The Sea Scout Experiments, October 1973

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1974

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Källström, C. (1974). *The Sea Scout Experiments, October 1973*. (Technical Reports TFRT-7063). Department of Automatic Control, Lund Institute of Technology (LTH).

Total number of authors:
1

THE SEA SCOUT EXPERIMENTS, OCTOBER 1973

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Report 7407(C) April 1974
Lund Institute of Technology
Division of Automatic Control

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Claes Källström

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1. INTRODUCTION

The purpose of the experiments was to investigate if a simple self-tuning regulator based on least squares identification and minimum variance control could perform a suitable course keeping of a ship. A self-tuning regulator combined with a Kalman filter and a yaw regulator were also tested.

The ship, t/t Sea Scout, is an 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 255 000 dwt or 339 000 m^3.

The experiments were performed during a voyage from Las Palmas to Cape Town between 1973-10-09 and 1973-10-20. The ship had a ballast of 103 000 dwt. The speed of the ship was about 16 - 17 knots, and the water was deep during all the experiments. The weather was fine, and the wind speed was at most 4 Beaufort (6 - 9 m/s, moderate breeze).

The regulators were implemented as Fortran subroutines for the process computer Kongsberg SM 306, which is a standard equipment. A special paper tape punch was installed for recording of the experiments.

Seven different experiments with the self-tuning regulator and one comparative experiment with Kockums PID-regulator were performed. Three data sets for system identification were also recorded. All experiments are described in Appendix C, and the notations are explained in Appendix A.

2. MEASUREMENT EQUIPMENT

Several measurement signals are usually read into the computer, and no special equipment had to be installed to carry through these experiments. Following measurement signals were used:

- Rudder servo position δ_s (scan cycle 1 s).
- Rudder angle δ (scan cycle 1 s).
- Forward velocity u (scan cycle 3 s).
- Cross velocity of bow v_1 (scan cycle 3 s).
- Cross velocity of stern v_2 (scan cycle 3 s).

The three velocities were measured by a doppler log, type Ametek Straza, with an accuracy of 0.02 knots.

- Yaw angular velocity r (scan cycle 1 s) measured with an accuracy of about 0.02 degr/s by a rate gyro manufactured by AB ATEW.
- Course Ψ (scan cycle 1/3 s) measured by a Sperry gyro compass, and transformed by a synchro-digital converter with an accuracy of about 0.09°.
- Number of revolutions of propeller n (scan cycle 1 s).

It was also intended to measure the pitch angular velocity q, but there was difficulties to get this signal into the computer.

3. THE AUTOPILOT

The purpose of the autopilot is to keep the ship on the desired course Ψ_{ref} in spite of disturbances from wind and waves, and to perform a suitable yaw when a new course is demanded. A schematic diagram of the autopilot, which was used during the experiments, is shown in fig. 3.1. Note, however, that it is possible to side-step the Kalman filter and put the measurements from the ship into the self-tuning regulator and into the yaw regulator instead of the state estimates from the filter.

It is also possible to use a combination of the measurements and the state estimates.

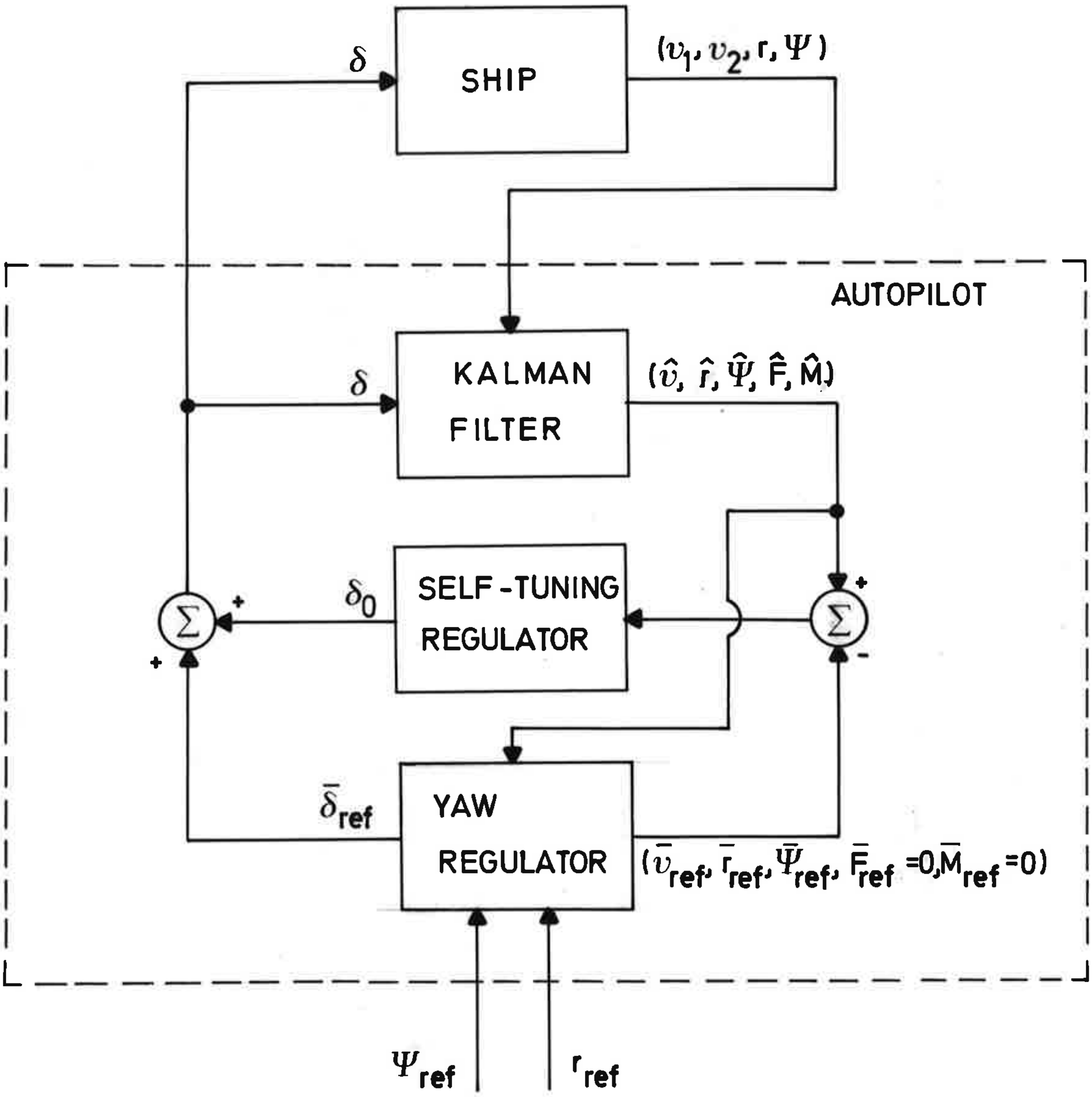

Fig. 3.1. Schematic diagram of the autopilot. r_{ref} is the reference value of the yaw angular velocity during the yaw. For course keeping only, $\bar{\delta}_{ref} = \bar{v}_{ref} = \bar{r}_{ref} = 0$ and $\bar{\Psi}_{ref} = \Psi_{ref}$.

3.1 The Kalman filter.

Following linear model of the ship and the resulting force and moment from the wind is used in the Kalman filter

$$
\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\Psi} \\ \dot{F} \\ \dot{M} \end{bmatrix} = \begin{bmatrix} \frac{V}{\ell} a_{11} & V q_1 a_{12} & 0 & 1 & 0 \\ \frac{V}{\ell^2 q_1} a_{21} & \frac{V}{\ell} a_{22} & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \Psi \\ F \\ M \end{bmatrix} + \begin{bmatrix} \frac{V^2}{\ell} q_1 b_{11} \\ \left(\frac{V}{\ell}\right)^2 b_{21} \\ 0 \\ 0 \\ 0 \end{bmatrix} \delta
$$

$$
\begin{bmatrix} v_1 \\ v_2 \\ r \\ \Psi \end{bmatrix} = \begin{bmatrix} q_2 & q_1 q_2 \ell_1 & 0 & 0 & 0 \\ q_2 & -q_1 q_2 \ell_2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \Psi \\ F \\ M \end{bmatrix} \tag{3.1}
$$

The notations are explained in appendix A. The parameters a_{11}, a_{12}, a_{21}, a_{22}, b_{11} and b_{21} have been determined for a sistership, (see Åström - Källström (1973)), and the same parameter values are used in this model

$$
\begin{aligned} a_{11} &= -0.3098 & a_{12} &= -0.226 \\ a_{21} &= -1.492 & a_{22} &= -1.791 \\ b_{11} &= -0.139 & b_{21} &= 1.00 \end{aligned} \tag{3.2}
$$

The Kalman filter is executed every second, so the continuous model (3.1) is transformed to a discrete model (Φ,Γ,Θ) with the sampling interval 1 s. The optimal state estimate $\hat{x} = (\hat{v},\hat{r},\hat{\Psi},\hat{F},\hat{M})^T$ is then given by (see Åström (1970))

$$\hat{x}(t/t) = \hat{x}(t/t-1) + K(y(t) - \Theta\hat{x}(t/t-1))$$

$$\hat{x}(t/t-1) = \Phi\hat{x}(t-1/t-1) + \Gamma\delta(t-1) \qquad (3.3)$$

where $y = (v_1,v_2,r,\Psi)^T$ and the notation $\hat{x}(t/t-1)$ means an estimate of x at time t based on measurements up to and including time t-1. The filter gain K is designed using the discrete model (Φ,Γ,Θ) and suitable state noise and measurement noise covariance matrices.

3.2 The self-tuning regulator.

The self-tuning regulator is described in Wittenmark (1973). Two different regulators were tried. Regulator 1 is based on the model

$$\Psi(t+1) - \Psi(t) = b_1\delta(t) + b_2\delta(t-1) + d_1v(t) + d_2r(t) + d_3F(t) + d_4M(t) + e(t+1) \qquad (3.4)$$

which can be derived from the continuous ship model (3.1) by sampling with the unit time and then adding the terms $b_2\delta(t-1)$ and $e(t+1)$. The first one of these terms can be justified from the time delay between the sampling event and the moment when the new rudder position is reached. $\{e(t)\}$ is a sequence of independent $N(0,\sigma)$ random variables. Note that v,r,F and M are regarded as feedforward signals in the model (3.4). The purpose of the control is now to minimize the loss function

$$\Sigma(\Psi(t) - \bar{\Psi}_{ref})^2 \qquad (3.5)$$

where $\bar{\Psi}_{ref}$ is assumed to be constant. The optimal control signal is determined from

$$\delta(t) = -\frac{1}{b_1}[(\Psi(t) - \bar{\Psi}_{ref}) + b_2\delta(t-1) + d_1v(t) + d_2r(t) + + d_3F(t) + d_4M(t)] \qquad (3.6)$$

where the parameters b_1, b_2, d_1, d_2, d_3 and d_4 in the model (3.4) are estimated using the least squares method. Note that it is not necessary to use the increment of the control variable, because the model (3.4) contains an integrator.

If the notations, which are used in fig. 3.1, are introduced in the control law (3.6), we obtain

$$\delta_o(t) = -\frac{1}{b_1}[(\hat{\Psi}(t) - \bar{\Psi}_{ref}(t)) + b_2\delta_o(t-1) + d_1(\hat{v}(t) - \bar{v}_{ref}(t)) + + d_2(\hat{r}(t) - \bar{r}_{ref}(t)) + d_3\hat{F}(t) + d_4\hat{M}(t)] \qquad (3.7)$$

Regulator 1 tries to beat the course error $\Psi-\bar{\Psi}_{ref}$ after one sampling interval. If the sampling length is too small, it is possible that the generated rudder deviations are too large for a good control of the ship. Therefore, another self-tuning regulator, which tries to beat the course error after three sampling intervals, was also used during the experiments. This one, regulator 2, is based on the model

$$\Psi(t+3) - \Psi(t) = b_1\delta(t) + b_2\delta(t-1) + d_1v(t) + d_2r(t) + d_3F(t) + + d_4M(t) + e(t+3) \qquad (3.8)$$

which is model (3.4) modified by introducing two pure time delays. The optimal control signal is determined from (3.6), or by using the notations in fig. 3.1, from (3.7).

3.3 The yaw regulator.

A yaw can be divided into three parts. During the initial phase the ship is taken from a straight course state to a stationary yaw state, which is maintained until the third phase, the yaw terminating, is begun. The purpose of the yaw regulator is to generate suitable reference values for the self-tuning regulator based on the new demanded course Ψ_{ref} and the desired yaw angular velocity r_{ref} during the yaw (see fig. 3.1).

If it is assumed that the linear ship model (3.1) is valid during a yaw, it can be concluded, that a specific constant rudder angle $\bar{\delta}_{ref}$ has to be applied to maintain the desired yaw angular velocity r_{ref}. This will also give a constant cross velocity $\bar{v}_{ref}$. Thus, the reference values during the second phase (the stationary yaw state), can be determined from

$$\frac{V}{\ell} a_{11} \bar{v}_{ref} + Vq_1 a_{12} r_{ref} + \hat{F} + \frac{V^2}{\ell} q_1 b_{11} \bar{\delta}_{ref} = 0$$

$$\frac{V}{\ell^2 q_1} a_{21} \bar{v}_{ref} + \frac{V}{\ell} a_{22} r_{ref} + \hat{M} + \left(\frac{V}{\ell}\right)^2 b_{21} \bar{\delta}_{ref} = 0 \tag{3.9}$$

$$\bar{r}_{ref} = r_{ref}$$

$$\bar{\Psi}_{ref}(t) = \int^{t} r_{ref}\, ds$$

During the initial phase the ship is transferred from the actual state $\hat{x}(t) = (\hat{v}(t), \hat{r}(t), \hat{\Psi}(t), \hat{F}(t), \hat{M}(t))^T$ to the state $x_1 = (\bar{v}_{ref}, \bar{r}_{ref}, \Psi_1, F_1, M_1)^T$, where $\bar{v}_{ref}$ and $\bar{r}_{ref}$ are determined from (3.9). This can be done during two or more sampling intervals, which can be concluded if the continuous, linear ship model (3.1) is transformed to a discrete model (Φ,Γ,Θ). The two rudder angles $\bar{\delta}_{ref}(t)$ and $\bar{\delta}_{ref}(t+1)$ as well as Ψ_1, F_1 and M_1 are determined from

$$x_1 = \Phi(\Phi\hat{x}(t) + \Gamma\,\bar{\delta}_{ref}(t)) + \Gamma\,\bar{\delta}_{ref}(t+1) \tag{3.10}$$

During the third phase the ship is transferred from the actual state $\hat{x}(t) = (\hat{v}(t), \hat{r}(t), \hat{\Psi}(t), \hat{F}(t), \hat{M}(t))^T$, where $\hat{v}(t) \simeq$ $\simeq \bar{v}_{ref}$ and $\hat{r}(t) \simeq \bar{r}_{ref}$, to the state $x_2 = (0, 0, \Psi_{ref}, F_2, M_2)^T$, where Ψ_{ref} is the new demanded course. This is done analogous to the initial phase, but because three elements of the final state vector x_2 are predestinated, at least three sampling intervals are required.

The computations in the yaw regulator require that some matrices are non-singular. If the parameter values (3.2) are put into the model (3.1), it can easily be checked that no problems will arise.

4. COMPUTER PROGRAMS

The computer programs for the experiments are mainly coded as Fortran subroutines. They were installed as an option in the standard real time task STEER, which is executed every second. See fig. 4.1. The subroutine AUTPIL is the administration routine for the experiments and calls other Fortran subroutines.

The subroutine AUTPIL is divided into two different parts. See fig. 4.2. If the parameter IDEXP is not equal to zero, then it is possible to use the program for system identification experiments. If IDEXP is equal to zero, then it is possible to use the autopilot, which is described in chapter 3, for control of the ship. Two versions of subroutine AUTPIL, corresponding to regulator 1 and regulator 2 described in section 3.2 were used. Both versions call the subroutines KALM, YAW and LSEST.

Subroutine KALM is the implementation of the Kalman filter, which is described in section 3.1. Subroutine YAW computes the reference values for the self-tuning regulator during a yaw. (Section 3.3). Subroutine LSEST, finally, performs the least squares identification for the self-tuning regulator.

Listing of all subroutines are given in appendix B.

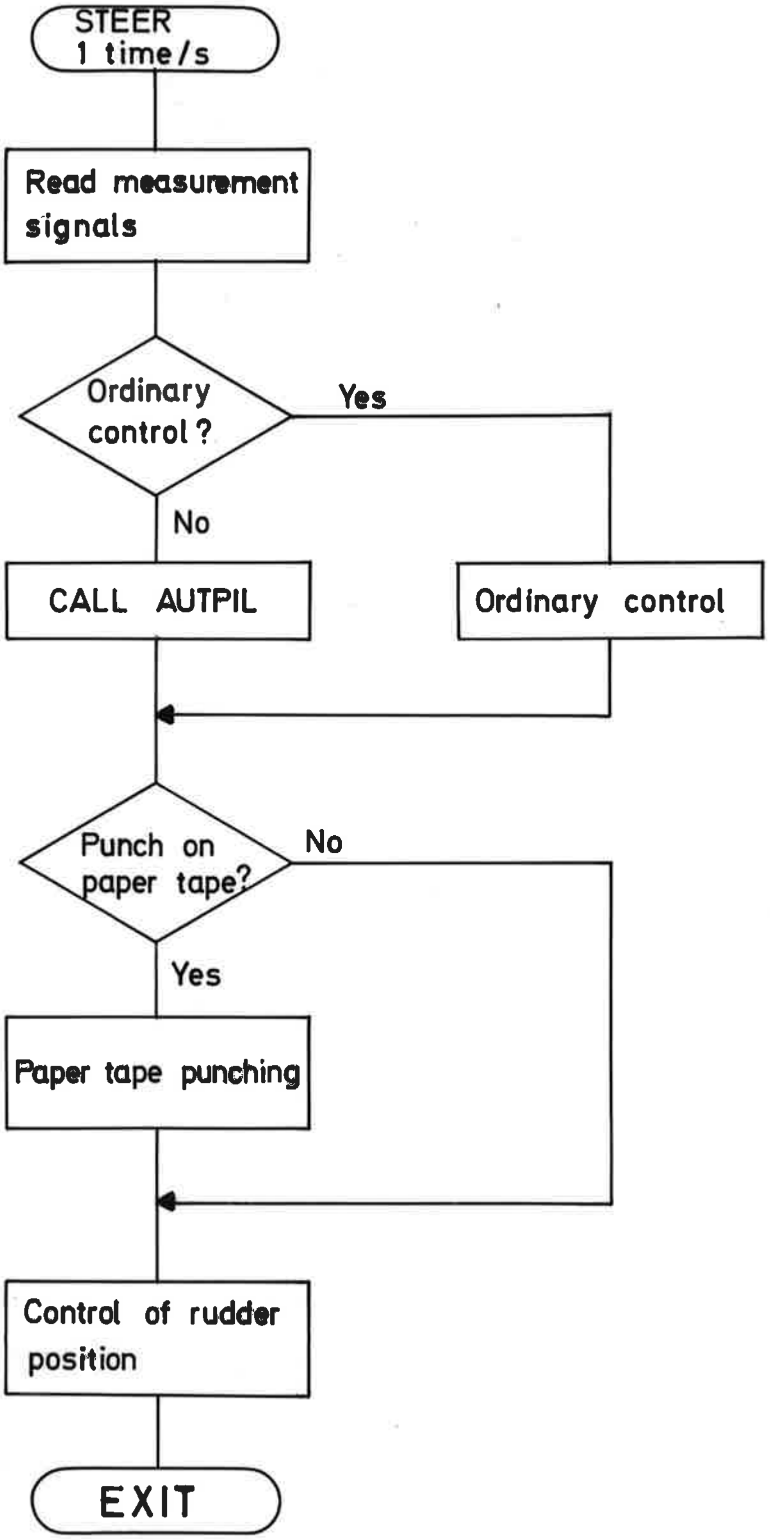

Fig. 4.1. Flow chart of the real time program STEER. The subroutine AUTPIL is the administration routine for the experiments.

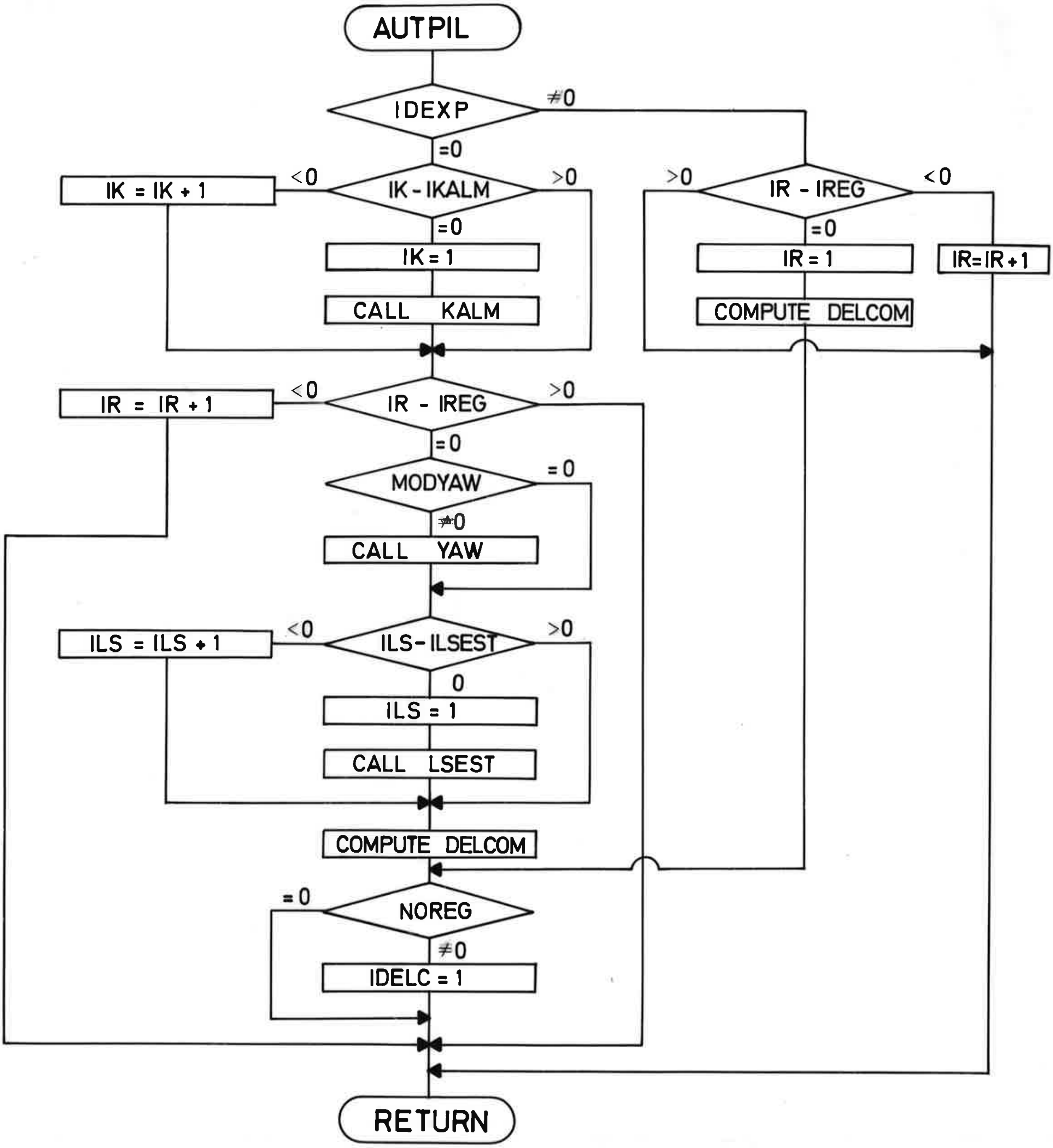

Fig. 4.2. Flow chart of subroutine AUTPIL.

5. EXPERIMENTS

The experiments are described in appendix C, where also plots of all the measurements are shown. A summary of the obtained mean values and standard deviations of the rudder angle δ and the course Ψ for some experiments is given in Table 5.1.

Experiment (all data if no times are given	δ degr		Ψ degr	
	Mean value	Standard deviation	Mean value	Standard deviation
A1	-0.33	1.06	141.905	0.230
A2	-0.67	3.50	142.170	0.440
A3	-0.47	3.48	142.147	0.522
A4	-0.65	1.58	142.040	0.310
A4 (4000-6360 s)	-0.63	1.55	142.053	0.213
A5	-0.49	1.18	141.833	0.829
A5 (5000-9500 s)	-0.42	0.90	141.909	0.222
B1 (0-1500 s)	-0.40	0.70	142.001	0.171
C1	-0.57	0.96	142.018	0.232

Table 5.1. Comparison of the rudder angle δ and the course ψ between different control experiments. The reference course Ψ_{ref} is equal to 142^{o}.

The first three experiments, A1, A2 and A3, show straight course keeping with regulator 1 (see section 3.2) and without Kalman filter, i.e. the only feedforward signals are the cross velocity v and the yaw angular velocity r. From experiment A2 (sampling interval 20 s) and experiment A3 (sampling interval 30 s) it can be concluded that regulator 1 generates too large rudder angles for a satisfactory control of the ship, although the course keeping is rather good. This depends on the quality of regulator 1, which tries to beat the course error after one sampling interval.

Not recorded experiments with regulator 1 showed that suitably small rudder angles were not obtained until the sampling interval was chosen as large as 60 s. The smaller rudder deviations in experiment A1 is due to the fact that the value of parameter b_1 in regulator 1 is fixed to 0.6.

Regulator 2 in combination with the Kalman filter is used in experiment A4. The sampling interval for the filter is 1 s and for the control 20 s. However, the measured course Ψ is put into the regulator instead of the estimated course $\hat{\Psi}$ from the filter. Although the regulator parameters are started from scratch, the control is rather good after 1000 s and quite satisfactory after 4000 s.

Experiment A5 shows straight course keeping with regulator 2 without the Kalman filter. The only feedforward signal is the yaw angular velocity r. The sampling interval is 20 s. The regulator parameters are started from scratch and therefore the control during the first 500 s is very bad. The control is rather good between 500 s and 5000 s and then quite satisfactory. Not recorded experiments with this regulator showed that it is possible to achieve still better control when the regulator parameters were tuned for six hours or more.

The first part of the experiment A6 is a test of yawing with the same regulator as in experiment A5. The reference course for the self-tuning regulator $\bar{\Psi}_{ref}$ is changed instantly. The second part of the experiment is an unsuccessful attempt to perform the same yawing with the yaw regulator. The computed reference values of the rudder angle $\bar{\delta}_{ref}$ are too large, and some modifications of the yaw regulator have to be done.

Experiment B1 shows control with Kockums PID-regulator and yaw regulator. The parameters of the regulator were manually tuned for the actual weather type. The first part of this experiment, the straight course keeping, can be compared with experiments

A1 - A5. The second part, the yawing, can be compared with experiment A6.

The same self-tuning regulator as in experiments A5 and A6 is used in experiment C1. The sampling interval for the control is 20 s, but data is punched every second. This experiment can be compared with the first part of experiment B1 too. The queer appearance of some of the curves is due to the scanning frequency and the discretizing effects (see chapter 2).

Three experiments for system identification, E1, E2 and E3, are finally shown in appendix C.

6. CONCLUSIONS

The experiments have shown that the self-tuning regulator is quite capable to perform a good course keeping of the ship. The weather, however, was fine during the experiments, and nothing can be concluded of the performance in hard weather or when the wind direction suddenly is changed. The water depth and the speed of the ship are other variables which can influence the steering.

The course keeping with the self-tuning regulator was almost as good as the control with an optimally tuned PID-regulator. The advantage of the self-tuning regulator is, of course, that no manual tuning of the parameters has to be done. The structure of the self-tuning regulator is almost the same as the PID-regulator, so course keeping with the self-tuning regulator can not be better than control with an optimally tuned PID-regulator.

Two pure time delays as in regulator 2 and a sampling interval of 20 s seem to be a good combination. When the weather is fine, a larger sampling interval is quite possible. A suitable value of the forgetting factor λ seems to be 0.99-0.995.

Only one experiment with the self-tuning regulator combined with the Kalman filter was performed, so it is not possible to conclude if, and how much, the course keeping can be improved.

The yaw regulator, finally, has to be modified to perform satisfactory yawing.

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 Scout, Mr. S. Nilsson.

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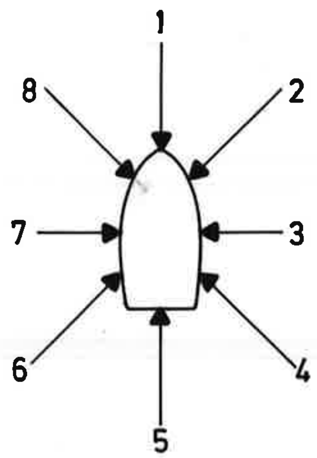
APPENDIX A

NOTATIONS

$a_{11}, a_{12}, a_{21}, a_{22}$	parameters of the linear ship model
b_{11}, b_{21}	parameters of the linear ship model
b_1, b_2	parameters of the self-tuning regulator
d_1, d_2, d_3, d_4	parameters of the self-tuning regulator
e	random variable
F	force per mass unit (m/s^2)
$\hat{F}$	estimate of the force per mass unit (m/s^2)
K	Kalman filter gain
ℓ	ship length (m), ℓ = 329.18 m
ℓ_1	distance from the centre of mass to the forward doppler log transmitter (m), ℓ_1 = 148.7 m
ℓ_2	distance from the centre of mass to the aft doppler log transmitter (m), ℓ_2 = 131.1 m
M	moment per moment of inertia ($degr/s^2$)
$\hat{M}$	estimate of moment per moment of inertia ($degr/s^2$)
n	number of revolutions of propeller (rpm)
P	covariance matrix of regulator parameter errors
q	pitch angular velocity (degr/s)
q_1	conversion factor from degrees to radians, q_1 = 0.017453293
q_2	conversion factor from m/s to knots, q_2 = 3600/1852
r	yaw angular velocity (degr/s)
$\hat{r}$	estimate of yaw angular velocity (degr/s)
r_{ref}	reference value of the yaw angular velocity during yawing (degr/s)
$\bar{r}_{ref}$	by the yaw regulator computed reference value of the yaw angular velocity (degr/s)
t	time (s)
u	forward velocity (knots)

V	speed of the ship (m/s)
v	cross velocity of the centre of mass (m/s)
$\hat{v}$	estimate of cross velocity of the centre of mass (m/s)
$\bar{v}_{ref}$	by the yaw regulator computed reference value of the cross velocity of the centre of mass (m/s)
v_1	cross velocity of bow (knots)
v_2	cross velocity of stern (knots)
$\hat{x}$	state estimate vector in the Kalman filter
Γ	discrete system matrix
δ	rudder angle (degr)
δ_o	by the self-tuning regulator computed rudder angle (degr)
δ_{com}	rudder angle command (degr)
δ_s	rudder servo position (degr)
$\bar{\delta}_{ref}$	by the yaw regulator computed reference value of the rudder angle (degr)
Θ	discrete system matrix
λ	exponential forgetting factor of the self-tuning regulator
Φ	discrete system matrix
Ψ	course (degr)
$\hat{\Psi}$	estimate of course (degr)
Ψ_{ref}	reference value of the course (degr)
$\bar{\Psi}_{ref}$	by the yaw regulator computed reference value of the course (degr)

The wind direction related to the ship is expressed as:



```
      SUBROUTINE AUTPIL
C
C     ADMINISTRATION SUBROUTINE FOR CONTROL
C     OF A SHIP.
C     REGULATOR 1.
C
C     AUTHOR, C.KALLSTROM 1973-09-22.
C
C     SUBROUTINE REQUIRED
C           KALM
C           YAW
C           LSEST
C
      COMMON/DATA/ IDUM1(4),DELTA,Z(4),IDUM2(9),PSIREF,
     1MODYAW,RREF,ISTBD,IPORT,IDELC,DELCOM,X(5),TH(6),
     2REF(4),IFLAG,INAUT,IP,IPRINT,IDEXP,IR,IREG,NOREG,
     3DELAMP,IK,IKALM,NX,NY,XKAL(5),IDUM3(258),AM(5,4),
     4AXKAL(5,5),PSIMAX,PSIRFO,PSIDIF,IYAW,IDUM4(3),RL,RL1,
     5IDUM5(162),ILS,ILSEST,PSIERR,VAL(7),IDUM6(93),S1,
     6IDUM7(9)
C
C     INITIALIZING IF INAUT=1.
C
      IF(INAUT) 20,20,10
   10 INAUT=0
      PSIRFO=PSIREF
      IYAW=0
      RL=RL1
      DO 12 I=1,7
   12 VAL(I)=0.
      REF(1)=0.
      REF(2)=0.
      REF(3)=PSIREF
      REF(4)=0.
C
C     IF IDEXP=1, COMPUTE DELCOM FOR IDENTIFICATION
C     EXPERIMENT.
C
   20 IF(IDEXP) 40,40,22
   22 IF(IR-IREG) 36,24,999
   24 IR=1
      IF(ISTBD+IPORT-1) 34,26,32
   26 IF(ISTBD) 30,30,28
   28 DELCOM=DELAMP
      GO TO 34
   30 DELCOM=-DELAMP
      GO TO 34
   32 DELCOM=0.
   34 ISTBD=0
      IPORT=0
      GO TO 990
C
   36 IR=IR+1
      GO TO 999
C
C     CALL KALM IF IK=IKALM.
C
   40 IF(IK-IKALM) 50,42,60
   42 IK=1
C
      CALL KALM
C
      DO 48 I=1,5
```

```
      S1=0.
      DO 44 J=1,4
44    S1=S1+AM(I,J)*Z(J)
      DO 46 J=1,5
46    S1=S1+AXKAL(I,J)*XKAL(J)
48    X(I)=S1
      GO TO 60
C
50    IK=IK+1
C
C     IF IR=IREG AND MODYAW=1, COMPUTE SET POINT VALUES.
C
60    IF(IR-IREG) 92,62,999
62    IR=1
      IF(MODYAW) 72,72,64
64    S1=PSIREF-PSIRFO
      IF(S1 .LE. -180.) S1=S1+360.
      IF(S1 .GT. 180.) S1=S1-360.
      IF(ABS(S1)-PSIMAX) 68,68,74
68    IF(IYAW) 76,70,76
70    MODYAW=0
72    REF(1)=0.
      REF(2)=0.
      REF(3)=PSIREF
      REF(4)=0.
      GO TO 78
C
74    IYAW=0
C
76    CALL YAW
C
78    PSIRFO=PSIREF
C
C     UPDATE THE LEAST SQUARES ESTIMATES, IF ILS=ILSEST.
C
      PSIERR=X(3)-REF(3)
      IF(PSIERR .LE. -180.) PSIERR=PSIERR+360.
      IF(PSIERR .GT. 180.) PSIERR=PSIERR-360.
C
      IF(ILS-ILSEST) 82,80,84
80    ILS=1
      IF(IDELC+1) 81,84,81
C
81    CALL LSEST
C
      GO TO 84
82    ILS=ILS+1
84    VAL(2)=VAL(1)
      VAL(3)=X(1)-REF(1)
      VAL(4)=X(2)-REF(2)
      VAL(5)=X(4)
      VAL(6)=X(5)
      VAL(7)=PSIERR
      IF(IDELC .EQ. -1) VAL(7)=0.
C
C     COMPUTE NEW CONTROL SIGNAL.
C
      S1=PSIERR
      DO 90 I=2,6
90    S1=S1+TH(I)*VAL(I)
      VAL(1)=-S1/TH(1)
      DELCOM=REF(4)+VAL(1)
      GO TO 990
C
```

```
   92   IR=IR+1
        GO TO 999
C
  990   IF(NOREG) 999,999,992
  992   IDELC=1
C
  999   RETURN
        END
```

```
      SUBROUTINE AUTPIL
C
C     ADMINISTRATION SUBROUTINE FOR CONTROL
C     OF A SHIP.
C     REGULATOR 2.
C
C     AUTHOR, C.KALLSTROM 1973-09-23.
C
C     SUBROUTINE REQUIRED
C           KALM
C           YAW
C           LSEST
C
      DIMENSION VAL1(7),VAL2(7)
C
      COMMON/DATA/ IDUM1(4),DELTA,Z(4),IDUM2(9),PSIREF,
     1MODYAW,RREF,ISTBD,IPORT,IDELC,DELCOM,X(5),TH(6),
     2REF(4),IFLAG,INAUT,IP,IPRINT,IDEXP,IR,IREG,NOREG,
     3DELAMP,IK,IKALM,NX,NY,XKAL(5),IDUM3(258),AM(5,4),
     4AXKAL(5,5),PSIMAX,PSIRFO,PSIDIF,IYAW,IDUM4(3),RL,RL1,
     5IDUM5(162),ILS,ILSEST,PSIERR,VAL(7),IDUM6(93),S1,
     6IDUM7(9)
C
C     INITIALIZING IF INAUT=1.
C
      IF(INAUT) 20,20,10
   10 INAUT=0
      PSIRFO=PSIREF
      IYAW=0
      RL=RL1
      DO 12 I=1,7
      VAL1(I)=0.
      VAL2(I)=0.
   12 VAL(I)=0.
      REFDO=0.
      REF(1)=0.
      REF(2)=0.
      REF(3)=PSIREF
      REF(4)=0.
C
C     IF IDEXP=1, COMPUTE DELCOM FOR IDENTIFICATION
C     EXPERIMENT.
C
   20 IF(IDEXP) 40,40,22
   22 IF(IR-IREG) 36,24,999
   24 IR=1
      IF(ISTBD+IPORT-1) 34,26,32
   26 IF(ISTBD) 30,30,28
   28 DELCOM=DELAMP
      GO TO 34
   30 DELCOM=-DELAMP
      GO TO 34
   32 DELCOM=0.
   34 ISTBD=0
      IPORT=0
      GO TO 990
C
   36 IR=IR+1
      GO TO 999
C
C     CALL KALM IF IK=IKALM.
C
   40 IF(IK-IKALM) 50,42,60
```

```
42      IK=1
C
        CALL KALM
C
        DO 48 I=1,5
        S1=0.
        DO 44 J=1,4
44      S1=S1+AM(I,J)*Z(J)
        DO 46 J=1,5
46      S1=S1+AXKAL(I,J)*XKAL(J)
48      X(I)=S1
        GO TO 60
C
50      IK=IK+1
C
C       IF IR=IREG AND MODYAW=1, COMPUTE SET POINT VALUES.
C
60      IF(IR-IREG) 92,62,999
62      IR=1
        IF(MODYAW) 72,72,64
64      S1=PSIREF-PSIRFO
        IF(S1 .LE. -180.) S1=S1+360.
        IF(S1 .GT. 180.) S1=S1-360.
        IF(ABS(S1)-PSIMAX) 68,68,74
68      IF(IYAW) 76,70,76
70      MODYAW=0
72      REF(1)=0.
        REF(2)=0.
        REF(3)=PSIREF
        REF(4)=0.
        GO TO 78
C
74      IYAW=0
C
76      CALL YAW
C
78      PSIRFO=PSIREF
C
C       UPDATE THE LEAST SQUARES ESTIMATES, IF ILS=ILSEST.
C
        PSIERR=X(3)-REF(3)
        IF(PSIERR .LE. -180.) PSIERR=PSIERR+360.
        IF(PSIERR .GT. 180.) PSIERR=PSIERR-360.
C
        IF(ILS-ILSEST) 82,80,84
80      ILS=1
C
81      CALL LSEST
C
        GO TO 84
82      ILS=ILS+1
84      DO 100 I=1,7
        VAL(I)=VAL2(I)
100     VAL2(I)=VAL1(I)
        VAL2(1)=DELTA-REFDO
        VAL1(2)=VAL2(1)
        VAL1(3)=X(1)-REF(1)
        VAL1(4)=X(2)-REF(2)
        VAL1(5)=X(4)
        VAL1(6)=X(5)
        VAL1(7)=PSIERR
C
C       COMPUTE NEW CONTROL SIGNAL.
C
```

```
      S1=PSIERR
      DO 90 I=2,6
   90 S1=S1+TH(I)*VAL1(I)
      VAL1(1)=-S1/TH(1)
      DELCOM=REF(4)+VAL1(1)
      REFDO=REF(4)
      GO TO 990
C
   92 IR=IR+1
      GO TO 999
C
  990 IF(NOREG) 999,999,992
  992 IDELC=1
C
  999 RETURN
      END
```

```
      SUBROUTINE KALM
C
C     SUBROUTINE TO COMPUTE THE STATE ESTIMATE
C     X(T/T)=X(T/T-1)+AK*EPS
C     WHERE
C     X(T/T-1)=FIKAL*X(T-1/T-1)+GAMKAL*DELTA(T-1)
C     EPS=EKAL*Z(T)-CKAL*X(T/T-1).
C
C     AUTHOR, C.KALLSTROM 1973-09-13.
C
C     SUBROUTINE REQUIRED
C           NONE
C
      COMMON/DATA/ IDUM1(4),DELTA,Z(4),IDUM2(80),NX,NY,XKAL(5),
     1FIKAL(5,5),GAMKAL(5),CKAL(4,5),EKAL(4,4),AK(5,4),IDUM3(405),
     2SL(5),X1(5),S1,IDUM4(9)
C
C     COMPUTE X(T/T-1)=FIKAL*X(T-1/T-1)+GAMKAL*DELTA(T-1)
C     AND STORE THE RESULT IN X1.
C
      DO 12 I=1,NX
      S1=GAMKAL(I)*DELTA
      DO 10 J=1,NX
   10 S1=S1+FIKAL(I,J)*XKAL(J)
   12 X1(I)=S1
C
C     COMPUTE EPS=EKAL*Z-CKAL*X(T/T-1) AND STORE
C     THE RESULT IN SL.
C
      DO 24 I=1,NY
      S1=0.
      DO 20 J=1,4
   20 S1=S1+EKAL(I,J)*Z(J)
      DO 22 J=1,NX
   22 S1=S1-CKAL(I,J)*X1(J)
   24 SL(I)=S1
C
      IF(SL(NY) .LE. -180.) SL(NY)=SL(NY)+360.
      IF(SL(NY) .GT. 180.) SL(NY)=SL(NY)-360.
C
C     COMPUTE X(T/T)=X(T/T-1)+AK*EPS AND STORE
C     THE RESULT IN XKAL.
C
      DO 32 I=1,NX
      S1=X1(I)
      DO 30 J=1,NY
   30 S1=S1+AK(I,J)*SL(J)
   32 XKAL(I)=S1
C
      IF(XKAL(3) .LT. 0.) XKAL(3)=XKAL(3)+360.
      IF(XKAL(3) .GE. 360.) XKAL(3)=XKAL(3)-360.
C
      RETURN
      END
```

```
      SUBROUTINE YAW
C
C     SUBROUTINE TO GENERATE SET POINT VALUES
C     DURING YAW.
C
C     AUTHOR, C.KALLSTROM 1973-09-21.
C
C     SUBROUTINE REQUIRED
C          NONE
C
      COMMON/DATA/ IDUM1(28),PSIREF,MODYAW,RREF,IDUM2(6),
     1X(5),TH(6),REF(4),IDUM3(6),IREG,IDUM4(422),PSIDIF,
     2IYAW,KYAW,KKYAW,LYAW,RL,RL1,RL2,RNOM,VNOM,DELNOM,
     3AYAW(2,3),CYAW,FIYAW(5,5),GAMYAW(5),REFN(4),REFNN(4),
     4X2(5),IDUM5(89),SL(5),X1(5),S1,S2,S3,S4
C
C     COMPUTE PSIDIF=PSIREF-PSI.
C
      PSIDIF=PSIREF-X(3)
      IF(PSIDIF .LE. -180.) PSIDIF=PSIDIF+360.
      IF(PSIDIF .GT. 180.) PSIDIF=PSIDIF-360.
C
C     INITIALIZE IF IYAW=0.
C
      IF(IYAW) 20,10,90
   10 IYAW=-1
      KKYAW=KYAW
      IF(PSIDIF .GE. 0.) RNOM=RREF
      IF(PSIDIF .LT. 0.) RNOM=-RREF
C
      RL=RL2
C
      VNOM=AYAW(1,1)*RNOM+AYAW(1,2)*X(4)+AYAW(1,3)*X(5)
      DELNOM=AYAW(2,1)*RNOM+AYAW(2,2)*X(4)+AYAW(2,3)*X(5)
C
C     TEST IF THE YAW IS TO BE TERMINATED.
C
   20 IF(PSIDIF-FLOAT(3*IREG*KYAW)*CYAW*RNOM) 22,22,24
   22 IF(RNOM) 30,80,80
   24 IF(RNOM)80,80,30
C
C     IF IYAW=-3, JUMP TO THE STATIONARY PHASE.
C
   30 IF(IYAW+2) 70,60,40
C
C     THE INITIAL PHASE.
C
   40 DO 46 I=1,5
      S1=0.
      DO 44 J=1,5
   44 S1=S1+FIYAW(I,J)*X(J)
   46 SL(I)=S1
C
      S1=VNOM
      S2=RNOM
      DO 48 J=1,5
      S1=S1-FIYAW(1,J)*SL(J)
   48 S2=S2-FIYAW(2,J)*SL(J)
C
      S3=0.
      S4=0.
      DO 50 J=1,5
      S3=S3+FIYAW(1,J)*GAMYAW(J)
```

```
50    S4=S4+FIYAW(2,J)*GAMYAW(J)
C
      SL(1)=S3*GAMYAW(2)-S4*GAMYAW(1)
      REF(4)=(S1*GAMYAW(2)-S2*GAMYAW(1))/SL(1)
      REFN(4)=(-S4*S1+S2*S3)/SL(1)
C
      REF(1)=X(1)
      REF(2)=X(2)
      REF(3)=X(3)
C
      DO 54 I=1,5
      S1=GAMYAW(I)*REF(4)
      DO 52 J=1,5
52    S1=S1+FIYAW(I,J)*X(J)
54    SL(I)=S1
C
      REFN(1)=SL(1)
      REFN(2)=SL(2)
      REFN(3)=SL(3)
C
      DO 58 I=1,5
      S1=GAMYAW(I)*REFN(4)
      DO 56 J=1,5
56    S1=S1+FIYAW(I,J)*SL(J)
58    X2(I)=S1
C
      IYAW=-2
      GO TO 999
C
60    DO 62 I=1,4
62    REF(I)=REFN(I)
C
      IYAW=-3
      GO TO 999
C
C     THE STATIONARY PHASE.
C
70    REF(1)=VNOM
      REF(2)=RNOM
      REF(3)=X2(3)
      REF(4)=DELNOM
C
      DO 74 I=1,5
      S1=GAMYAW(I)*DELNOM
      DO 72 J=1,5
72    S1=S1+FIYAW(I,J)*X2(J)
74    SL(I)=S1
C
      DO 76 I=1,5
76    X2(I)=SL(I)
C
      IF(X2(3) .LT. 0.) X2(3)=X2(3)+360.
      IF(X2(3) .GE. 360.) X2(3)=X2(3)-360.
C
      GO TO 999
C
C     THE TERMINATING PHASE.
C
80    IF(IYAW+3) 82,82,84
82    IF(PSIDIF*RNOM) 84,84,86
84    KKYAW=1
C
86    IYAW=1
      LYAW=1
```

```
            GO TO 102
C
90          IF(IYAW-2) 100,140,150
C
100         IF(PSIDIF*RNOM) 84,84,102
C
102         IF(LYAW-KKYAW) 104,103,103
C
103         S1=0.
            S2=0.
            S3=PSIREF
            GO TO 106
104         S4=FLOAT(KKYAW-LYAW)/FLOAT(KKYAW)
            S1=X(1)*S4
            S2=X(2)*S4
            S4=1.-0.5/FLOAT(KKYAW-LYAW+1)
            S3=X(3)+X(2)*FLOAT(3*IREG)*S4
C
106         DO 110 I=1,5
            S4=0.
            DO 108 J=1,5
108         S4=S4+FIYAW(I,J)*X(J)
110         SL(I)=S4
            DO 114 I=1,5
            S4=0.
            DO 112 J=1,5
112         S4=S4+FIYAW(I,J)*SL(J)
114         X1(I)=S4
            DO 116 J=1,5
            S1=S1-FIYAW(1,J)*X1(J)
            S2=S2-FIYAW(2,J)*X1(J)
116         S3=S3-FIYAW(3,J)*X1(J)
C
            IF(S3 .LE. -180.) S3=S3+360.
            IF(S3 .GT. 180.) S3=S3-360.
C
            DO 120 I=1,5
            S4=0.
            DO 118 J=1,5
118         S4=S4+FIYAW(I,J)*GAMYAW(J)
120         SL(I)=S4
            DO 124 I=1,3
            S4=0.
            DO 122 J=1,5
122         S4=S4+FIYAW(I,J)*SL(J)
124         X1(I)=S4
C
             S4=X1(1)*SL(2)*GAMYAW(3)+X1(2)*SL(3)*GAMYAW(1)+
           1X1(3)*SL(1)*GAMYAW(2)-GAMYAW(1)*SL(2)*X1(3)-
           2GAMYAW(2)*SL(3)*X1(1)-GAMYAW(3)*SL(1)*X1(2)
C
             REF(4)=(S1*SL(2)*GAMYAW(3)+S2*SL(3)*GAMYAW(1)+
           1S3*SL(1)*GAMYAW(2)-GAMYAW(1)*SL(2)*S3-
           2GAMYAW(2)*SL(3)*S1-GAMYAW(3)*SL(1)*S2)/S4
C
             REFN(4)=(X1(1)*S2*GAMYAW(3)+X1(2)*S3*GAMYAW(1)+
           1X1(3)*S1*GAMYAW(2)-GAMYAW(1)*S2*X1(3)-
           2GAMYAW(2)*S3*X1(1)-GAMYAW(3)*S1*X1(2))/S4
C
             REFNN(4)=(X1(1)*SL(2)*S3+X1(2)*SL(3)*S1+
           1X1(3)*SL(1)*S2-S1*SL(2)*X1(3)-
           2S2*SL(3)*X1(1)-S3*SL(1)*X1(2))/S4
C
             REF(1)=X(1)
```

```
            REF(2)=X(2)
            REF(3)=X(3)
      C
            DO 128 I=1,5
            S1=GAMYAW(I)*REF(4)
            DO 126 J=1,5
      126   S1=S1+FIYAW(I,J)*X(J)
      128   X1(I)=S1
      C
            REFN(1)=X1(1)
            REFN(2)=X1(2)
            REFN(3)=X1(3)
      C
            DO 132 I=1,3
            S1=GAMYAW(I)*REFN(4)
            DO 130 J=1,5
      130   S1=S1+FIYAW(I,J)*X1(J)
      132   REFNN(I)=S1
      C
            IYAW=2
            GO TO 999
      C
      140   DO 142 I=1,4
      142   REF(I)=REFN(I)
            IYAW=3
            GO TO 999
      C
      150   DO 152 I=1,4
      152   REF(I)=REFNN(I)
      C
            IF(LYAW-KKYAW) 154,156,156
      154   LYAW=LYAW+1
            IYAW=1
            GO TO 999
      C
      156   IYAW=0
            MODYAW=0
            RL=RL1
      C
      999   IF(REF(3) .LT. 0.) REF(3)=REF(3)+360.
            IF(REF(3) .GE. 360.) REF(3)=REF(3)-360.
            RETURN
            END
```

```
      SUBROUTINE LSEST
C
C     LEAST SQUARES IDENTIFICATION OF THE PARAMETERS
C     TH(1),...,TH(6) IN THE MODEL
C        PSI(T)-PSIREF(T)=PSI(T-1)-PSIREF(T-1)+
C        TH(1)*DELTA(T-1)+TH(2)*DELTA(T-2)+
C        TH(3)*(V(T-1)-VREF(T-1))+TH(4)*(R(T-1)-RREF(T-1))+
C        TH(5)*F(I-1)+TH(6)*M(T-1)+E(T).
C
C     AUTHOR, C.KALLSTROM 1973-09-20.
C
C     SUBROUTINE REQUIRED
C           NONE
C
      COMMON/DATA/ IDUM1(56),TH(6),IDUM2(448),RL,IDUM3(167),
     1PSIERR,VAL(7),COV(21),SL(10),S1,S2,S3,S4
C
      S1=PSIERR-VAL(7)
      DO 10 I=1,6
10    S1=S1-TH(I)*VAL(I)
C
      DO 22 I=1,6
      S2=0.
      DO 20 J=1,6
      L=I*(I-1)/2+J
      IF(J .GT. I) L=J*(J-1)/2+I
20    S2=S2+COV(L)*VAL(J)
22    SL(I)=S2
C
      S2=1.
      DO 30 I=1,6
30    S2=S2+VAL(I)*SL(I)
C
      DO 40 I=1,6
40    TH(I)=TH(I)+SL(I)*S1/S2
C
      DO 50 I=1,6
      DO 50 J=1,I
      L=I*(I-1)/2+J
50    COV(L)=(COV(L)-SL(I)*SL(J)/S2)/RL
C
      RETURN
      END
```

APPENDIX C

Experiment A1

Date: 73 - 10 - 13
Time: 21^{05} - 22^{25}
Position: N 02° W 11°

Wind direction: 2 (see appendix A)

Wind speed: 2 - 3 Beaufort (2 - 6 m/s, light to gentle breeze)

Wave height: 1 - 2 m

Regulator 1
No Kalman filter
No yaw
Calibration of the rudder servo:
10 volts = 36.9°
-10 volts = -43.1°

Model in the regulator:

$$(\Psi(+1) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = 0.6\ \delta(t) + b_2\delta(t-1) + d_1v(t) + $$
$$+ d_2r(t) + e(t+1)$$

$$v(t) = v_2(t)/q_2 + q_1\ell_2r(t)$$

Regulator:

$$\delta(t) = -\frac{1}{0.6}\left[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_1v(t) + d_2r(t)\right]$$

Sampling interval: 20 s
Forgetting factor λ: 0.99
Rudder limits: $\pm 3^{\circ}$
$\Psi_{ref} = 142^{\circ}$

Initial values:

$$\begin{bmatrix} b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1283 \\ -1.6632 \\ 45.6731 \end{bmatrix} \qquad P = \begin{bmatrix} 0.005976 & & \\ -0.04553 & 1.447 & \\ -0.1061 & -0.5359 & 30.97 \end{bmatrix}$$

Regulator:

$$\delta(t) = -1.6667(\Psi(t) - \Psi_{ref}) - 0.2138\ \delta(t-1) + 2.7720\ v(t) - 76.1218\ r(t)$$

Final values:

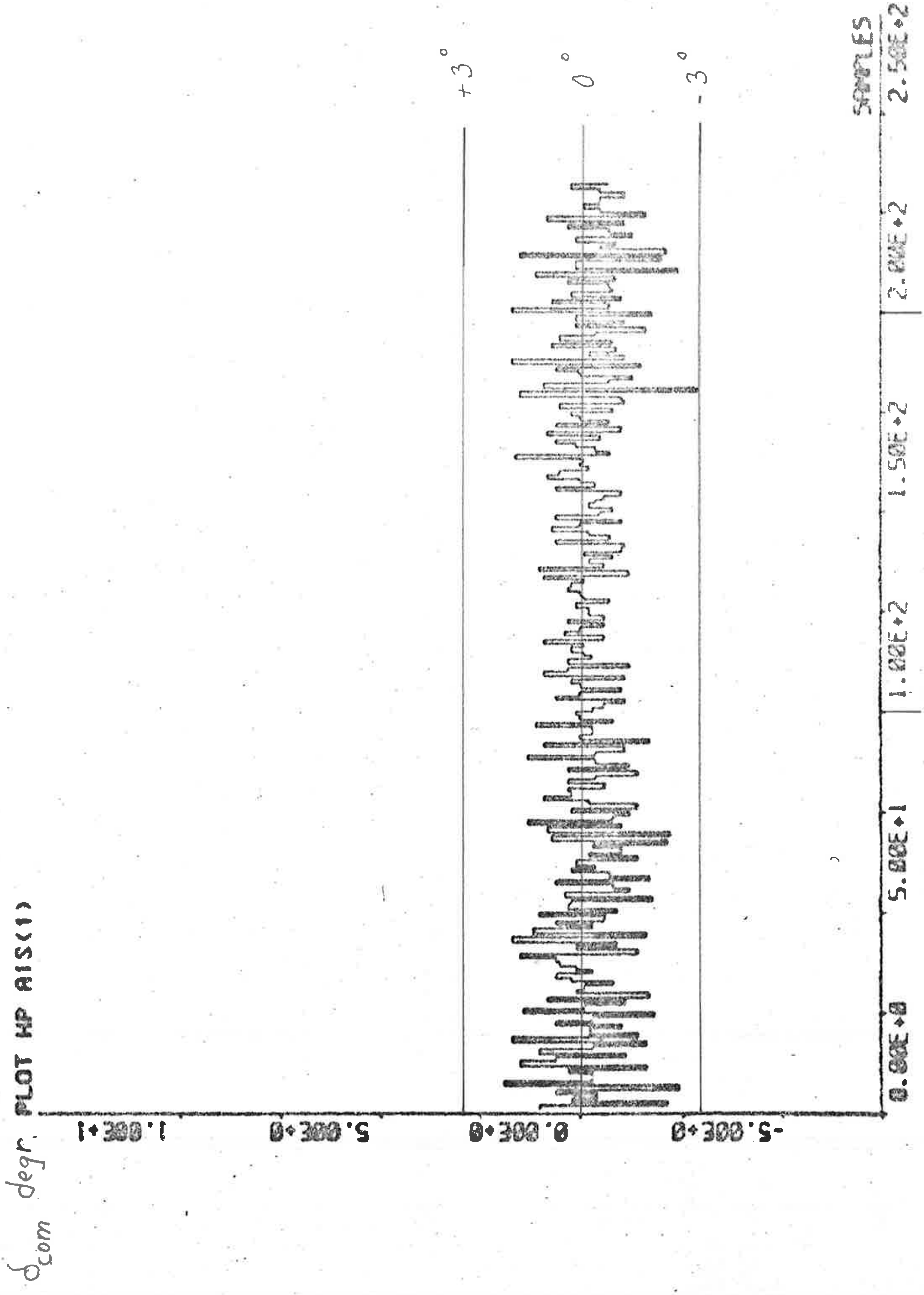
$$\begin{bmatrix} b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1459 \\ -0.7773 \\ 41.0180 \end{bmatrix} \qquad P = \begin{bmatrix} 0.01705 & & \\ -0.08942 & 2.249 & \\ -0.2811 & 0.6094 & 51.10 \end{bmatrix}$$

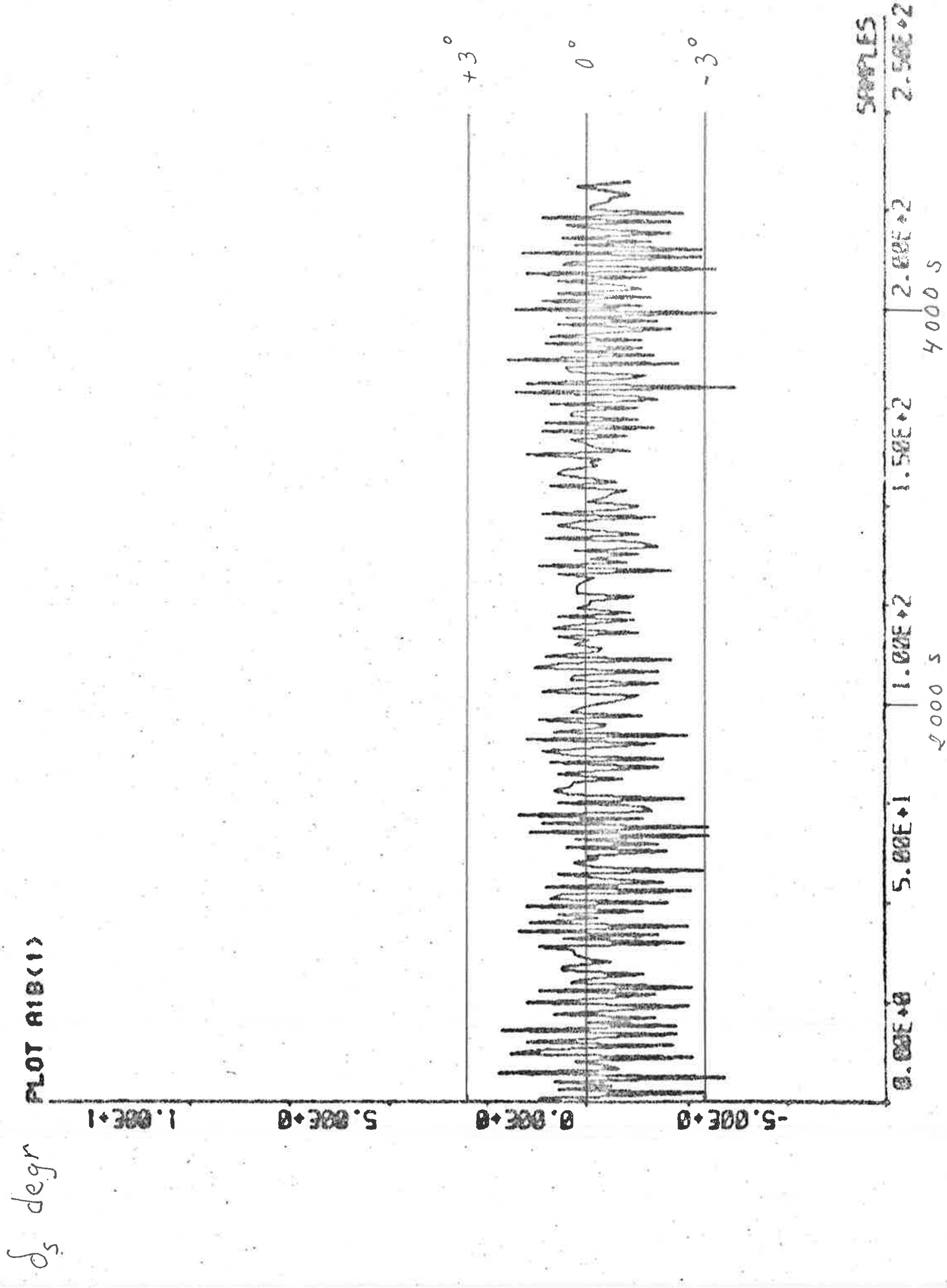
Regulator:

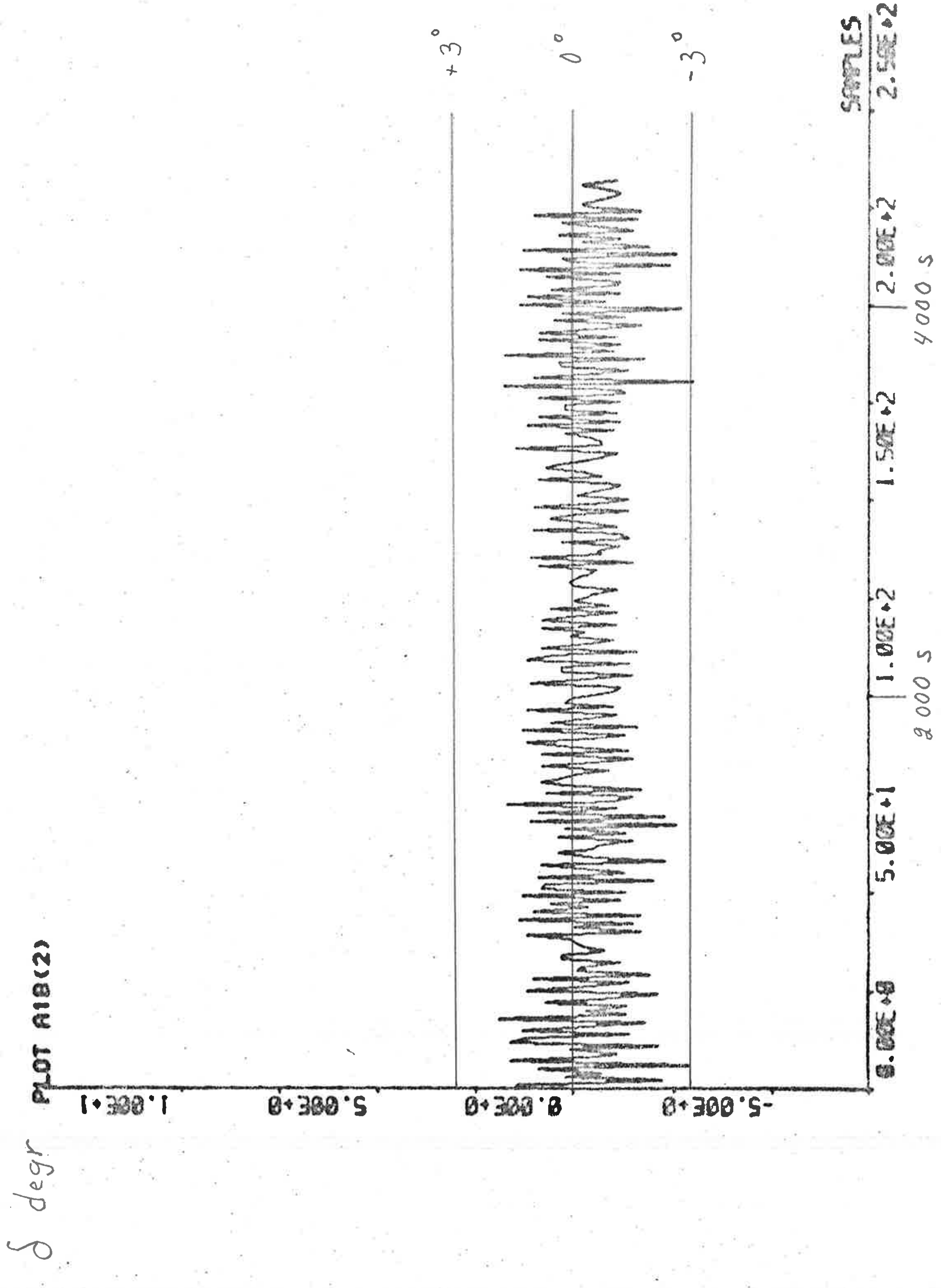
$$\delta(t) = -1.6667(\Psi(t) - \Psi_{ref}) - 0.2432\ \delta(t-1) + 1.2955\ v(t) - 68.3633\ r(t)$$

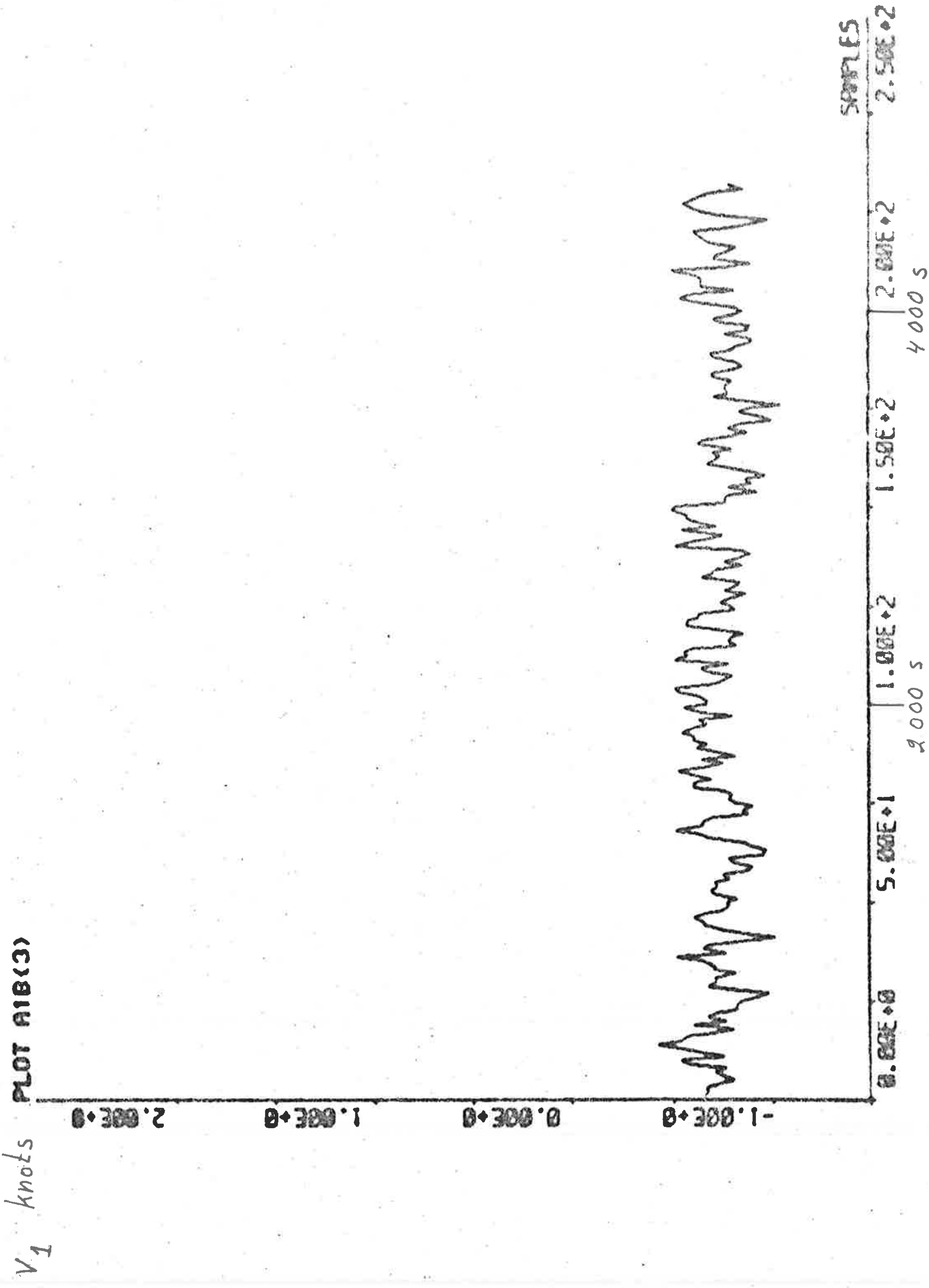
Statistics:

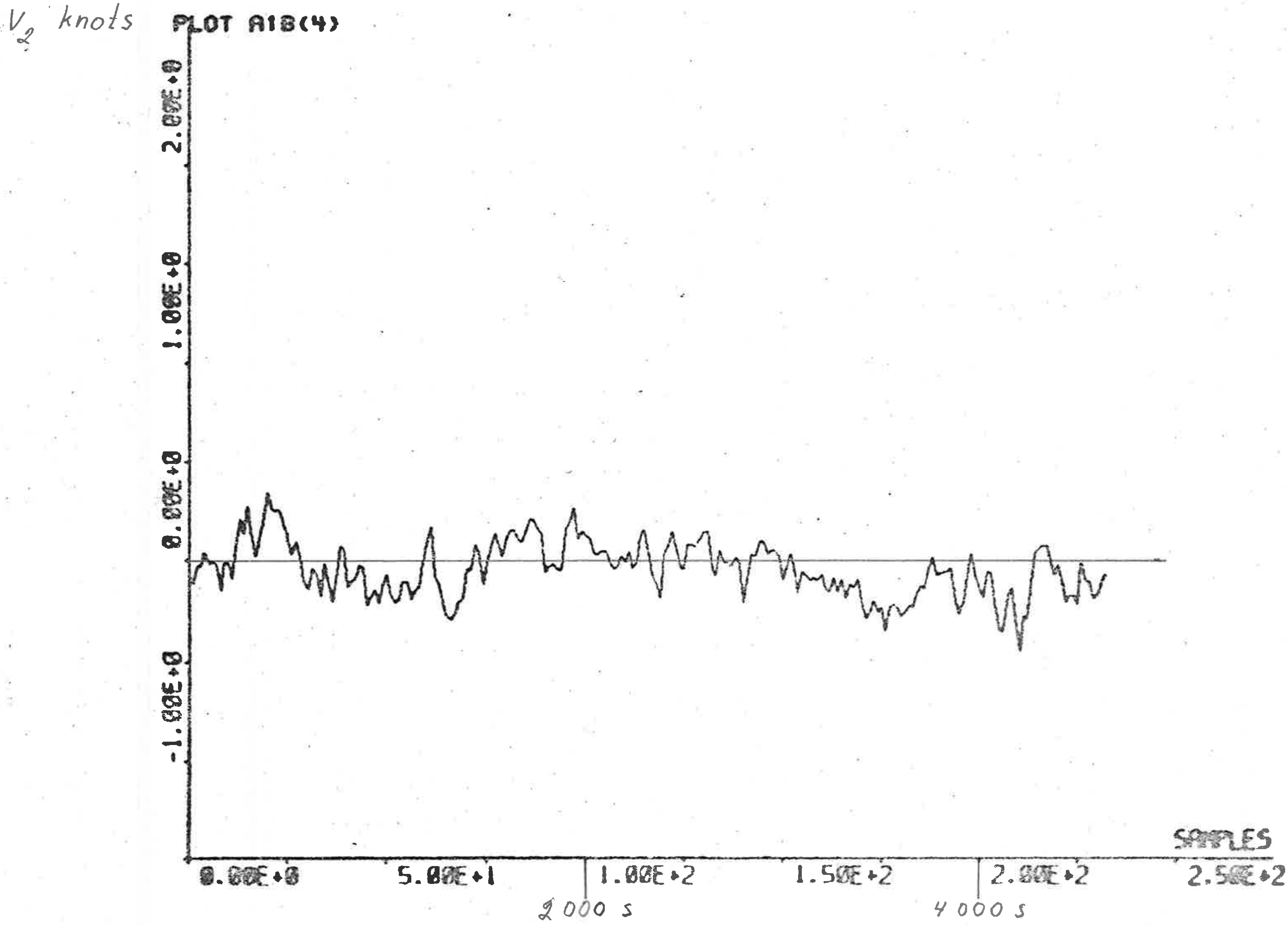
		Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-0.24	0.90	-2.9	1.9
δ_s	degr	-0.35	1.29	-3.7	2.2
δ	degr	-0.33	1.06	-3.0	1.9
v_1	knots	-0.729	0.117	-1.05	-0.43
v_2	knots	-0.049	0.138	-0.45	0.34
r	degr/s	0.0072	0.0106	-0.027	0.049
Ψ	degr	141.905	0.230	141.33	142.47
u	knots	16.532	0.130	16.13	16.90
v	m/s	-0.009	0.074	-0.19	0.18

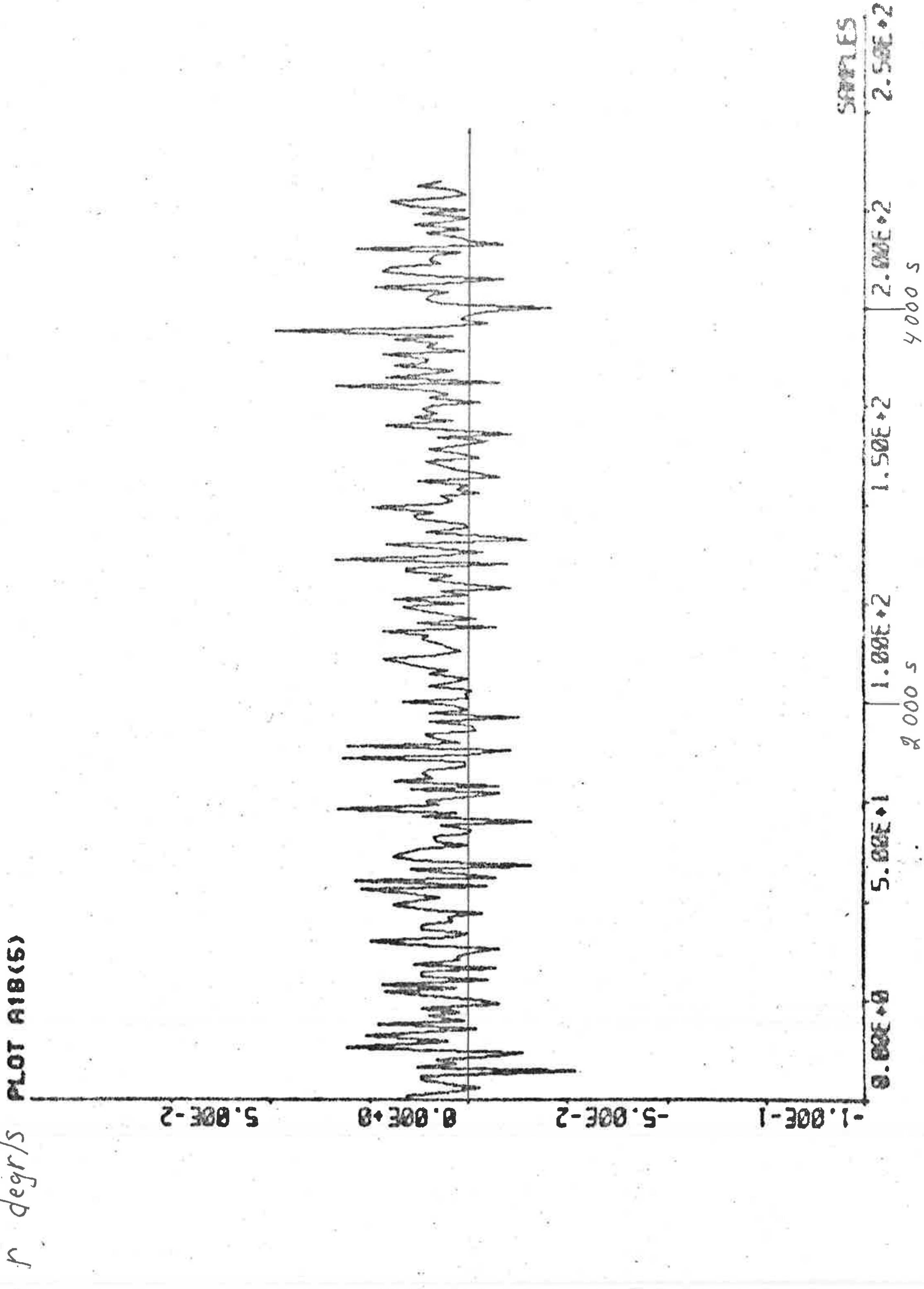

PLOT HP AIS(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δcom degr.

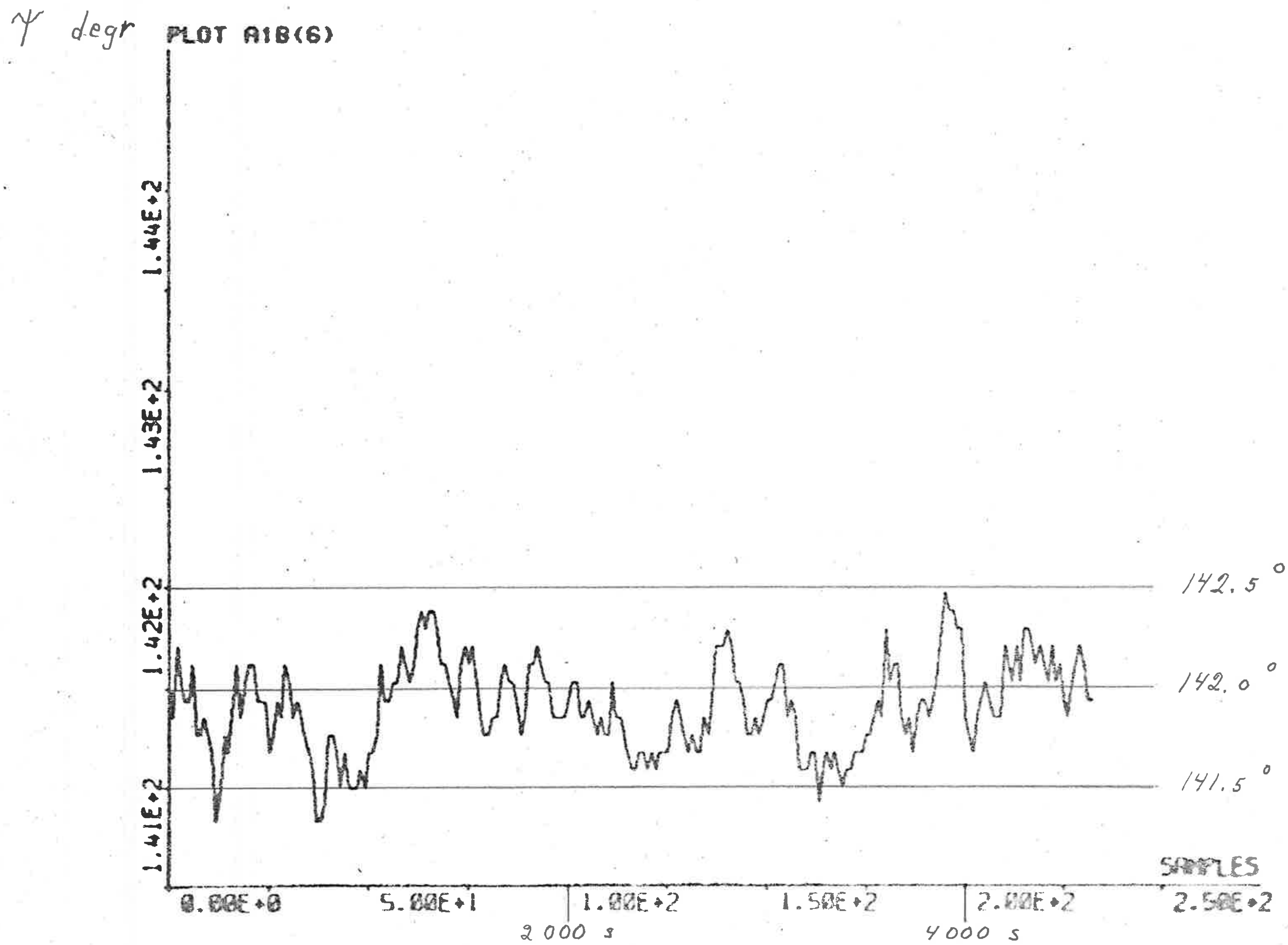

PLOT A1B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δs degr

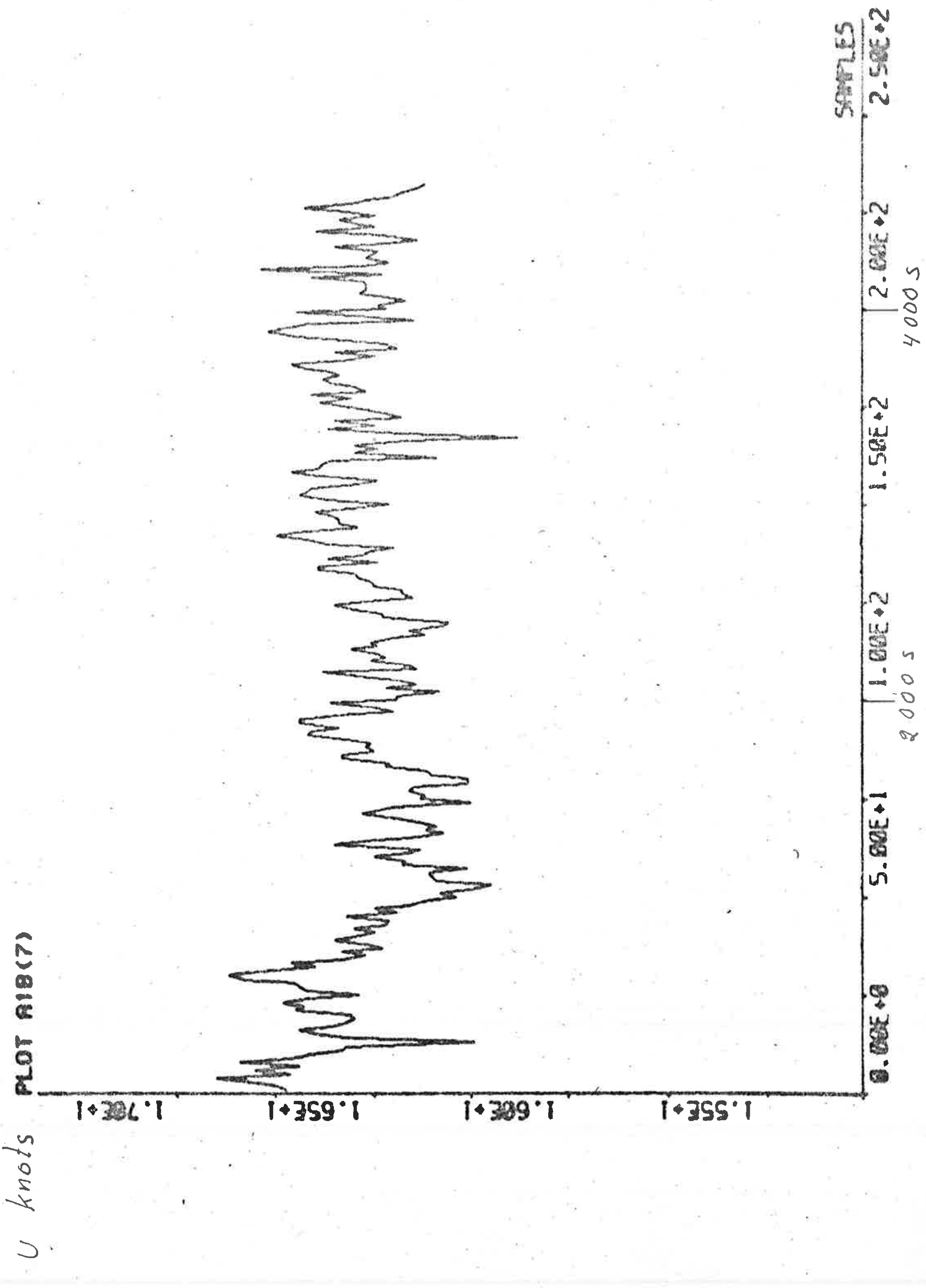

PLOT A1B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr
+3°
0°
-3°
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s

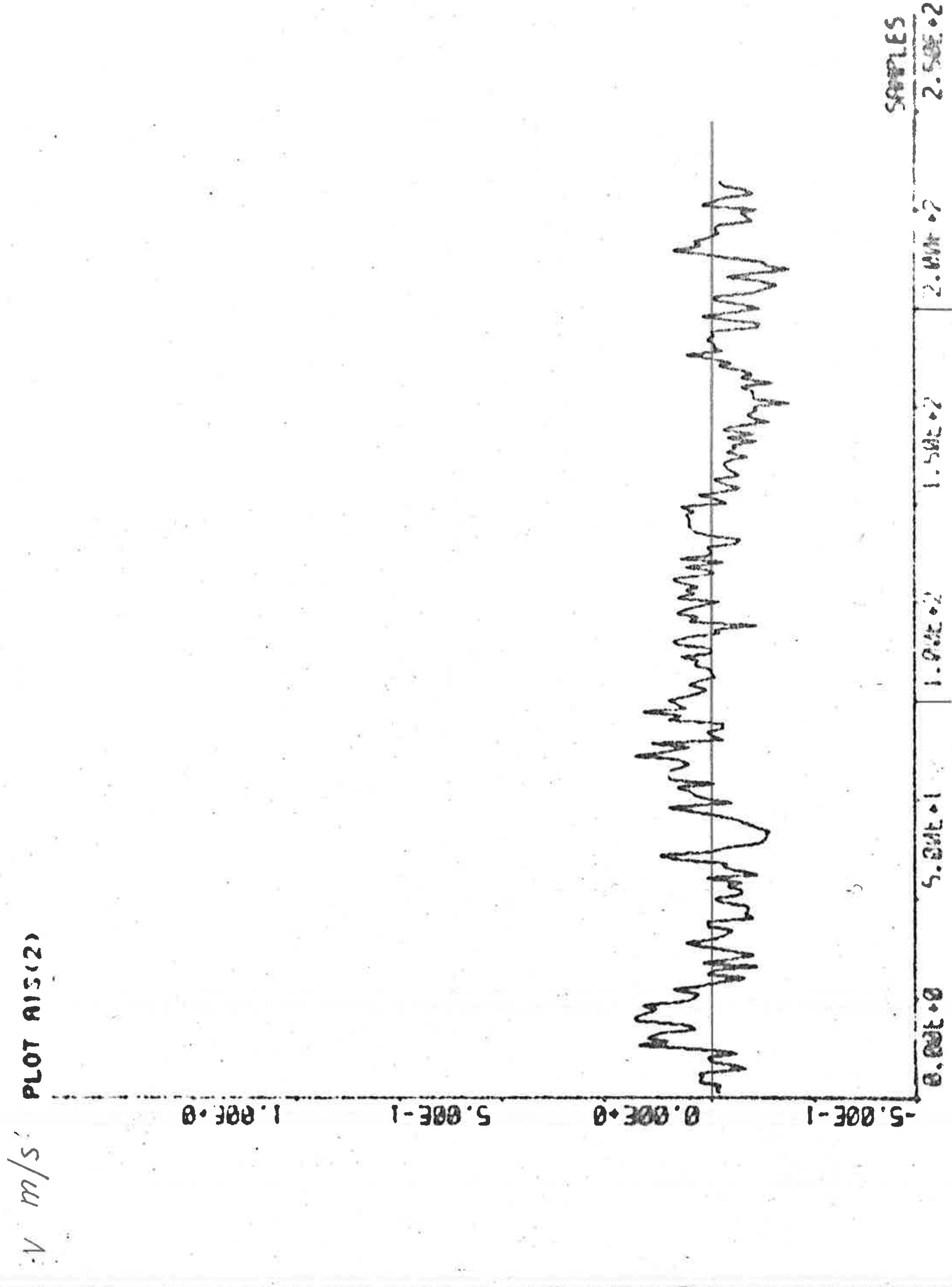

PLOT A1B(3)
V_1 knots
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s

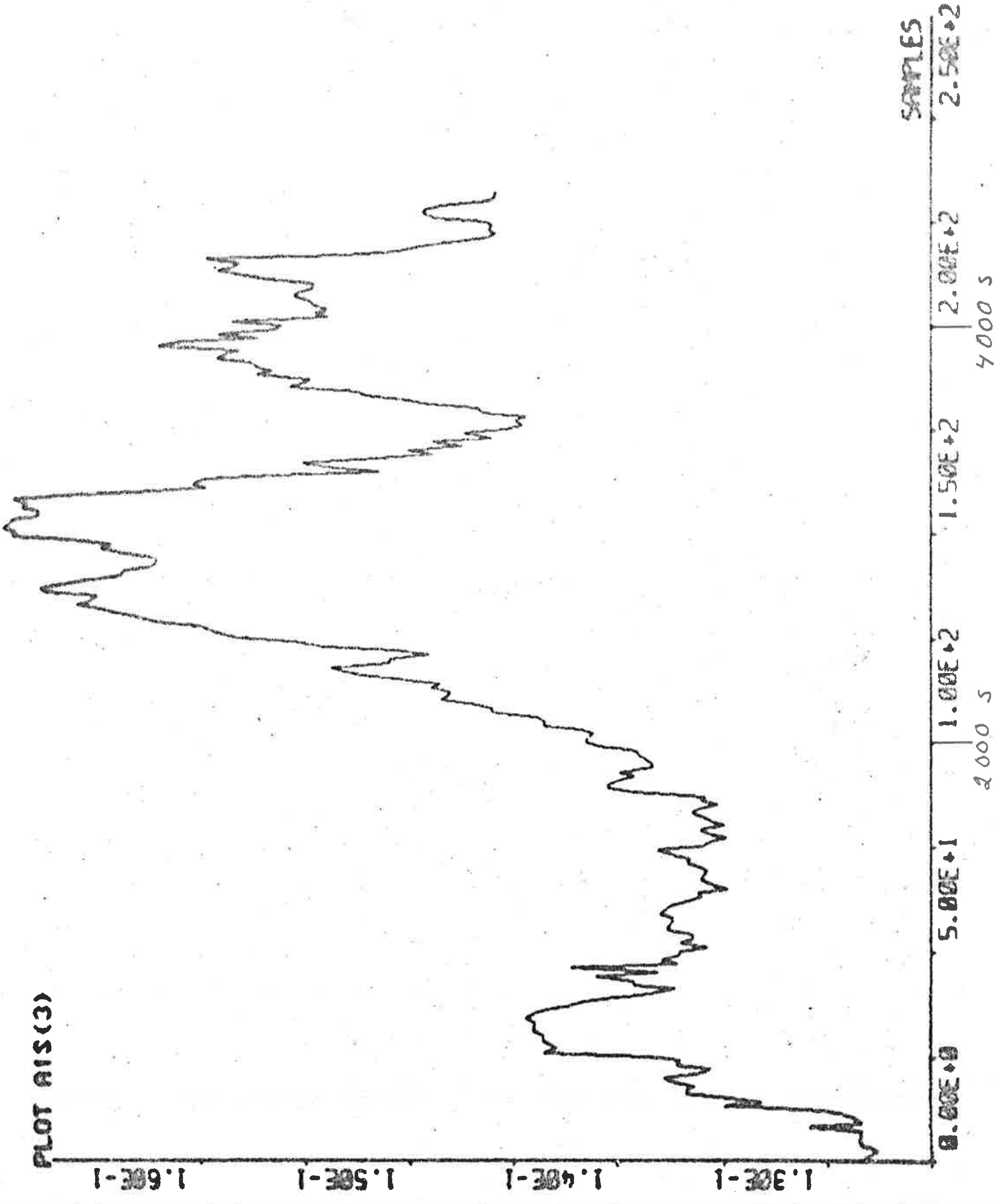

V2 knots
PLOT A18(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s


PLOT A1B(S)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s

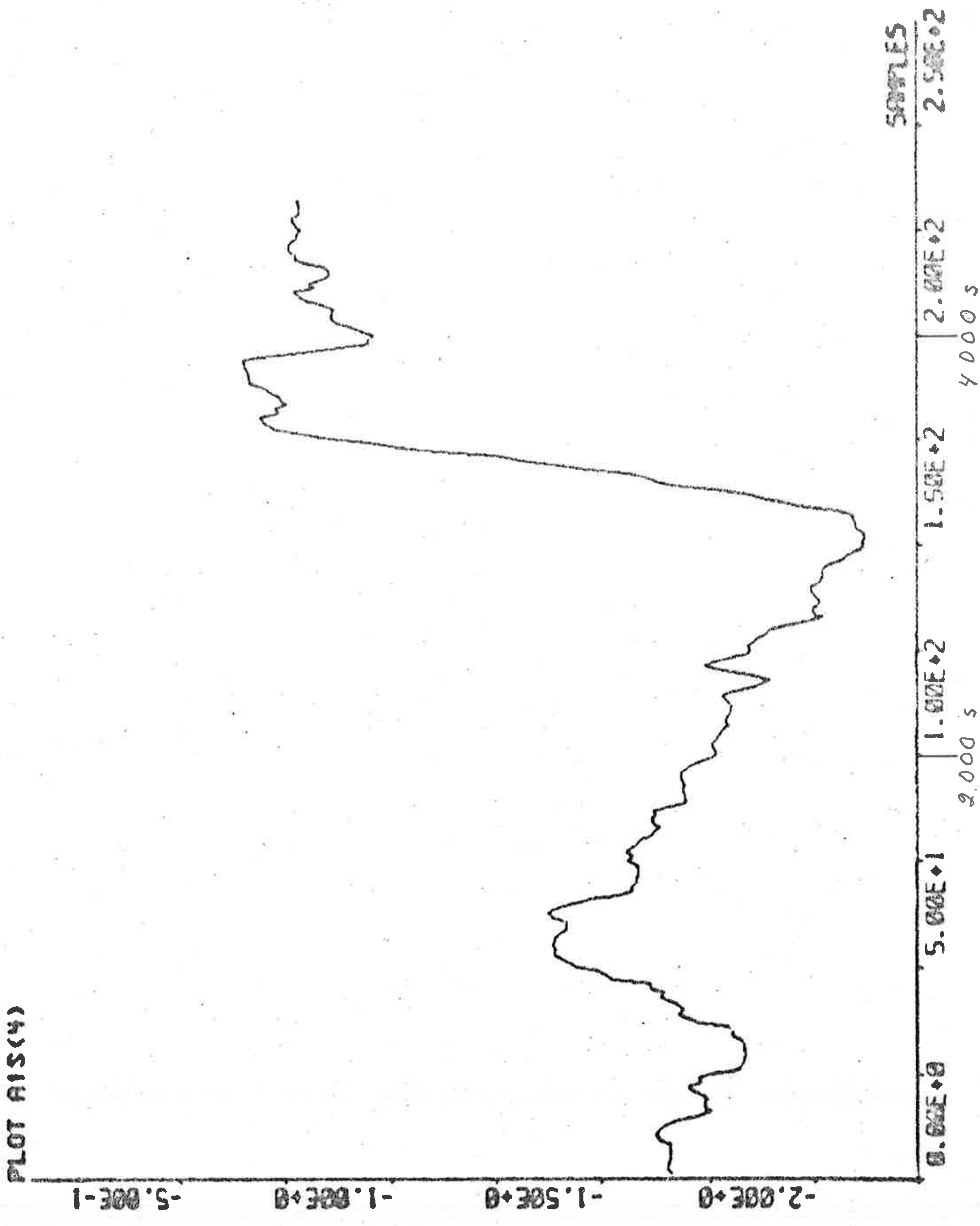

ψ degr
PLOT A1B(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
142.5°
142.0°
141.5°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s


PLOT A18(7)
1.70E+1
1.65E+1
1.60E+1
1.55E+1
U knots
0.00E+0
5.00E+1
1.00E+2
2000 s
1.50E+2
2.00E+2
4000 s
2.50E+2
SAMPLES

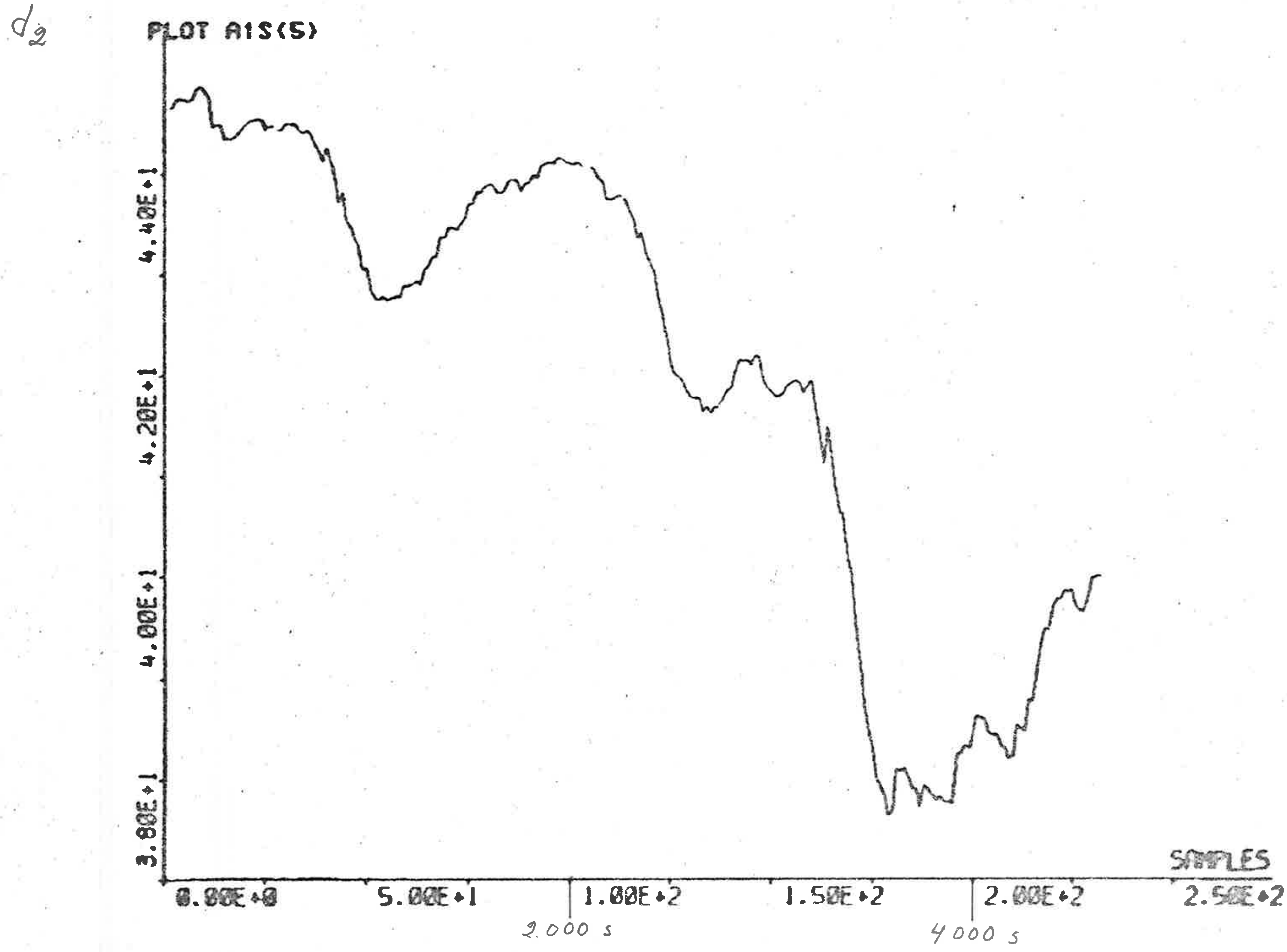

PLOT A15(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
SAMPLES
2.50E+2
2000 s
4000 s
V m/s


PLOT AIS(3)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
1.30E-1
1.40E-1
1.50E-1
1.60E-1

b2


PLOT AIS(4)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
-5.00E-1
-1.00E+0
-1.50E+0
-2.00E+0

d_1


d2
PLOT A1S(5)
4.40E+1
4.20E+1
4.00E+1
3.80E+1
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

Experiment A2.

