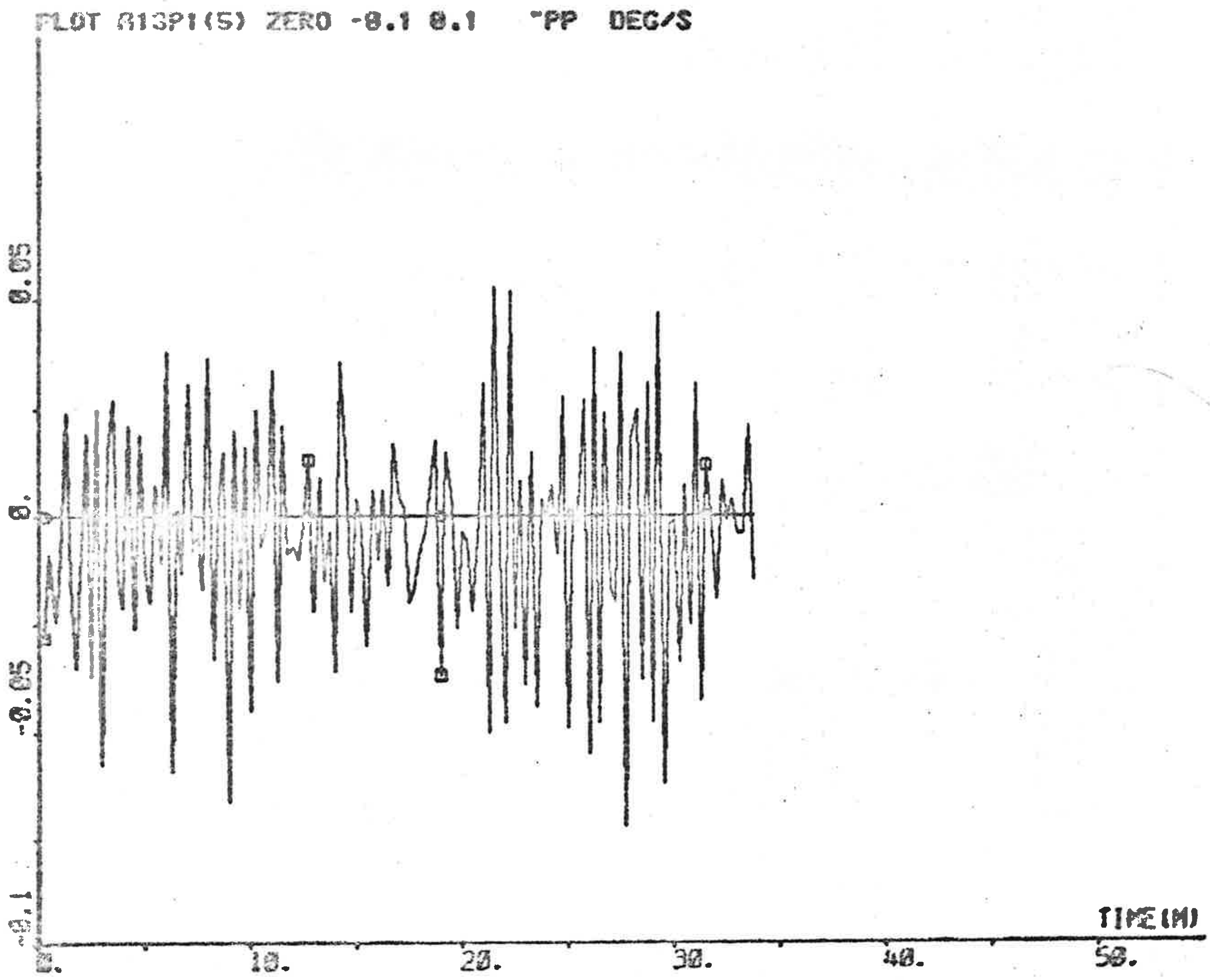
$V_1 = 0.257$

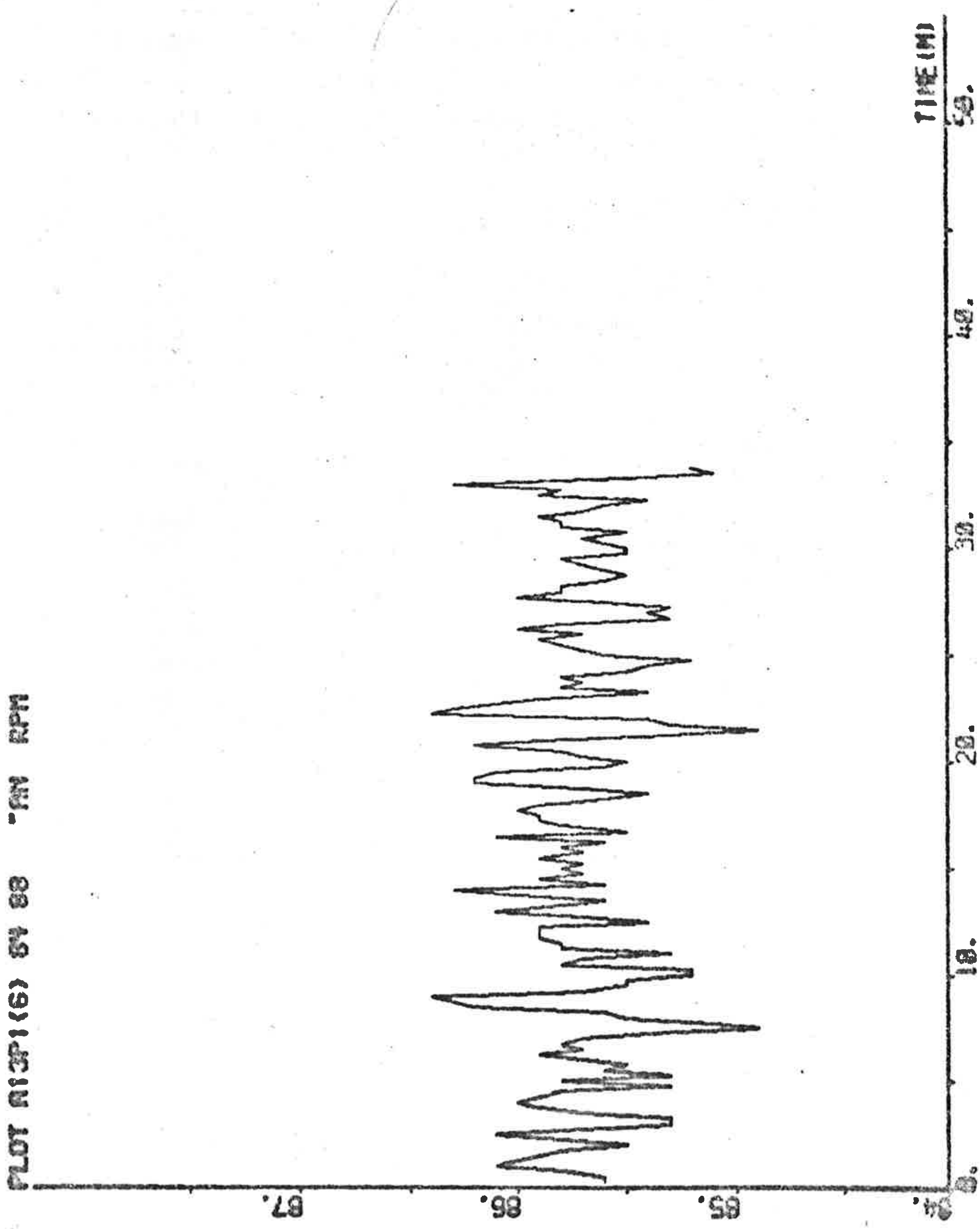
