The Sea Scout Experiments, October 1973

Källström, Claes

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

CLAES KÄLLSTRÖM

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

THE SEA SCOUT EXPERIMENTS, OCTOBER 1973

Claes Källström

TABLE OF CONTENTS

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:

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

- o 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.
- o 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°.
- o 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.

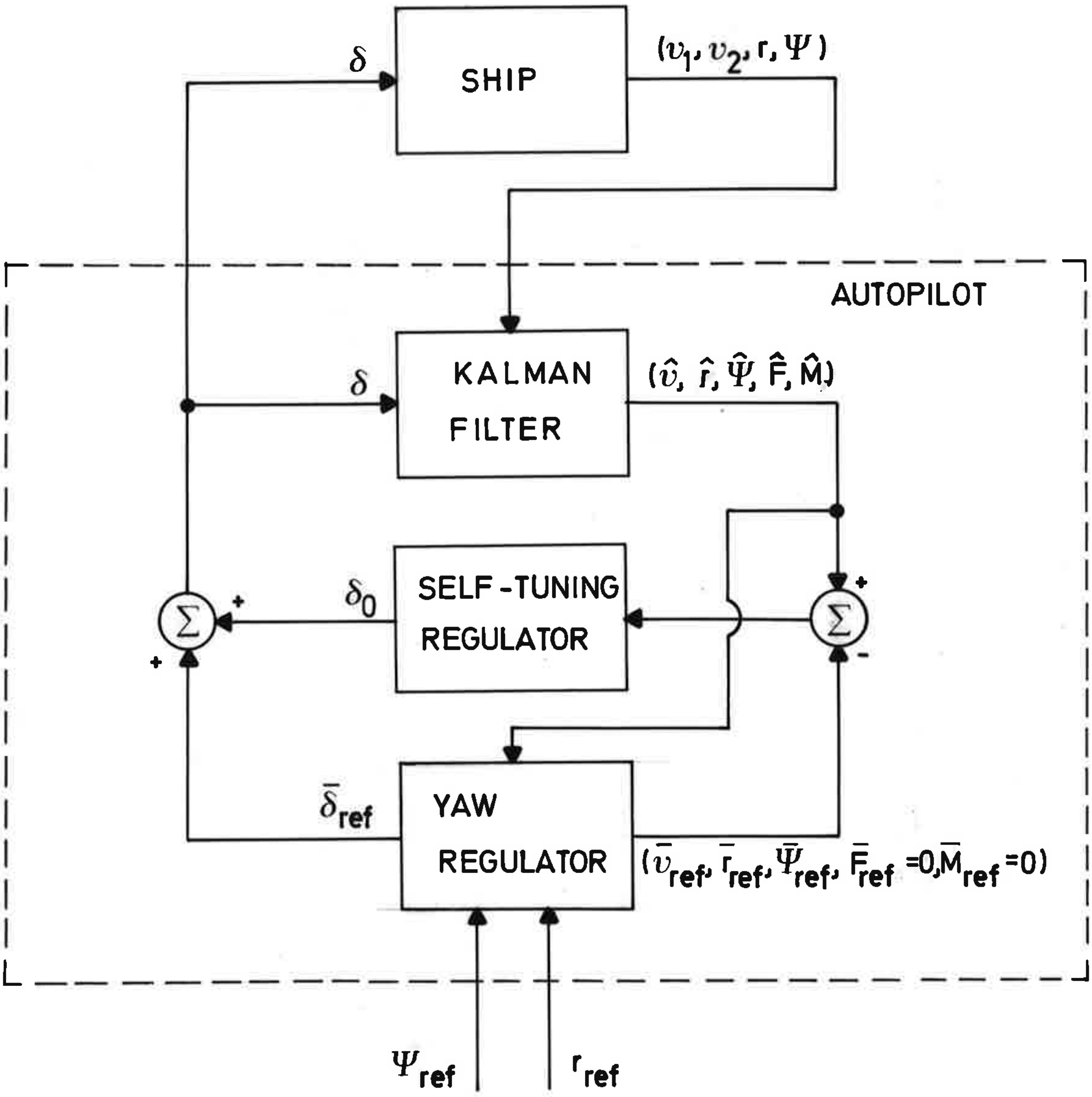


Fig. 3.1. Schematic diagram of the autopilot. r_{ref} is the reference value of the yaw angular velocity during the yaw. For course keeping only, $\bar{\delta}_{ref} = \bar{v}_{ref} = \bar{r}_{ref} = 0$ and $\bar{\Psi}_{ref} = \Psi_{ref}$.

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

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \\ \dot{F} \\ \dot{M} \end{bmatrix} = \begin{bmatrix} \frac{V}{\ell} a_{11} & Vq_1 a_{12} & 0 & 1 & 0 \\ \frac{V}{\ell^2 q_1} a_{21} & \frac{V}{\ell} a_{22} & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \\ F \\ M \end{bmatrix} + \begin{bmatrix} \frac{V^2}{\ell} q_1 b_{11} \\ \left(\frac{V}{\ell}\right)^2 b_{21} \\ 0 \\ 0 \\ 0 \end{bmatrix} \delta$$

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

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))

$$\begin{aligned} \hat{x}(t/t) &= \hat{x}(t/t-1) + K(y(t) - \Theta\hat{x}(t/t-1)) \\ \hat{x}(t/t-1) &= \Phi\hat{x}(t-1/t-1) + \Gamma\delta(t-1) \end{aligned} \qquad (3.3)$$

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

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

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

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

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

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

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

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.