Date: 73 - 10 - 14
Time: 21^{22} - 22^{27}
Position: S 03° W 06°

Wind direction: 2 (see appendix A)
Wind speed: 3 Beaufort (4 - 6 m/s, gentle breeze)
Wave height: Small waves

Regulator 1.
No Kalman filter
No yaw
Calibration of the rudder servo:
10 volts = 36.9°
-10 volts = -43.1°

Model in the regulator:

$$(\Psi(t+1) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = b_1\delta(t) + b_2\delta(t-1) + d_1v(t) + d_2r(t) + e(t+1)$$

$$v(t) = v_2(t)/q_2 + q_1\ell_2 r(t)$$

Regulator:

$$\delta(t) = -\frac{1}{b_1}[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_1v(t) + d_2r(t)]$$

Sampling interval: 20 s
Forgetting factor λ: 0.90 (0 - 300 s)
0.98 (300 - 2960 s)
0.99 (2960 - 3740 s)
Rudder limits: ± 3° (0 - 440 s)
± 4° (440 - 1300 s)
± 3° (1300 - 3740 s)

$\Psi_{ref} = 142°$

Intitial values:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1061 \\ -0.0857 \\ -2.0213 \\ 3.8205 \end{bmatrix} \qquad P \text{ unknown}$$

Regulator:

$$\delta(t) = -9.4251(\Psi(t) - \Psi_{ref}) + 0.8077\delta(t-1) + 19.0509v(t) - 36.0085r(t)$$

Final values:

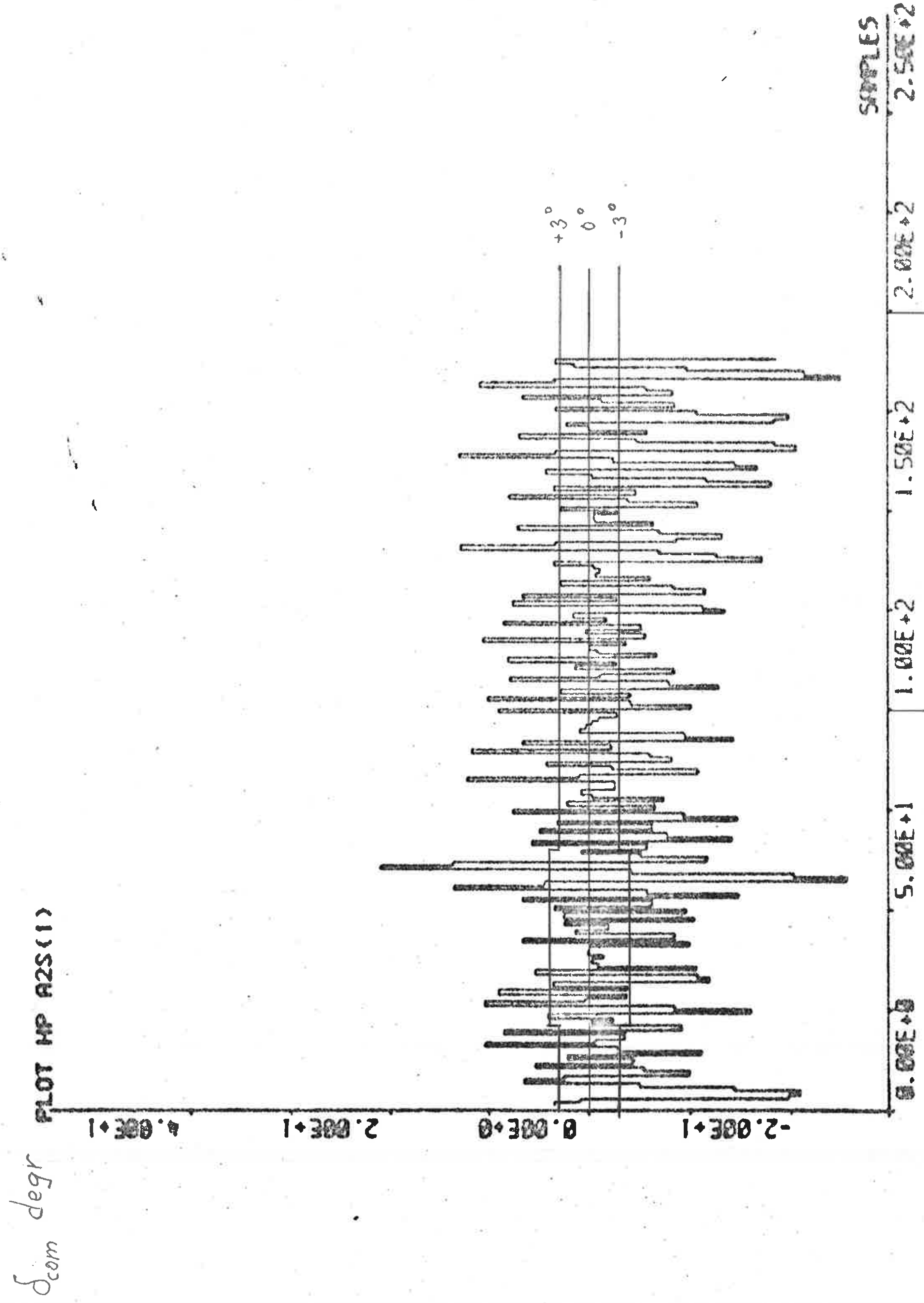
$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.0539 \\ 0.0722 \\ 0.1378 \\ 10.1910 \end{bmatrix} \qquad P = \begin{bmatrix} 0.002527 & & & \\ -0.0004532 & 0.001894 & & \\ -0.01273 & -0.002010 & 1.950 & \\ 0.2788 & -0.1606 & -6.901 & 73.72 \end{bmatrix}$$

Regulator:

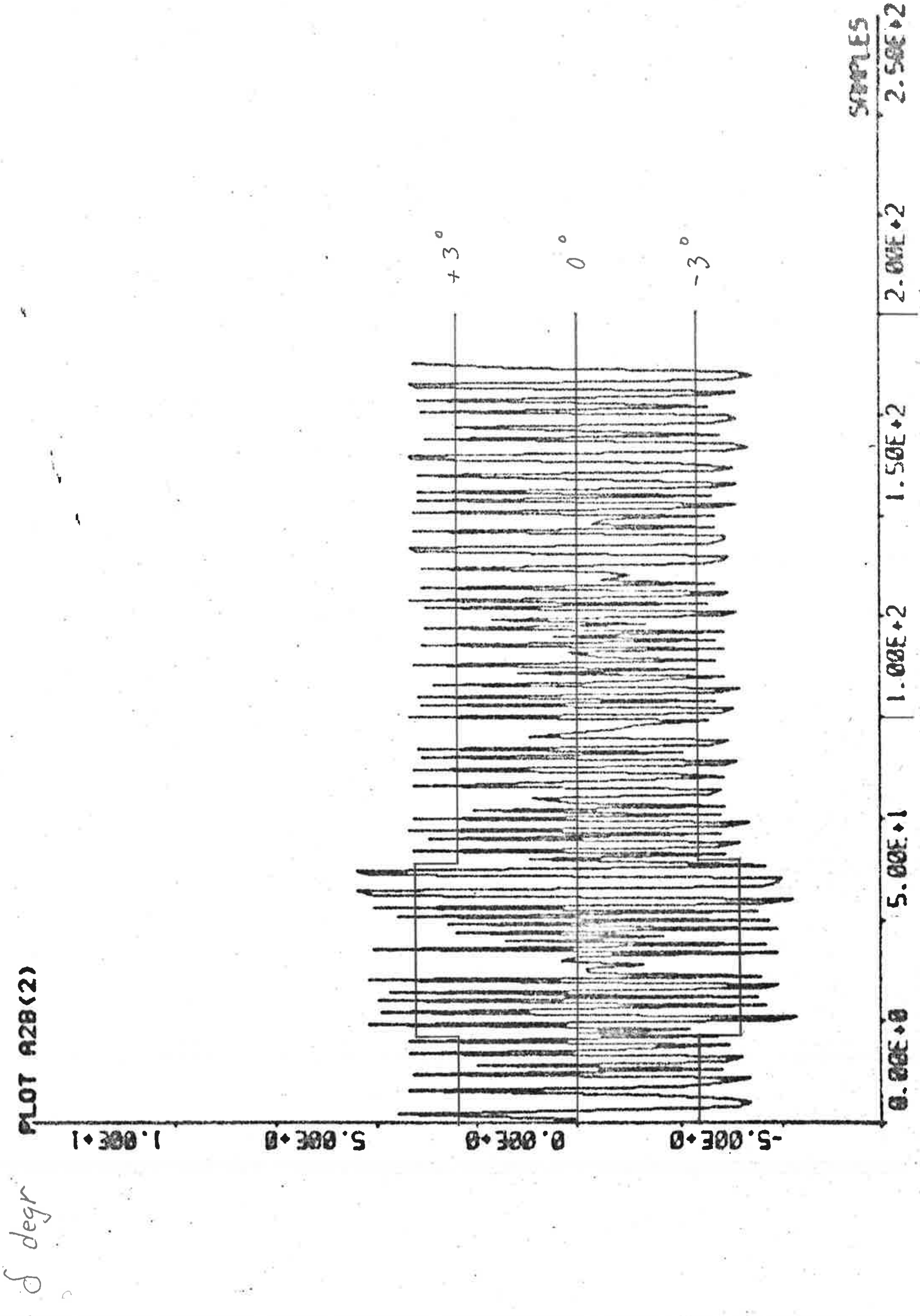
$$\delta(t) = -18.5529(\Psi(t) - \Psi_{ref}) - 1.3395\delta(t-1) - 2.5566v(t) - 189.0724r(t)$$

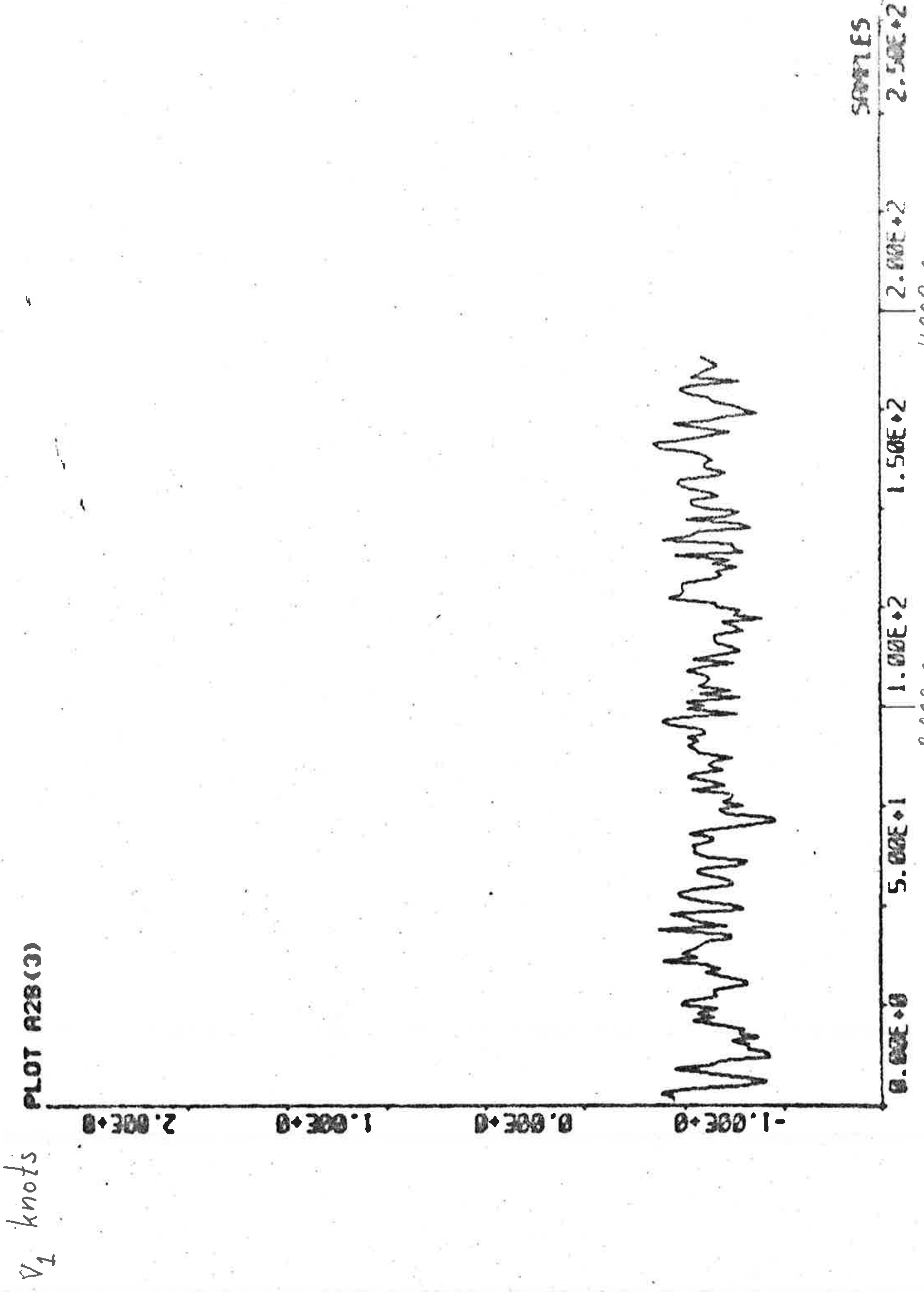
Statistics:

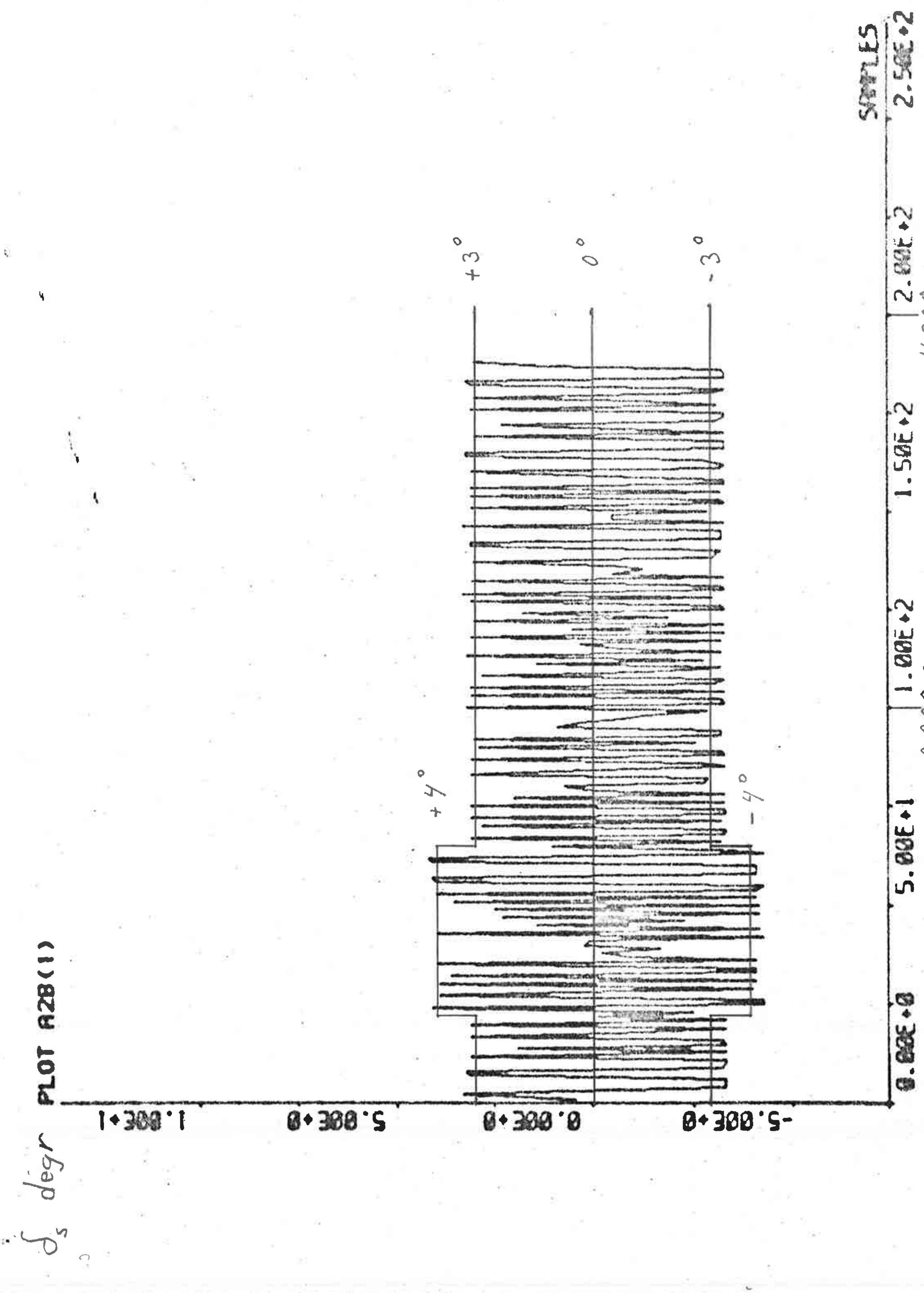
		Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-2.93	8.50	-25.8	21.0
δ_s	degr	-0.75	2.93	-4.3	4.2
δ	degr	0.67	3.50	-5.4	5.5
v_1	knots	-0.633	0.125	-0.96	-0.35
v_2	knots	0.078	0.145	-0.48	0.54
r	degr/s	0.0072	0.0278	-0.072	0.100
Ψ	degr	142.170	0.440	140.98	144.32
u	knots	16.743	0.125	16.39	17.01
v	m/s	0.056	0.103	-0.24	0.36

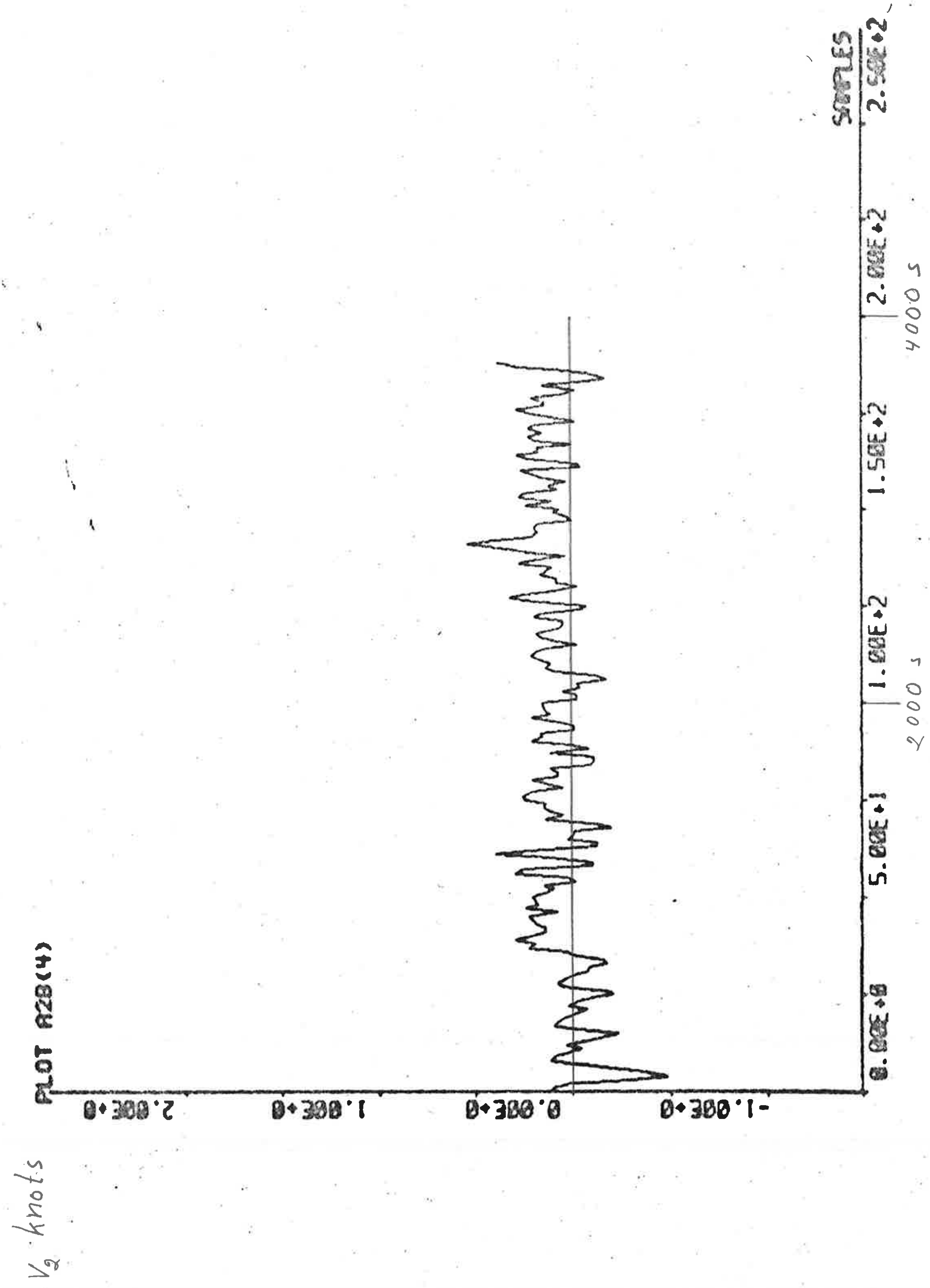


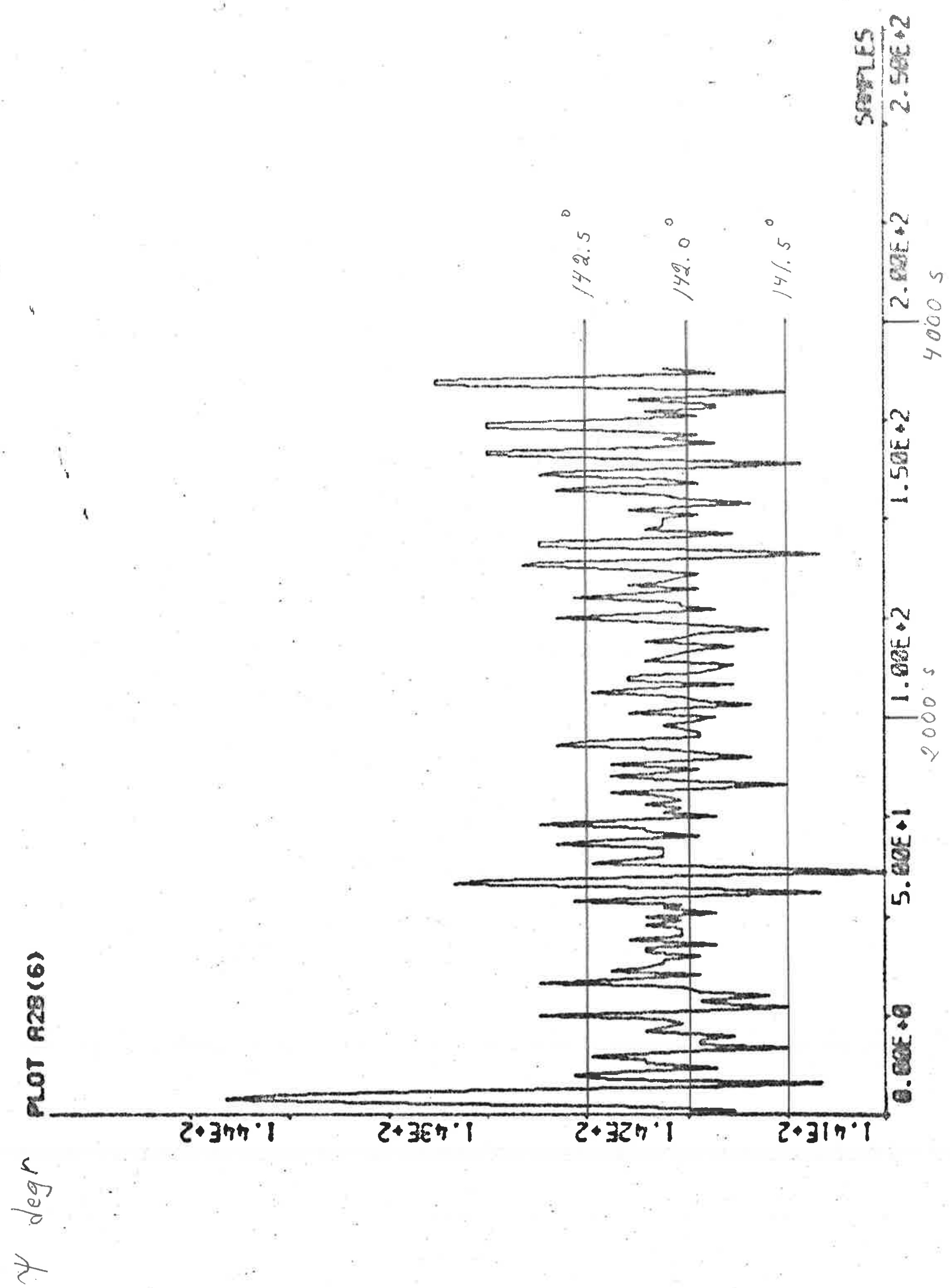
PLOT HP A2S(1)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
4.00E+1
2.00E+1
0.00E+0
-2.00E+1
+3°
0°
-3°
2000 s
4000 s
δ_{com} degr

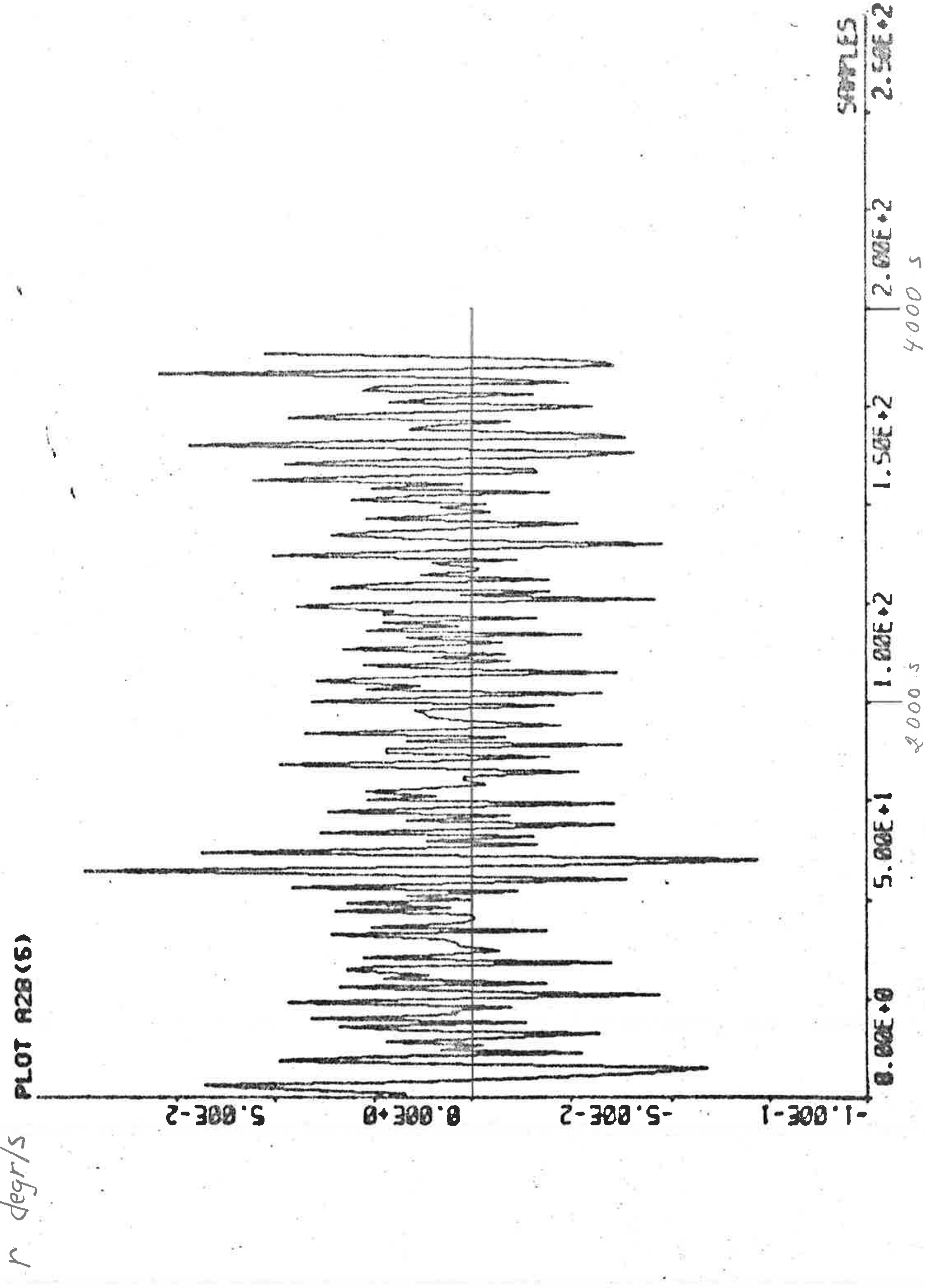

PLOT A2B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δ degr

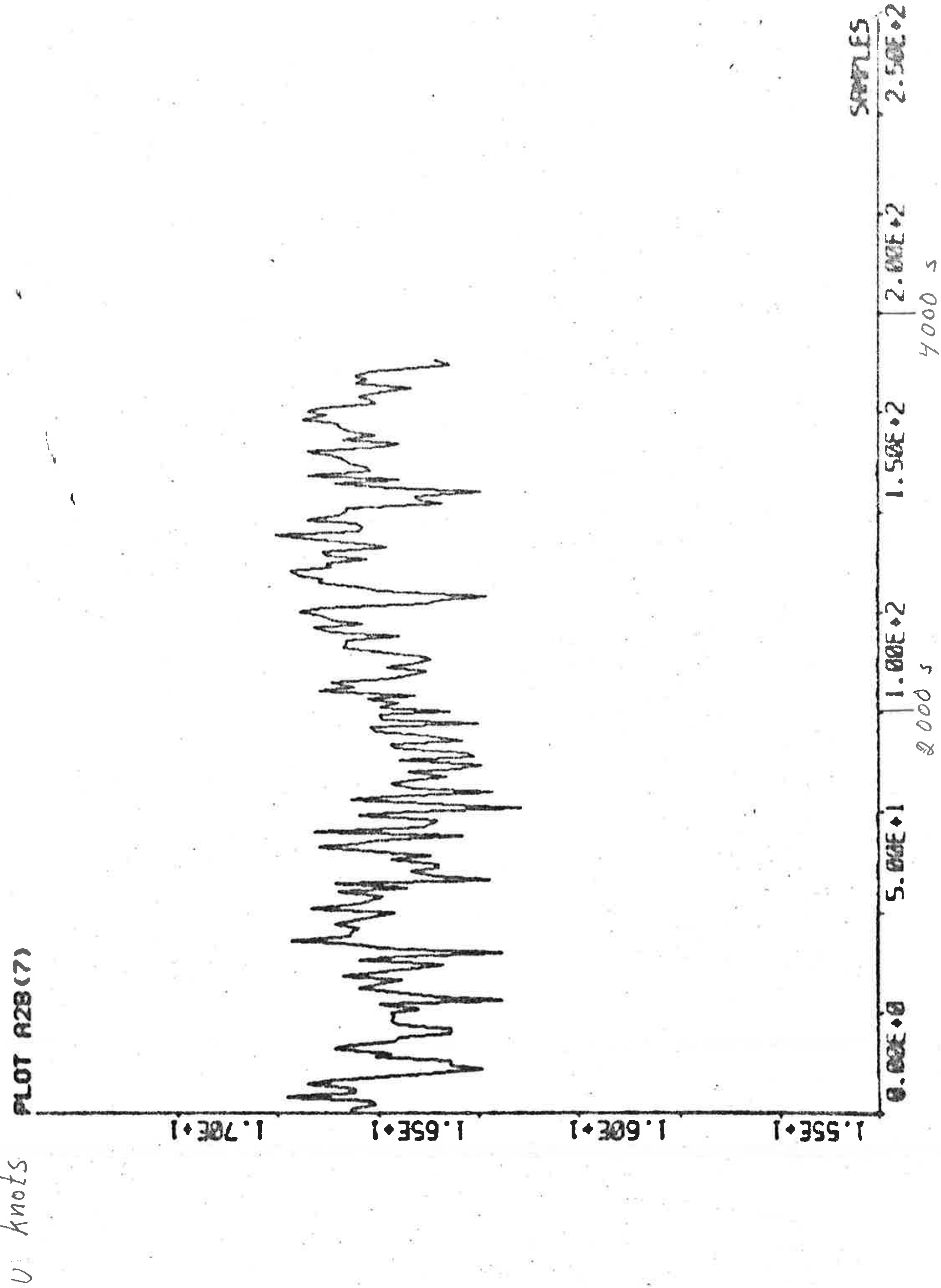

PLOT A2B(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
v_1 knots

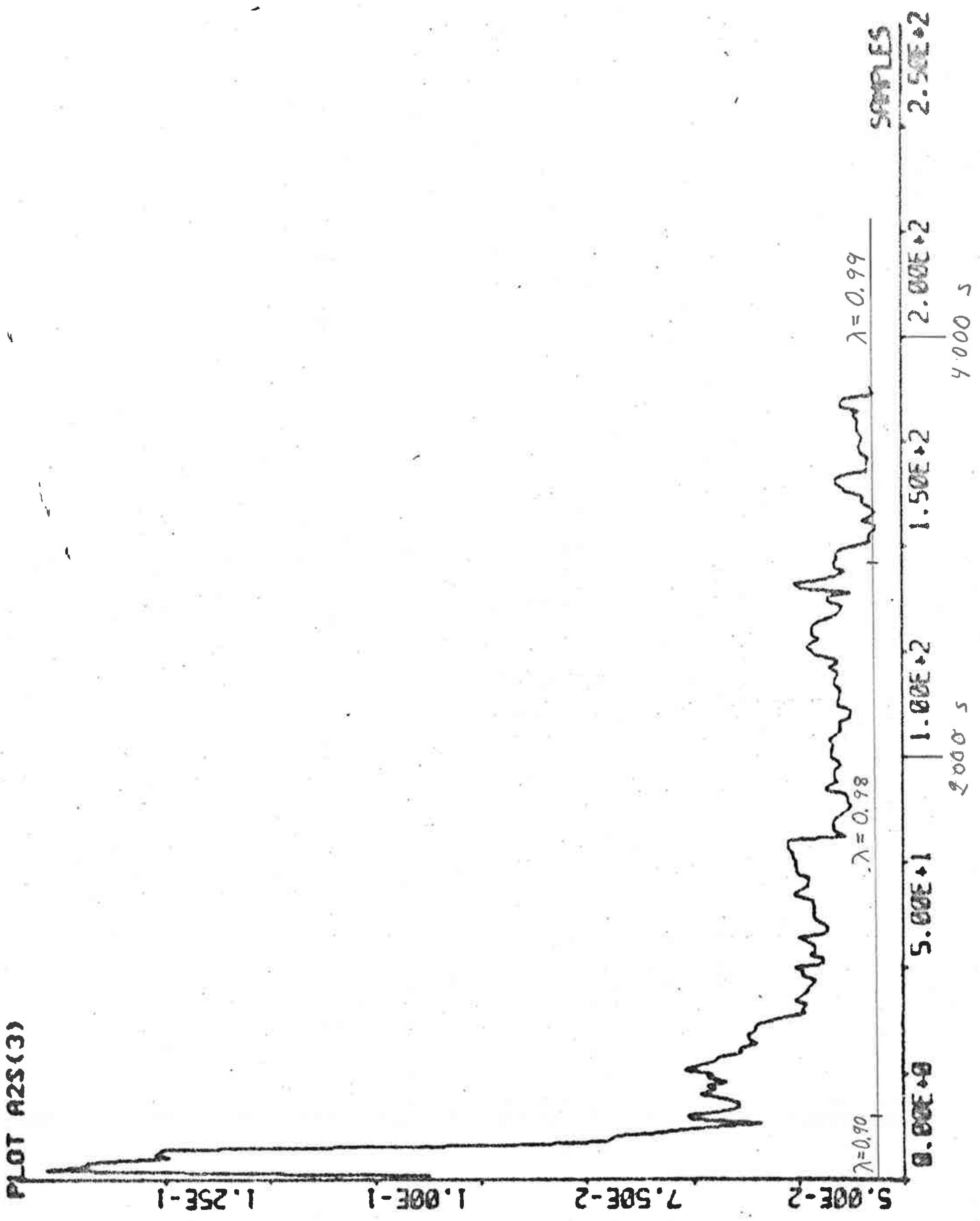

PLOT A2B(1)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
+4°
-4°
2000 s
4000 s
δ_s degr


PLOT A2B(4)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
2000 s
4000 s
V_2 knots

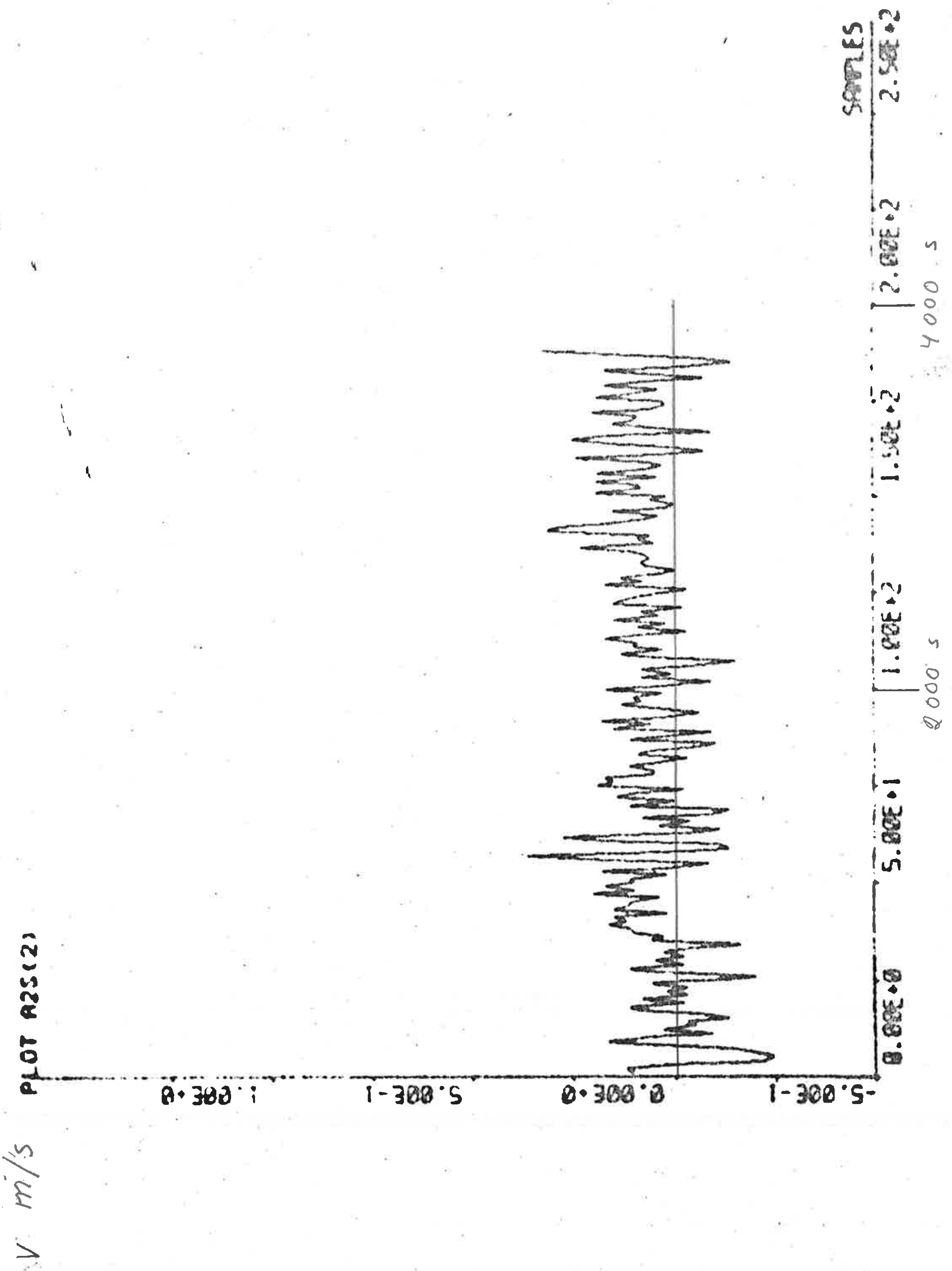

PLOT A2B(6)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
1.41E+2
1.42E+2
1.43E+2
1.44E+2
142.5°
142.0°
141.5°
ψ degr

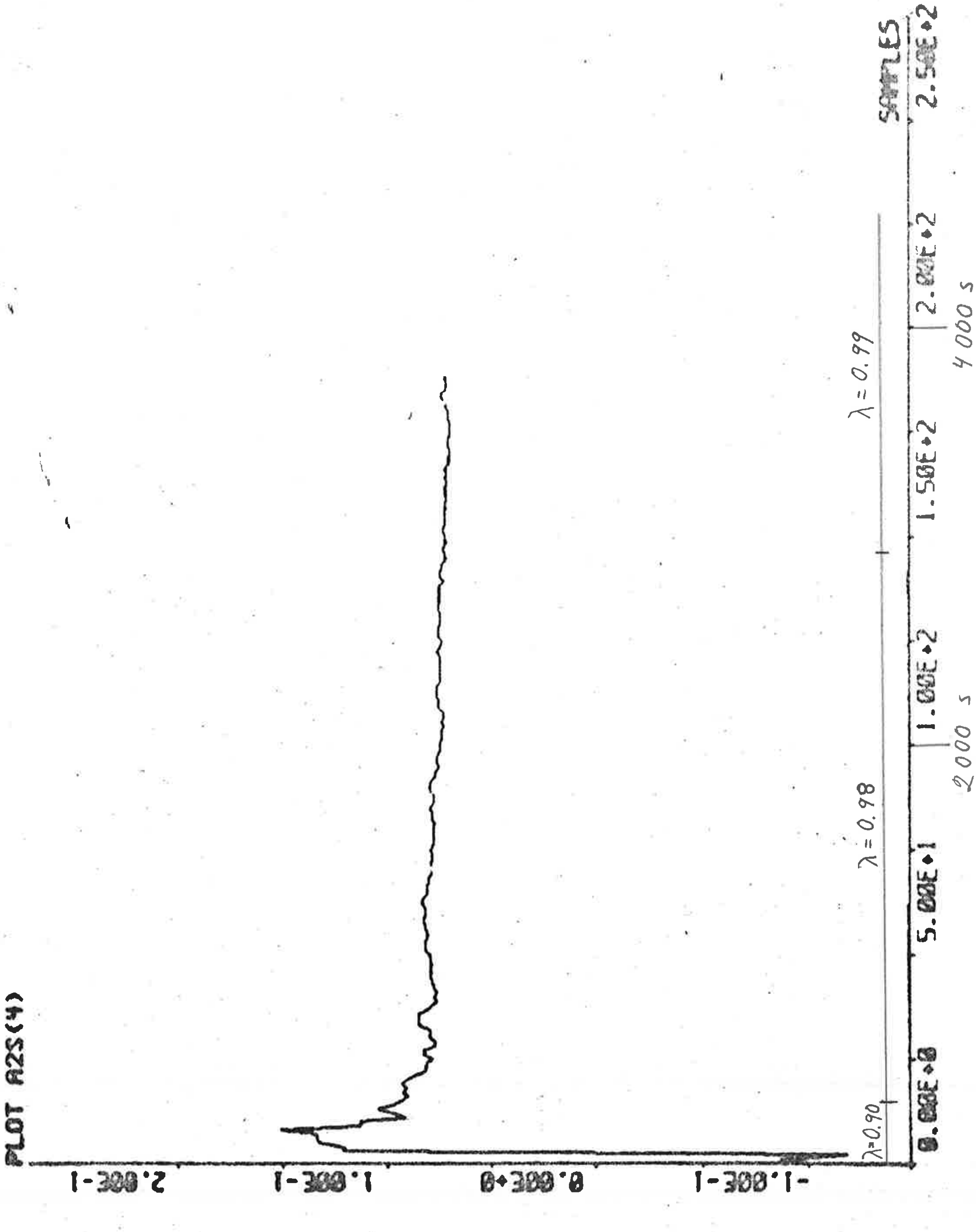

PLOT A2B(5)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s
2000 s
4000 s


PLOT A2B(7)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
1.70E+1
1.65E+1
1.60E+1
1.55E+1
2000 s
4000 s
U knots

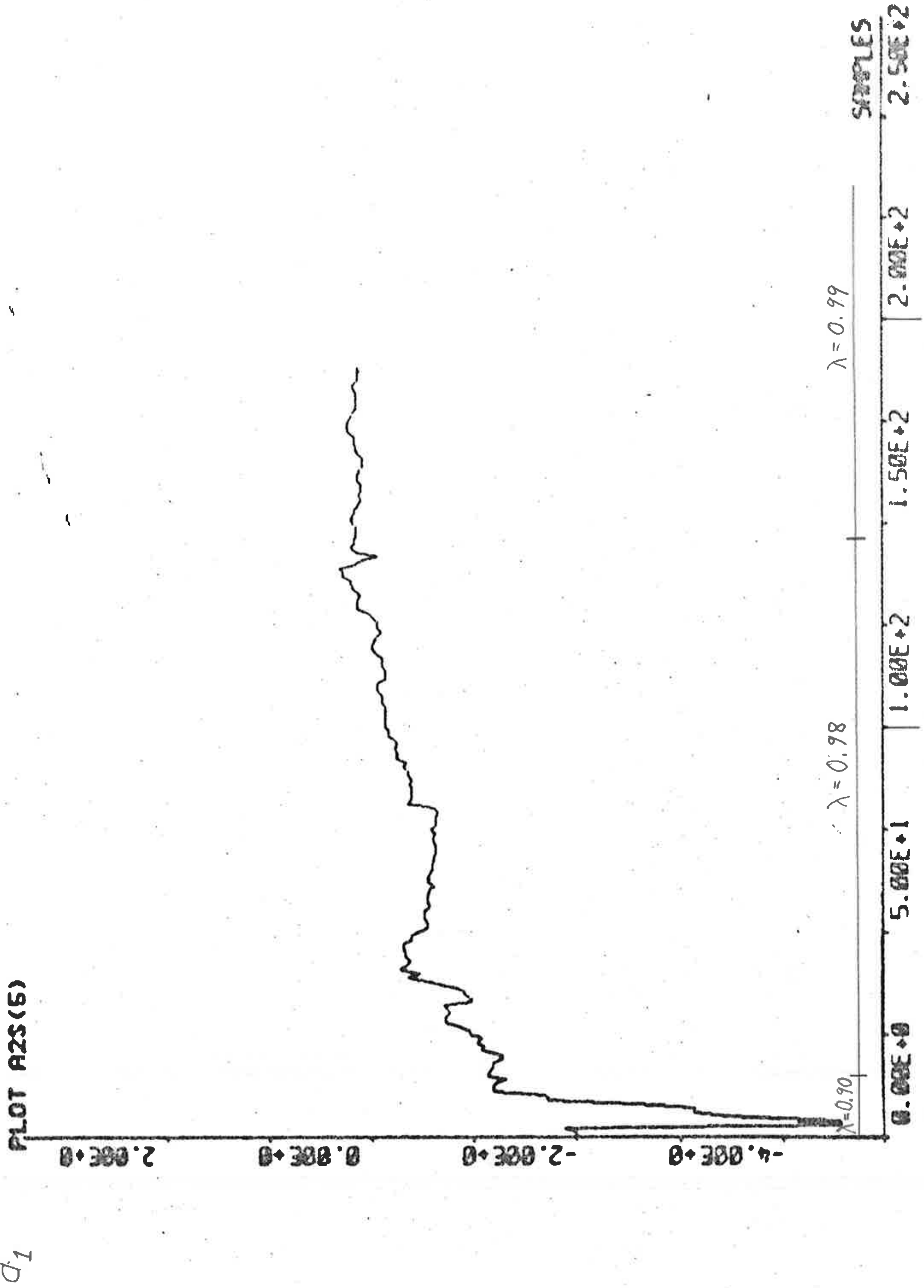

PLOT A2S(3)
1.25E-1
1.00E-1
7.50E-2
5.00E-2
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.90
λ=0.98
λ=0.99
2000 s
4000 s

b1

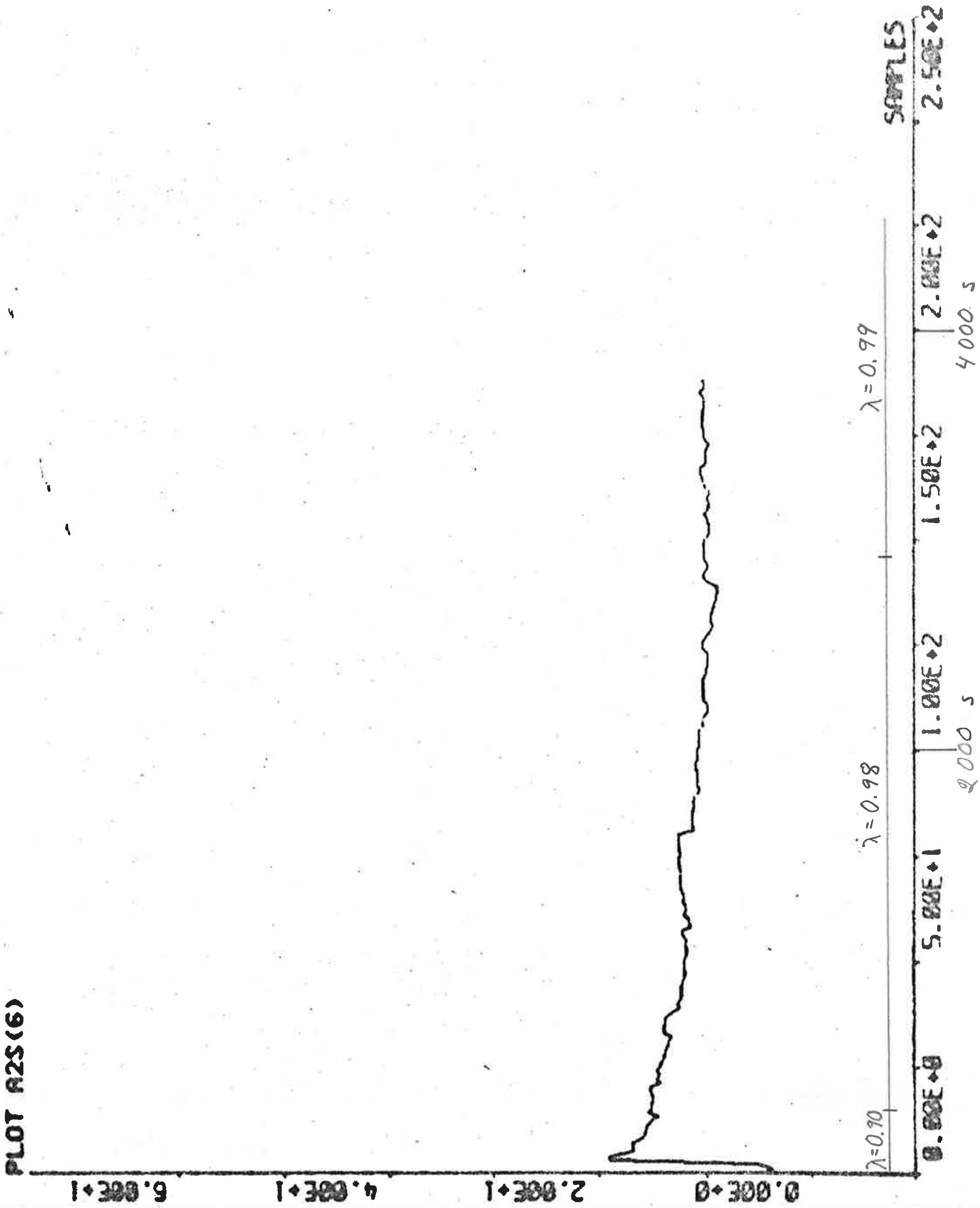

PLOT A2S(2)
V m/s
-5.00E-1
0.00E+0
5.00E-1
1.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
0000 s
4000 s


PLOT A2S(4)
2.00E-1
1.00E-1
0.00E+0
-1.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.90
λ=0.98
λ=0.99
2000 s
4000 s

b2


PLOT A2S(5)
2.00E+0
0.00E+0
-2.00E+0
-4.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.90
λ=0.98
λ=0.99
2000 s
4000 s

d_1


PLOT A2S(6)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
0.00E+0
2.00E+1
4.00E+1
6.00E+1
λ=0.90
λ=0.98
λ=0.99
2000 s
4000 s

d2

Experiment A3.

Date: 73 - 10 - 14

Time: 22^{50} - 00^{05}

Position: S 04° W 05°

Wind direction: 2 (see appendix A)

Wind speed: 3 Beaufort (4 - 6 m/s, gentle breeze)

Wave height: Small waves

Regulator 1.

No Kalman filter

No yaw

Calibration of the rudder servo:

10 volts = 36.9°

-10 volts = -43.1°

Model in the regulator:

$$(\Psi(t+1) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = b_1\delta(t) + b_2\delta(t-1) + d_1 v(t) + d_2 r(t) + e(t+1)$$

$$v(t) = v_2(t)/q_2 + q_1 \ell_2 r(t)$$

Regulator:

$$\delta(t) = -\frac{1}{b_1}[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_1 v(t) + d_2 r(t)]$$

Sampling interval: 30 s

Forgetting factor λ: 0.98 (0 - 3150 s)

0.99 (3150 - 4440 s)

Rudder limits: $\pm 3^{\circ}$

$\Psi_{ref} = 142^{\circ}$

Initial values:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.0558 \\ 0.0699 \\ 0.0145 \\ 10.4461 \end{bmatrix} \qquad P = \begin{bmatrix} 0.002527 & & & \\ -0.000453 & 0.001894 & & \\ -0.01273 & -0.002010 & 1.950 & \\ 0.2788 & -0.1606 & -6.901 & 73.72 \end{bmatrix}$$

Regulator:

$$\delta(t) = -17.9211(\Psi(t) - \Psi_{ref}) - 1.2527\delta(t-1) - 0.2599v(t) - 187.2061r(t)$$

Final values:

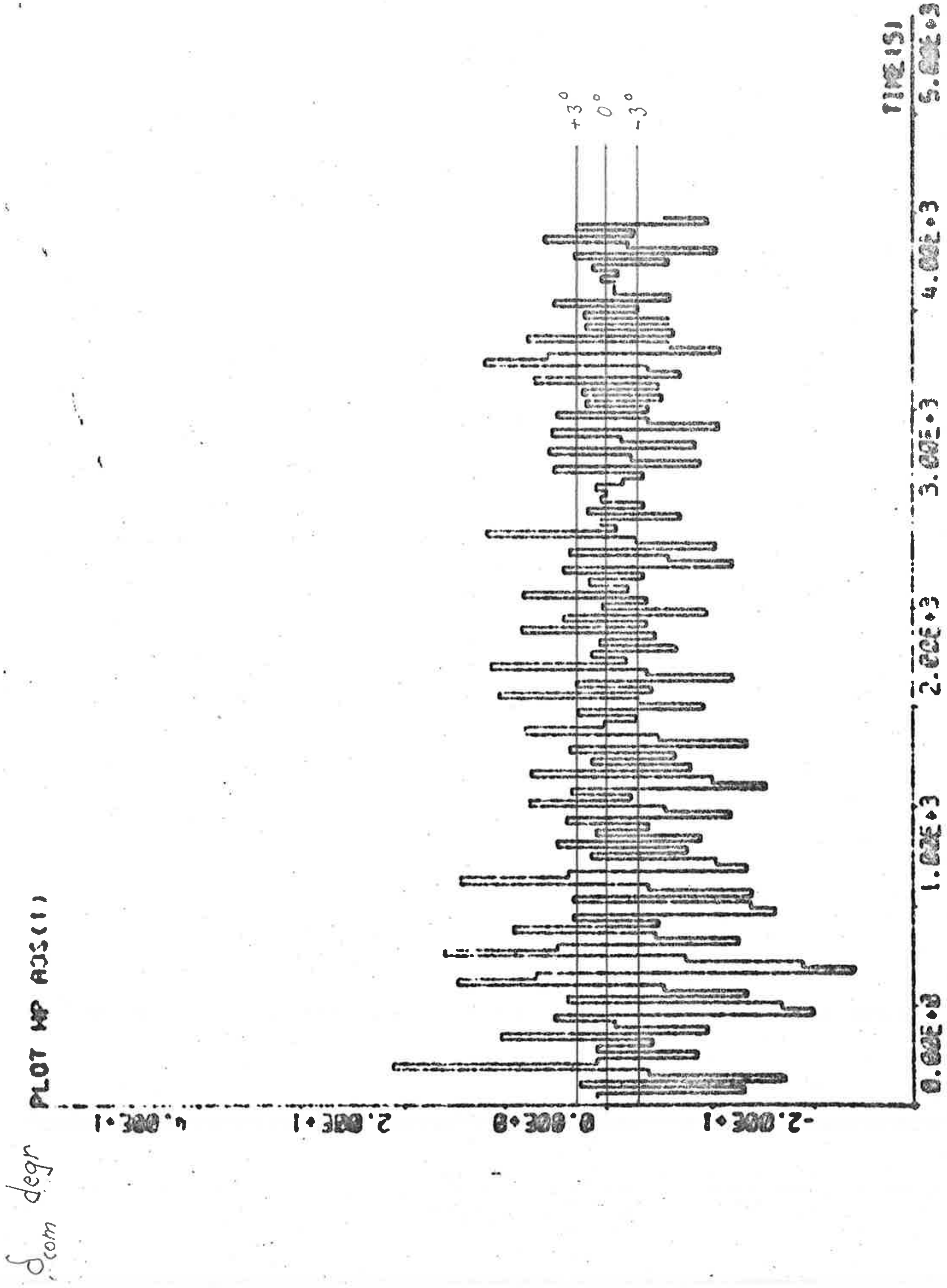
$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1243 \\ 0.1252 \\ 0.1451 \\ 11.1929 \end{bmatrix} \qquad P = \begin{bmatrix} 0.003153 & & & \\ -0.0004958 & 0.002615 & & \\ -0.01788 & 0.007169 & 0.9782 & \\ 0.3555 & -0.2717 & -5.138 & 78.06 \end{bmatrix}$$

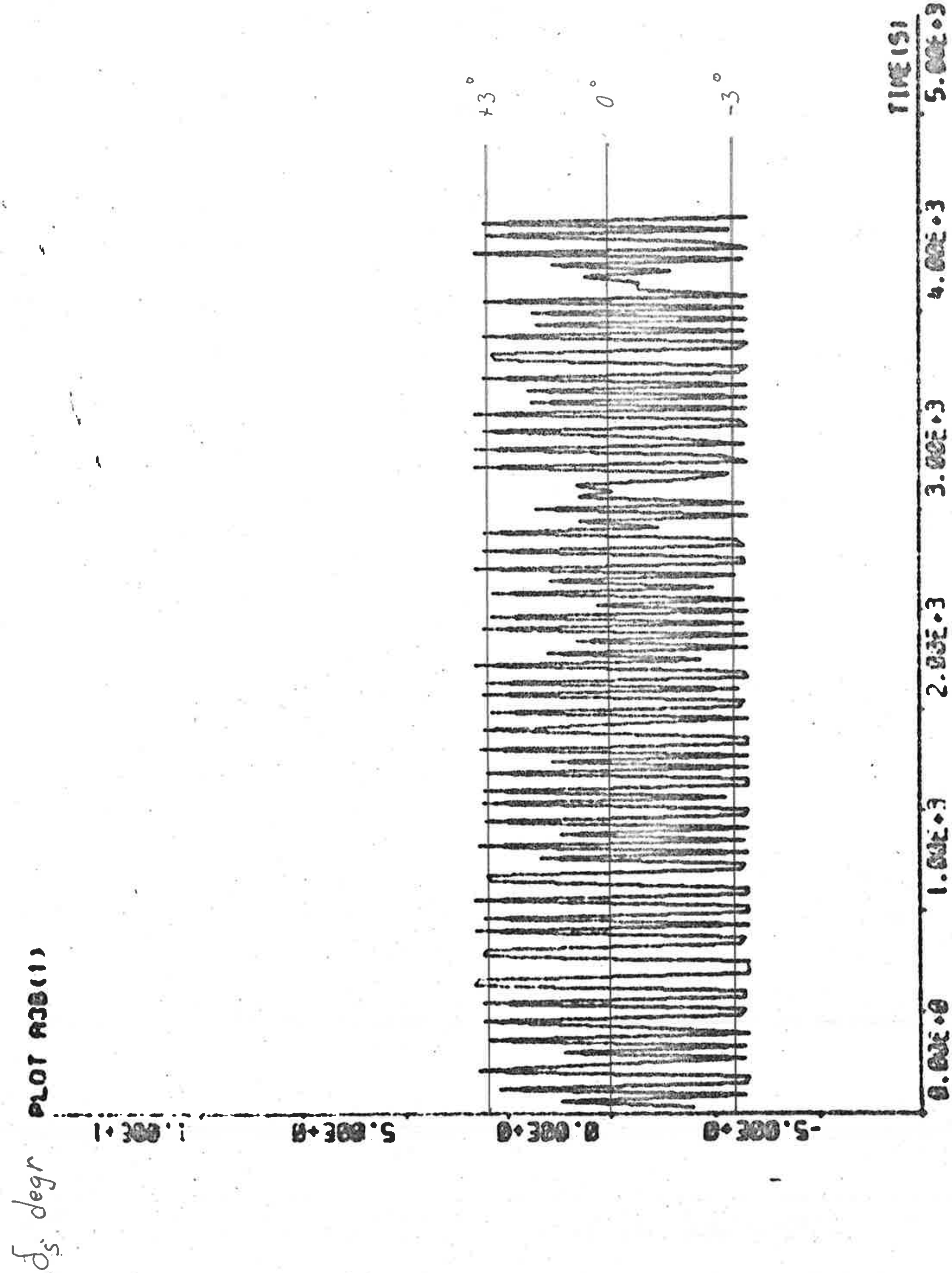
Regulator:

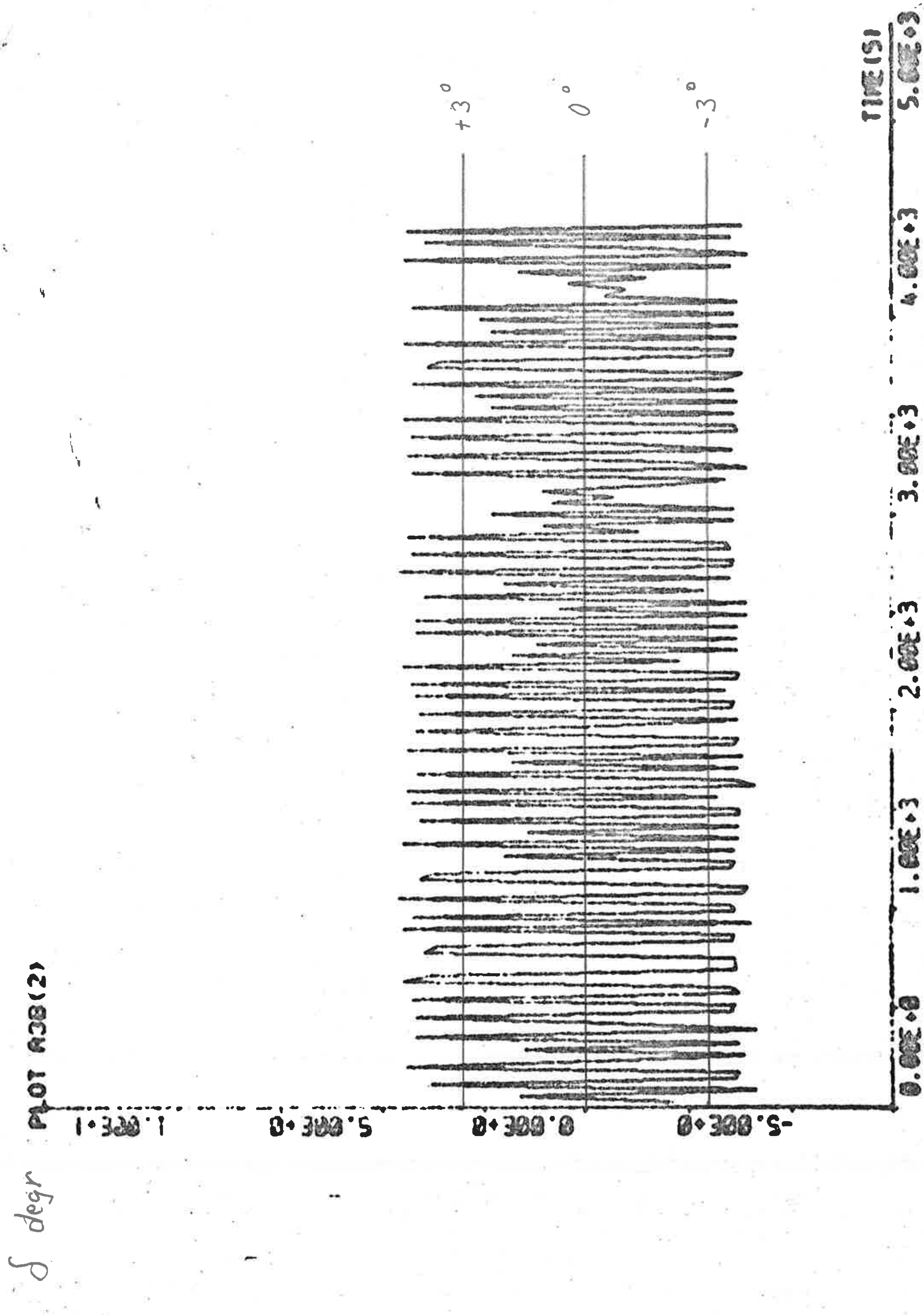
$$\delta(t) = -8.0451(\Psi(t) - \Psi_{ref}) - 1.0072\delta(t-1) - 1.1673v(t) - 90.0475r(t)$$

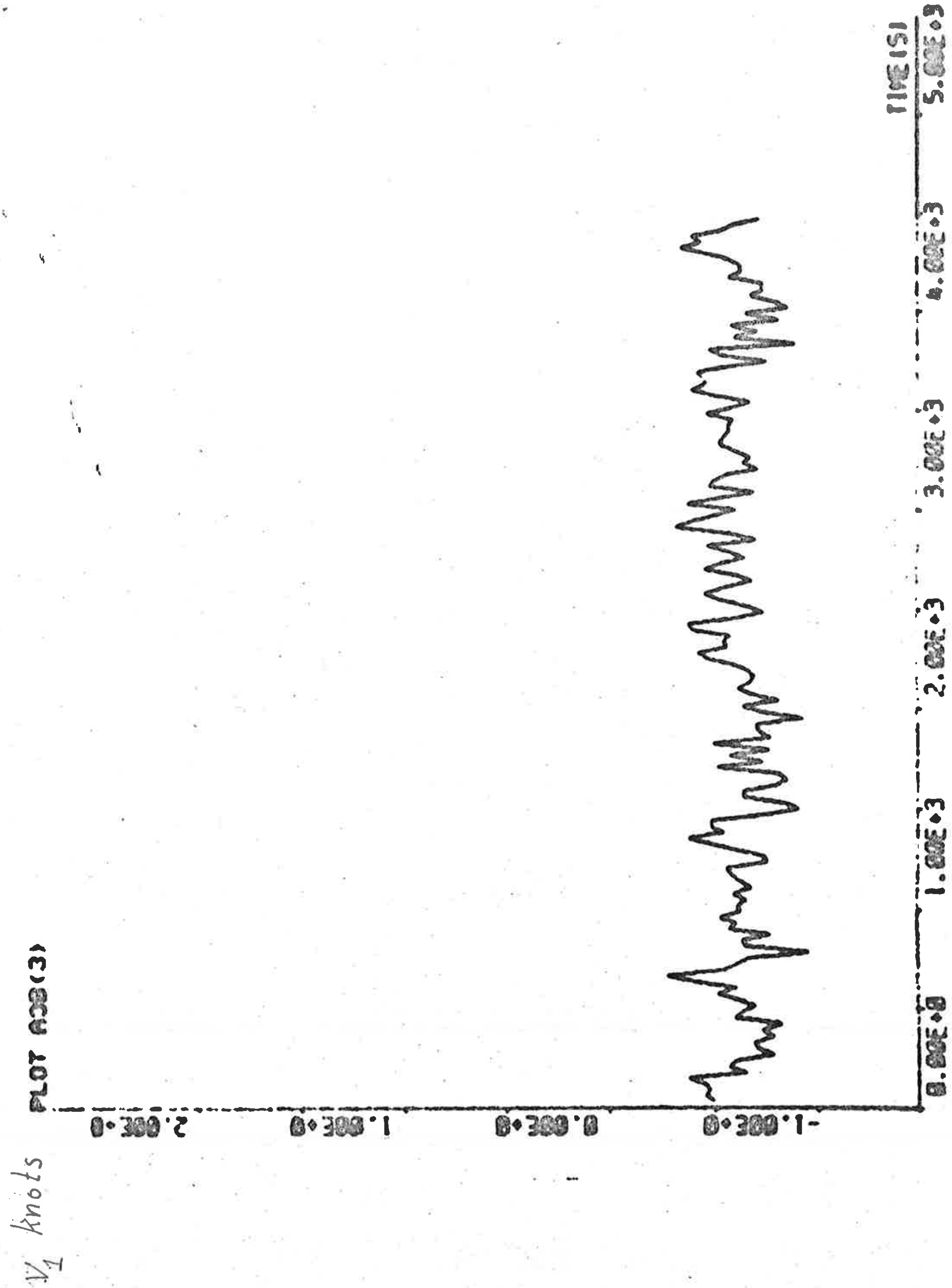
Statistics:

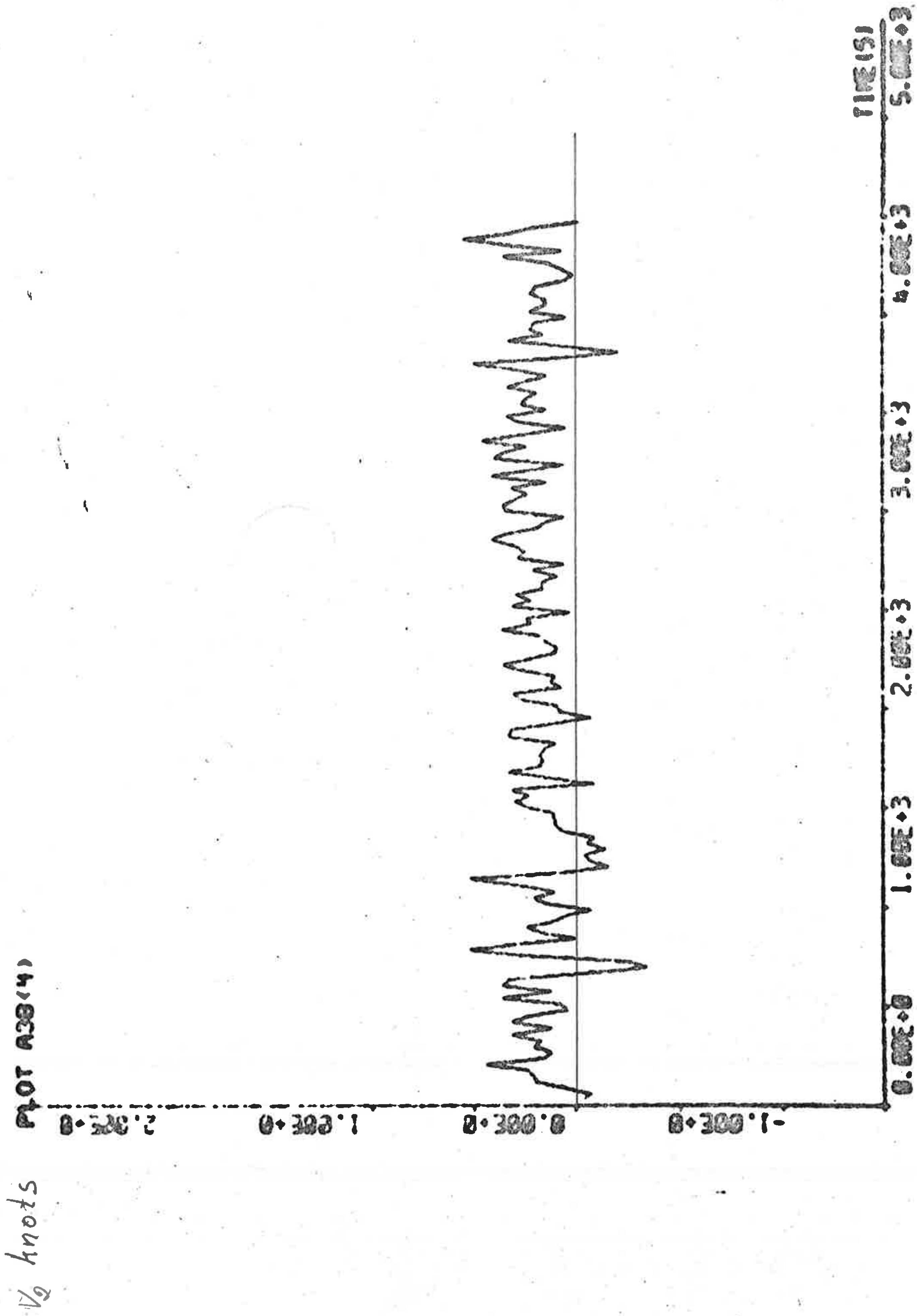
		Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-2.05	7.66	-24.2	21.1
δ_s	degr	-0.63	2.81	-3.3	3.3
δ	degr	-0.47	3.48	-4.1	4.6
v_1	knots	-0.605	0.129	-0.95	-0.28
v_2	knots	0.177	0.151	-0.34	0.55
r	degr/s	0.0076	0.0347	-0.063	0.097
Ψ	degr	142.147	0.522	140.71	143.88
u	knots	16.640	0.153	16.13	17.00
v	m/s	0.109	0.115	-0.20	0.38

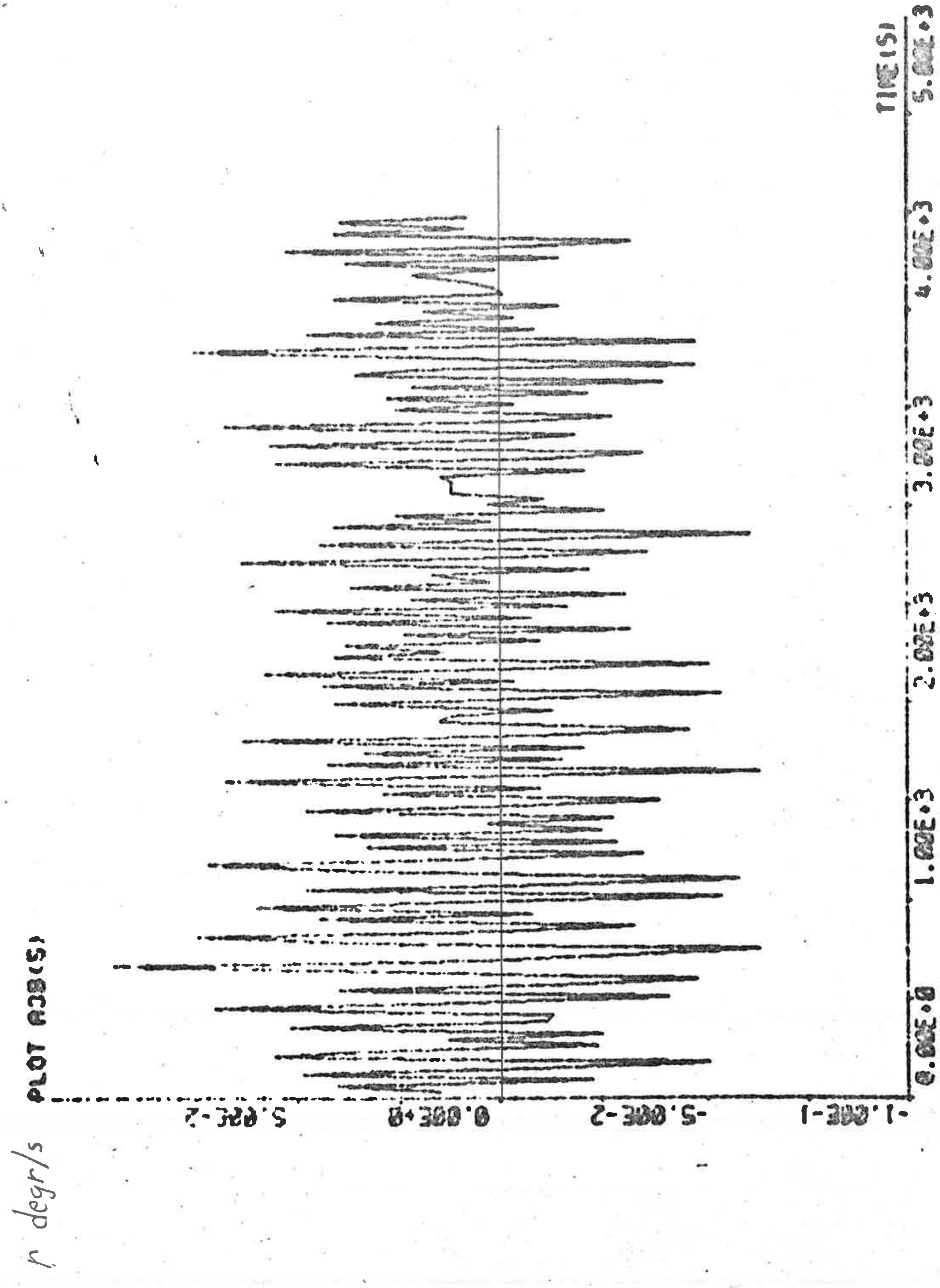

PLOT XP
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
4.00E+1
2.00E+1
0.00E+0
-2.00E+1
+3°
0°
-3°
degr

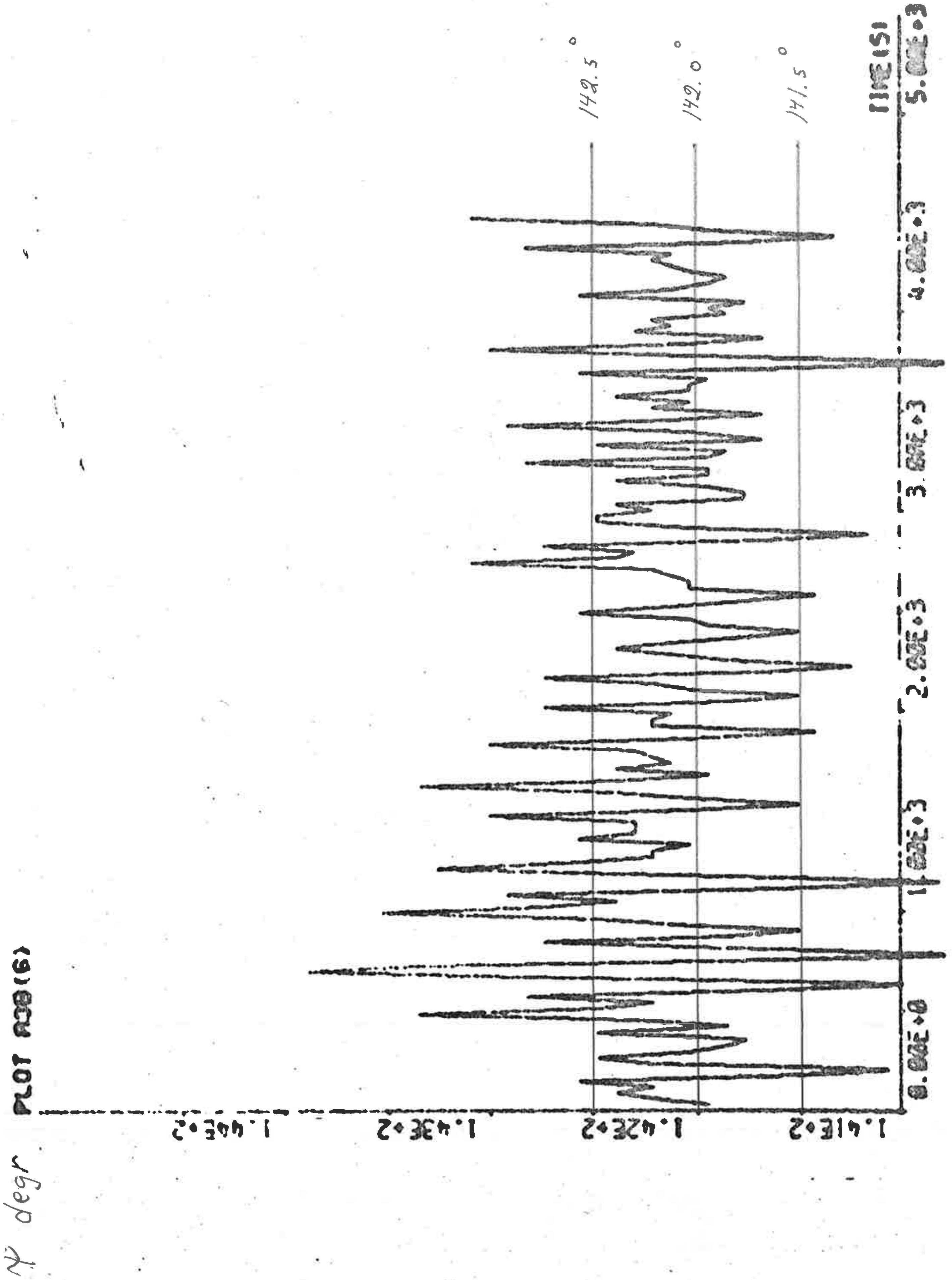

PLOT A3B(1)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
+3°
0°
-3°
δs degr

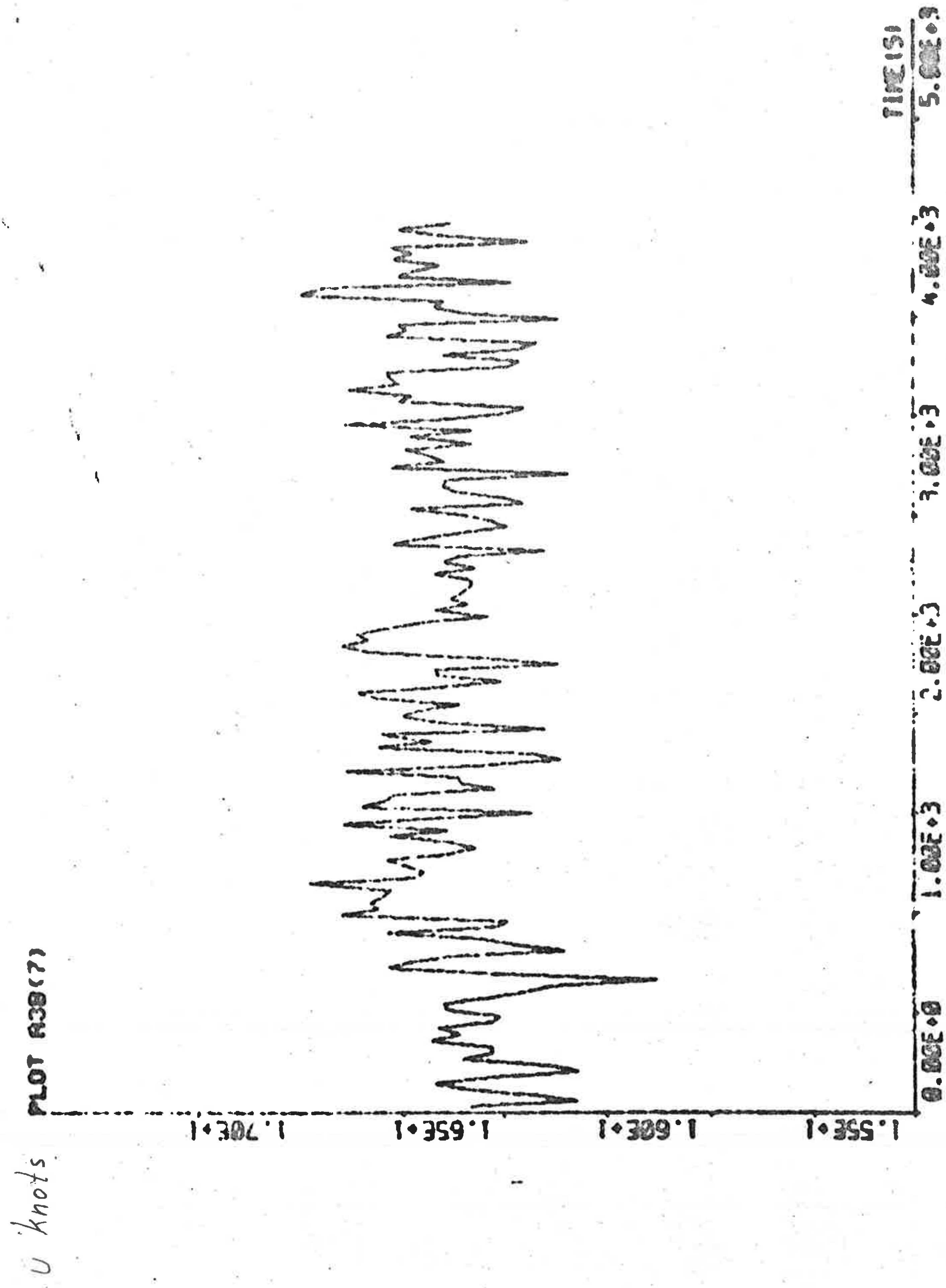

PLOT A38(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
δ degr


PLOT A3B(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)
V1 knots

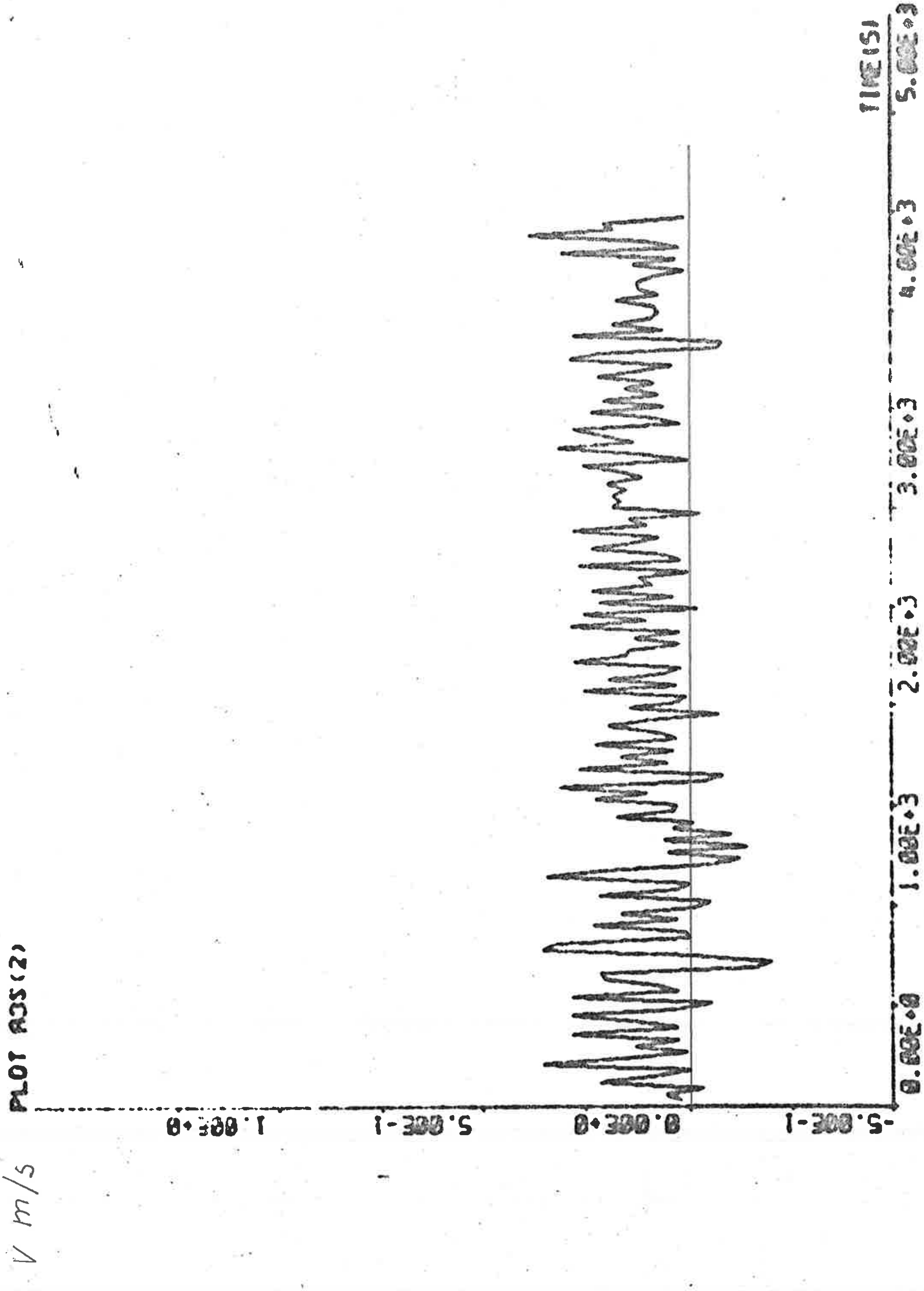

PLOT A38(4)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
Vg knots

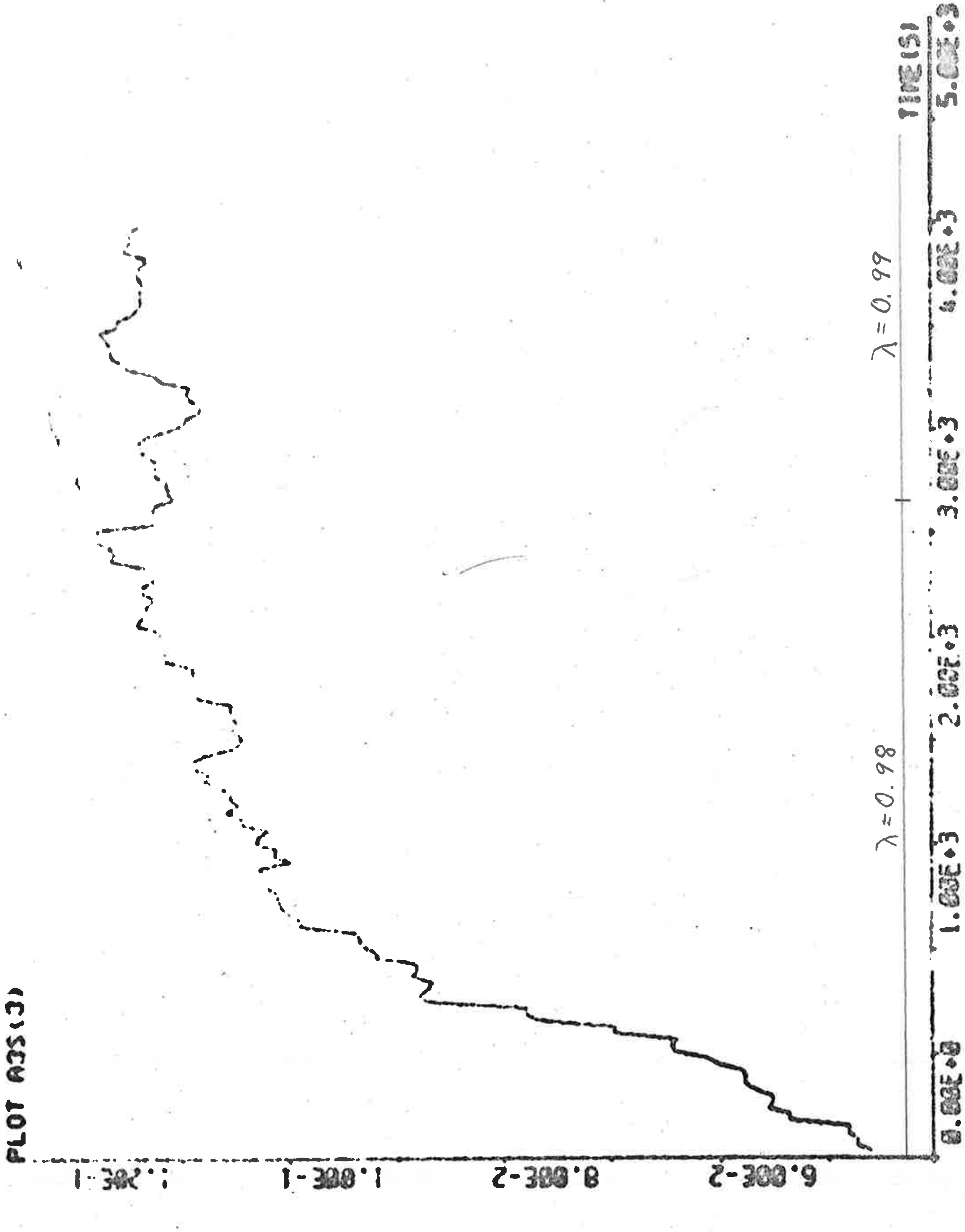

PLOT A3B(S)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s


PLOT A3B(6)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.41E+2
1.42E+2
1.43E+2
1.44E+2
142.5°
142.0°
141.5°
ψ degr

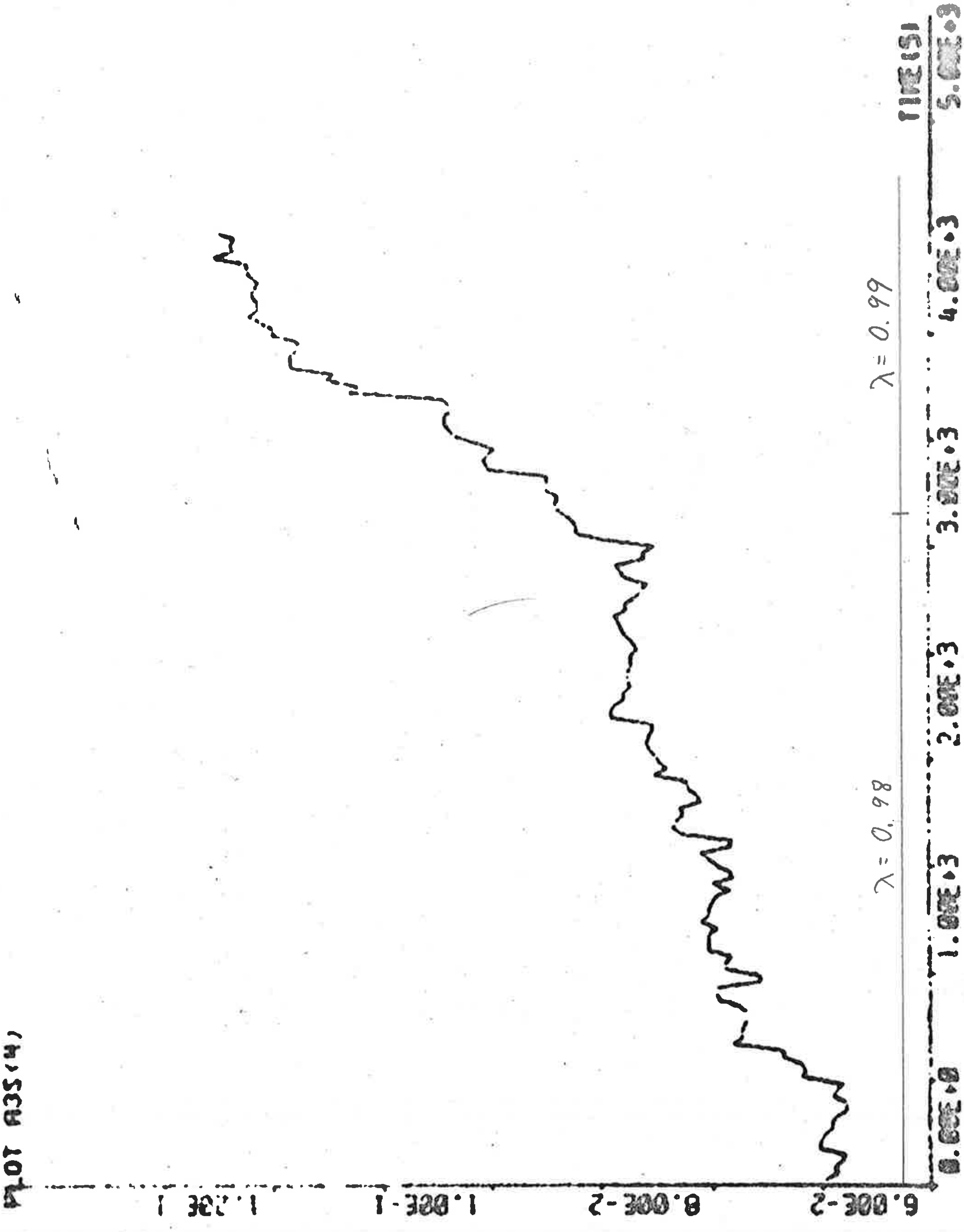


PLOT A38(7)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.555E+1
1.605E+1
1.655E+1
1.705E+1
U knots

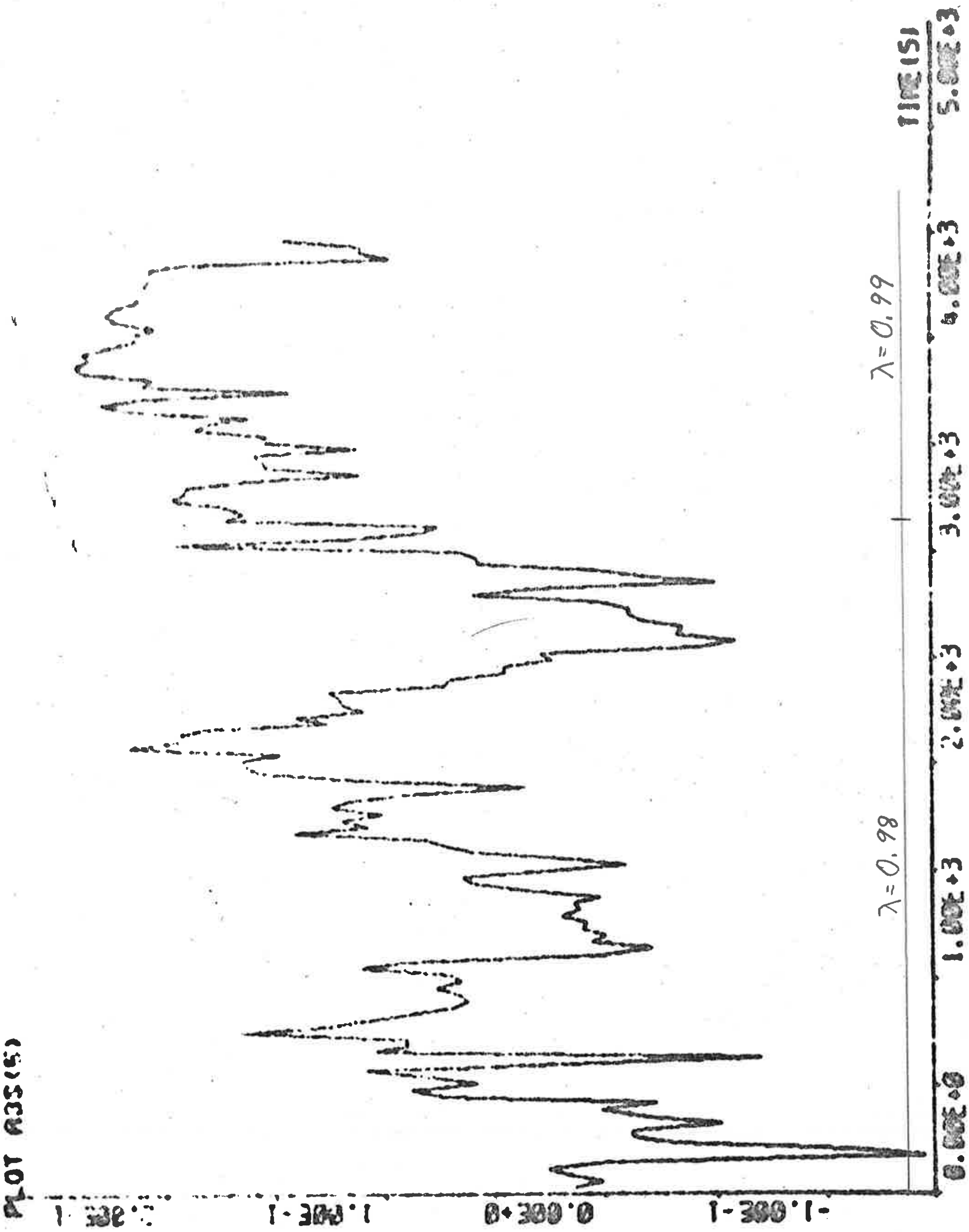

PLOT A3S(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E-1
0.00E+0
5.00E-1
1.00E+0
V m/s


PLOT A3S(3)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
6.00E-2
8.00E-2
1.00E-1
λ=0.98
λ=0.99

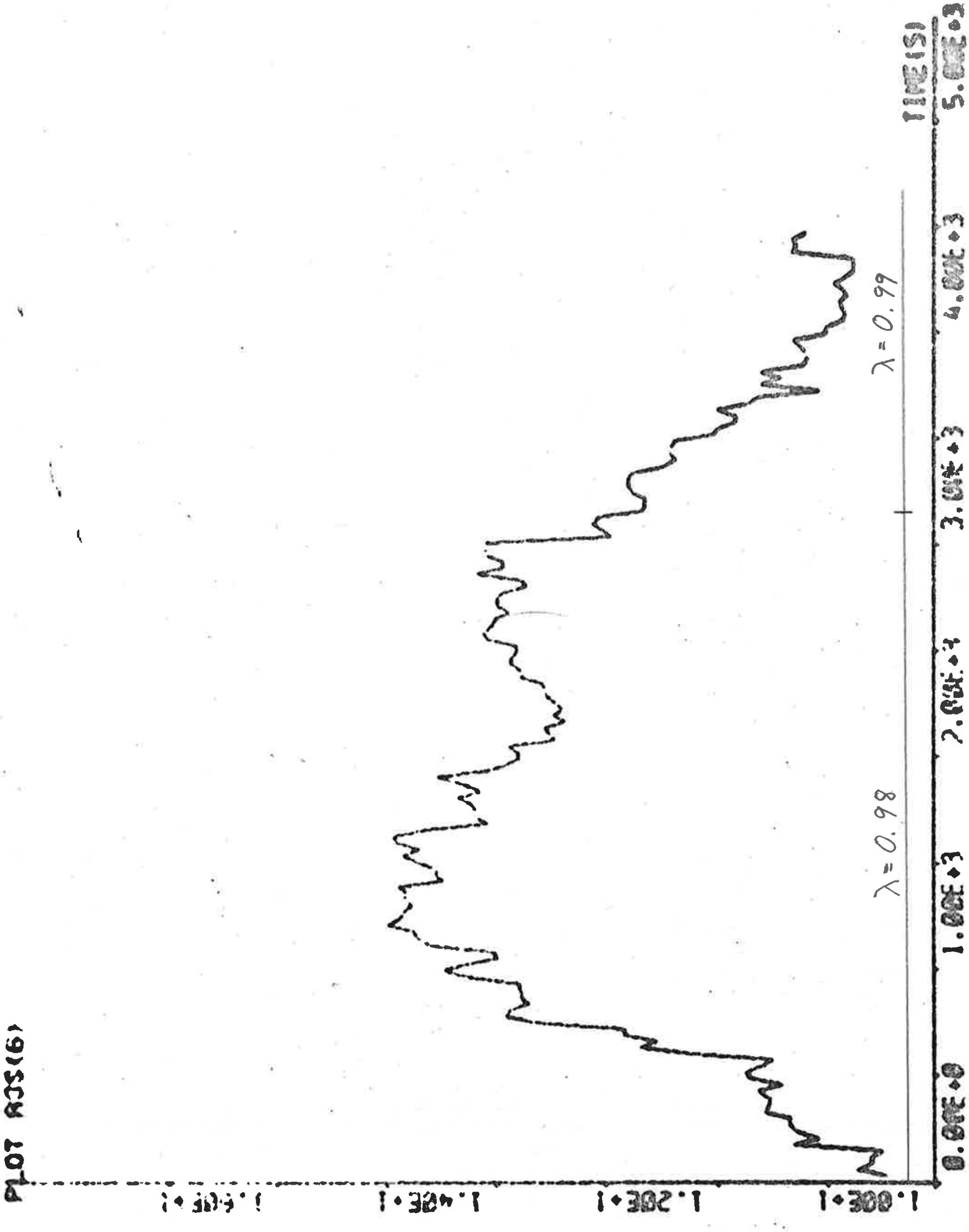
b_1


PLOT A3S(4)
6.00E-2
8.00E-2
1.00E-1
1.20E 1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
λ = 0.98
λ = 0.99

b2



d_1


PLOT RJS(6)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
1.20E+1
1.40E+1
1.60E+1
λ = 0.98
λ = 0.99

Experiment A4.