$V_2 = 0.186$

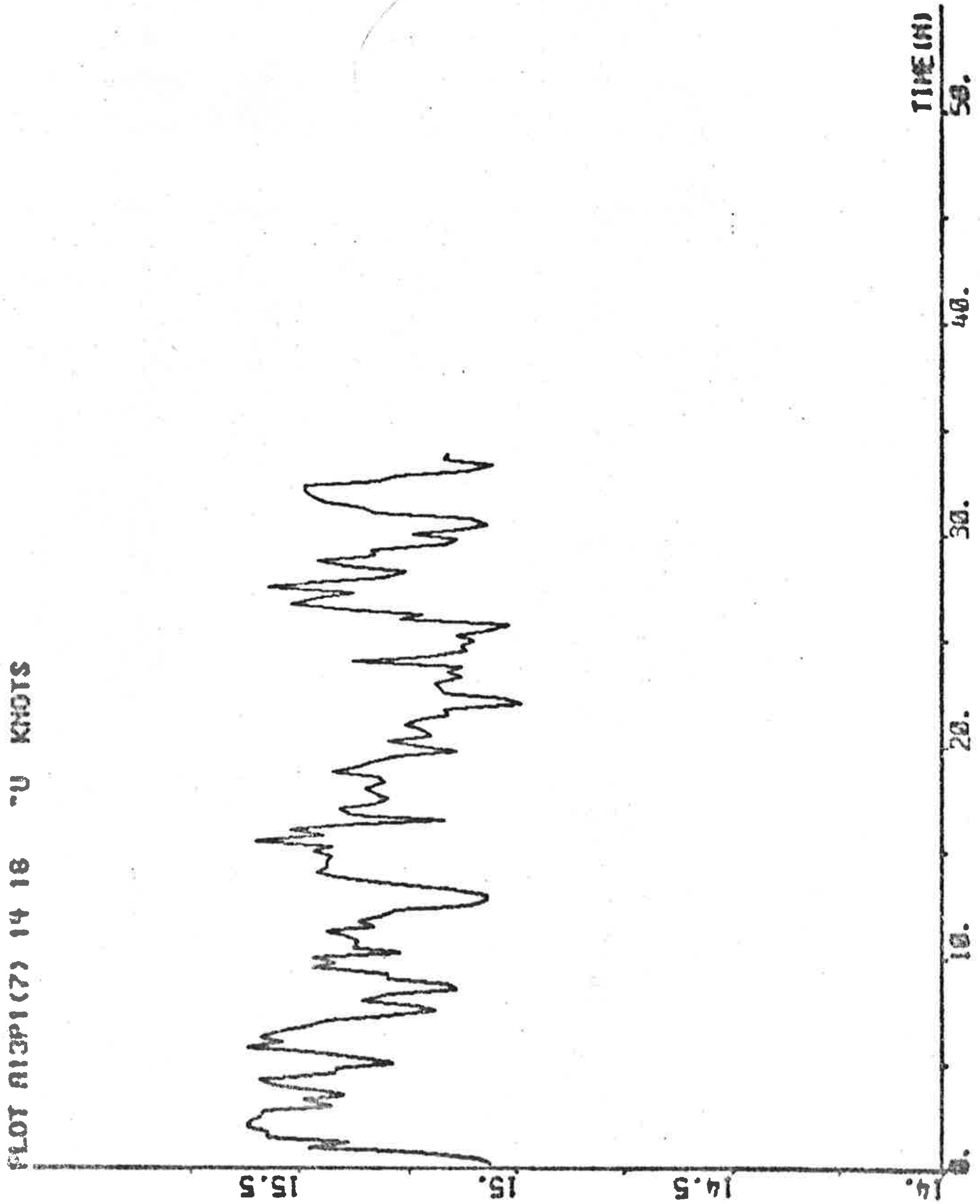

PLOT HP A13P1(1) ZERO -5 7 'DELCOC DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