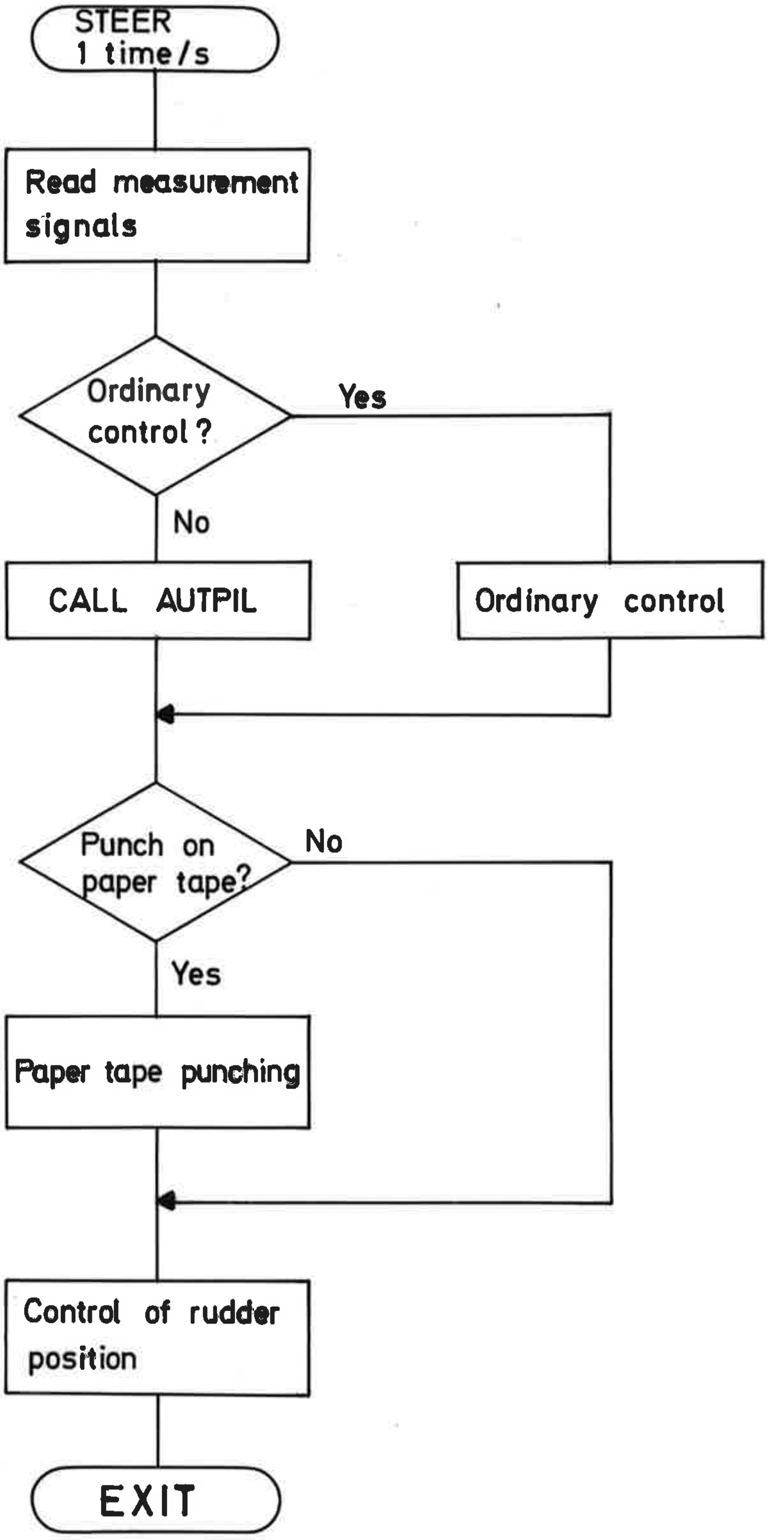


Fig. 4.1. Flow chart of the real time program STEER. The subroutine AUTPIL is the administration routine for the experiments.