Date: 73 - 10 - 17

Time: 11^{20} - 13^{05}

Position: S 18° E 04°

Wind direction: 1 (see appendix A)

Wind speed: 3 Beaufort (4 - 6 m/s, gentle breeze)

Wave height: 2 m (swells)

Regulator 2

The Kalman filter is used

No yaw

Calibration of the rudder servo:

+10 volts = 36.9°

-10 volts = -43.1°

Notice that the bias of the v_1-measurements is compensated by adding 0.5 knots to the real measurements.

Kalman filter:

The filter gain K was designed using the discrete version (sampling interval 1 s) of the ship model (3.1) with parameter values (3.2) in section 3.1 and with V = 16 knots. The following discrete covariance matrices were used:

$$\tilde{R}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10^{-6} & 0 \\ 0 & 0 & 0 & 0 & 10^{-6} \end{bmatrix}$$

$$\tilde{R}_2 = \begin{bmatrix} 10^{-4} & 0 & 0 & 0 \\ 0 & 10^{-4} & 0 & 0 \\ 0 & 0 & 4\cdot 10^{-6} & 0 \\ 0 & 0 & 0 & 0.04 \end{bmatrix}$$

Then the obtained filter gain is

$$K = \begin{bmatrix} 0.12891058 & 0.14051798 & -0.030690178 & -0.35489838\cdot 10^{-5} \\ 0.049646431 & -0.048602321 & 0.2597713 & 0.22859683\cdot 10^{-4} \\ 0.043028929 & -0.043429249 & 0.22859683 & 0.0059597731 \\ 0.047347144 & 0.050175780 & -0.0074789646 & 0.14807539\cdot 10^{-5} \\ 0.031192278 & -0.028210525 & 0.15706198 & -0.60248673\cdot 10^{-5} \end{bmatrix}$$

The initial state estimate vector in the Kalman filter is

$$\hat{x}(0) = \begin{bmatrix} 0.02 \\ 0.002 \\ 142.0 \\ 0.00831 \\ 0.00312 \end{bmatrix}$$

Model in the regulator:

$$(\Psi(t+3) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = b_1\delta(t) + b_2\delta(t-1) + d_1\hat{v}(t) +$$

$$+ d_2\hat{r}(t) + d_3\hat{F}(t) + d_4\hat{M}(t) + e(t+3)$$

Notice that the measured course is used instead of the estimated course.

Regulator:

$$\delta(t) = -\frac{1}{b_1}[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_1\hat{v}(t) + d_2\hat{r}(t) + d_3\hat{F}(t) +$$

$$+ d_4\hat{M}(t)]$$

Sampling interval: 20 s
Forgetting factor λ: 0.95 (0 - 960 s)
0.98 (960 - 2560 s)
0.99 (2560 - 6360 s)
Rudder limits: $\pm 3^{o}$
$\Psi_{ref} = 142^{o}$

Initial values:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad P = 10 * I$$

Regulator:

$$\delta(t) = -(\Psi(t) - \Psi_{ref})$$

Final values:

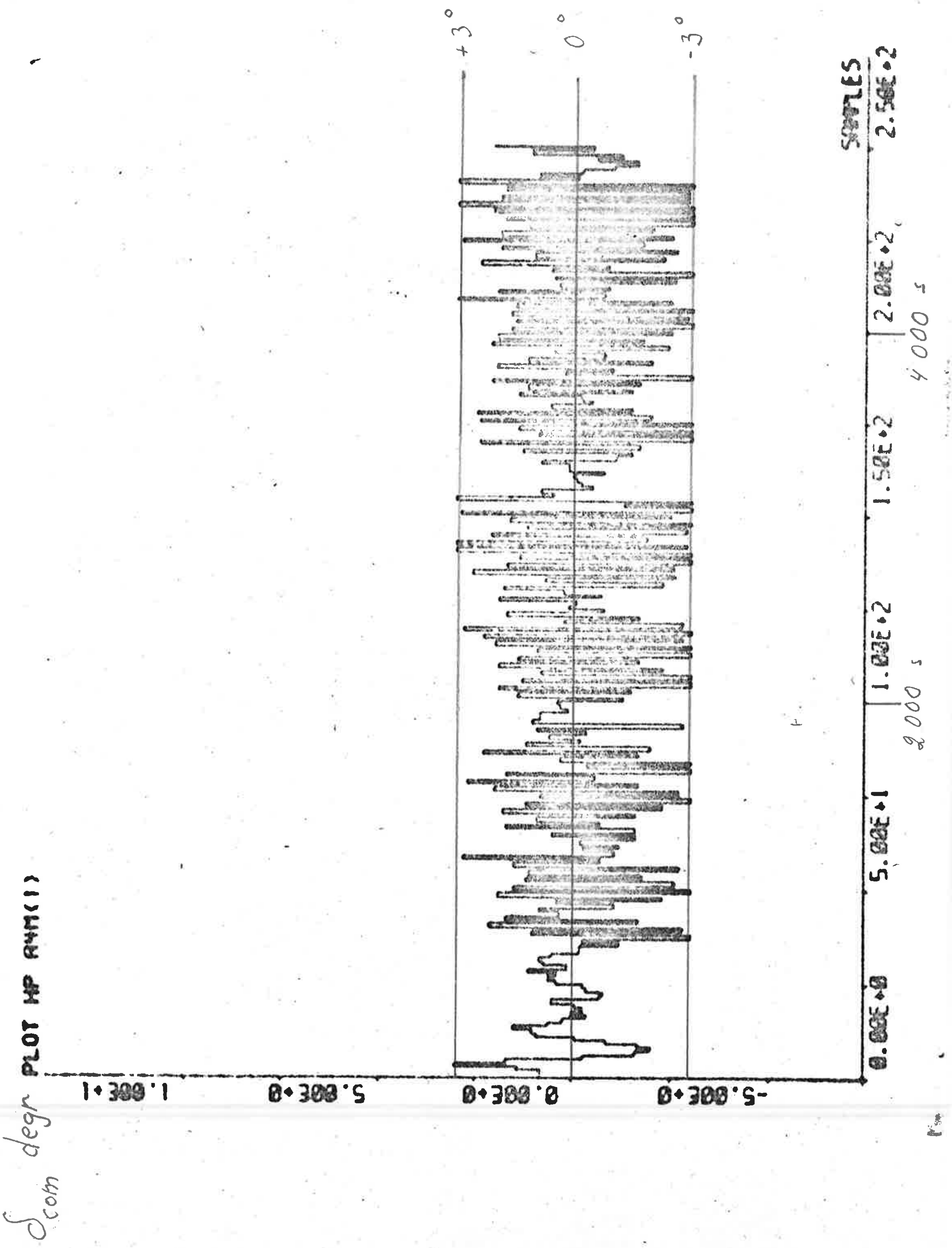
$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix} = \begin{bmatrix} 0.1199 \\ 0.1598 \\ 1.9656 \\ -1.7123 \\ -18.5008 \\ 2.3772 \end{bmatrix} \qquad P \text{ unknown}$$

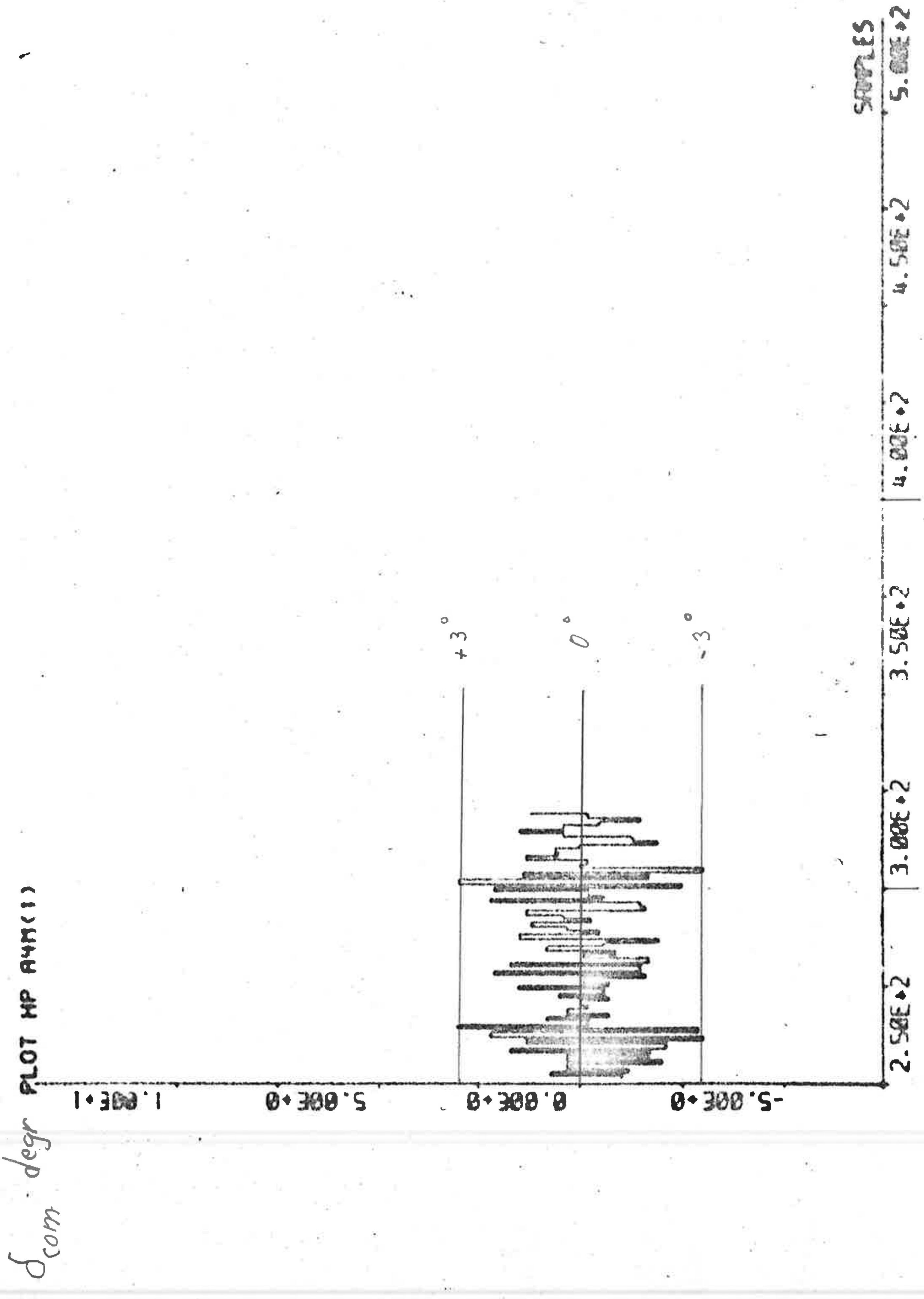
Regulator:

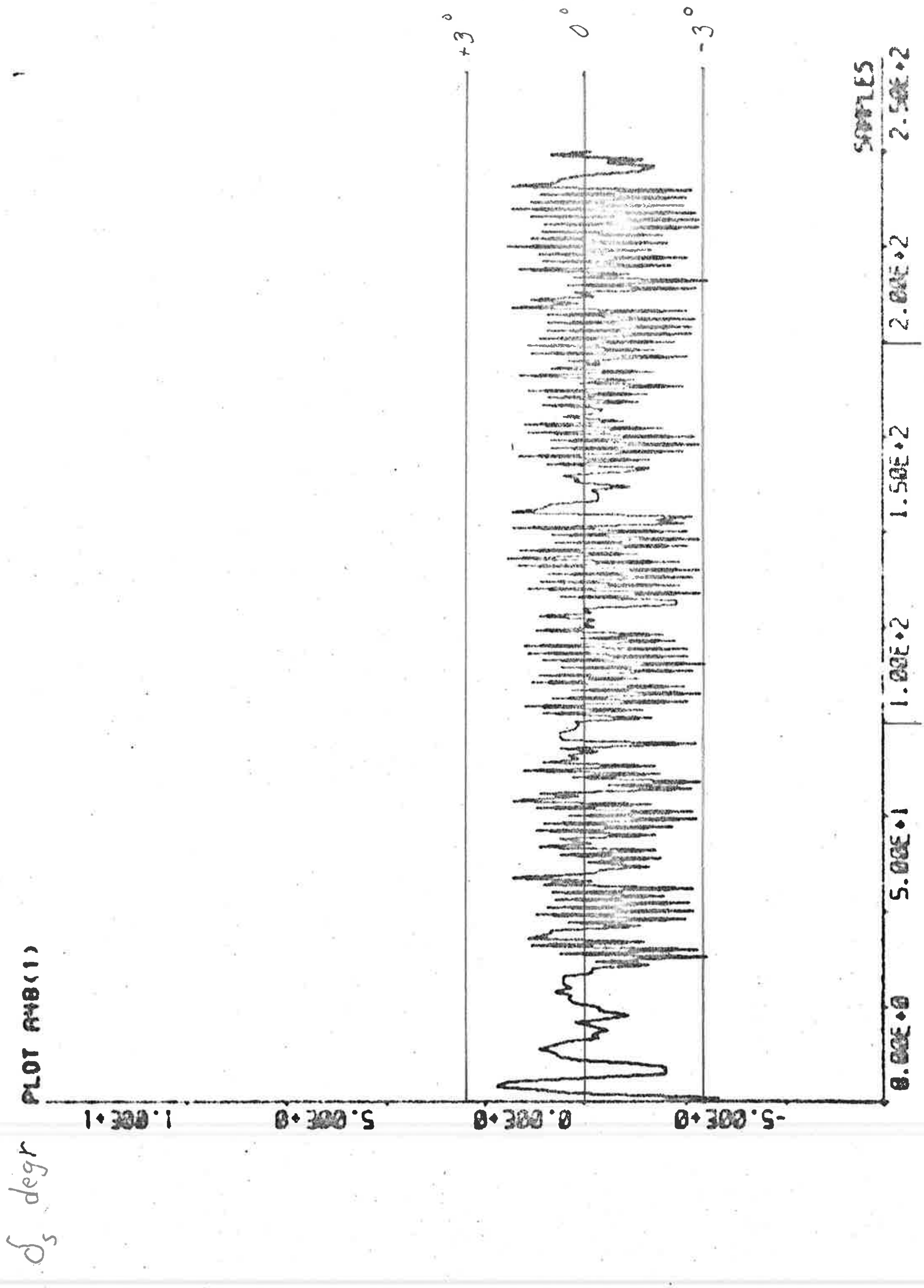
$$\delta(t) = -8.3403(\Psi(t) - \Psi_{ref}) - 1.3328\delta(t-1) - 16.3937\hat{v}(t) + $$
$$+ 14.2811\hat{r}(t) + 154.3019\hat{F}(t) - 19.8265\hat{M}(t)$$

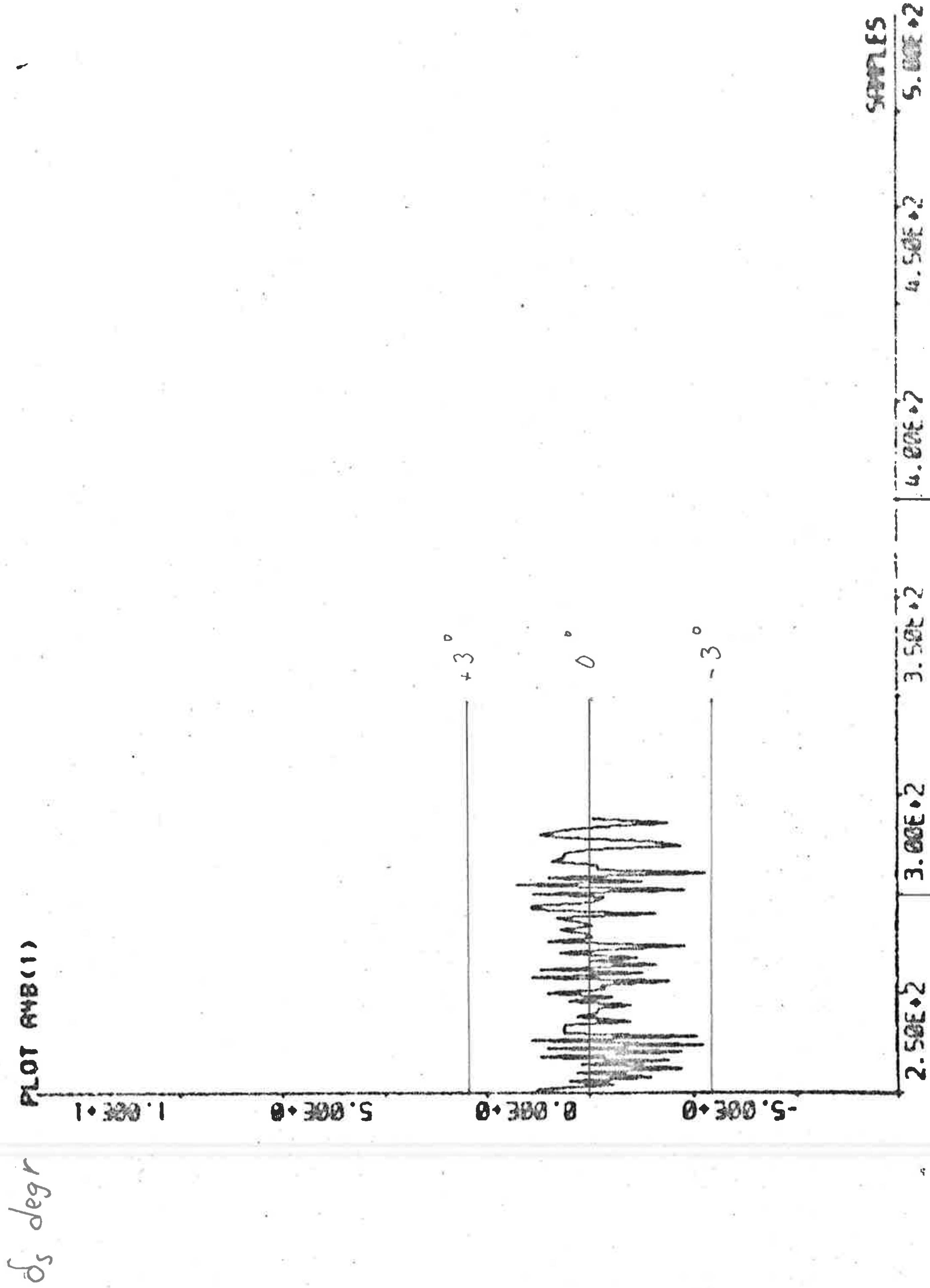
Statistics:

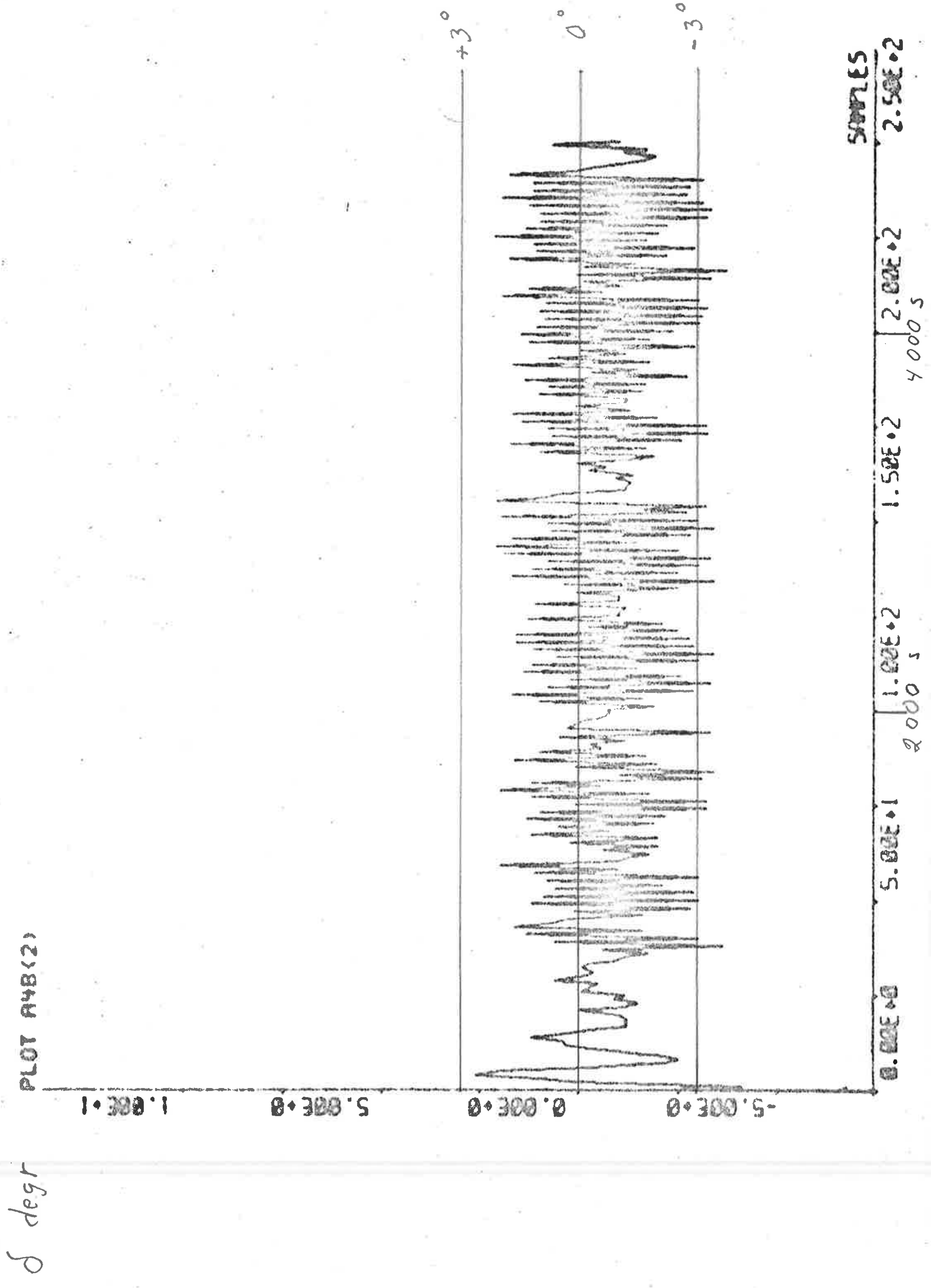
		0 - 6360 s (all data)				4000 - 6360 s			
		Mean value	Standard deviation	Minimum value	Maximum value	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-0.18	1.73	-3.0	3.0	-0.17	1.73	-3.0	3.0
δ_s	degr	-0.38	1.47	-3.3	2.2	-0.33	1.45	-3.1	1.9
δ	degr	-0.65	1.58	-4.1	2.6	-0.63	1.55	-3.7	2.2
v_1	knots	0.069	0.177	-0.36	0.67	-0.004	0.159	-0.36	0.53
v_2	knots	0.107	0.143	-0.36	0.59	0.113	0.109	-0.23	0.35
r	degr/s	0.0026	0.0163	-0.054	0.041	0.0023	0.0153	-0.041	0.041
Ψ	degr	142.040	0.310	141.06	143.26	142.053	0.213	141.50	142.56
u	knots	16.601	0.188	16.05	17.06	16.595	0.159	16.25	17.02
$\hat{v}$	m/s	0.046	0.058	-0.14	0.24	0.030	0.053	-0.09	0.17
$\hat{r}$	degr/s	-0.0016	0.0167	-0.049	0.052	-0.0070	0.0128	-0.038	0.024
$\hat{F}$	m/s^2	-0.000051	0.004593	-0.01978	0.01757	-0.000399	0.004050	-0.01082	0.00892
$\hat{M}$	$degr/s^2$	0.000461	0.002965	-0.00810	0.01095	-0.000067	0.002544	-0.00641	0.00594

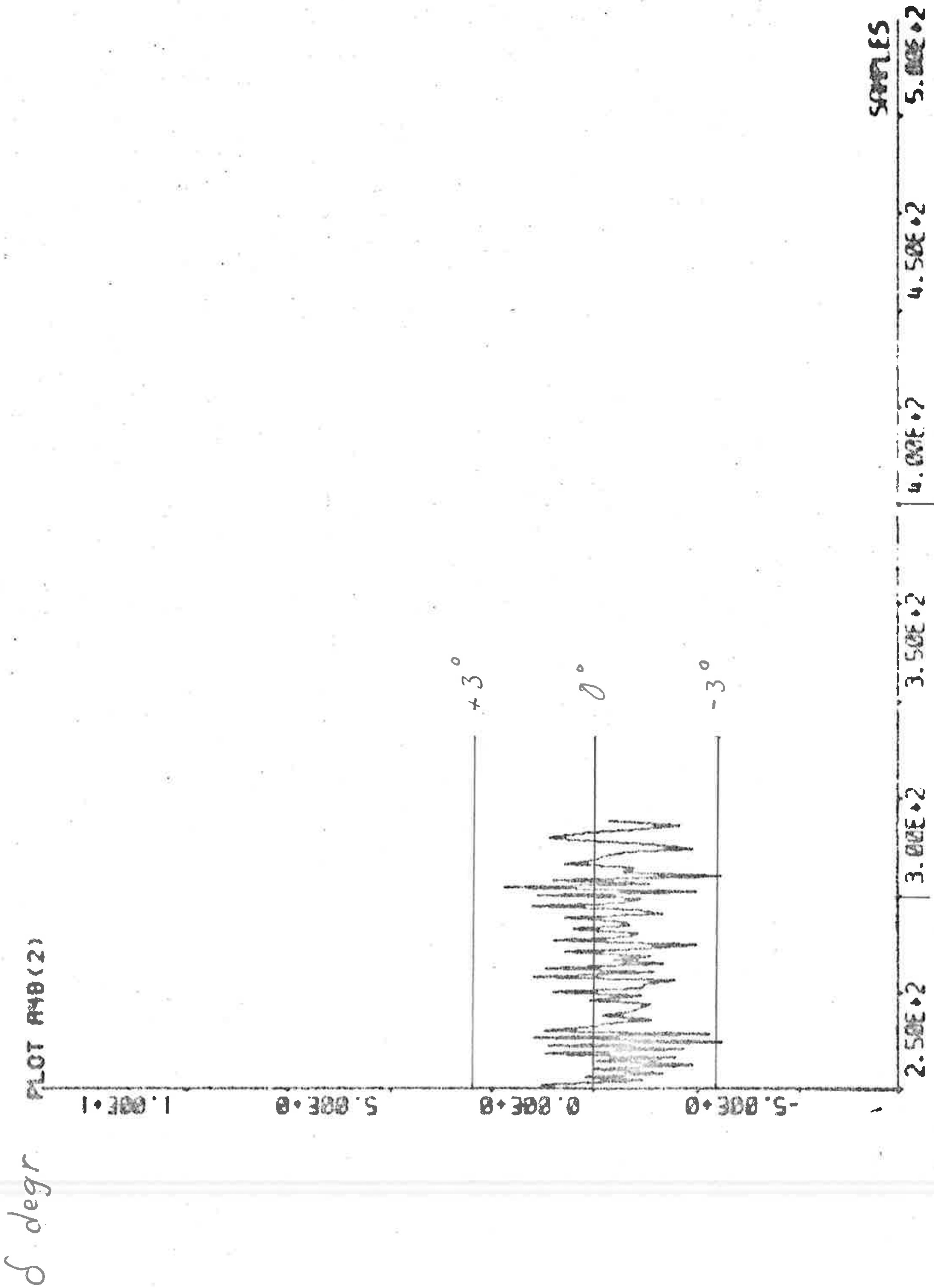

PLOT HP R4M(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δcom degr

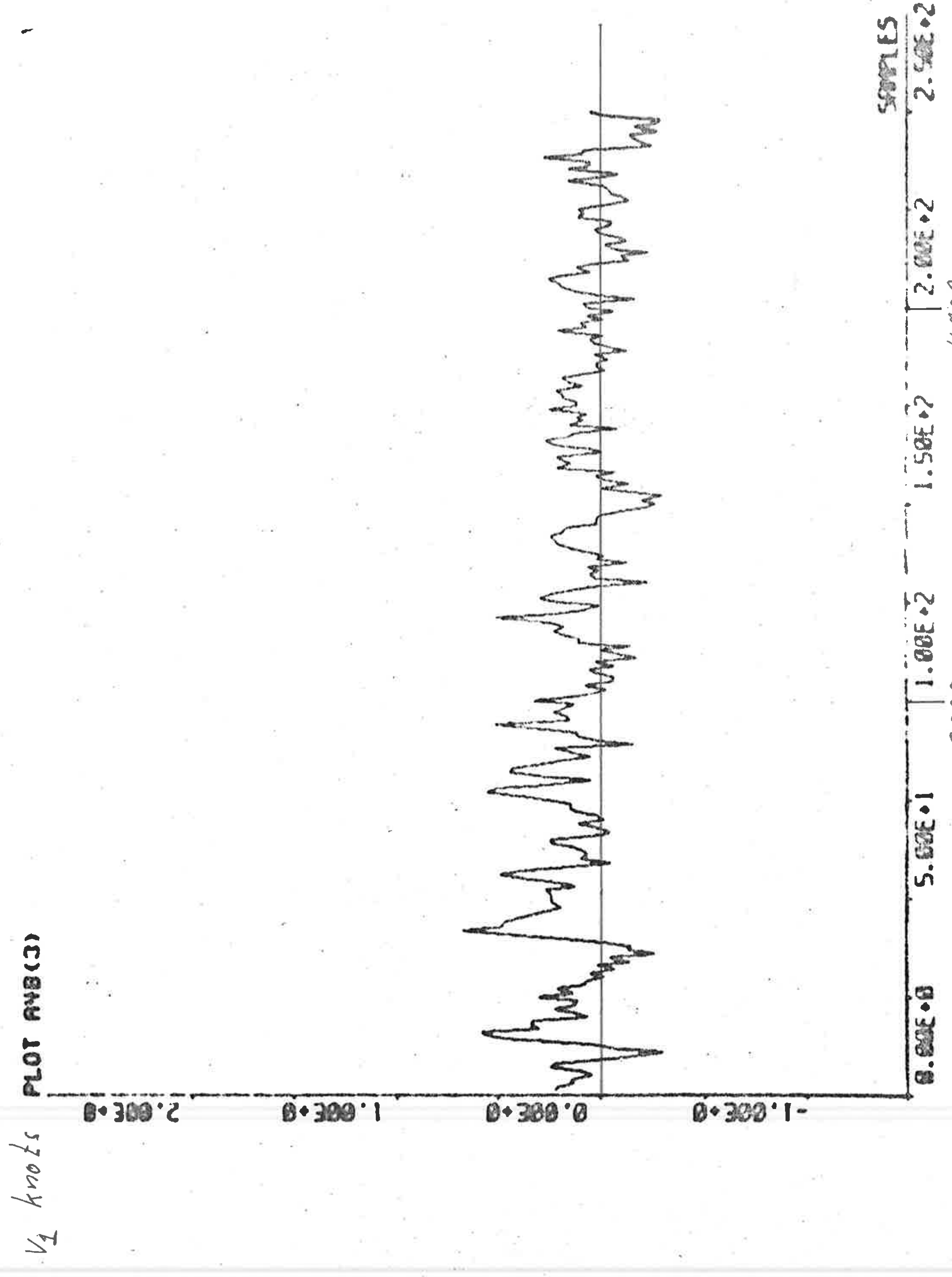

PLOT HP A4M(1)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
6000 s
8000 s
δ_{com} degr


PLOT A+B(1)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
2000 s
4000 s
δs degr

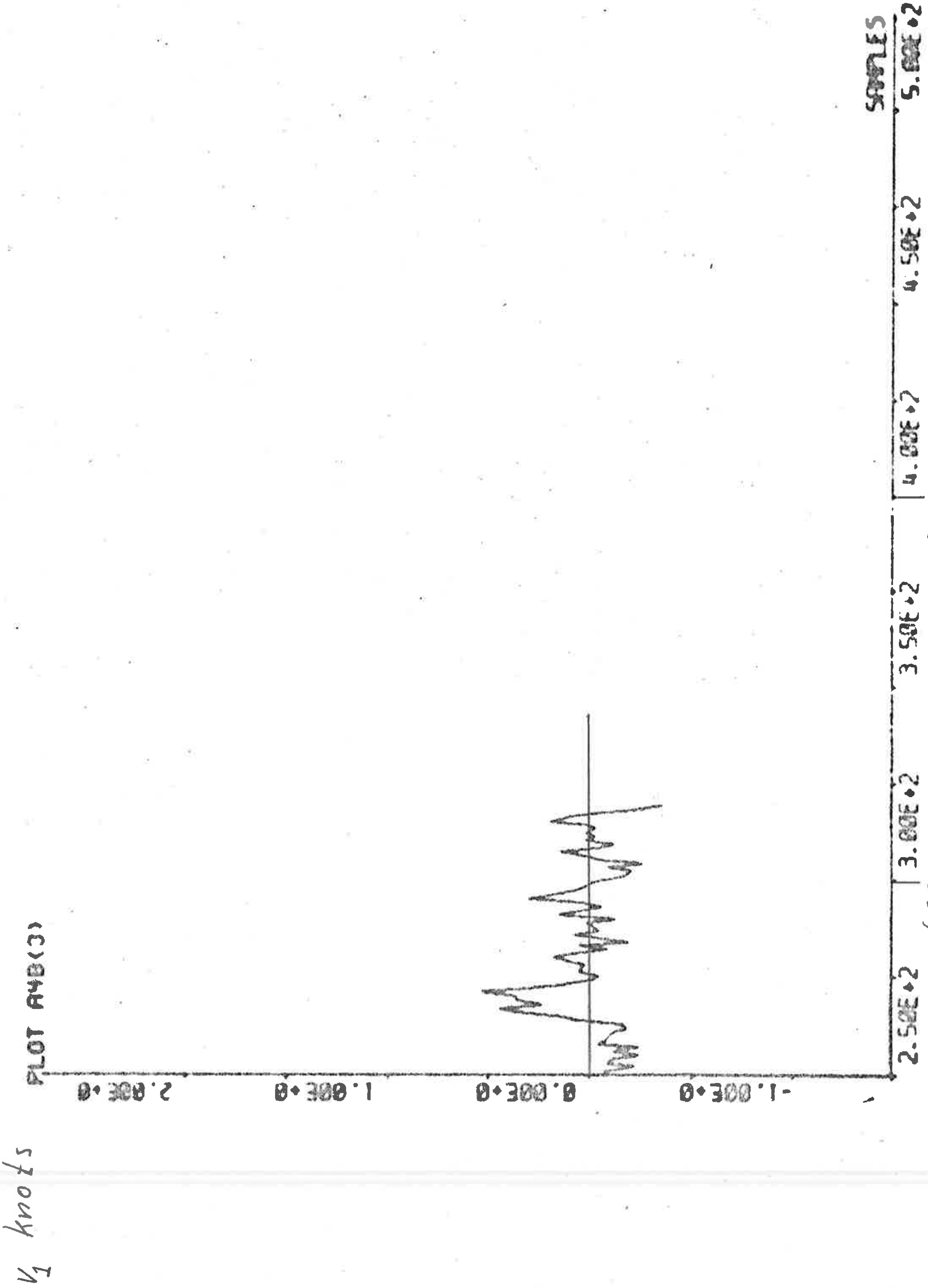

PLOT AYB(1)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
6000 s
8000 s
δs degr

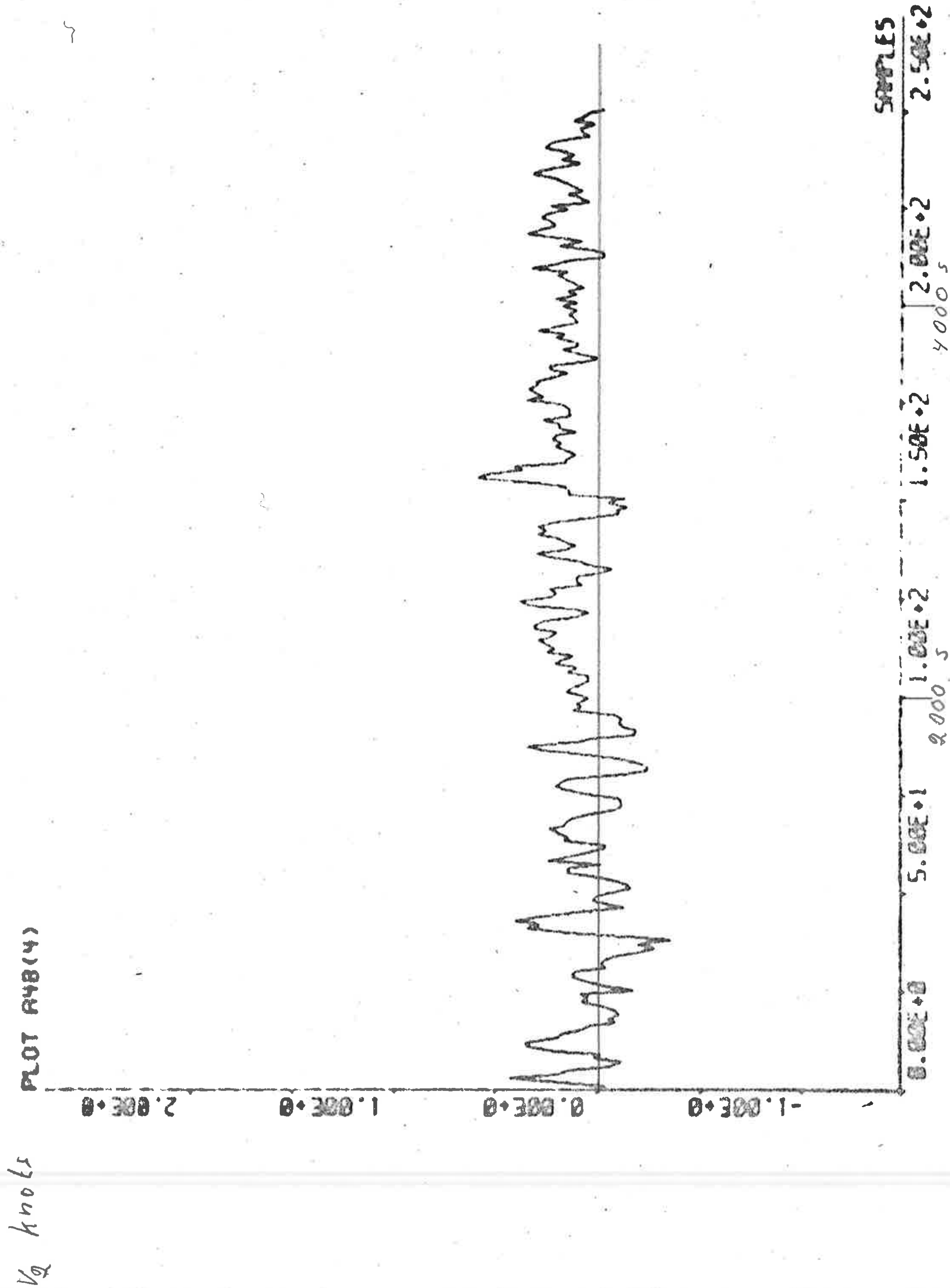

PLOT A4B(2)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
+3°
0°
-3°
δ degr

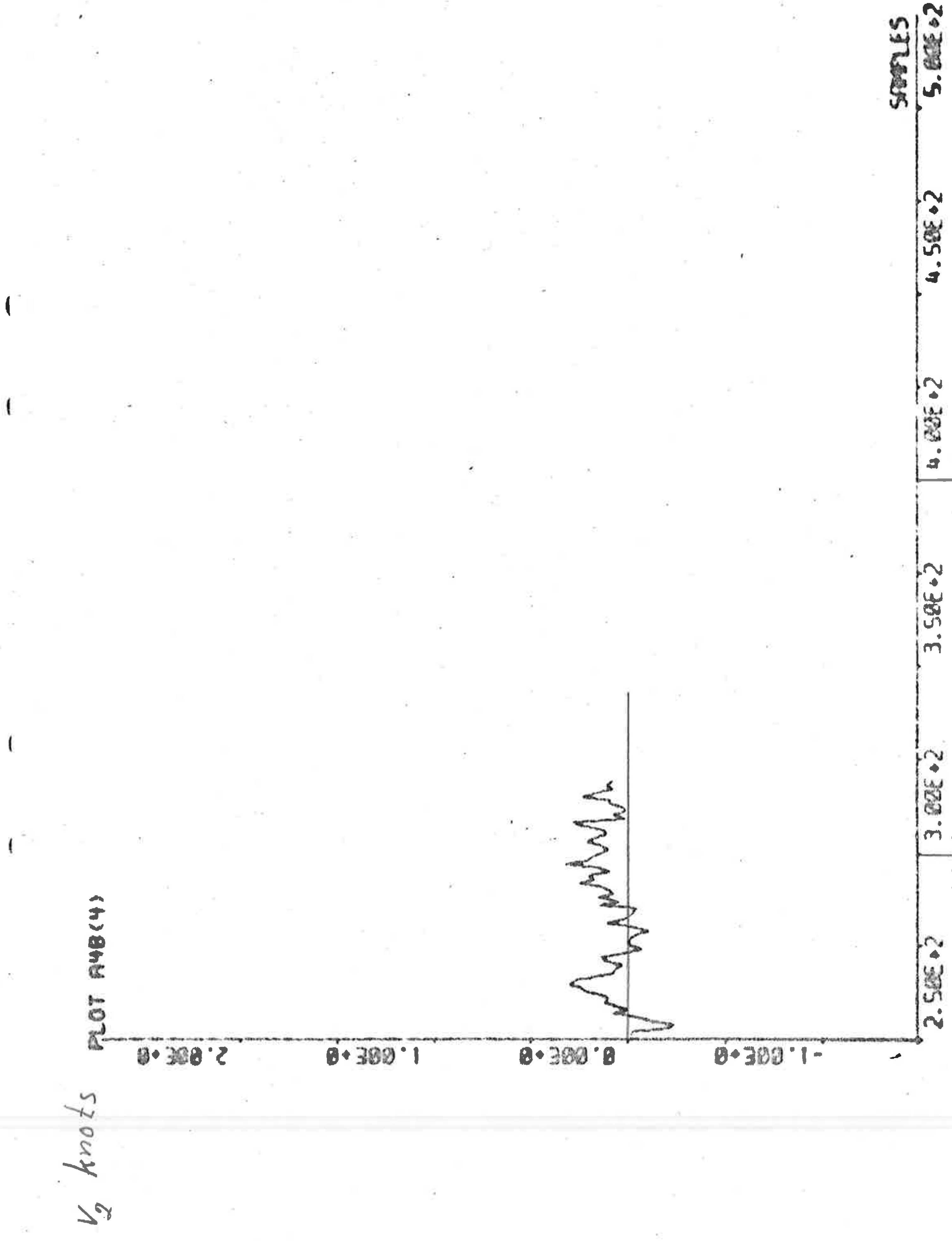

PLOT A4B(2)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
6000 s
8000 s
δ degr



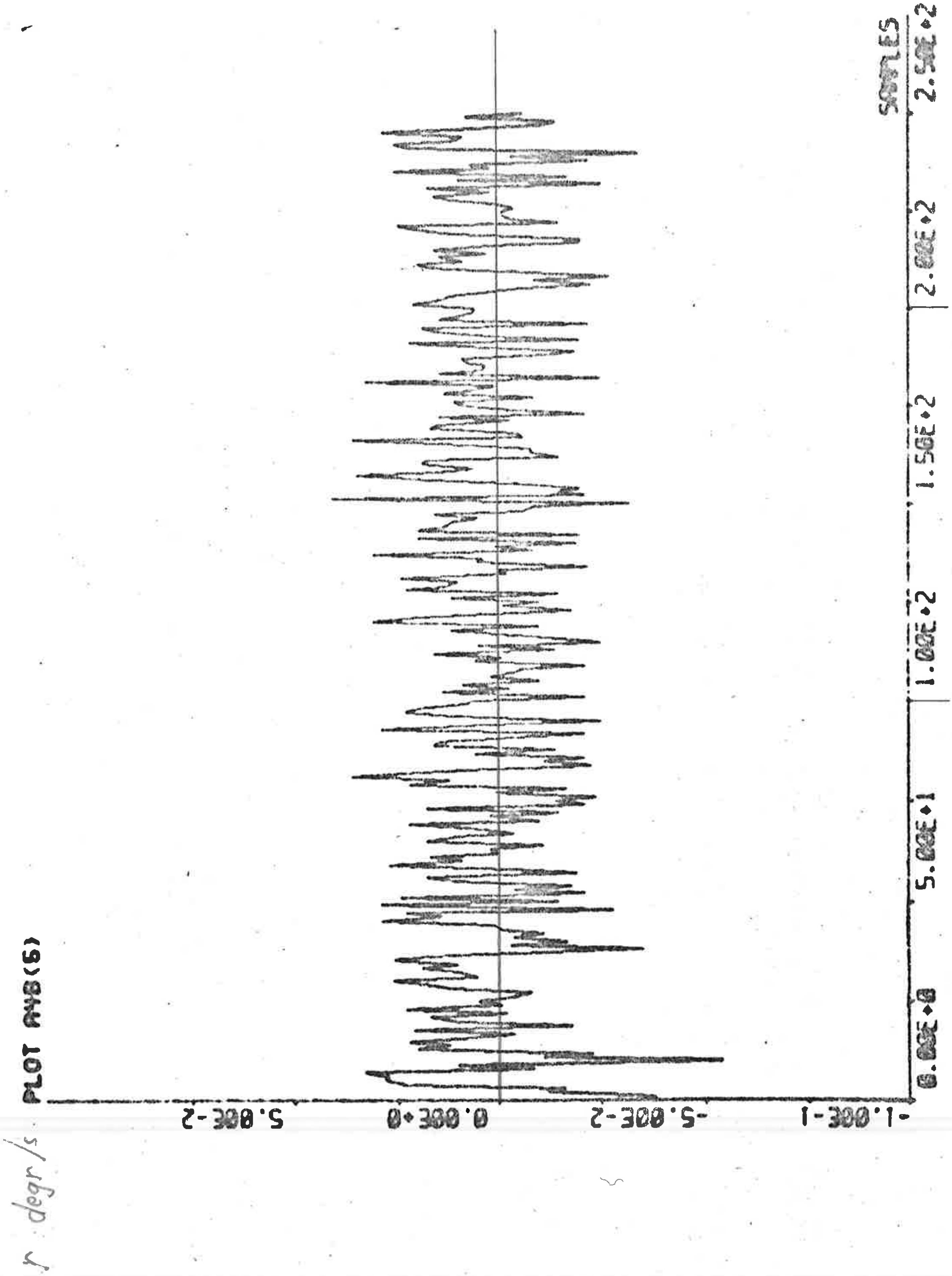
PLOT AVB(3)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
V1 knots

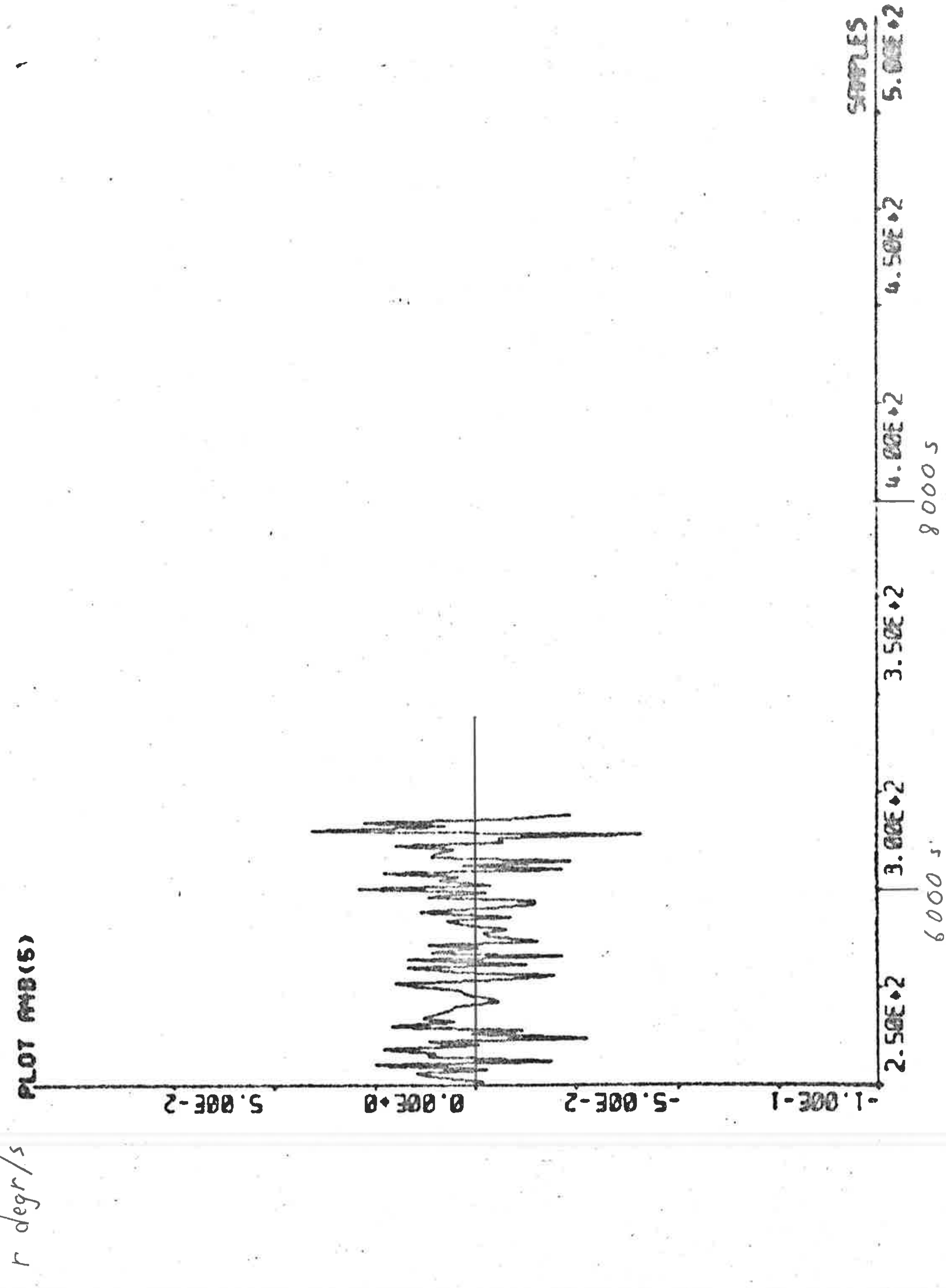

PLOT A4B(3)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_1 knots

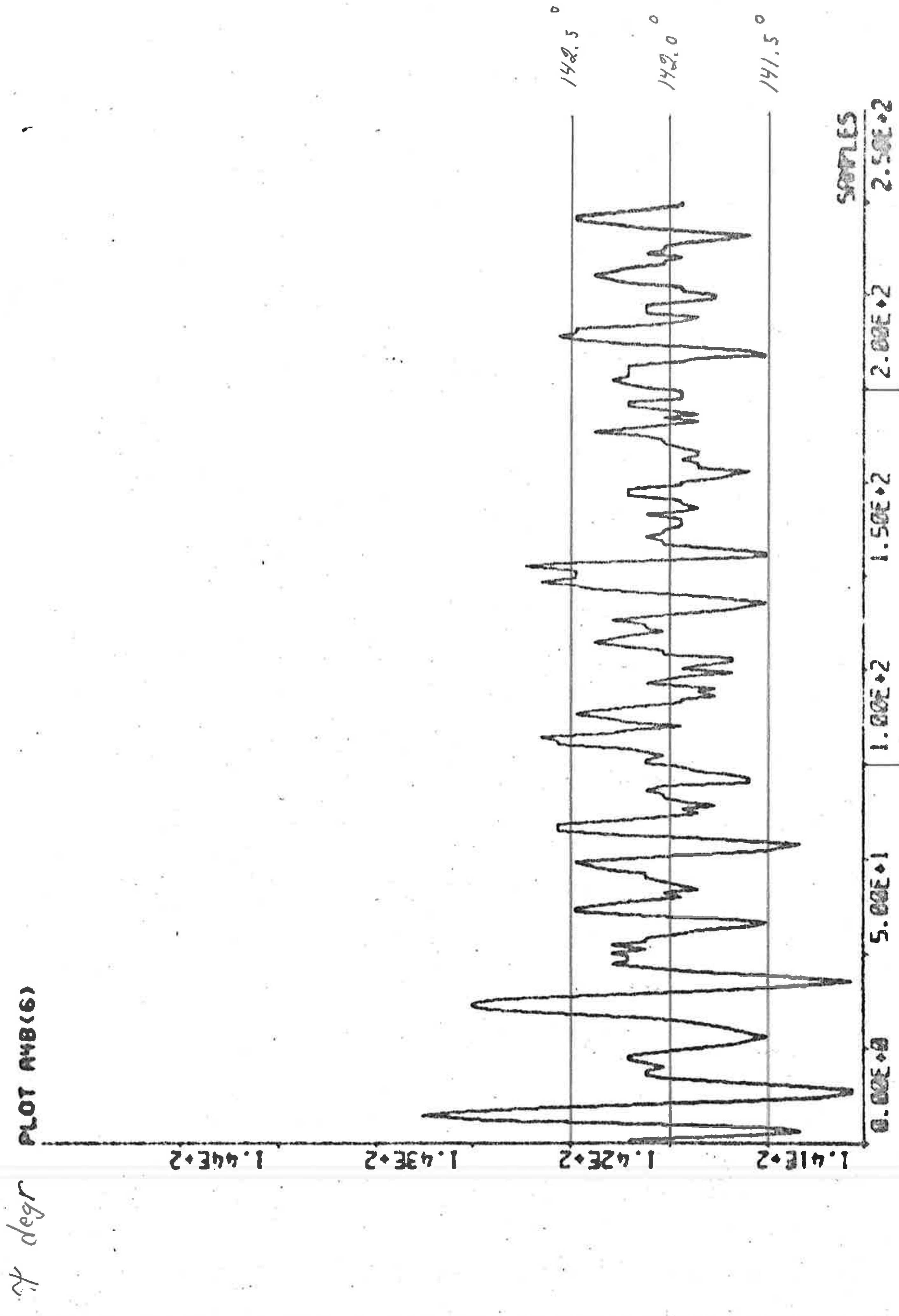

PLOT R4B(4)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
2000 s
4000 s
Vq knots

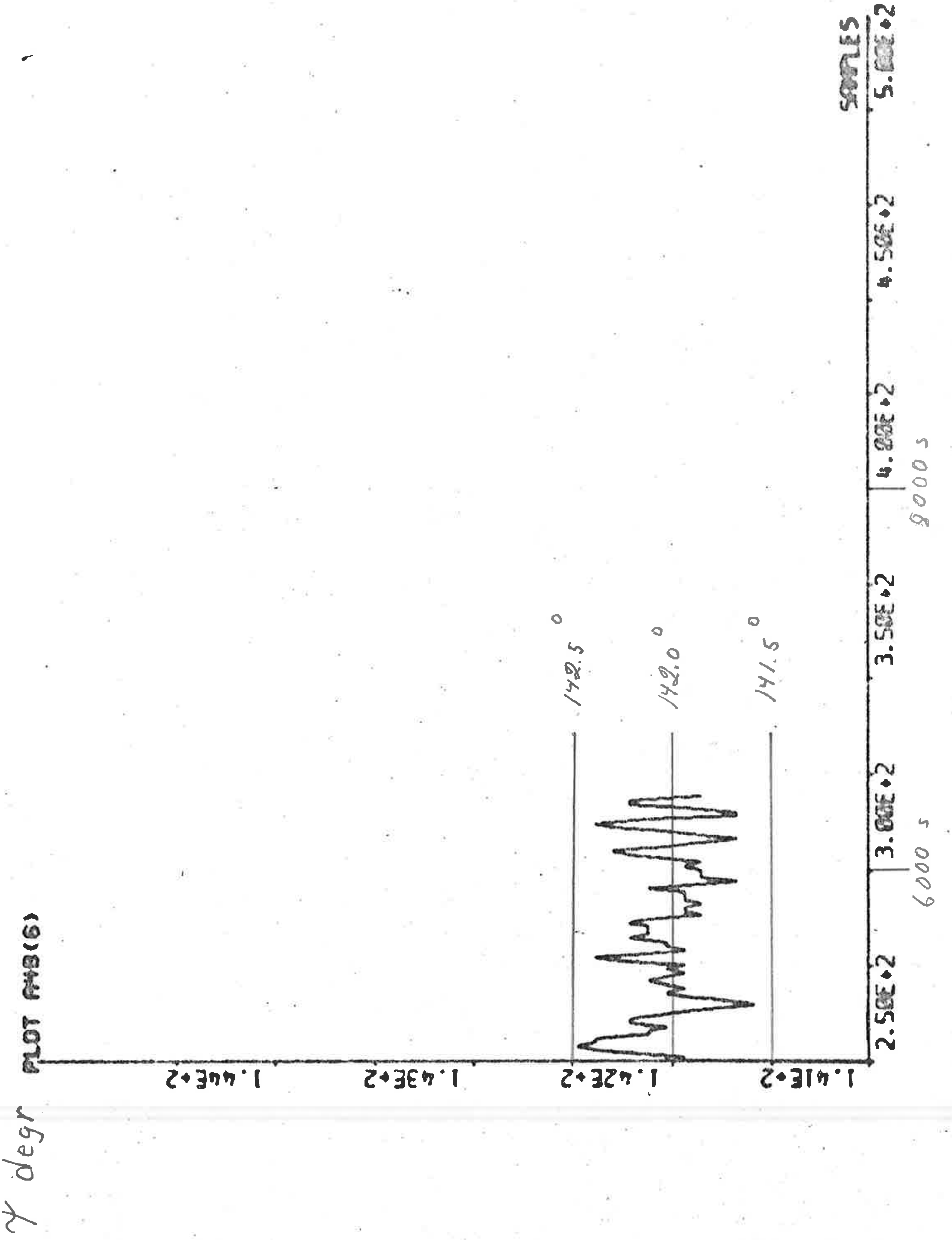


PLOT A4B(4)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
2.000E+0
1.000E+0
0.000E+0
-1.000E+0
6000 s
8000 s
V2 knots

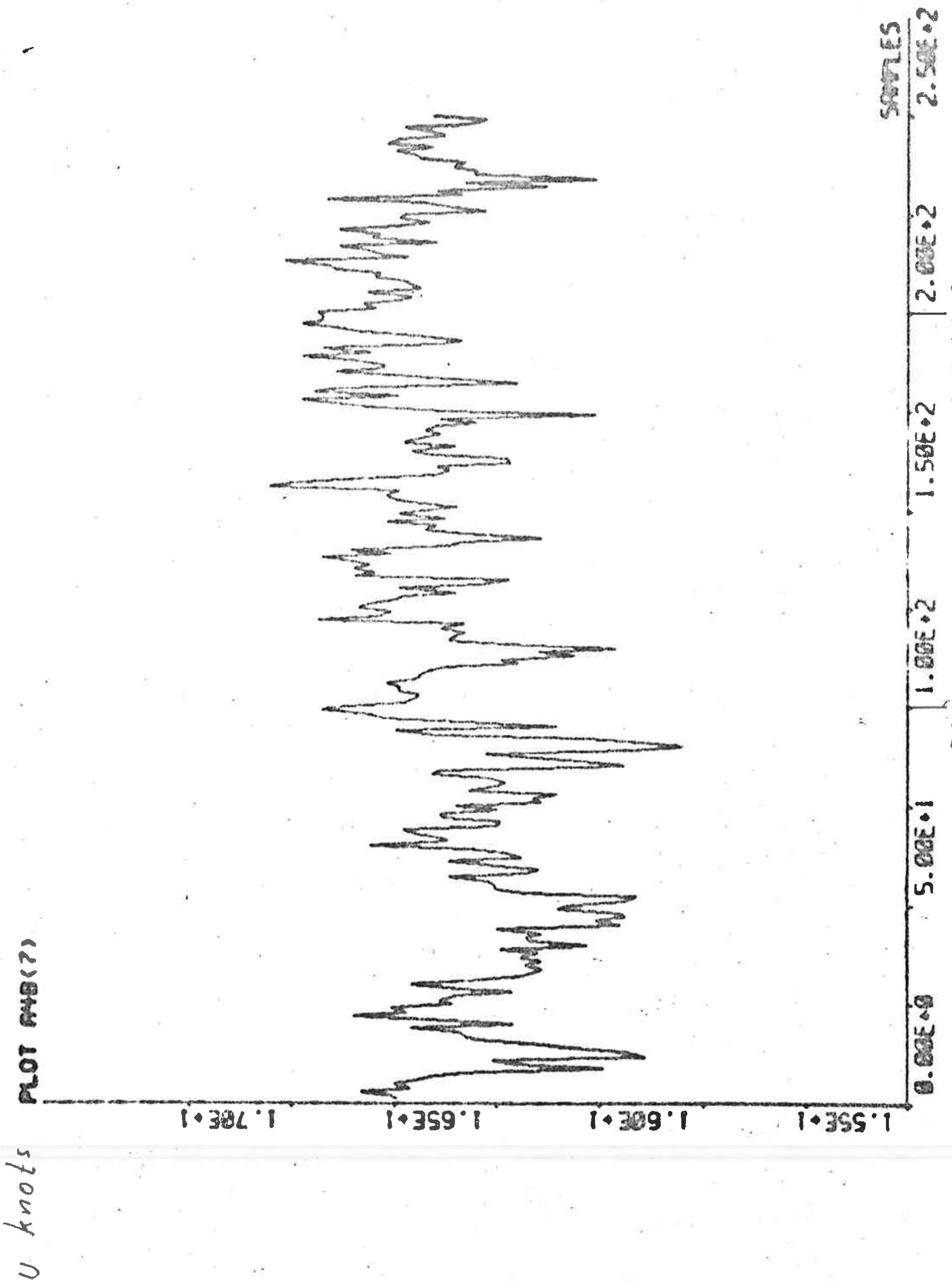

PLOT AYB(S)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s
2000 s
4000 s


PLOT AMB(S)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
6000 s
8000 s
r degr/s

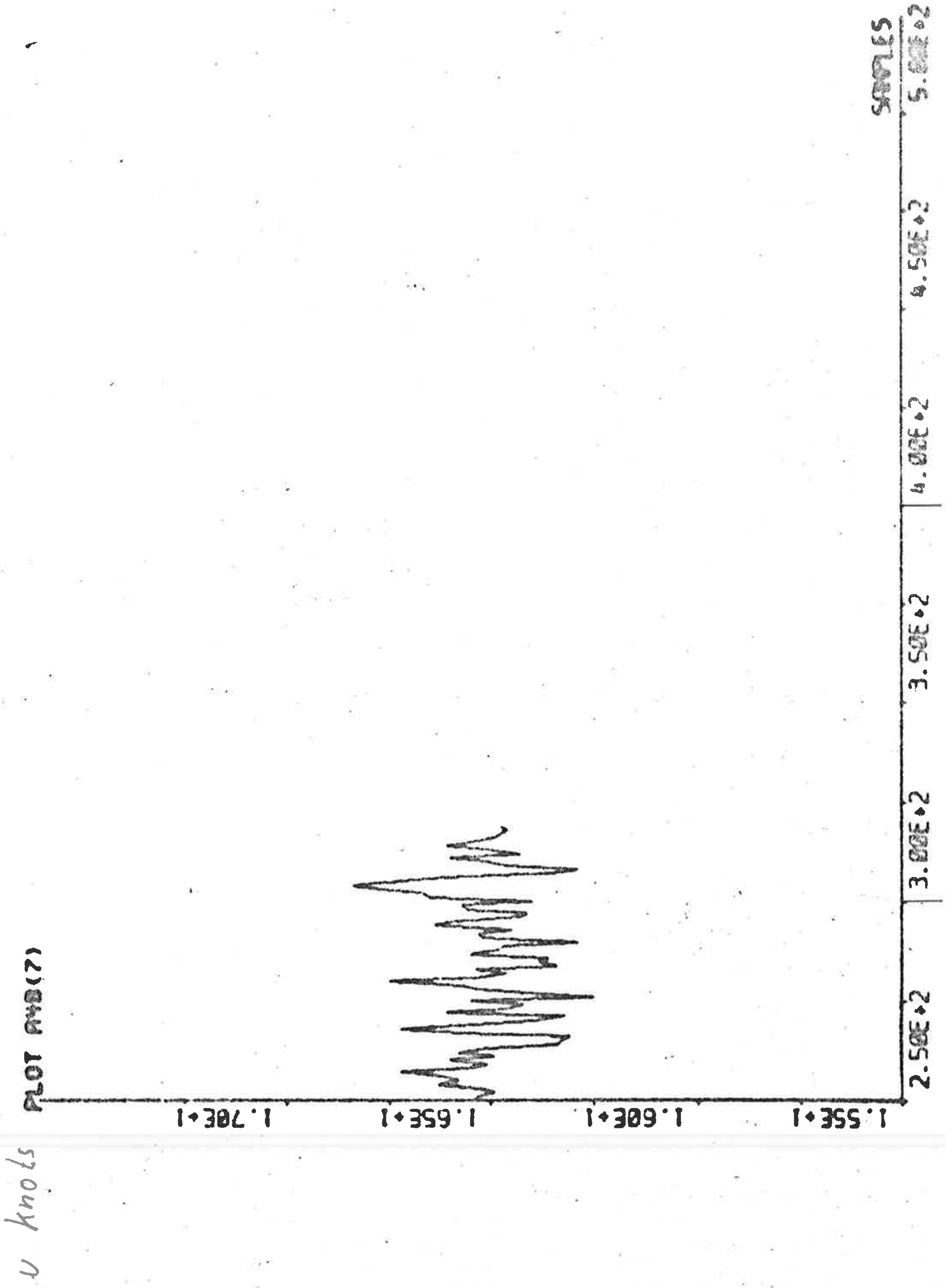

PLOT AVB(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
142.5°
142.0°
141.5°
2000 s
4000 s

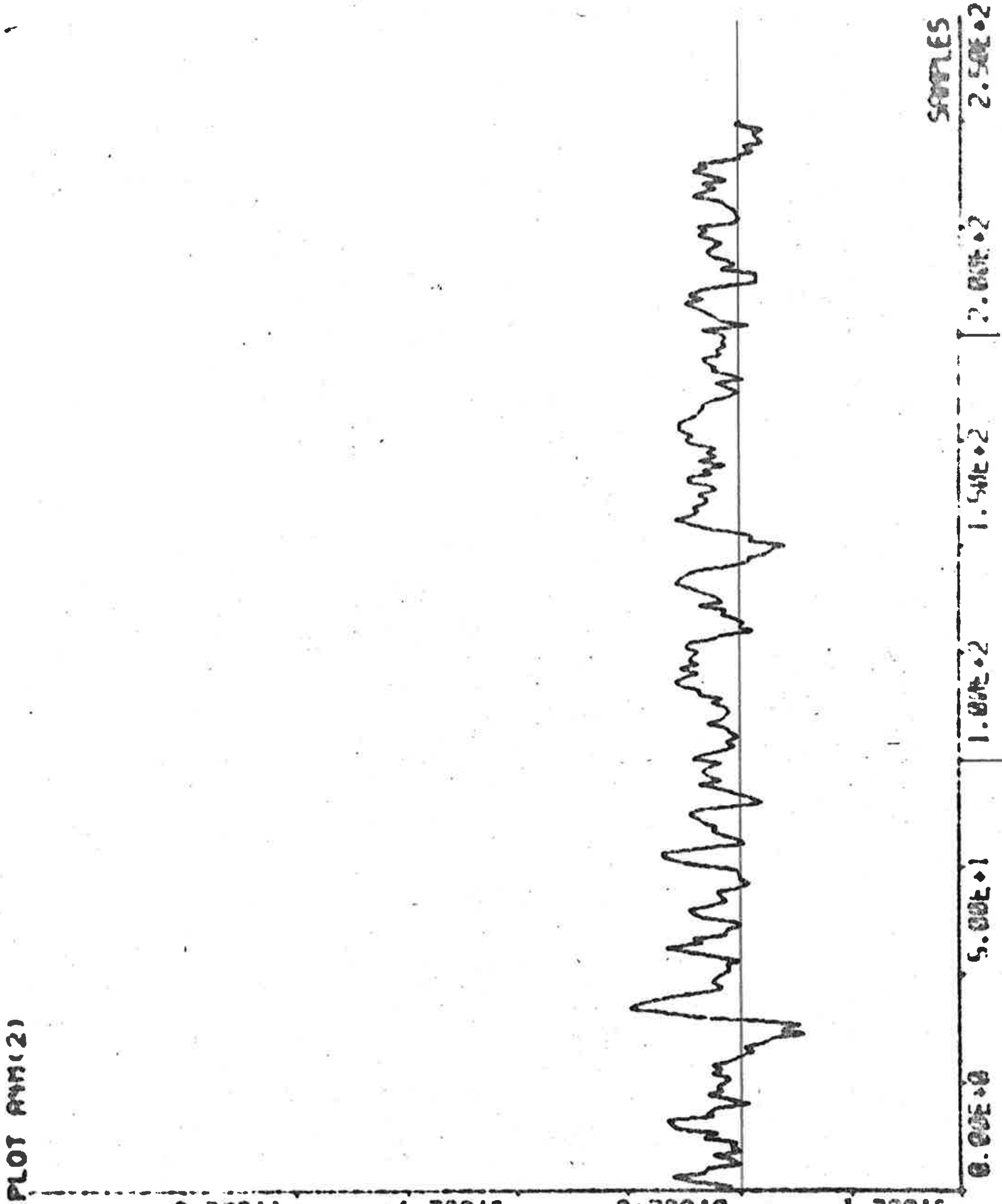


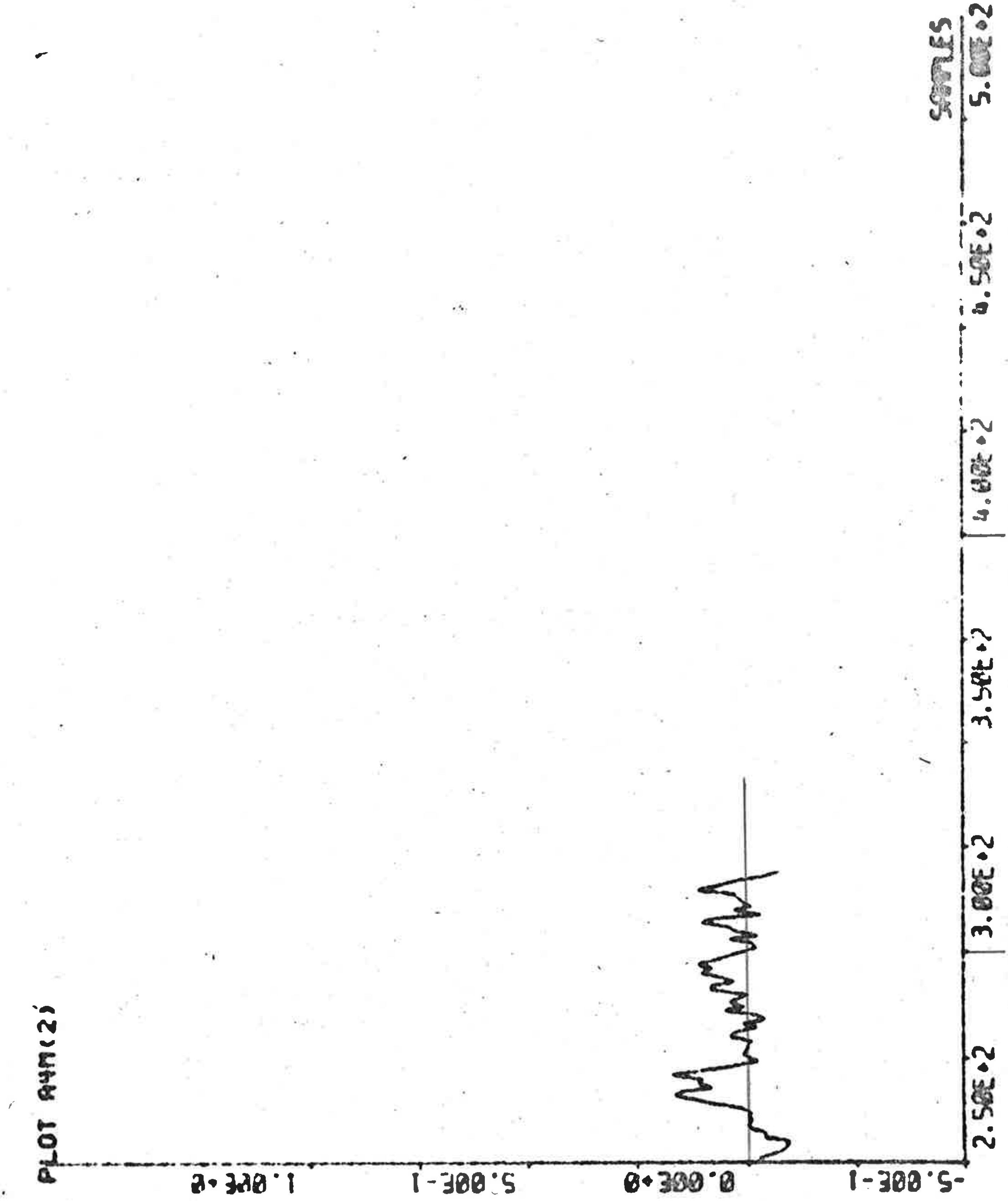
PLOT A+B(6)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
1.41E+2
1.42E+2
1.43E+2
1.44E+2
142.5°
142.0°
141.5°
6000 s
8000 s
γ degr

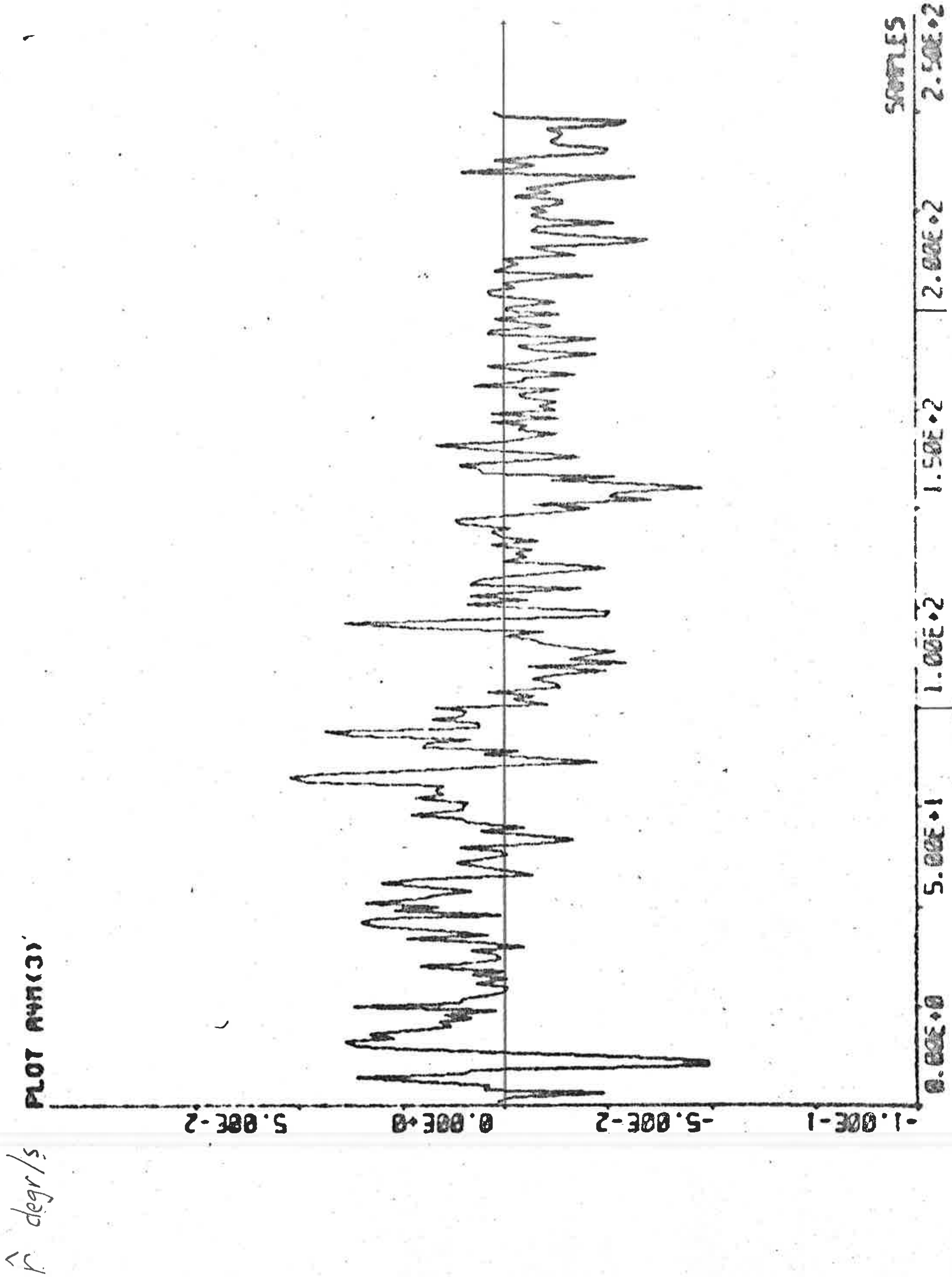


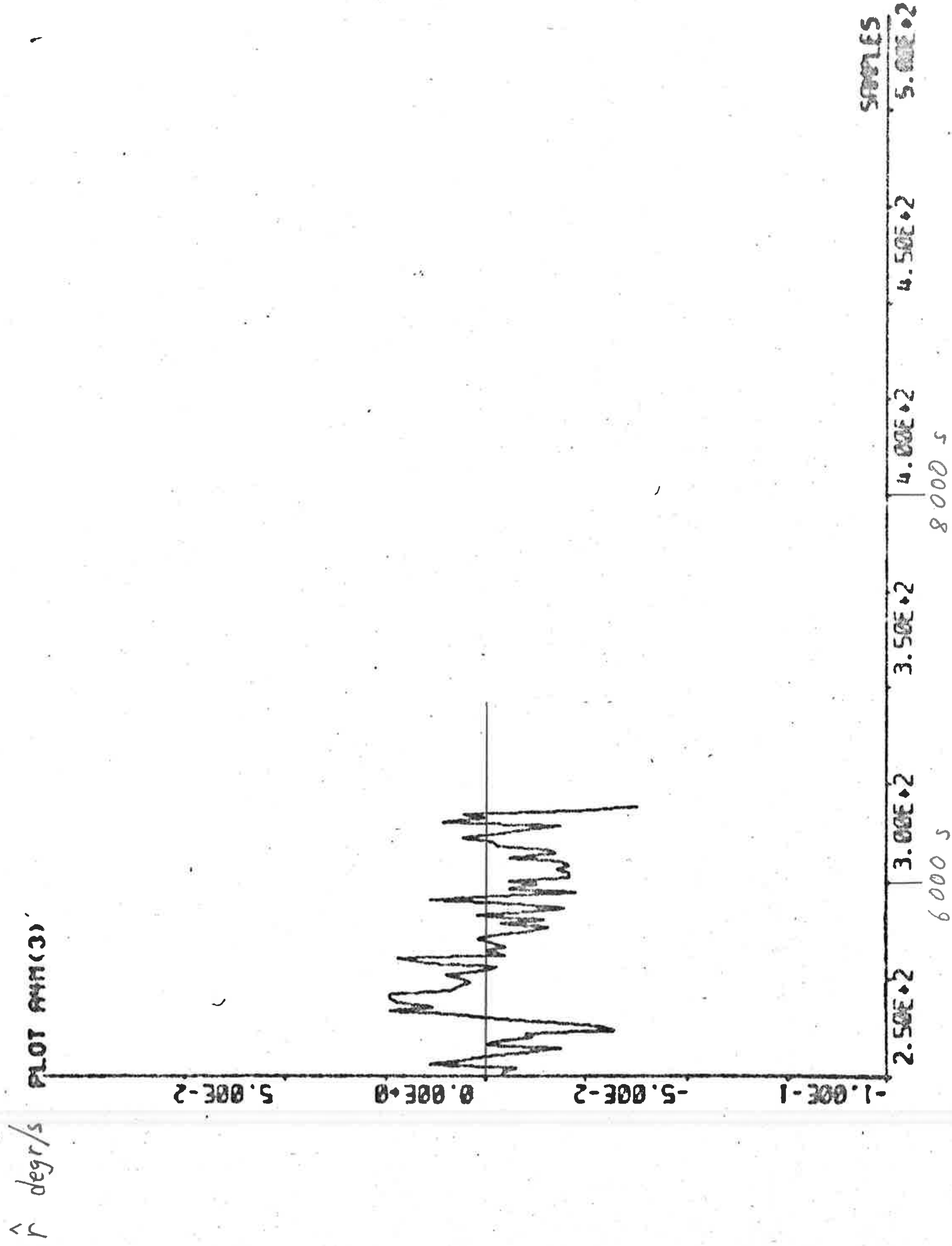
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
1.55E+1
1.60E+1
1.65E+1
1.70E+1
2000 s
4000 s
U knots

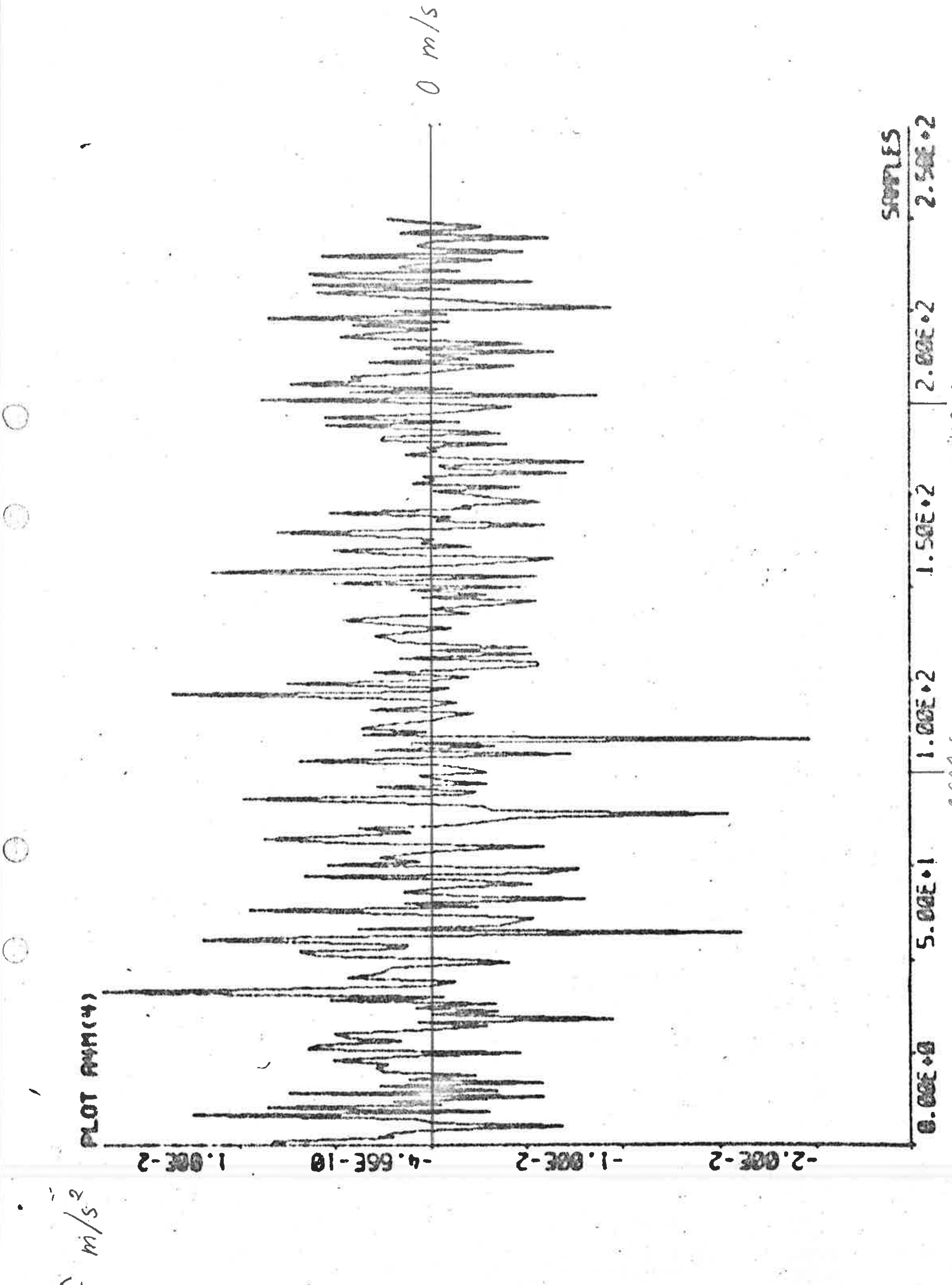

PLOT AVB(7)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
1.55E+1
1.60E+1
1.65E+1
1.70E+1
6000 s
8000 s
v knots

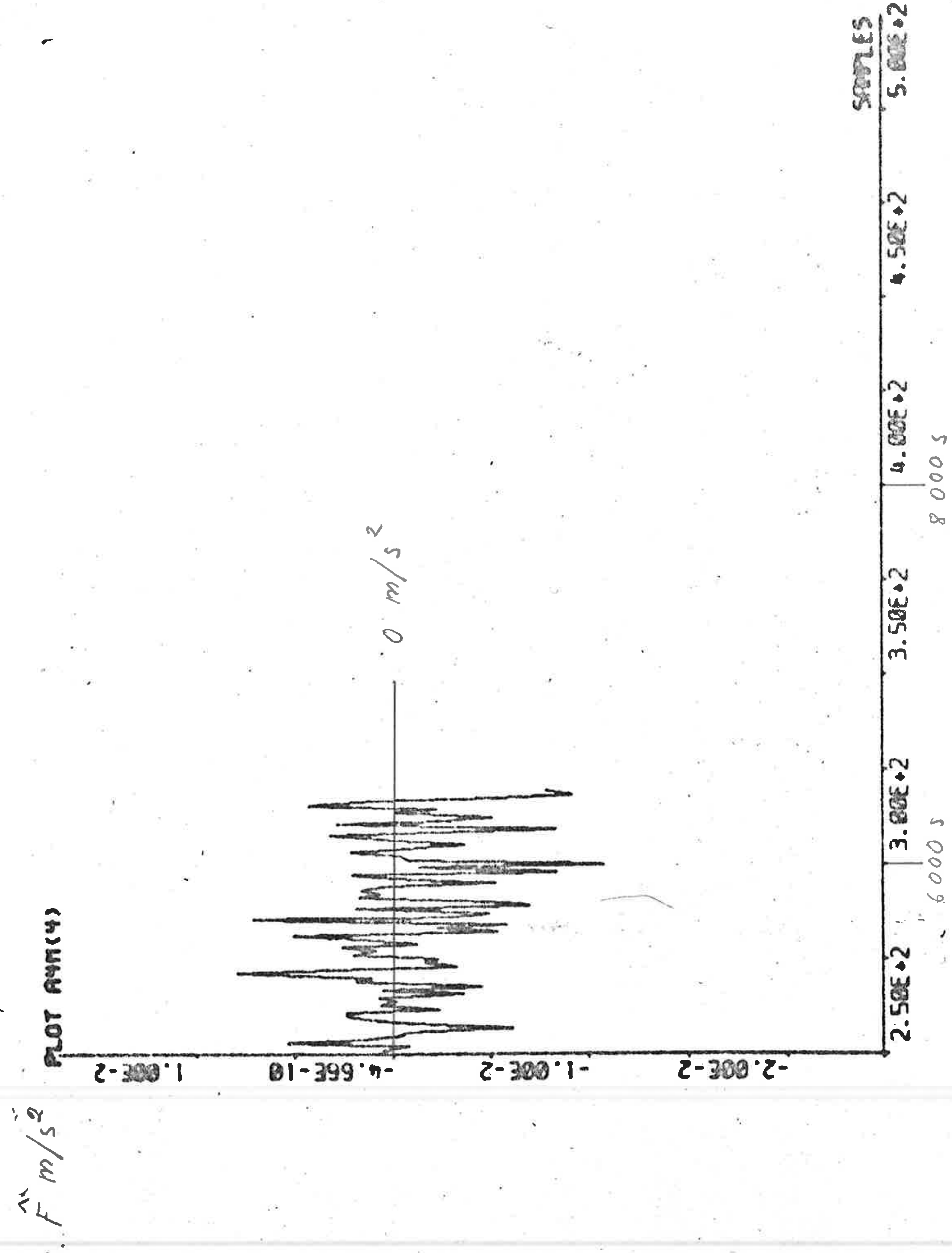

PLOT AMM(2)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
-5.00E-1
0.00E+0
5.00E-1
1.00E+0
2000 s
4000 s

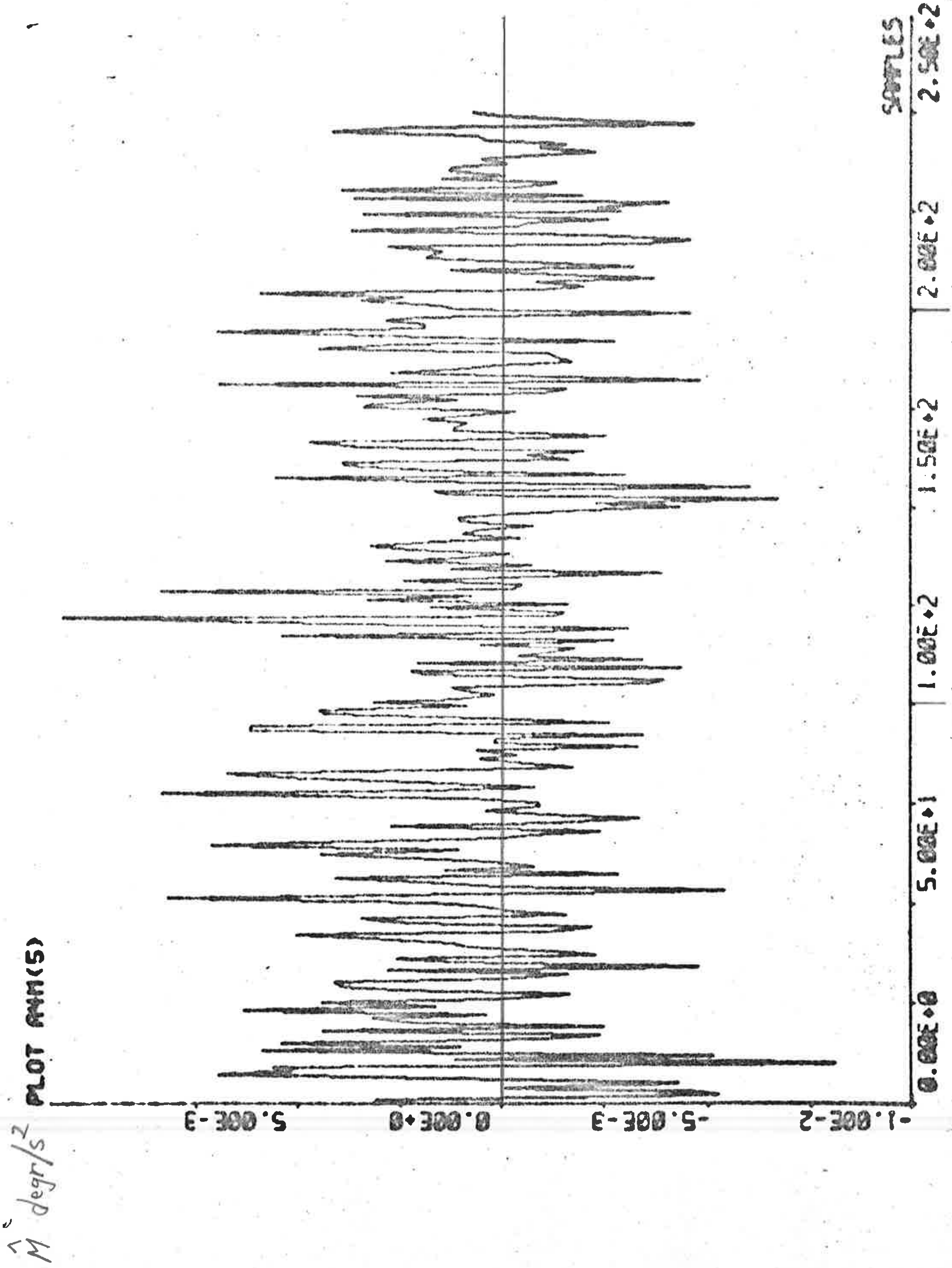

PLOT A4M(2)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
-5.00E-1
0.00E+0
5.00E-1
1.00E+0