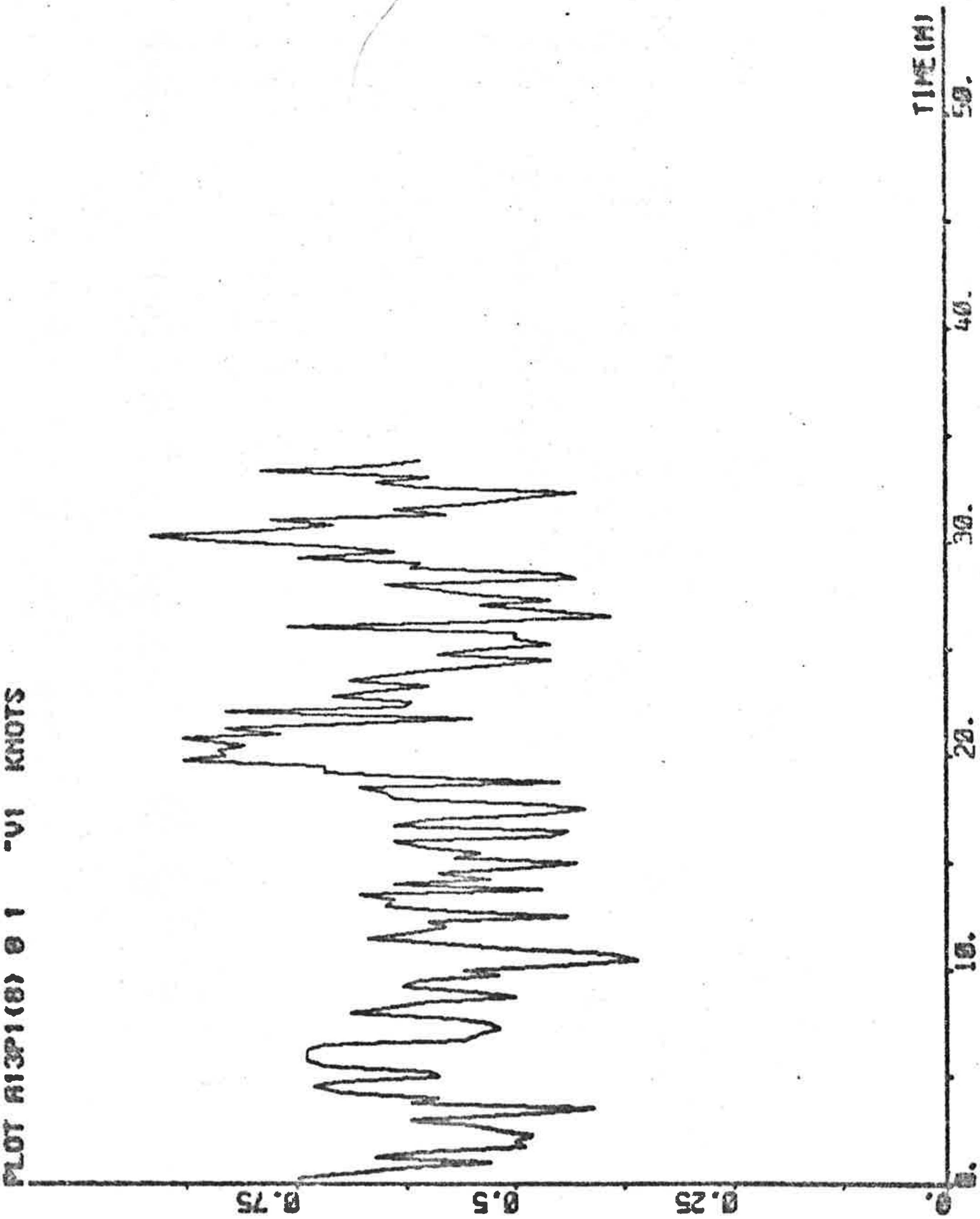

PLOT A13P1(3) ZERO -5 7 *DELTAS DEG
TIME (M)
0.
10.
20.
30.
40.
50.
3.
0.
-3.
-6.