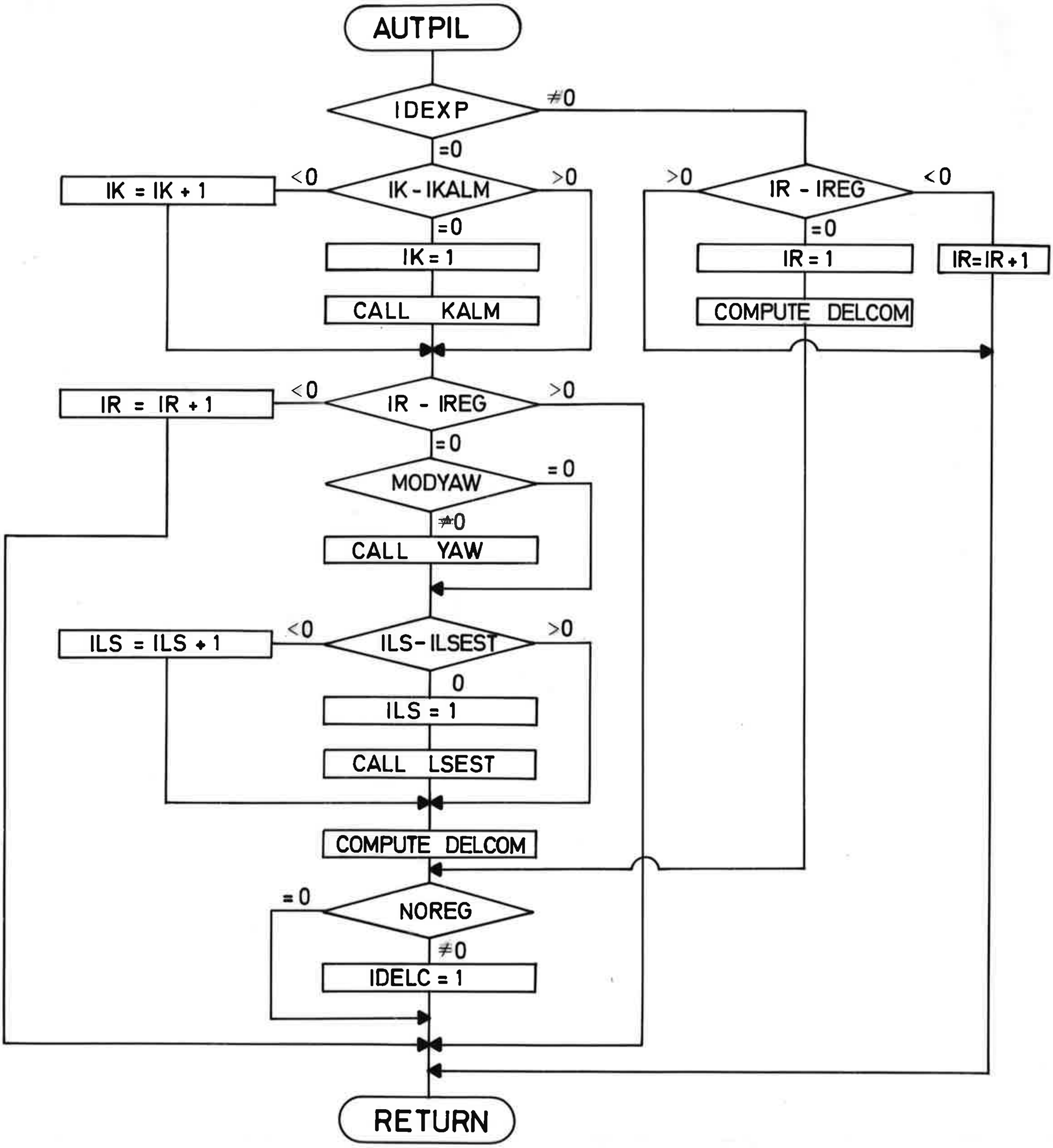


Fig. 4.2. Flow chart of subroutine AUTPIL.

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.

REFERENCES

Åström, K. J. (1970), "Introduction to Stochastic Control Theory", Academic Press, New York.

Åström, K. J. and Källström, C. (1973), "Application of System Identification Techniques to the Determination of Ship Dynamics", Proc. of the 3rd IFAC Symposium on Identification and System Parameter Estimation, The Hague/Delft, the Netherlands.

Wittenmark, B. (1973), "A Self-tuning Regulator", Report 7311, Division of Automatic Control, Lund Institute of Technology, Lund, Sweden.

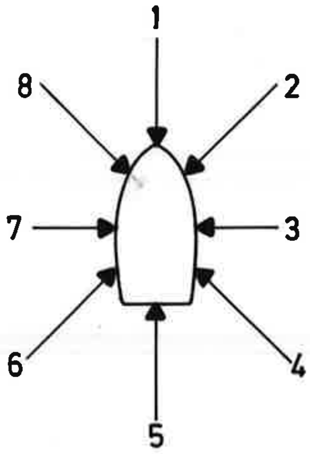
APPENDIX A

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), $\ell = 329.18$ m
ℓ_1	distance from the centre of mass to the forward doppler log transmitter (m), $\ell_1 = 148.7$ m
ℓ_2	distance from the centre of mass to the aft doppler log transmitter (m), $\ell_2 = 131.1$ 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: ±3°
$\Psi_{ref} = 142^{\circ}$

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:

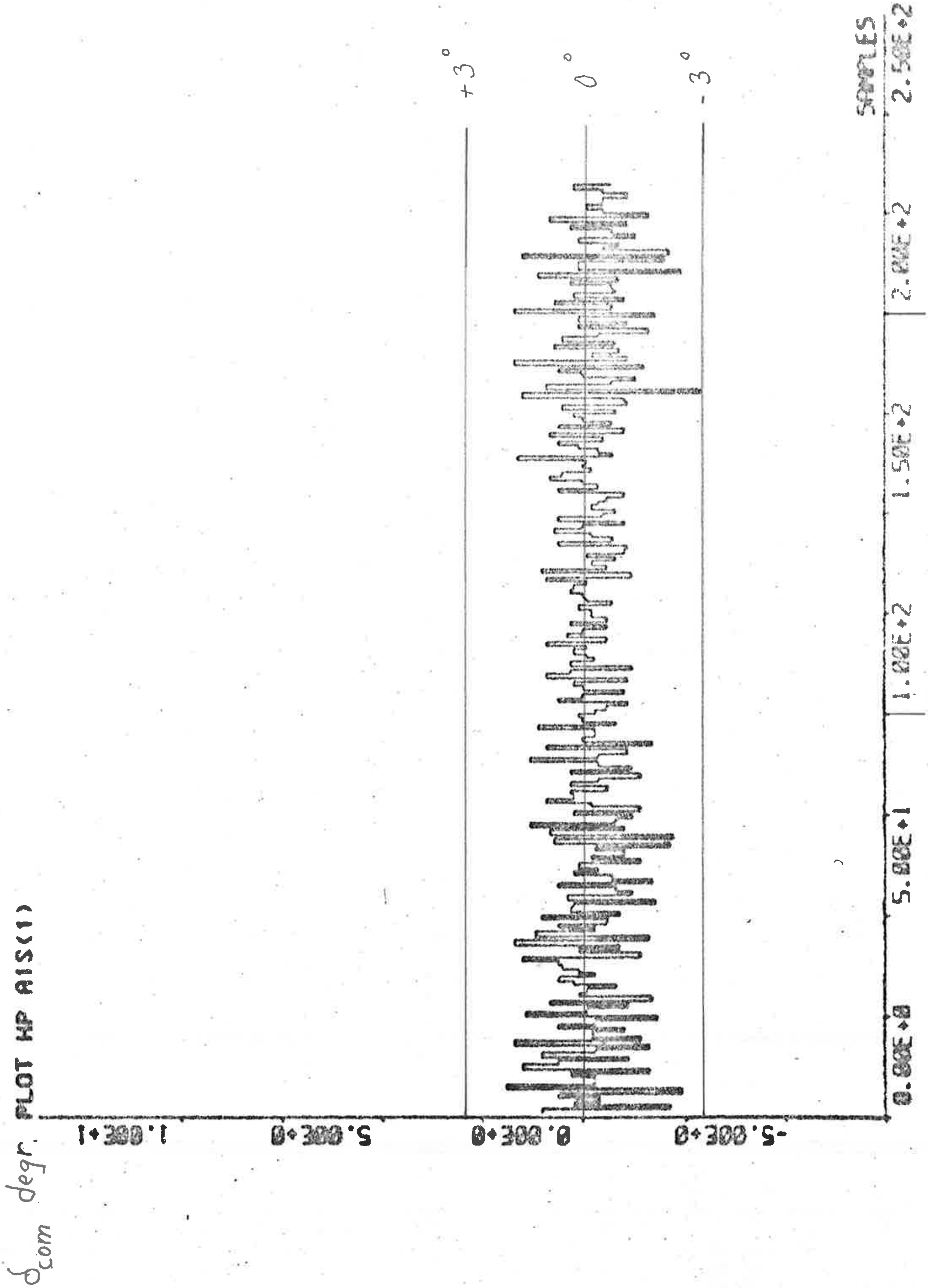
$$\begin{bmatrix} b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1459 \\ -0.7773 \\ 41.0180 \end{bmatrix} \qquad P = \begin{bmatrix} 0.01705 & & \\ -0.08942 & 2.249 & \\ -0.2811 & 0.6094 & 51.10 \end{bmatrix}$$