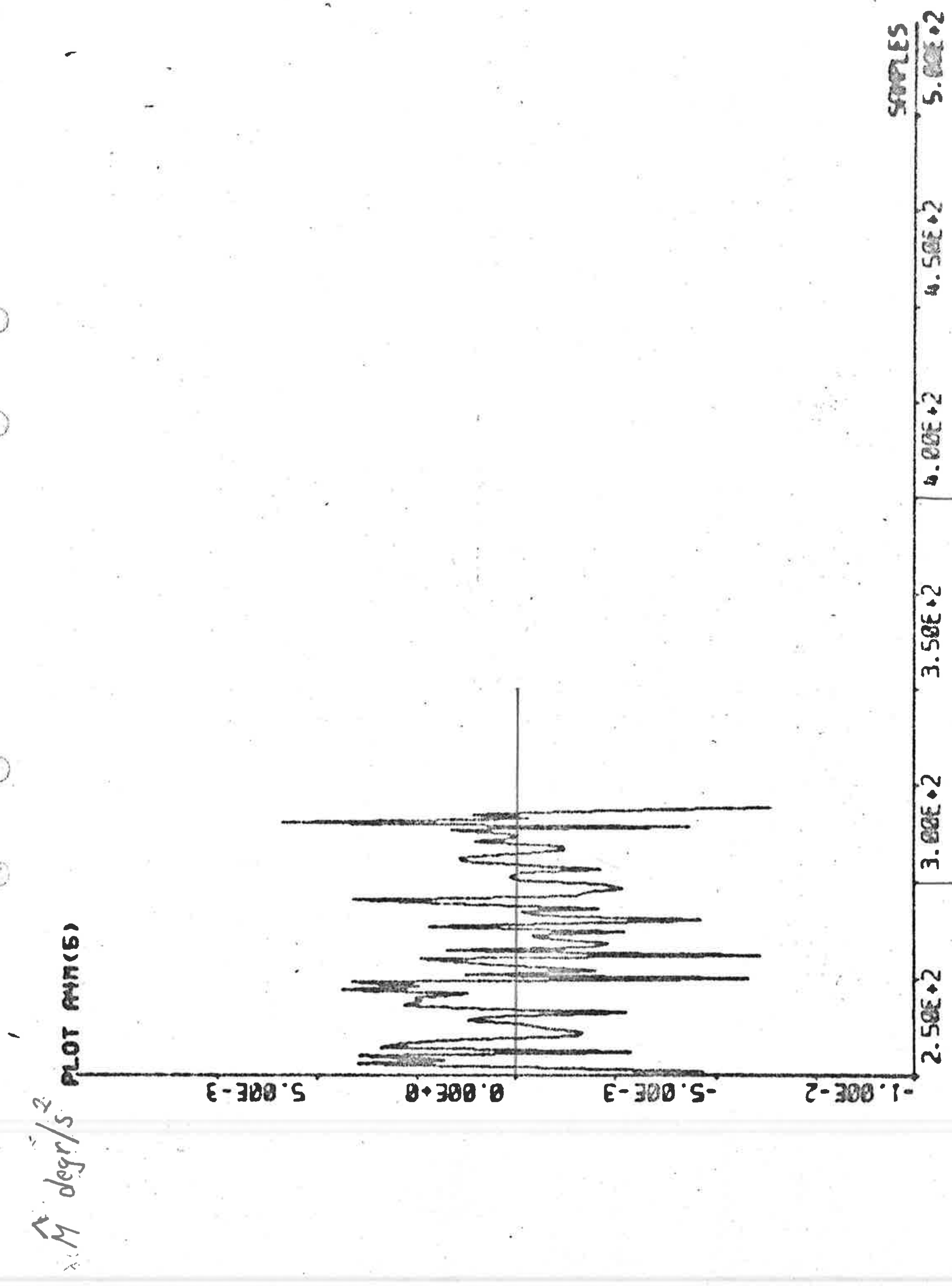

PLOT AVM(3)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
r̂ degr/s

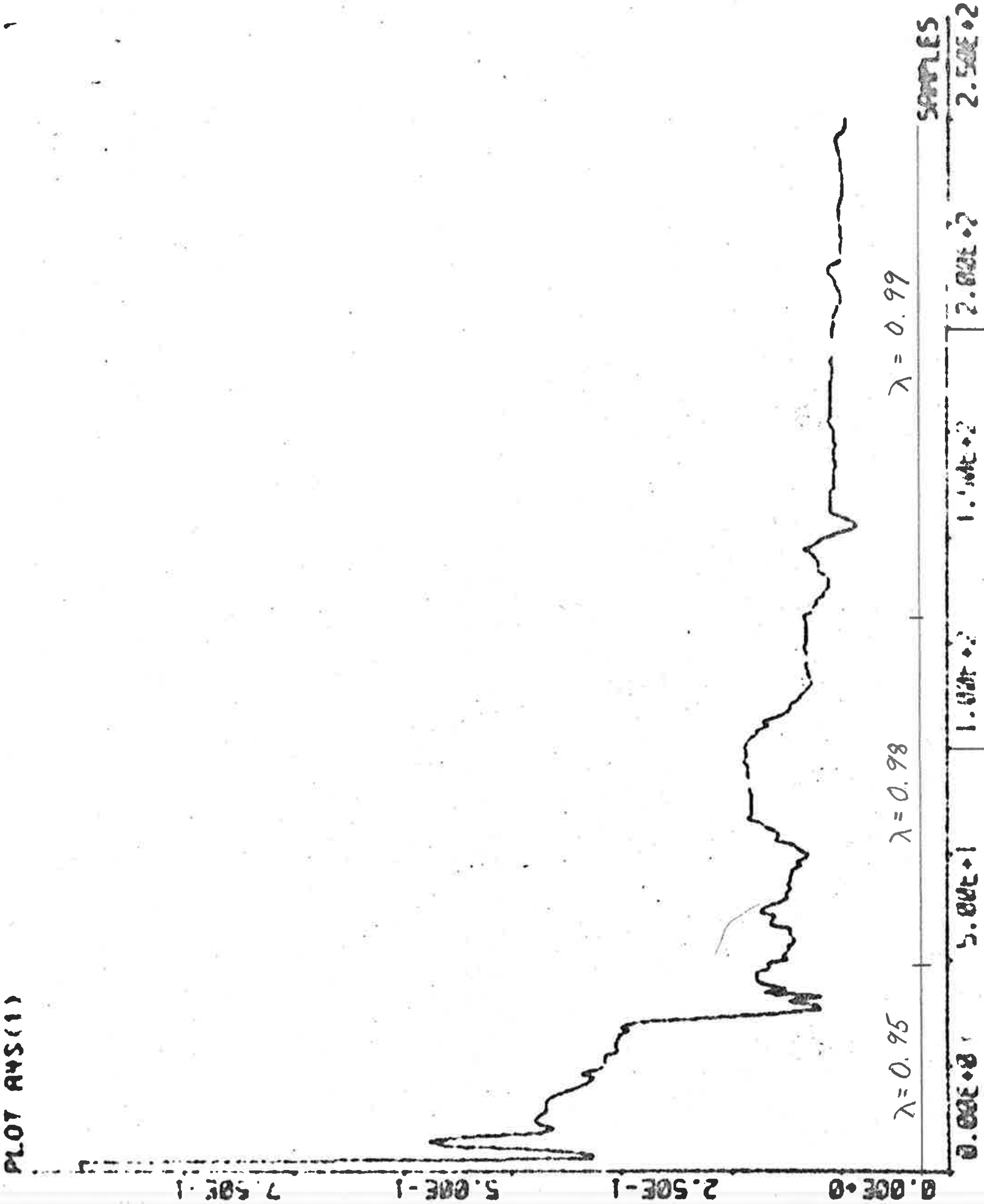

PLOT AYM(3)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
SAMPLES
6000 s
8000 s
r̂ degr/s


0 m/s²
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
0.00E+0
5.00E+1
1.00E+2
2000 s
1.50E+2
2.00E+2
4000 s
2.50E+2
SAMPLES
F̂ m/s²

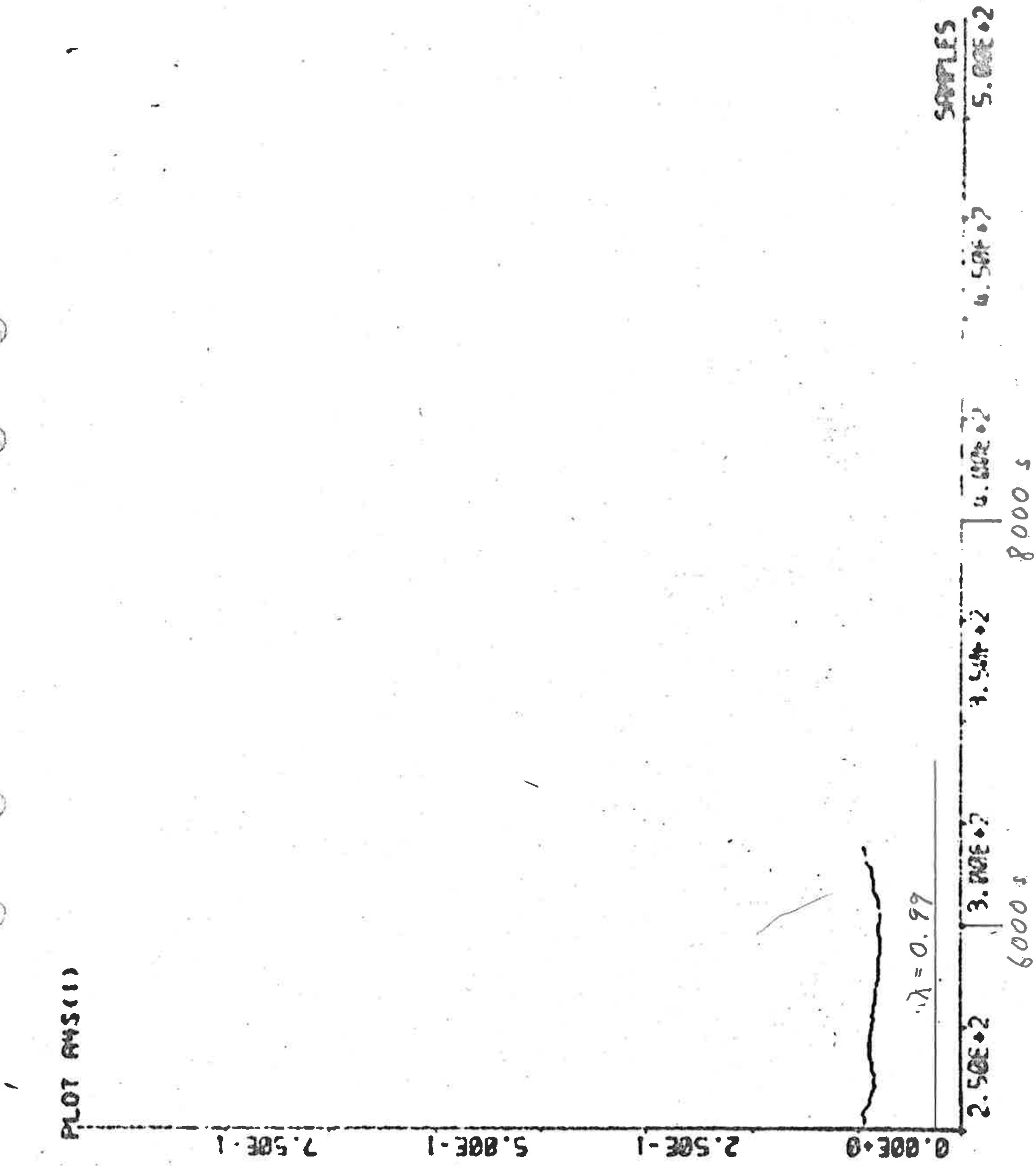

SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
0 m/s²
6000 s
8000 s


PLOT AMM(5)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
M degr/s²

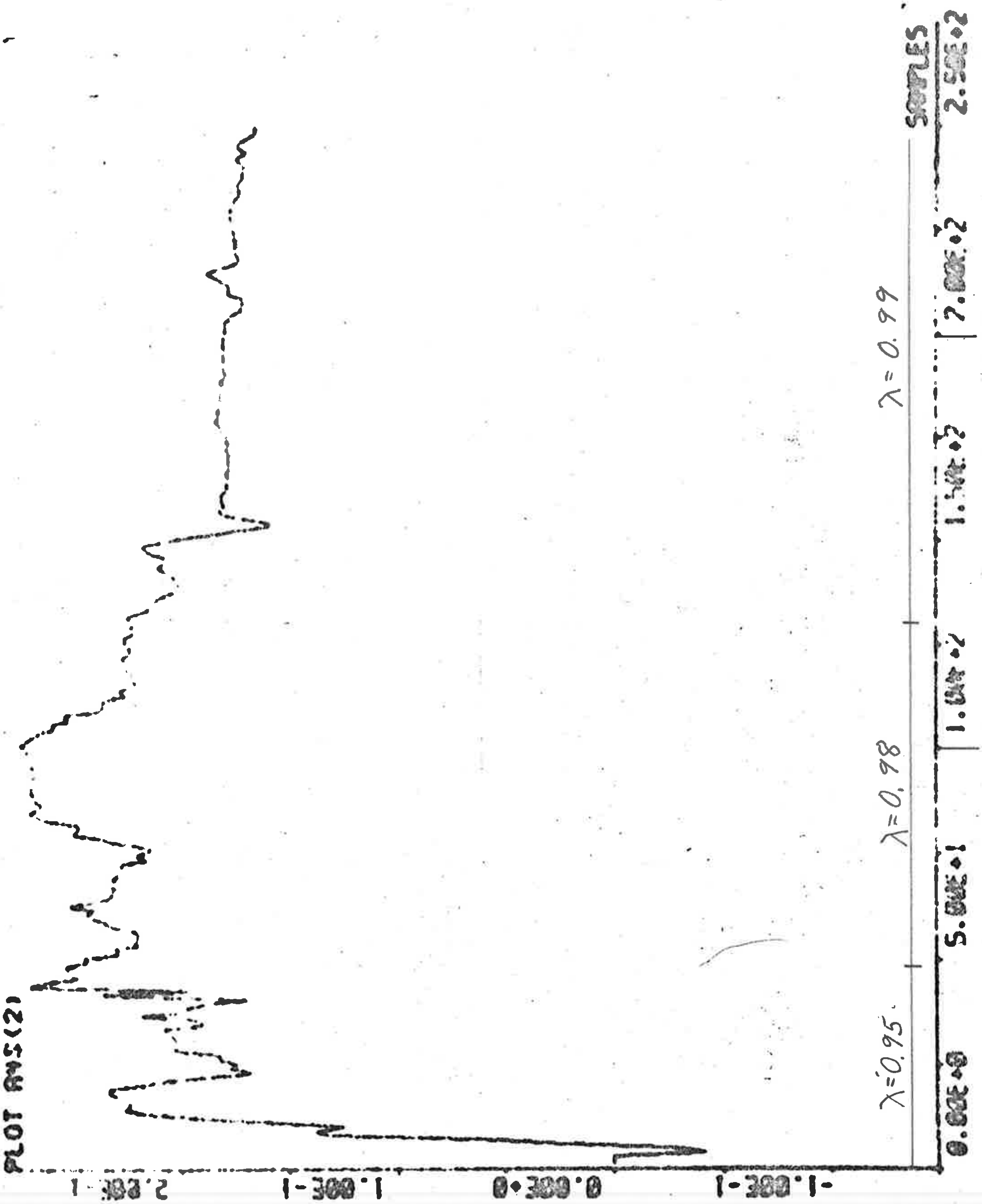

SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
6000 s
8000 s
M degr/s²


PLOT AVS(1)
SAMPLES
λ = 0.95
λ = 0.98
λ = 0.99
2000 s
4000 s
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
0.00E+0
2.50E-1
5.00E-1
7.50E-1

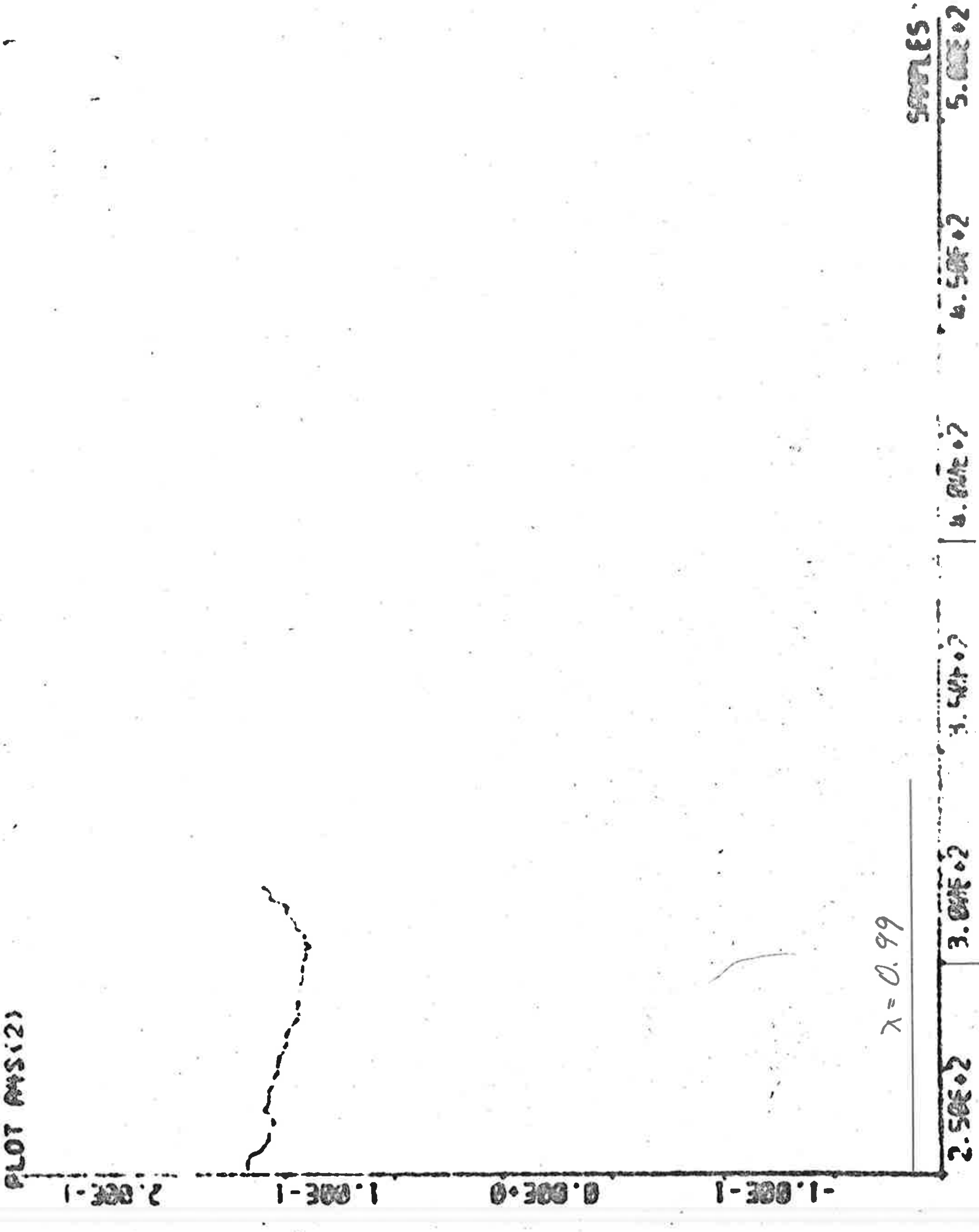
b1


PLOT RMS(1)
SAMPLES
0.00E+0
2.50E-1
5.00E-1
7.50E-1
2.50E+2
3.00E+2
5.00E+2
λ = 0.99
6000 s
8000 s

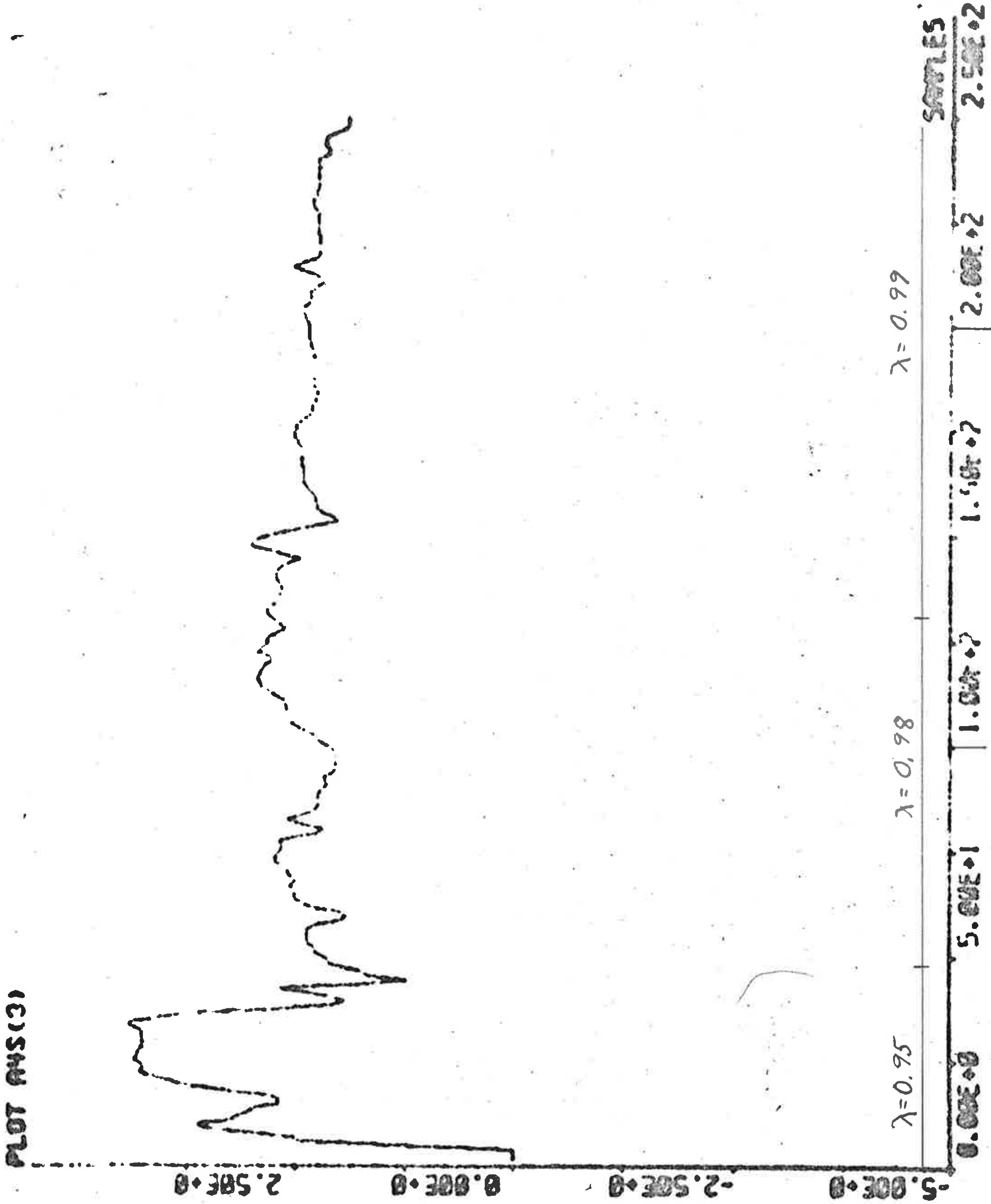
b1

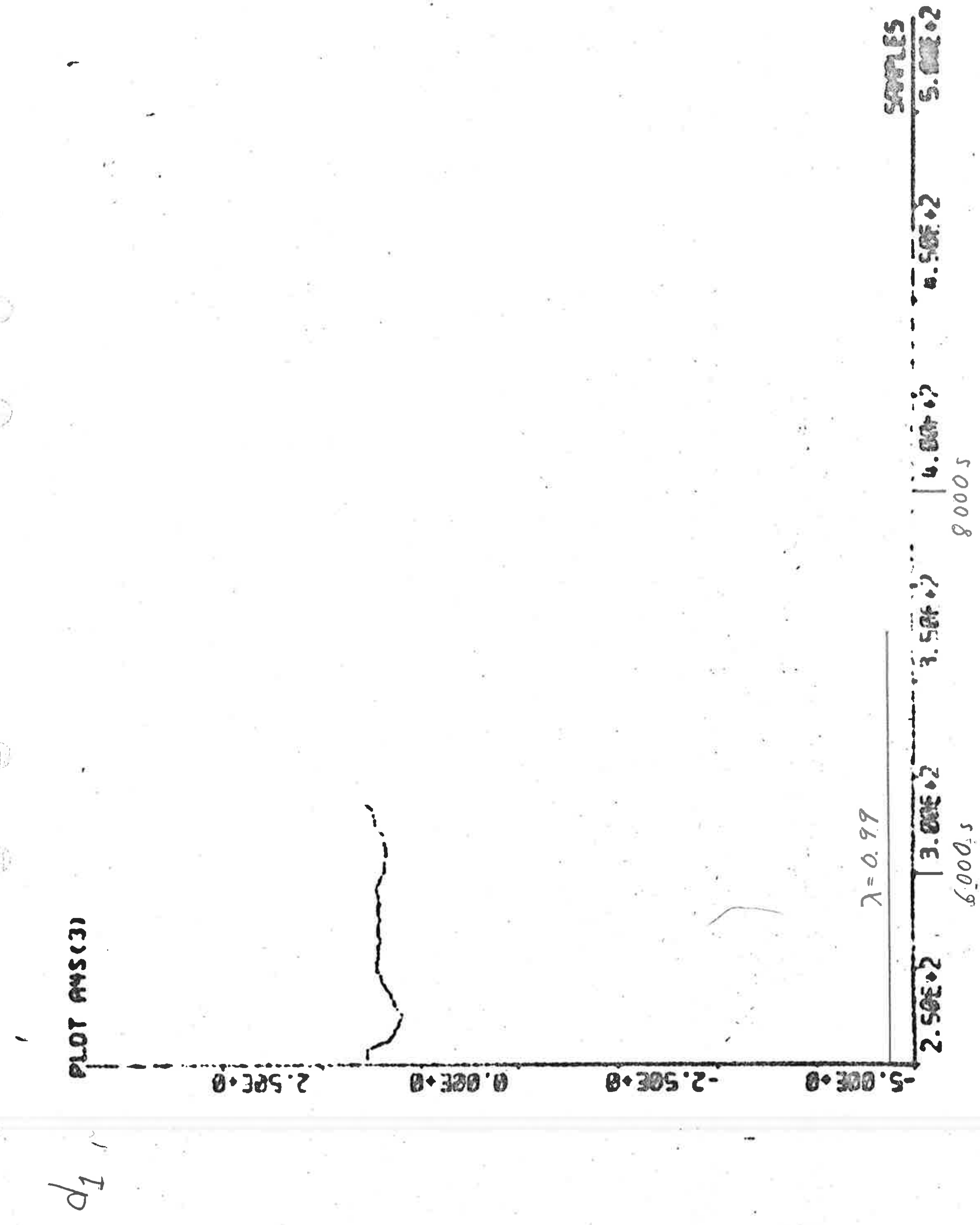

PLOT AVS(2)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
-1.00E-1
0.00E+0
1.00E-1
2.00E-1
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s

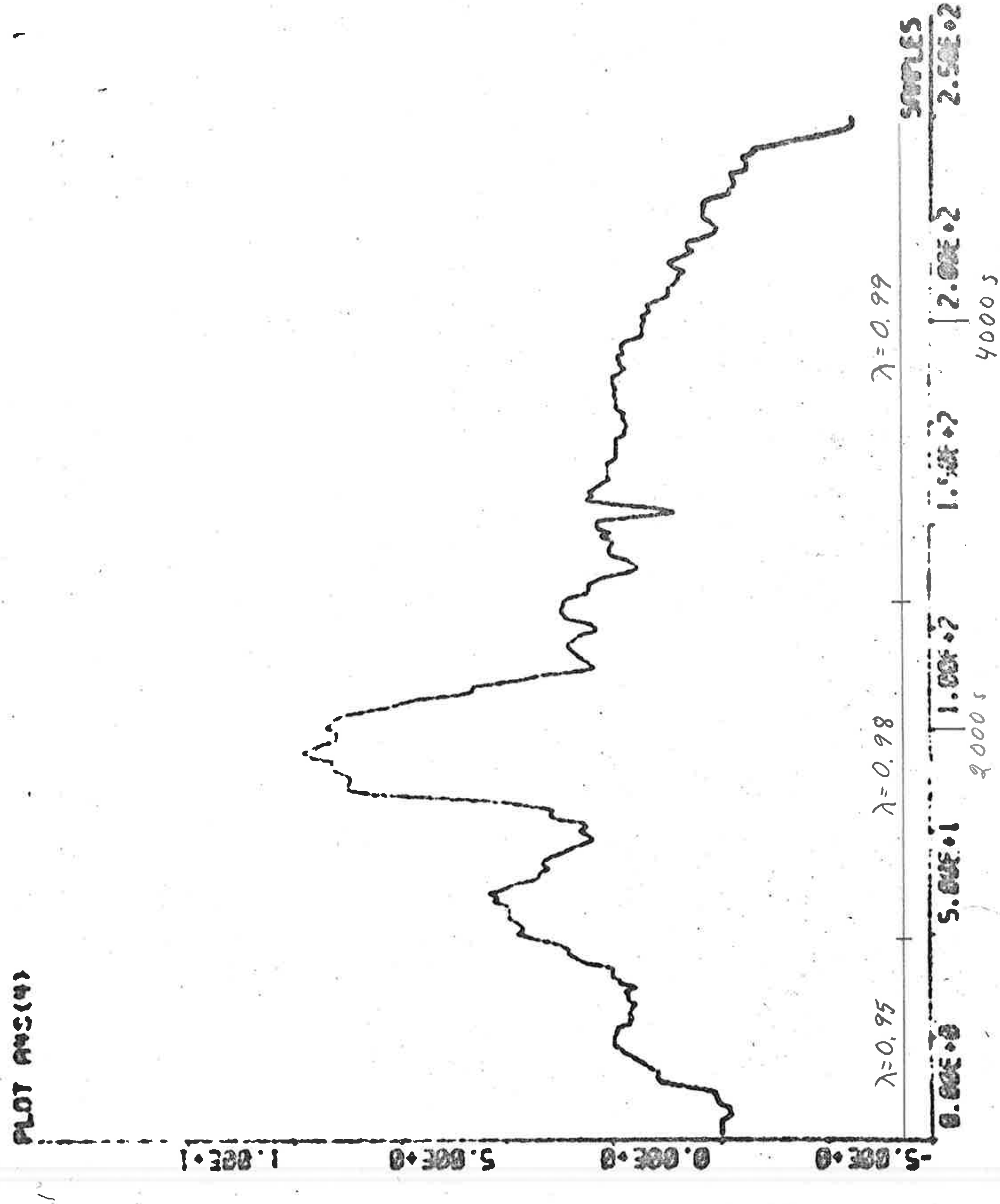
b2

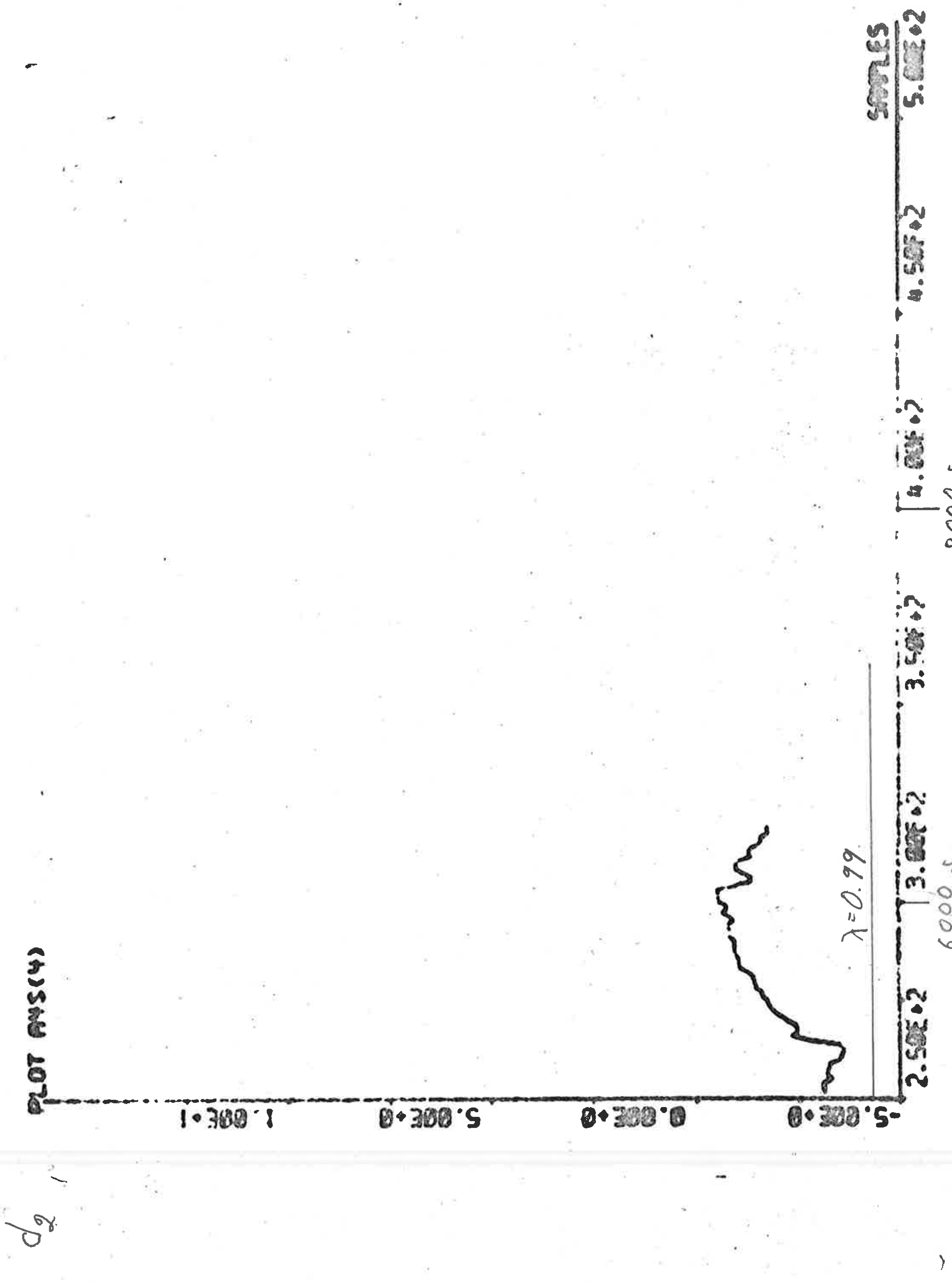

PLOT AHS(2)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
-1.00E-1
0.00E+0
1.00E-1
2.00E-1
λ = 0.99
6000 s
8000 s

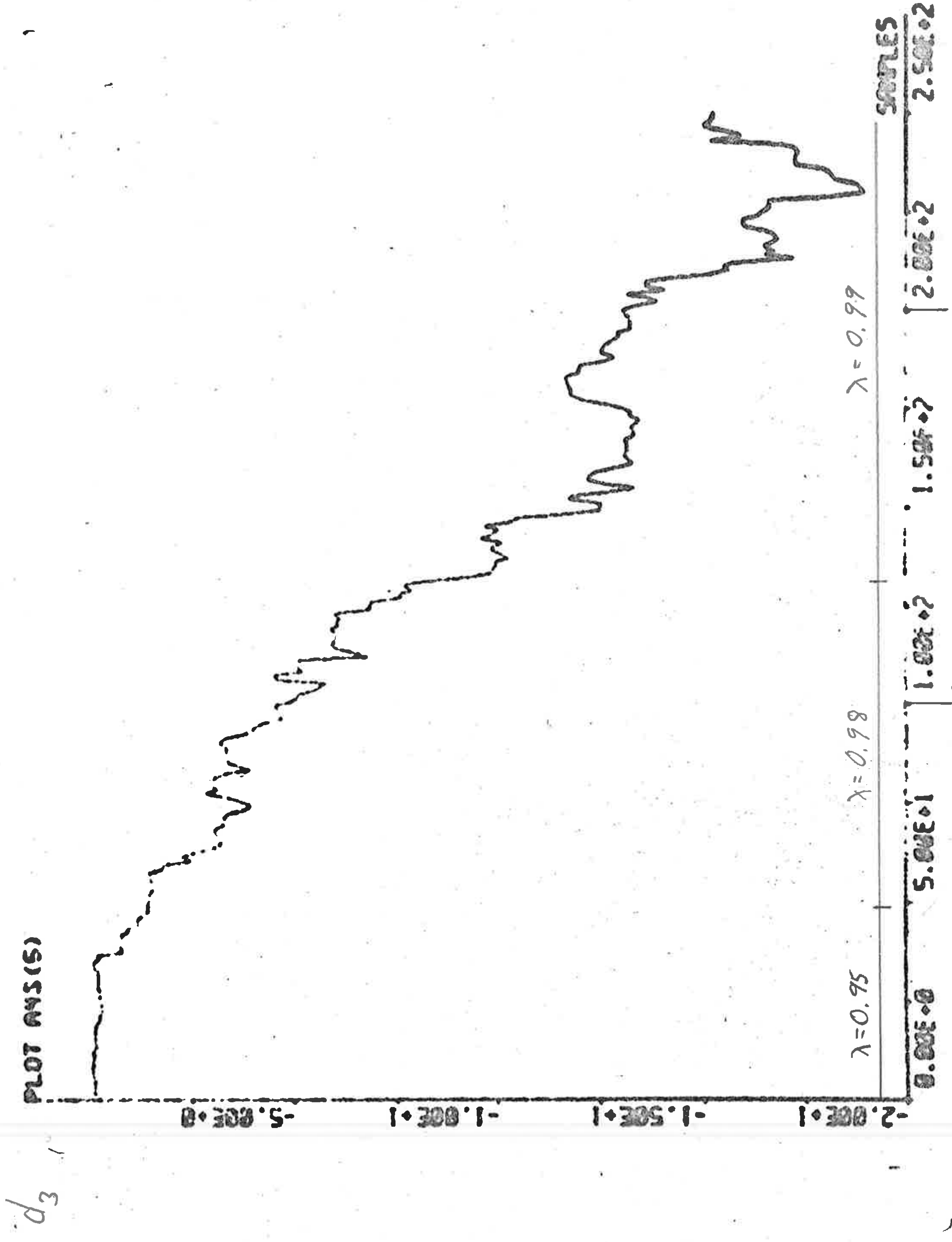
b2

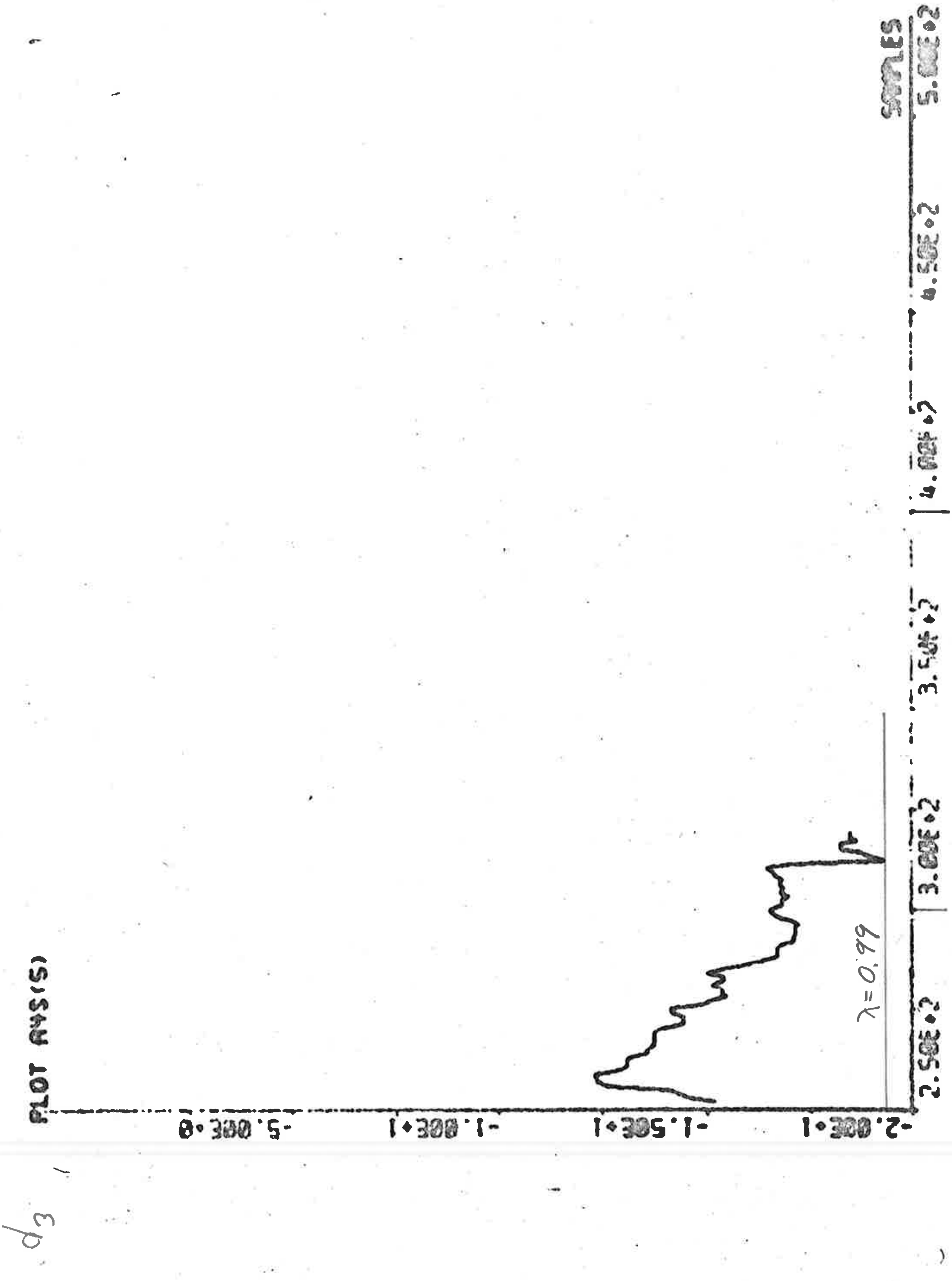

PLOT AMS(3)
2.50E+0
0.00E+0
-2.50E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s

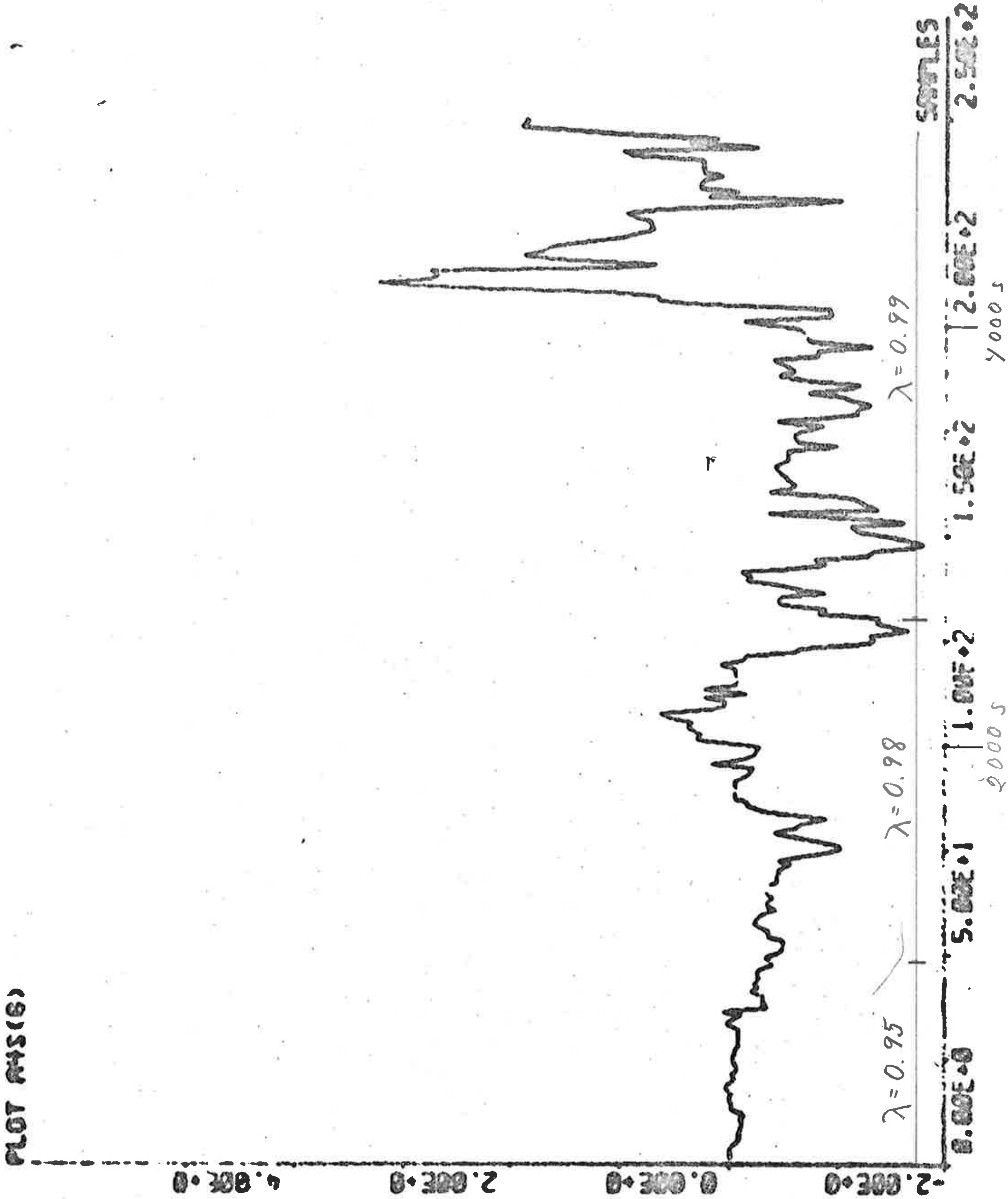

PLOT A4S(3)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
2.50E+0
0.00E+0
-2.50E+0
-5.00E+0
λ = 0.99
6000 s
8000 s
d_1

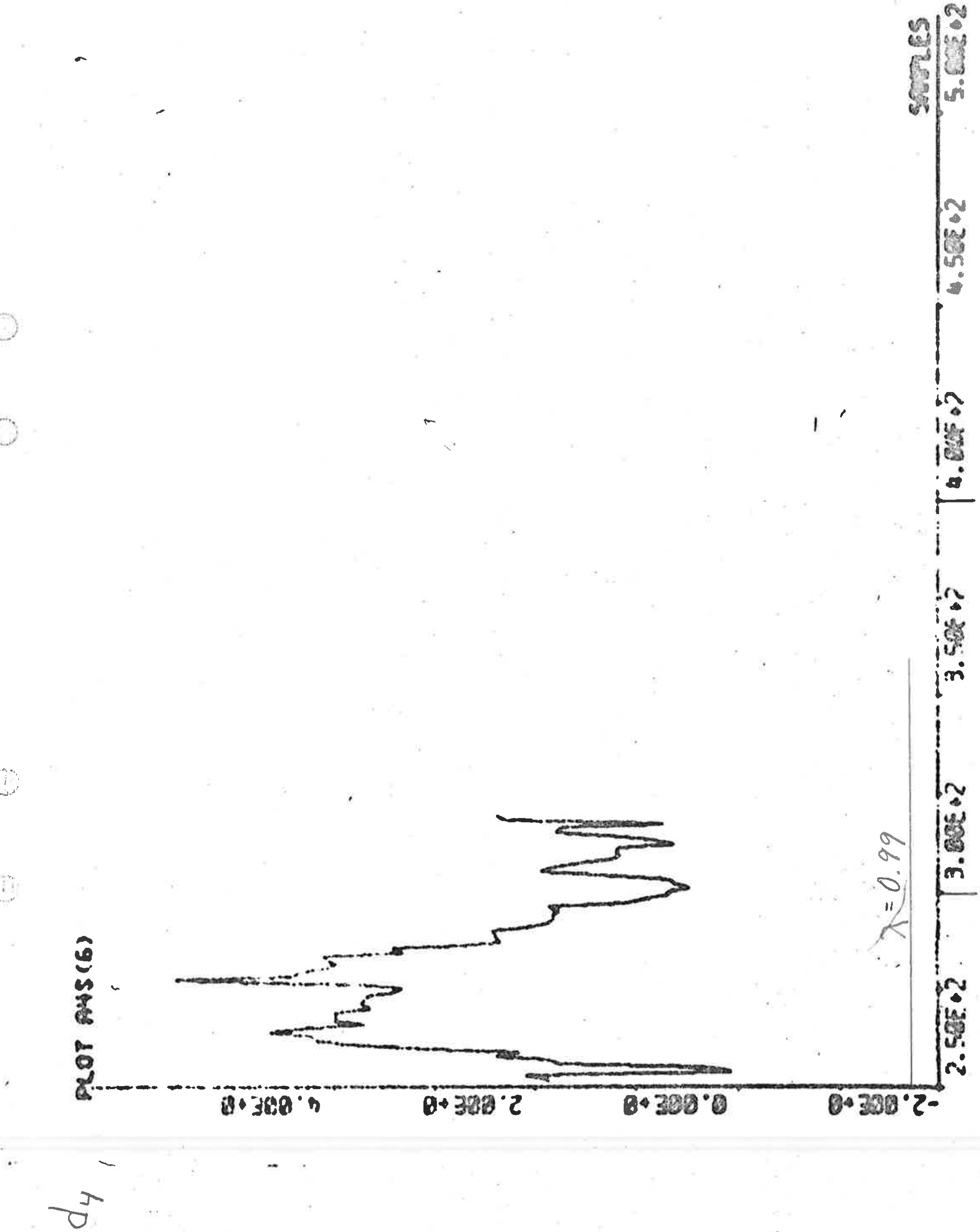

PLOT
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s


PLOT ANS(4)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
λ=0.99
6000 s
8000 s
d2


PLOT AVS(S)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
-5.00E+0
-1.00E+1
-1.50E+1
-2.00E+1
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s
d3


SAMPLES
λ=0.99
6000 s
8000 s
d3


PLOT AHS(6)
4.00E+0
2.00E+0
0.00E+0
-2.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s


PLOT RMS(6)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
-2.00E+0
0.00E+0
2.00E+0
4.00E+0
λ = 0.99
6000 s
8000 s
d4

Experiment A5

Date: 73 - 10 - 17
Time: 14^{25} - 17^{00}
Position: S 18° E 04°

Wind direction: 1 (see appendix A)
Wind speed: 3 Beaufort (4 - 6 m/s, gentle breeze)
Wave height: 2 m (swells)

Regulator 2

The Kalman filter is used, but no state estimates are put into the regulator.
No yaw

Calibration of the rudder servo:

+ 10 volts = 36.9°
-10 volts = -43.1°

Notice that the bias of the v_1-measurements is compensated by adding 0.5 knots to the real measurements.

Kalman filter:

The same filter gain as during experiment A4 is used. The initial state estimate vector in the Kalman filter is

$$\hat{x}(0) = \begin{bmatrix} -0.04 \\ 0.0 \\ 142.0 \\ -0.01498 \\ 0.00720 \end{bmatrix}$$

Model in the regulator:

$$(\Psi(t+3) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = b_1\delta(t) + b_2\delta(t-1) + d_2r(t) + e(t+3)$$

Regulator:

$$\delta(t) = -\frac{1}{b_1}[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_2 r(t)]$$

Sampling interval:	20 s	
Forgetting factor λ:	0.90	(0 - 800 s)
	0.98	(800 - 2220 s)
	0.99	(2220 - 3400 s)
	0.995	(3400 - 9500 s)
Rudder limits:	$\pm 3^o$	(0 - 1000 s)
	$\pm 5^o$	(1000 - 9500 s)

$\Psi_{ref} = 142^o$

Initial values:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \qquad P = 100 * I$$

Regulator:

$$\delta(t) = -(\Psi(t) - \Psi_{ref})$$

Final values:

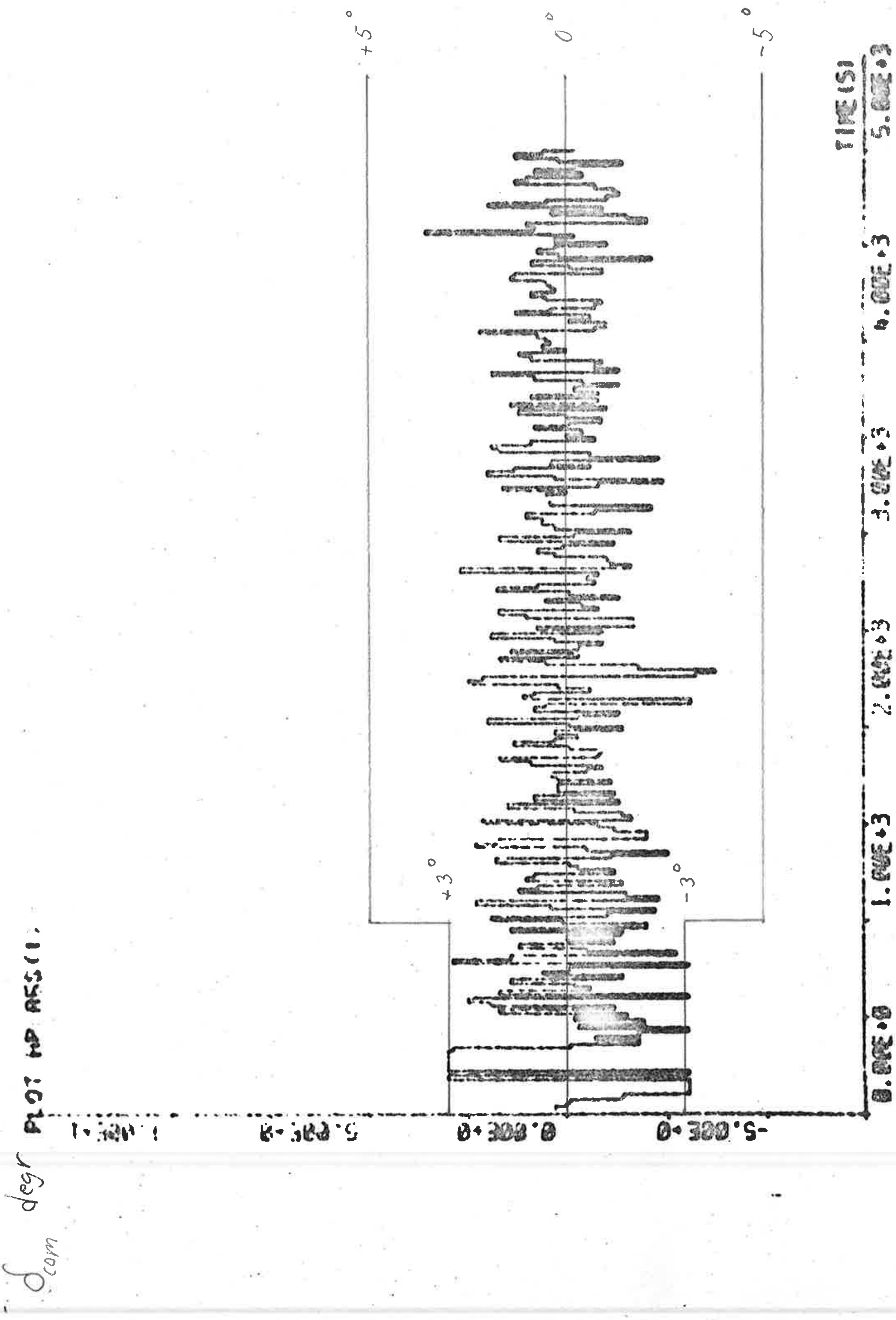
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.3544 \\ 0.0249 \\ 14.1280 \end{bmatrix} \qquad P = \begin{bmatrix} 0.02550 & & \\ -0.01440 & 0.01420 & \\ 1.413 & -0.9150 & 102.4 \end{bmatrix}$$

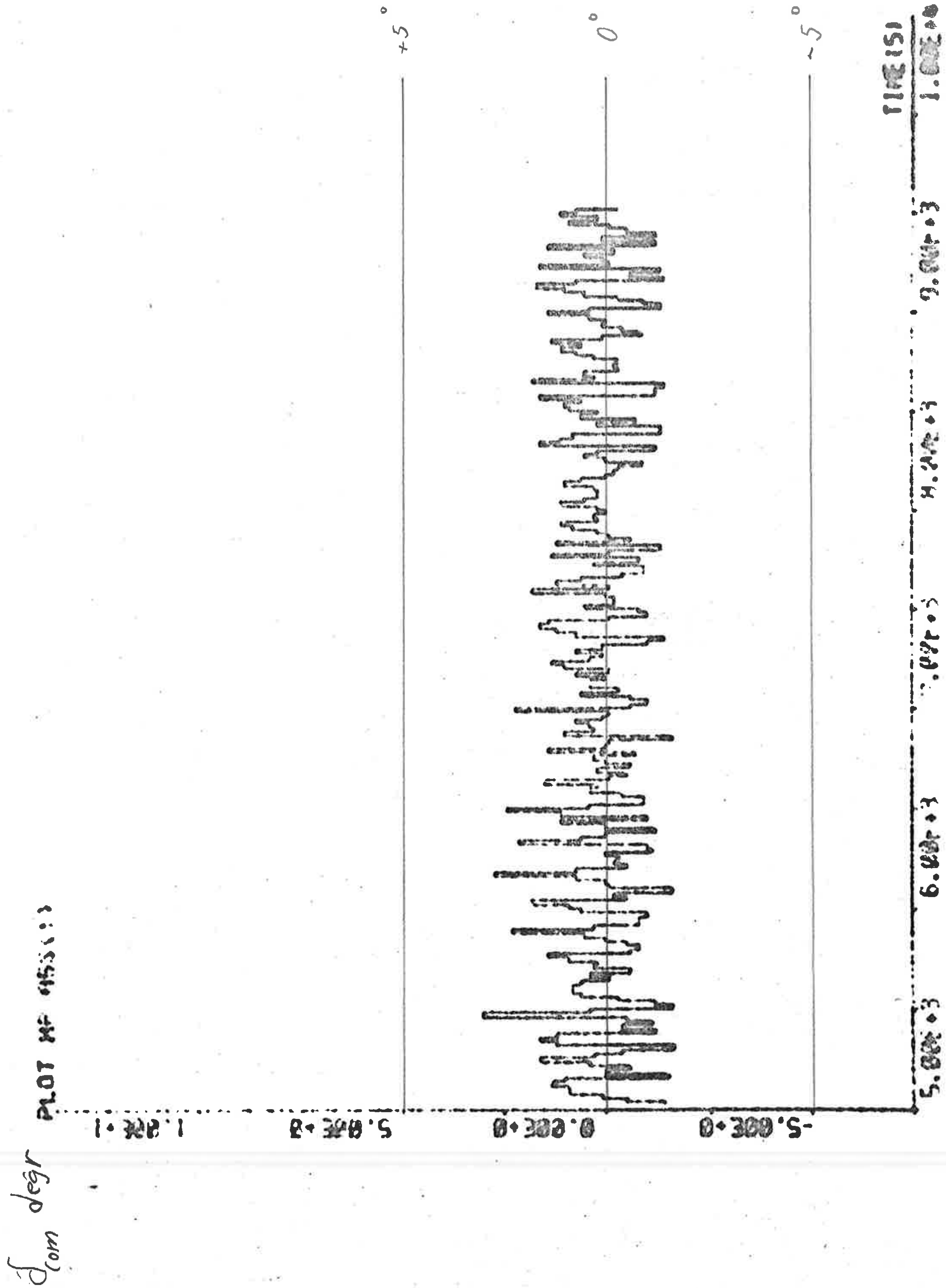
Regulator:

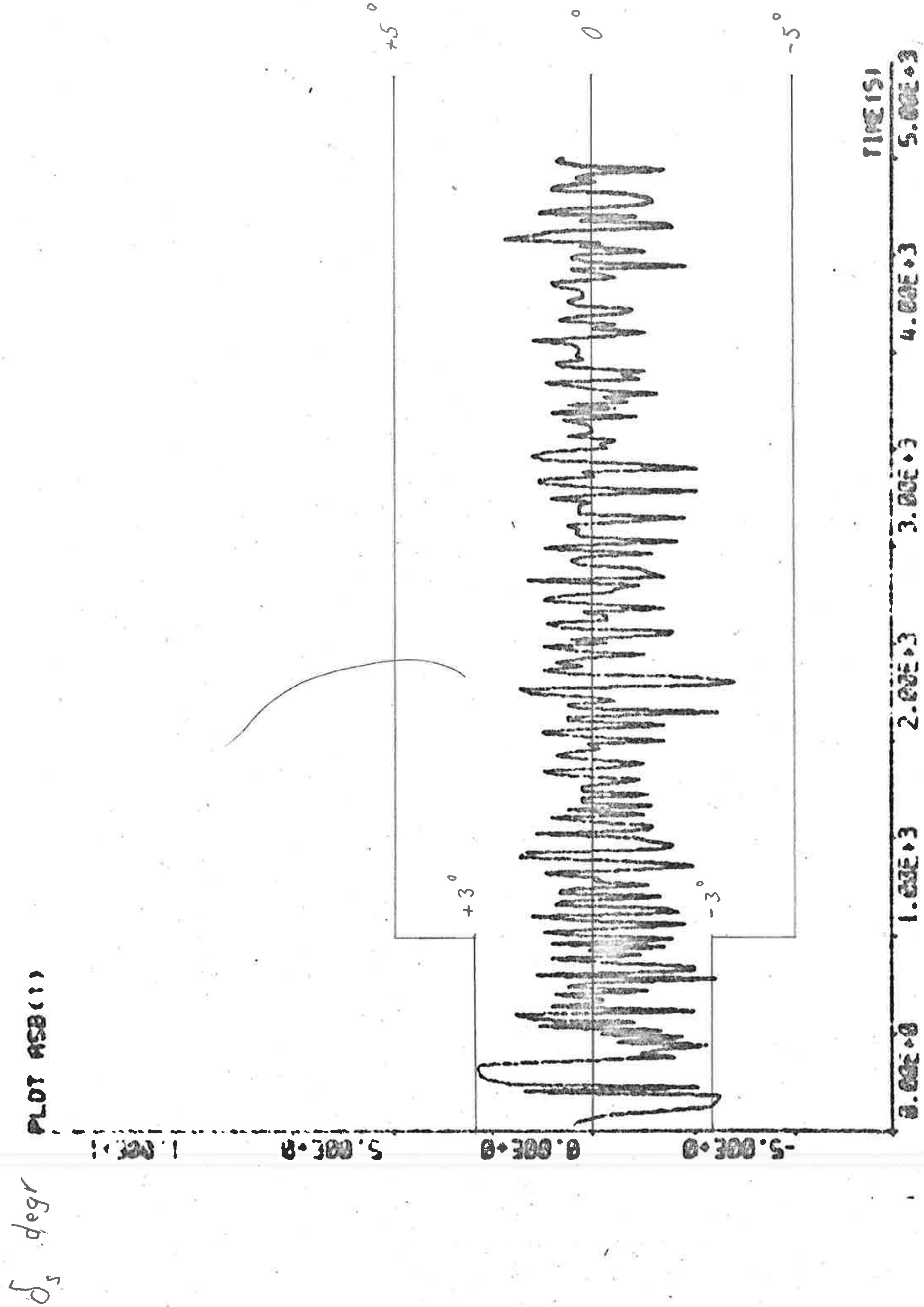
$$\delta(t) = -2.8217(\Psi(t) - \Psi_{ref}) - 0.0703\delta(t-1) - 39.8646r(t)$$

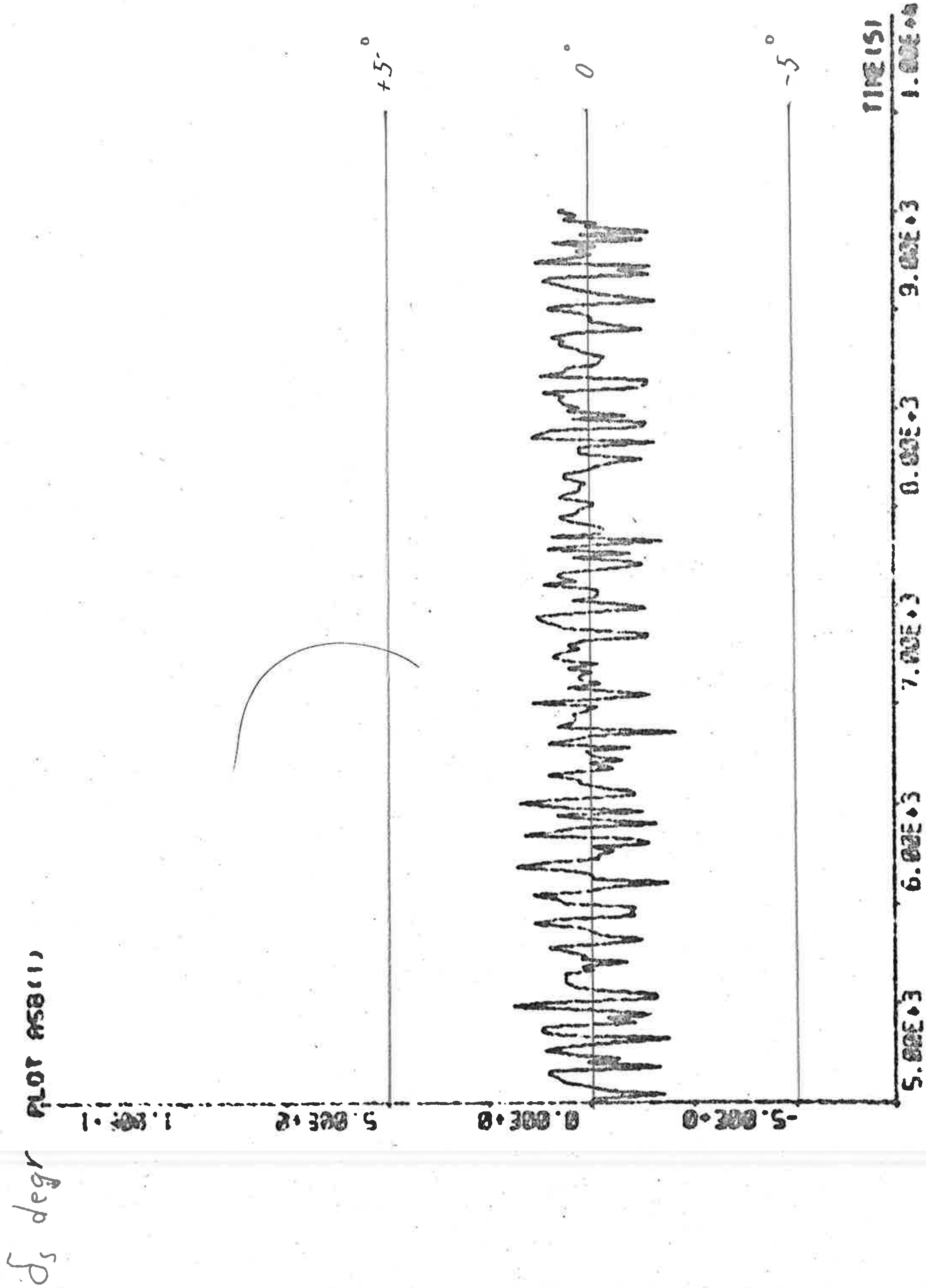
Statistics:

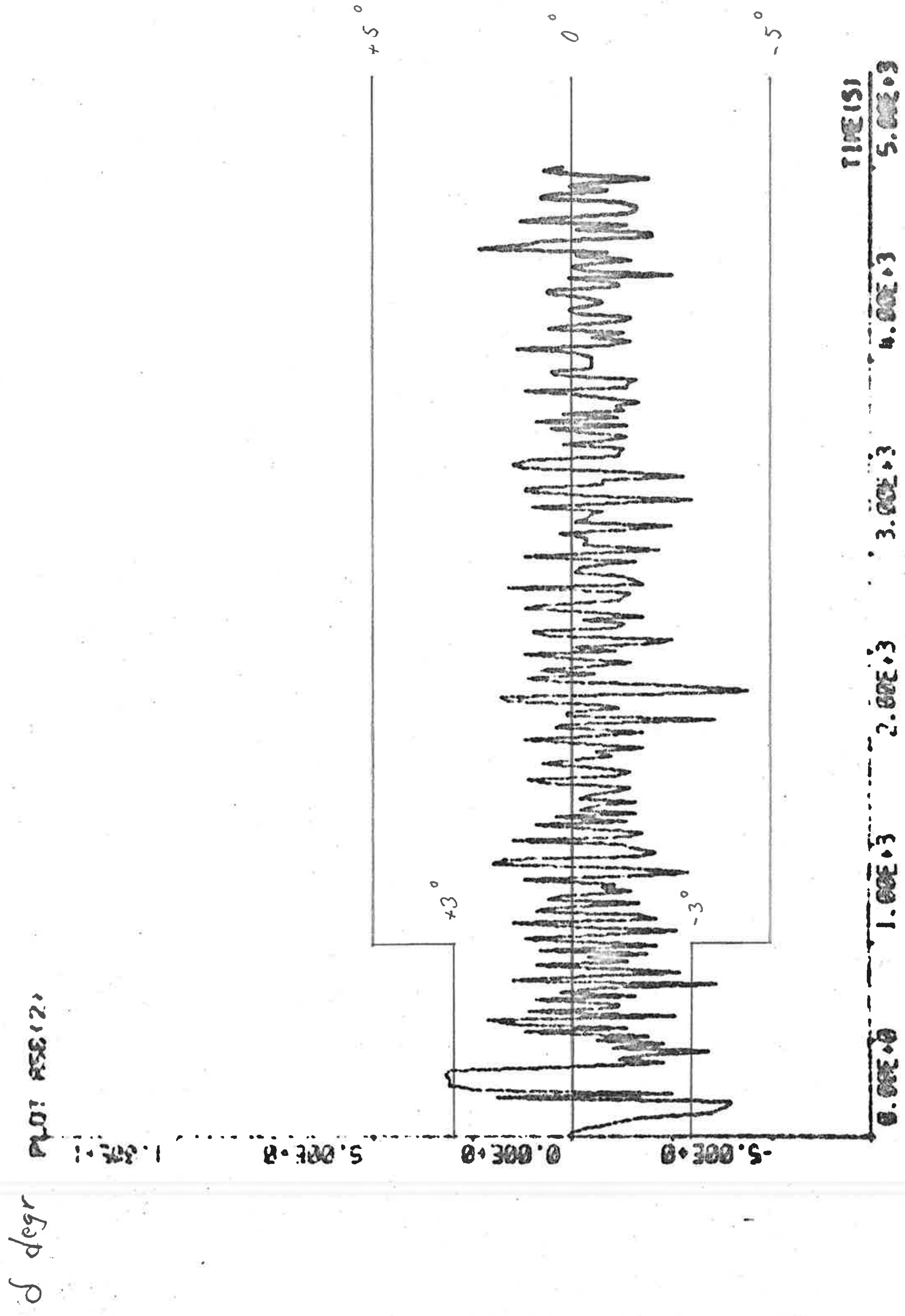
		0 - 9500 s (all data)				5000 - 9500 s			
		Mean value	Standard deviation	Minimum value	Maximum value	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	0.06	1.21	-3.7	3.6	0.15	0.91	-1.6	3.0
δ_s	degr	-0.10	1.11	-3.5	2.9	0.02	0.85	-2.1	1.9
δ	degr	-0.49	1.18	-4.4	3.2	-0.42	0.90	-2.2	2.1
v_1	knots	-0.009	0.231	-0.48	1.4	-0.071	0.155	-0.44	0.34
v_2	knots	0.115	0.177	-1.01	0.85	0.121	0.114	-0.23	0.52
r	degr/s	0.0037	0.0192	-0.094	0.085	0.0040	0.0156	-0.052	0.044
Ψ	degr	141.833	0.829	134.65	143.53	141.909	0.222	141.42	142.47
u	knots	16.390	0.214	15.64	16.95	16.385	0.211	15.86	16.84
$\hat{v}$	m/s	0.029	0.079	-0.26	0.45	0.015	0.051	-0.13	0.13
$\hat{F}$	m/s^2	-0.000145	0.004194	-0.02206	0.01552	-0.000254	0.003831	-0.01263	0.01324
$\hat{M}$	$degr/s^2$	0.000198	0.003047	-0.00932	0.00952	-0.000291	0.002857	-0.00932	0.00952

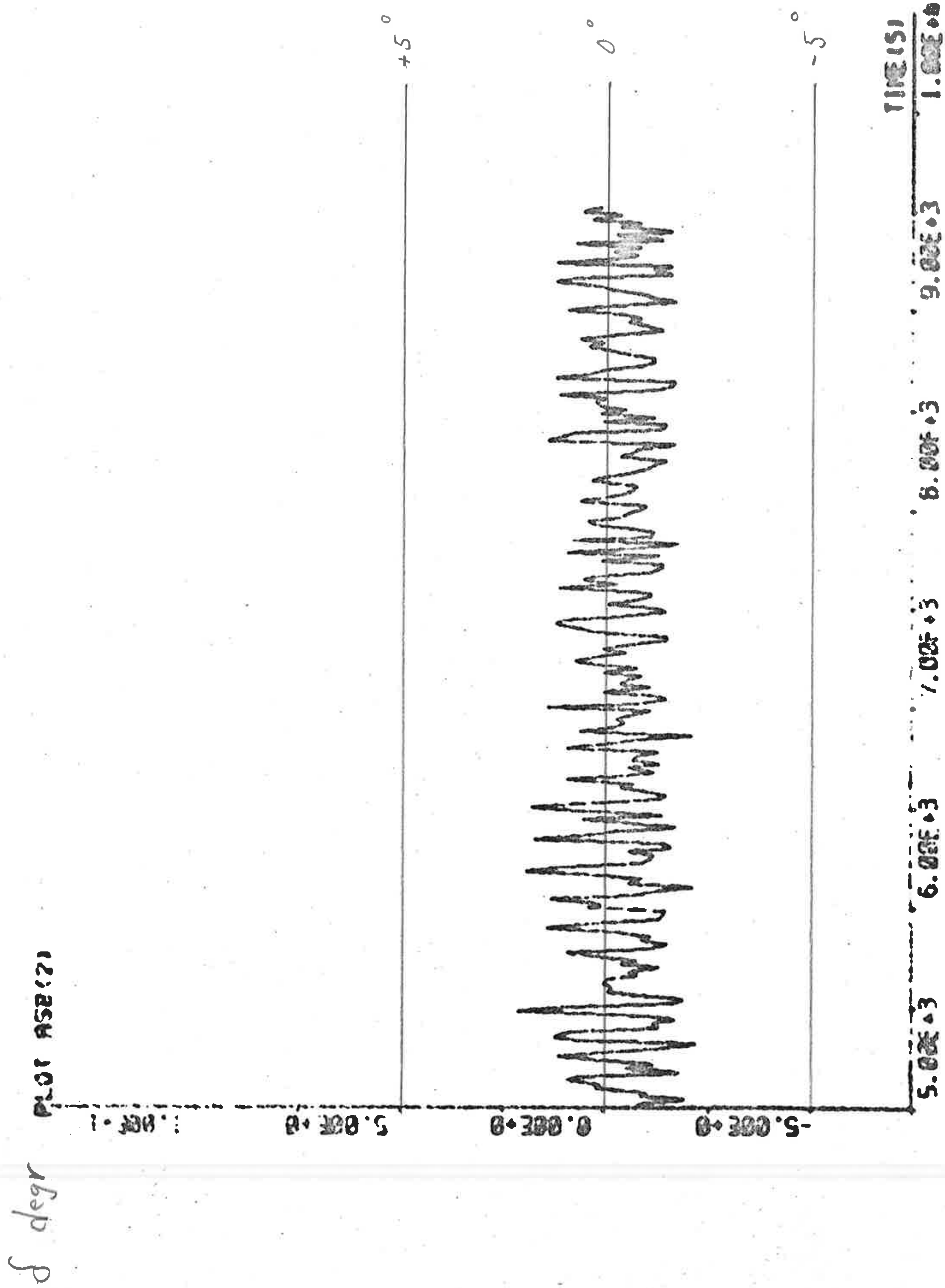

PLOT HP RES(1
TIME (S)
+5°
0°
-5°
+3°
-3°
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
δcom degr

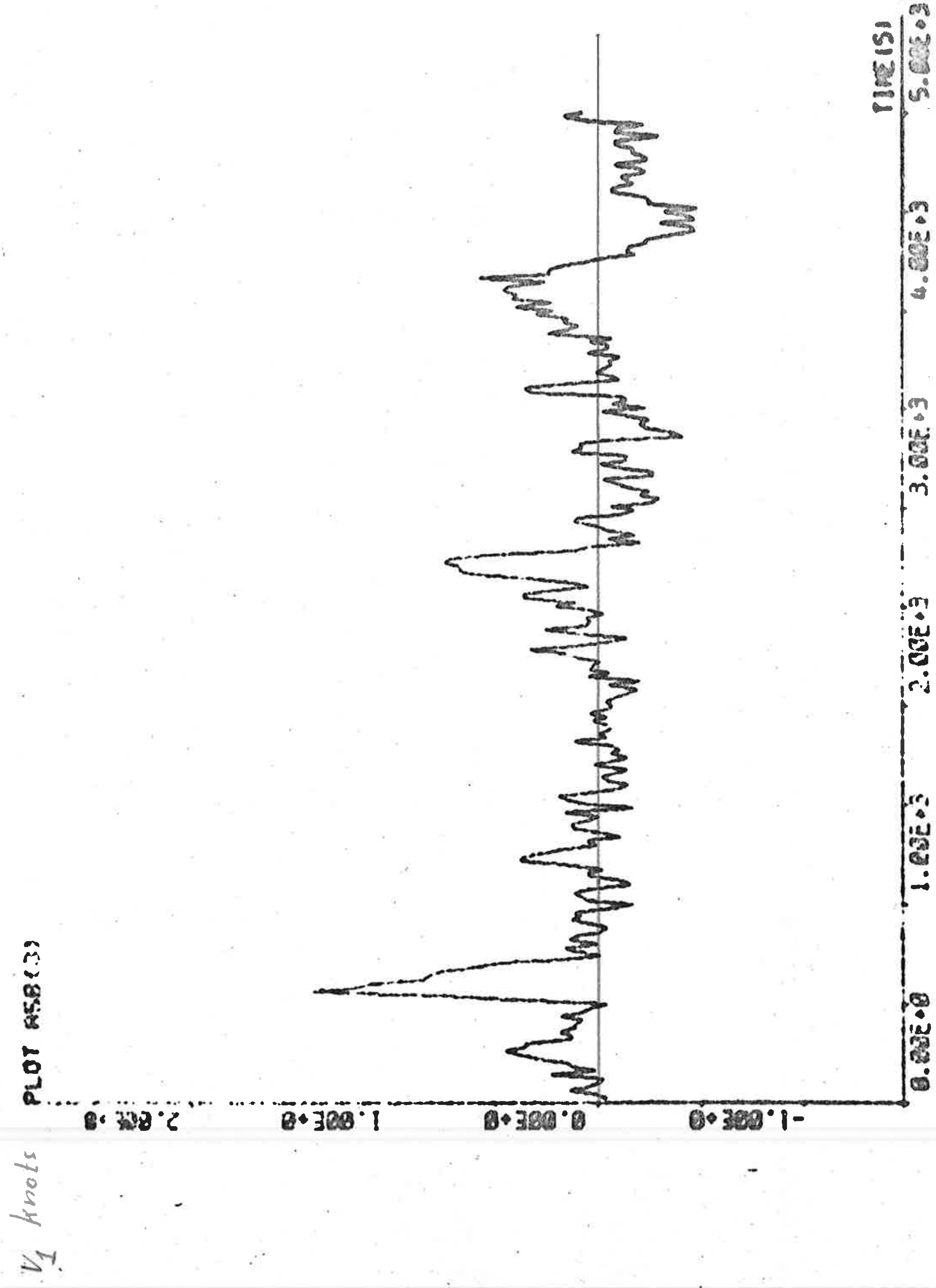

PLOT OF
TIME (S)
+5°
0°
-5°
1.00E+1
5.00E+0
0.000E+0
-5.00E+0
δcom degr

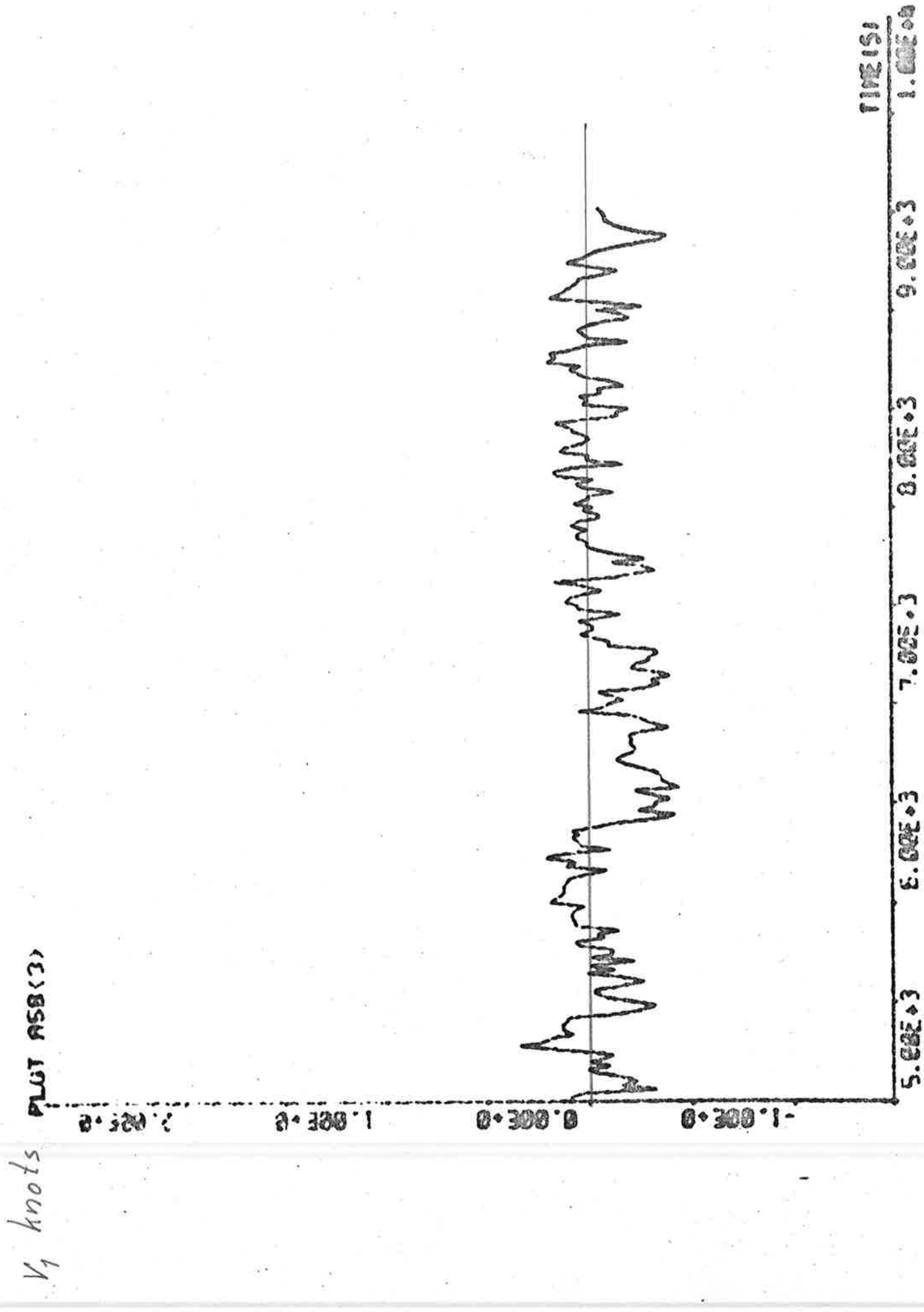

PLOT ASB(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E+0
0.00E+0
5.00E+0
+5°
0°
-5°
+3°
-3°
δs degr


PLOT ASB(1)
TIME (S)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
5.00E+3
6.00E+3
7.00E+3
9.00E+3
1.00E+4
+5°
0°
-5°
δs degr


PLOT ASE(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E-0
0.00E+0
-5.00E-0
+5°
0°
-5°
+3°
-3°
δ degr

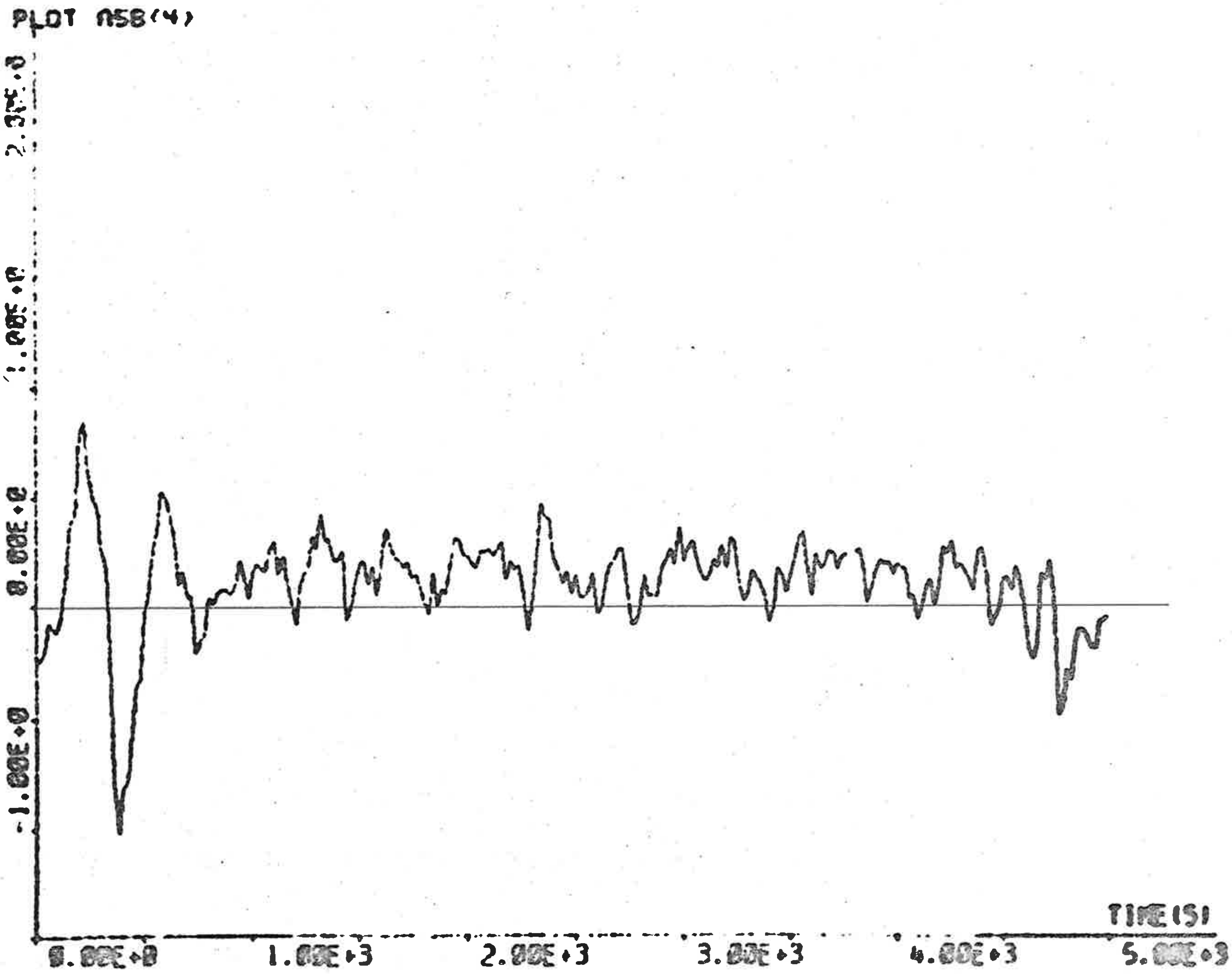

PLOT ASE(2)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
9.00E+3
1.00E+4
-5.00E+0
0.00E+0
5.00E+0
+5°
0°
-5°
δ degr

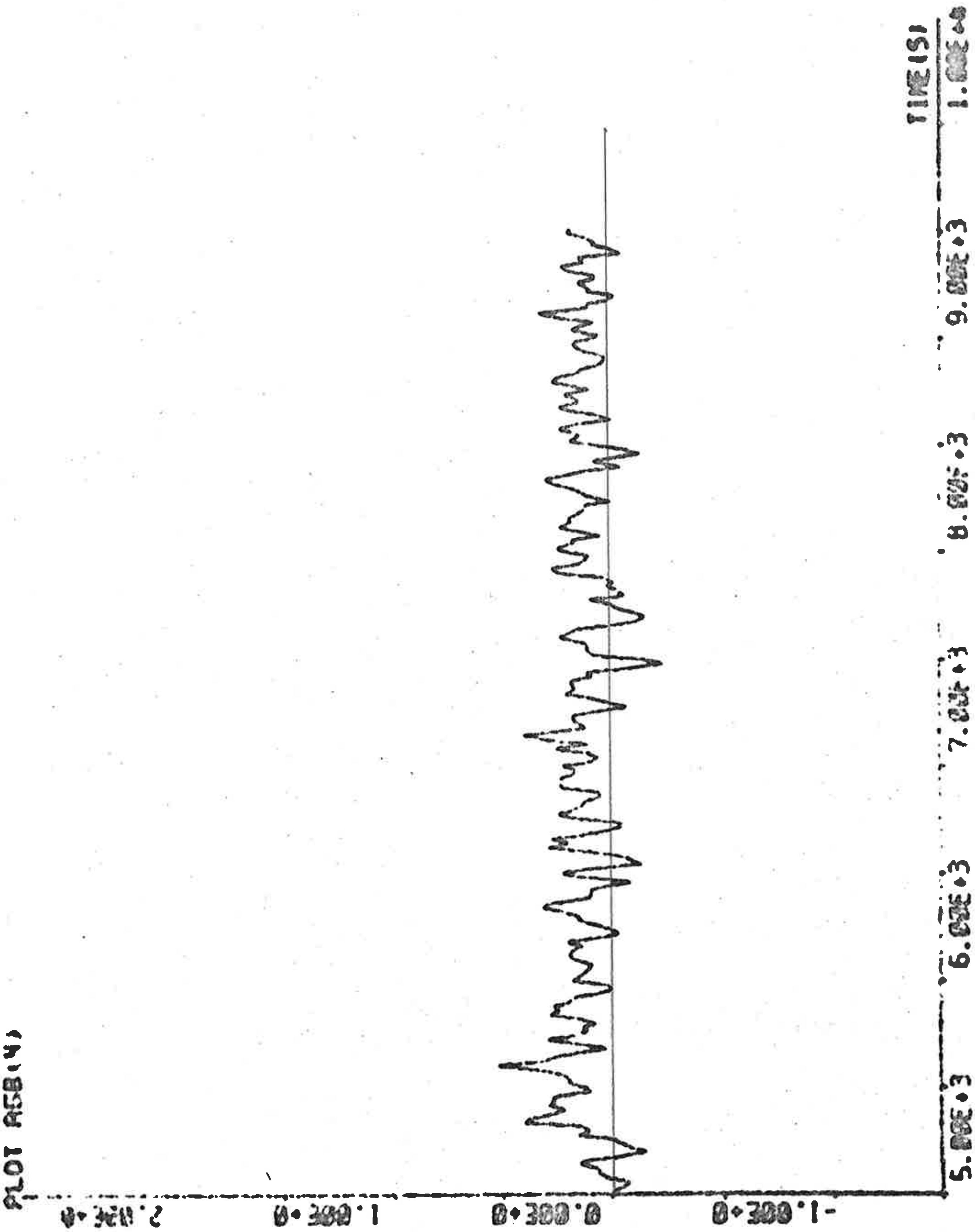

PLOT RSB(3)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
V_1 knots



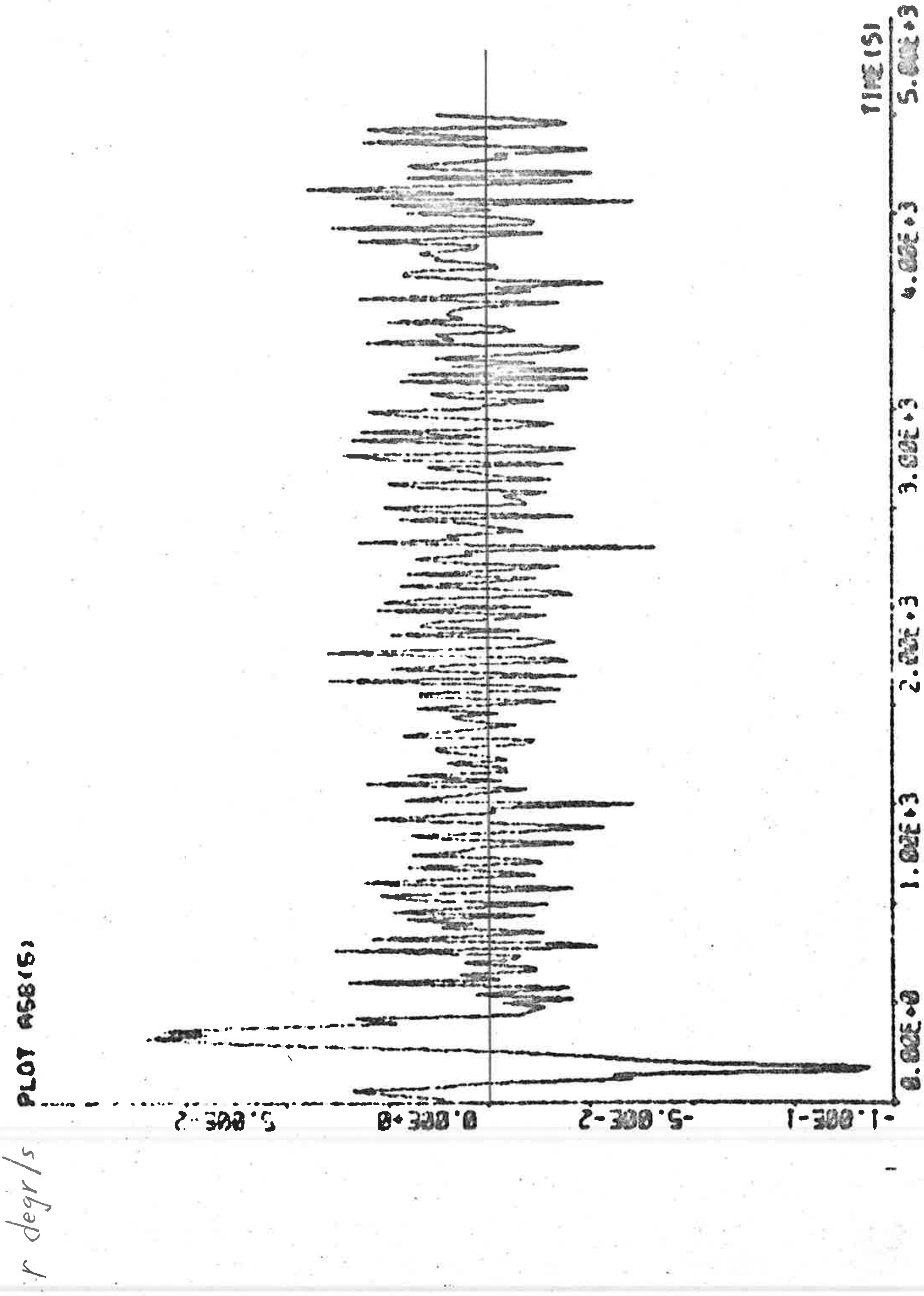
PLOT ASB(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
TIME (S)
V1 knots