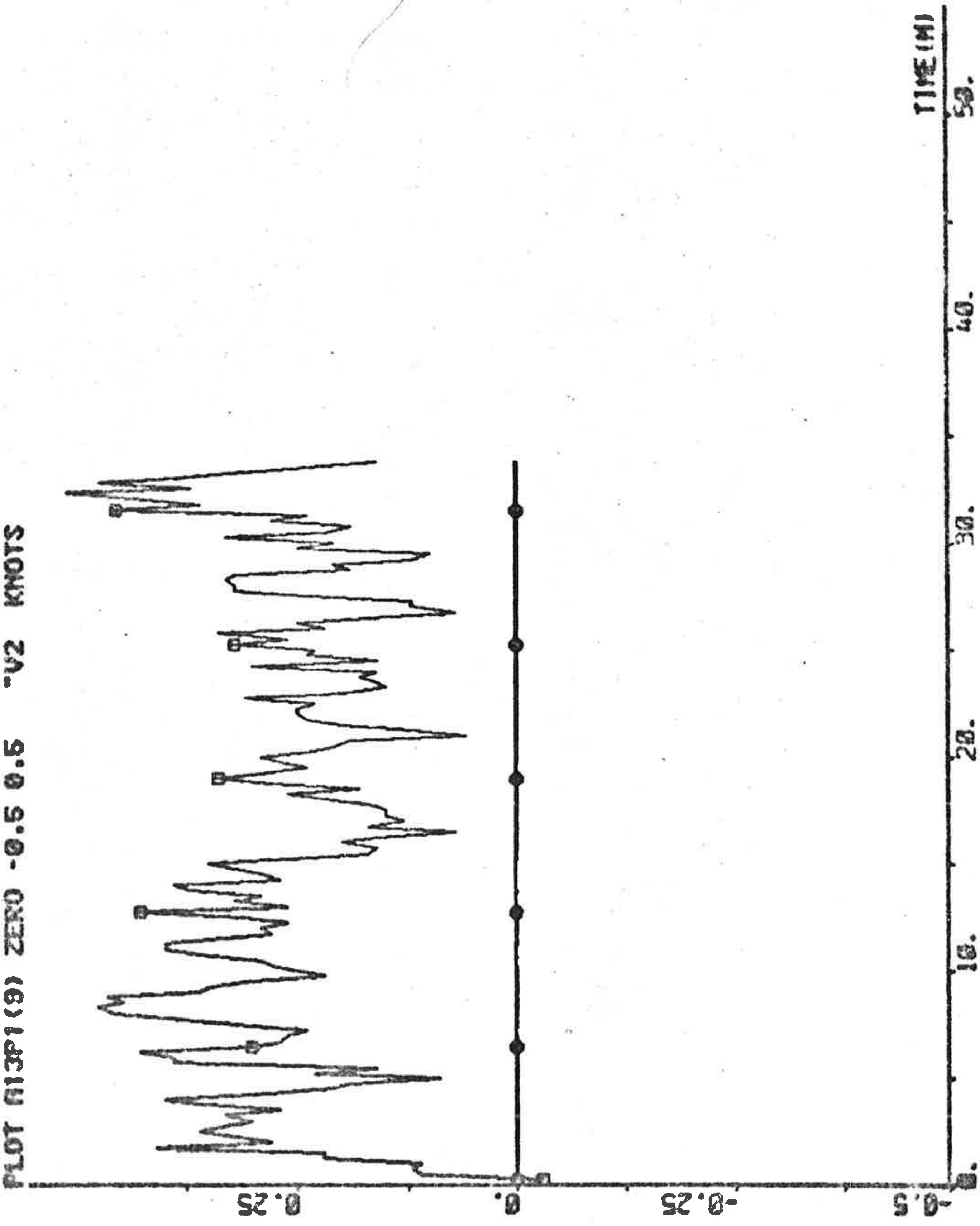

PLOT A13P1(4) ZERO -5 7 °DELTA DEG
3.
0.
-3.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)