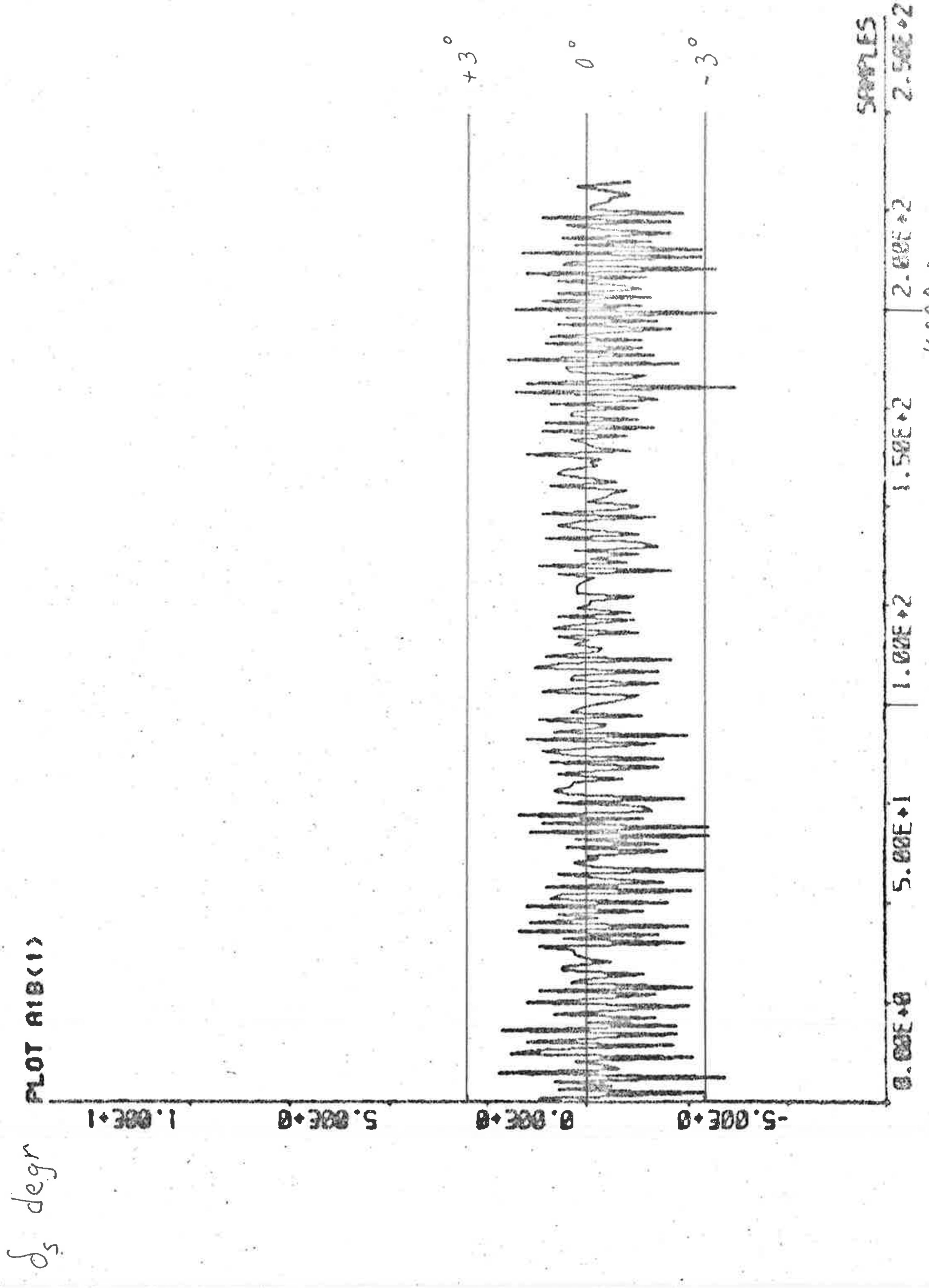
Regulator:

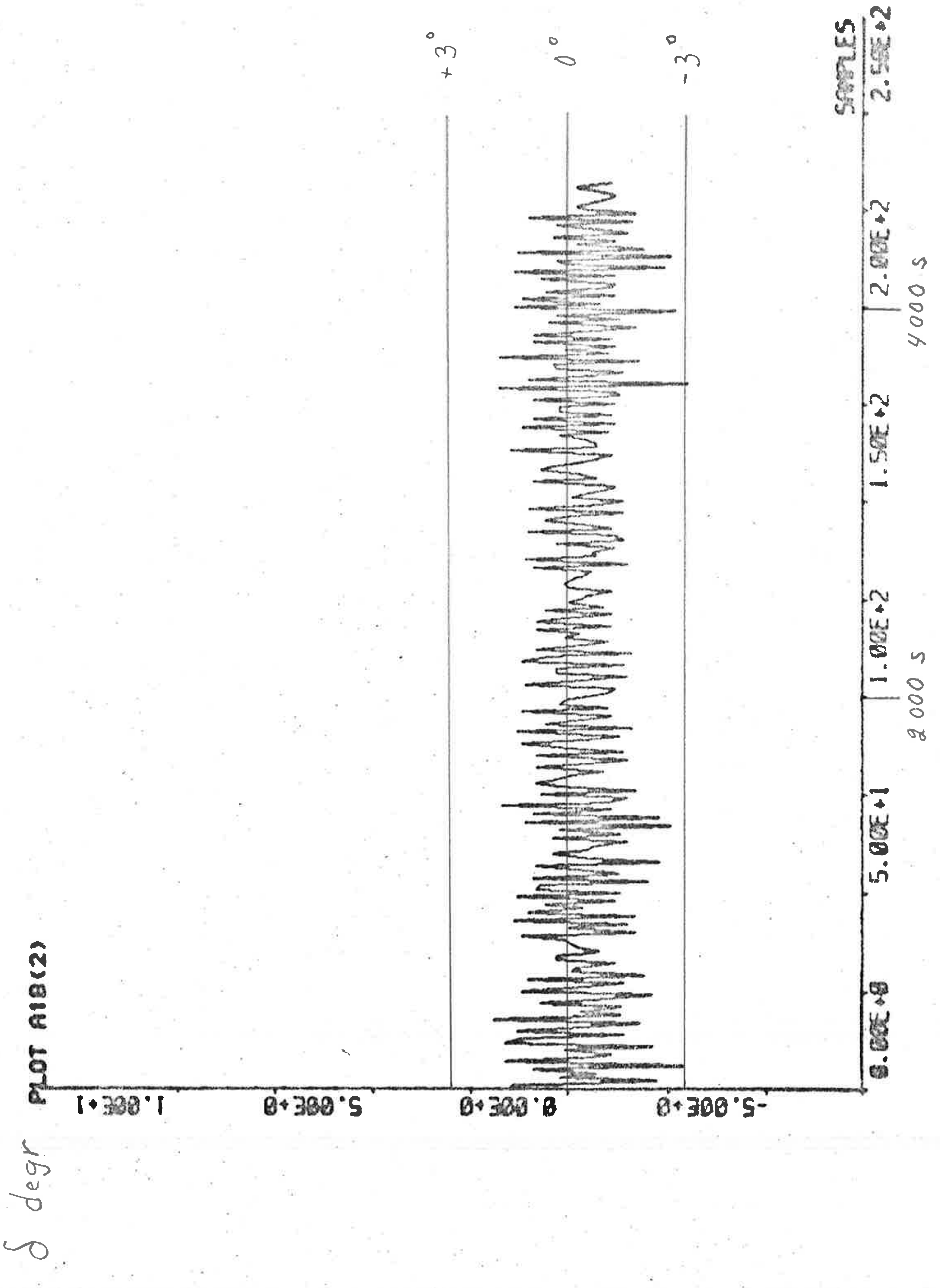
$$\delta(t) = -1.6667(\Psi(t) - \Psi_{ref}) - 0.2432\ \delta(t-1) + 1.2955\ v(t) - 68.3633\ r(t)$$

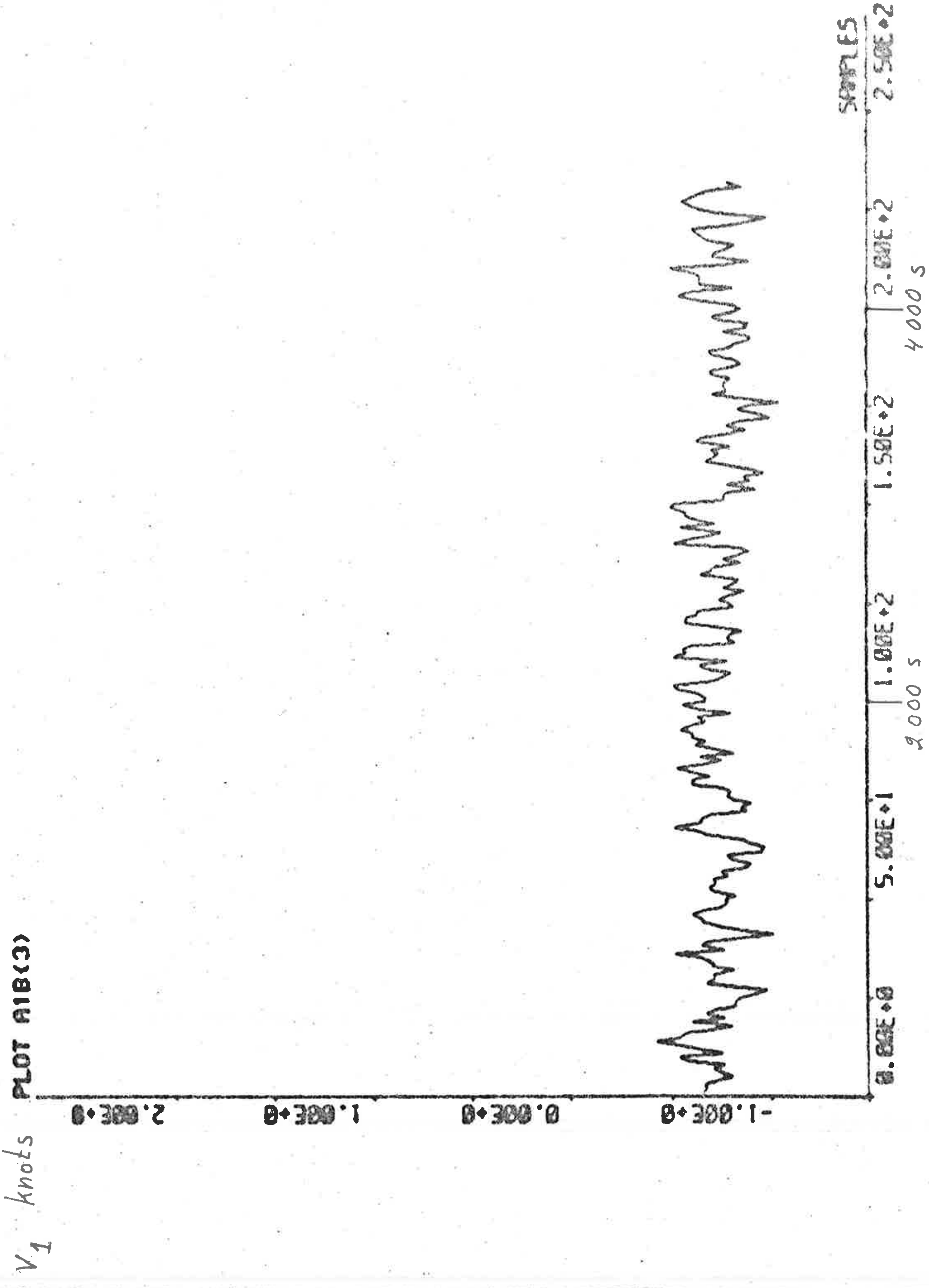
Statistics:

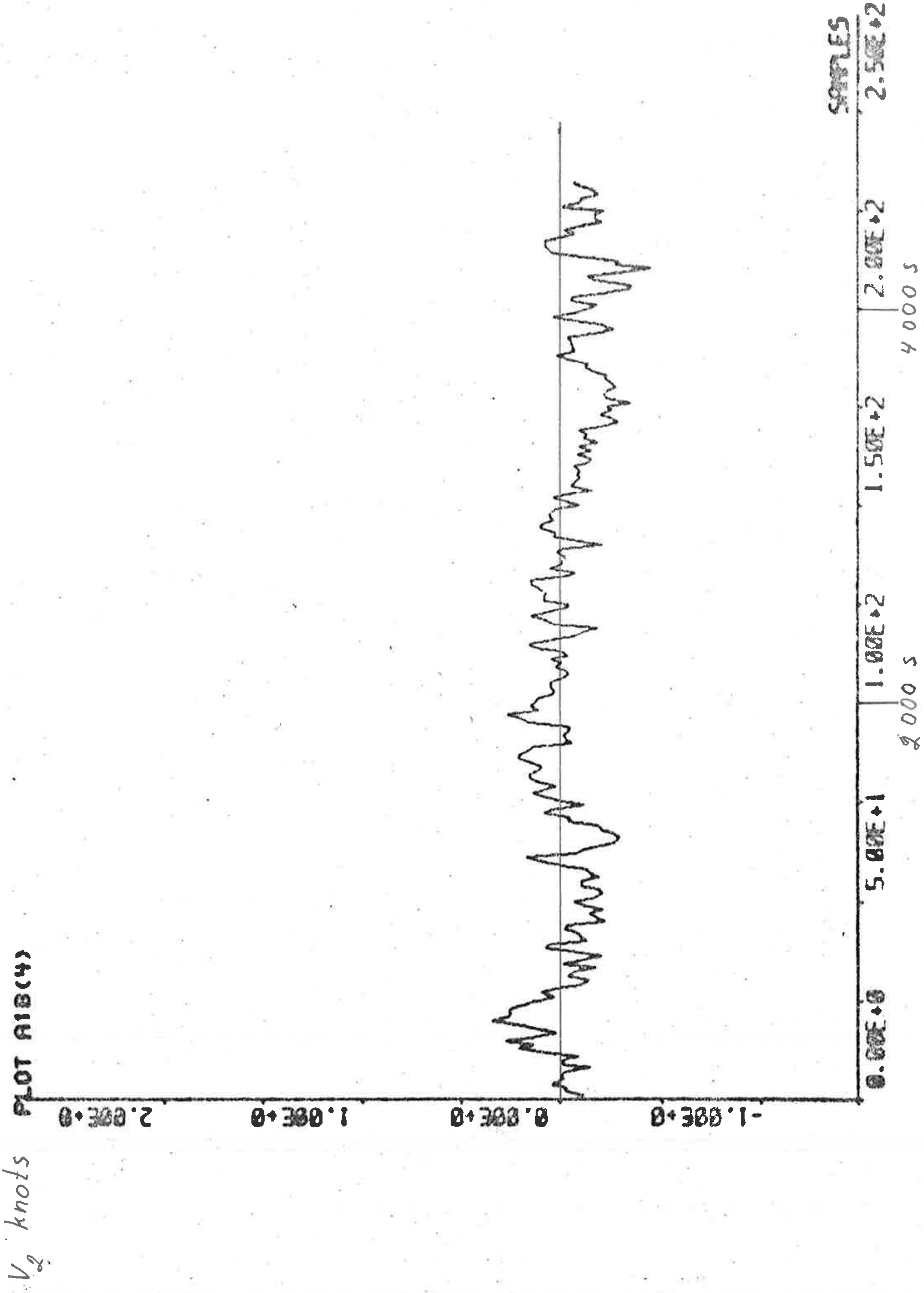
		Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-0.24	0.90	-2.9	1.9
δ_s	degr	-0.35	1.29	-3.7	2.2
δ	degr	-0.33	1.06	-3.0	1.9
v_1	knots	-0.729	0.117	-1.05	-0.43
v_2	knots	-0.049	0.138	-0.45	0.34
r	degr/s	0.0072	0.0106	-0.027	0.049
Ψ	degr	141.905	0.230	141.33	142.47
u	knots	16.532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