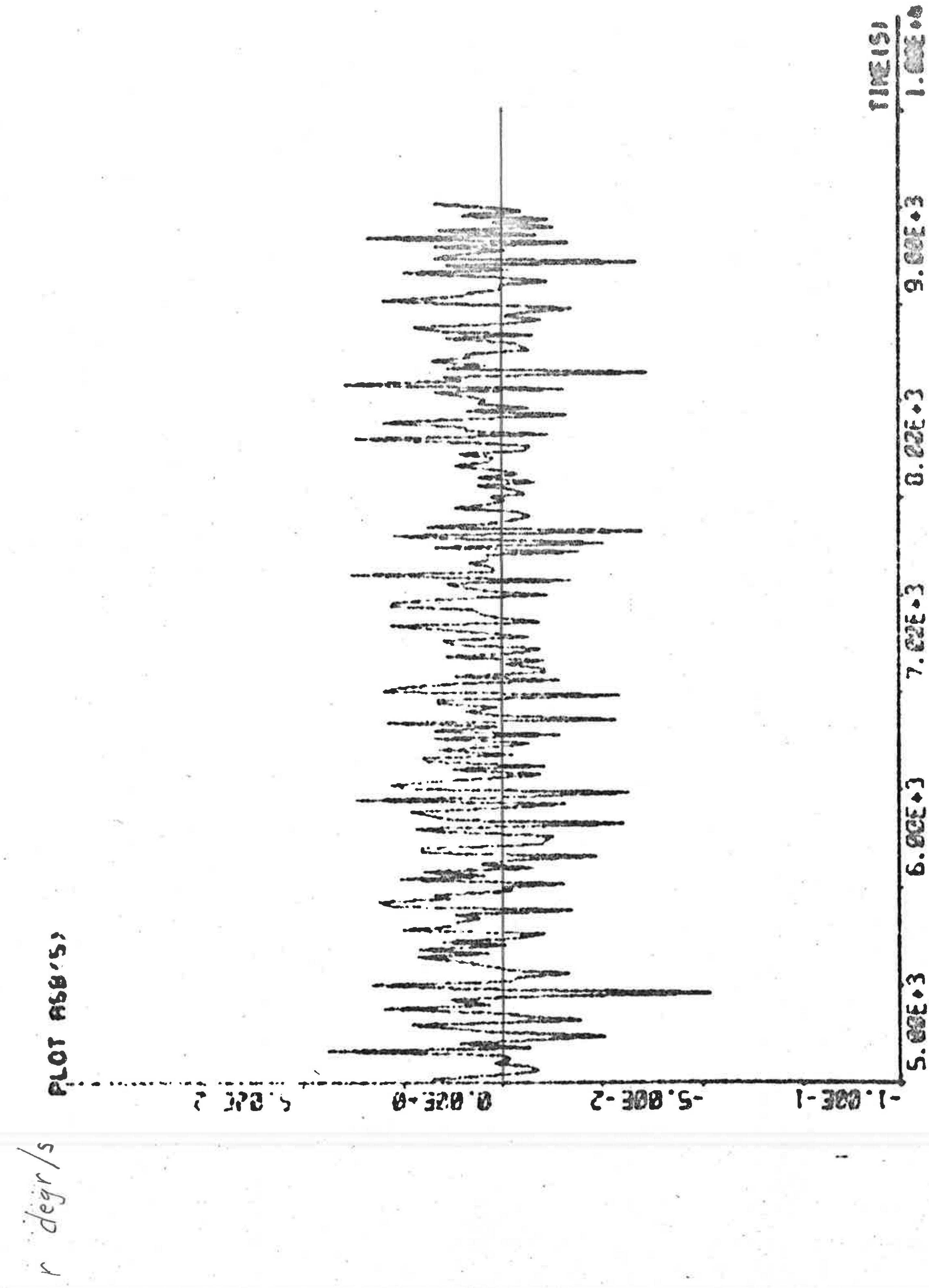
½ knots

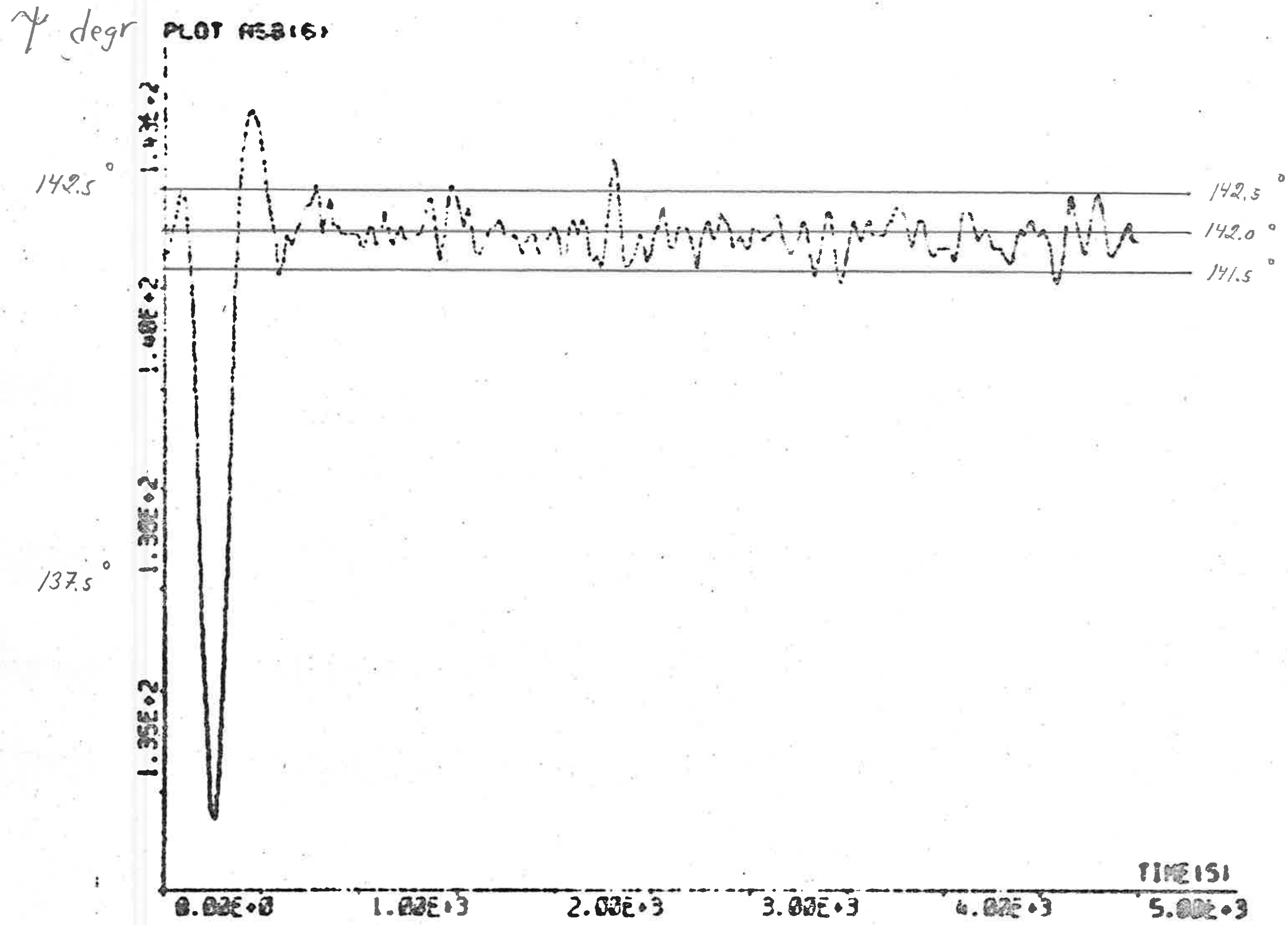

PLOT ASB(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

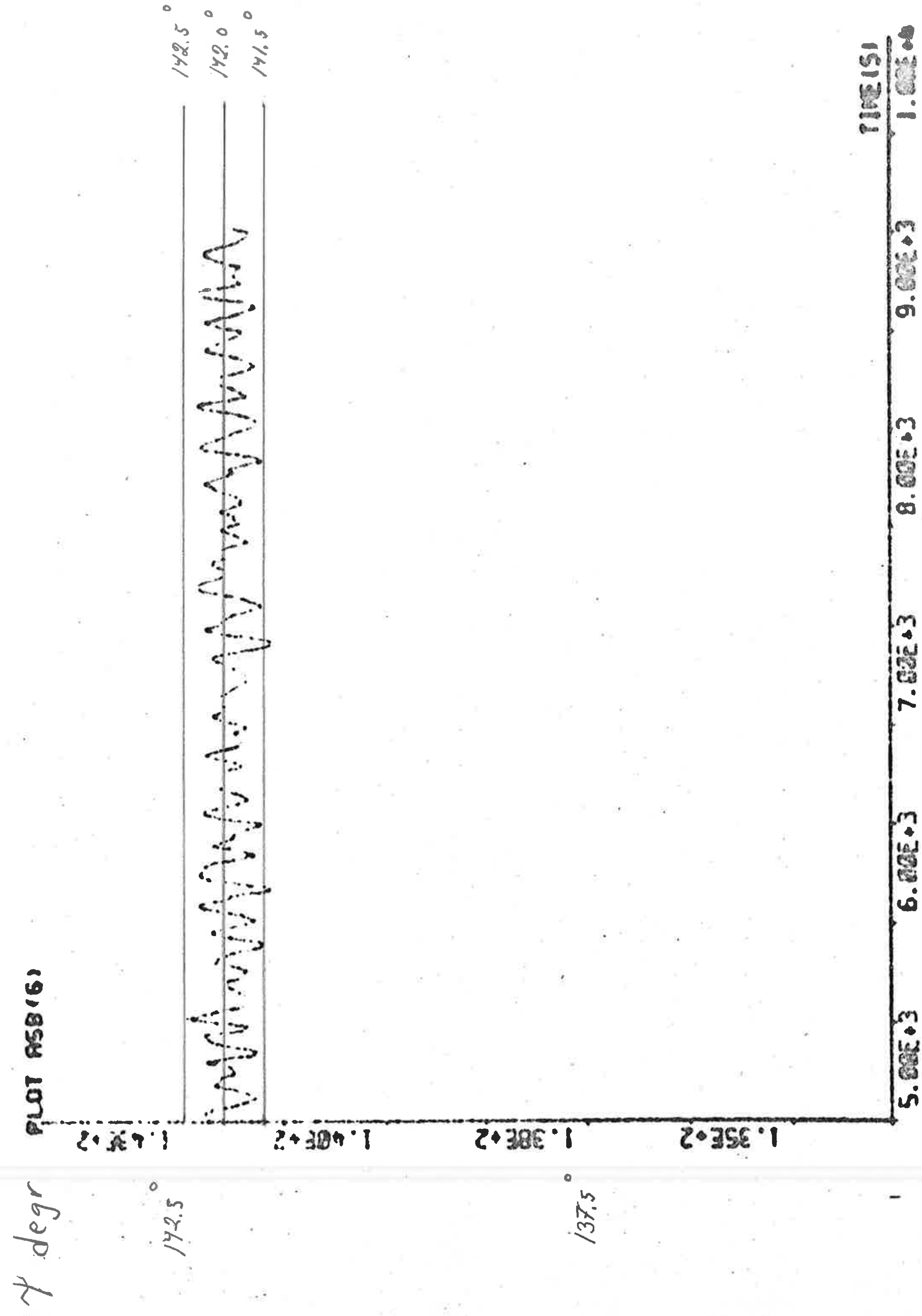

PLOT ABS(V)
TIME(S)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4

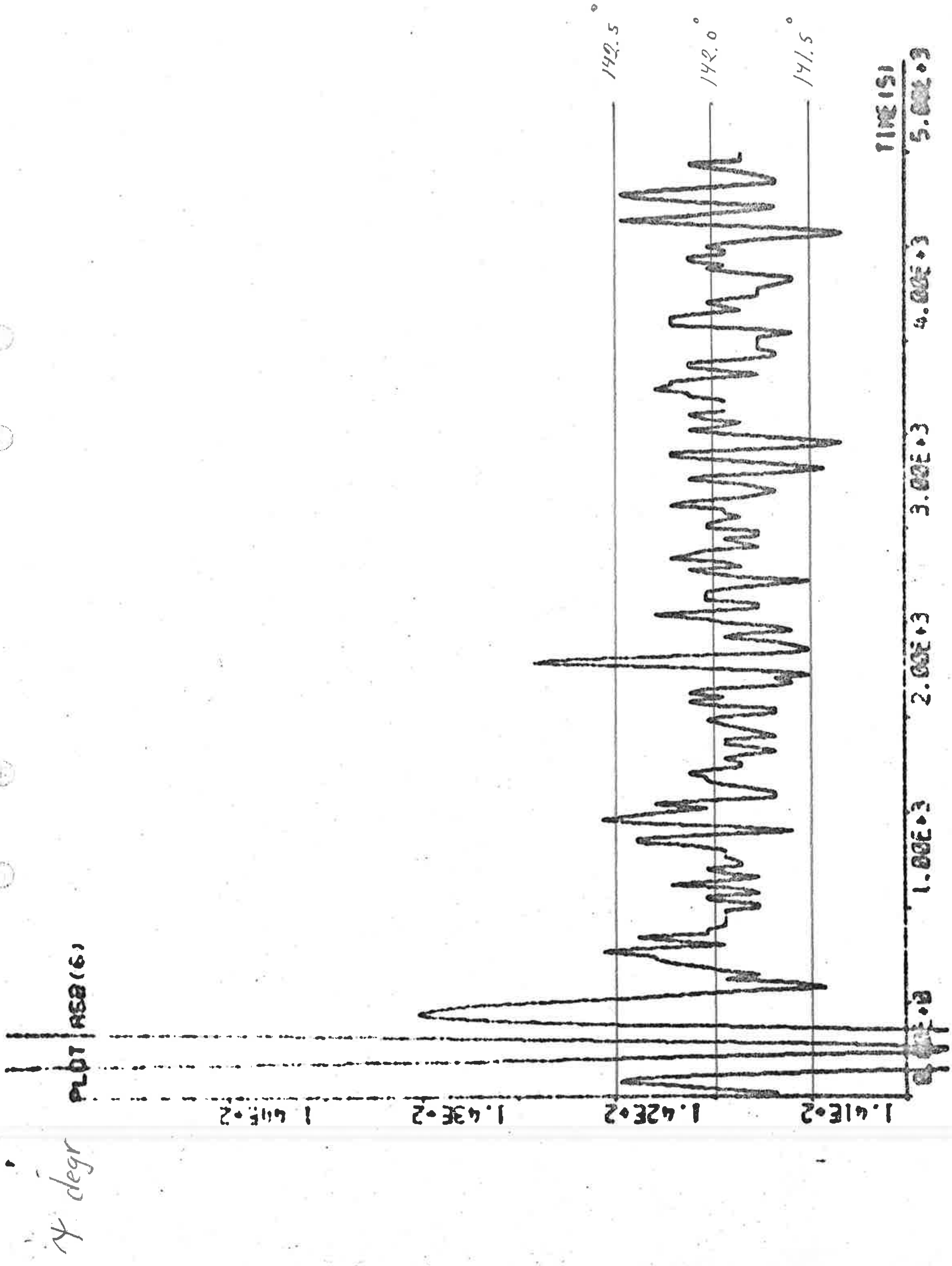
V_2 knots

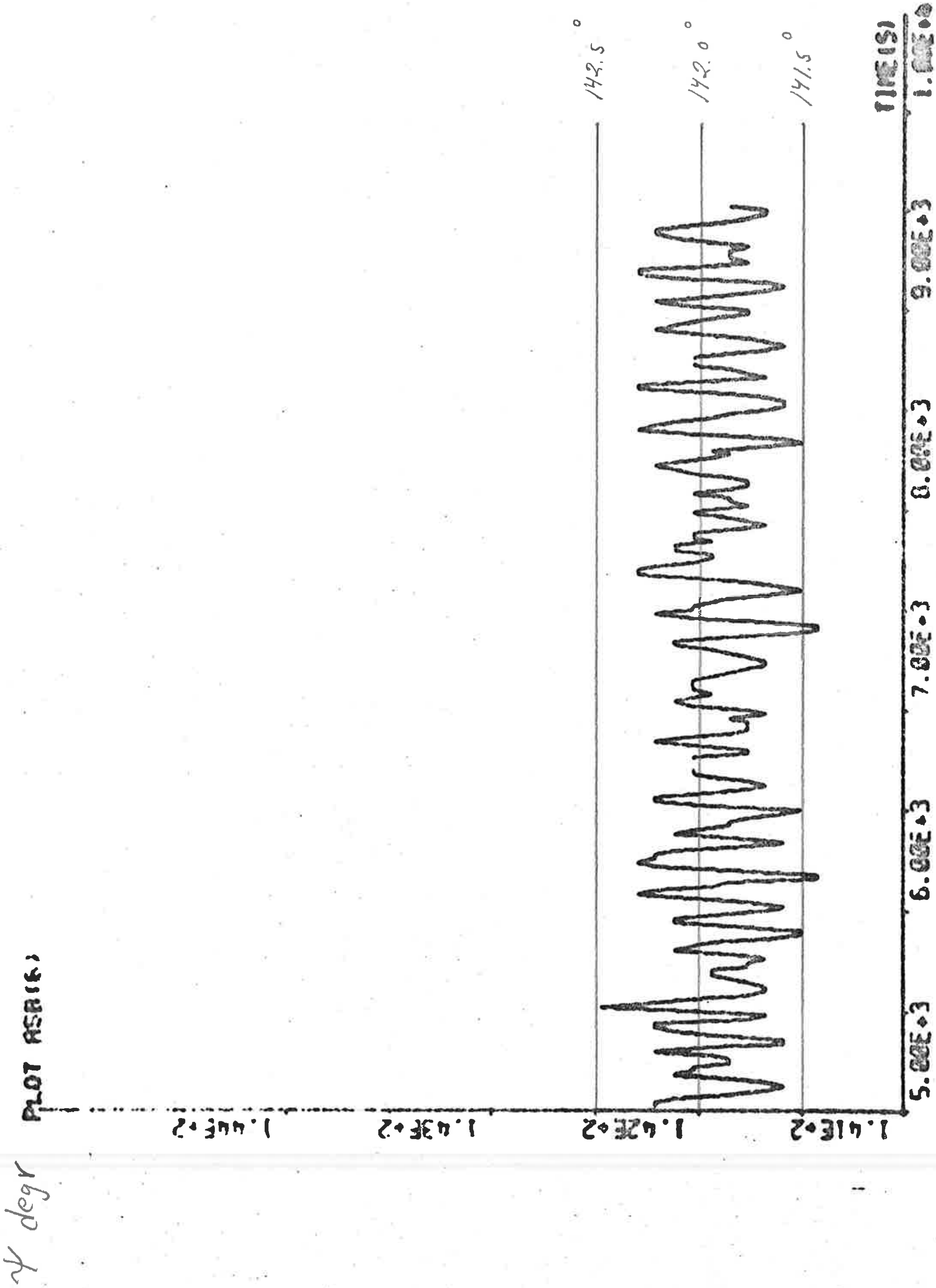

PLOT AS8(S)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-1.00E-1
-5.00E-2
0.00E+0
5.00E-2
r degr/s

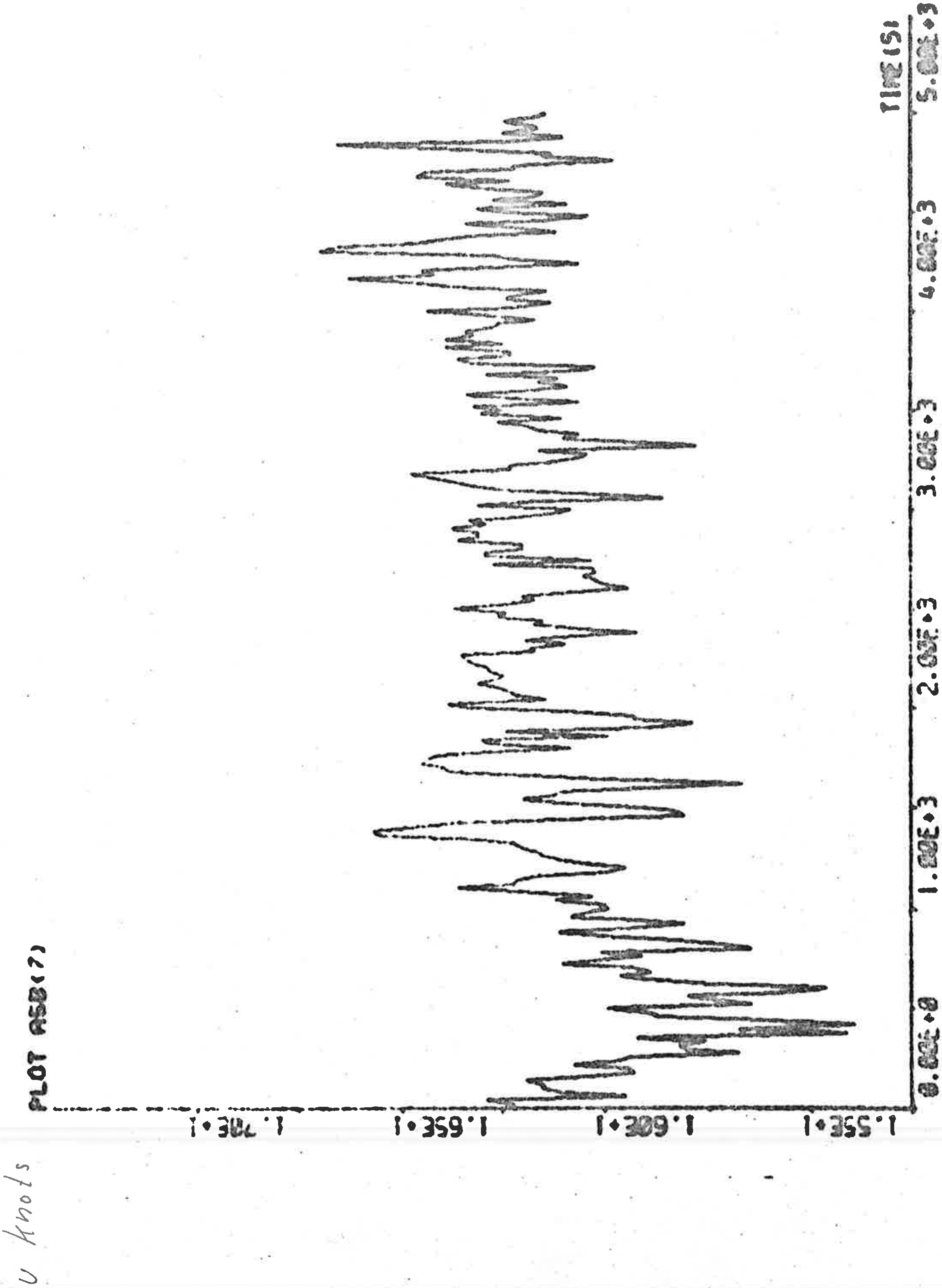

PLOT ASB(5)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
-1.00E-1
-5.00E-2
0.00E+0
5.00E-2
r degr/s

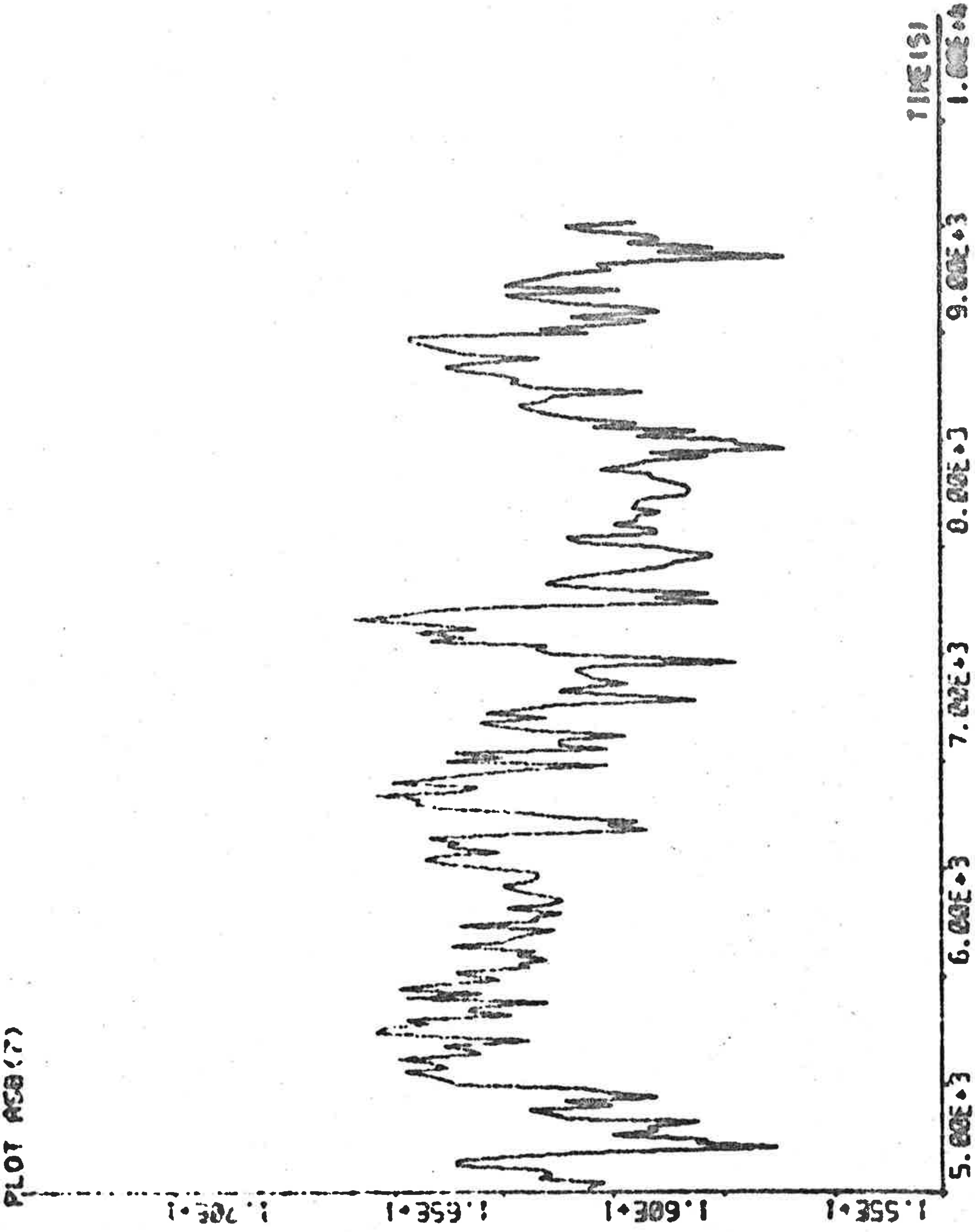

ψ degr
PLOT
142.5°
137.5°
142.5°
142.0°
141.5°
1.35E+2
2.00E+3
3.00E+3
TIME(S)


PLOT ASB(6)
TIME(S)
5.00E+3
6.00E+3
8.00E+3
1.40E+2
1.38E+2
1.35E+2
142.5°
142.0°
141.5°
137.5°

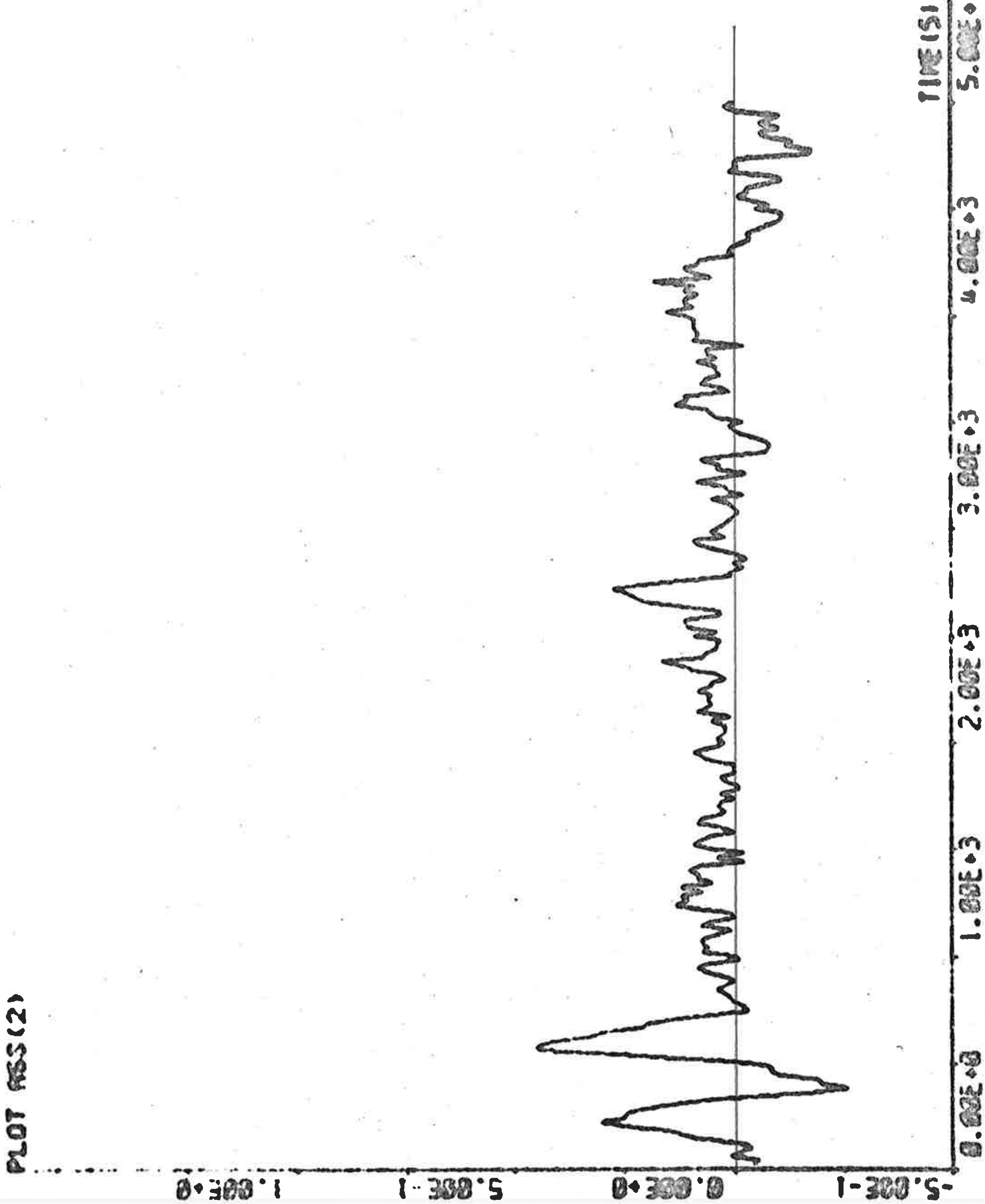

PLOT ABS(6)
TIME (S)
1.41E+2
1.42E+2
1.43E+2
1.44E+2
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
142.5°
142.0°
141.5°
Ψ degr

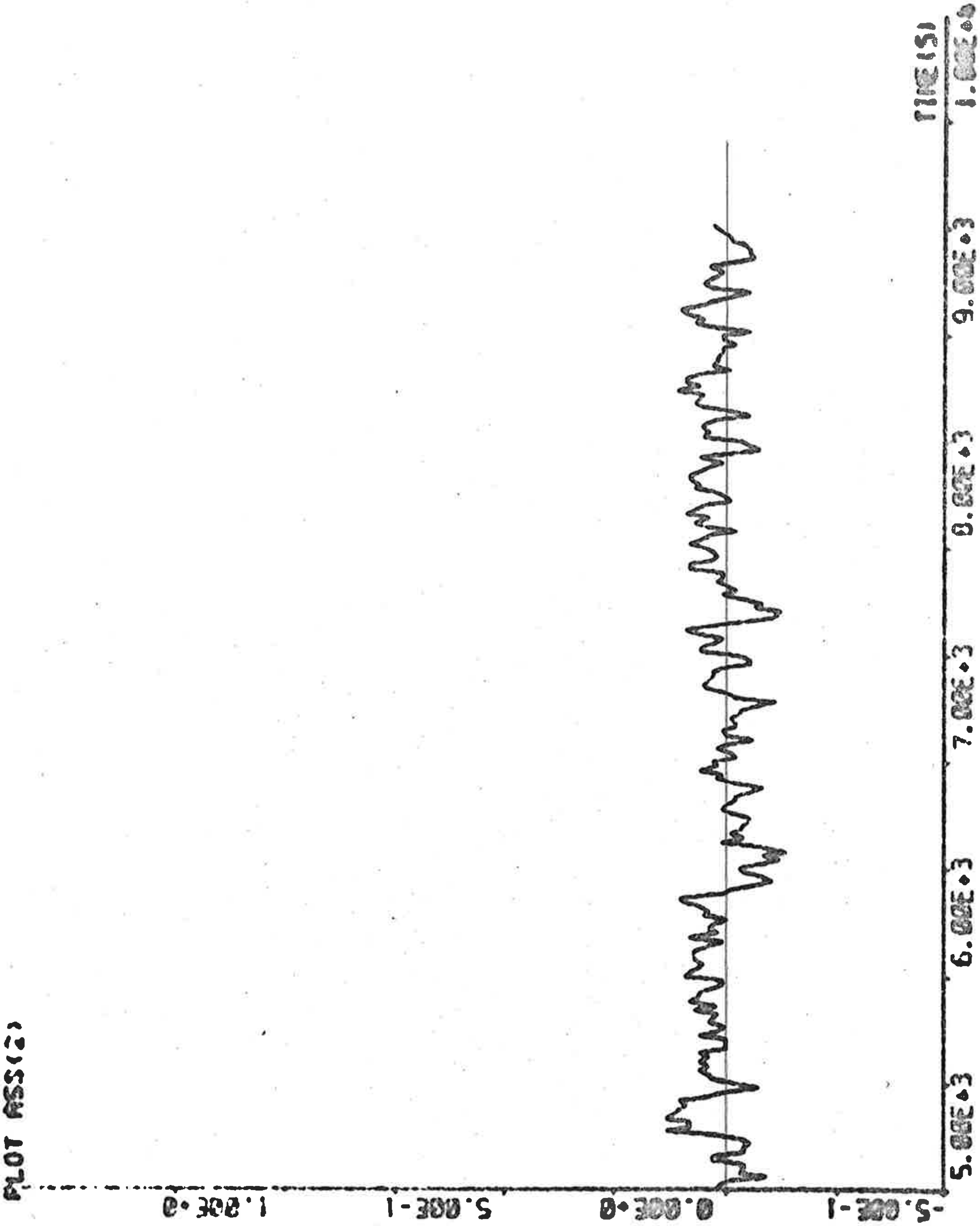

PLOT ASR(K)
TIME (S)
1.41E+2
1.42E+2
1.43E+2
1.44E+2
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
142.5°
142.0°
141.5°
ψ degr

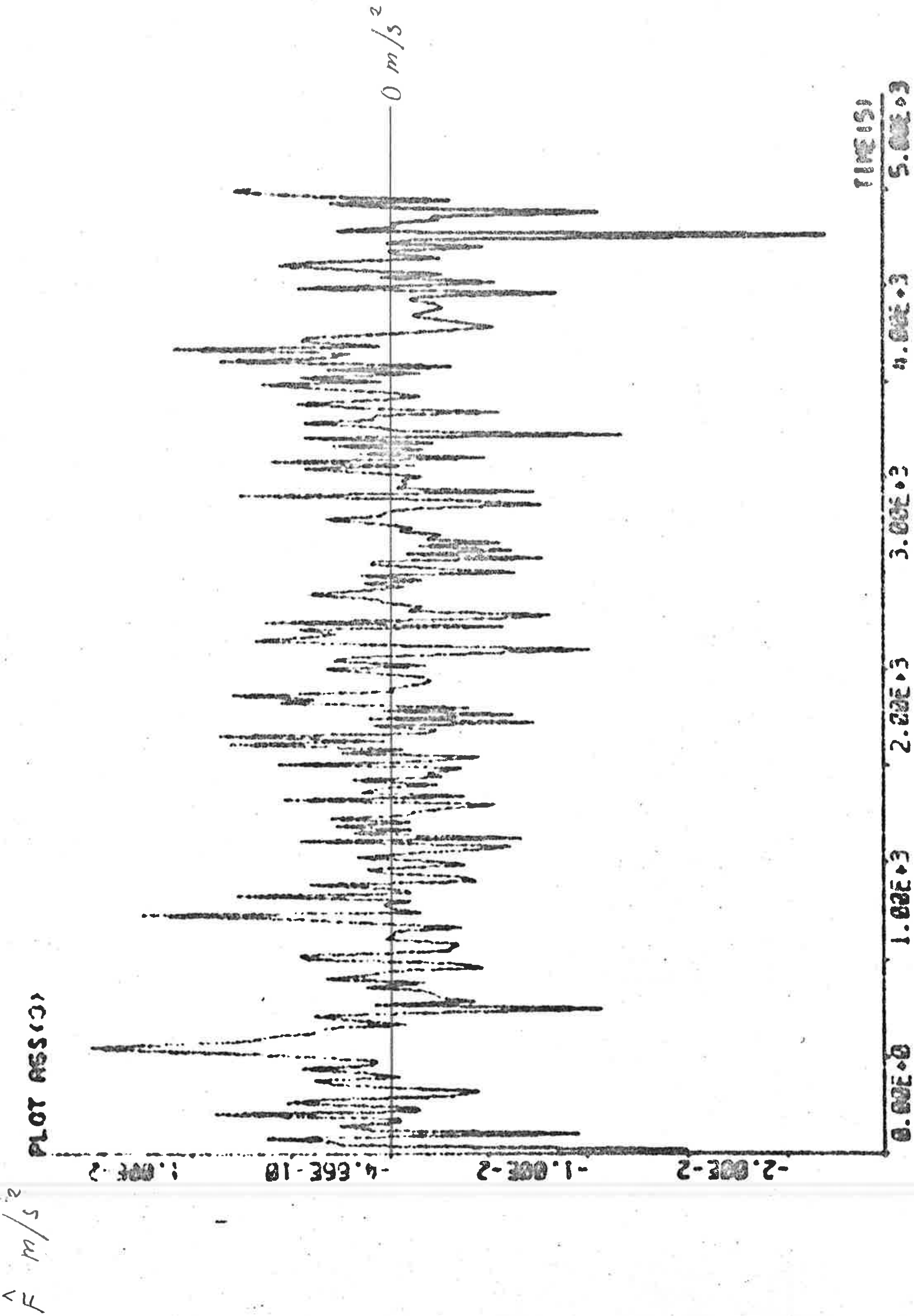

PLOT ASB(7)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.55E+1
1.60E+1
1.65E+1
1.70E+1
u knots

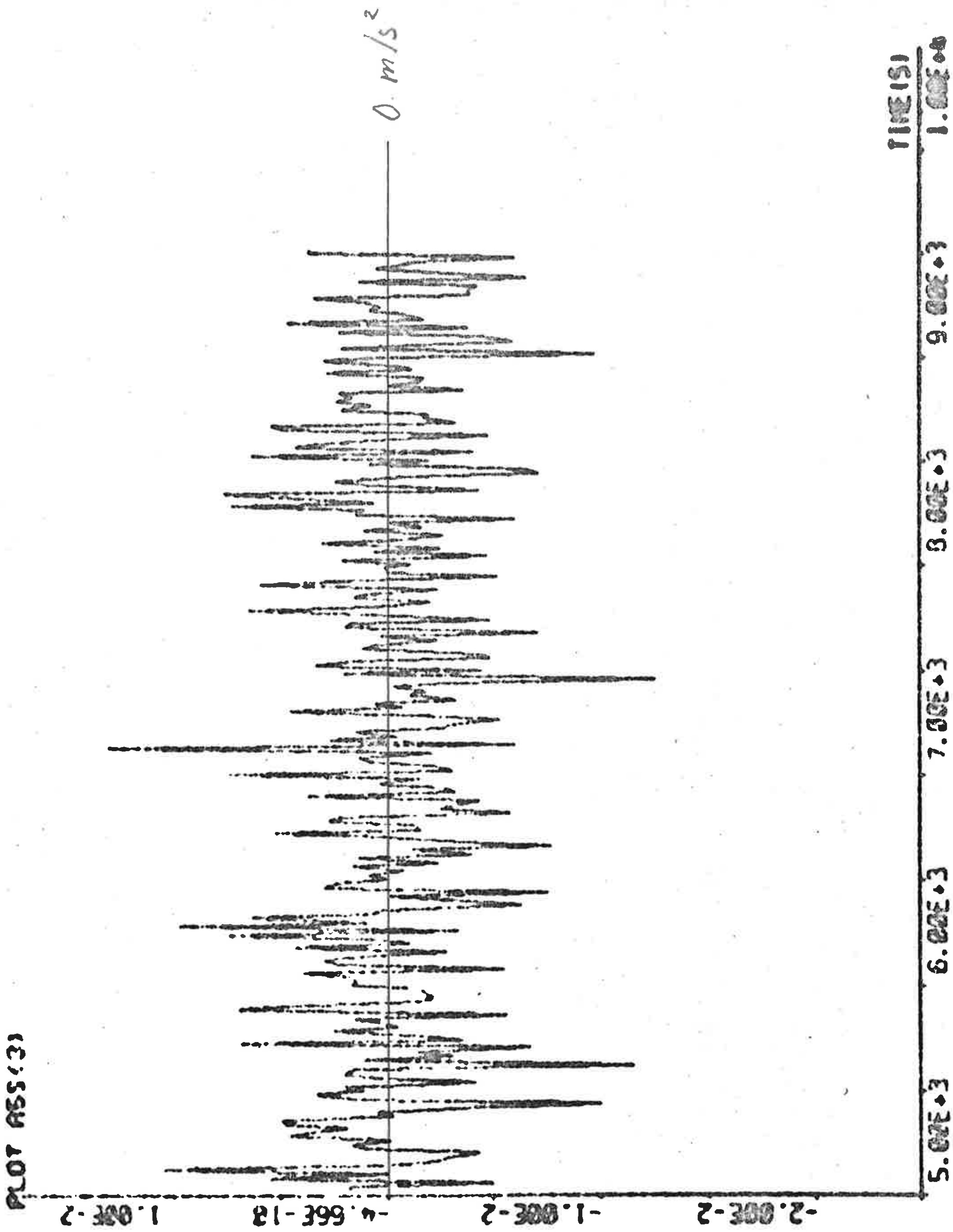


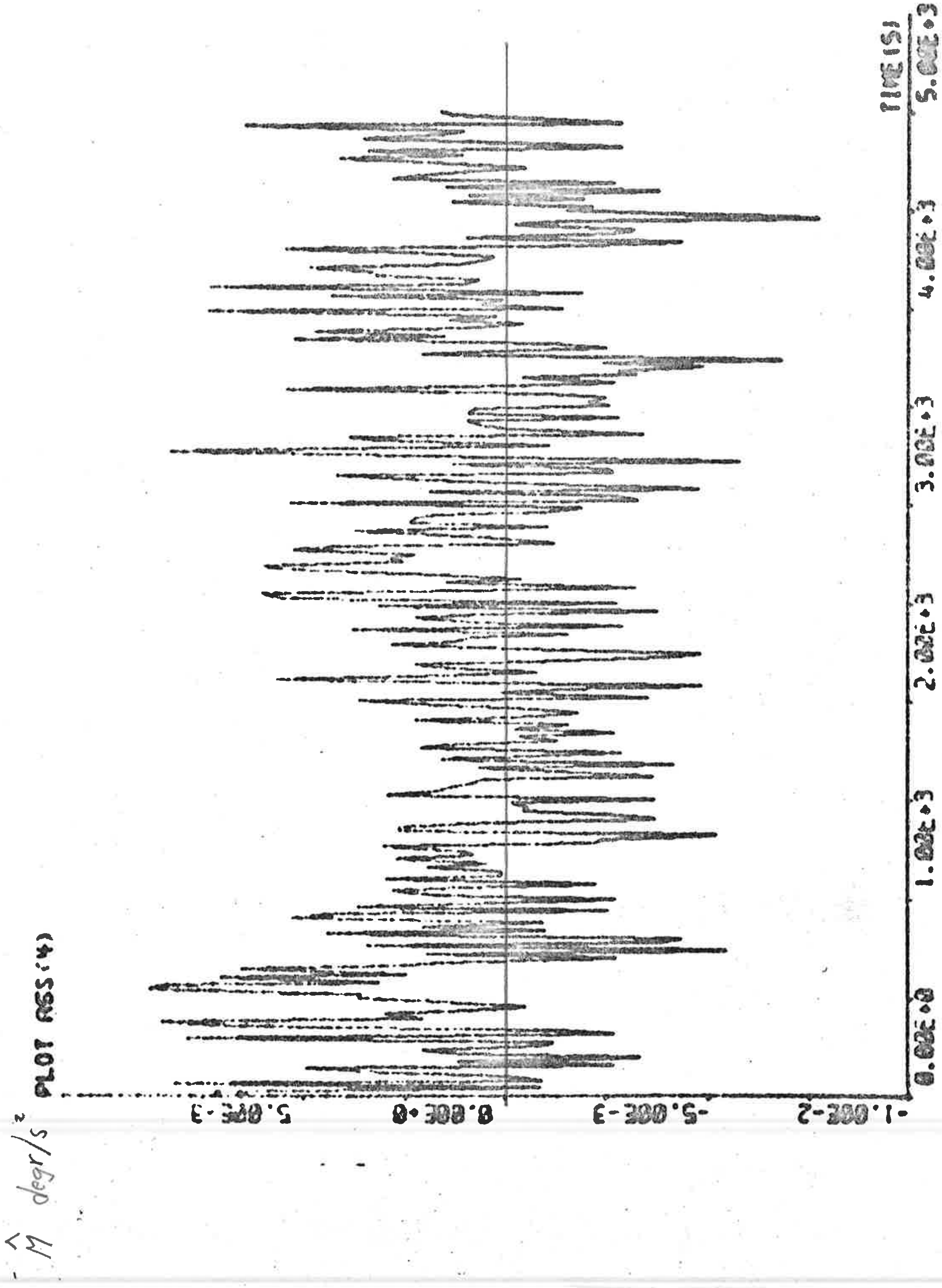
u knots

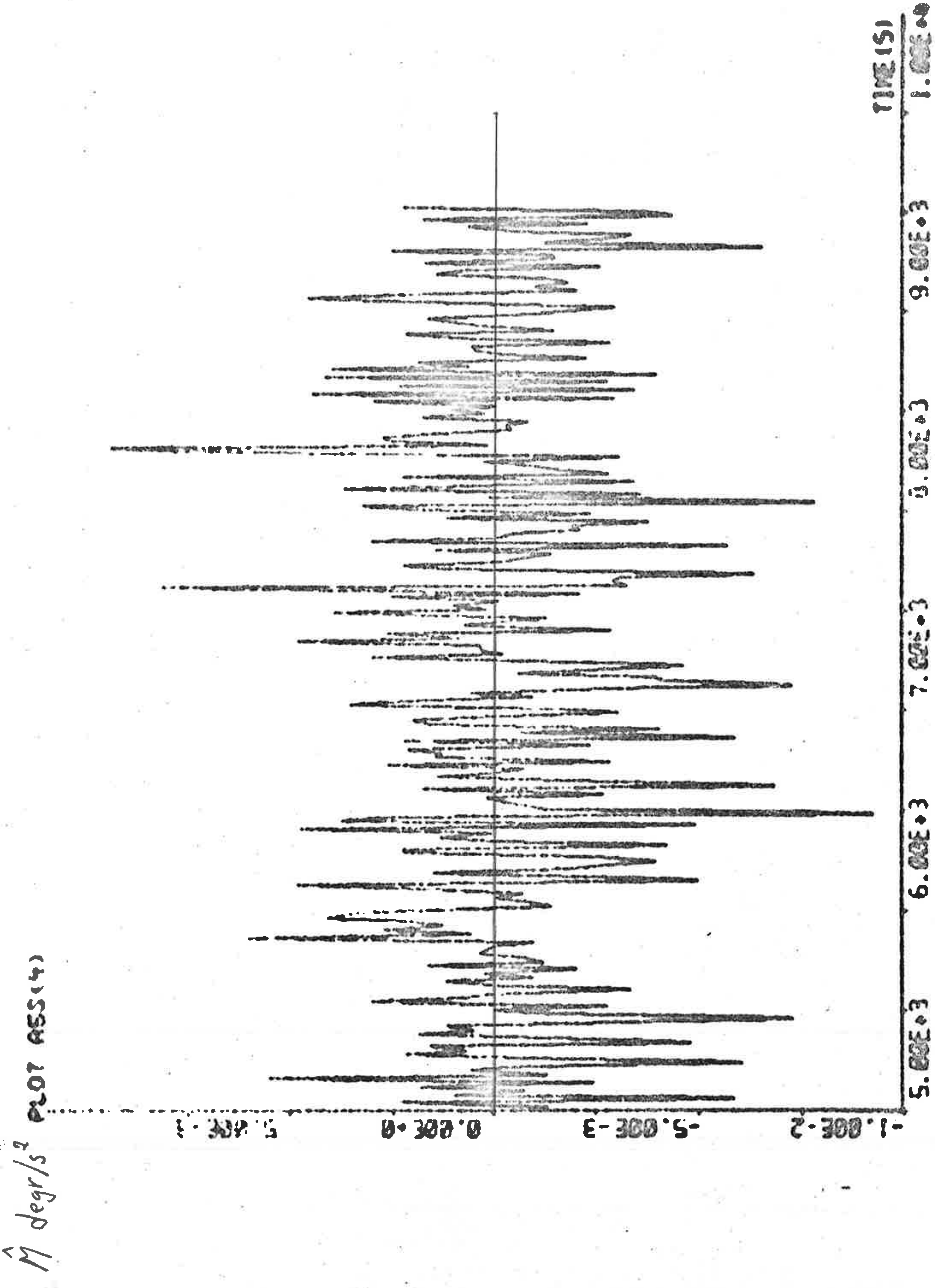

PLOT RSS(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

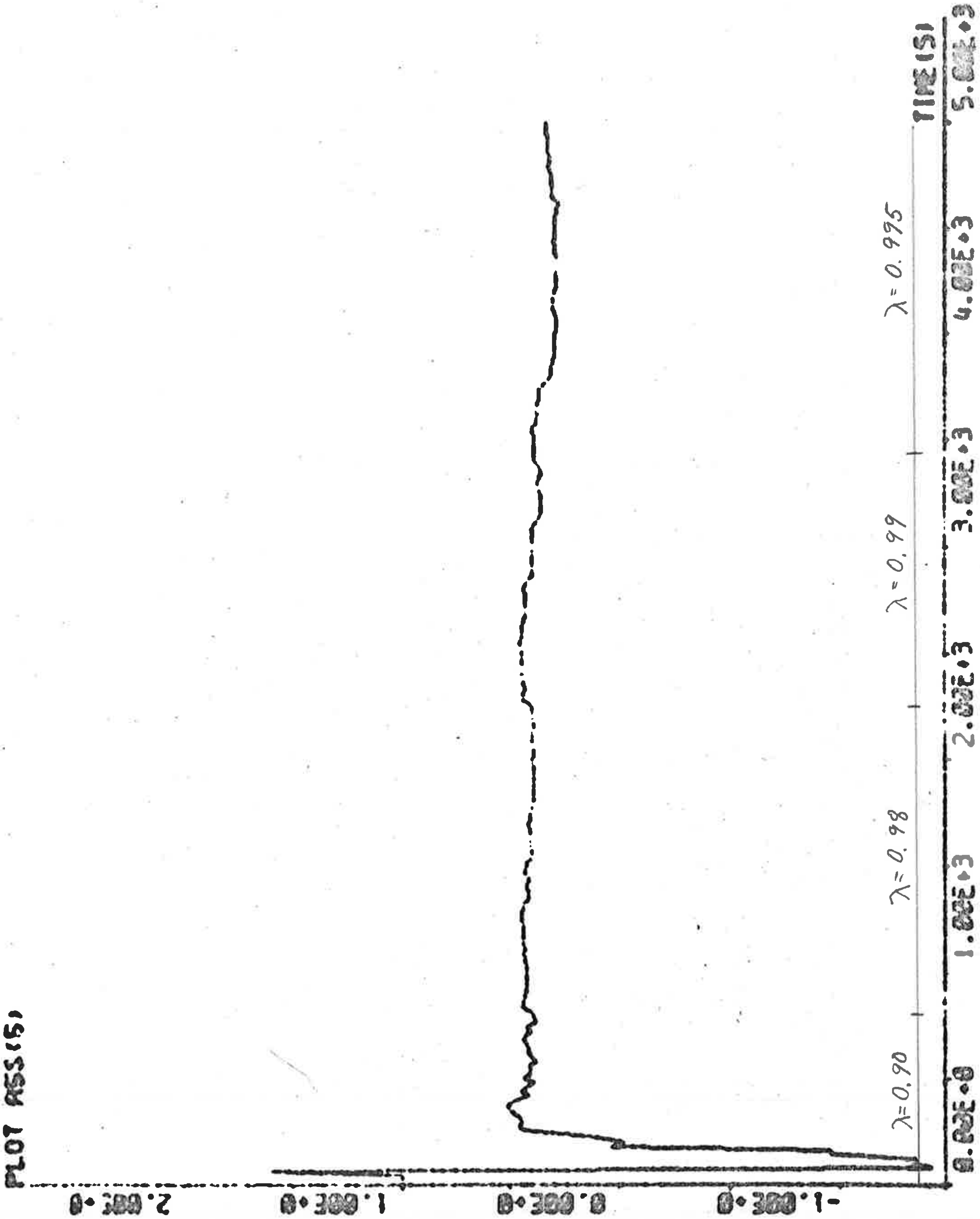

PLOT ASS(2)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
-5.00E-1
0.00E+0
5.00E-1
1.00E+0


0 m/s²
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
m/s²

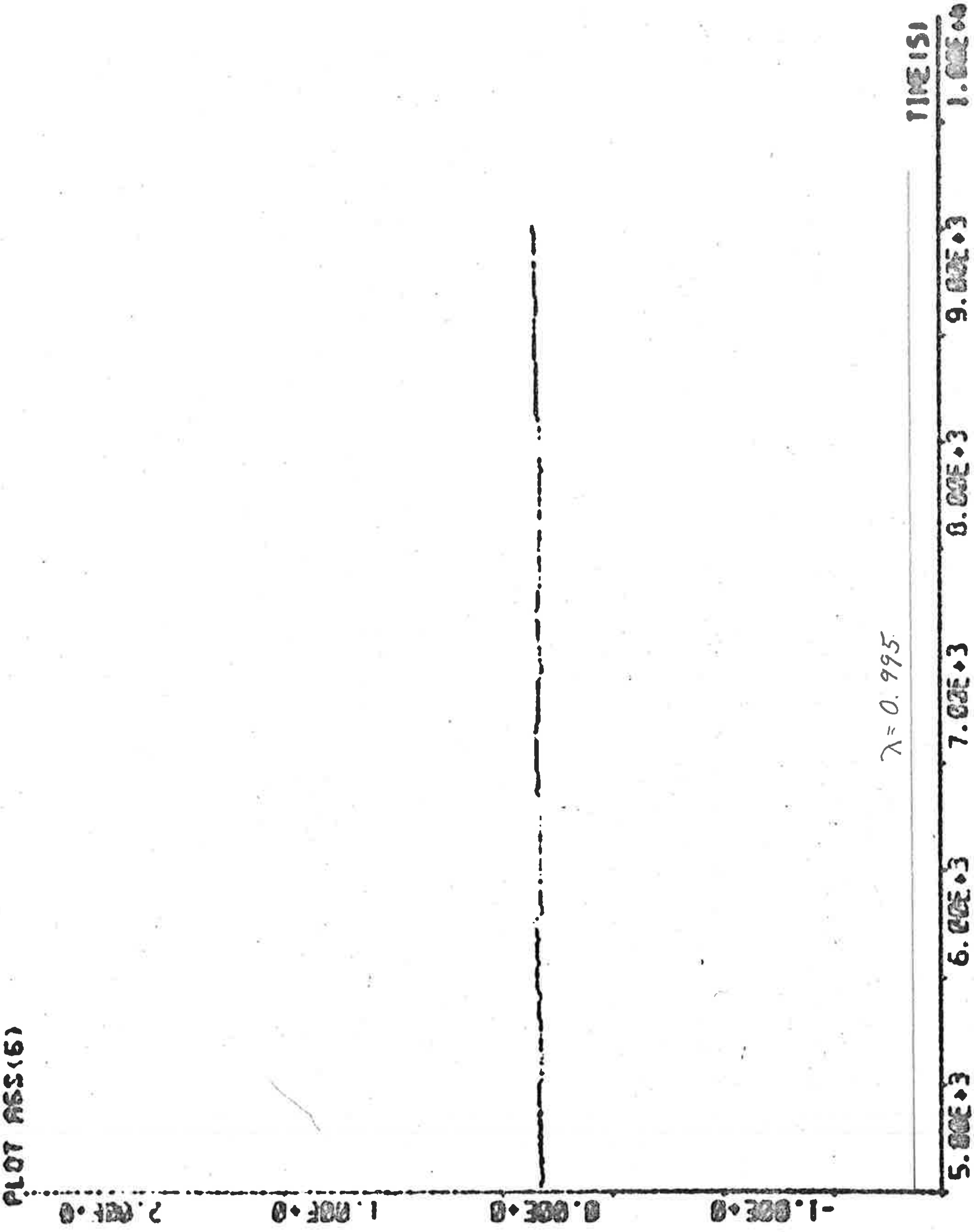

PLOT ASS(3)
0 m/s²
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E-2
-4.66E-18
-1.00E-2
-2.00E-2


PLOT ACC(4)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
degr/s²

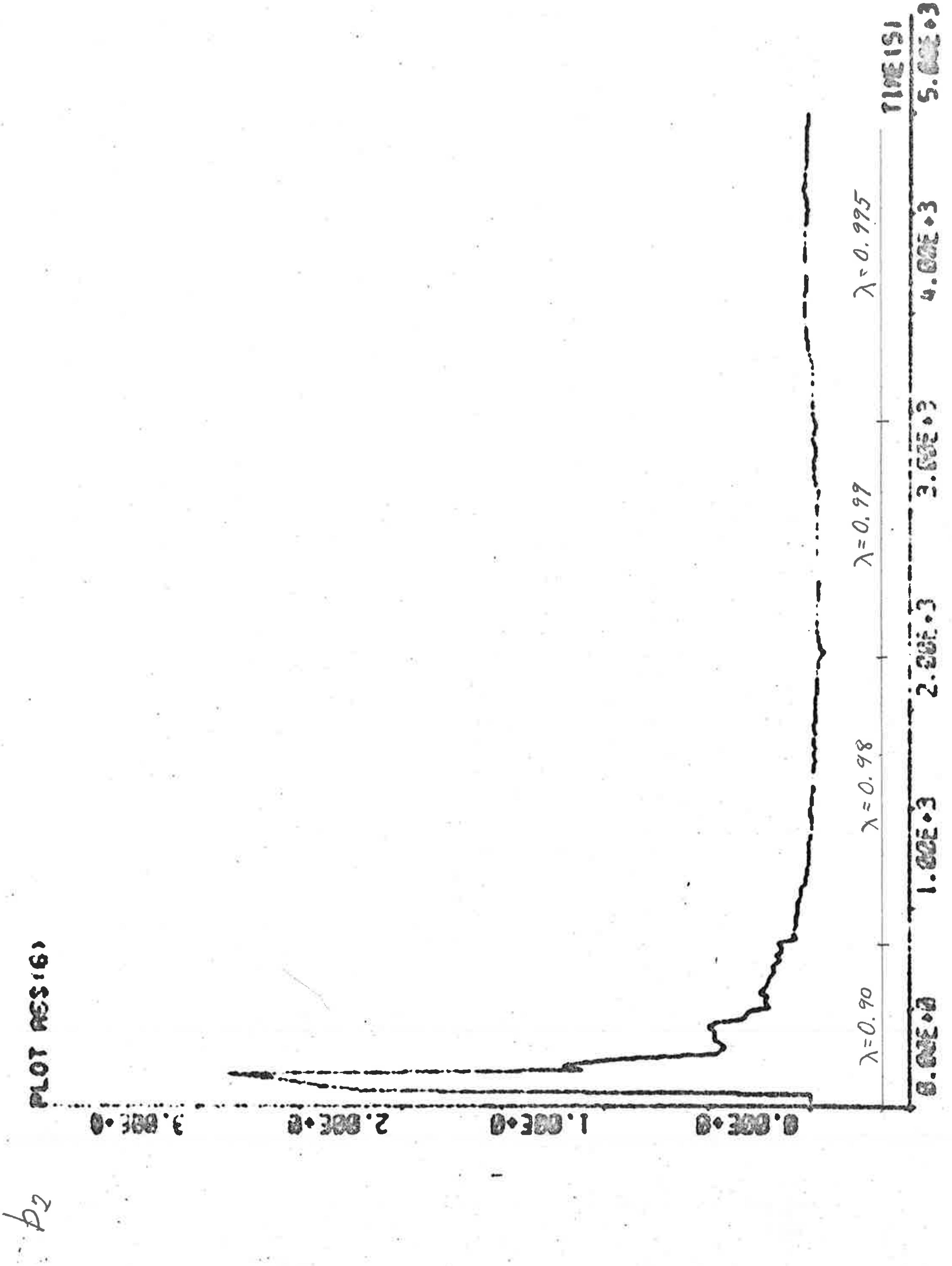

PLOT ASS(4)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
$\hat{M}$ degr/s²

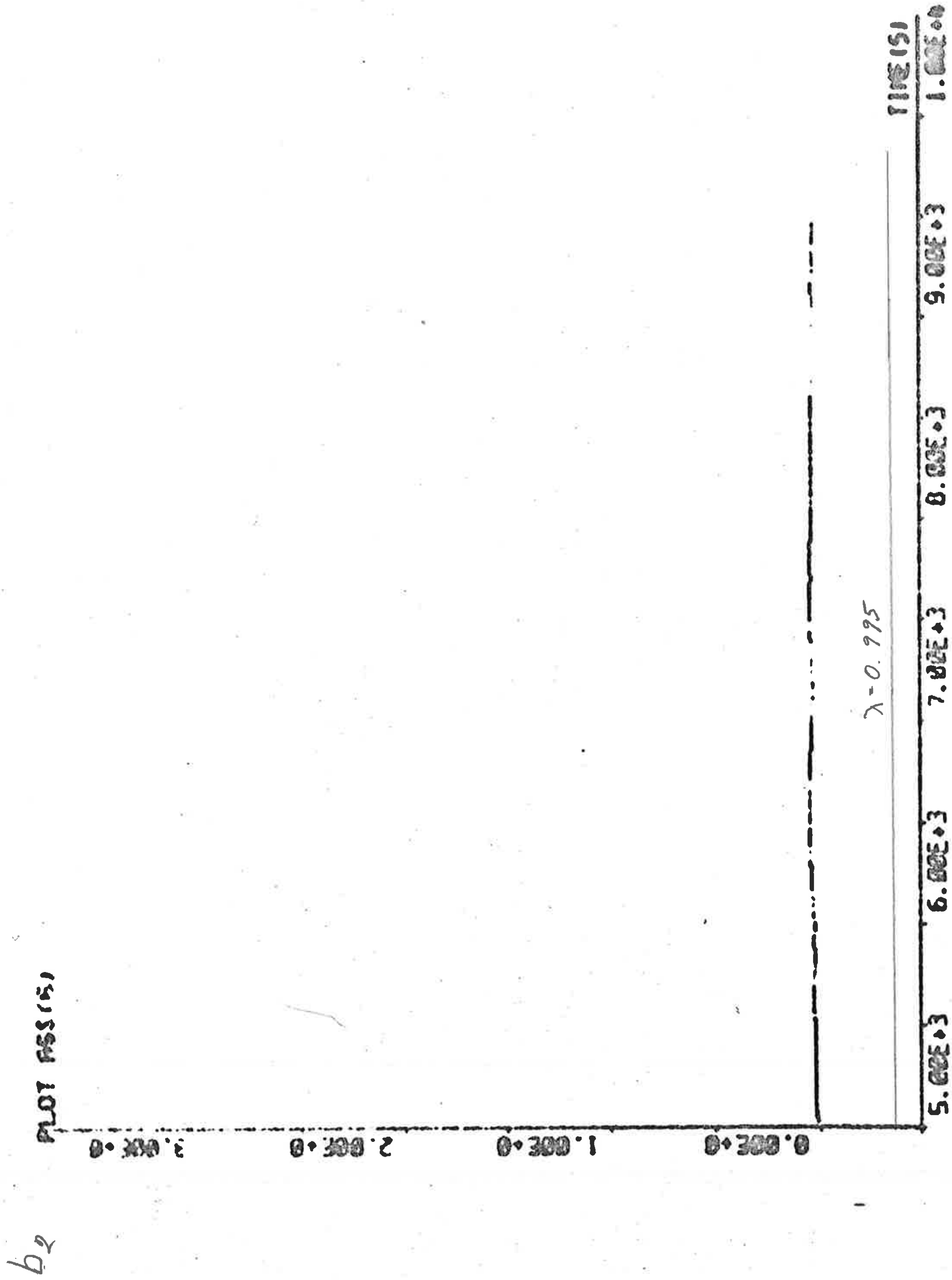

PLOT ASS(5)
TIME (S)
λ=0.90
λ=0.98
λ=0.99
λ=0.995
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0

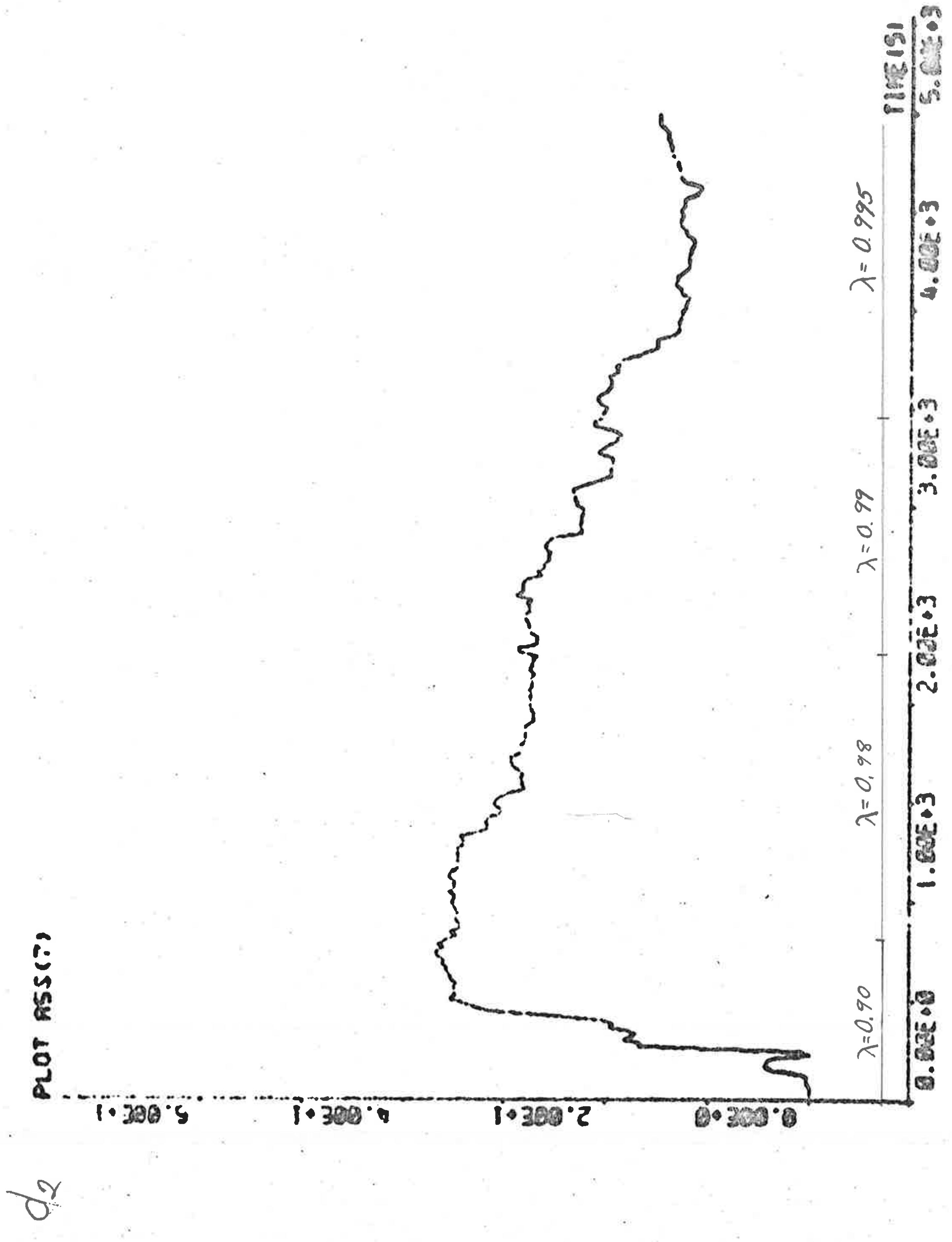
b_1

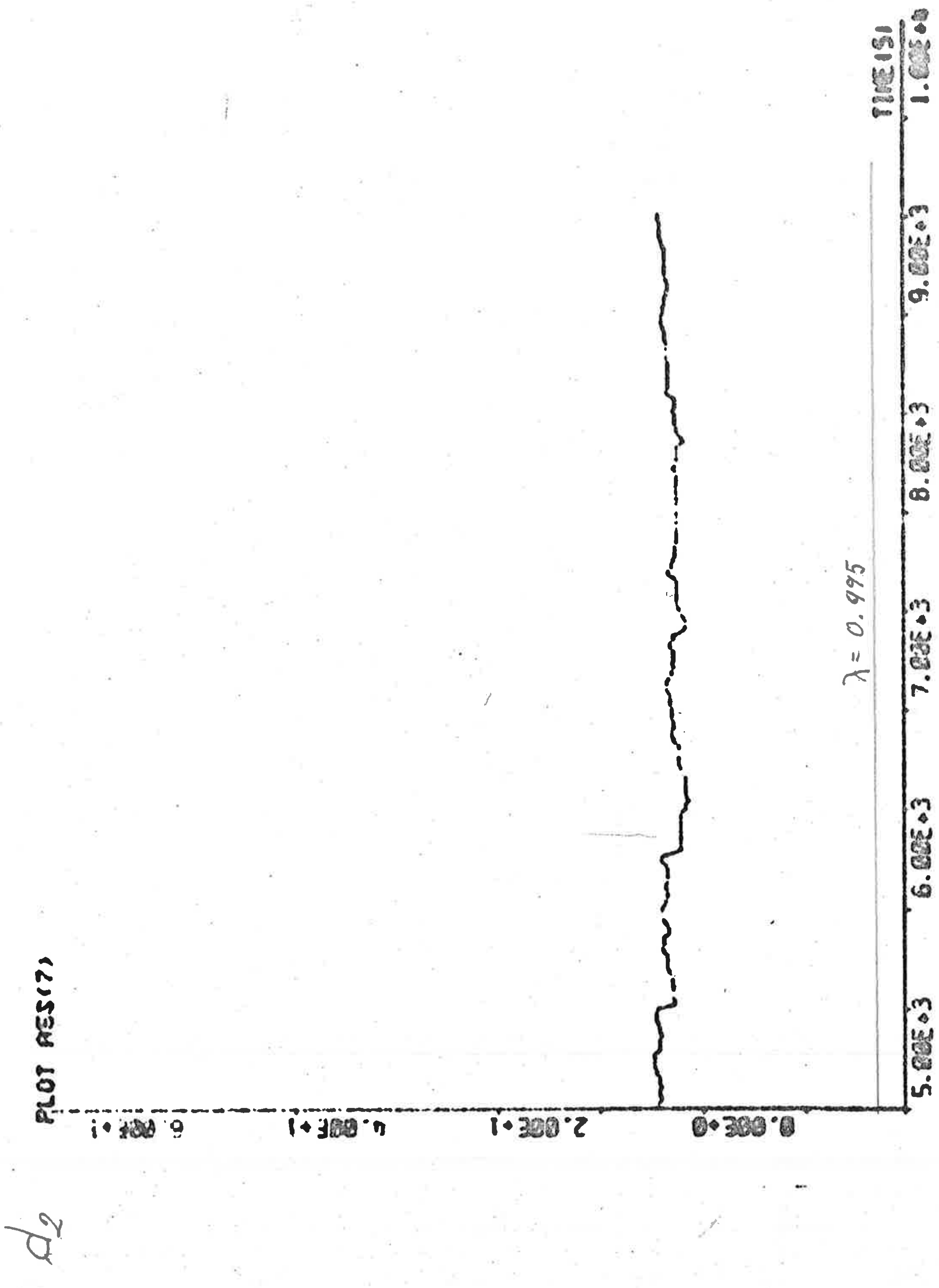


b1


PLOT RES(6)
TIME(S)
λ=0.90
λ=0.98
λ=0.99
λ=0.995
0.00E+0
1.00E+0
2.00E+0
3.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
p2


TIME (S)
1.00E+4
9.00E+3
8.00E+3
7.00E+3
6.00E+3
5.00E+3
λ=0.995
0.00E+0
1.00E+0
2.00E+0
3.00E+0
PLOT ASS(5)
b2


PLOT RSS(7)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E-1
4.00E-1
λ=0.90
λ=0.98
λ=0.99
λ=0.995
d2


PLOT RES(7)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
0.00E+0
2.00E-1
4.00E-1
6.00E-1
λ = 0.995
d2

Experiment A6

Date: 73 - 10 - 17
Time: 20^{40} - 22^{00}
Position: S 19° E 05°

Wind direction: 1 (see appencix A)
Wind speed: 4 Beaufort (6 - 9 m/s, moderate breeze)
Wave height: Noticeable rollings

Regulator 2

The Kalman filter is used, but no state estimates are put into the regulator. The first part of the experiment (0 - 3220 s) is a test of yawing with the self-tuning regulator without the yaw regulator, i.e. $\bar{\Psi}_{ref}$ is put equal to Ψ_{ref} (see fig. 3.1 in chapter 3). The second part of the experiment (3220 - 5360 s) is an unsuccessful attempt to perform the same yawing with the yaw regulator.

Calibration of the rudder servo:

+10 volts = 36.9°
-10 volts = -43.1°

Notice that the bias of the v_1-measurements is compensated by adding 0.5 knots to the real measurements.

Kalman filter:

The same filter gain as during experiments A4 and A5 is used. The initial state estimate vector in the Kalman filter is

$$\hat{x}(0) = \begin{bmatrix} 0.01 \\ 0.0 \\ 142.0 \\ 0.00208 \\ -0.00460 \end{bmatrix}$$

Model in the regulator:

$$(\Psi(t+3) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = b_1\delta(t) + b_2\delta(t-1) + d_2 r(t) + e(t+3)$$

Regulator:

$$\delta(t) = -\frac{1}{b_1}[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_2 r(t)]$$

Sampling interval:	20 s	
Forgetting factor λ:	0.995	(0 - 3700 s)
	0.99	(3700 - 5360 s)
Rudder limits:	$\pm 10^\circ$	(0 - 3220 s)
	$\pm 10^\circ, \pm 5^\circ, \pm 3^\circ$	(3220 - 5360 s)

Ψ_{ref}: 142°, 144°, 136°, 150°, 142°, 144°, 142°

Initial values:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.3914 \\ -0.0819 \\ 18.3687 \end{bmatrix} \qquad P = \begin{bmatrix} 0.02742 & & \\ -0.01544 & 0.01486 & \\ 1.445 & -0.9178 & 99.54 \end{bmatrix}$$

Regulator:

$$\delta(t) = -2.5549(\Psi(t) - \Psi_{ref}) + 0.2092\delta(t-1) - 46.9308r(t)$$

Values after 3220 s:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.7227 \\ -0.2554 \\ 38.2554 \end{bmatrix} \qquad P \text{ unknown}$$

Regulator:

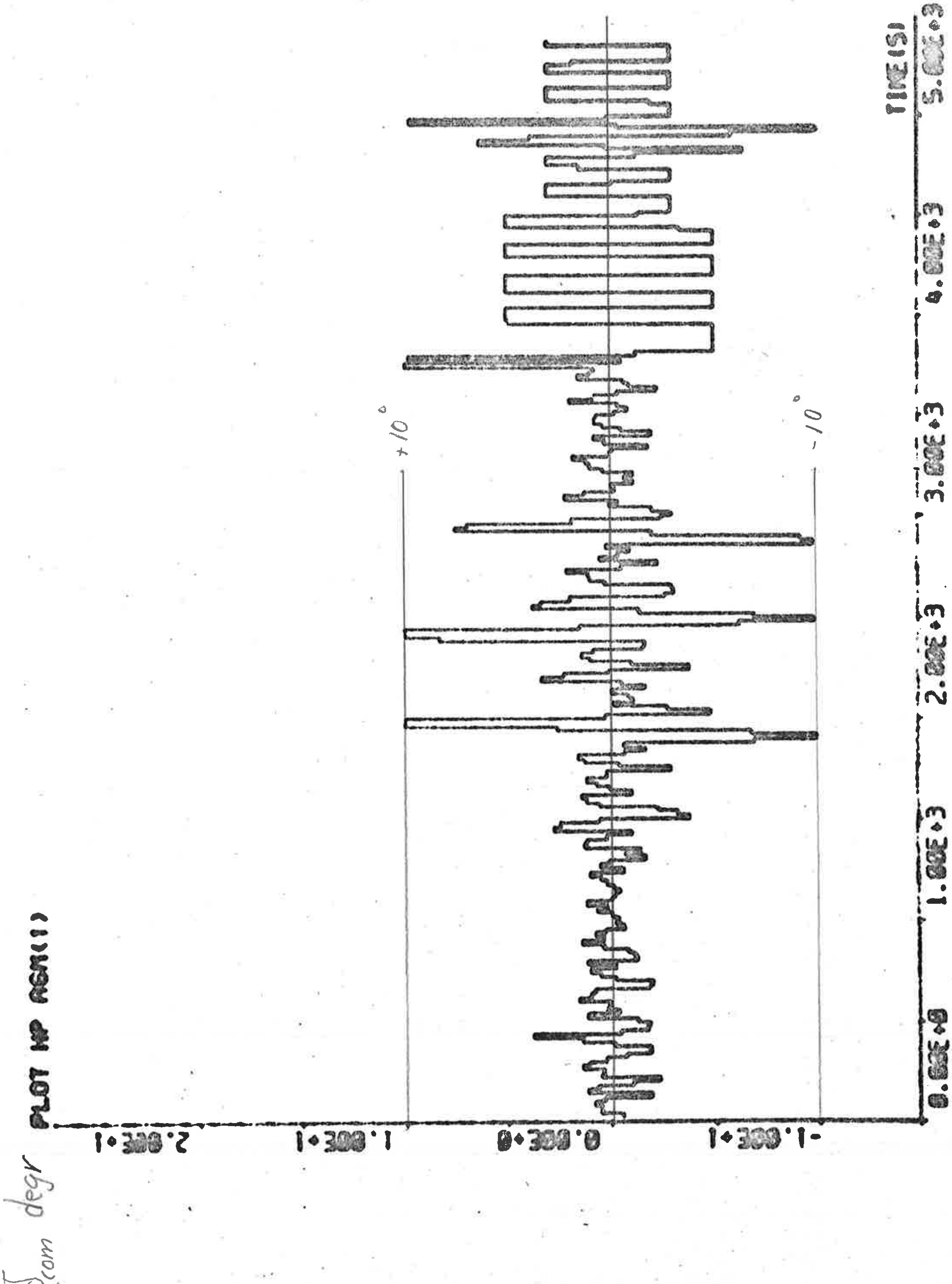
$$\delta(t) = -1.3837(\Psi(t) - \Psi_{ref}) + 0.3534\delta(t-1) - 52.9340r(t)$$

Final values:

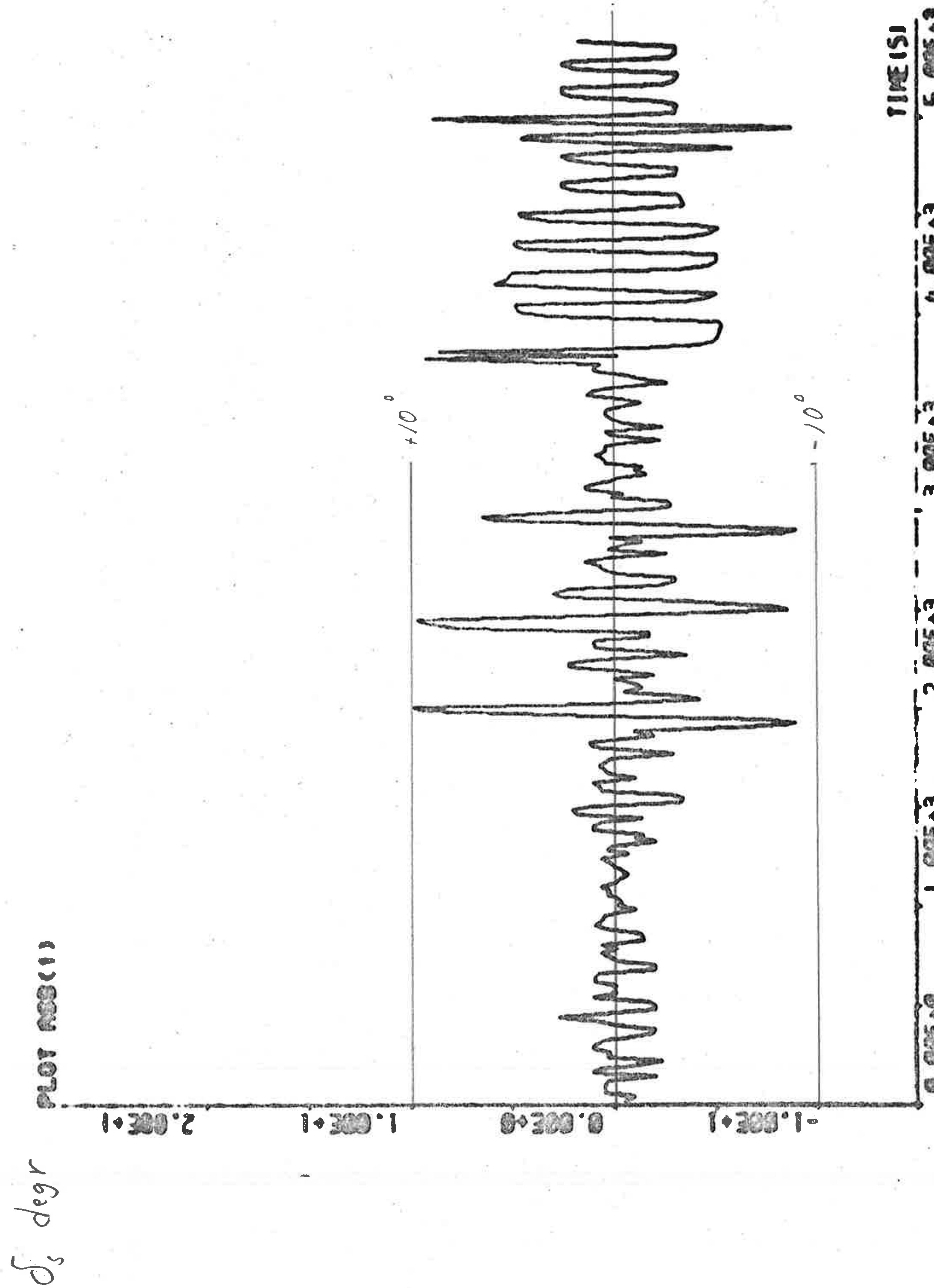
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.0925 \\ 0.0631 \\ 1.7870 \end{bmatrix} \qquad P = \begin{bmatrix} 0.0000154 & & \\ -0.0000017 & 0.0000511 & \\ 0.001778 & -0.006988 & 1.277 \end{bmatrix}$$

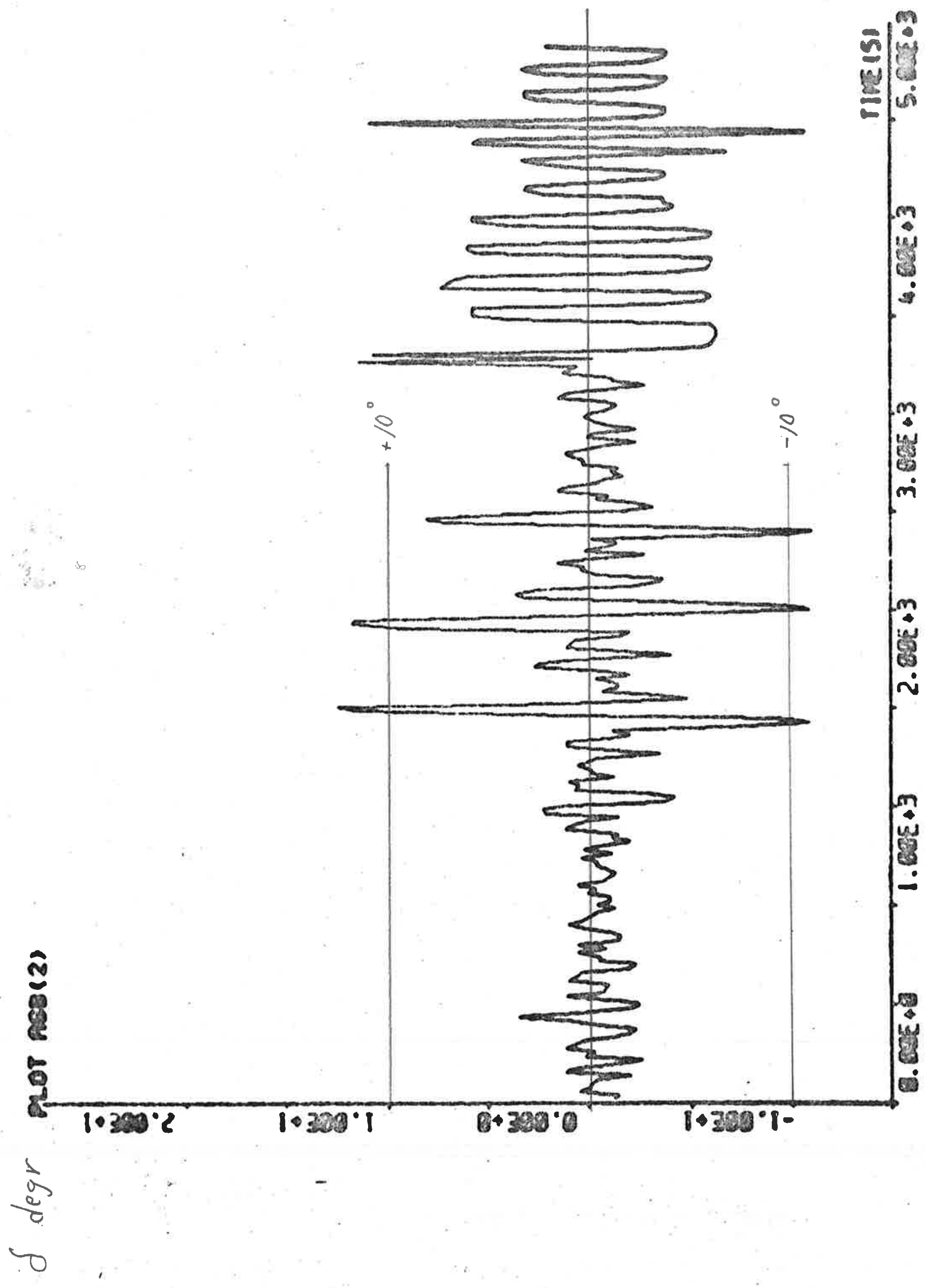
Regulator:

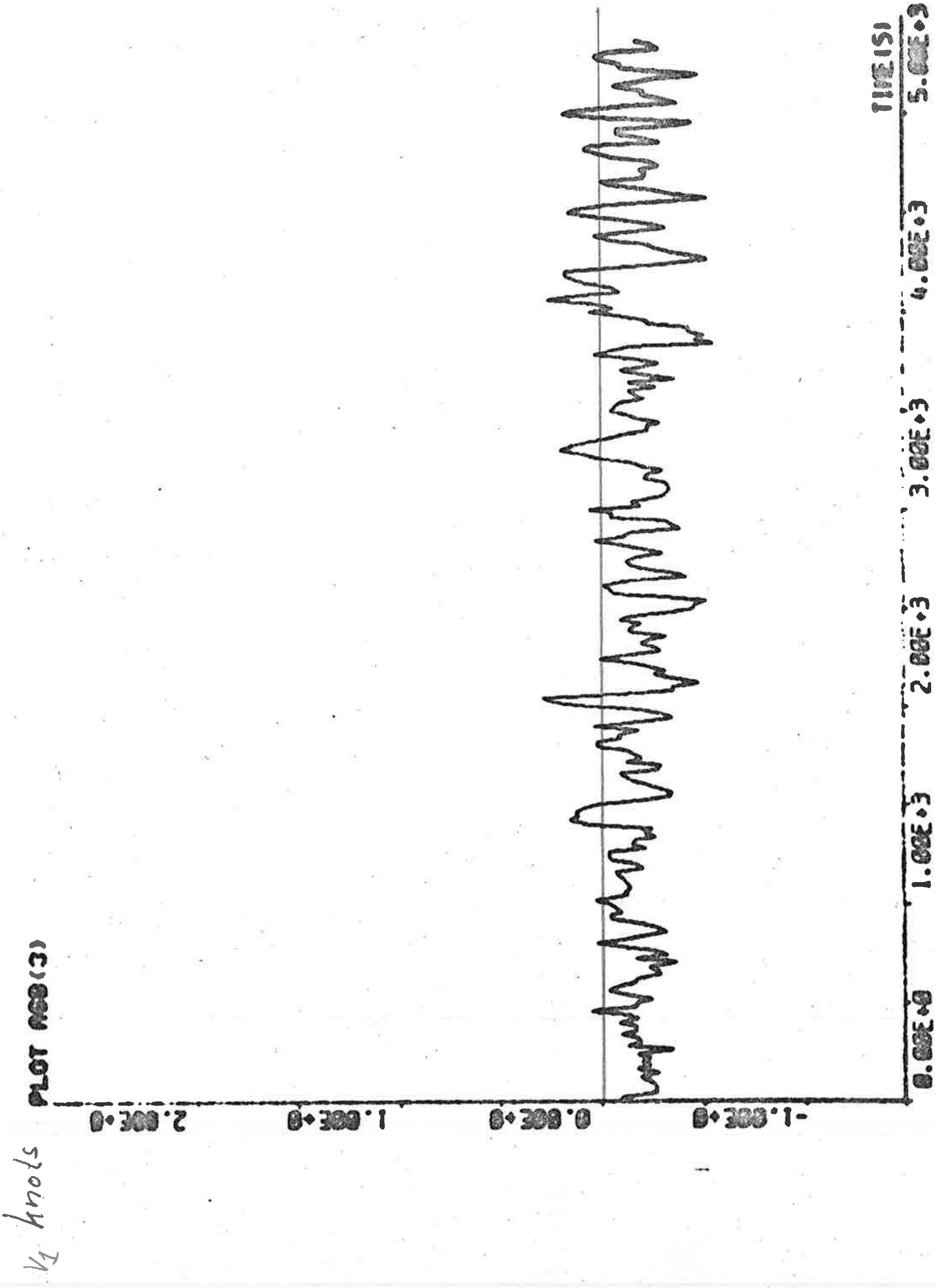
$$\delta(t) = -10.8108(\Psi(t) - \Psi_{ref}) - 0.6822\delta(t-1) - 19.3189r(t)$$

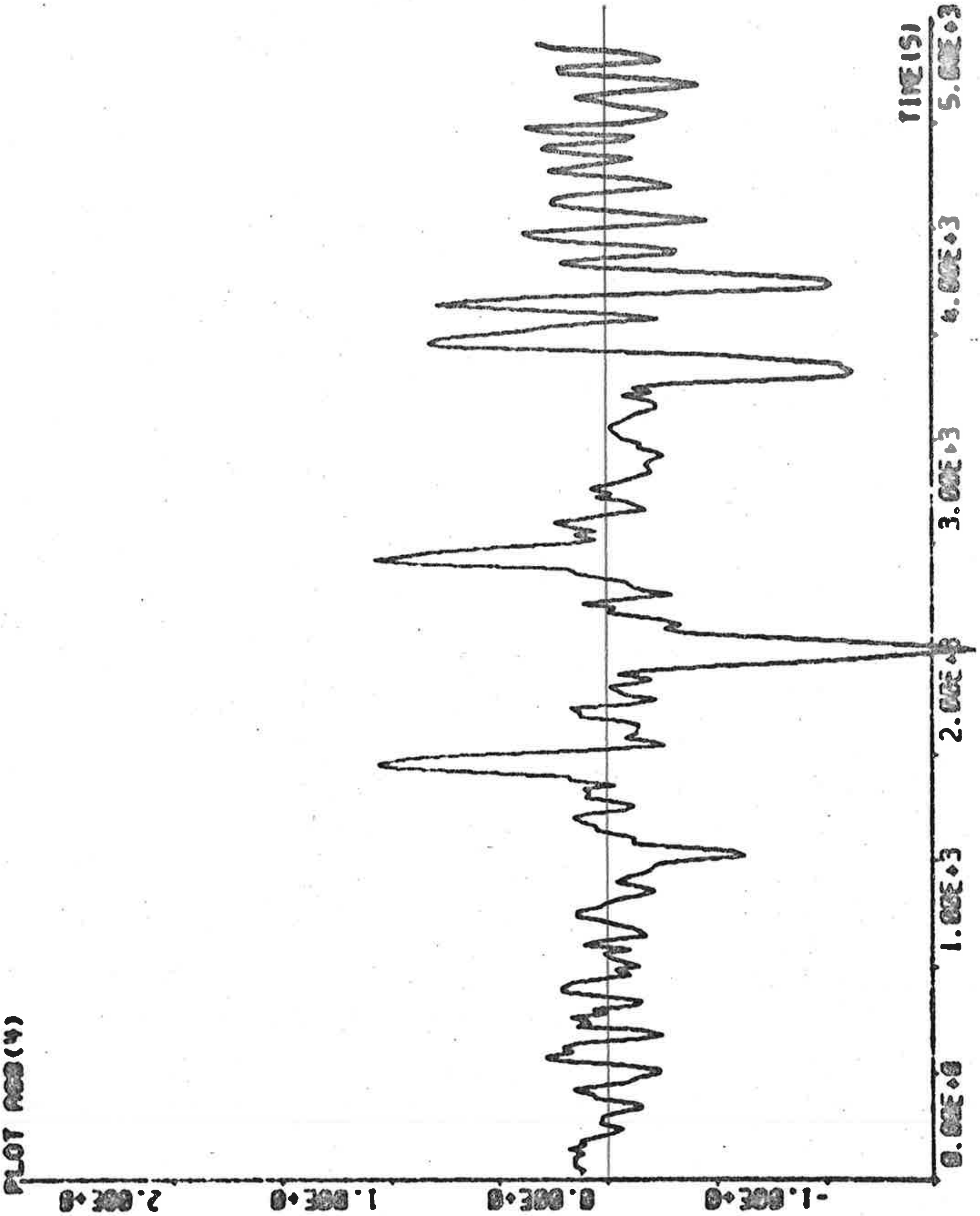


PLOT HP ASM(1)
2.00E+1
1.00E+1
0.00E+0
-1.00E+1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
+10°
-10°
δcom degr

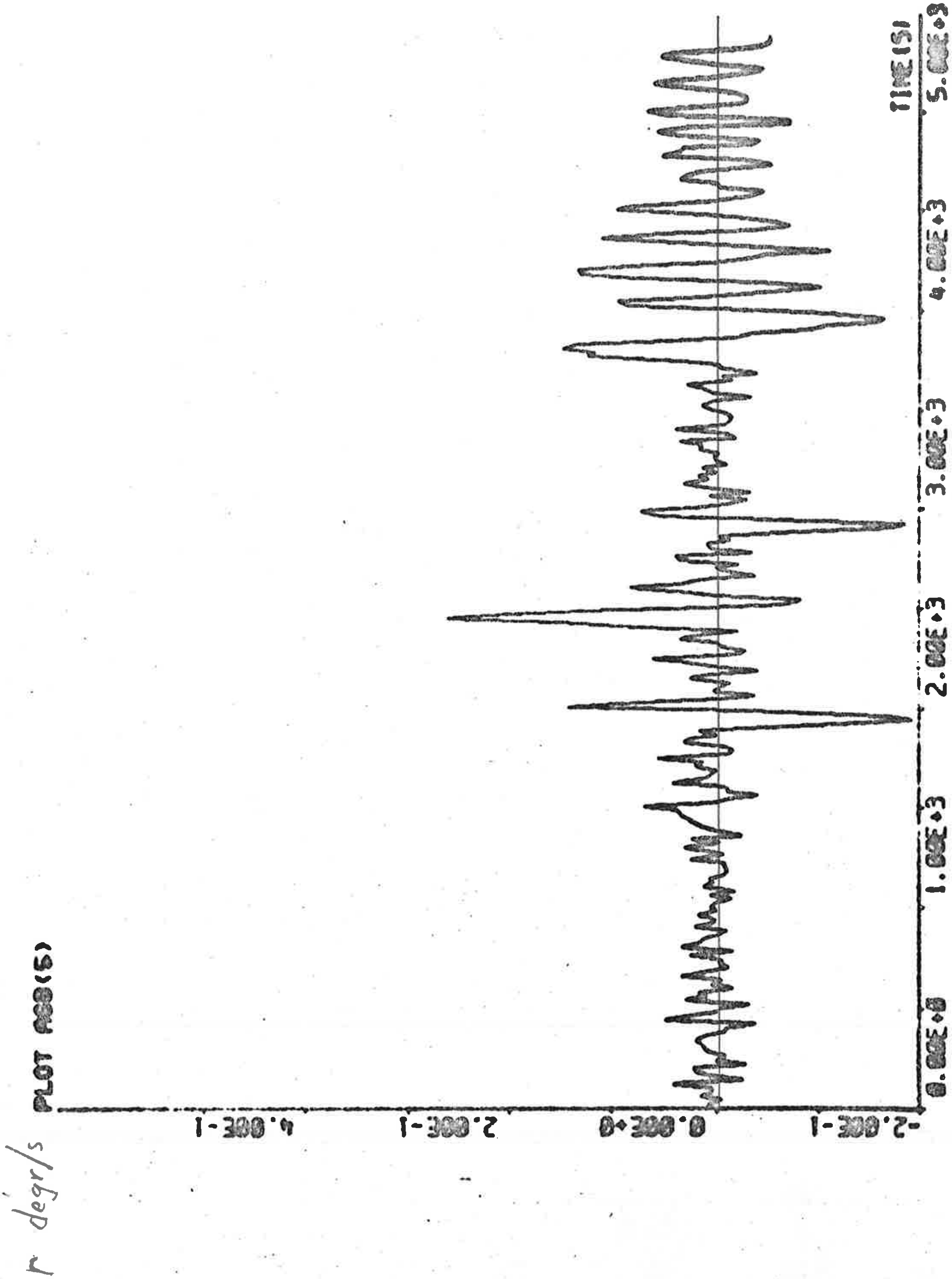

TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+1
1.00E+1
0.00E+0
-1.00E+1
+10°
-10°
δs degr


PLOT ASB(2)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+1
1.00E+1
0.00E+0
-1.00E+1
+10°
-10°
δ degr