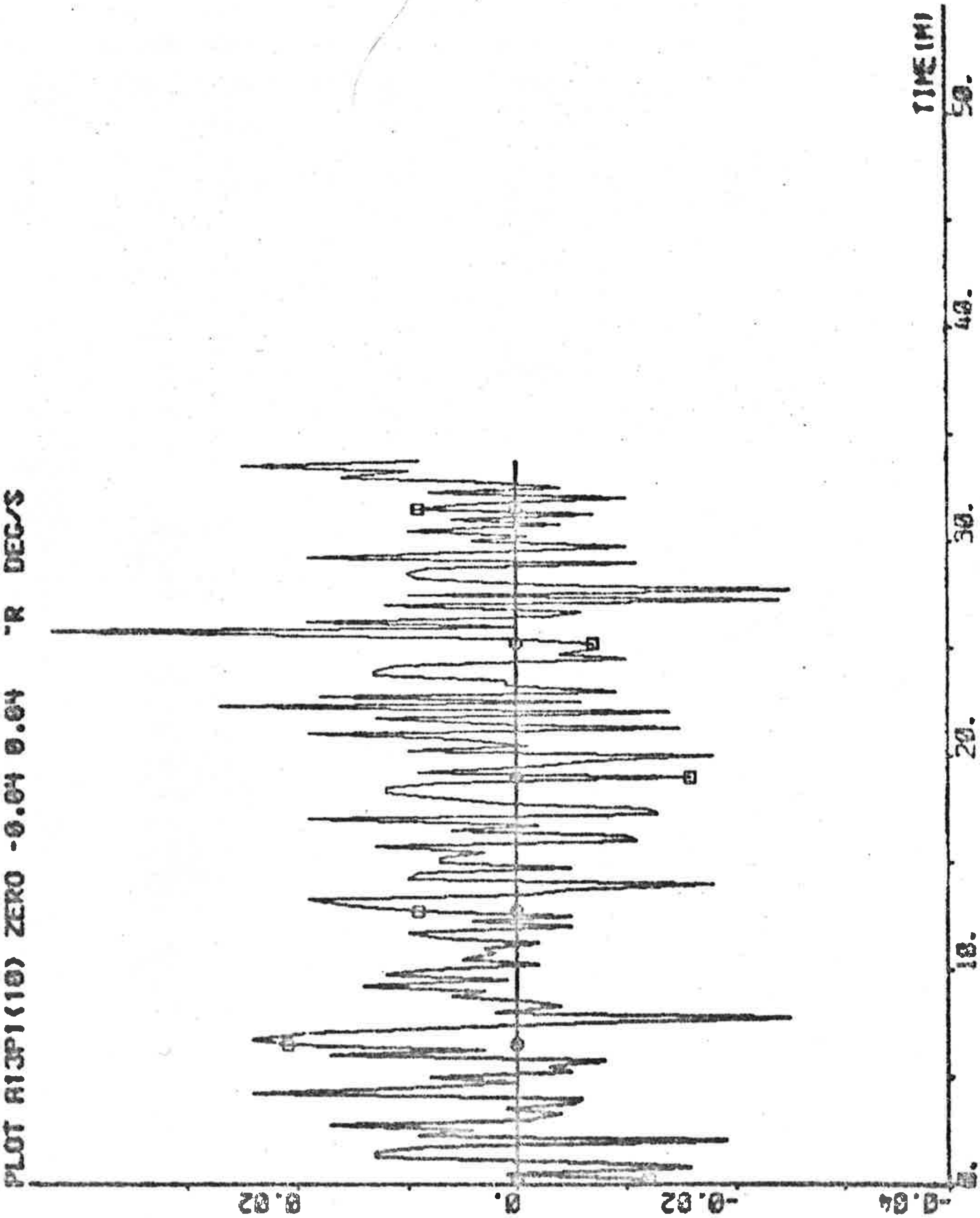

PLOT R13P1(S) ZERO -0.1 0.1 "PP DEG/S
0.05
0.
-0.05
-0.1
0.
10.
20.
30.
40.
50.
TIME(M)