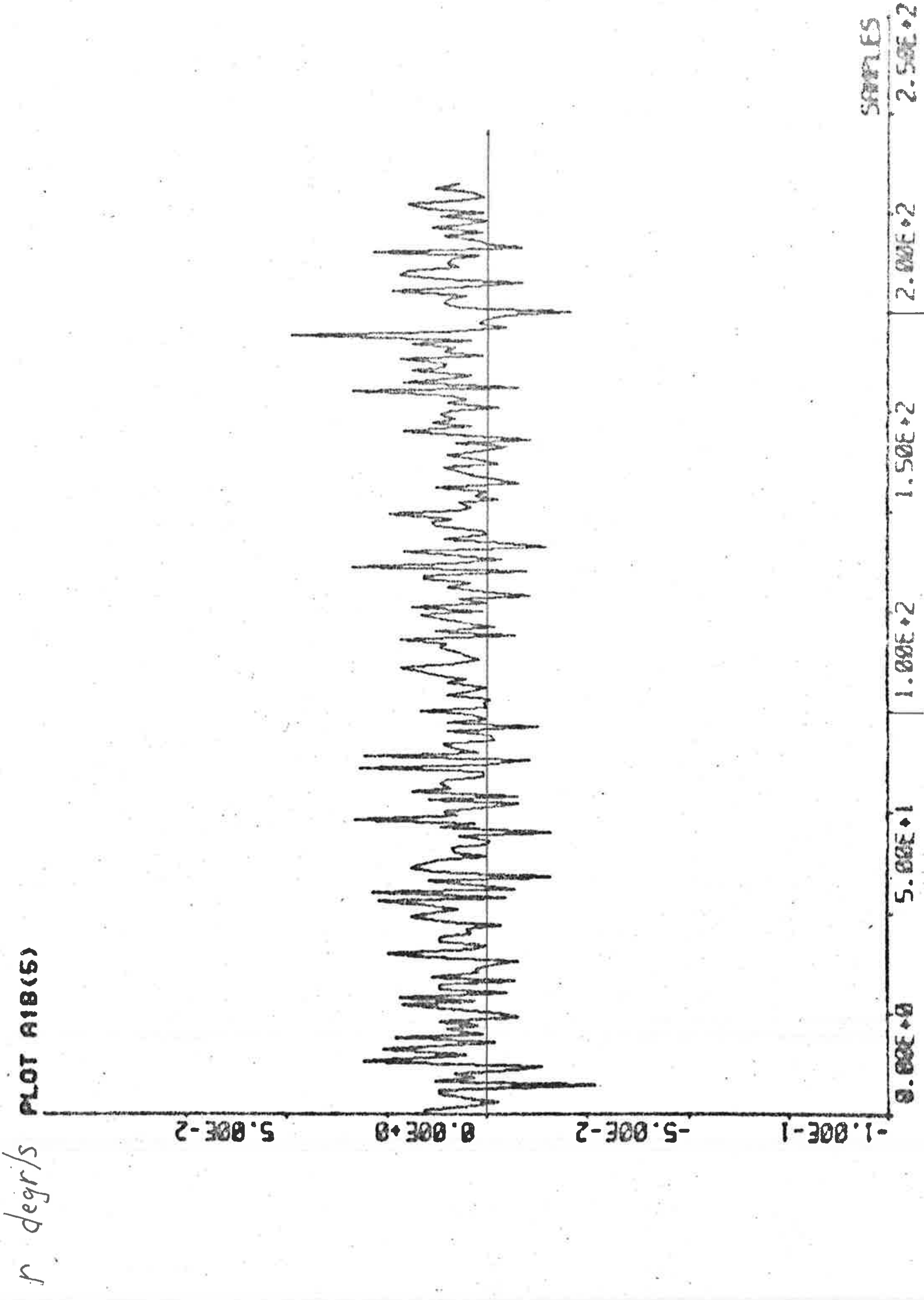

PLOT HP AIS(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δ_{com} degr.