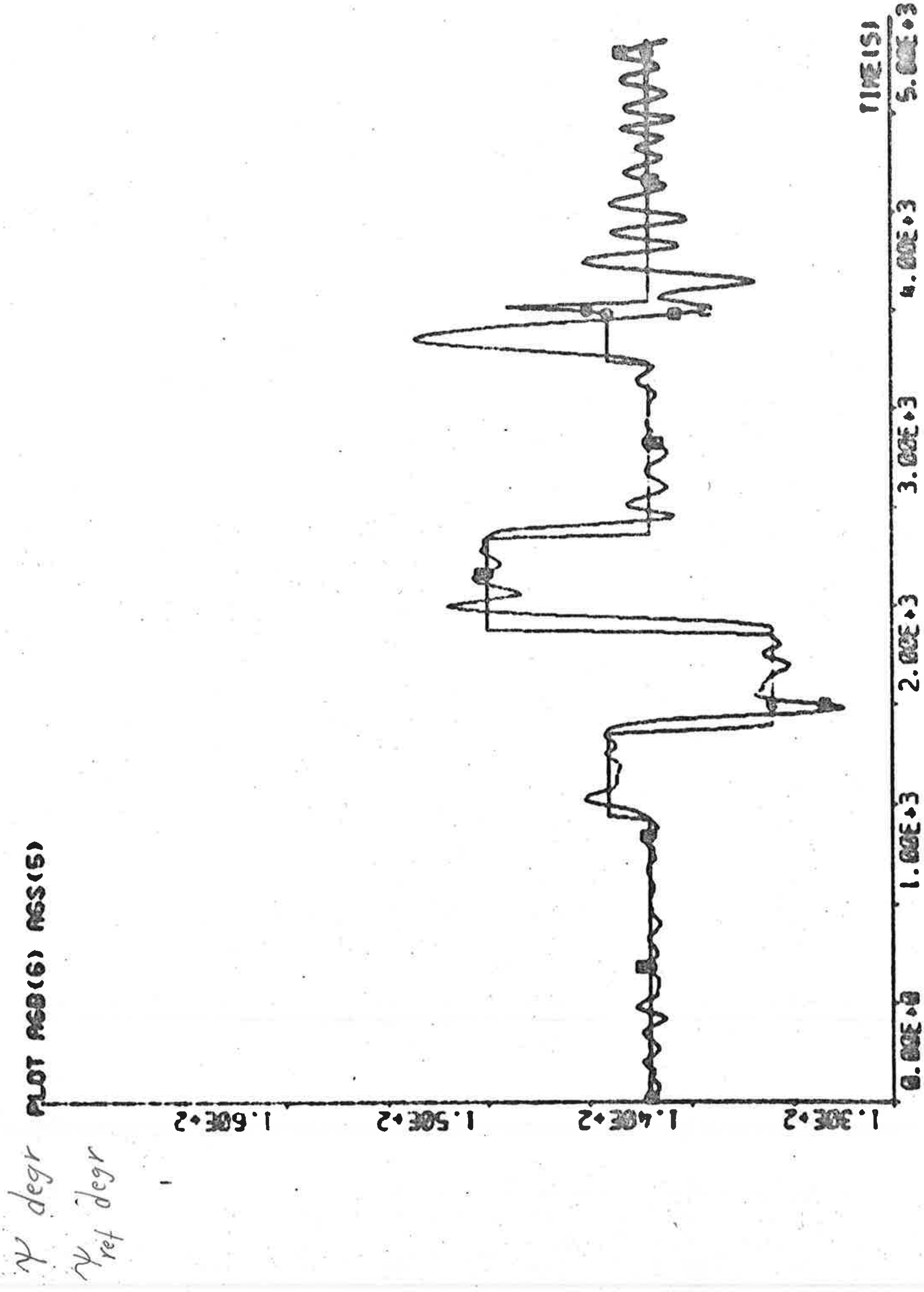

PLOT ROB(3)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V1 knots

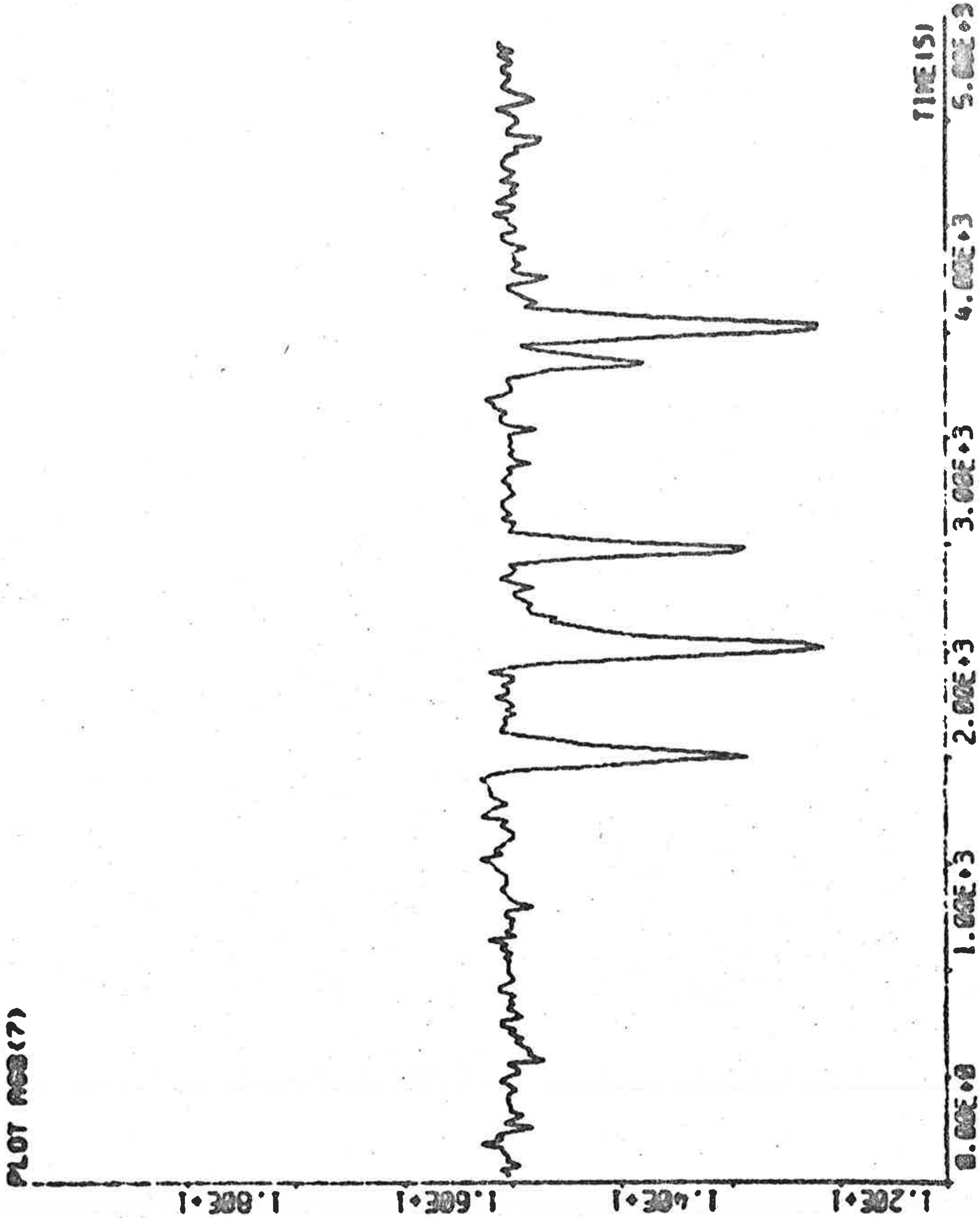

2.00E+0
1.00E+0
0.00E+0
-1.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

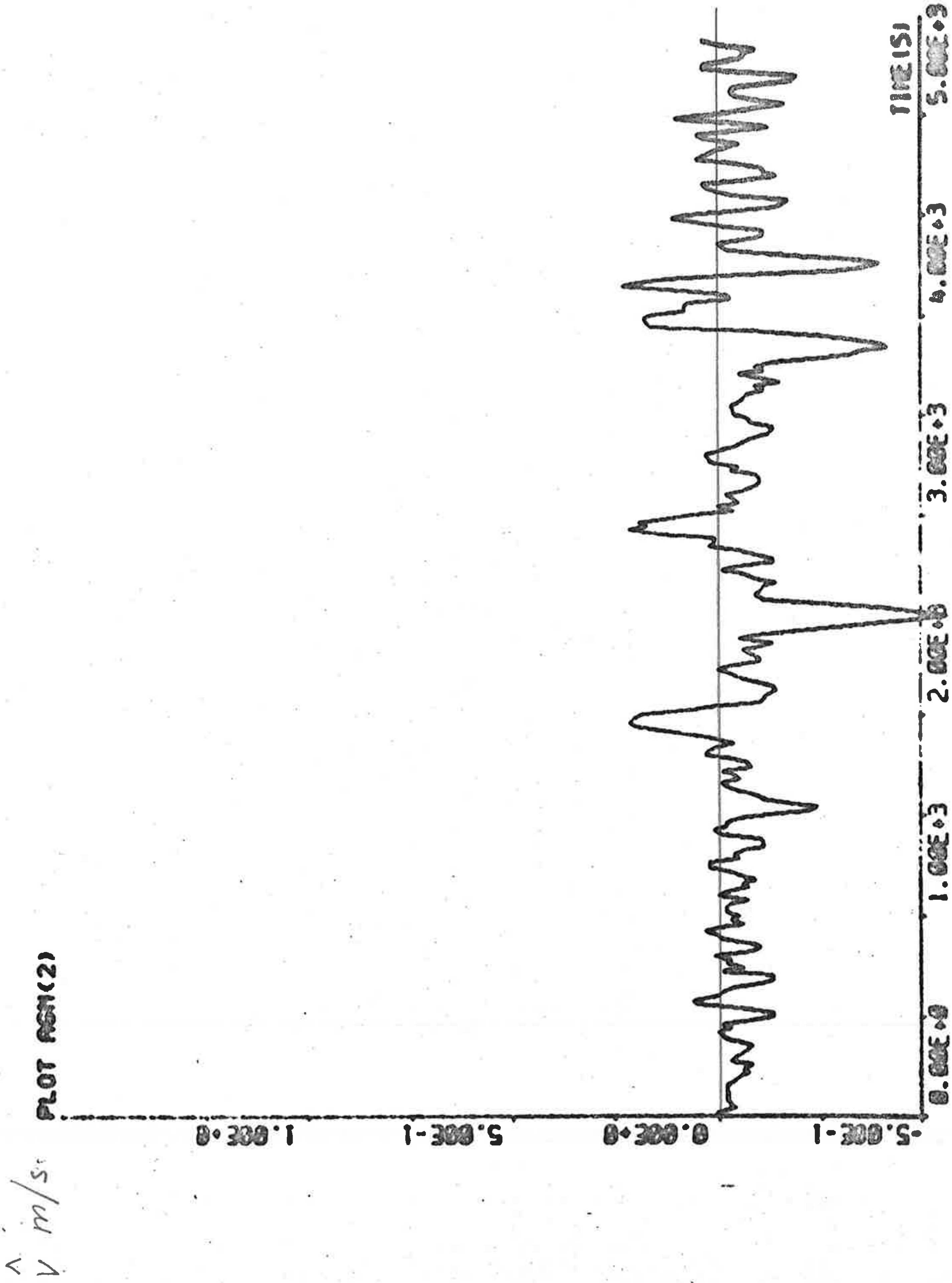
V_2 knots

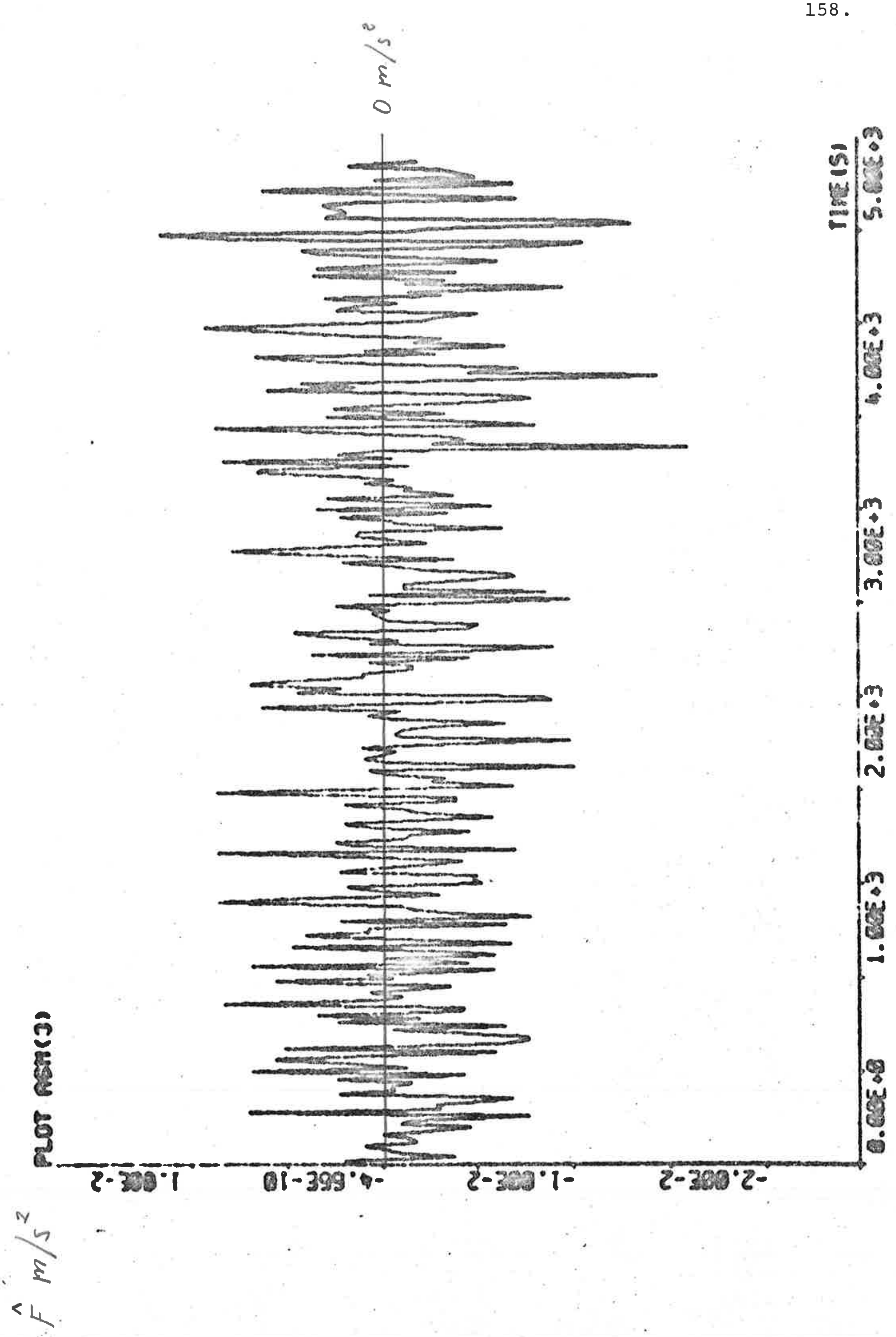


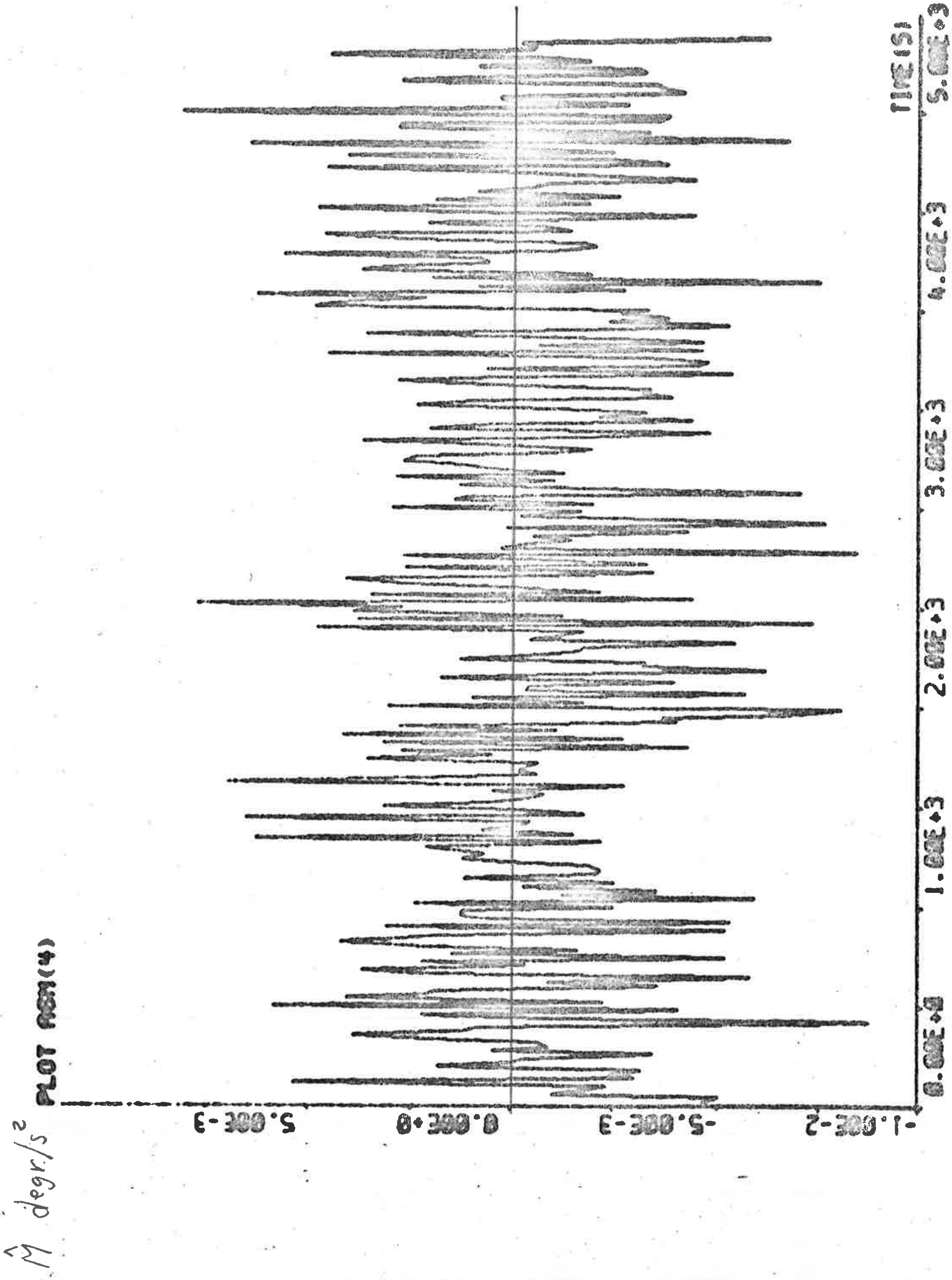
PLOT
4.00E-1
2.00E-1
0.00E+0
-2.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
r degr/s

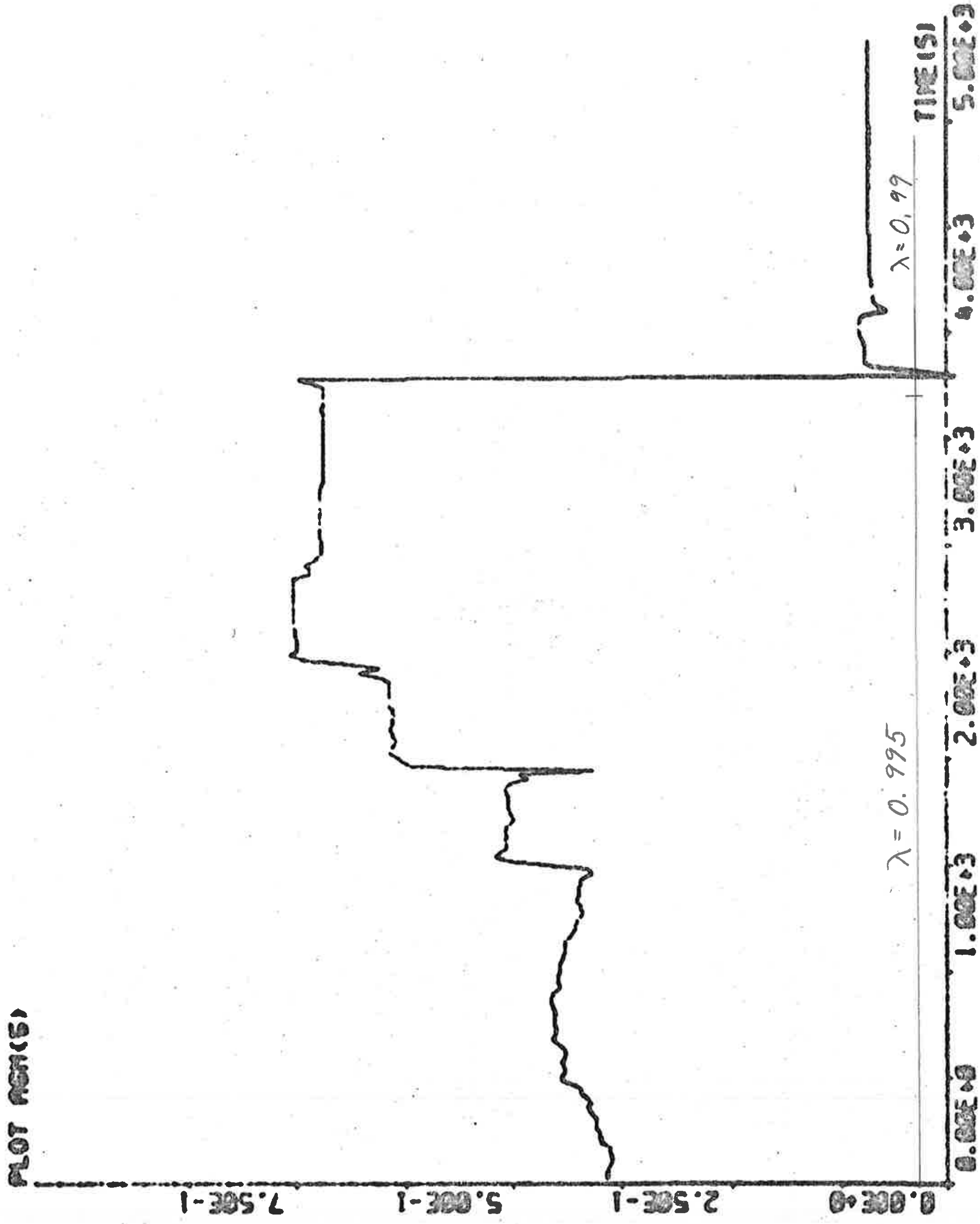

PLOT ASB(6) ASS(5)
1.60E+2
1.50E+2
1.40E+2
1.30E+2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
ψ degr
ψref degr


PLOT
(7)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.20E+1
1.40E+1
1.60E+1
1.80E+1

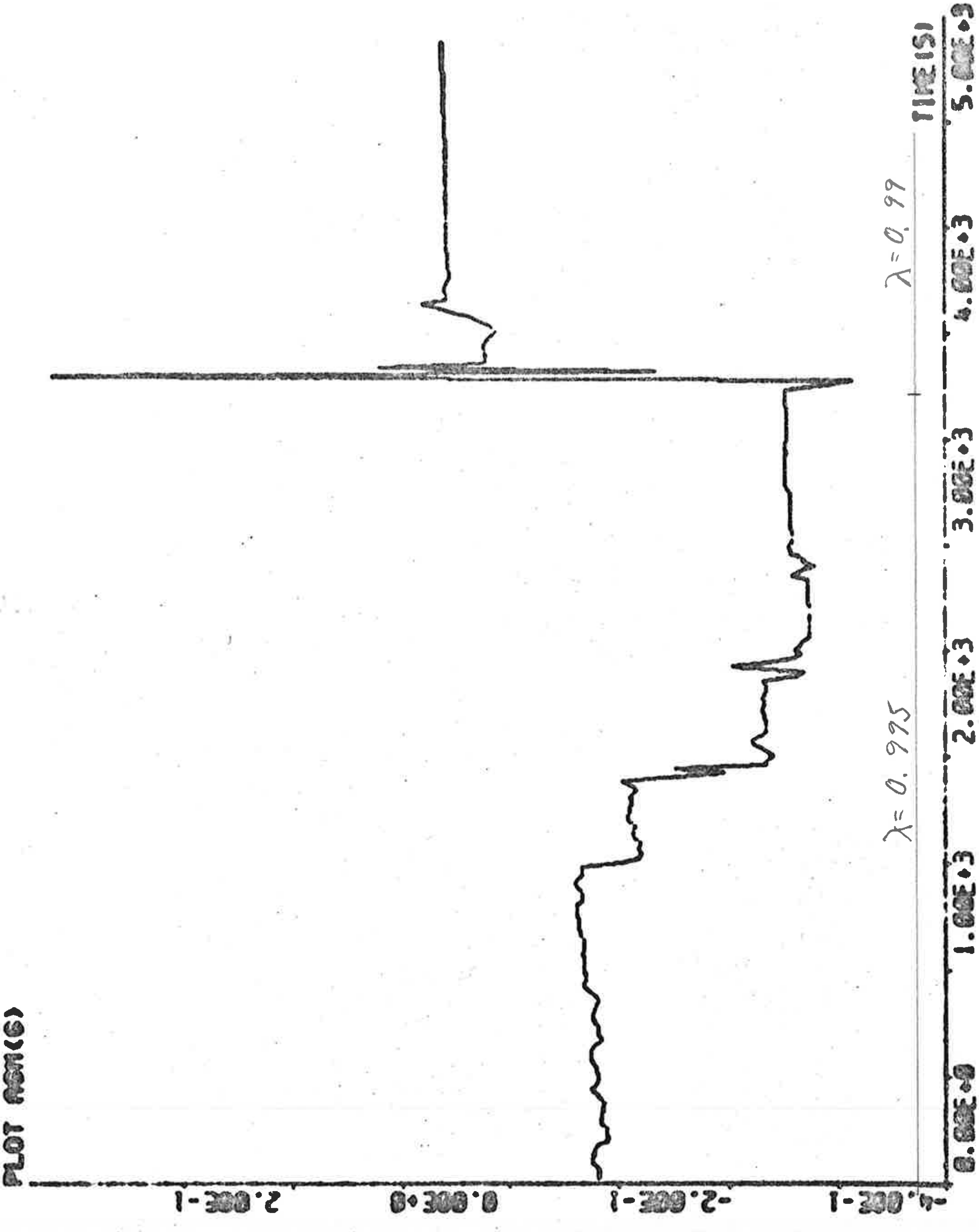

PLOT
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
-5.00E-1
0.00E+0
5.00E-1
1.00E+0
v m/s

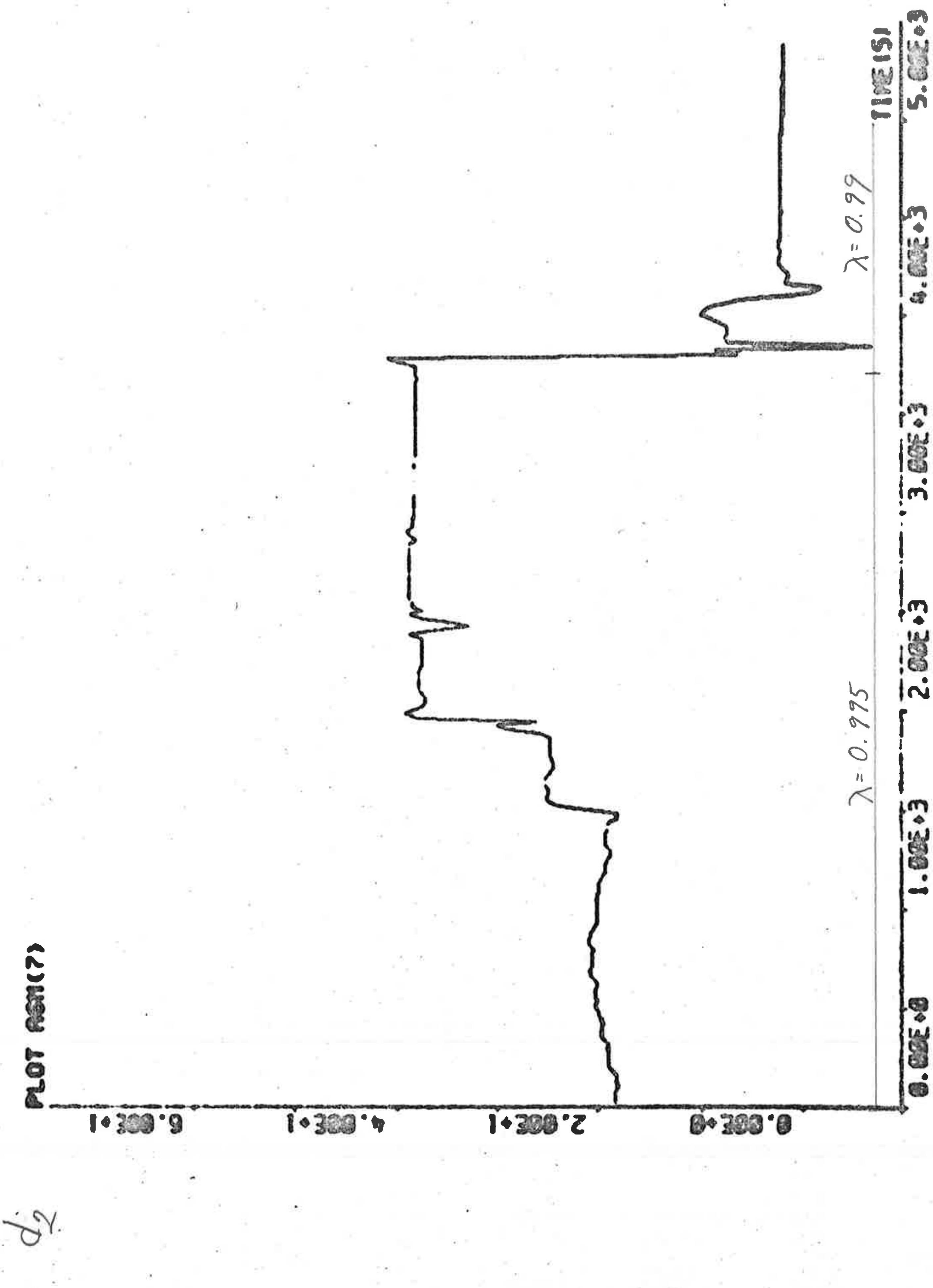

PLOT ASM(3)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
0 m/s²
F̂ m/s²


PLOT
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
M̂ degr./s²


PLOT
0.00E+0
2.50E-1
5.00E-1
7.50E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
λ = 0.995
λ = 0.99

b1


PLOT
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-4.00E-1
-2.00E-1
0.00E+0
2.00E-1
λ= 0.995
λ=0.99


PLOT ASM(7)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
0.00E+0
2.00E+1
4.00E+1
6.00E+1
λ = 0.995
λ = 0.99
d2

Experiment B1

Date: 73 - 10 - 17

Time: 19^{00} - 20^{00}

Position: S 19° E 05°

Wind direction: 1 (see appendix A)

Wind speed: 4 Beaufort (6 - 9 m/s, moderate breeze)

Wave height: Noticeable rollings

Kockums PID-regulator and yaw regulator

Test of yaws

Calibration of the rudder servo:

+10 volts = 36.9°

-10 volts = -43.1°

Notice that the bias of the v_1-measurements is compensated by adding 0.5 knots to the real measurements.

PID-regulator:

$$\delta(t) = -k_1(\Psi(t) - \Psi_{ref}) + k_2 r(t) + \frac{1}{4k_2}\int^{t}(\Psi(s) - \Psi_{ref})ds$$

The parameters k_1 and k_2 were manually tuned for the actual weather disturbances:

k_1 = 1.5

k_2 = 80.0

Sampling interval: 15 s

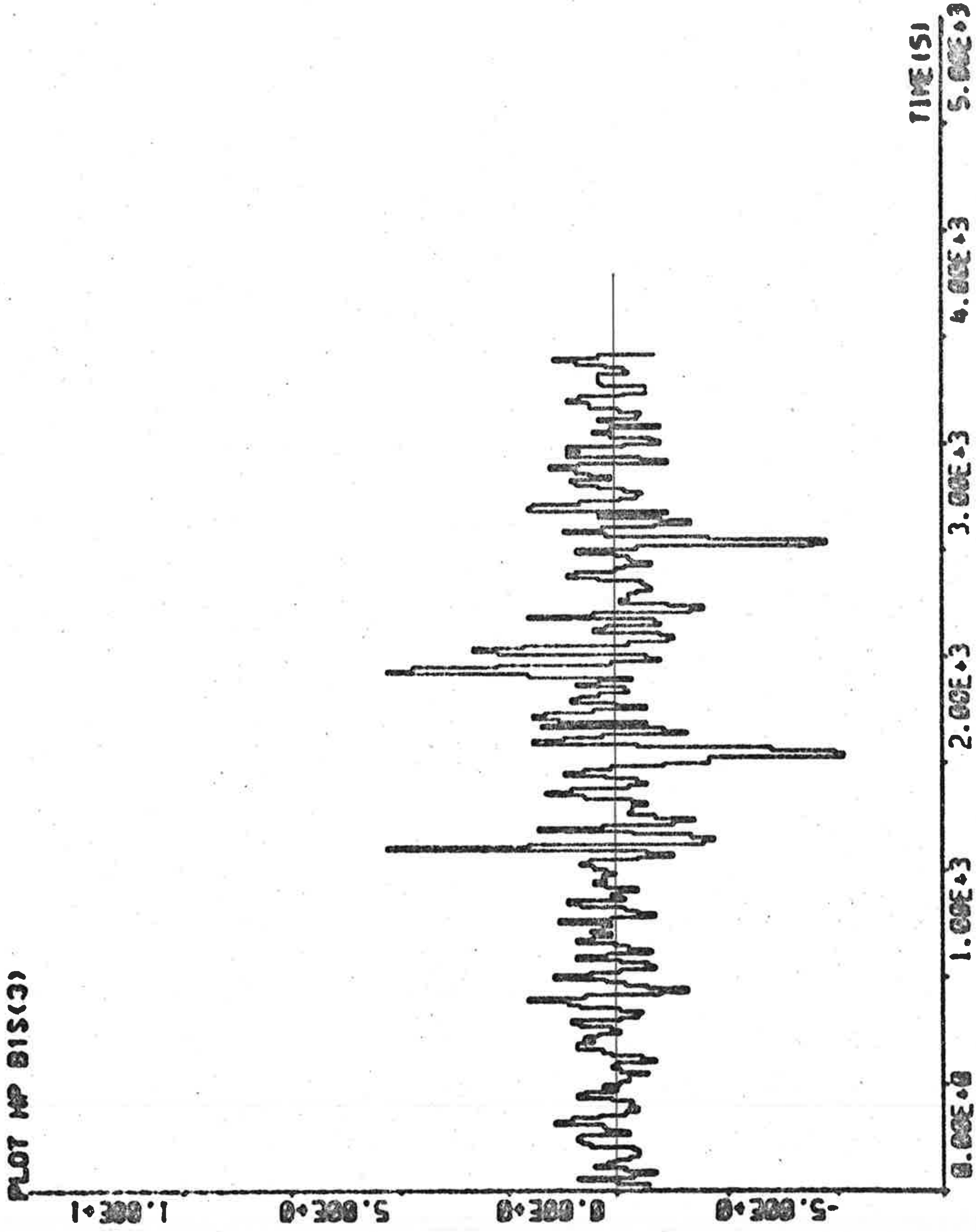
Rudder limits: ±15°

Maximum yaw rate r during yaws: 0.1 degr/s

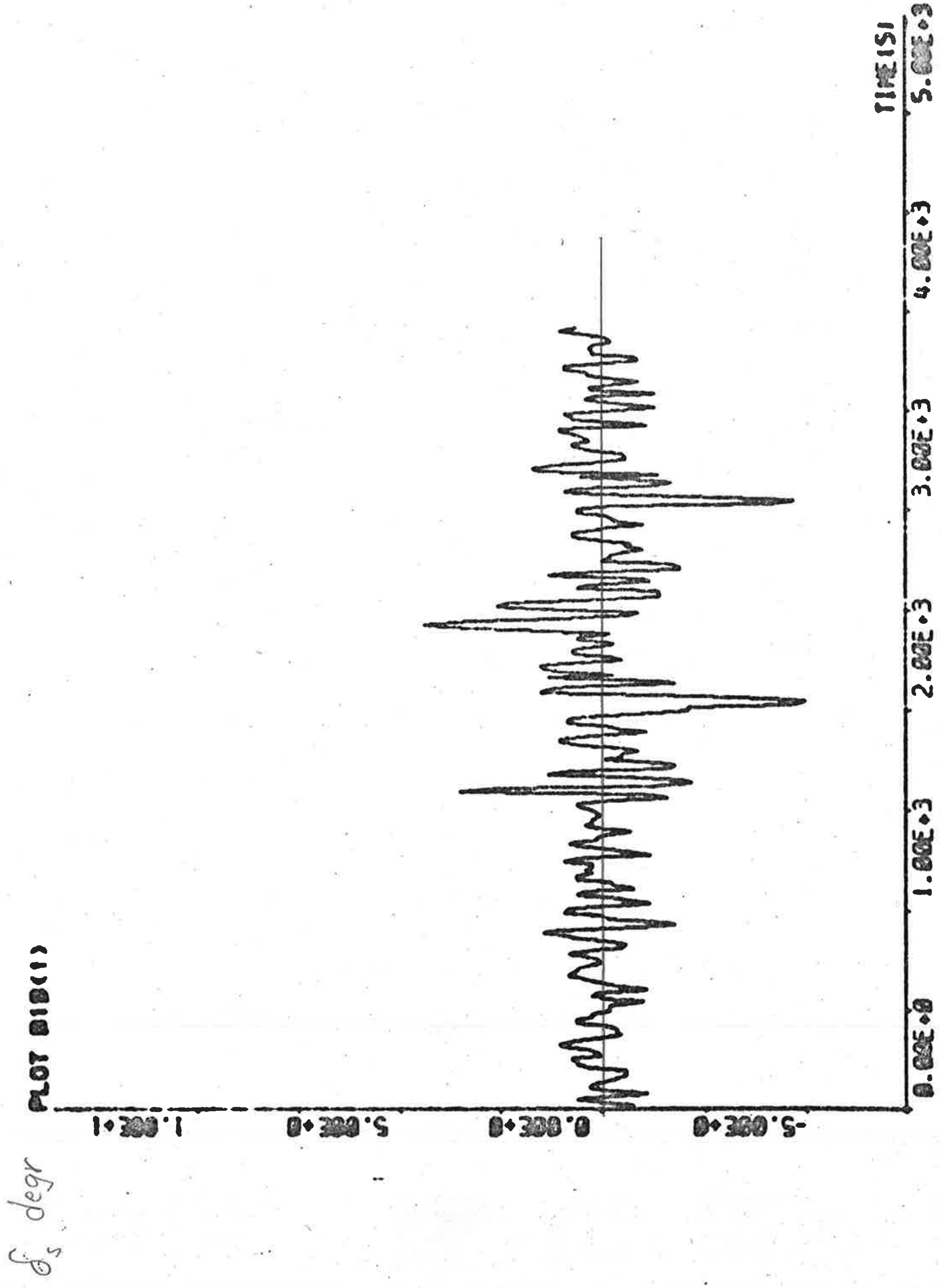
Ψ_{ref}: 142°, 144°, 136°, 150°, 142°

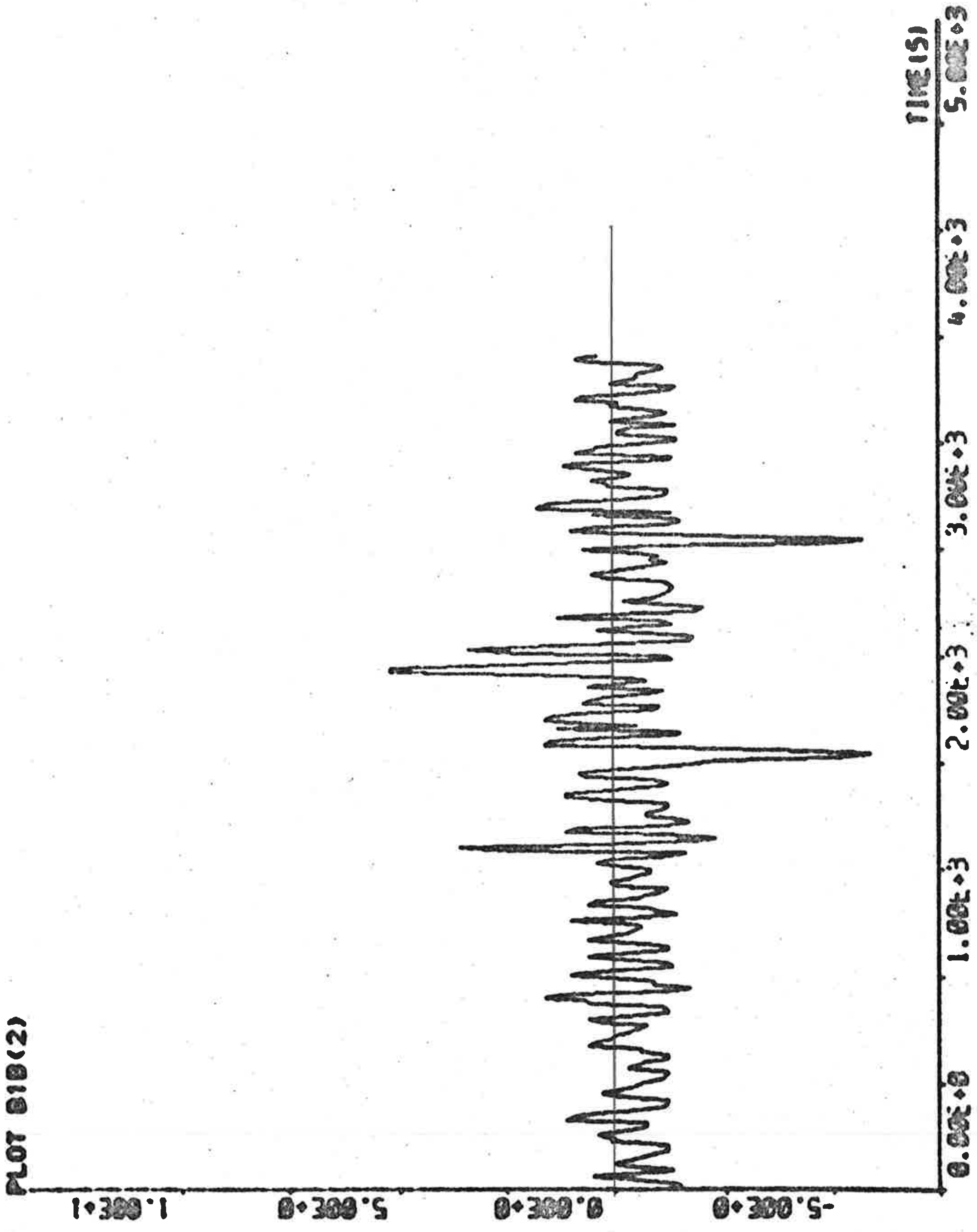
Statistics:

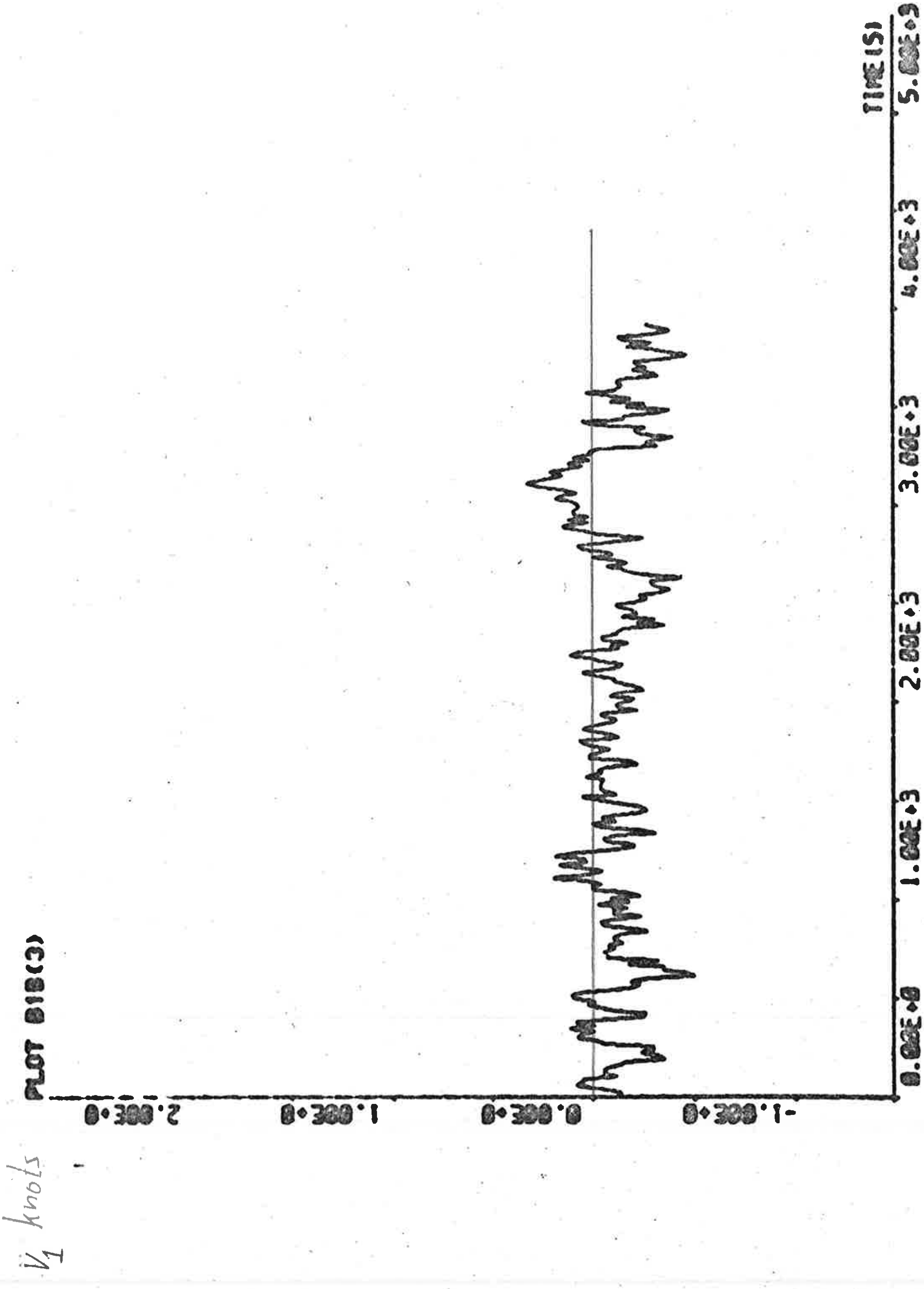
	0 - 1500 s			
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	0.13	0.63	-1.6	2.0
δ_s degr	0.05	0.58	-1.8	1.4
δ degr	-0.40	0.70	-1.7	1.6
v_1 knots	-0.102	0.135	-0.50	0.19
v_2 knots	0.014	0.128	-0.21	0.37
r degr/s	0.0030	0.0099	-0.021	0.030
Ψ degr	142.001	0.171	141.59	142.38
v knots	16.087	0.110	15.79	16.44
q degr/s	0.1047	0.1233	-0.224	0.439
n rpm	82.30	0.37	81.4	83.1

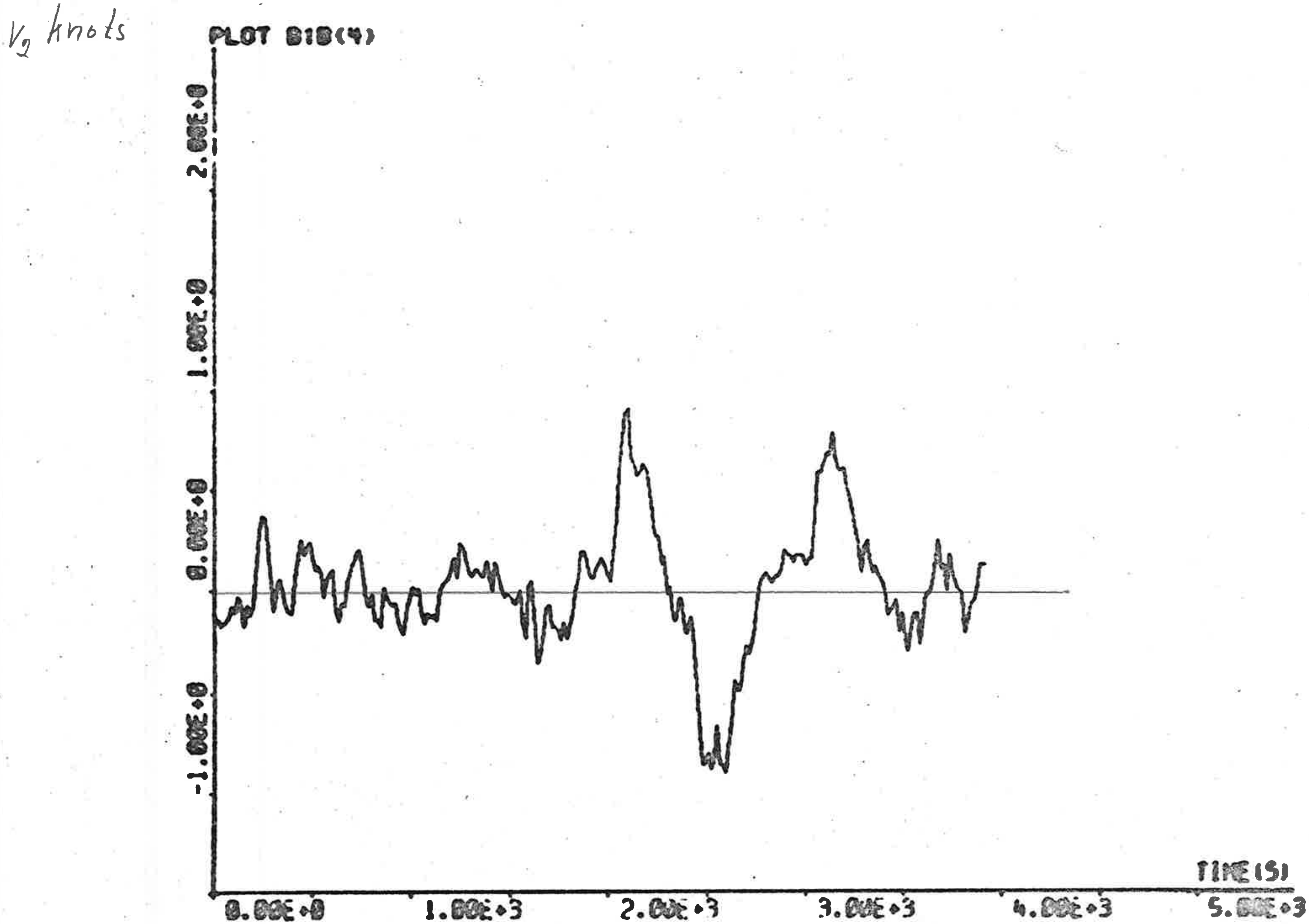


δ_{com} degr

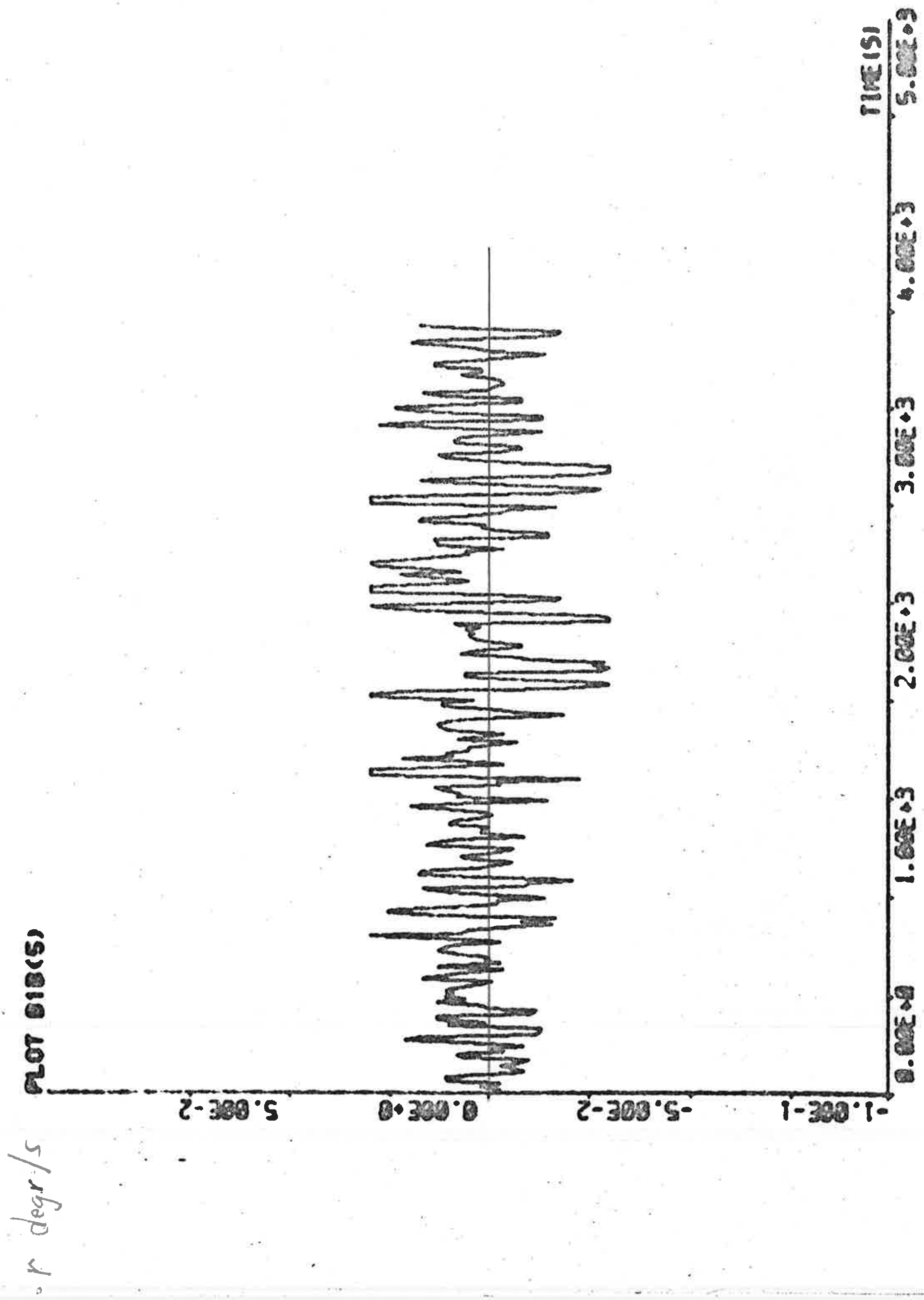

PLOT BIB(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δs degr

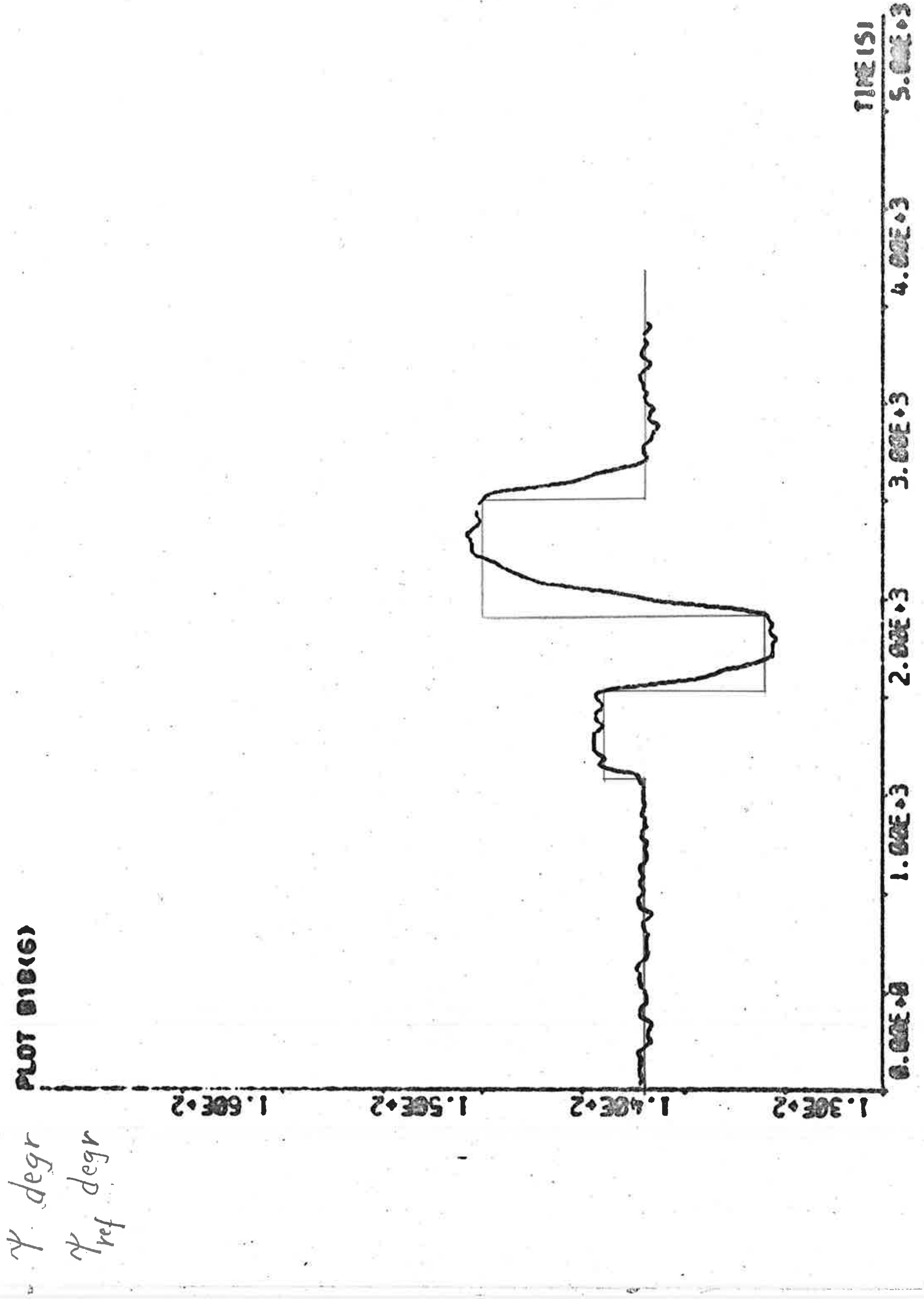

PLOT B1B(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0

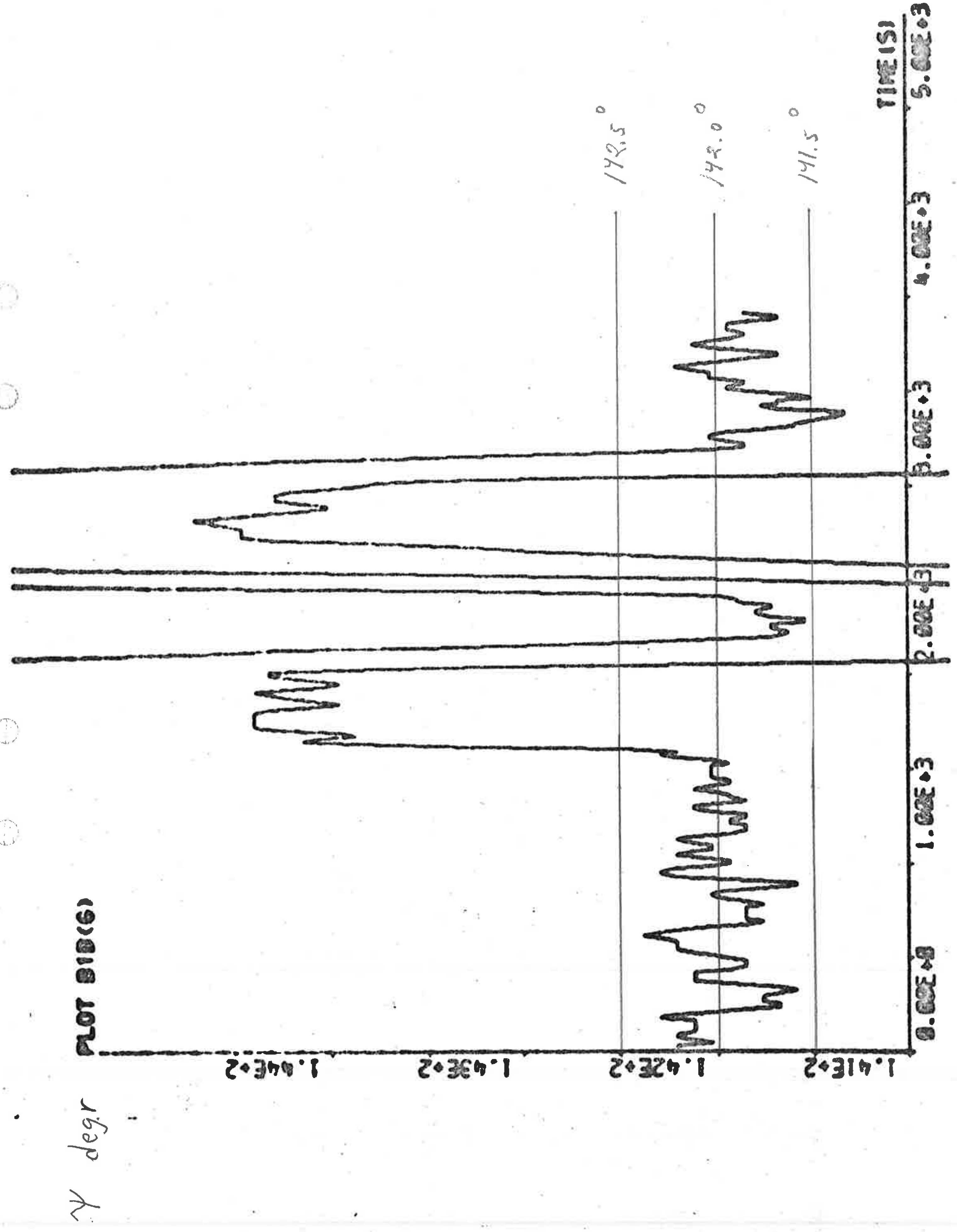

PLOT B1B(3)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_1 knots

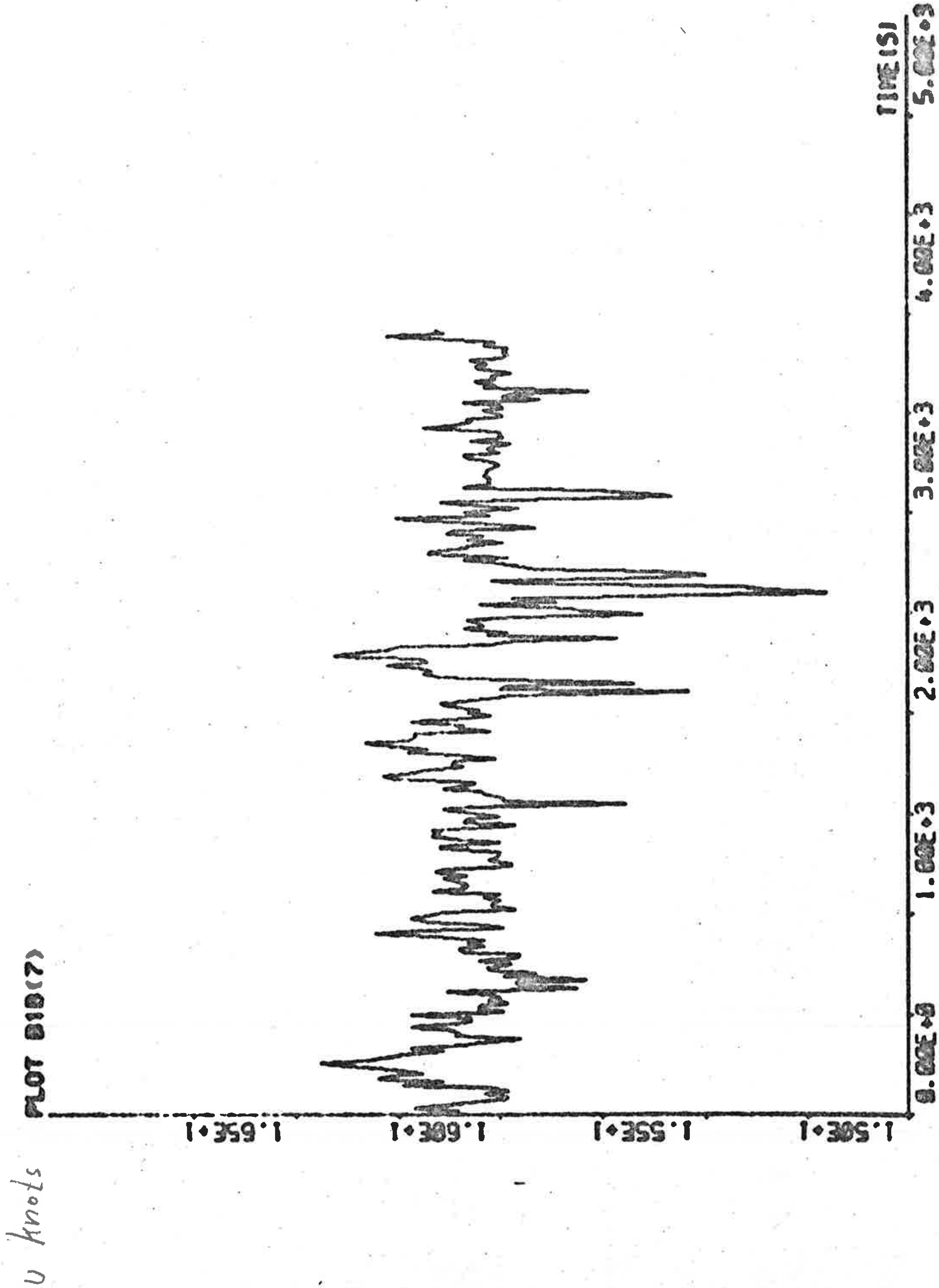


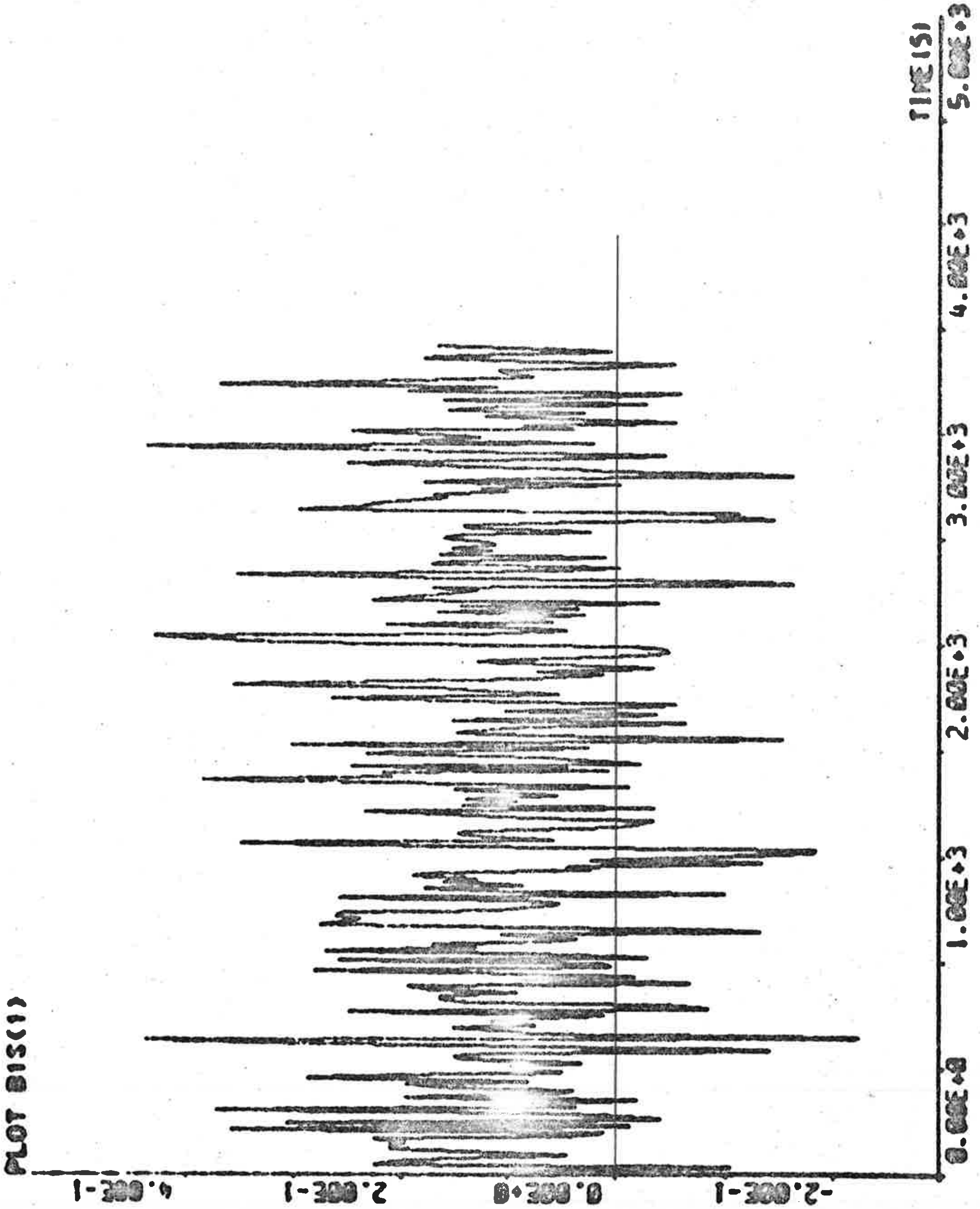
V_g knots
PLOT B1B(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


PLOT B1B(S)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s

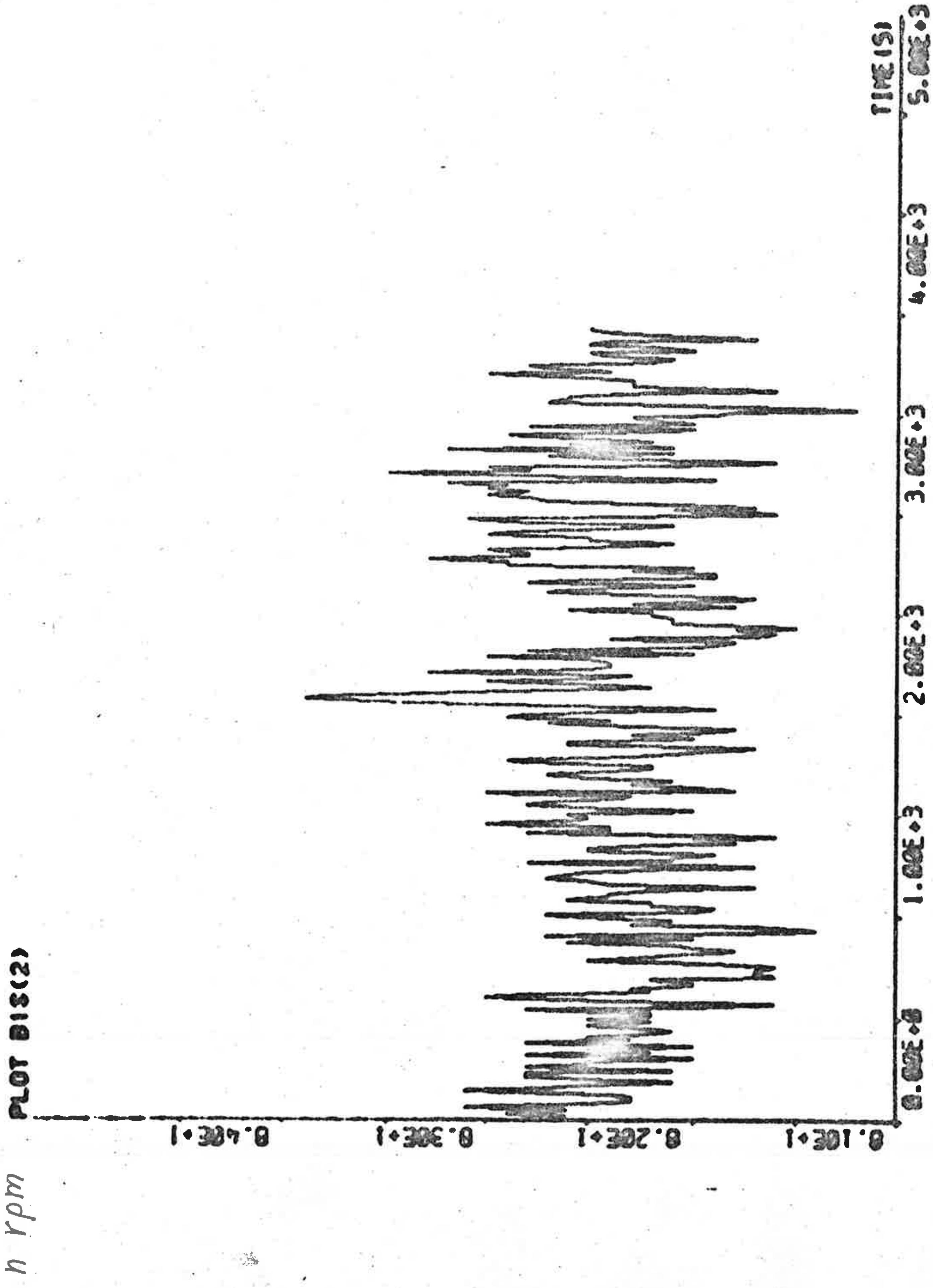

PLOT B18(6)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.30E+2
1.40E+2
1.50E+2
1.60E+2
ψ degr
ψ_{ref} degr


PLOT B1B(6)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.41E+2
1.42E+2
1.43E+2
1.44E+2
142.5°
142.0°
141.5°
ψ degr


PLOT D1D(7)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.50E+1
1.55E+1
1.60E+1
1.65E+1
u knots


PLOT BIS(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
4.00E-1
2.00E-1
0.00E+0
-2.00E-1

9 degr/s


PLOT BIS(2)
0.10E+1
0.20E+1
0.30E+1
0.40E+1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
n rpm

Experiment C1

Date: 73 - 10 -17

Time: 22^{40} - 23^{40}

Position: S 19° E 05°

Wind direction: 1 (see appendix A)

Wind speed: 4 Beaufort (6 - 9 m/s, moderate breeze)

Wave height: Noticeable rollings

Regulator 2

No Kalman filter

No yaw

Data is punched every second during the experiment

Calibration of the rudder servo:

10 volts = 36.9°

-10 volts = -43.1°

Notice that the bias of the v_1-measurements is compensated by adding 0.5 knots to the real measurements.

Model in the regulator:

$$(\Psi(t+3) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = b_1\delta(t) + b_2\delta(t-1) + d_2r(t) + e(t+3)$$

Regulator:

$$\delta(t) = -\frac{1}{b_1}[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_2r(t)]$$

Sampling interval for punching: 1 s

Sampling interval for control: 20 s

Forgetting factor λ: 0.98

Rudder limits: Unknown

$\Psi_{ref} = 142^{\circ}$

Initial values:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.353 \\ 0 \\ 14.197 \end{bmatrix} \qquad P = \begin{bmatrix} 0.0000274 & & \\ -0.0000026 & 0.0000891 & \\ 0.003203 & -0.01229 & 2.253 \end{bmatrix}$$

Regulator:

$$\delta(t) = -2.83(\Psi(t) - \Psi_{ref}) - 40.218r(t)$$

Final values:

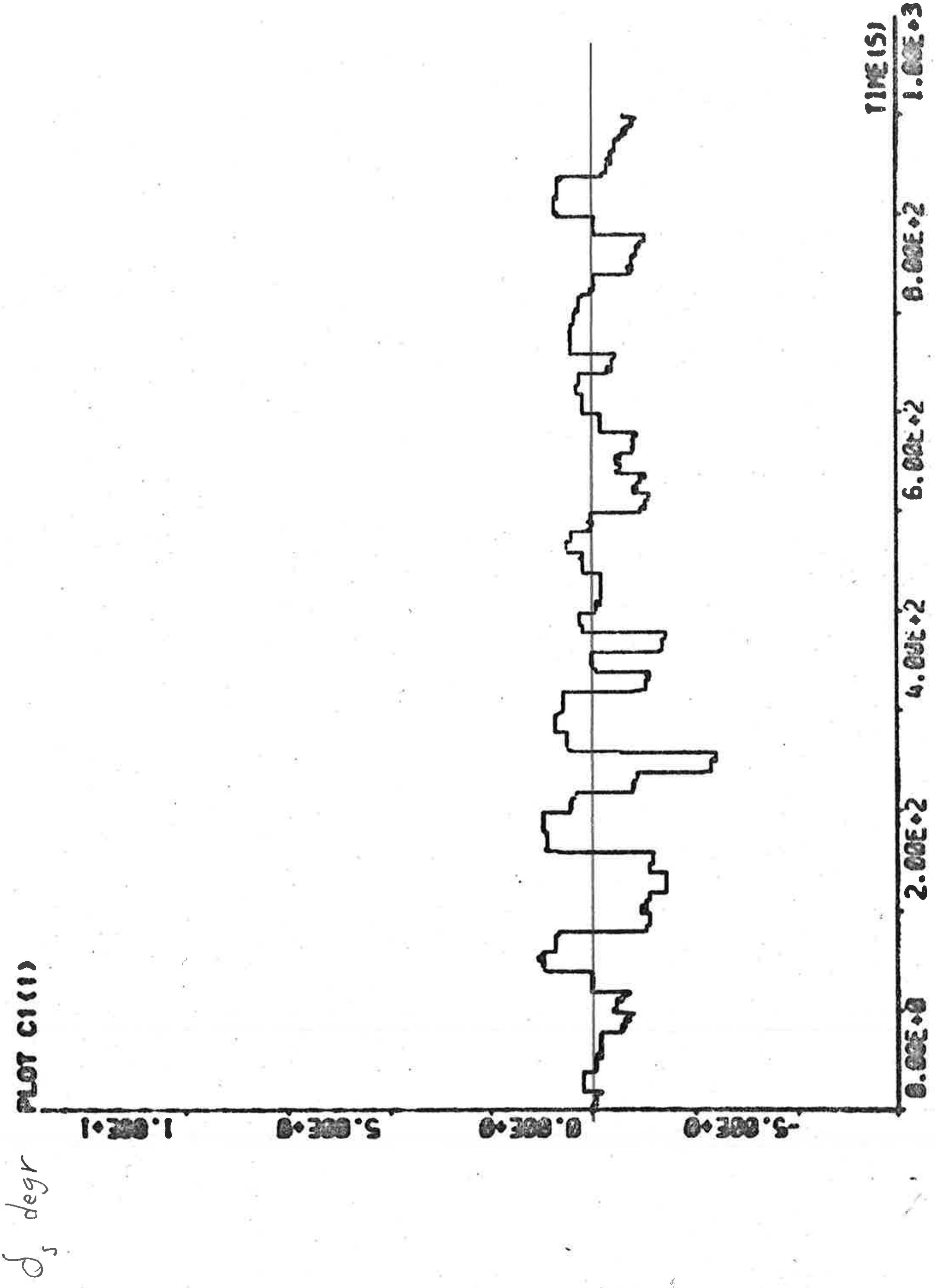
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.353 \\ 0.003 \\ 13.729 \end{bmatrix} \qquad P \text{ unknown}$$

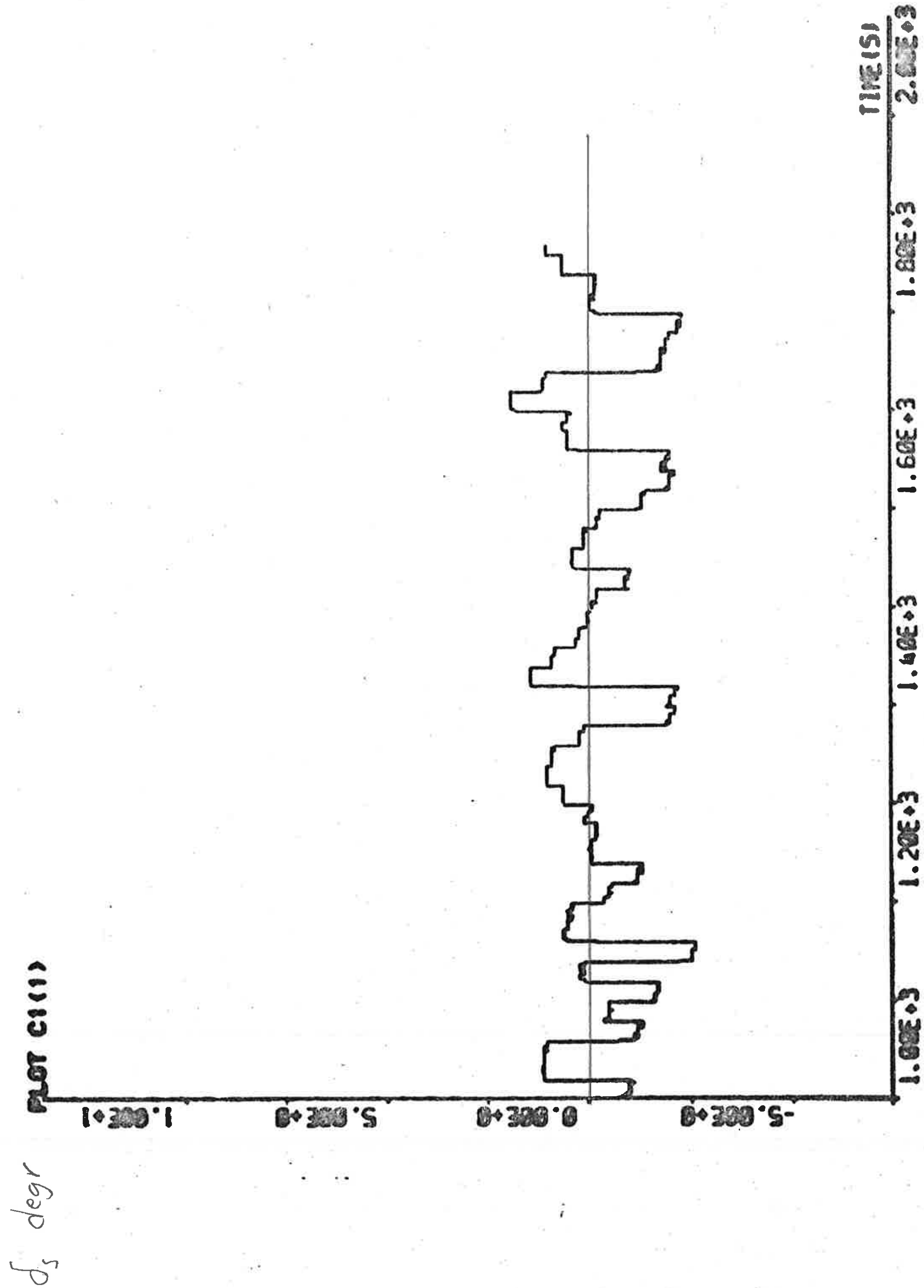
Regulator:

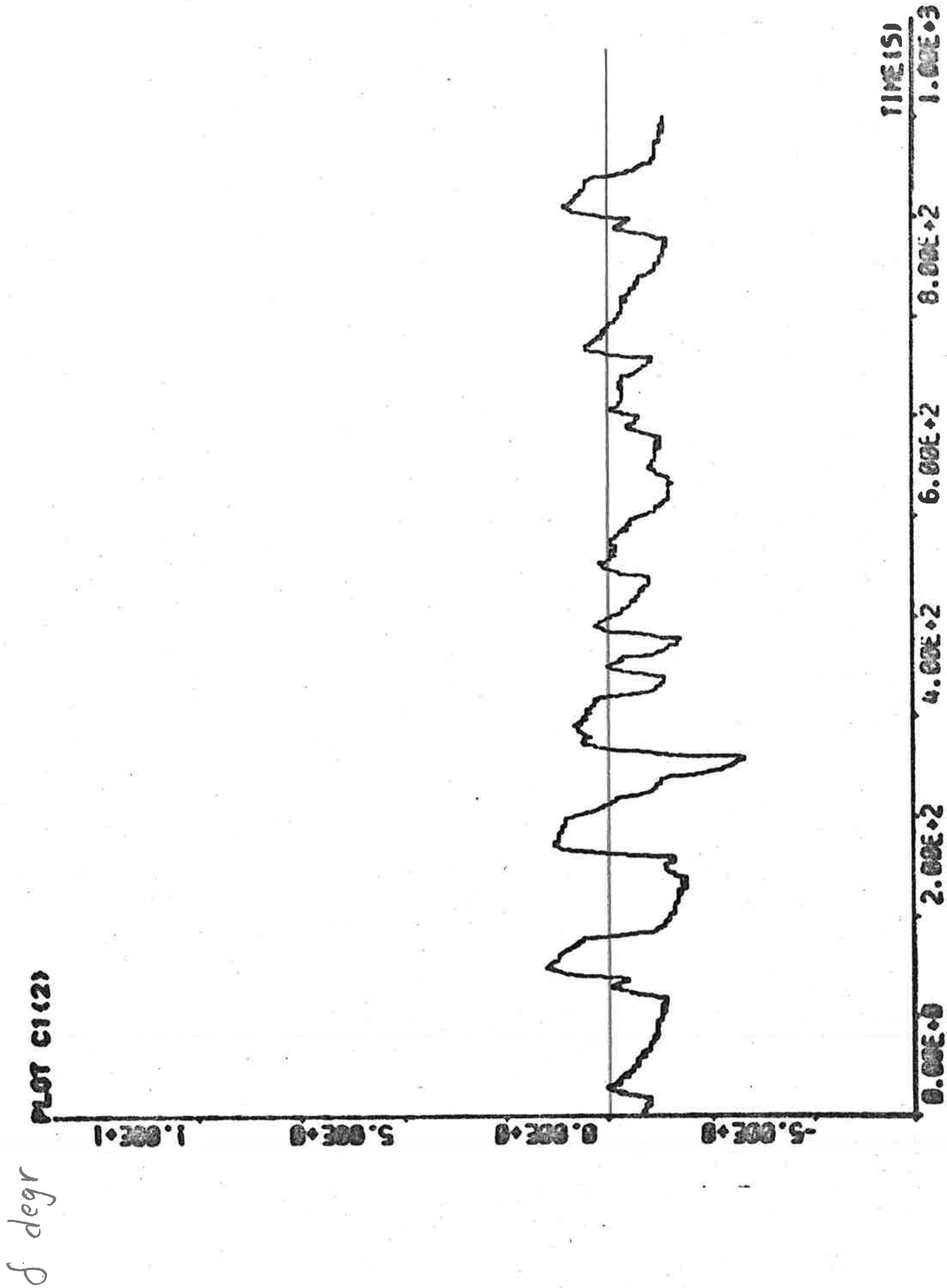
$$\delta(t) = -2.83(\Psi(t) - \Psi_{ref}) - 0.008\delta(t-1) - 38.892r(t)$$

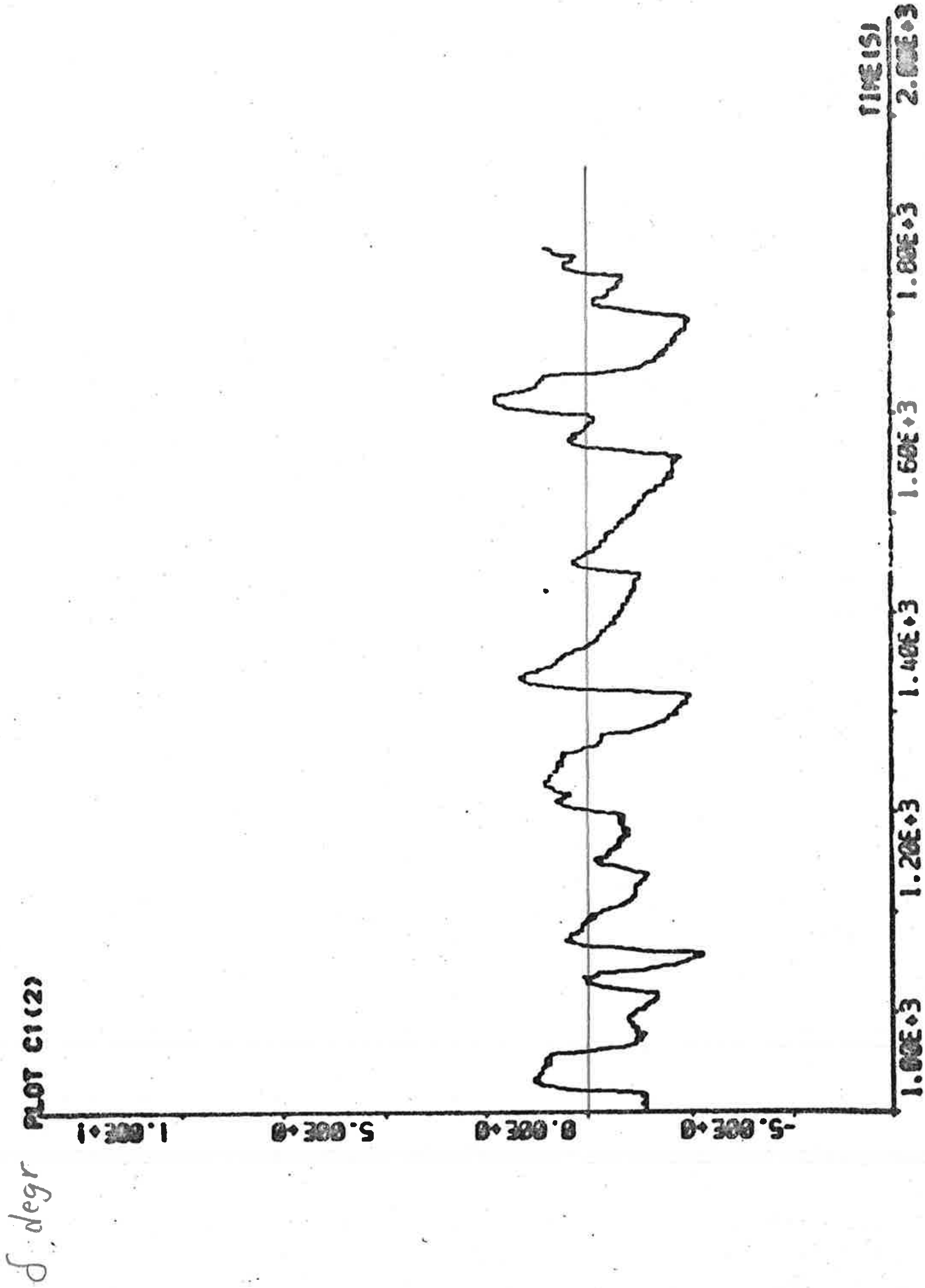
Statistics:

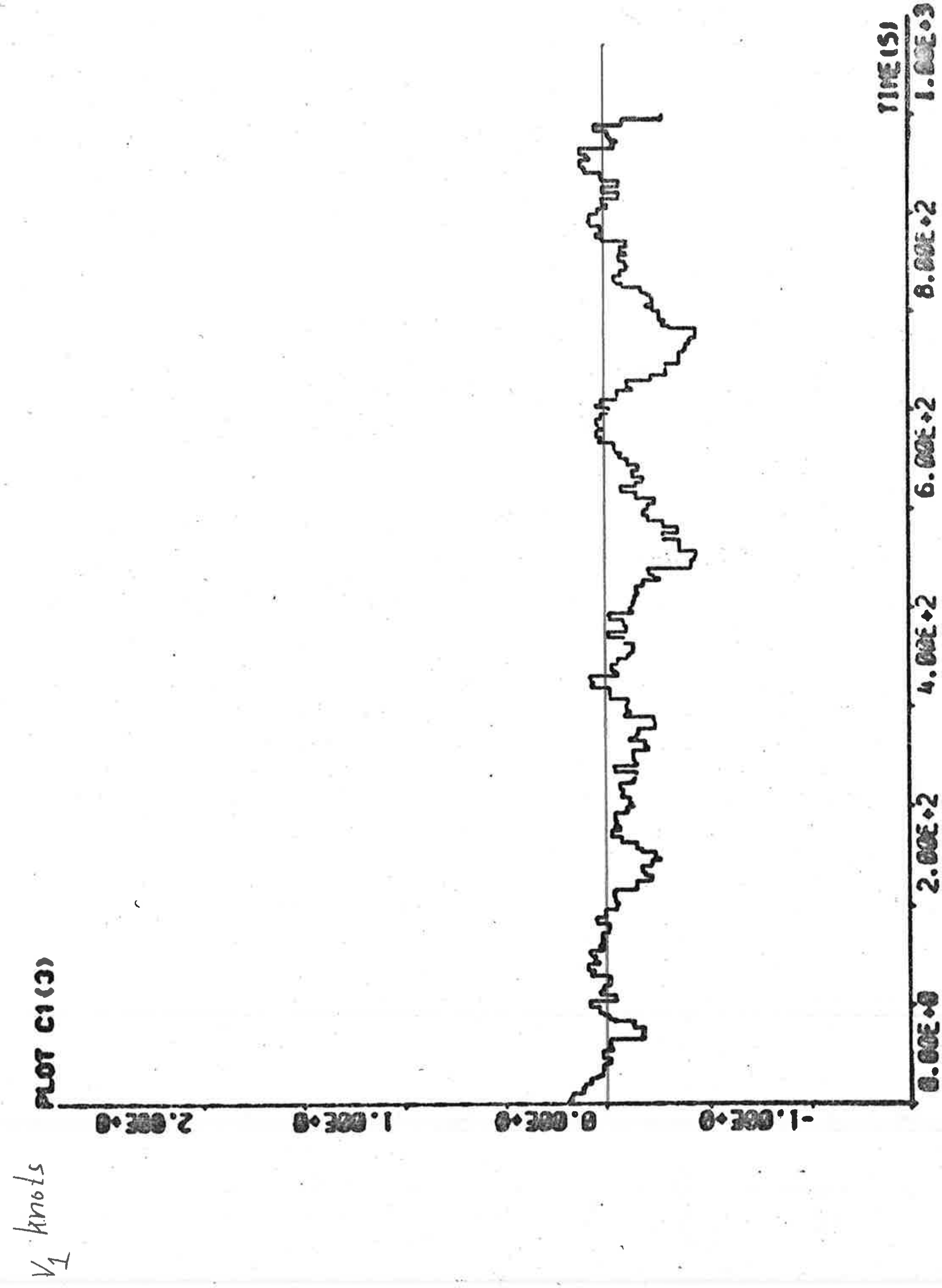
		Mean value	Standard deviation	Minimum value	Maximum value
δ_s	degr	-0.26	1.00	-3.0	1.9
δ	degr	-0.57	0.96	-3.3	2.2
v_1	knots	-0.129	0.145	-0.47	0.19
v_2	knots	0.036	0.119	-0.26	0.29
r	degr/s	0.0031	0.0171	-0.058	0.055
Ψ	degr	142.018	0.232	141.50	142.65
u	knots	16.036	0.136	15.47	16.30

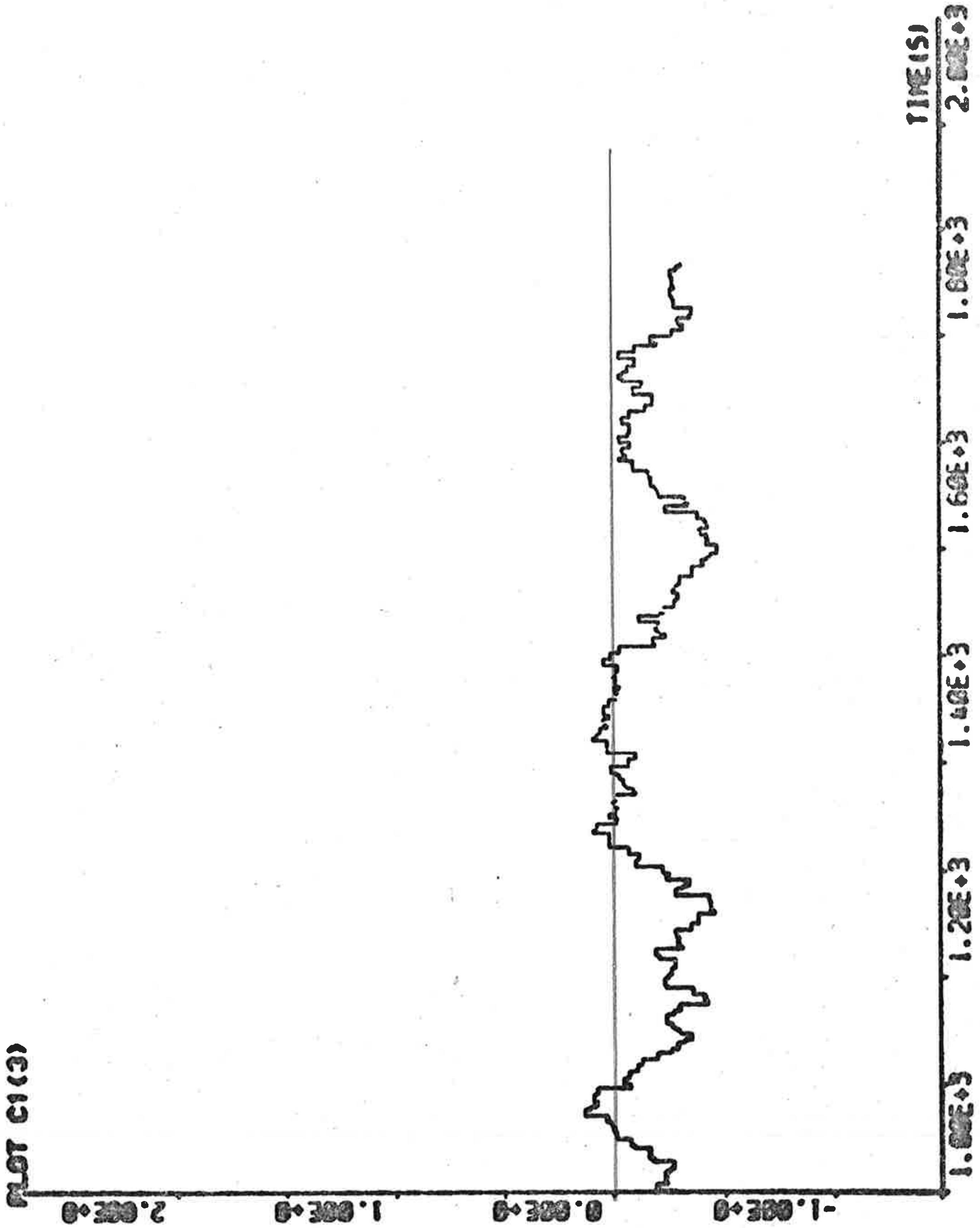

PLOT C1(1)
TIME(S)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δs degr


PLOT C1(1)
TIME(S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δs degr

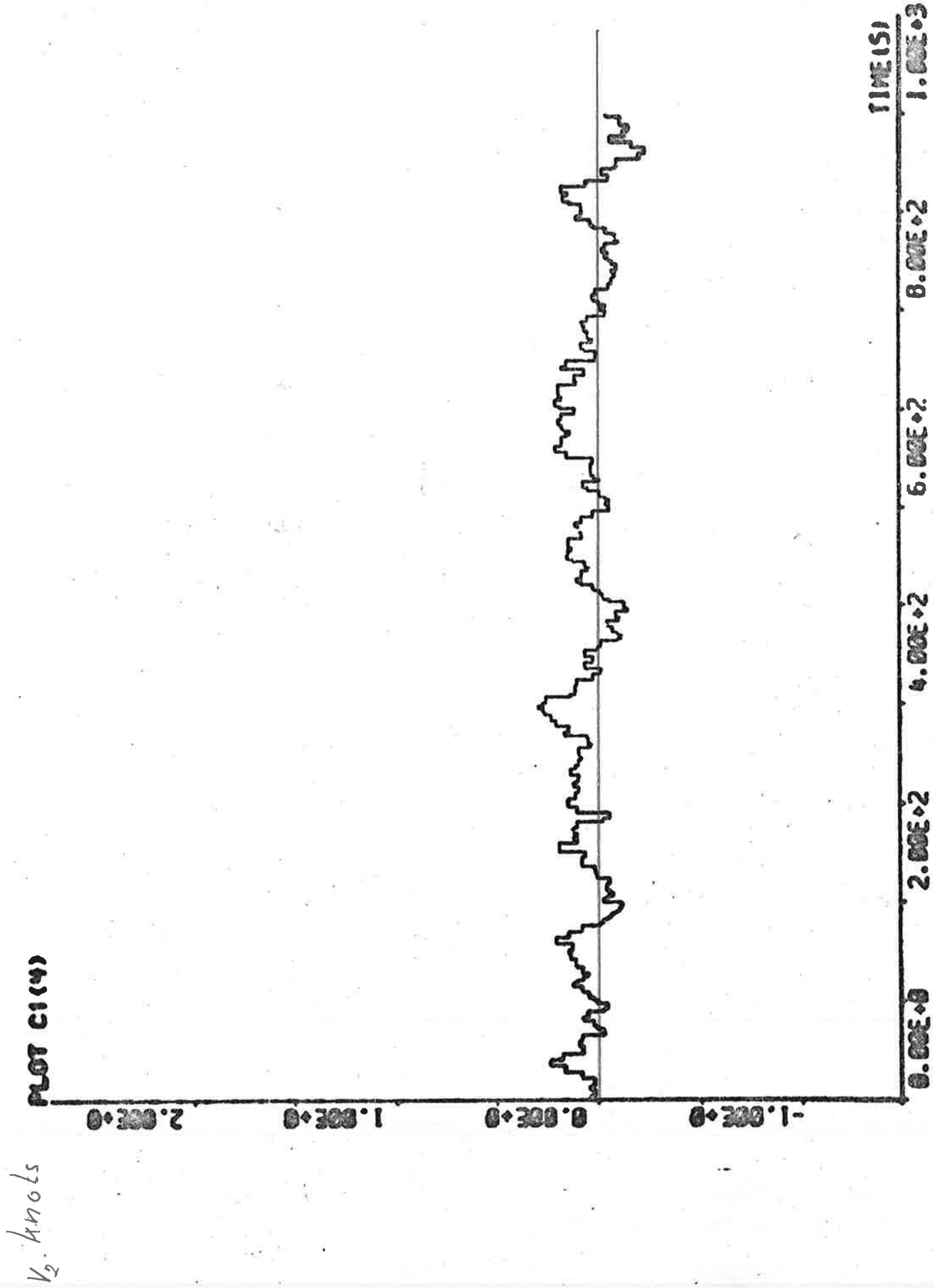

PLOT C1(2)
TIME (S)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr

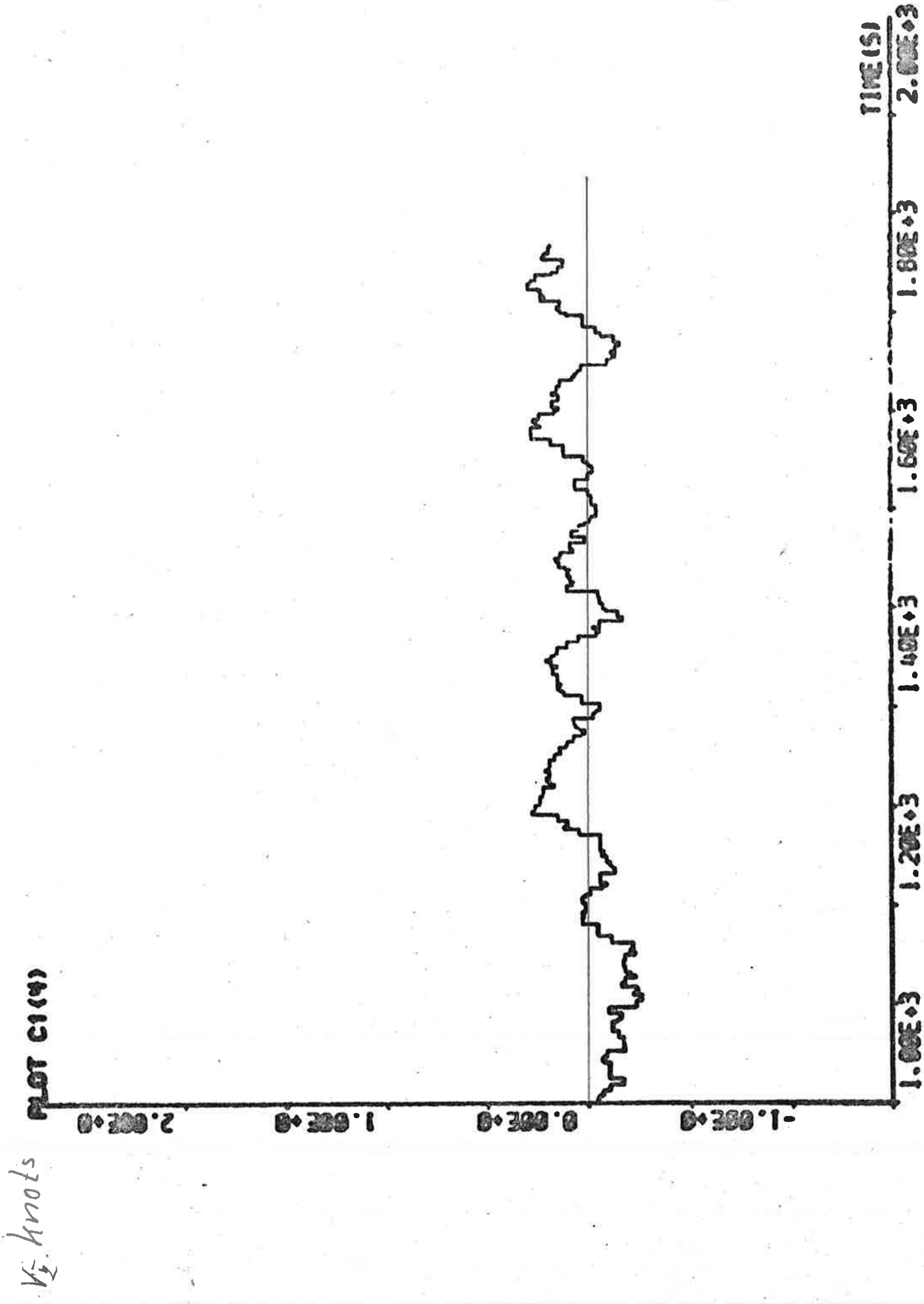

PLOT C1(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
δ degr

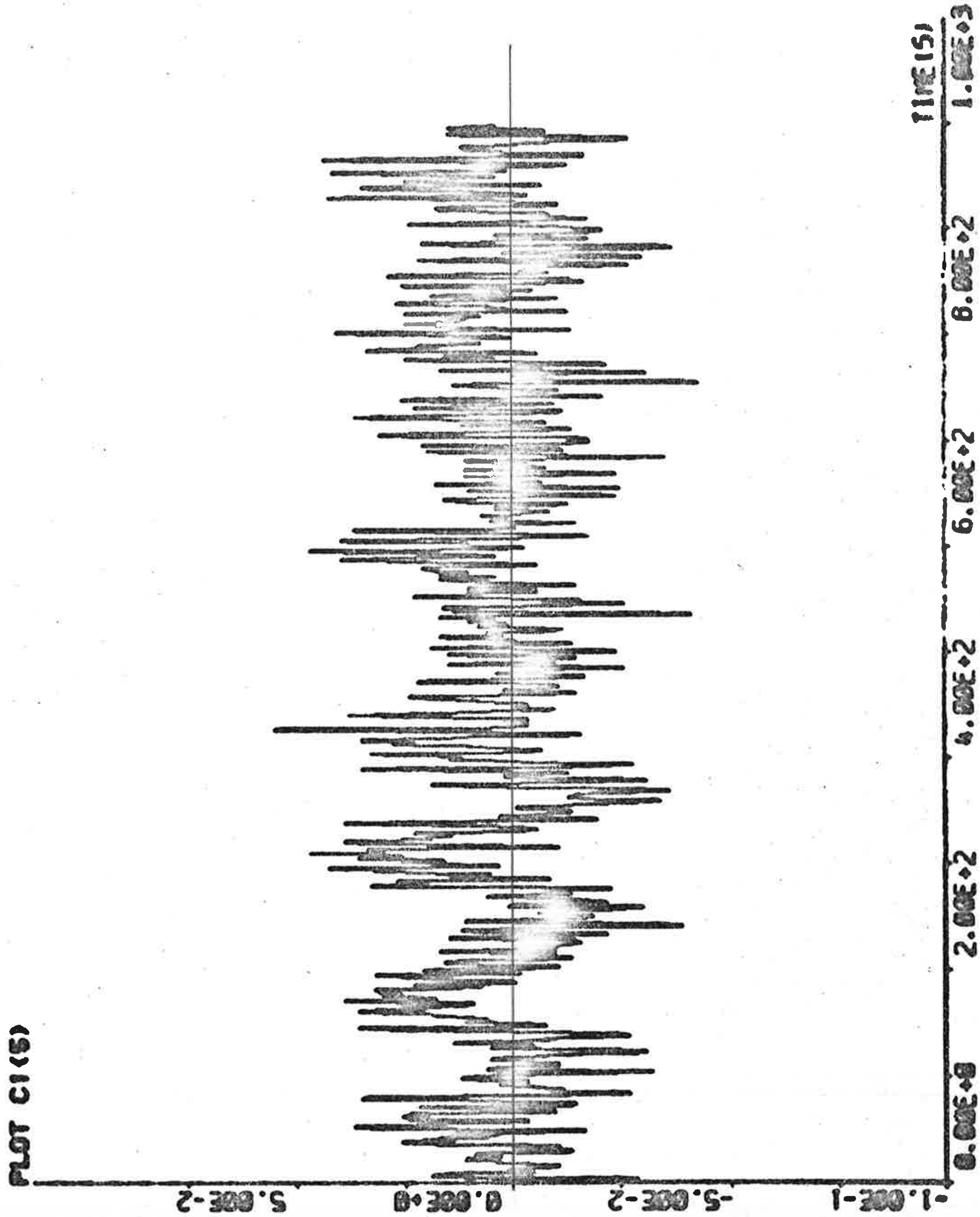

PLOT C1(3)
TIME(S)
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V1 knots


PLOT C1(3)
TIME (S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0

V_1 knots

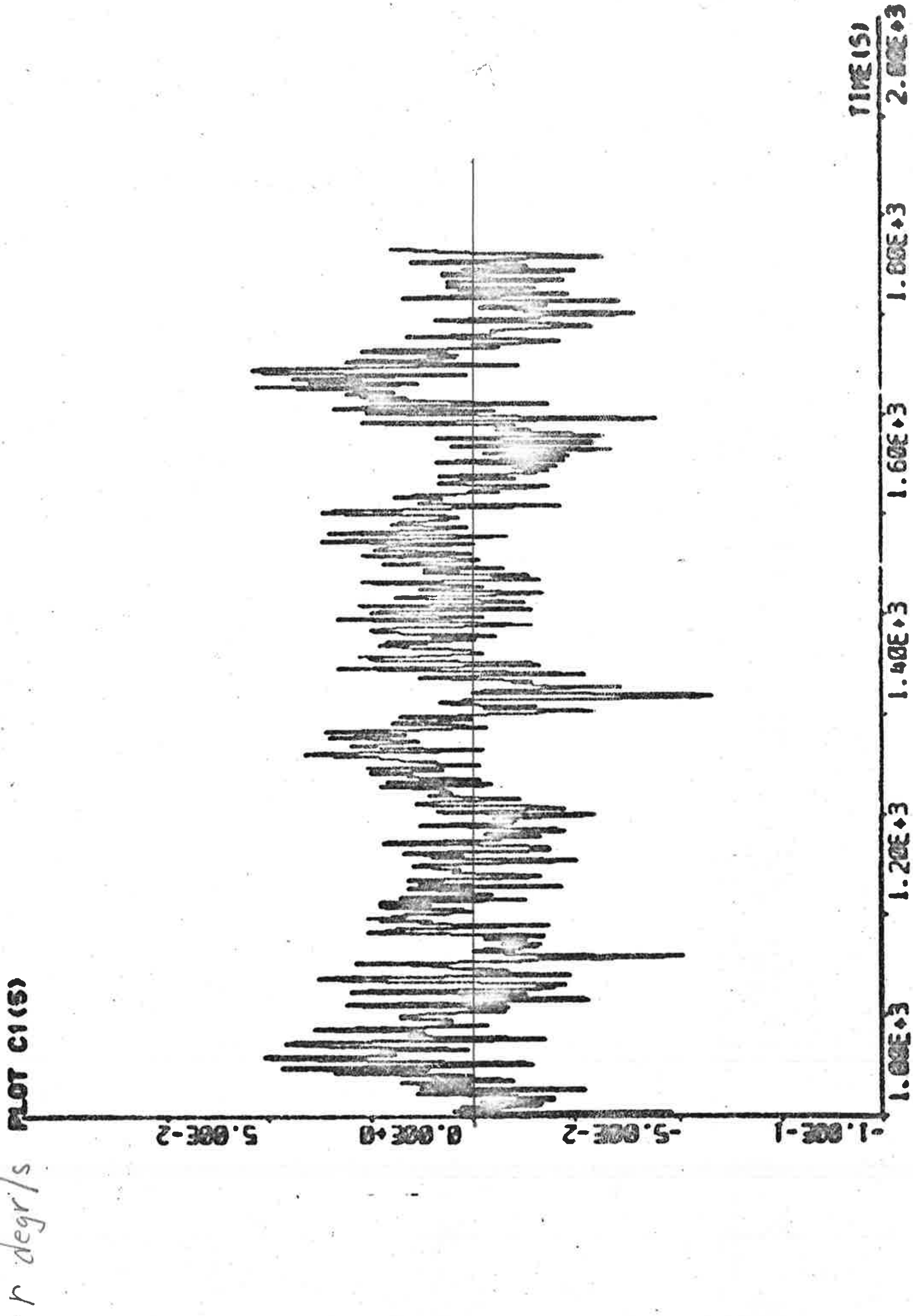

PLOT C1 (4)
TIME (S)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V2 knots