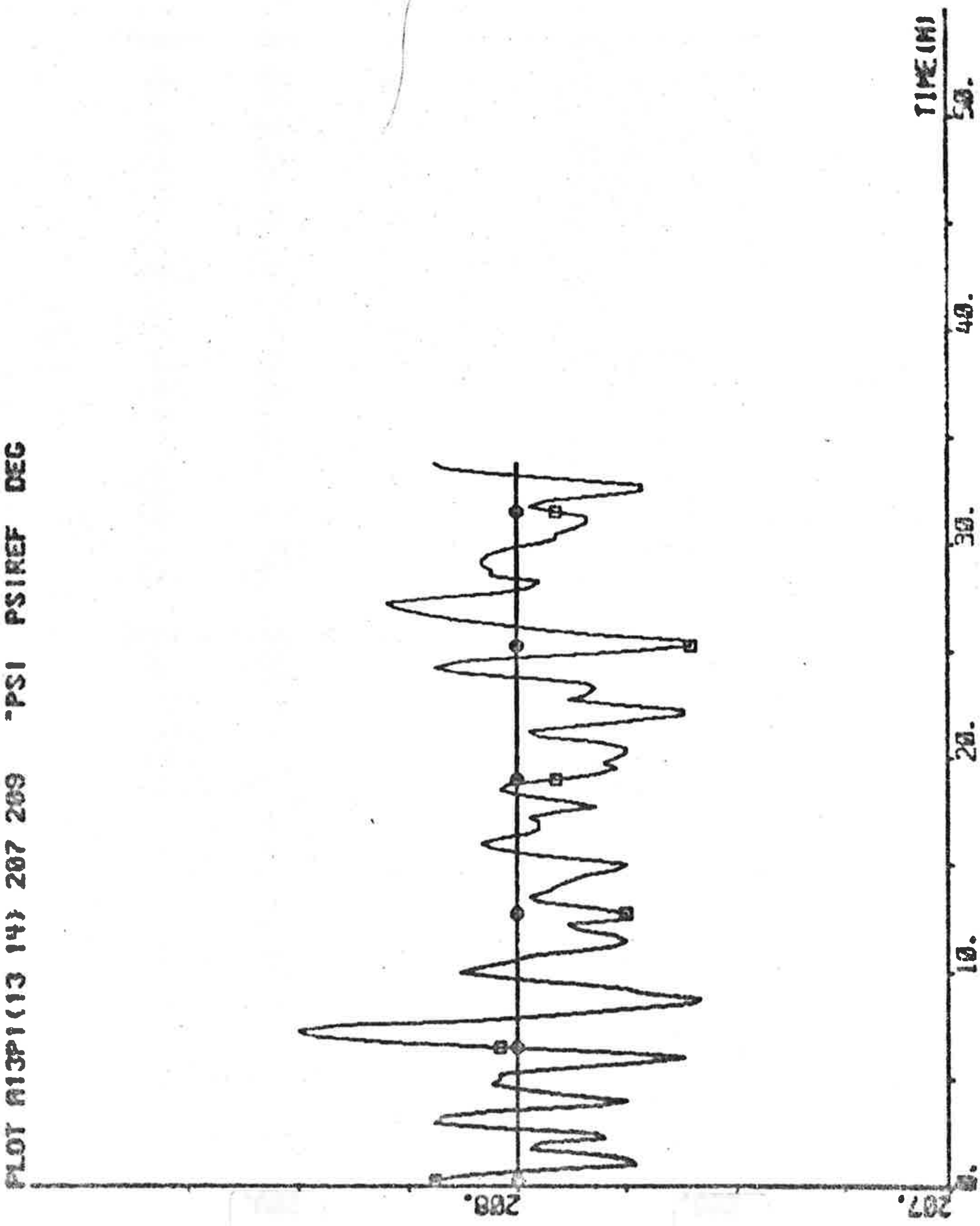

PLOT A13P1(6) 54 88 "AN RPM
87.
86.
85.
84.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A13P1(7) 14 18 "U KNOTS
15.5
15.
14.5
14.
10.
20.
30.
40.
50.
TIME (H)


KNOTS
TIME (M)
0.
10.
20.
30.
40.
50.
0.25
0.5
0.75


PLOT A13P1(9) ZERO -0.5 0.5 "V2 KNOTS
0.25
0.
-0.25
-0.5
10.
20.
30.
40.
50.
TIME (H)


PLOT A13P1(10) ZERO -0.04 0.04 'R DEG/S
0.02
0.
-0.02
-0.04
0.
10.
20.
30.
40.
50.
TIME(M)



PLOT A13P1(13 14) 207 209 *PSI PSIREF DEG
207.
208.
0.
10.
20.
30.
40.
50.
TIME(M)