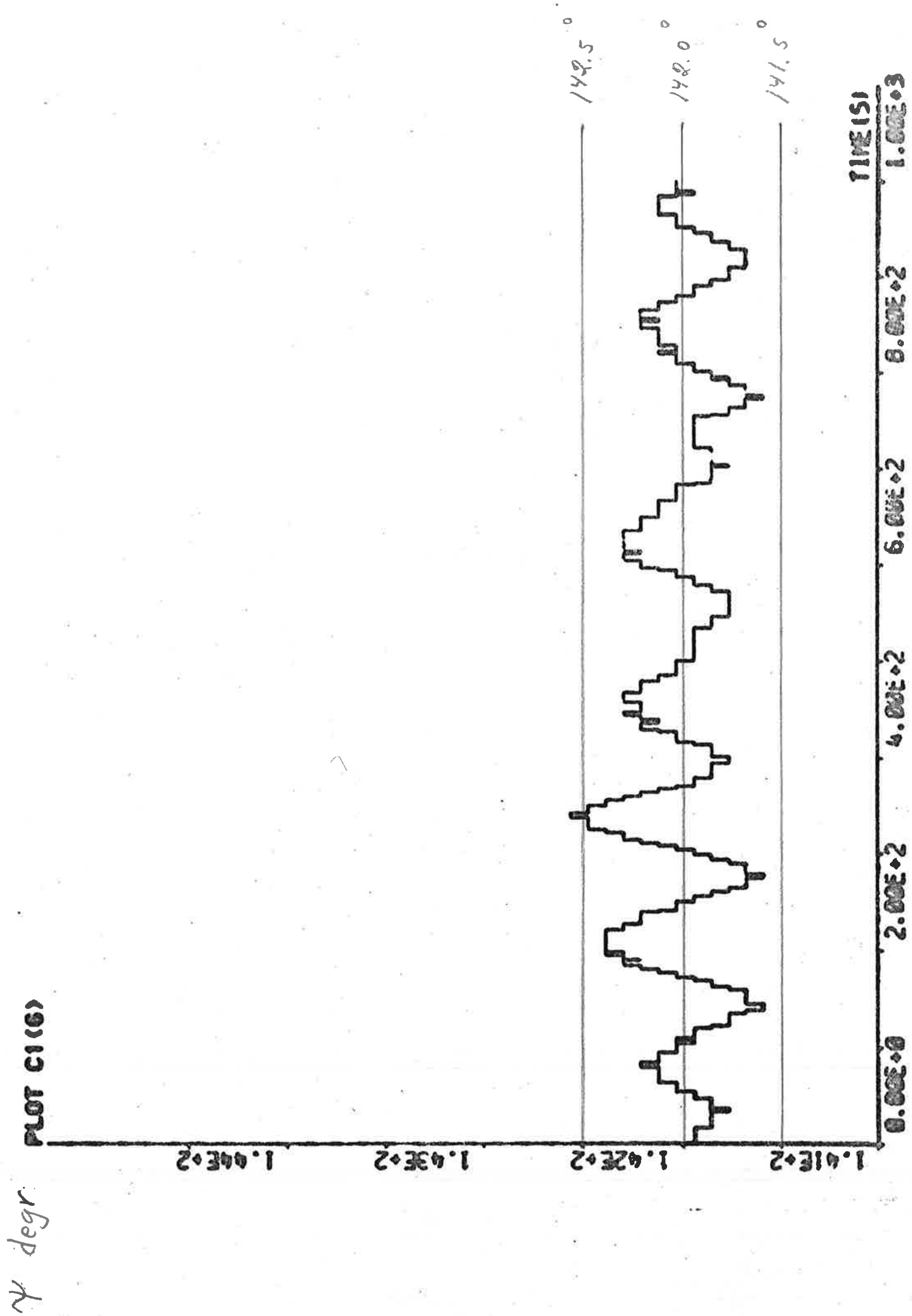

PLOT C1(4)
TIME (S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
Vz knots

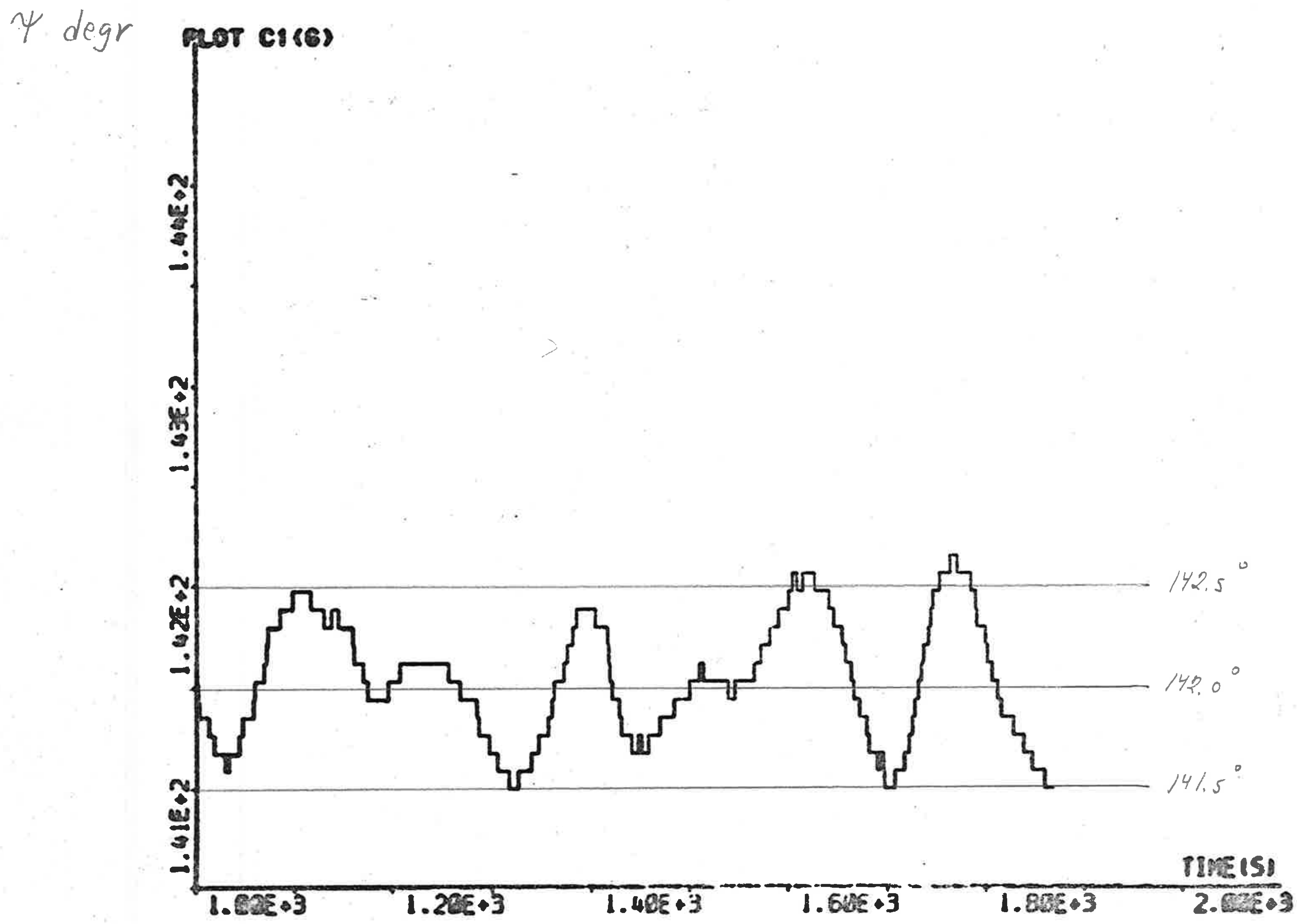


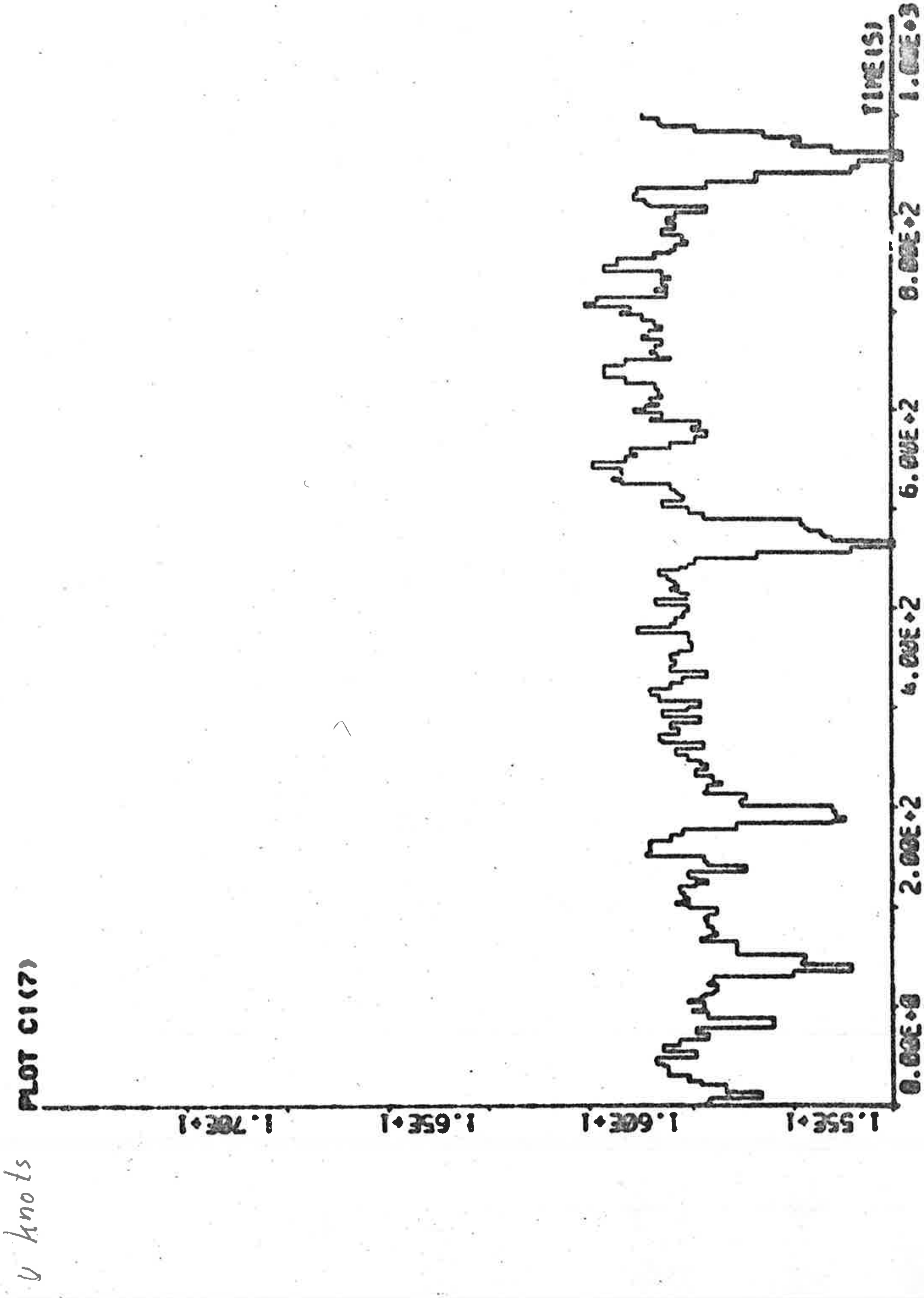
PLOT C1 (S)
TIME (S)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1

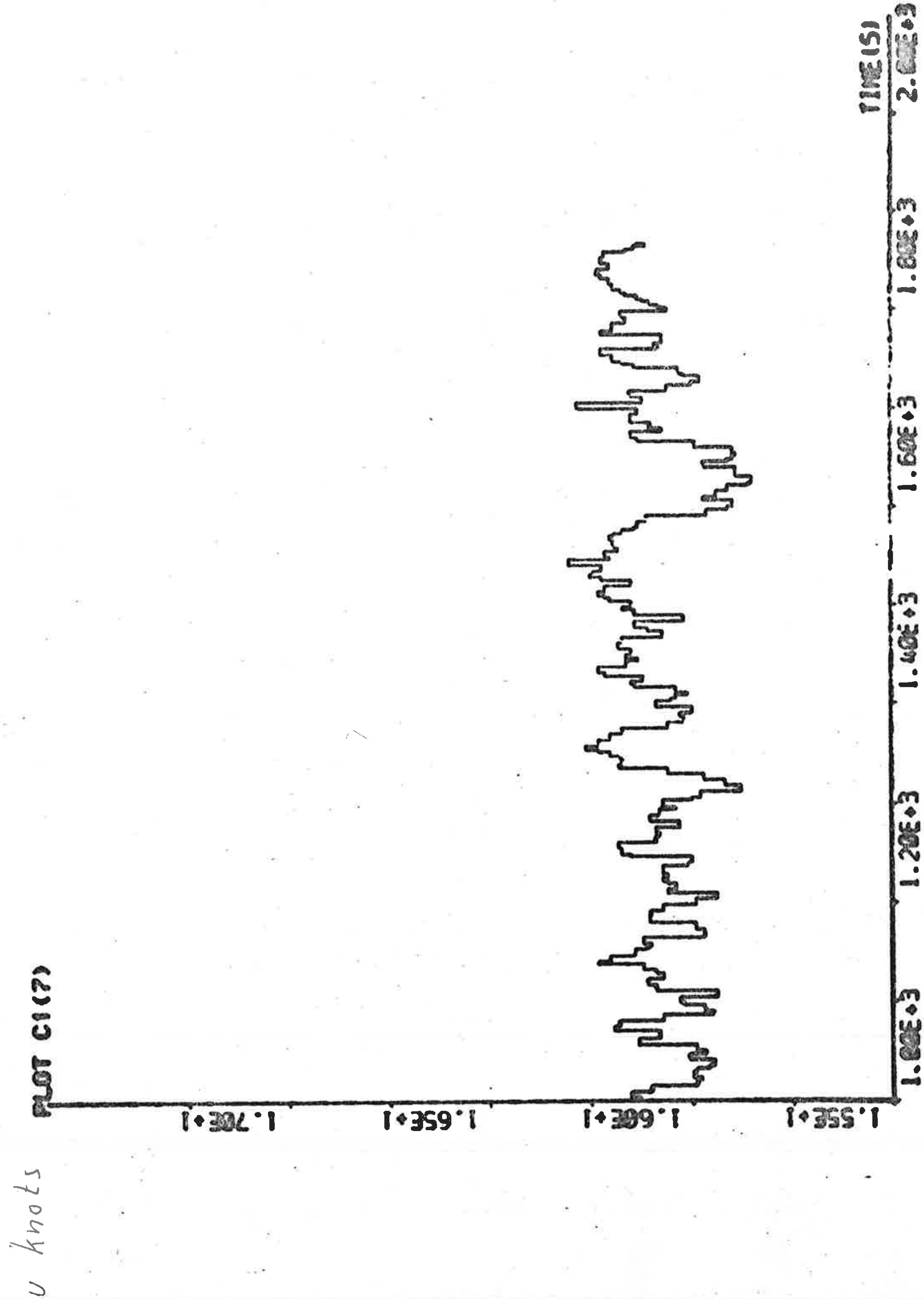
r degr/s


PLOT C1(S)
TIME(S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s


PLOT C1(6)
TIME (S)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
1.41E+2
1.42E+2
1.43E+2
1.44E+2
142.5°
142.0°
141.5°
ψ degr


Ψ degr
PLOT C1(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
142.5°
142.0°
141.5°
TIME(S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3


PLOT C1(7)
TIME(S)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
1.55E+1
1.60E+1
1.65E+1
1.70E+1
v knots


PLOT C1(7)
TIME (S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
1.55E+1
1.60E+1
1.65E+1
1.70E+1
u knots

Experiment E1

Date: 73 - 10 - 11

Time: 21^{00} - 22^{00}

Position: N 11° W 18°

Wind direction: 4 (see appendix A

Wind speed: 1 - 2 Beaufort (0.5 - 4 m/s, light air to light breeze)

Wave heights: Small waves

Experiment for system identification.

Calibration of the rudder servo:

10 volts = 36.5°

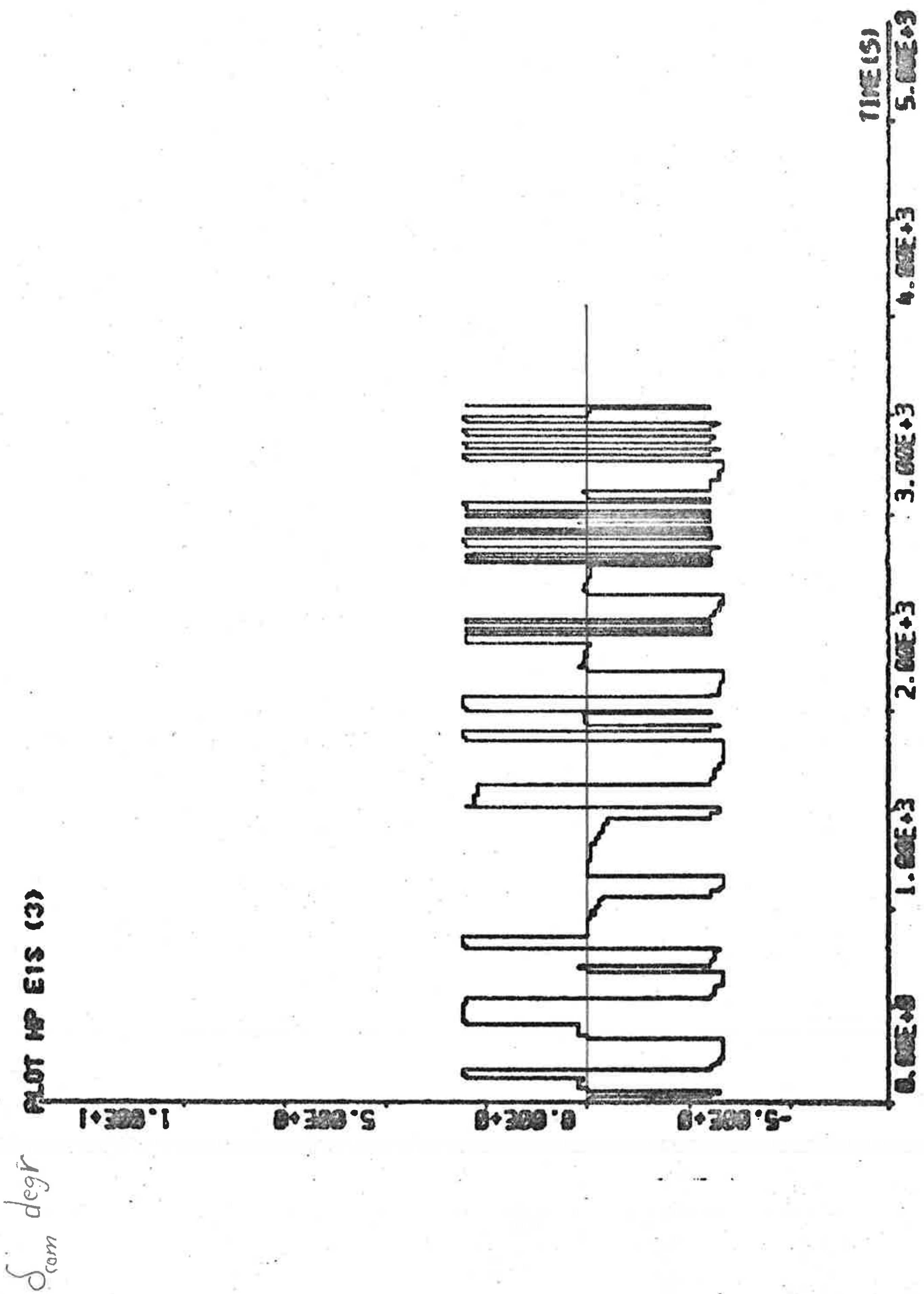
-10 volts = -43.5°

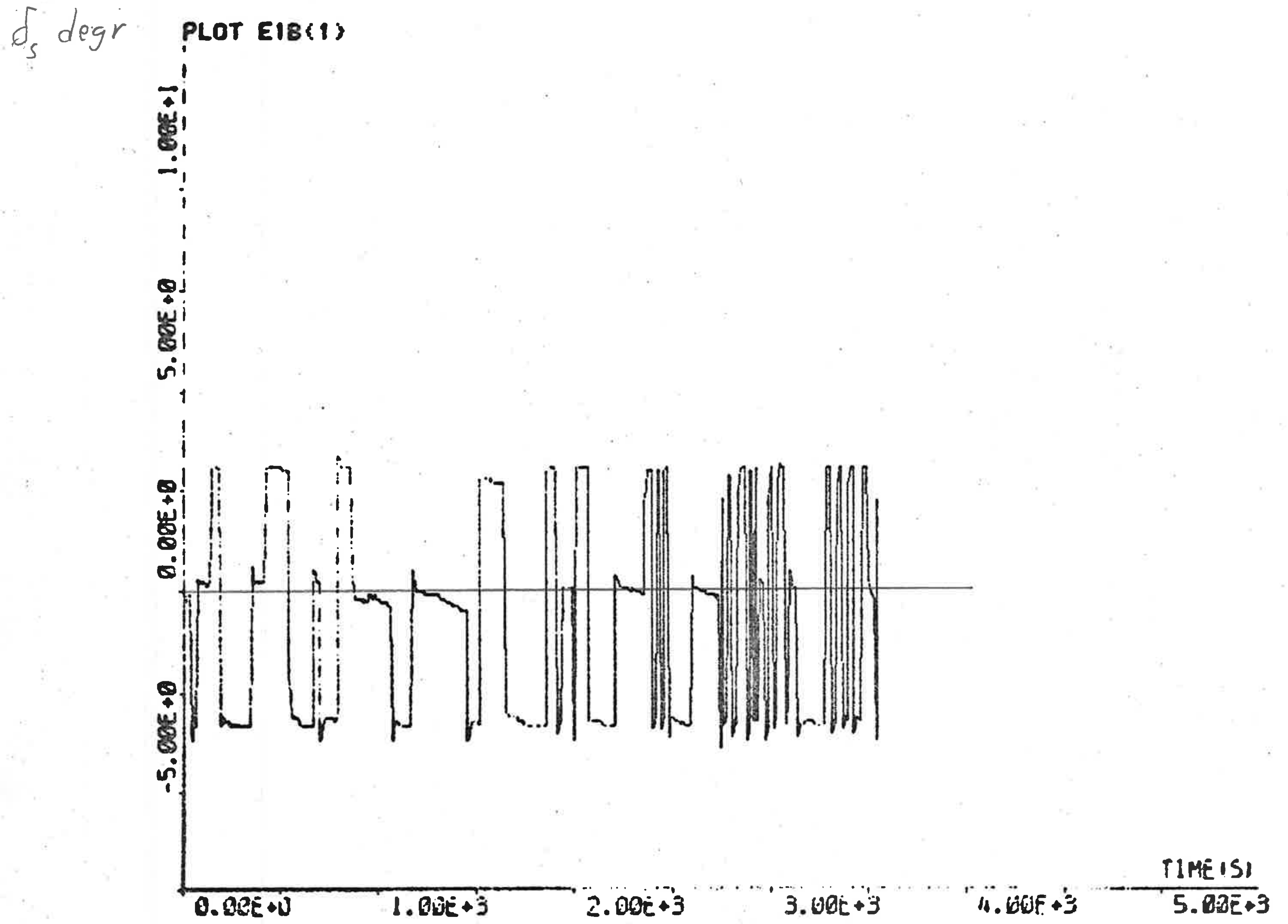
Sampling interval: 10 s

Rudder angles: +3°, 0°, -3°

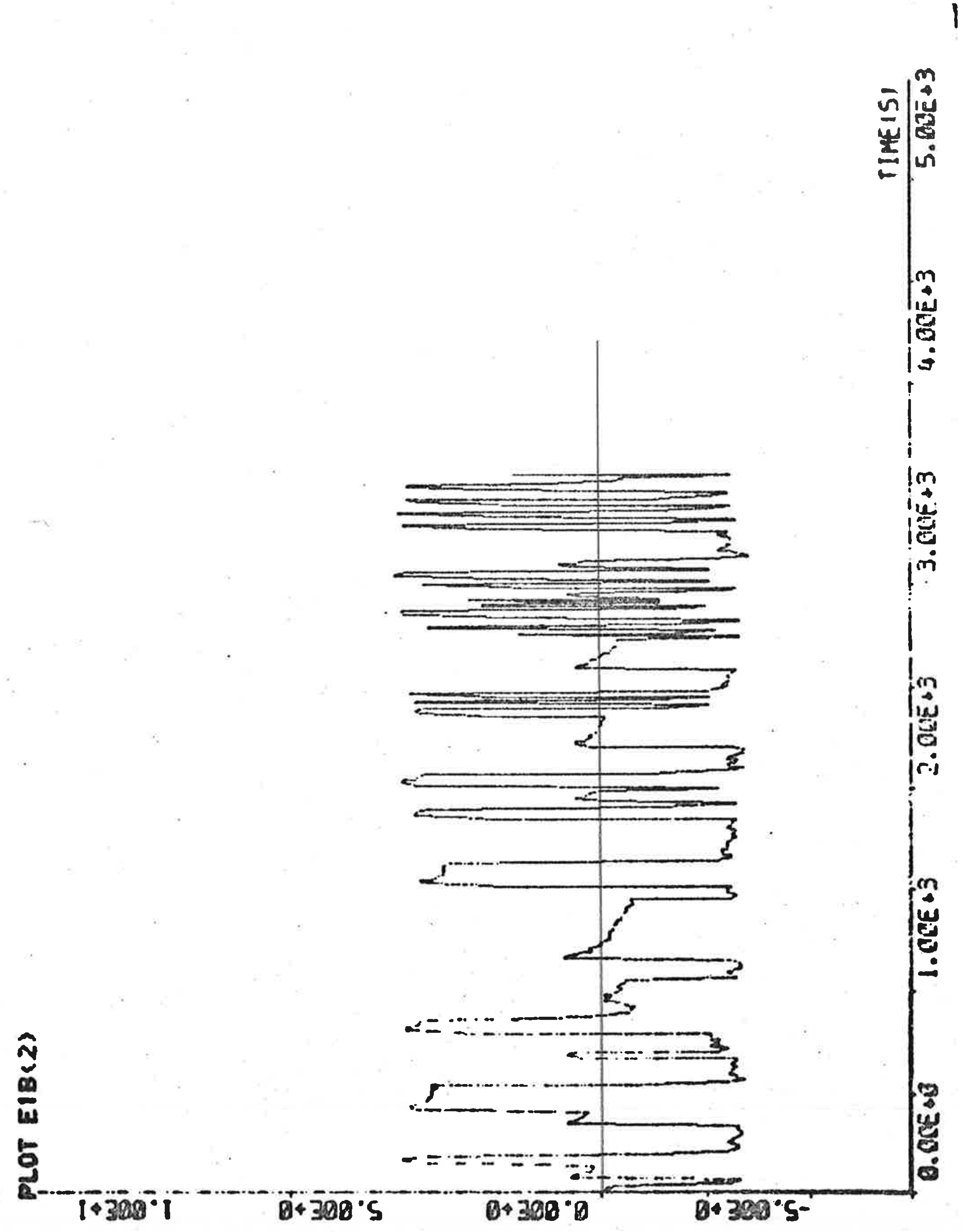
Statistics:

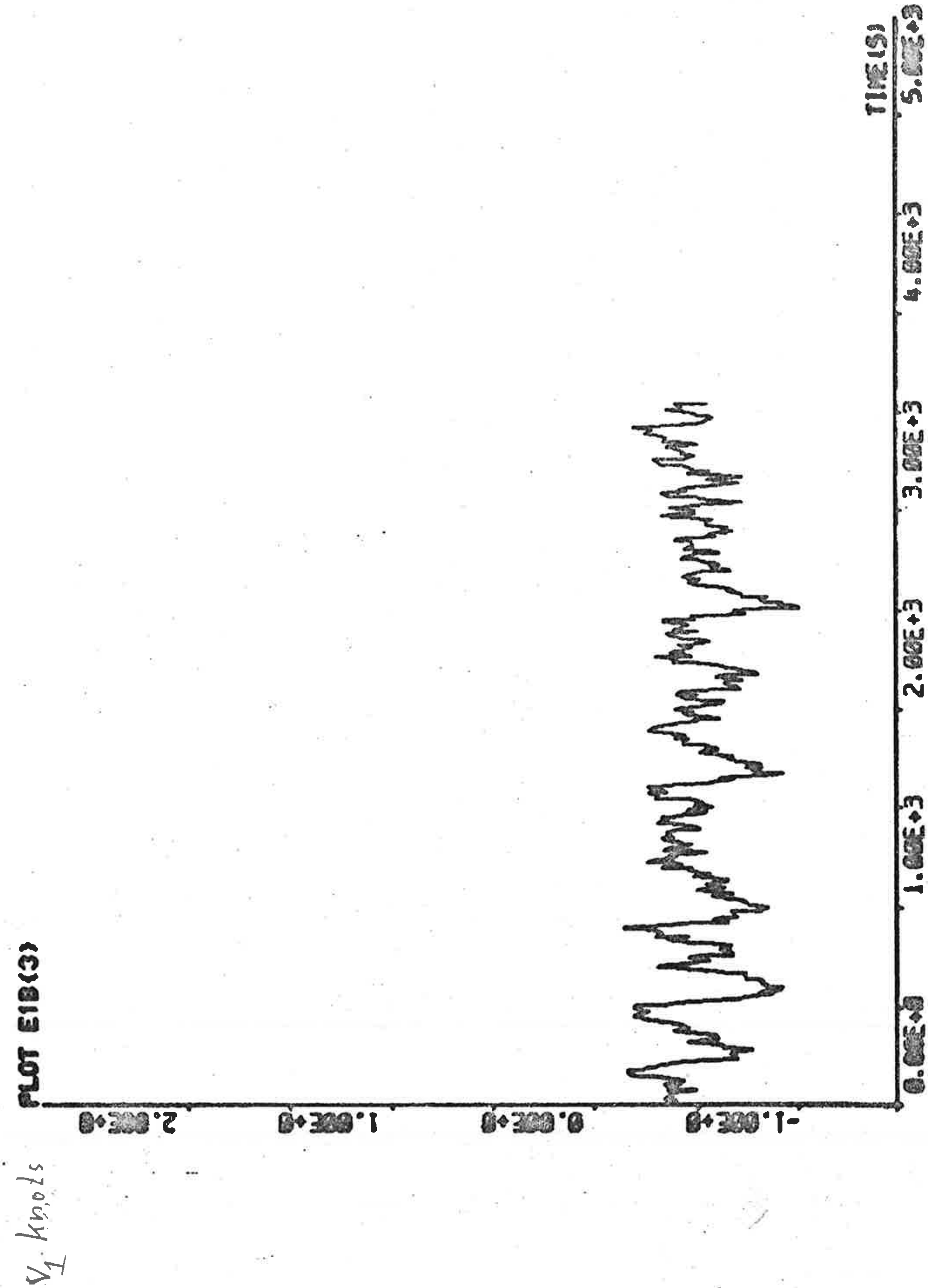
		Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-0.65	2.47	-3.3	3.1
δ_s	degr	-0.72	2.50	-3.9	3.4
δ	degr	-0.28	2.75	-3.5	5.0
v_1	knots	-0.506	0.164	-1.01	-0.14
v_2	knots	0.206	0.497	-1.15	1.13
r	degr/s	0.0087	0.0549	-0.110	0.160
ψ	degr	182.754	3.722	176.60	192.10
u	knots	16.896	0.653	14.10	17.70
q	degr/s	0.1273	0.0886	-0.156	0.367
r	rpm	83.20	0.75	81.4	84.7

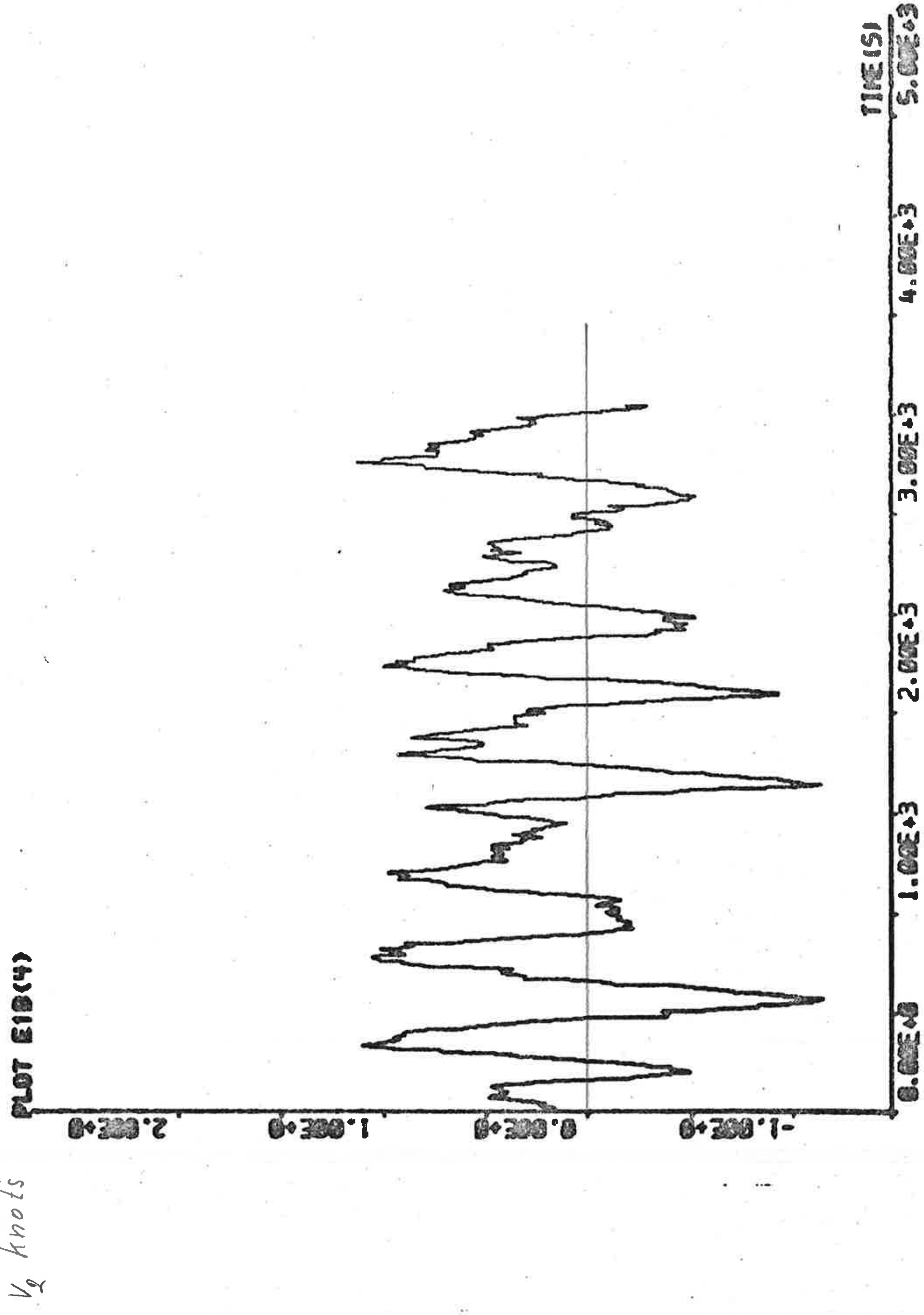

PLOT HP E1S (3)
TIME(S)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+3
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
δcom degr

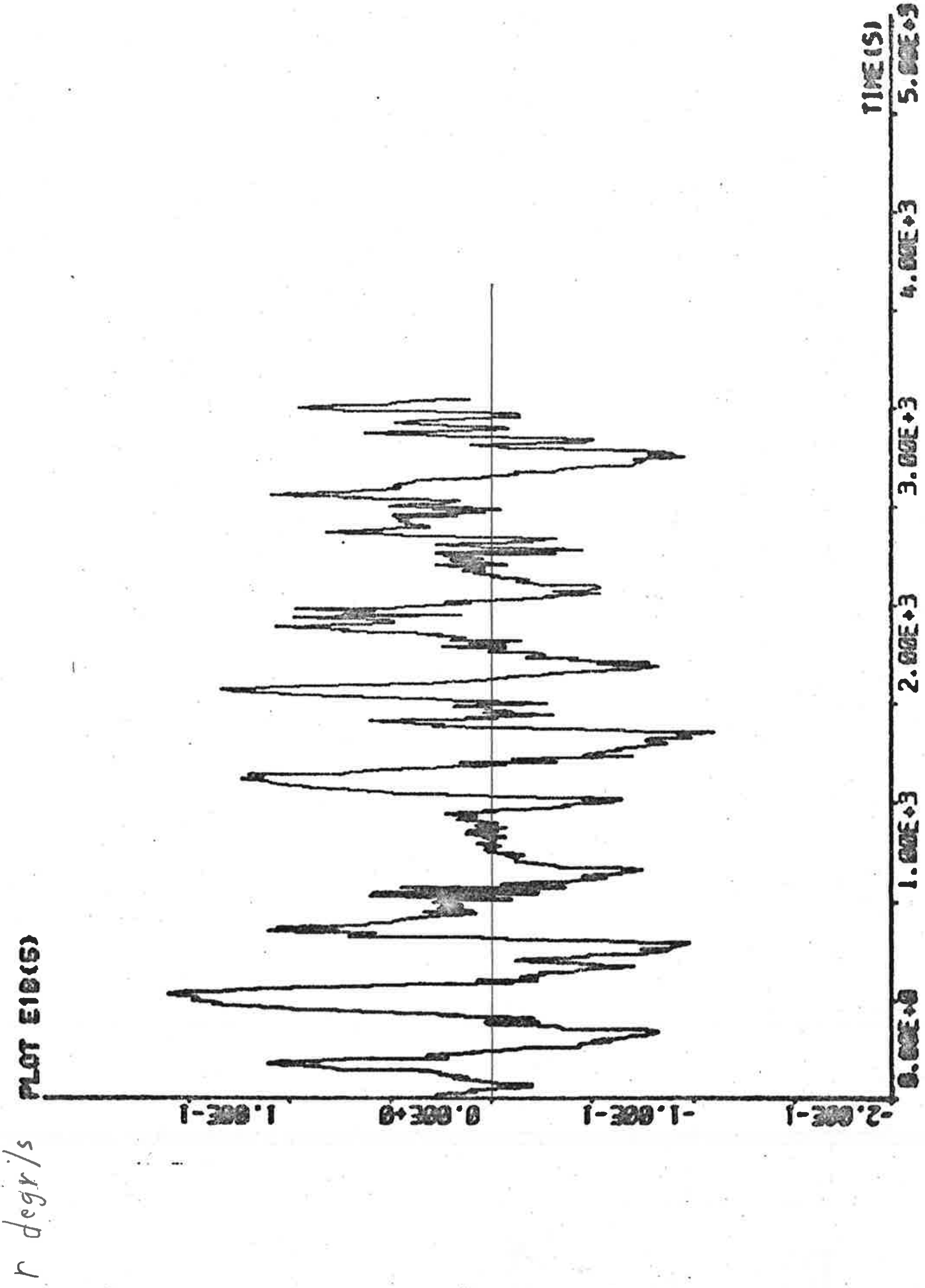


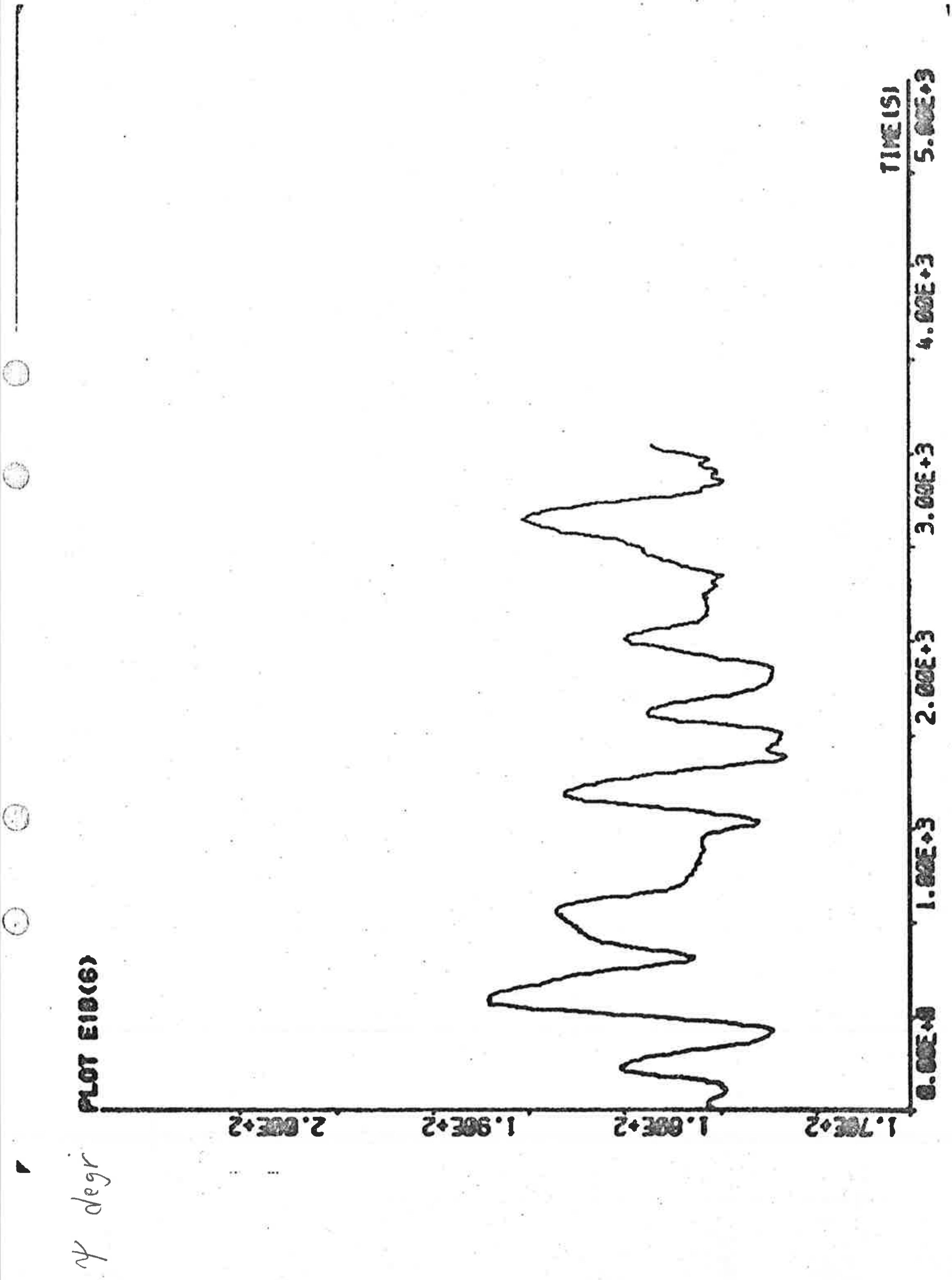
δs degr
PLOT E1B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

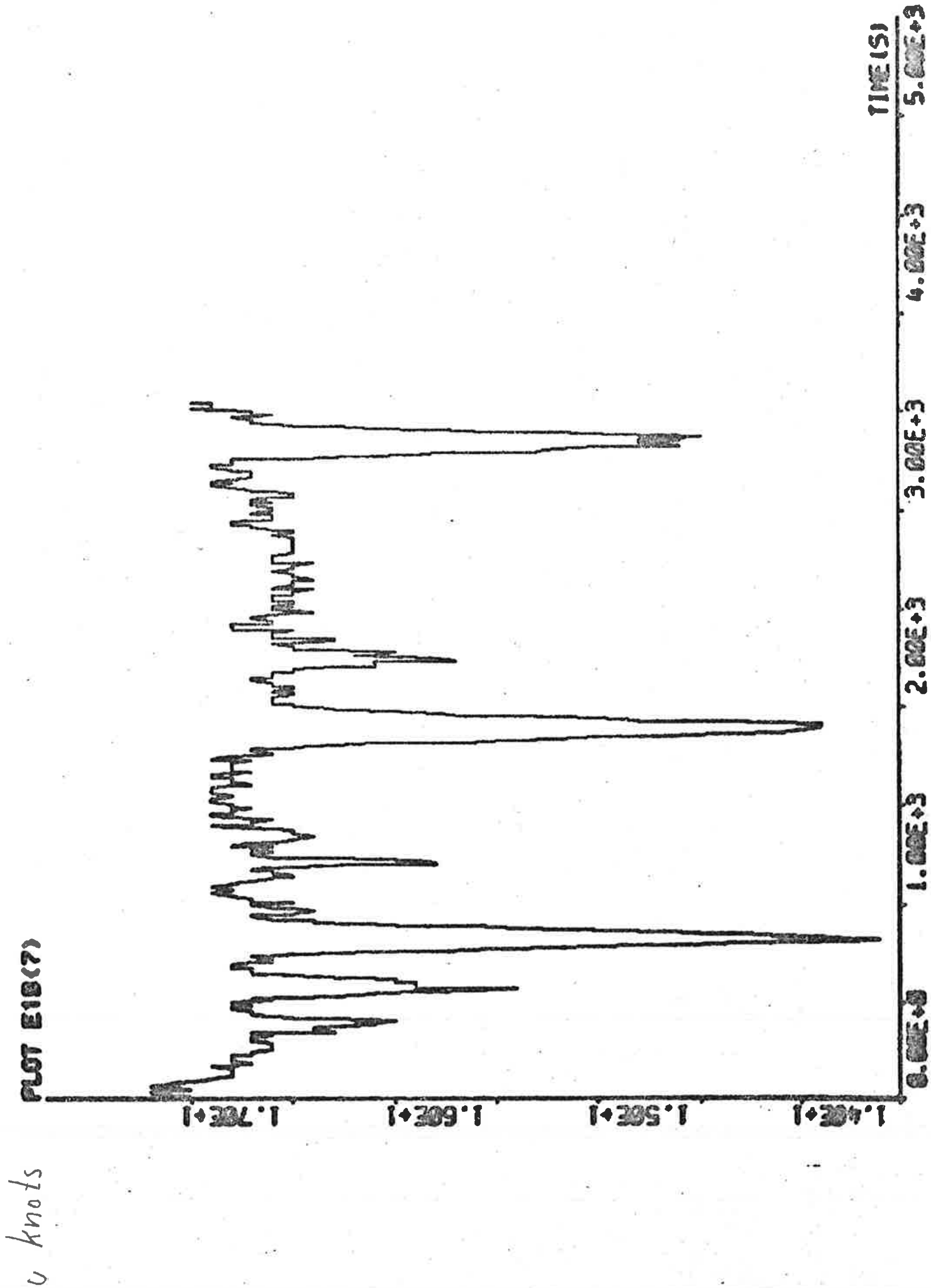

PLOT E1B(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E+0
0.00E+0
5.00E+0
1.00E+1

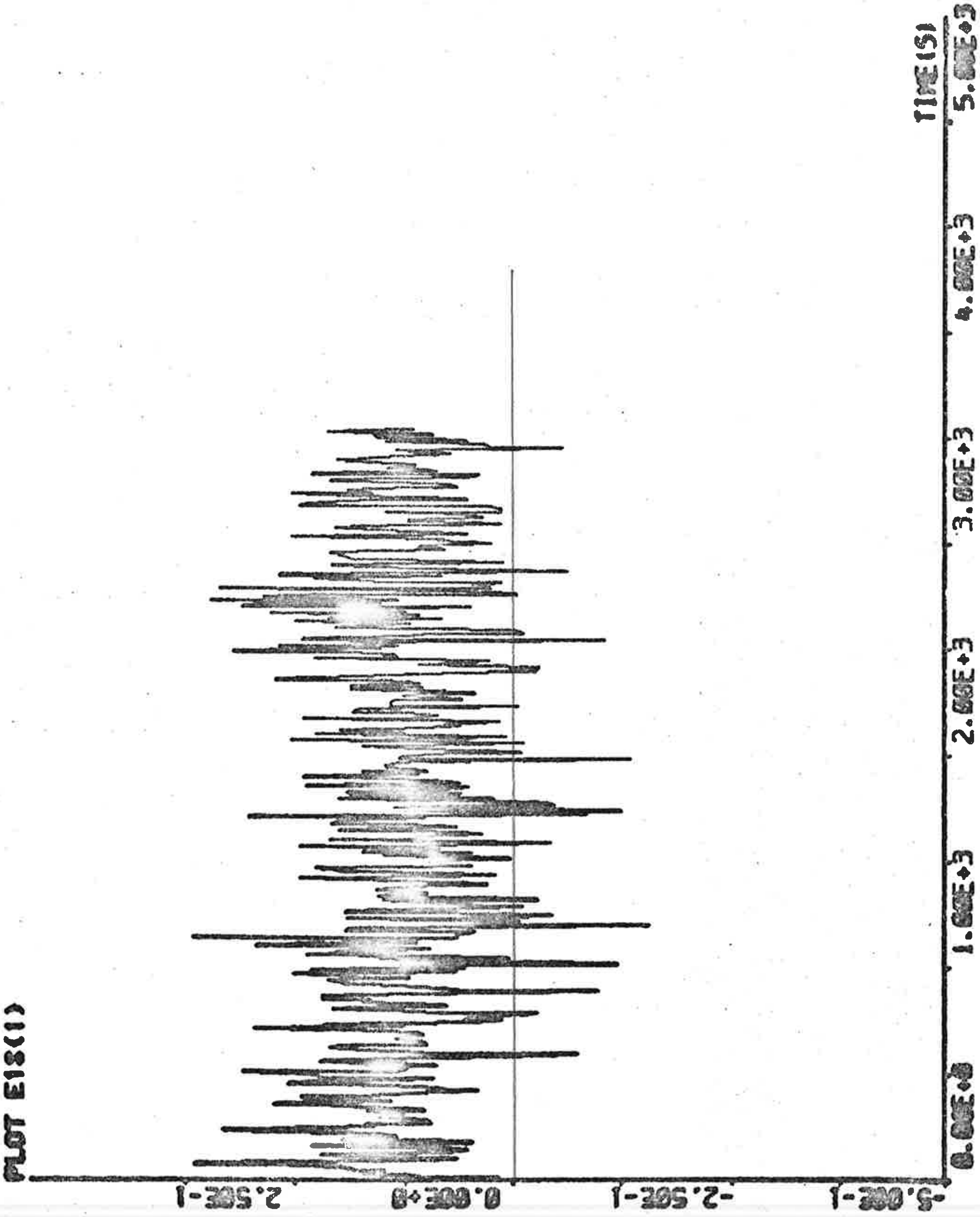

PLOT E1B(3)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_1 knots


PLOT E18(4)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_2 knots

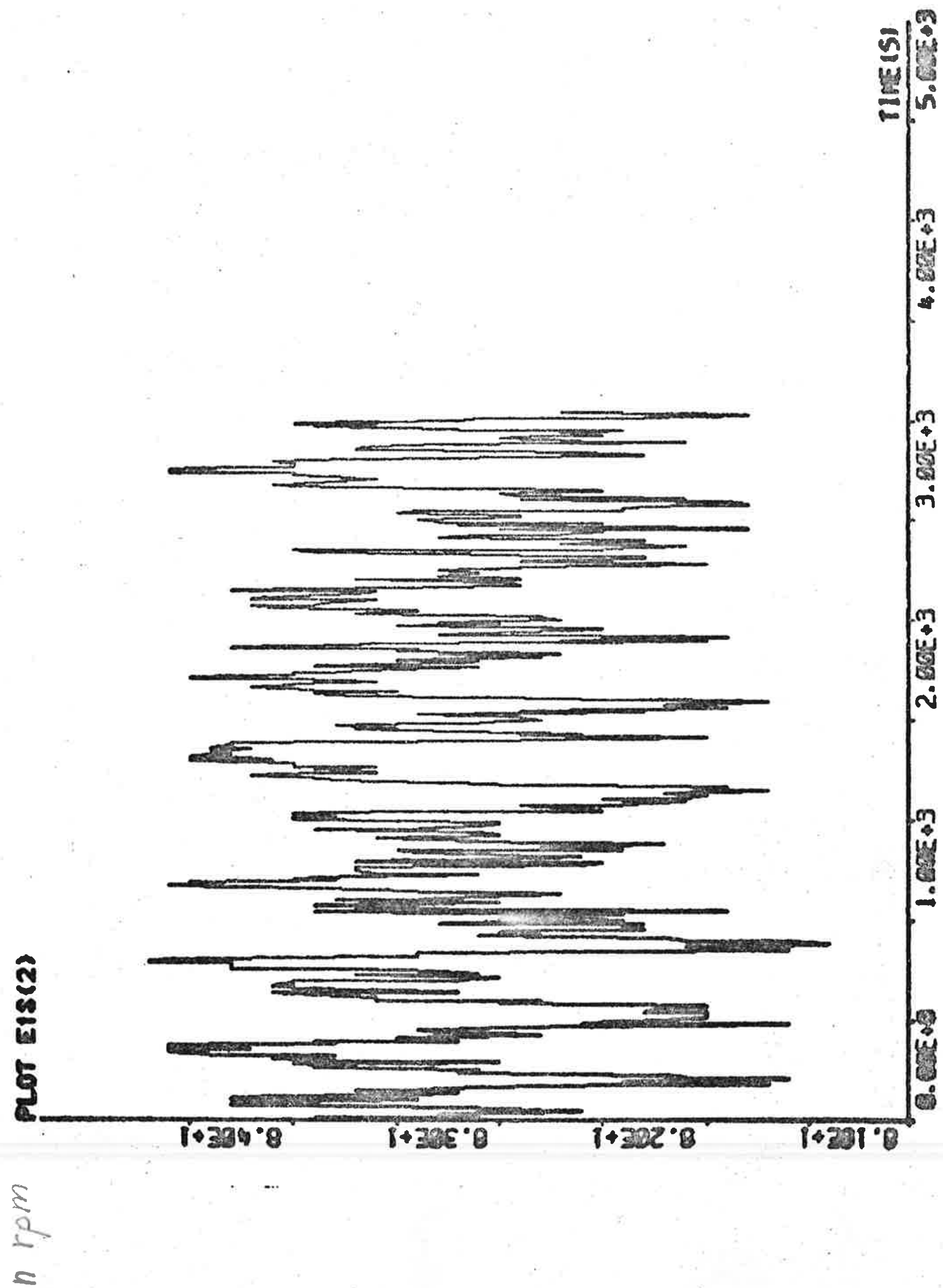

PLOT E18(5)
TIME (S)
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
r degr/s


PLOT E18(6)
TIME (S)
1.98E+2
3.00E+3
4.00E+3
Ψ degr


PLOT E18(7)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.70E+1
1.60E+1
1.50E+1
1.40E+1
u knots


PLOT E1S(1)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.50E-1
0.00E+0
-2.50E-1
-5.00E-1

q degr/s


PLOT EIS(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
8.40E+1
8.30E+1
8.20E+1
8.10E+1
n rpm

Experiment E2

Date: 73 - 10 - 15
Time: 19^{30} - 21^{30}
Position: S 09° W 02°

Wind direction: 1 (see appendix A)
Wind speed: 3 Beaufort (4 - 6 m/s, gentle breeze)
Wave height: 1.5 m, small rollings

Experiment for system identification.

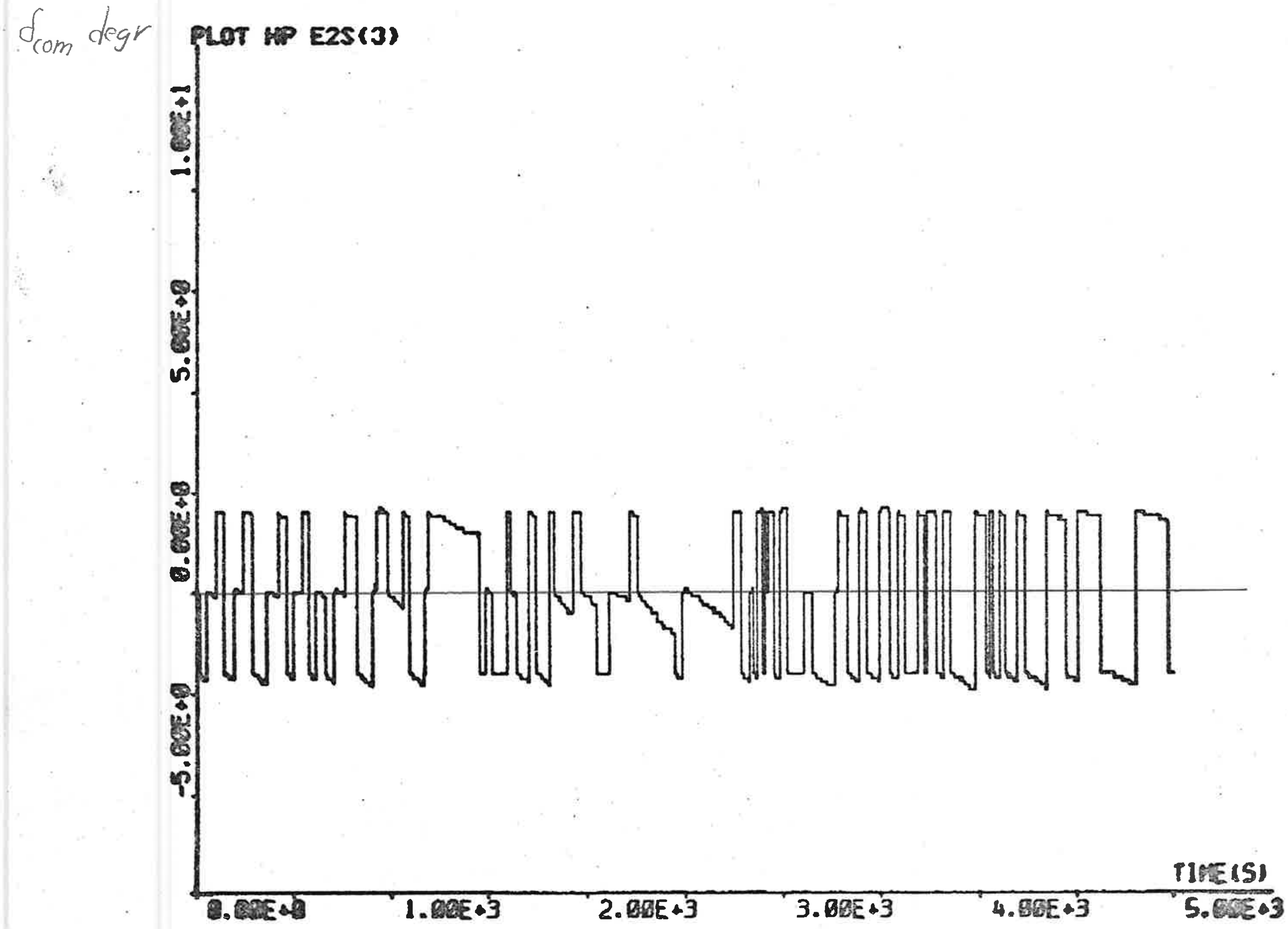
Calibration of the rudder servo:

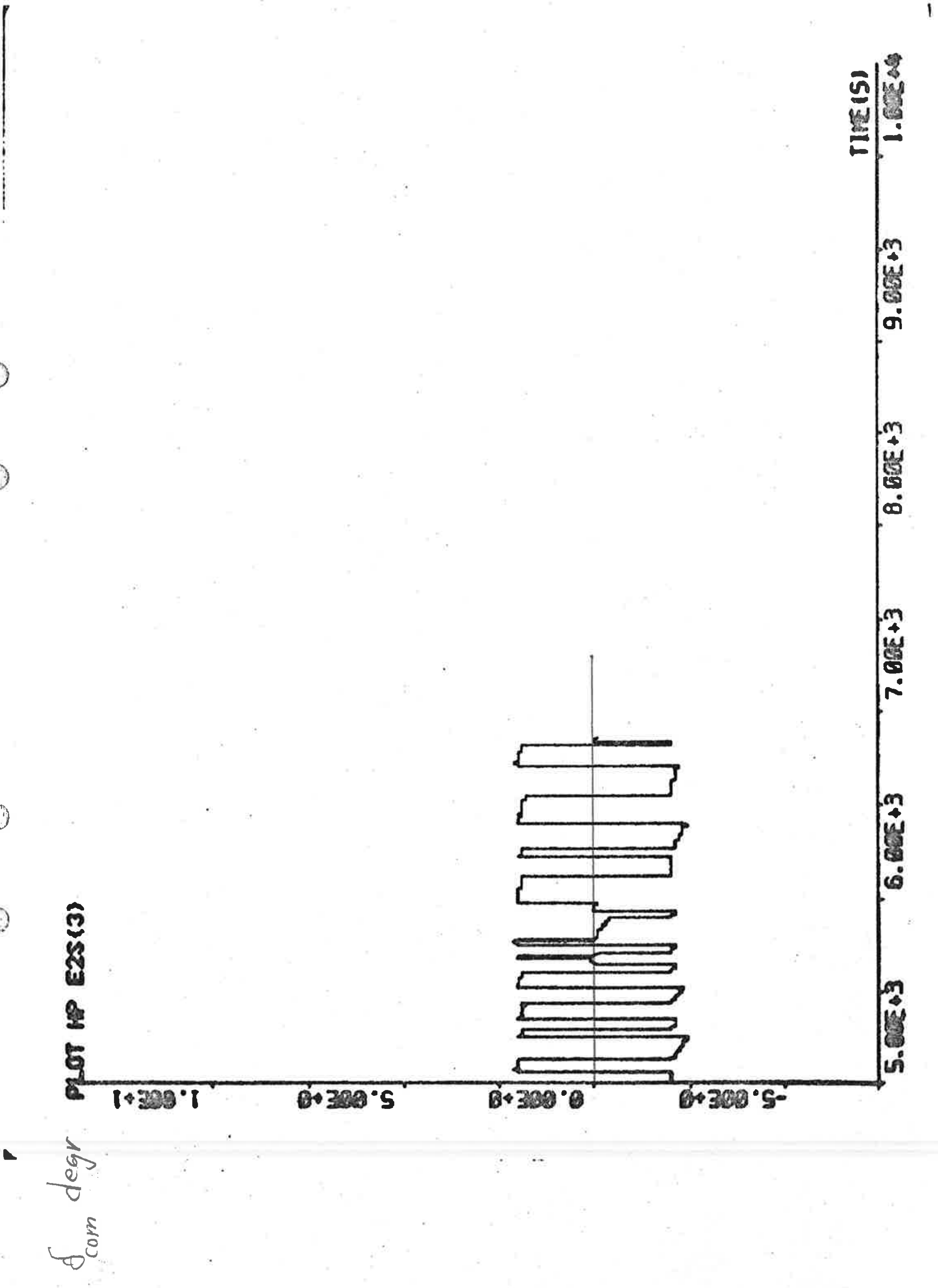
10 volts = 36.9°
-10 volts = -43.1°

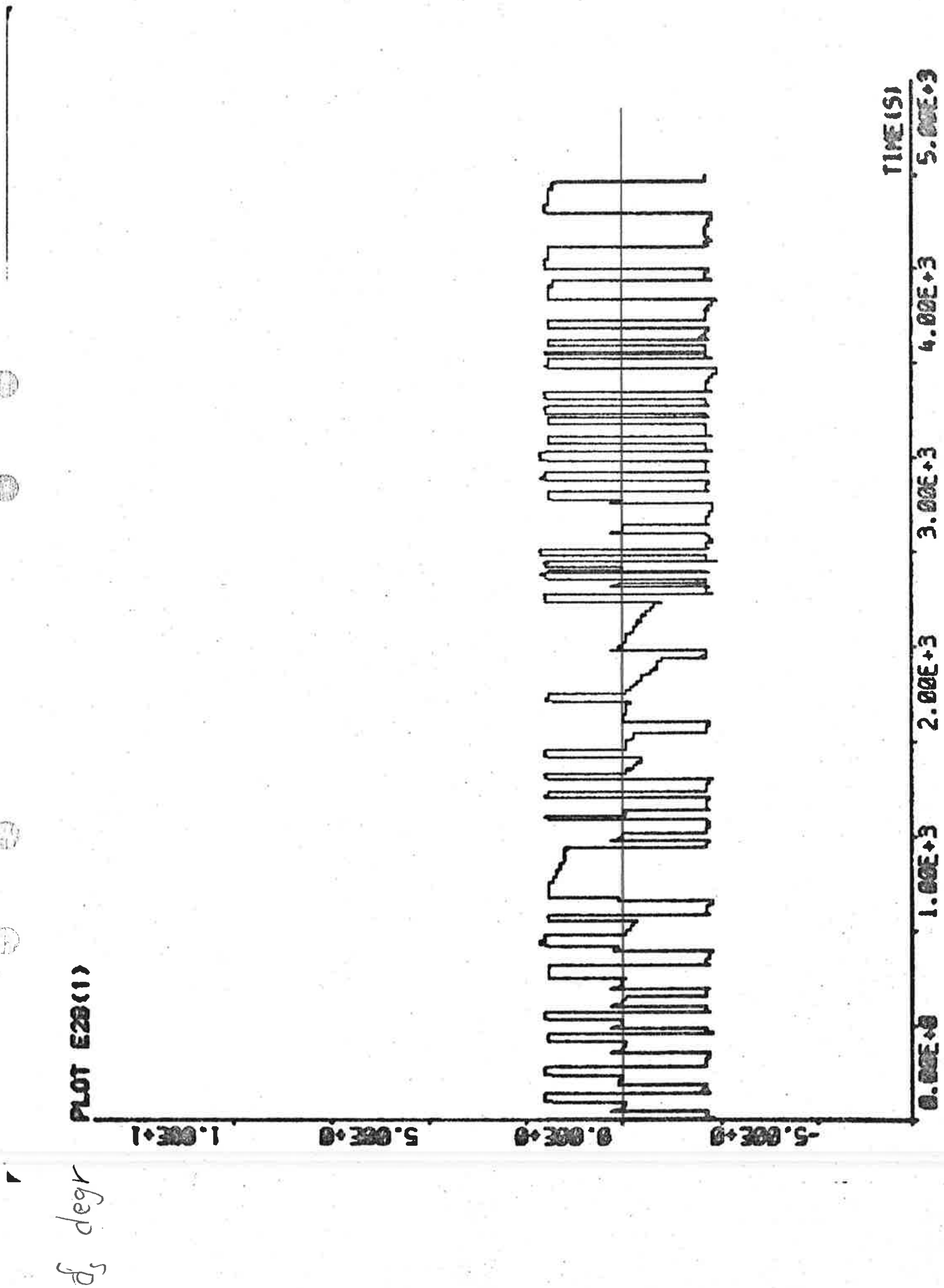
Sampling interval: 5 s
Rudder angles: +2°, 0°, -2°

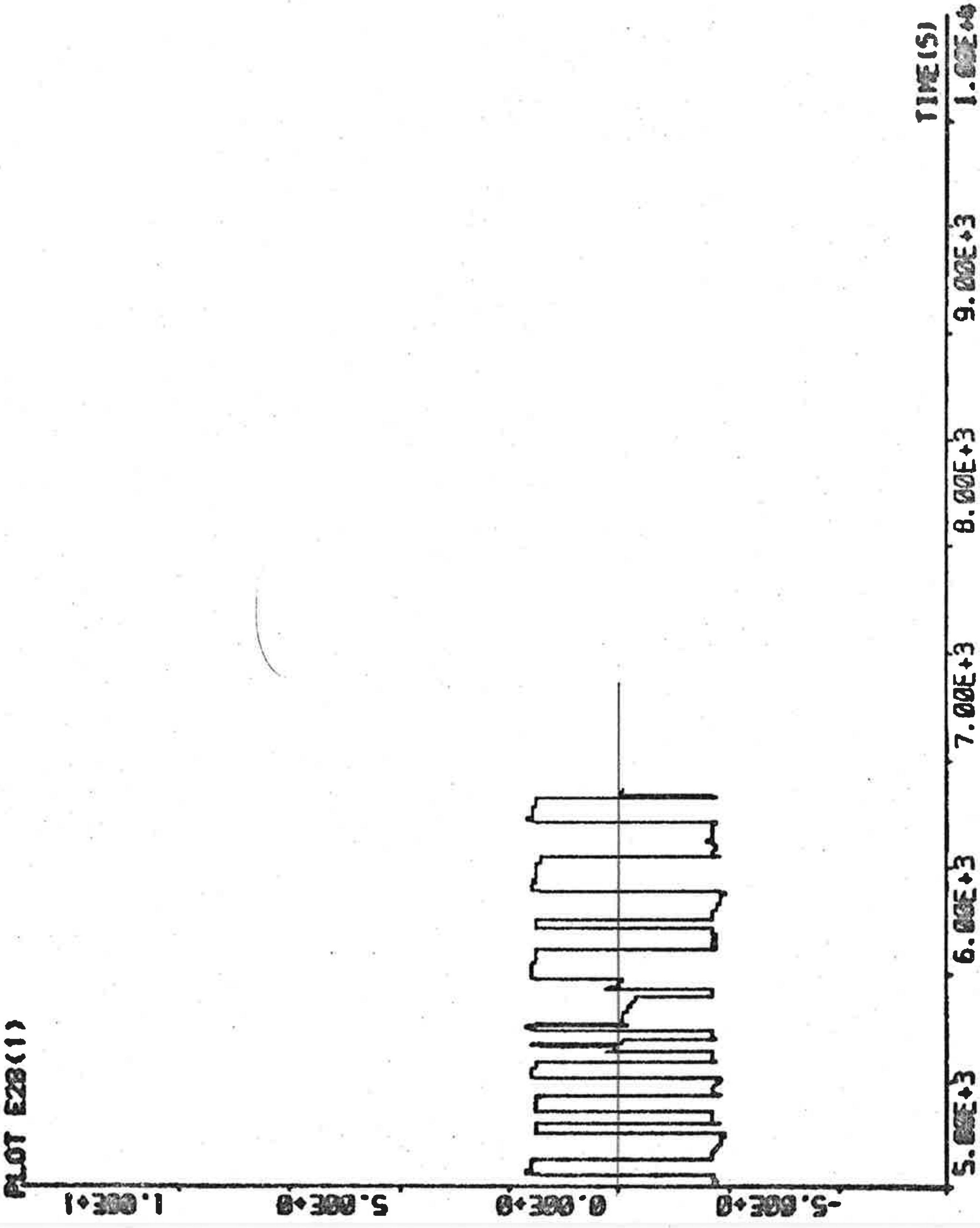
Statistics:

	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.22	1.77	-2.4	2.1
δ_s degr	-0.24	1.79	-2.4	2.1
δ degr	-0.43	1.85	-2.9	2.5
v_1 knots	-0.567	0.146	-1.01	-0.16
v_2 knots	0.112	0.361	-1.01	1.12
r degr/s	0.0067	0.0383	-0.099	0.117
Ψ degr	145.572	6.290	137.64	159.96
u knots	16.742	0.189	15.78	17.13
r rpm	82.88	0.62	81.1	84.4

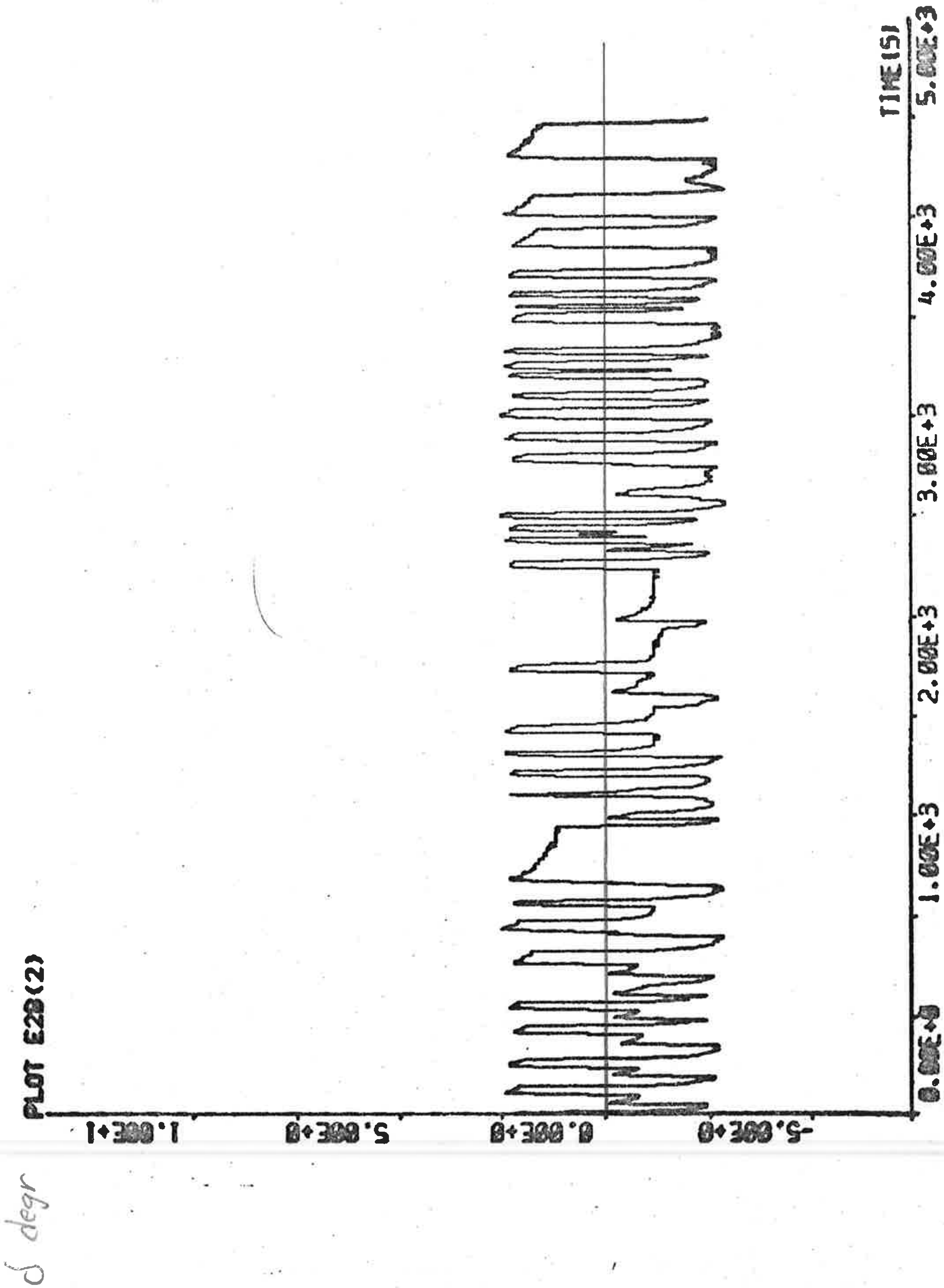

δcom degr
PLOT HP E2S(3)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

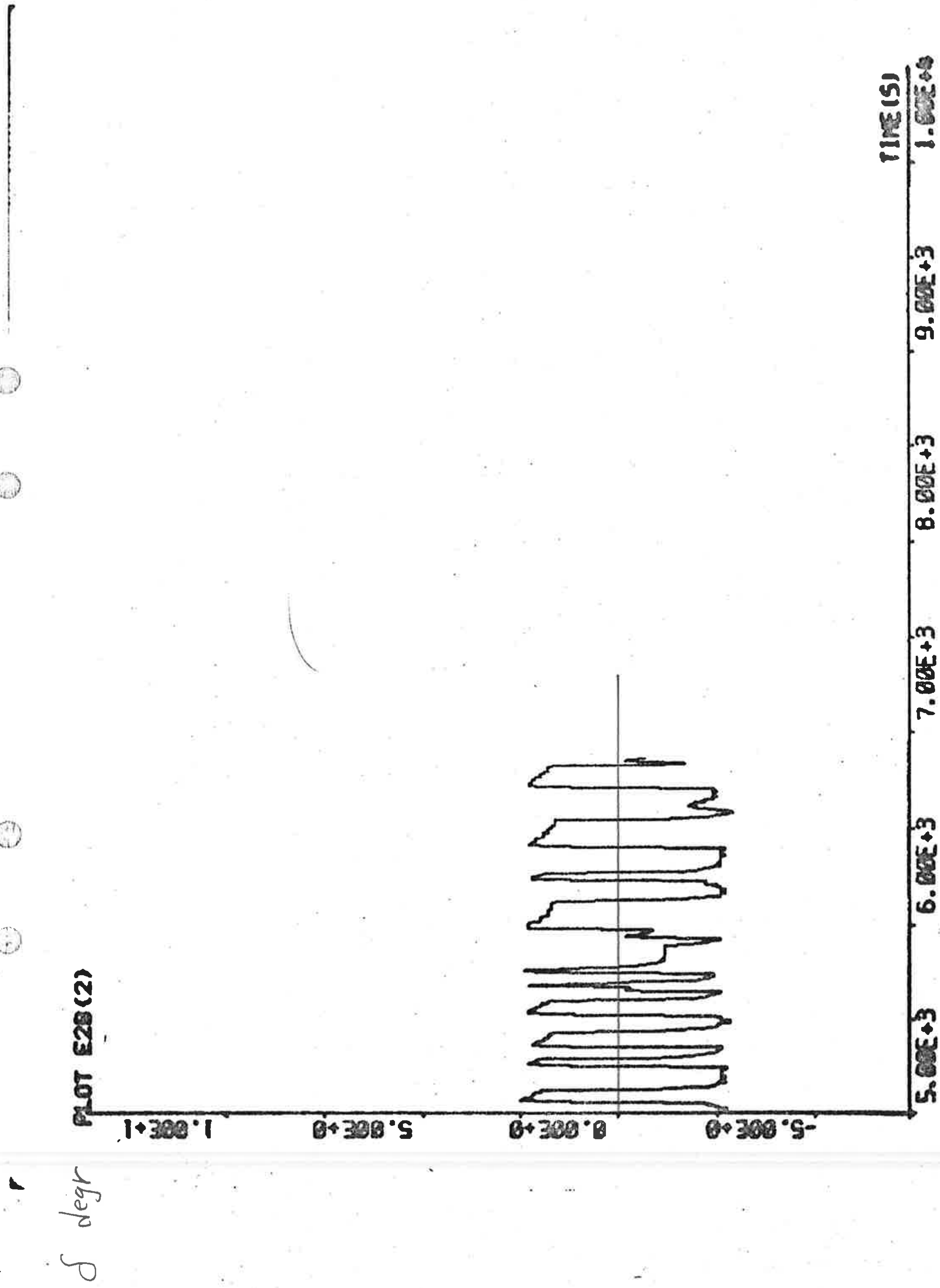

PLOT HP E2S(3)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)
δcom degr

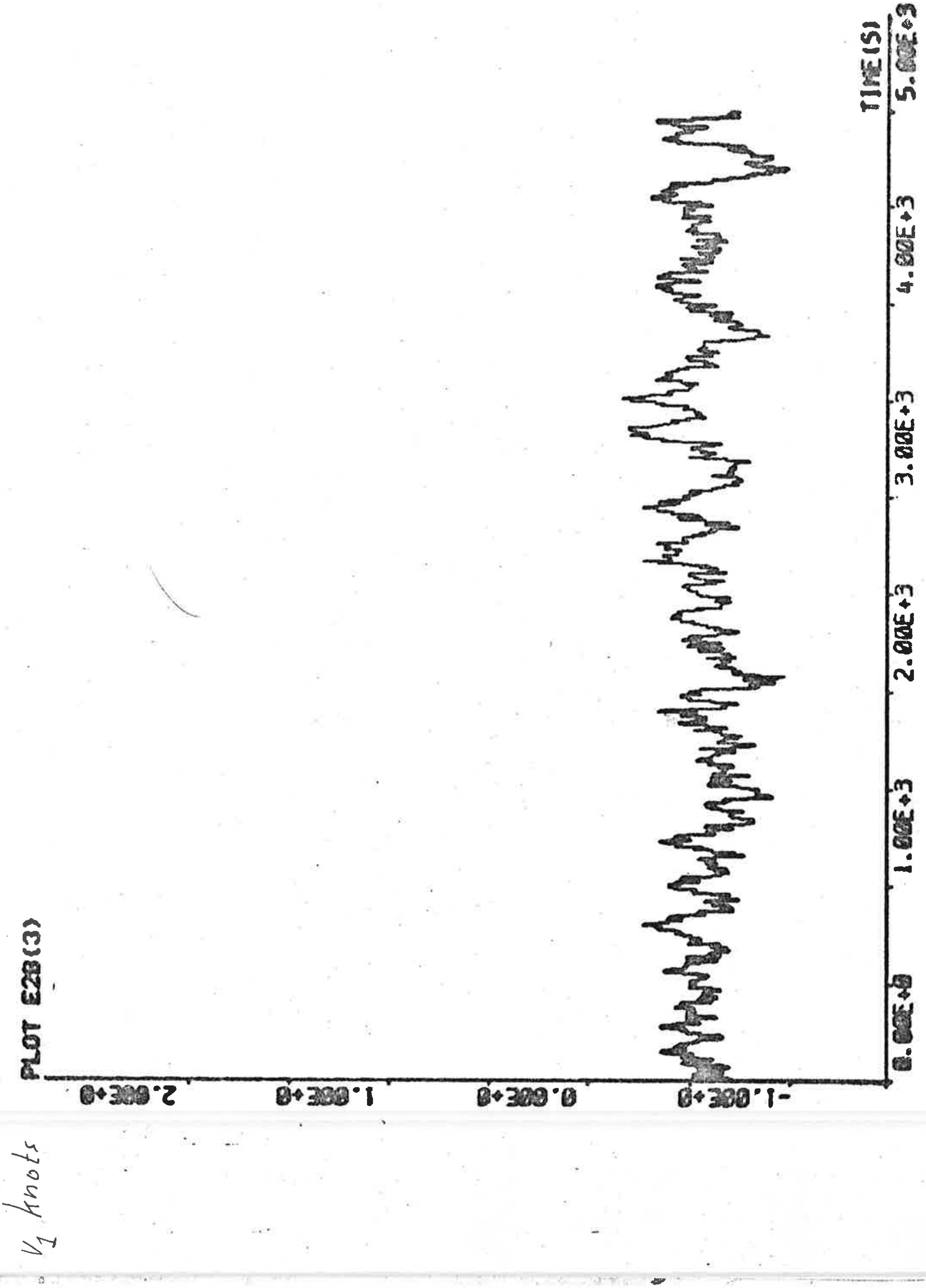

PLOT E28(1)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δs degr

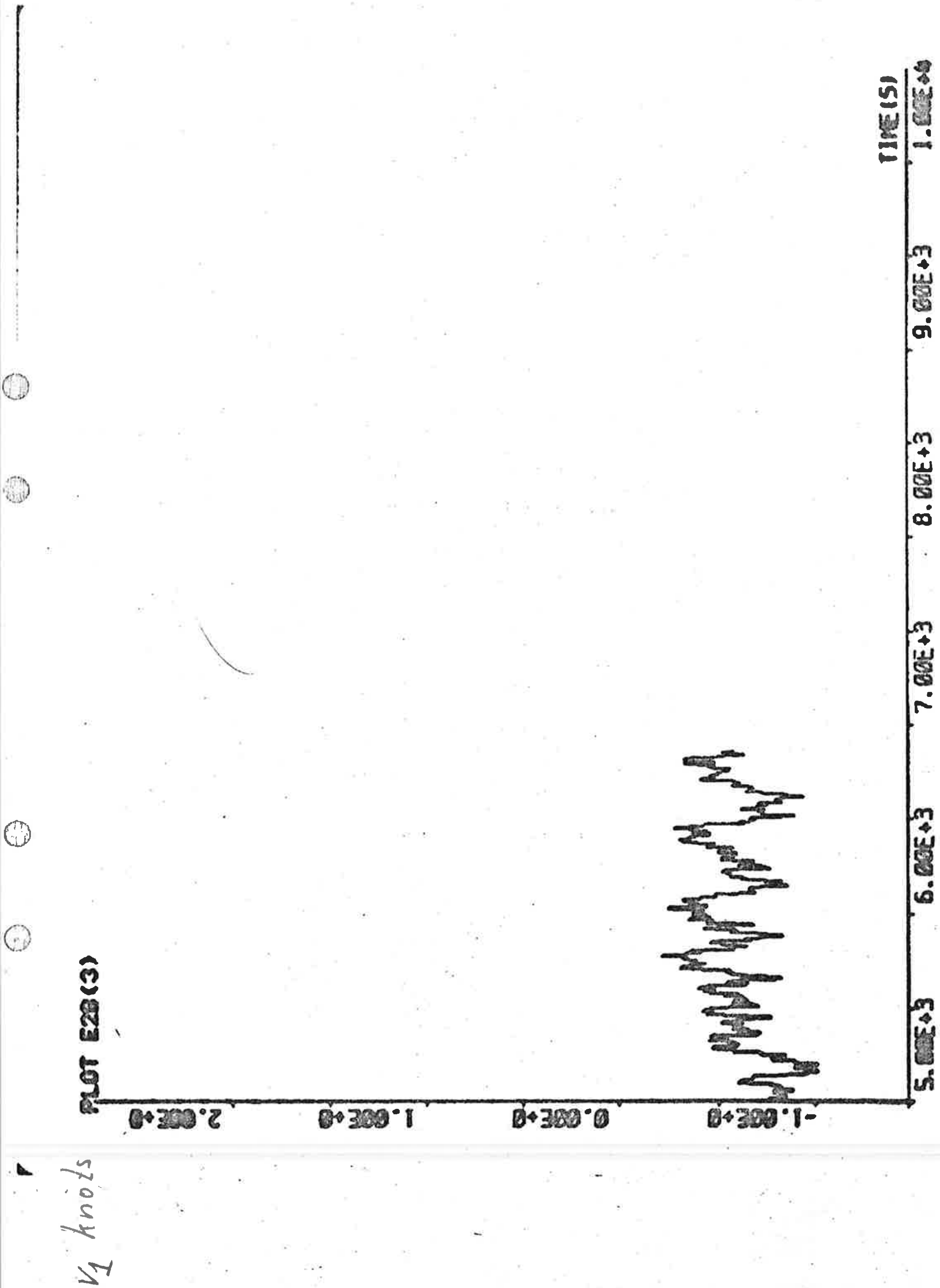

PLOT E2B(1)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E+1
5.00E+0
0.00E+0
-5.00E+0

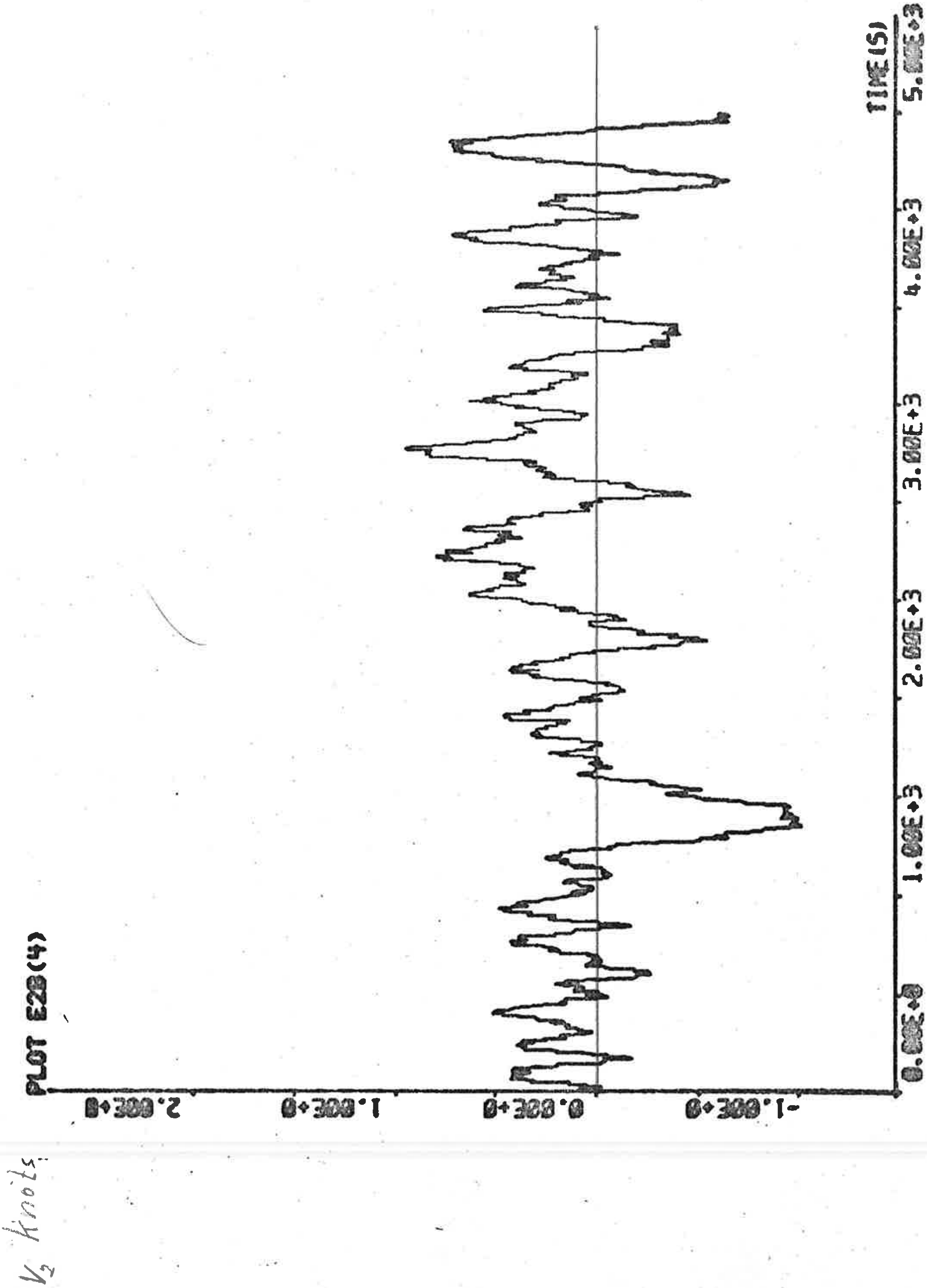
δ_5 degr

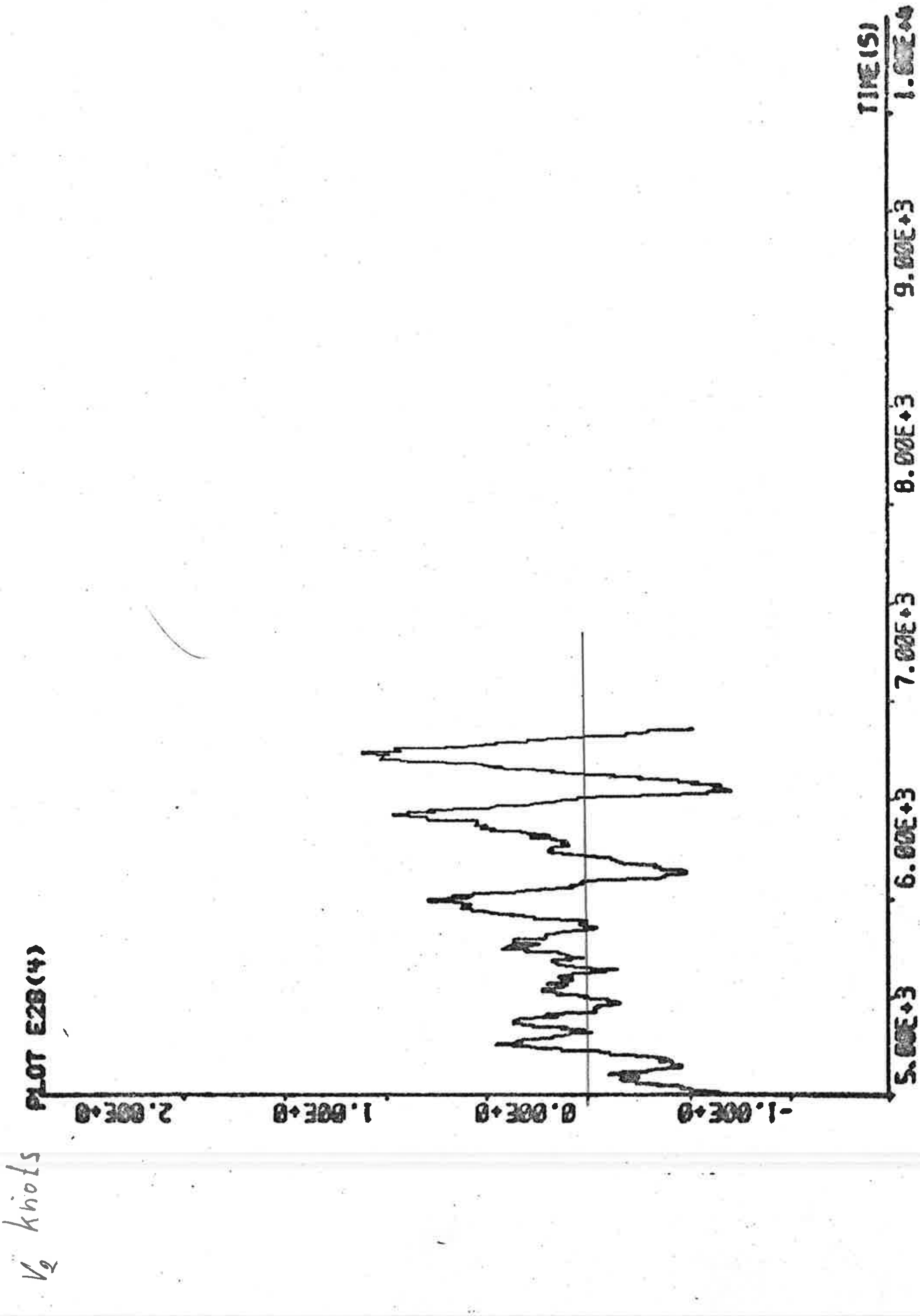

PLOT E2B(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr

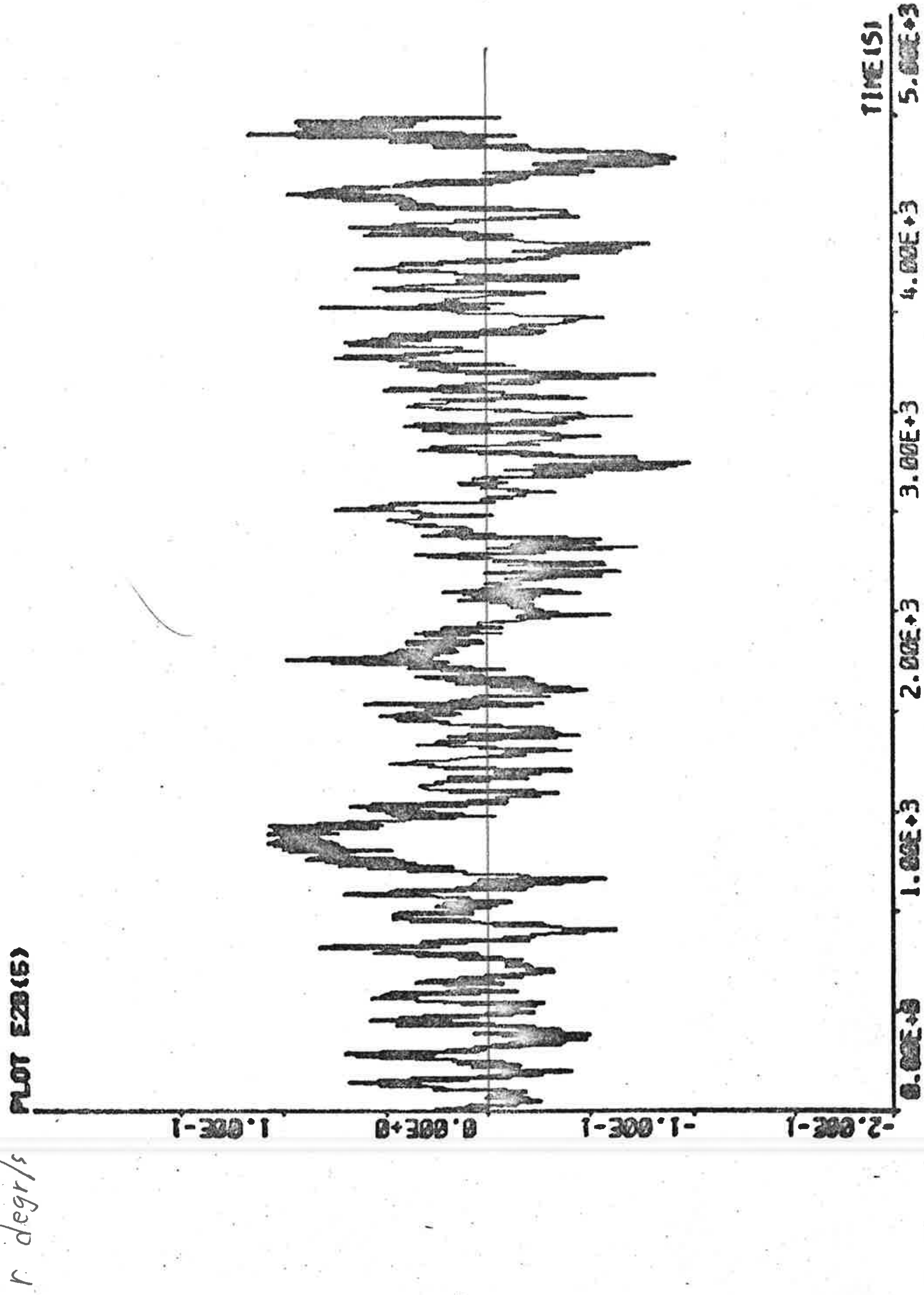

PLOT E28(2)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr

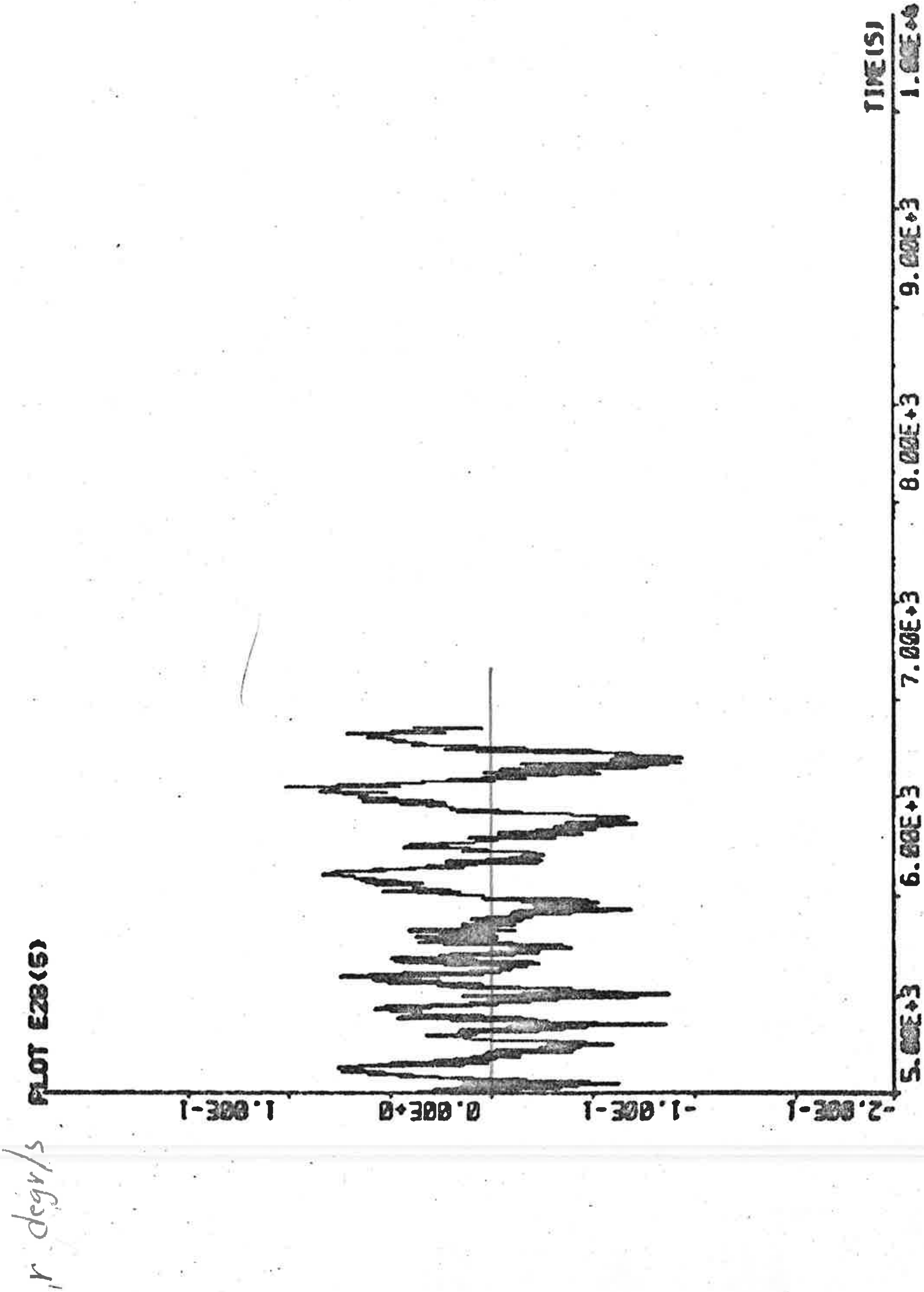

PLOT E2B(3)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
V1 knots

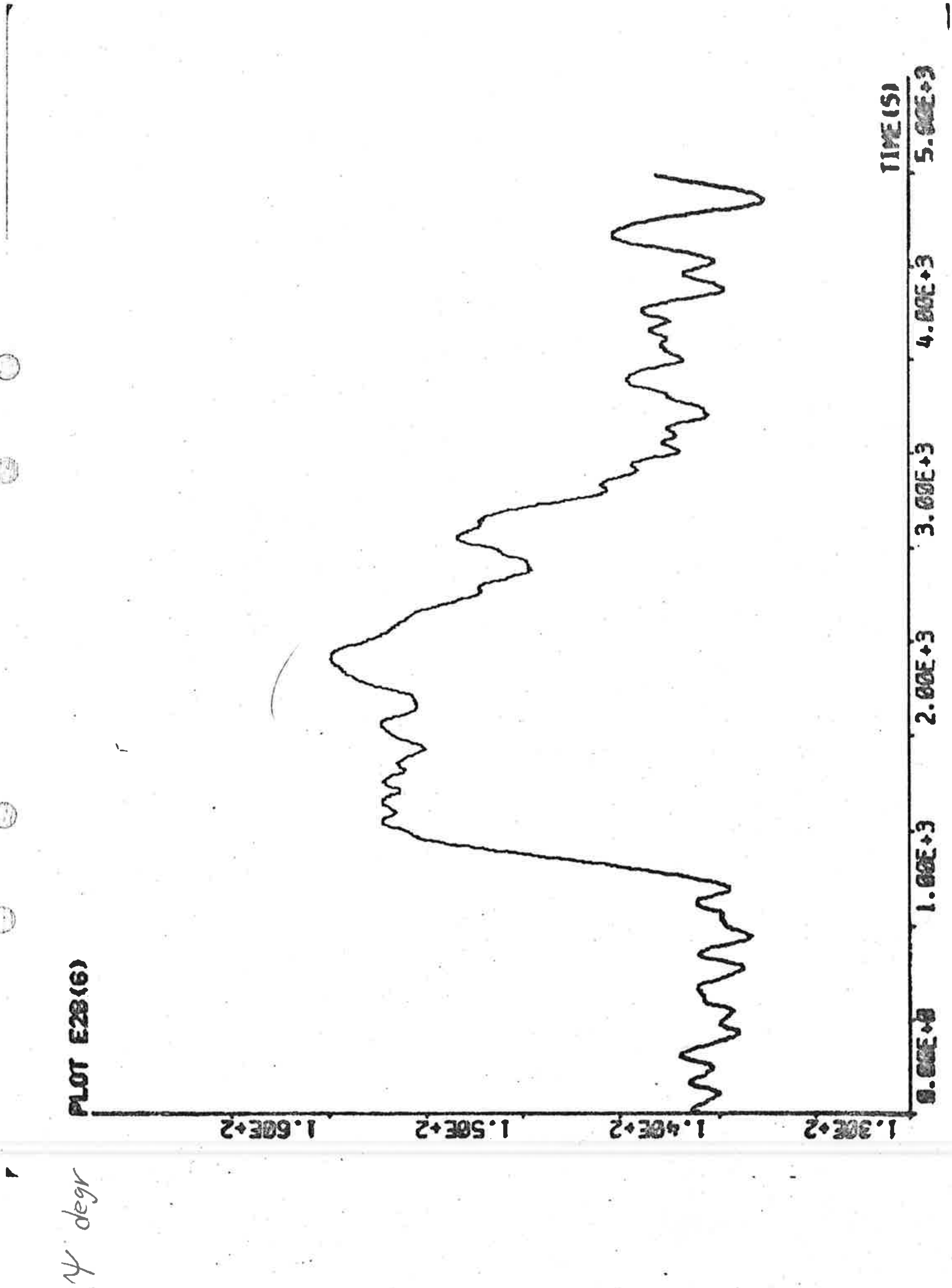

PLOT E2B(3)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
V1 knots

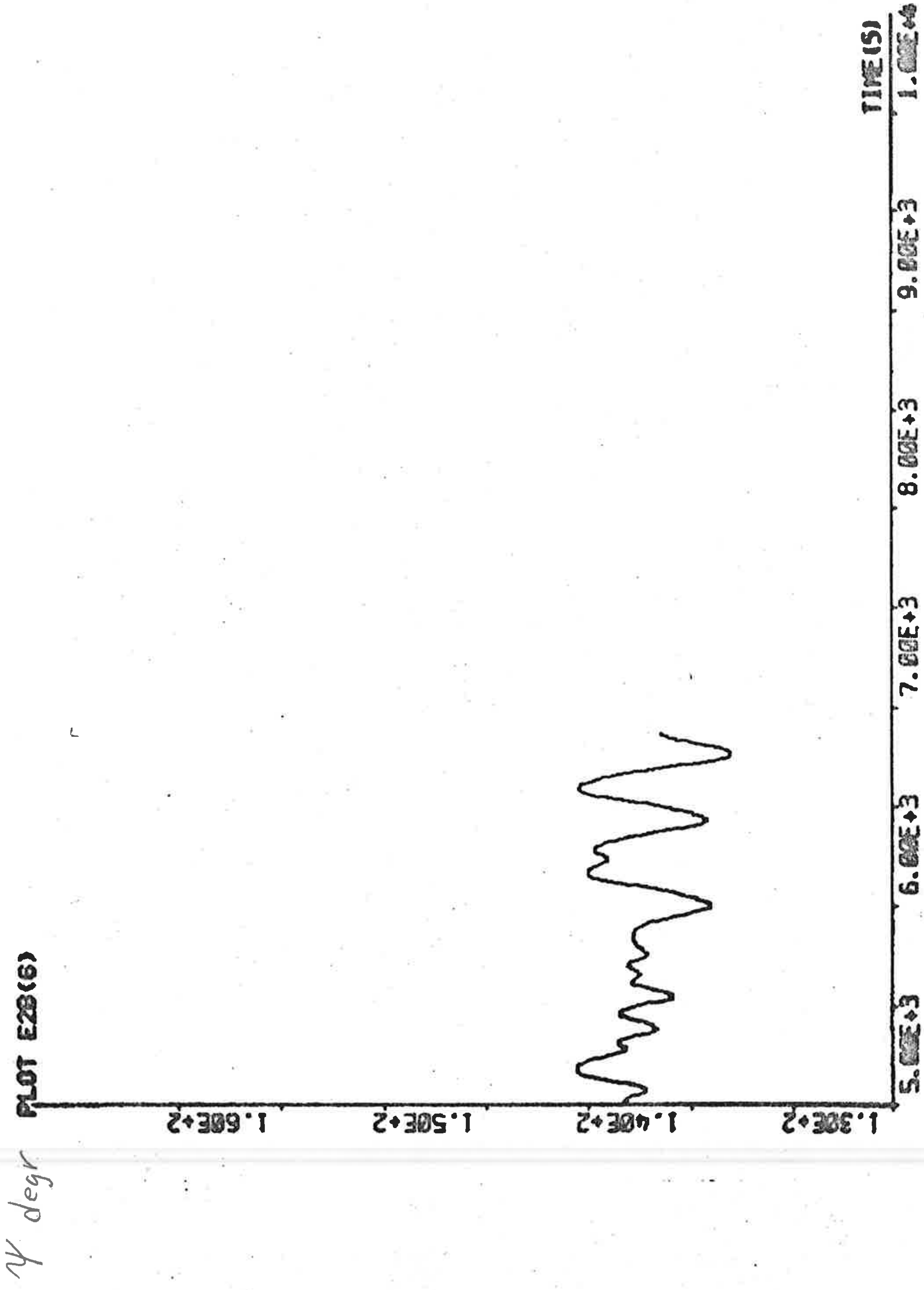

PLOT E2B(4)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_2 knots

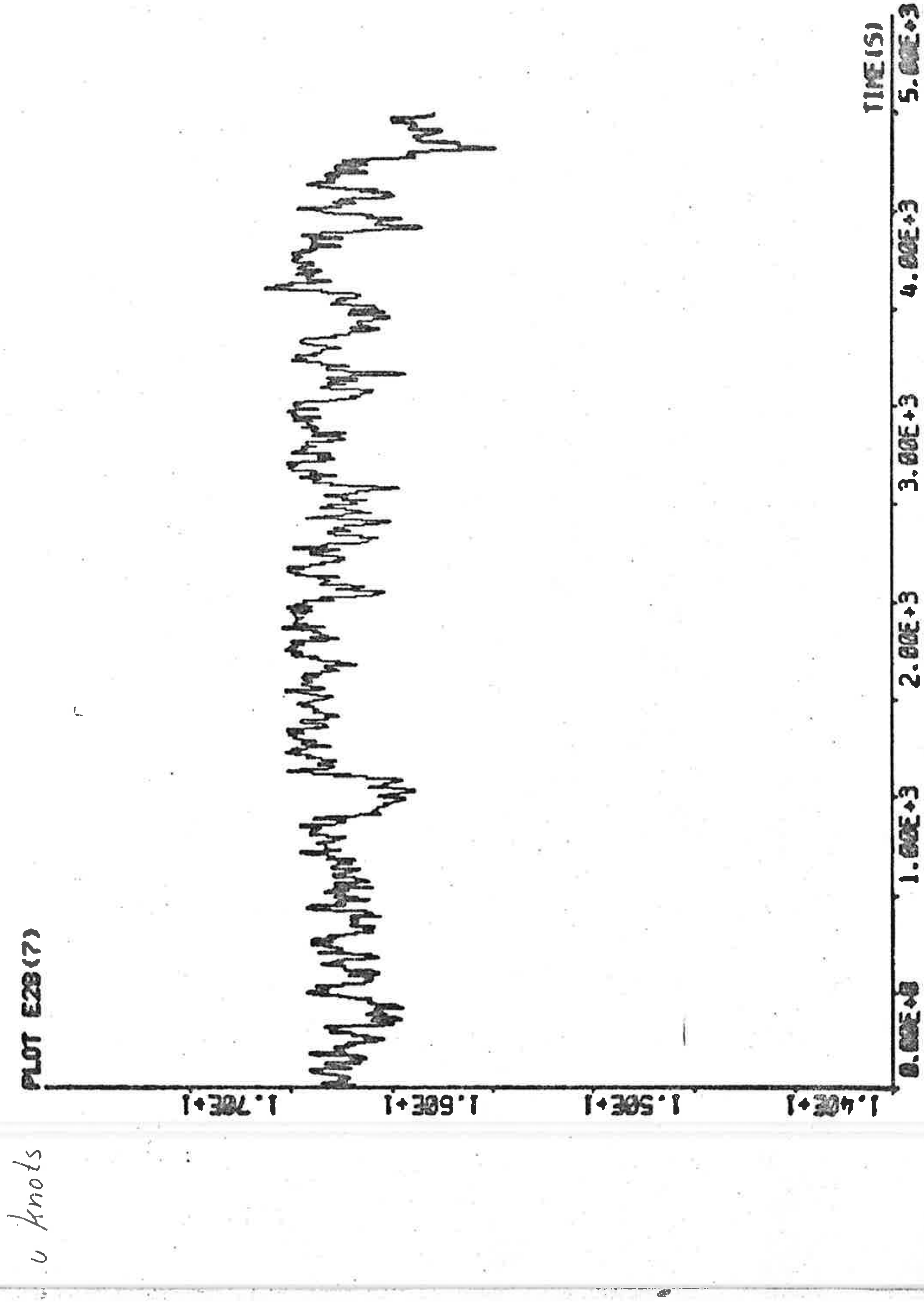

PLOT E2B(4)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
V2 knots

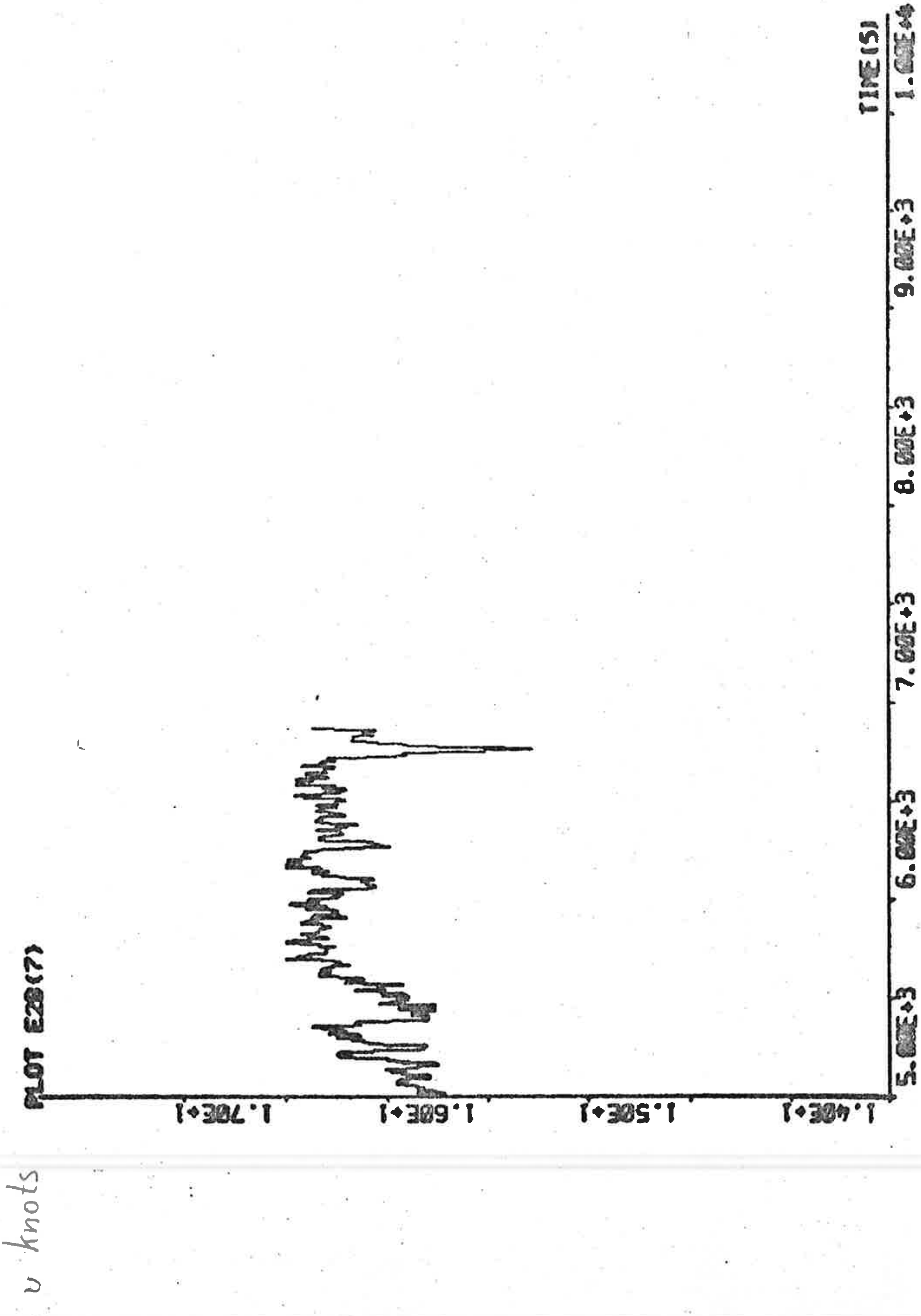

PLOT E2B(5)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
r degr/s

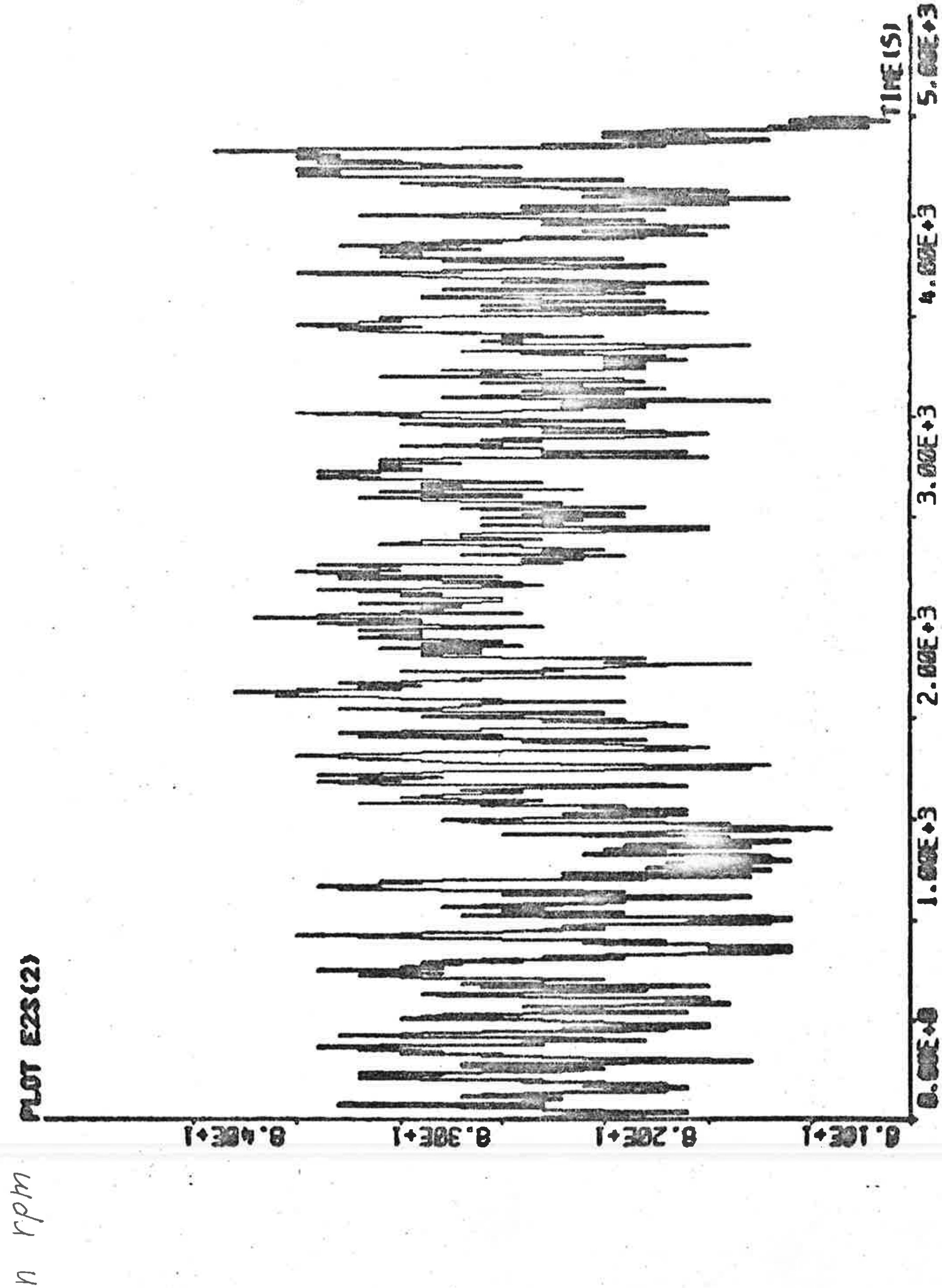

PLOT E28(S)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
r degr/s

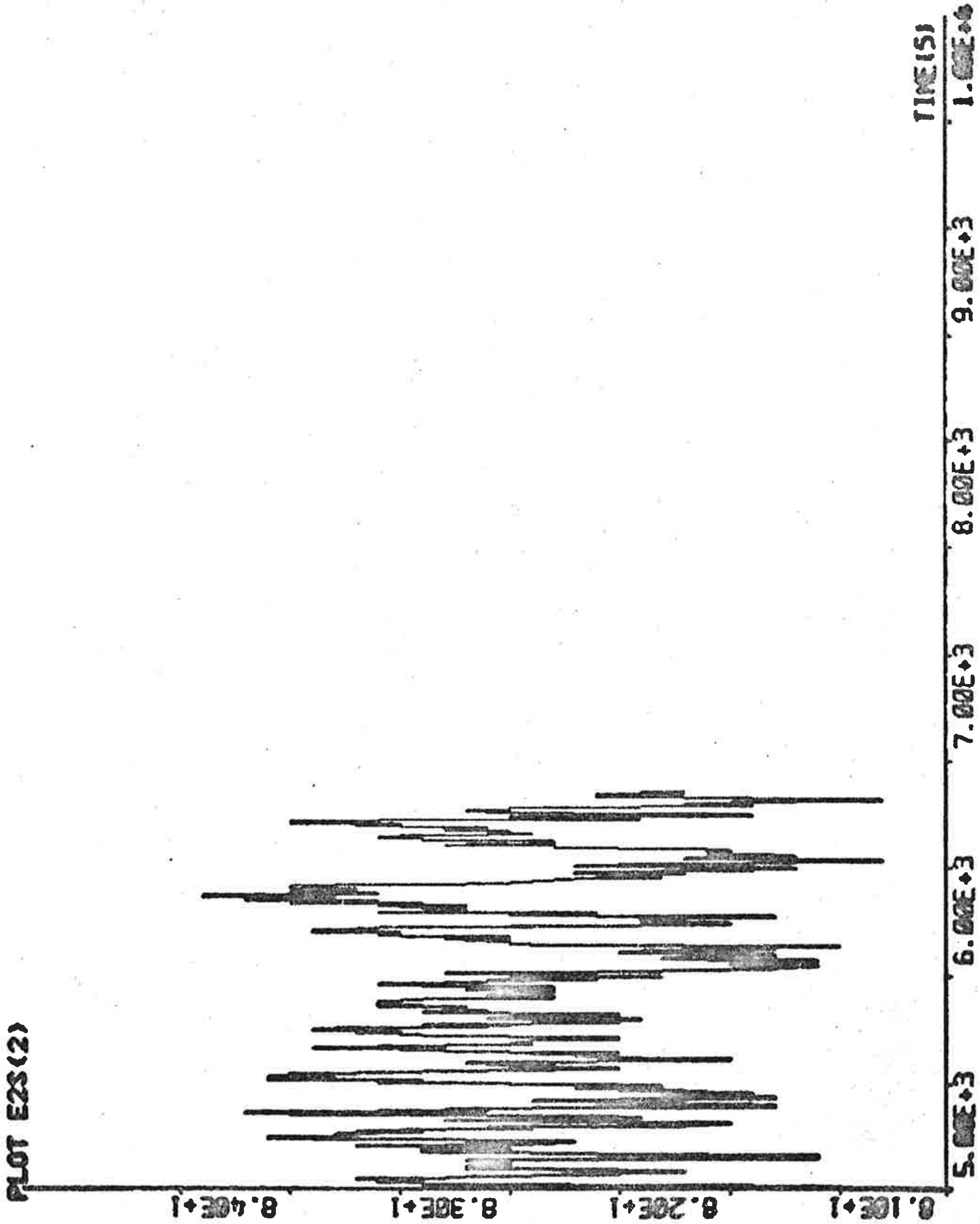

PLOT E2B(6)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.30E+2
1.40E+2
1.50E+2
1.60E+2
ψ degr


PLOT E2B(6)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.30E+2
1.40E+2
1.50E+2
1.60E+2
ψ degr


PLOT E28(7)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.40E+1
1.50E+1
1.60E+1
1.70E+1
u knots


PLOT E28(7)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.40E+1
1.50E+1
1.60E+1
1.70E+1
v knots


PLOT E2S(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
8.10E+1
8.20E+1
8.30E+1
8.40E+1
n rpm


PLOT E2S(2)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
8.10E+1
8.20E+1
8.30E+1
8.40E+1

Experiment E3

Date: 73 - 10 - 15
Time: 22^{00} - 23^{50}
Position: S 09° W 02°

Wind direction: 1 (see appendix A)
Wind speed: 3 Beaufort (4 - 6 m/s, gentle breeze)
Wave height: 1.5 m, rollings

Experiment for system identification.

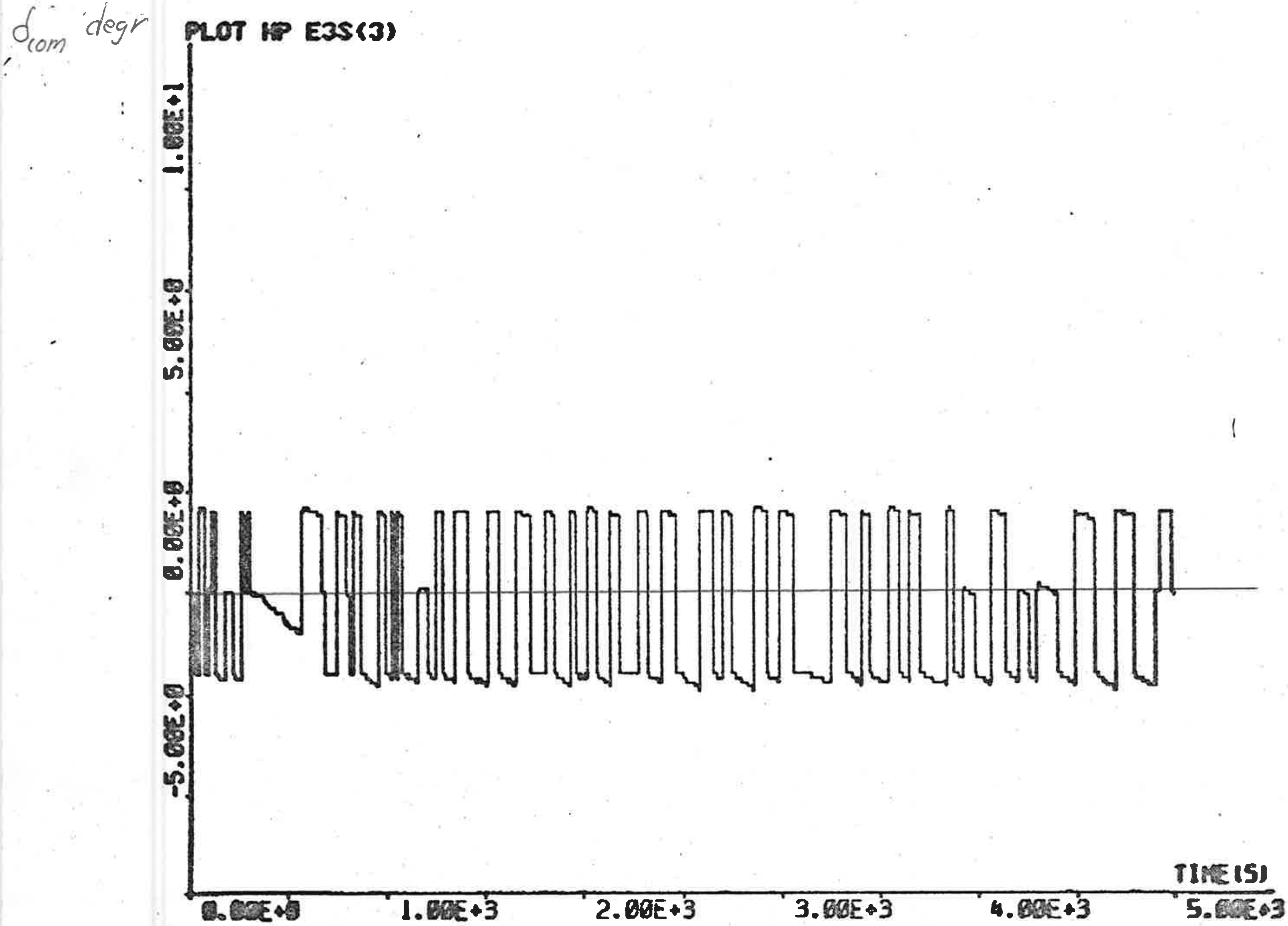
Calibration of the rudder servo:

10 volts = 36.9°
-10 volts = -43.1°

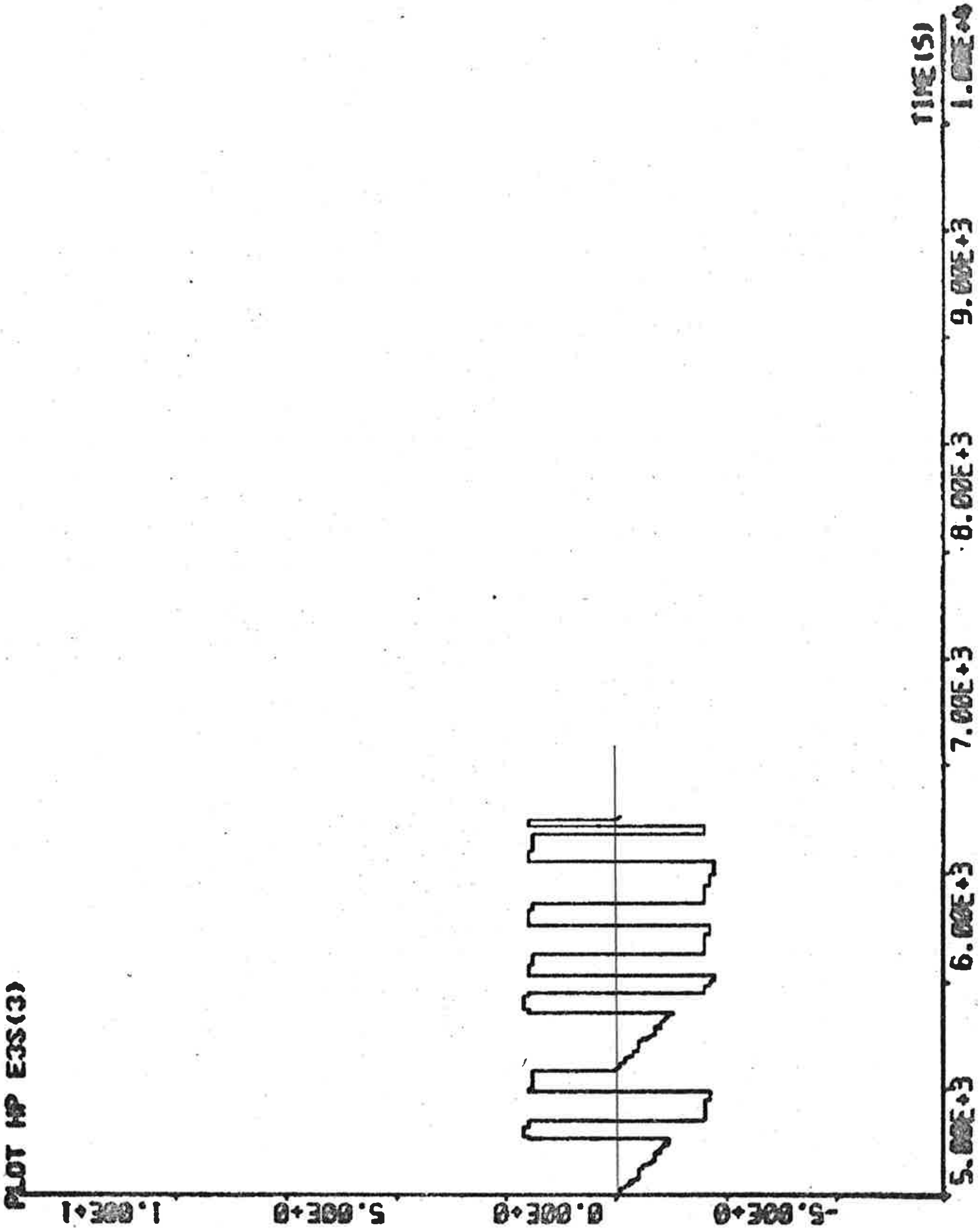
Sampling interval: 5 s
Rudder angles: +2°, 0°, -2°

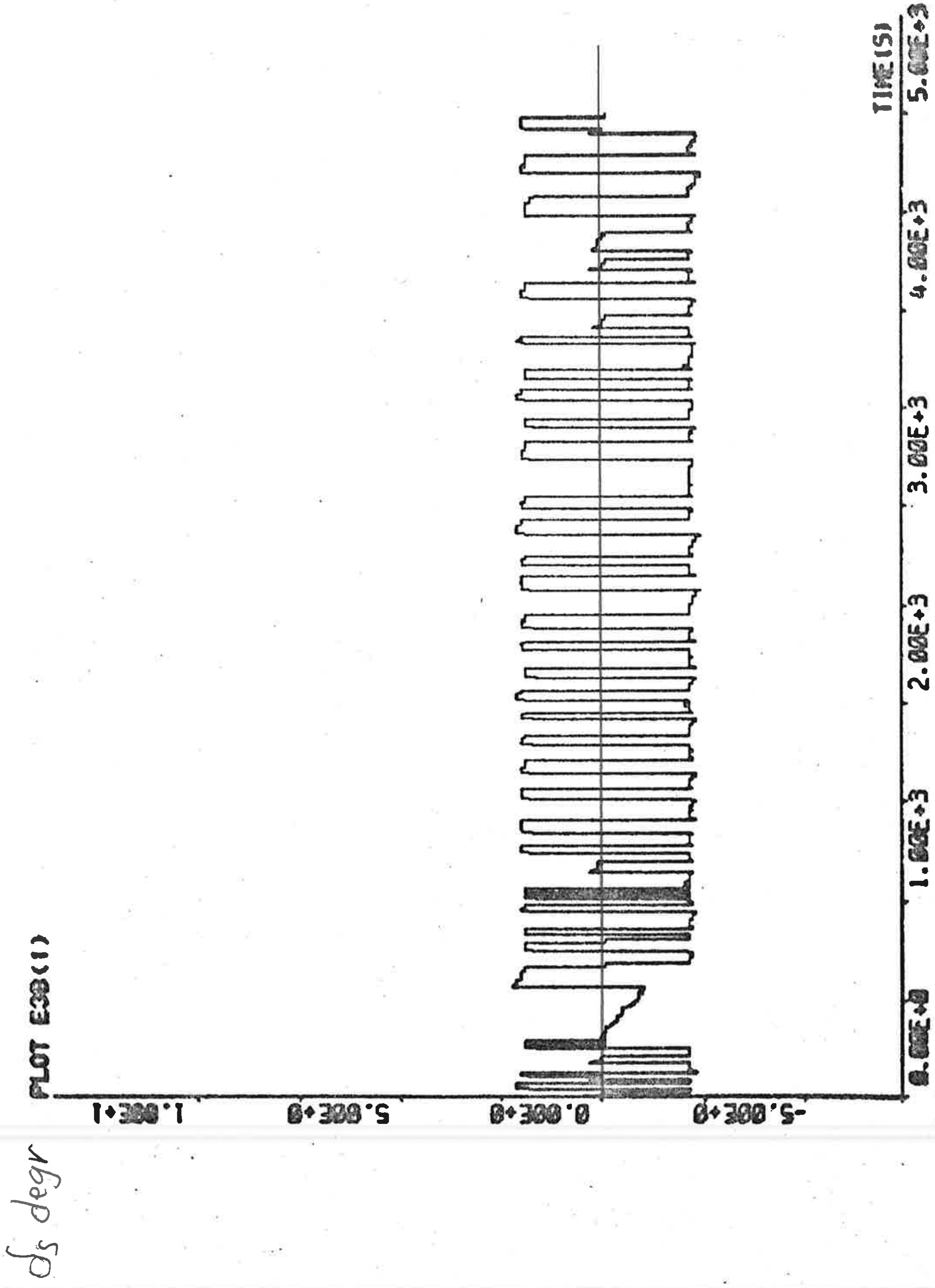
Statistics:

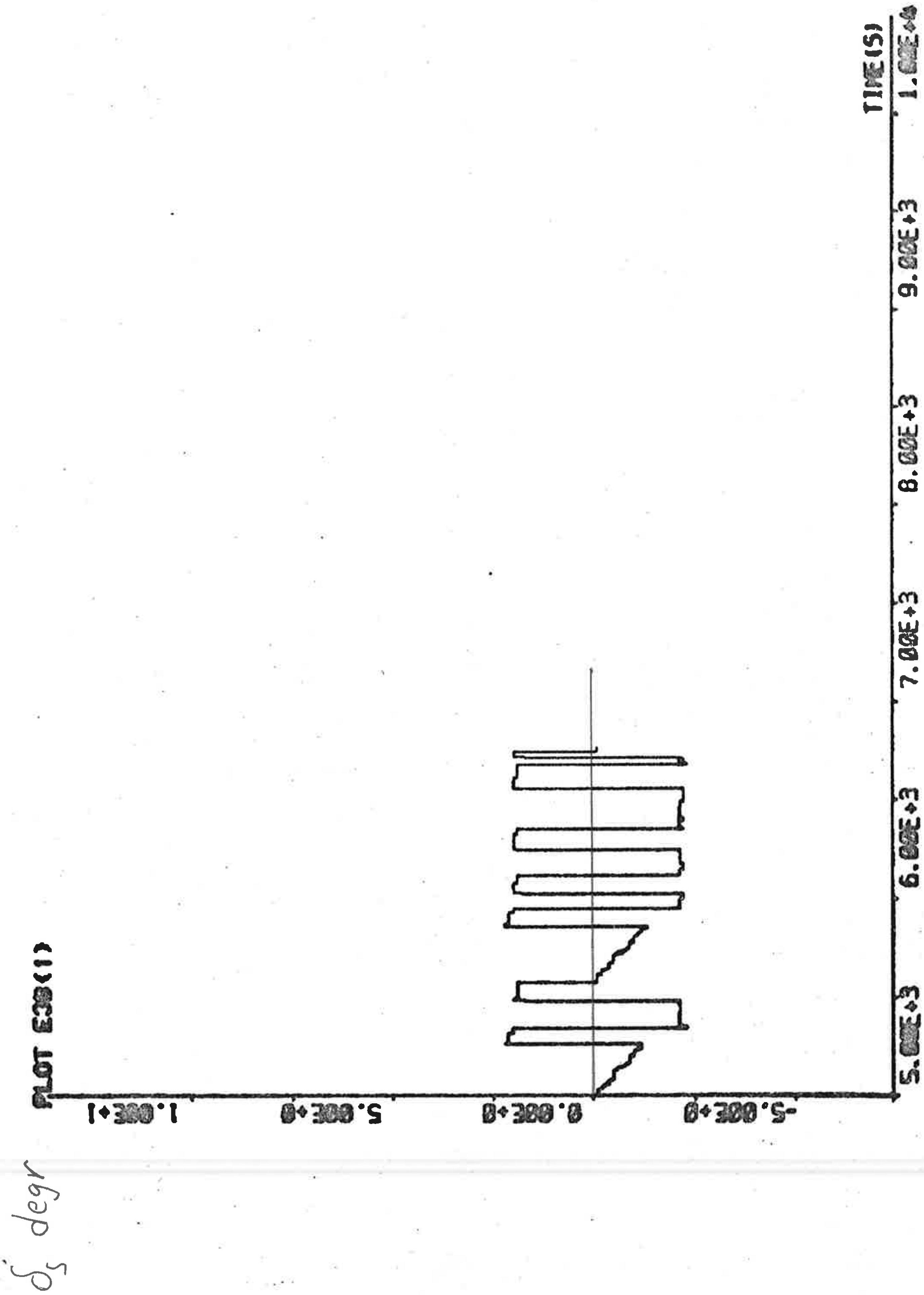
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.38	1.82	-2.4	2.1
δ_s degr	-0.40	1.84	-2.4	2.2
δ degr	-0.58	1.91	-2.8	2.6
v_1 knots	-0.677	0.156	-1.05	-0.25
v_2 knots	0.015	0.300	-0.99	0.77
r degr/s	0.0063	0.0372	-0.084	0.112
Ψ degr	142.136	1.838	137.20	147.57
u knots	16.816	0.119	16.46	17.08
r rpm	82.85	0.60	81.3	84.3

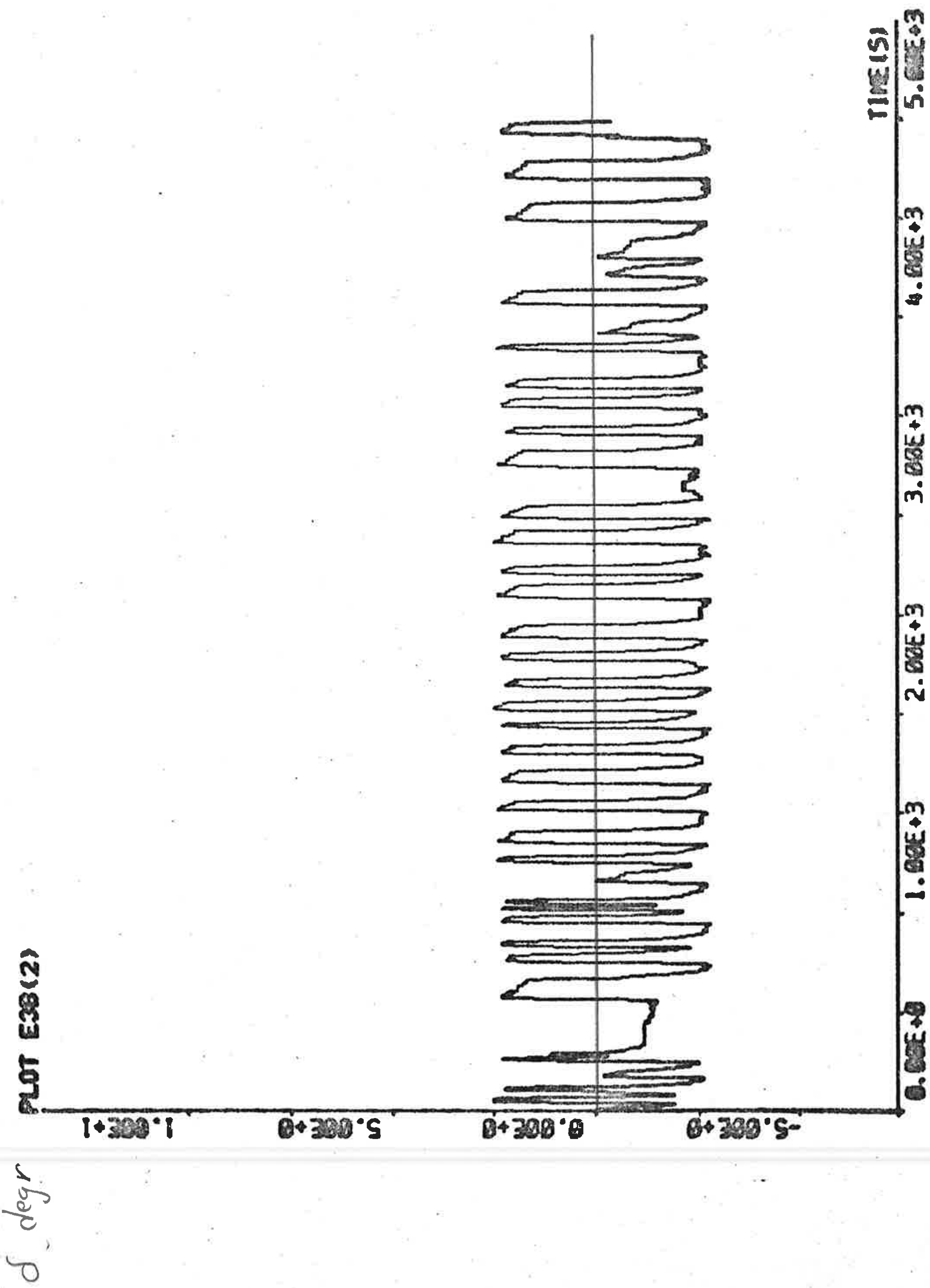


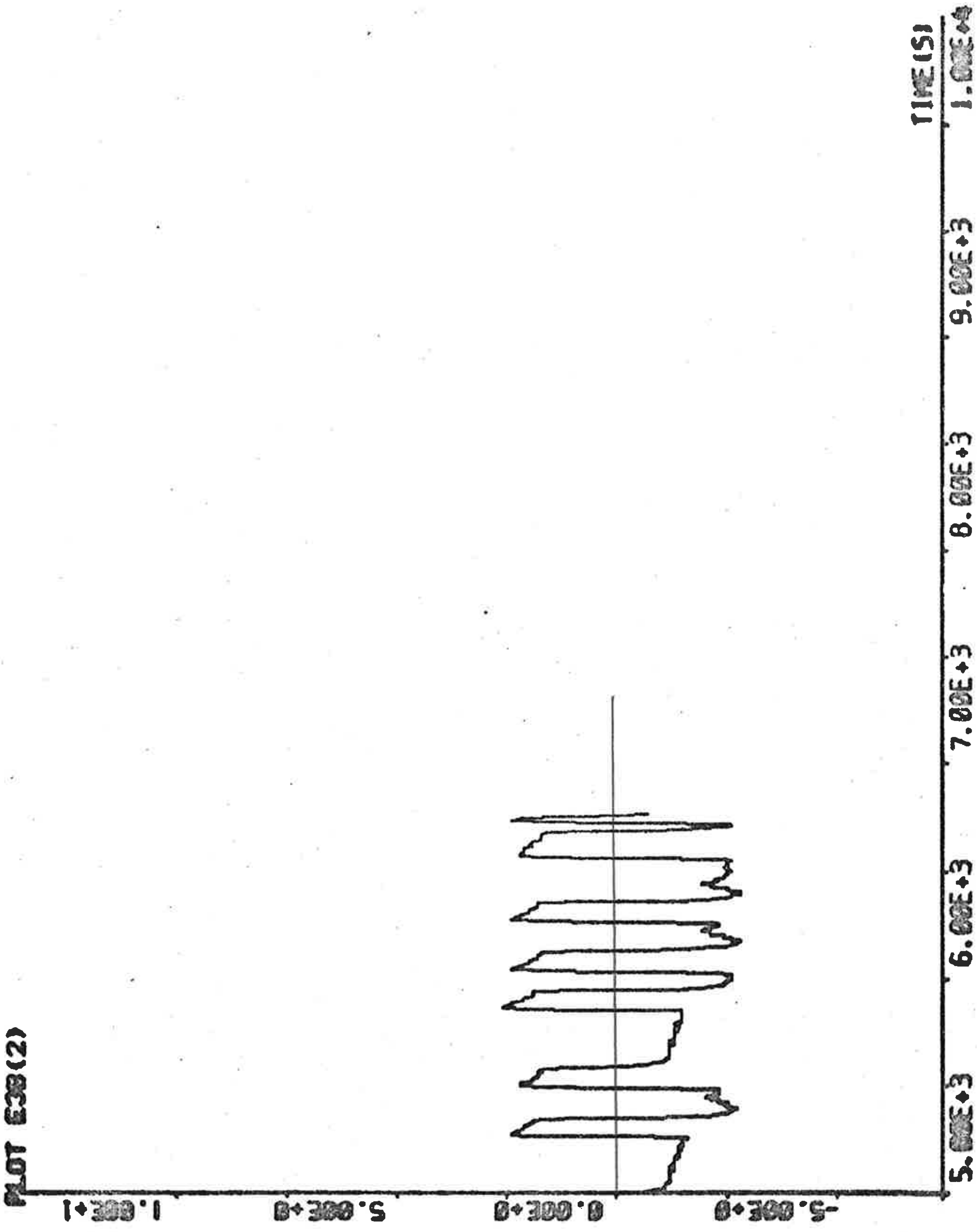
δcom degr
PLOT HP E3S(3)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

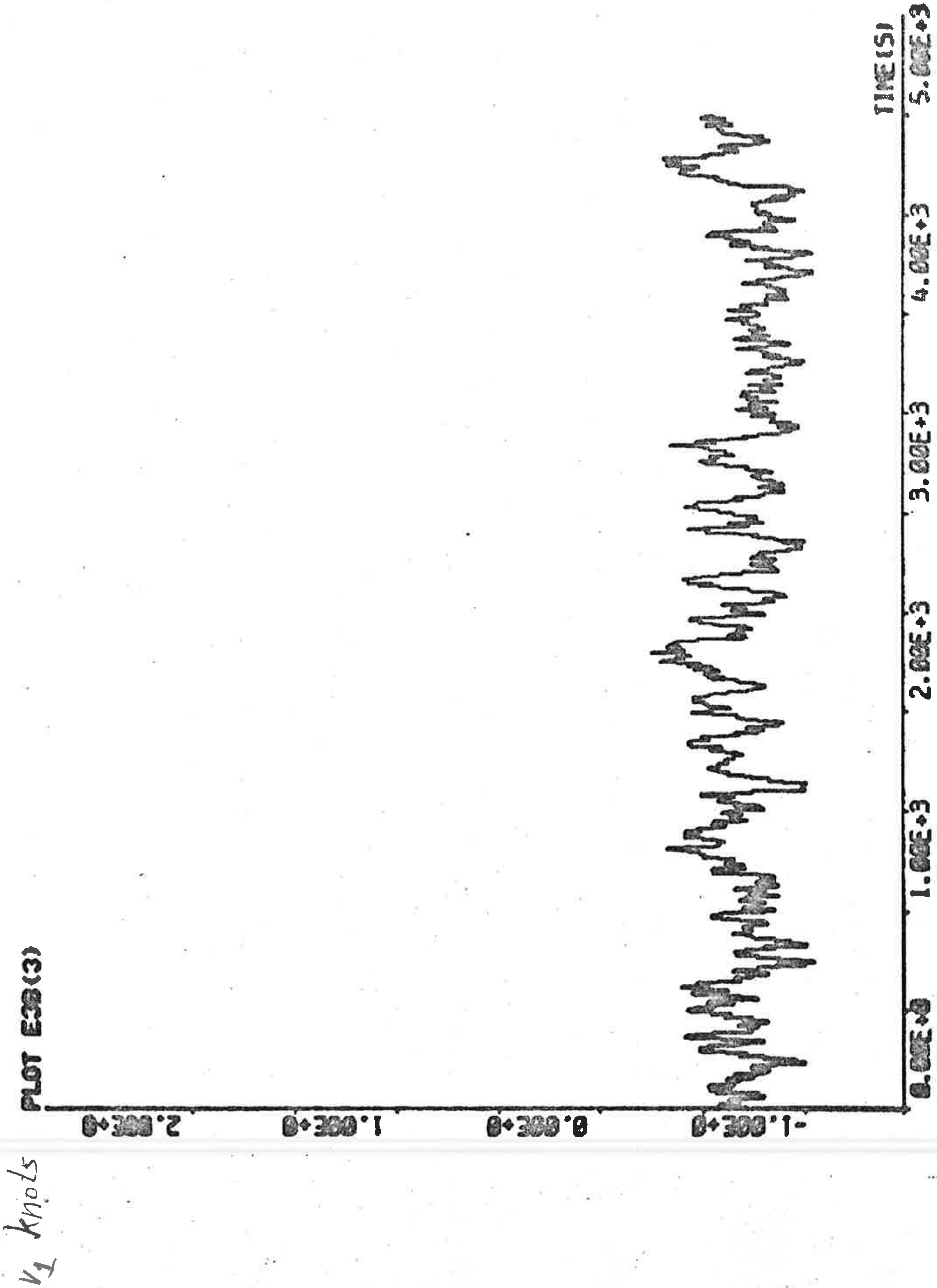

PLOT HP E3S(3)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E+1
5.00E+0
0.00E+0
-5.00E+0

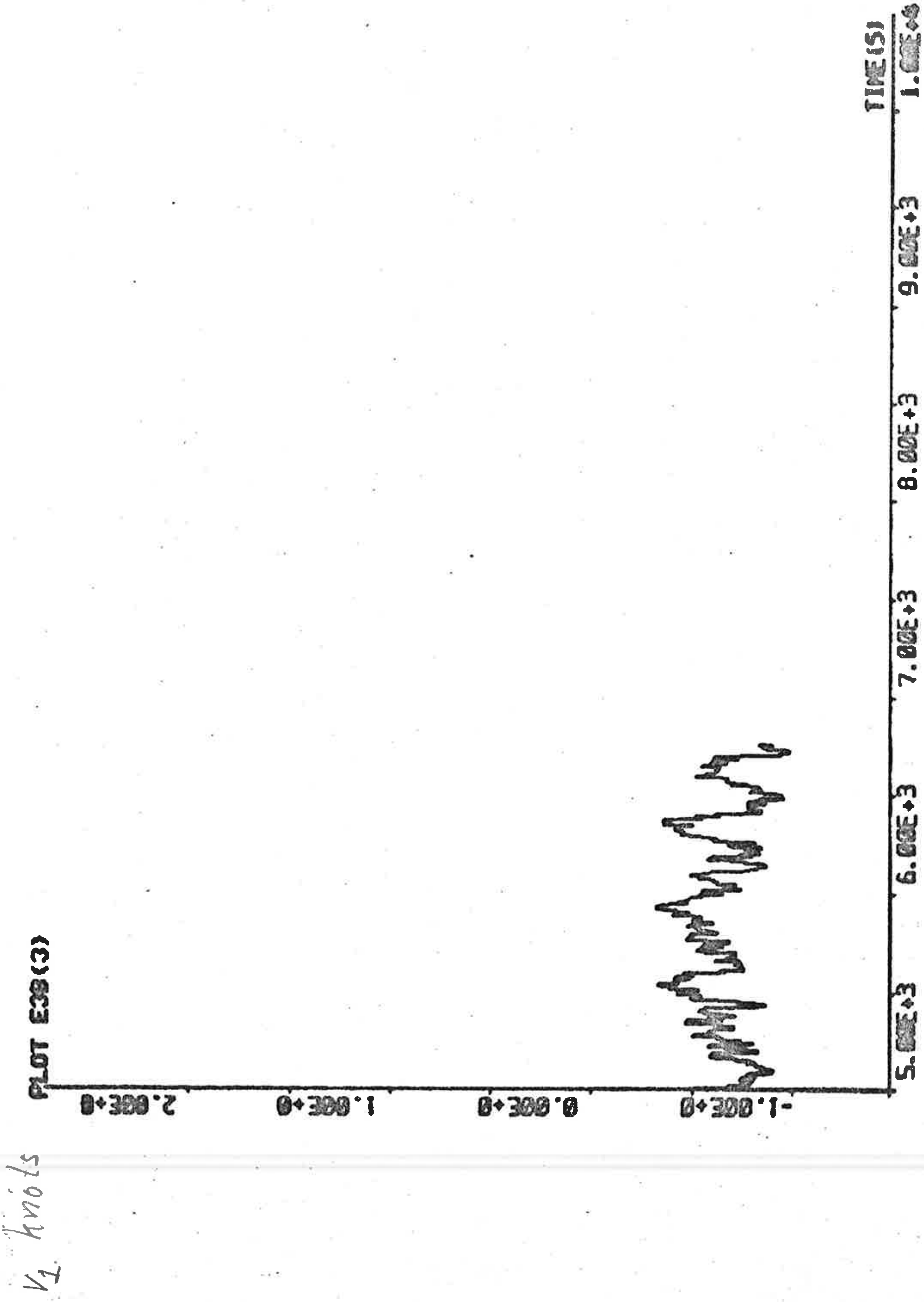

PLOT E3B(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δs degr

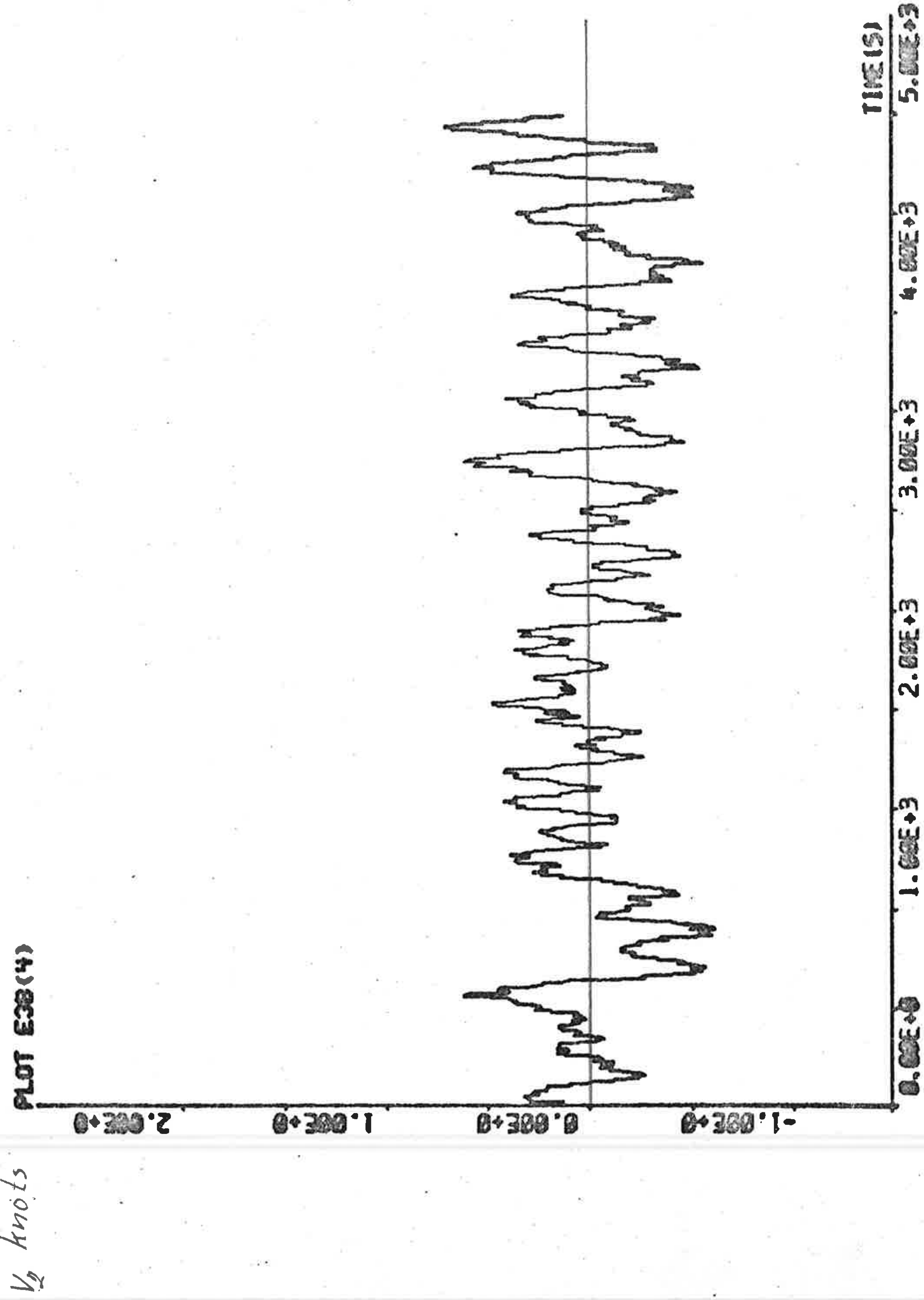

PLOT E3B(1)
TIME(S)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
δs degr

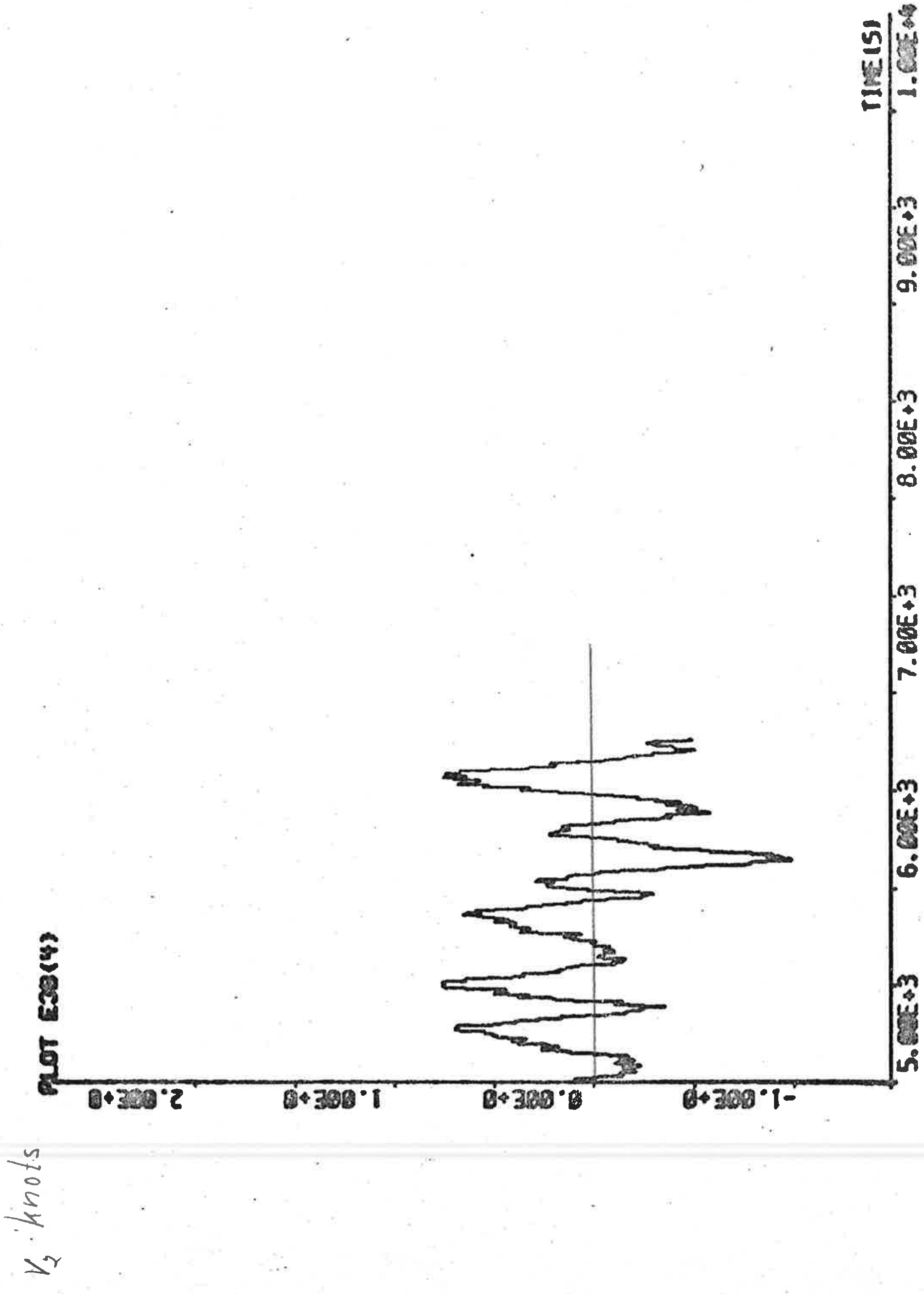

PLOT E38(2)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr

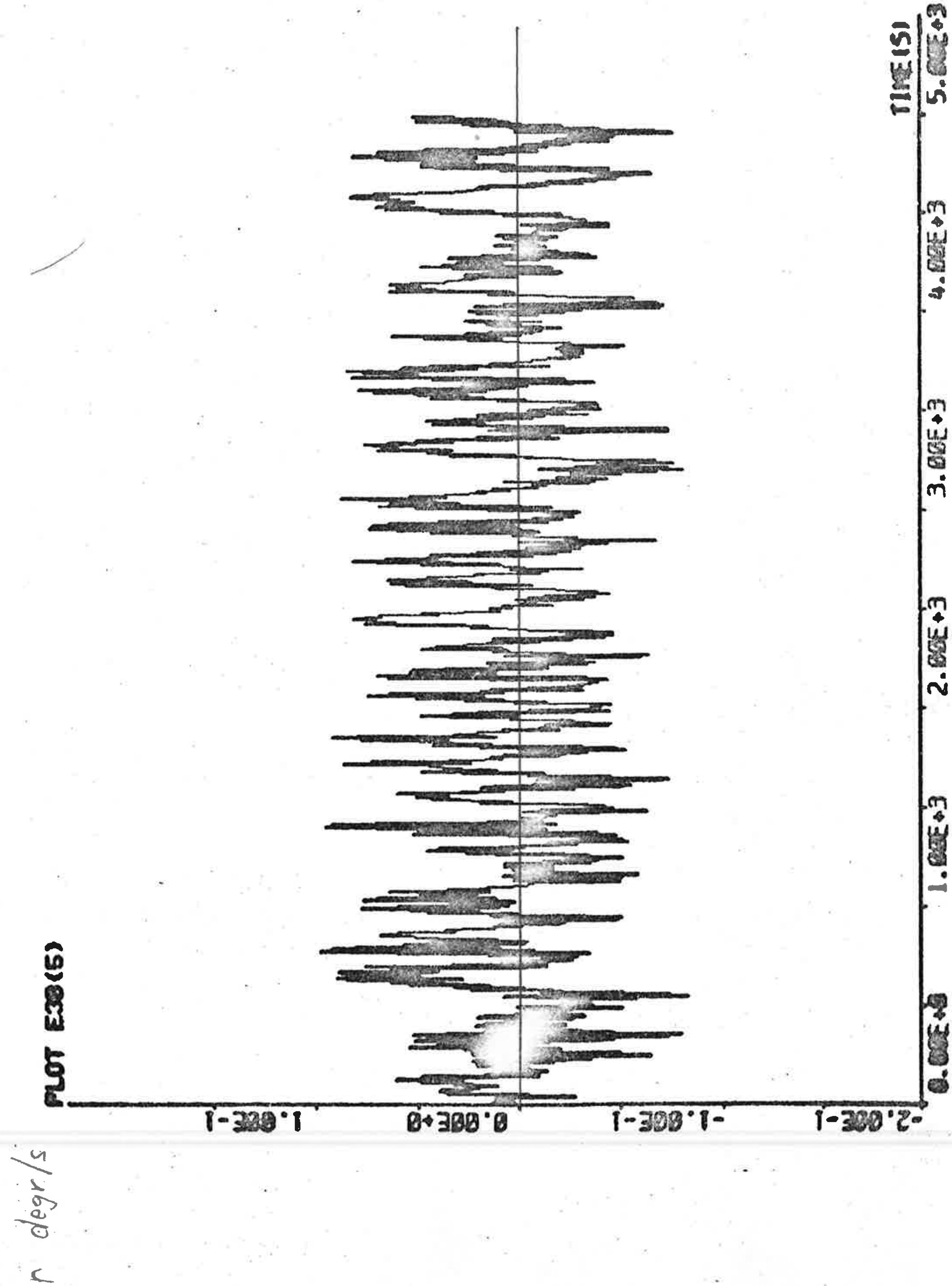

PLOT E3B(2)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E+1
5.00E+0
0.00E+0
-5.00E+0

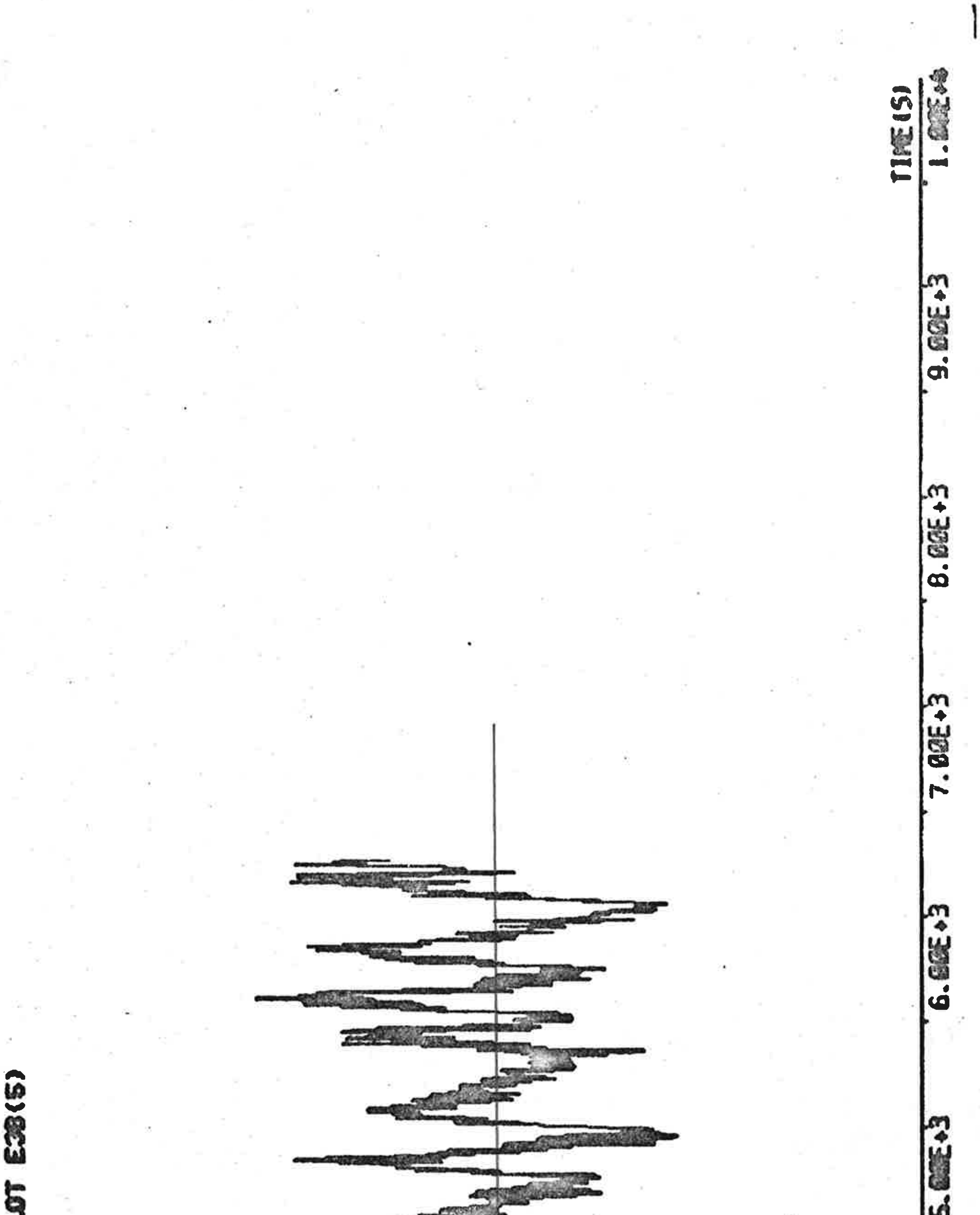

PLOT E3B(3)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
v1 knots


PLOT E38(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME (S)
V1 knots


PLOT E38(4)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_z knots

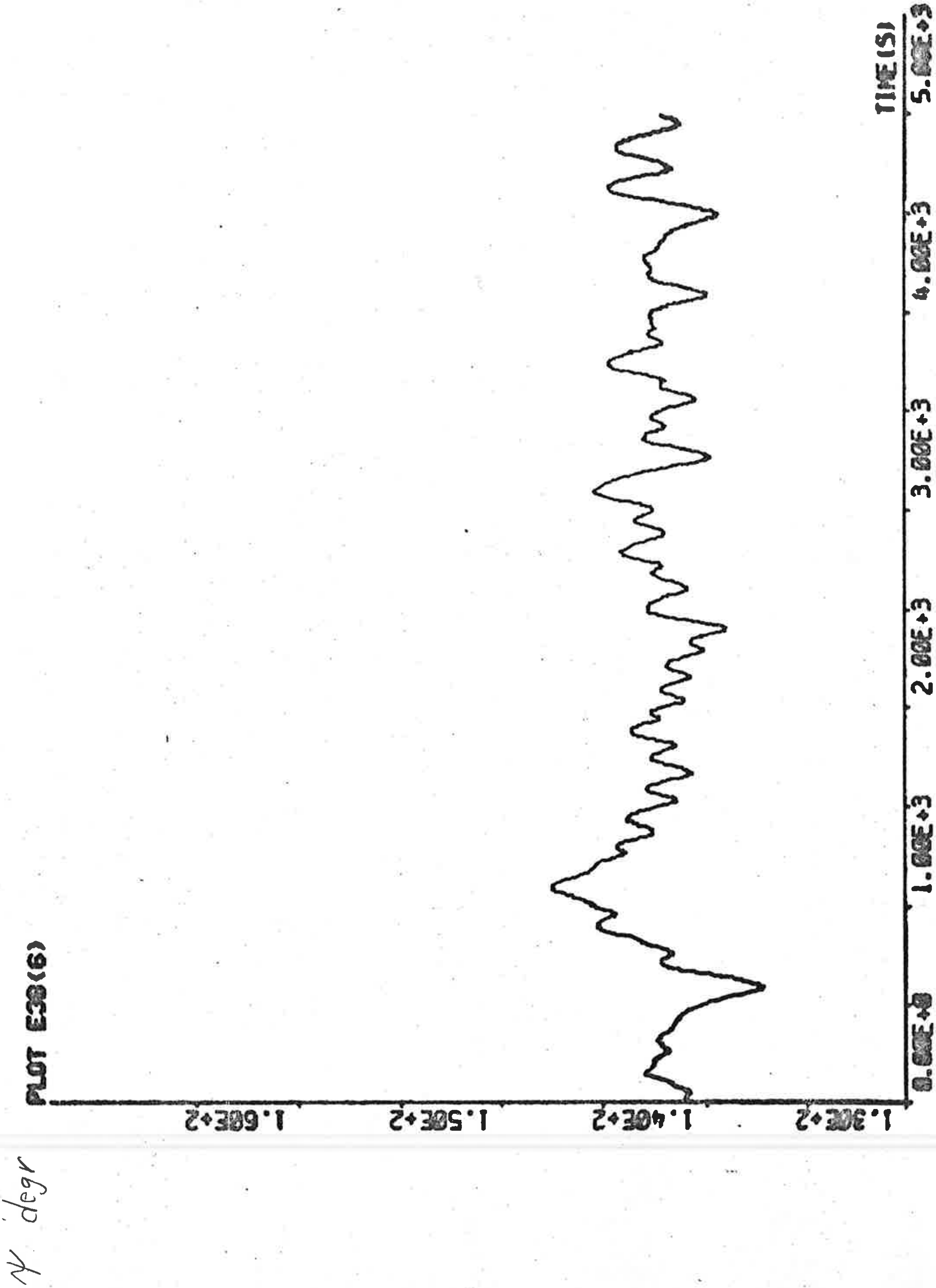

PLOT E38(4)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
V_z knots

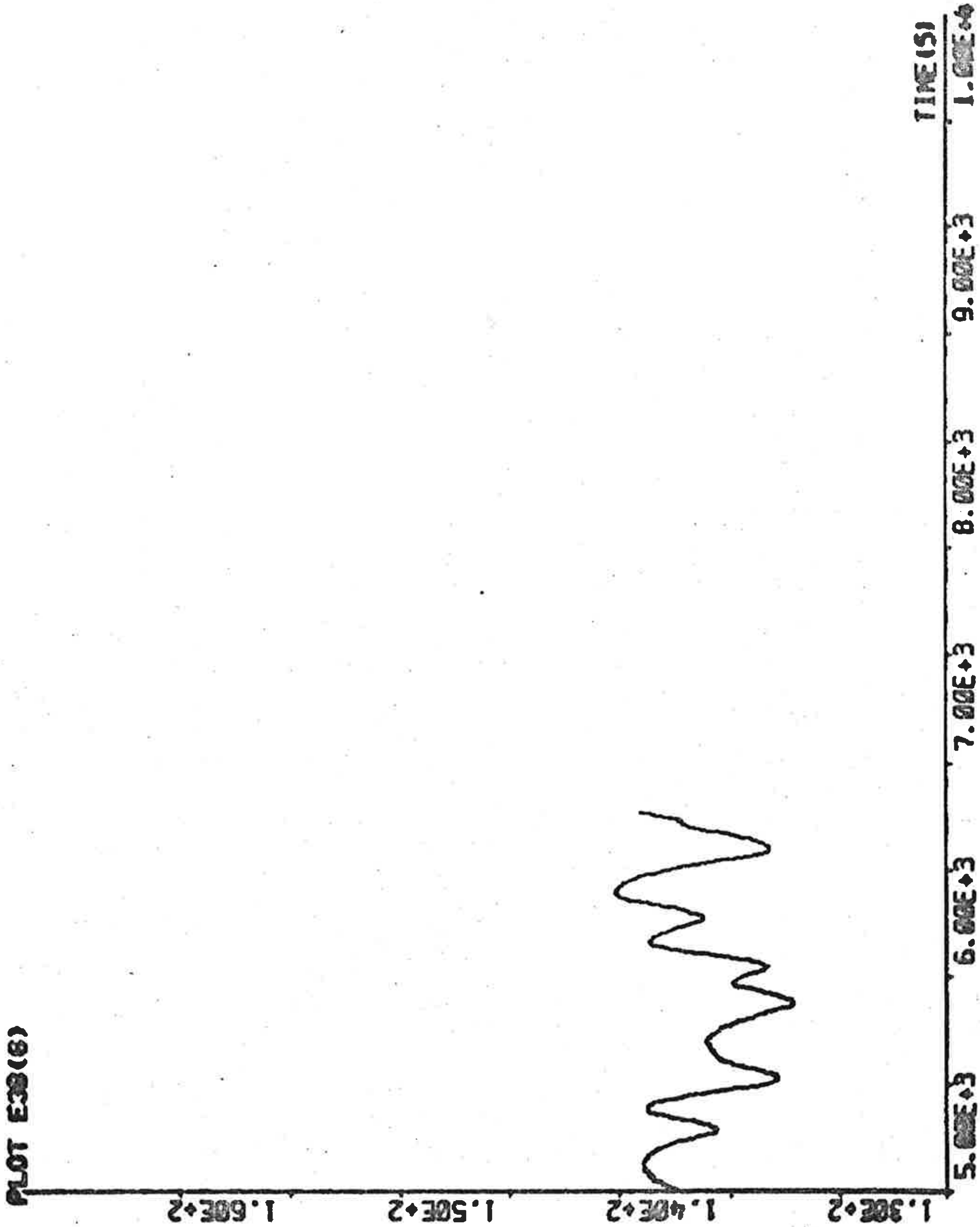

PLOT E30(5)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
r degr/s

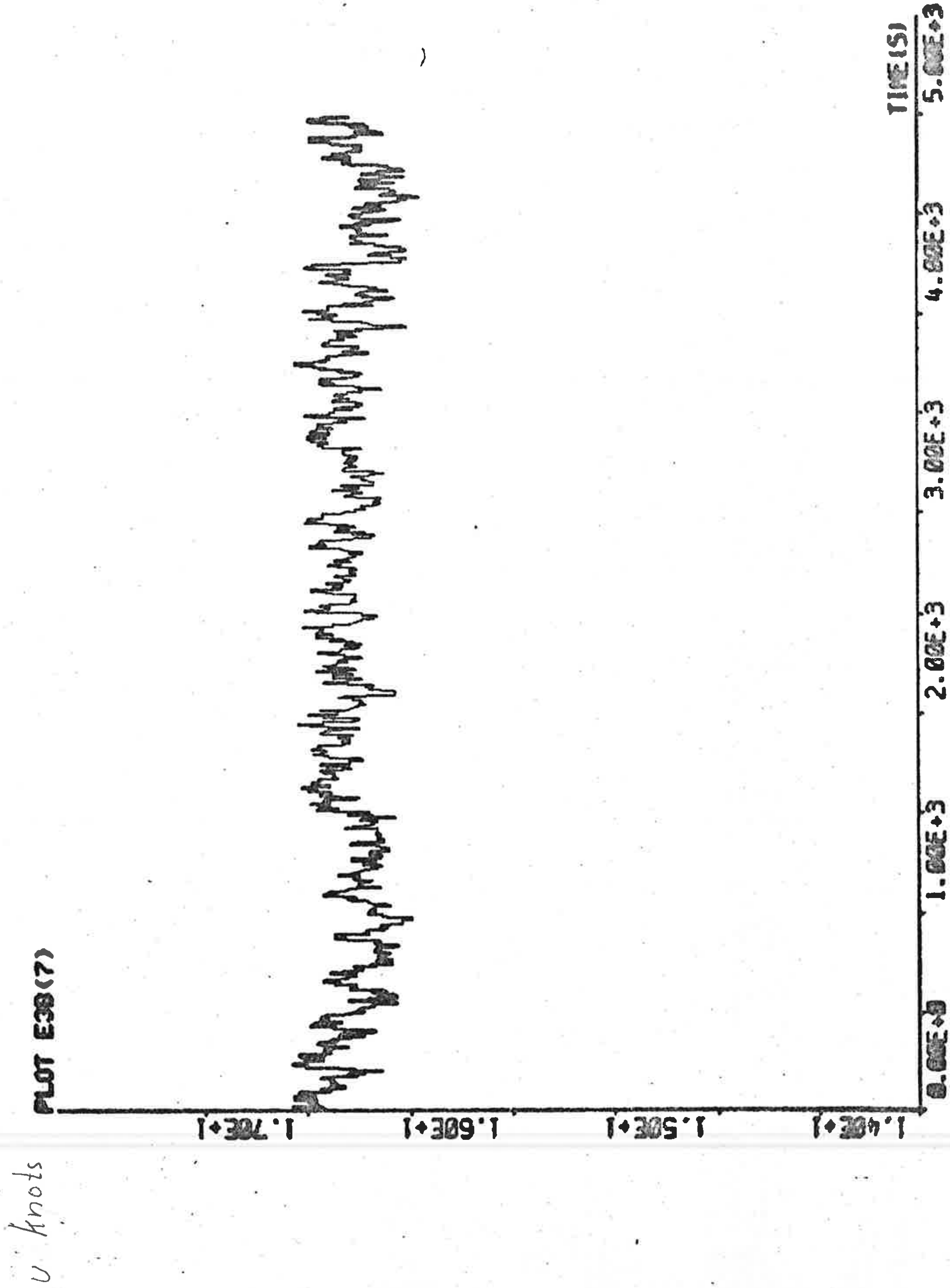


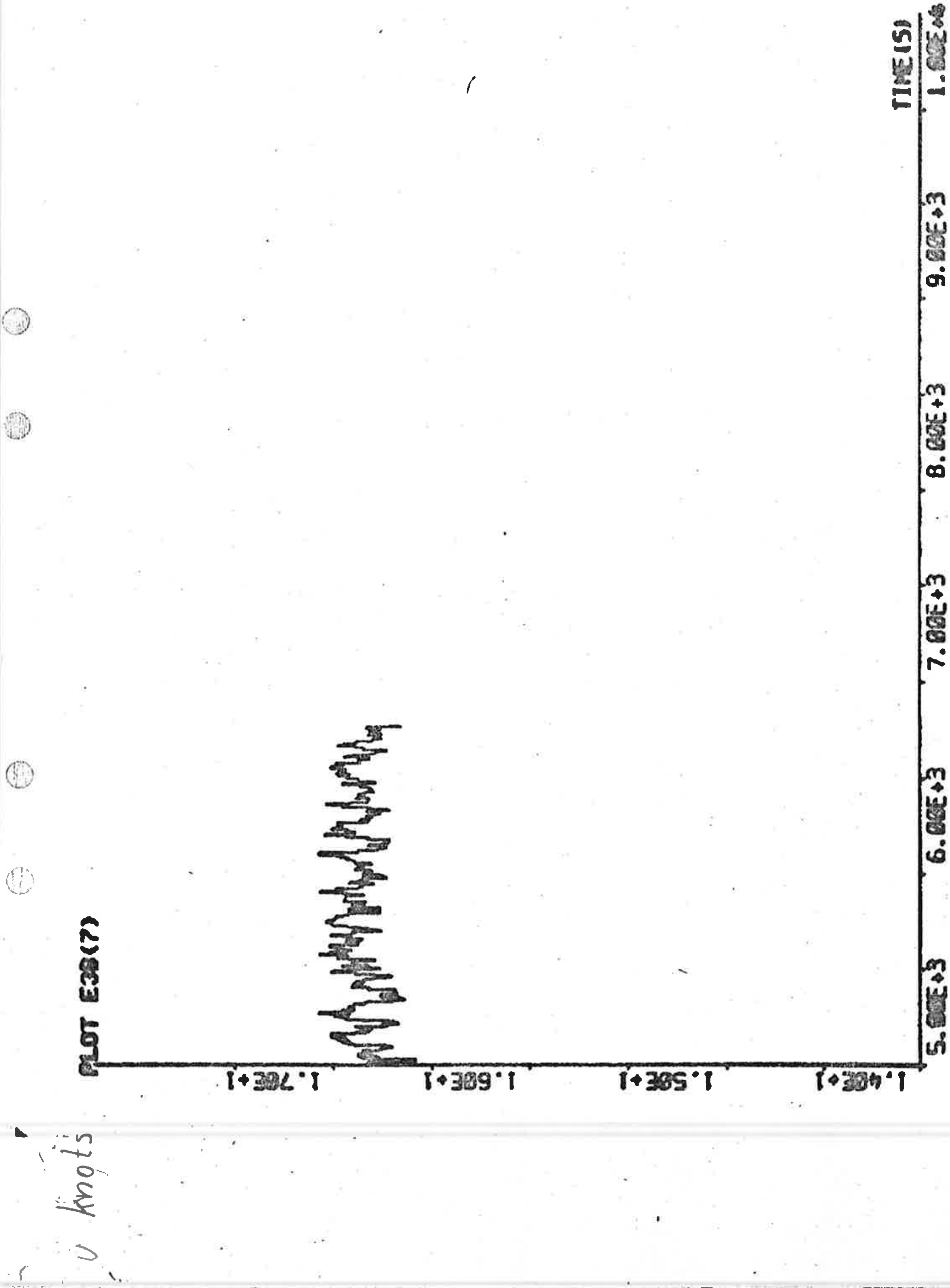
PLOT E3B(5)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1

r degr/s

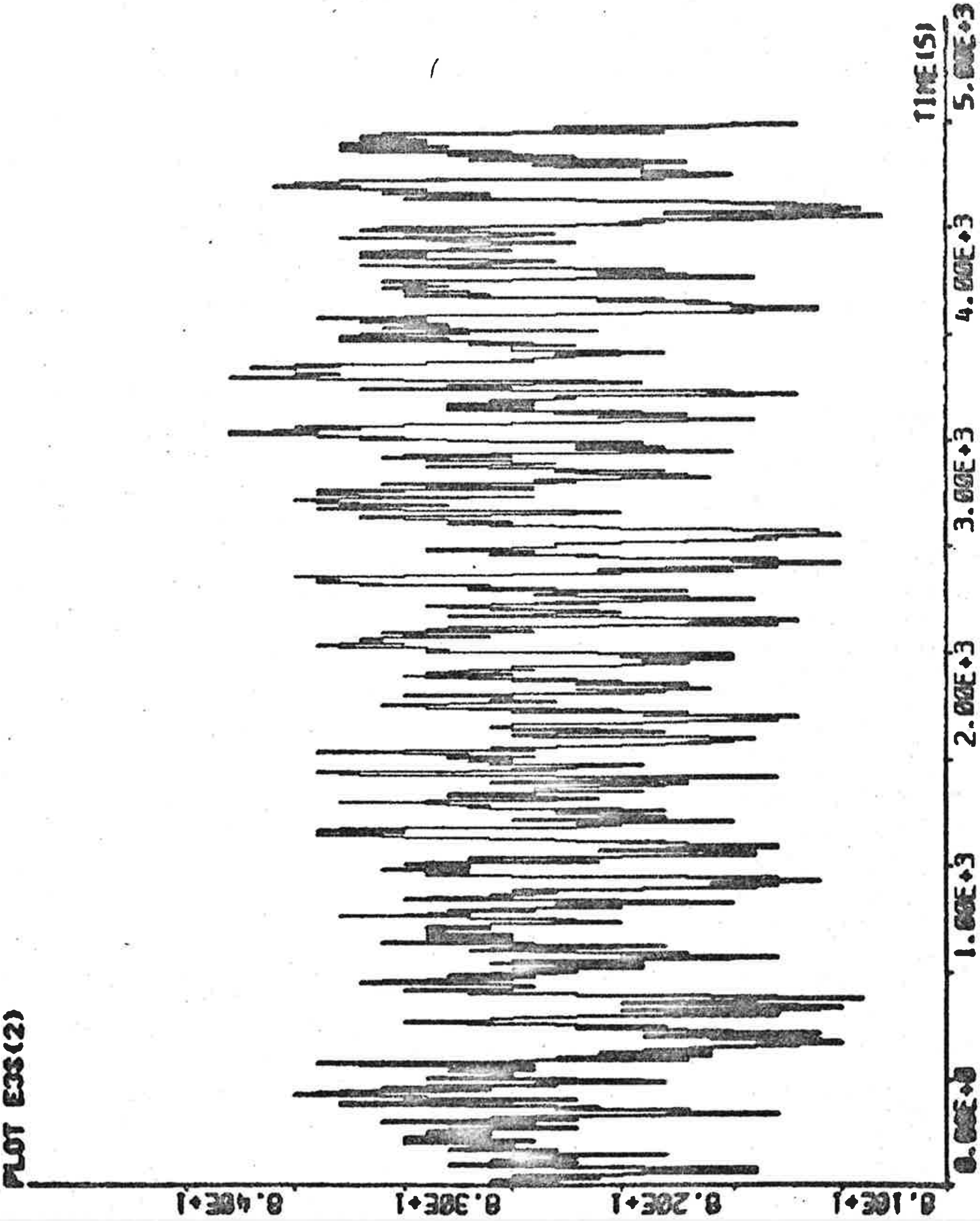

PLOT E38(6)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.30E+2
1.40E+2
1.50E+2
1.60E+2
ψ degr

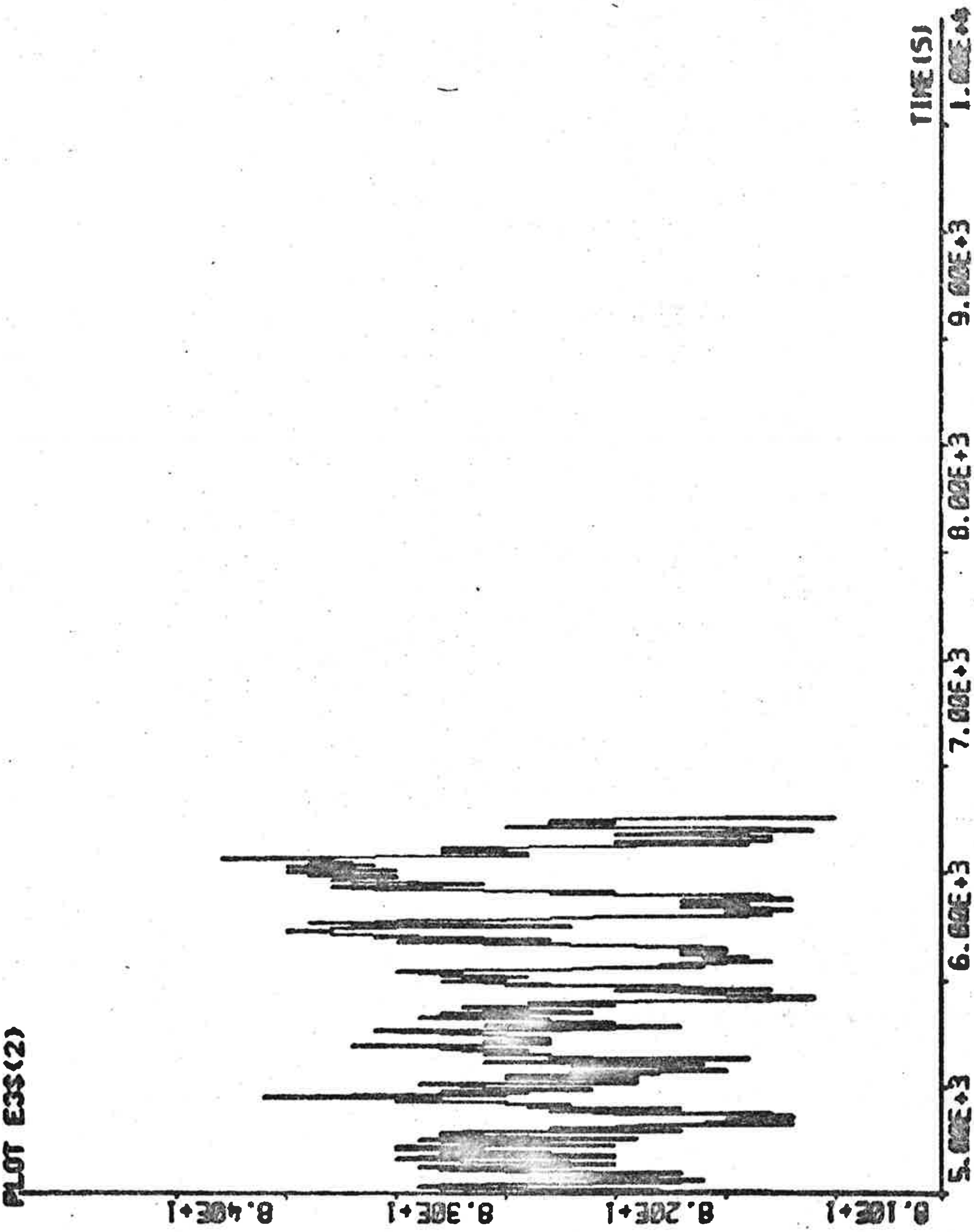

TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.30E+2
1.40E+2
1.50E+2
1.60E+2


PLOT E38(7)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.70E+1
1.60E+1
1.50E+1
1.40E+1
u knots



PLOT E38(7)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.40E+1
1.50E+1
1.60E+1
1.70E+1
v knots


TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
0.10E+1
0.20E+1
0.30E+1
0.40E+1


PLOT E33(2)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
8.10E+1
8.20E+1
8.30E+1
8.40E+1