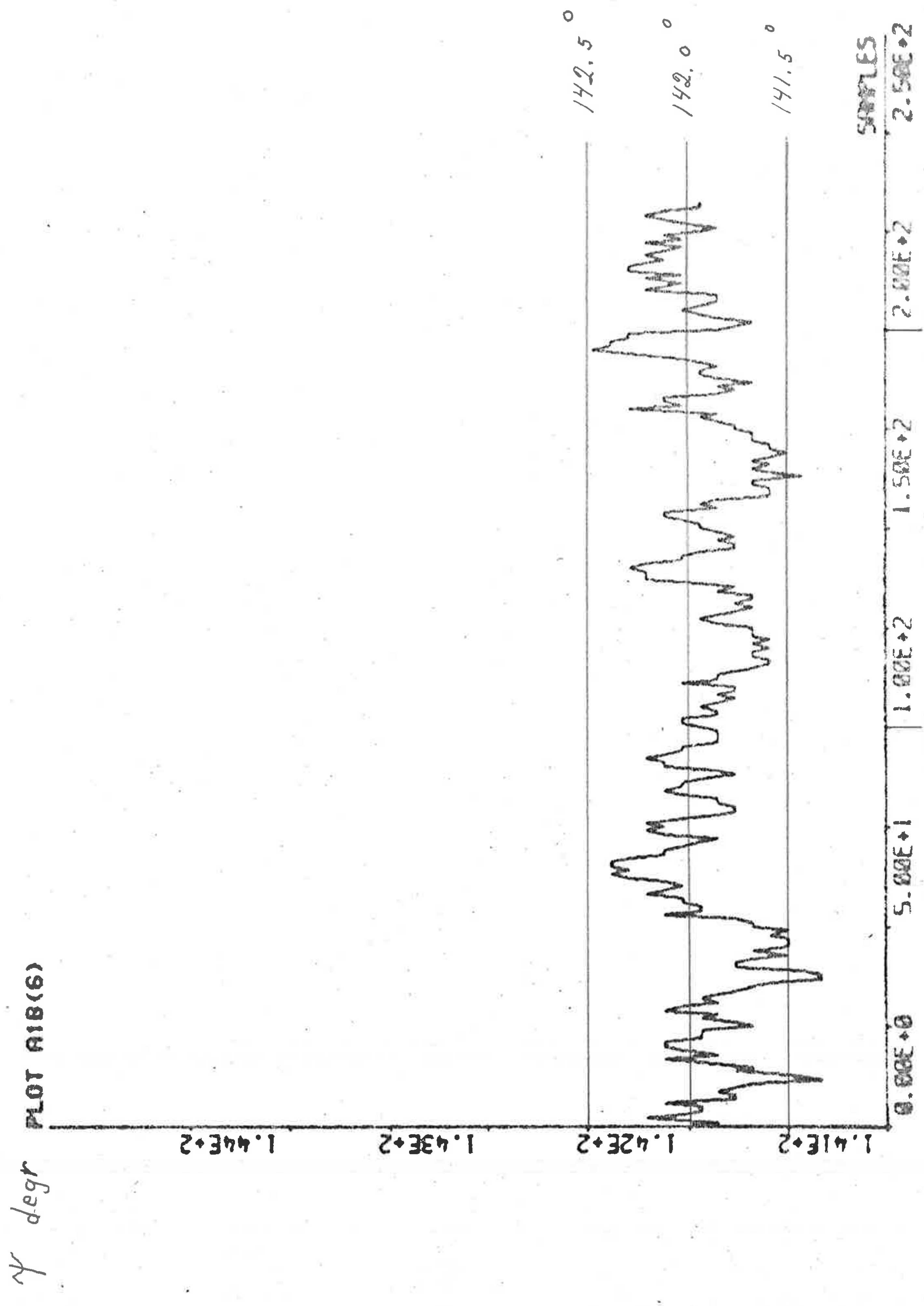

PLOT A1B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δ_s degr

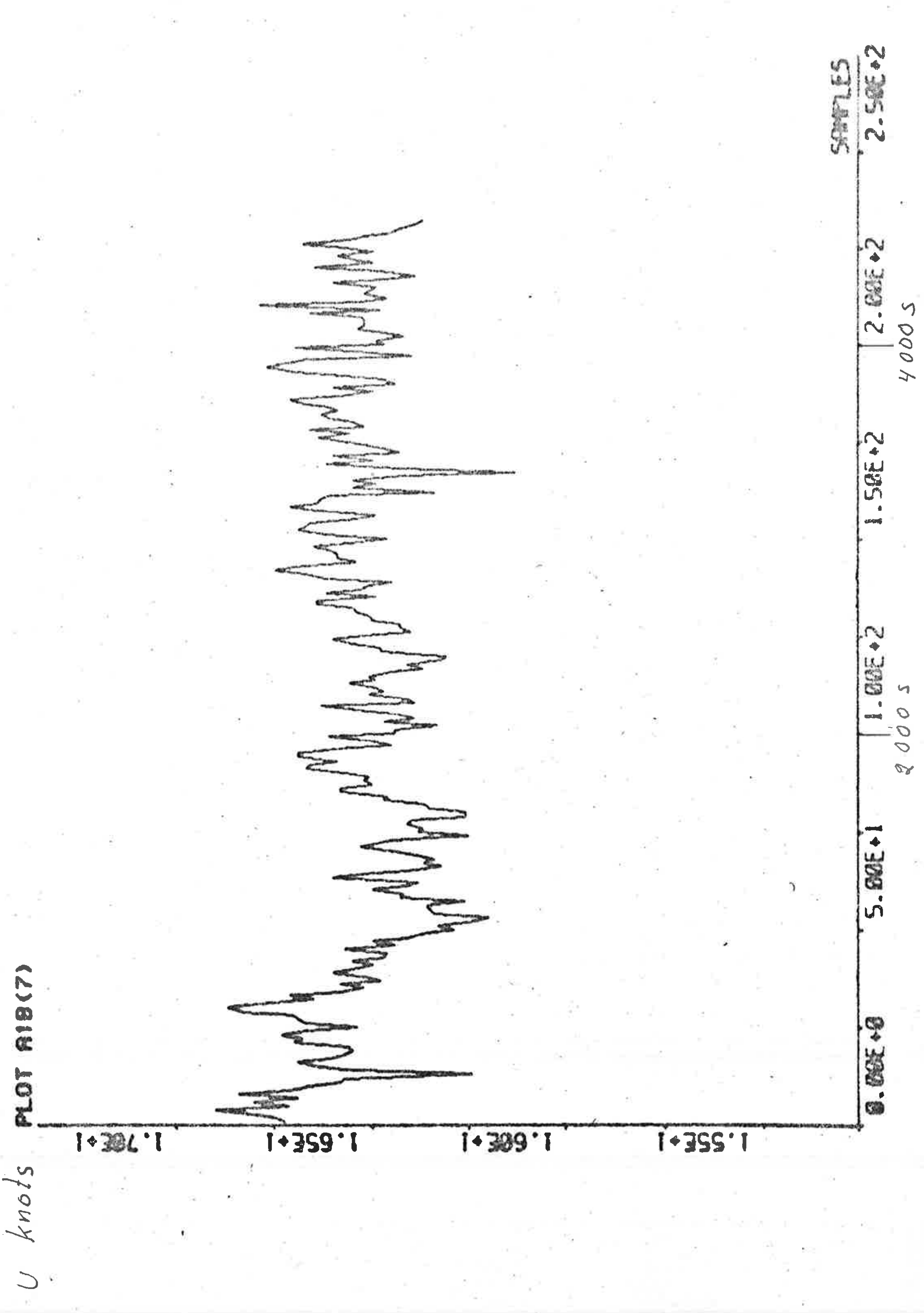

PLOT A1B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr
+3°
0°
-3°
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s

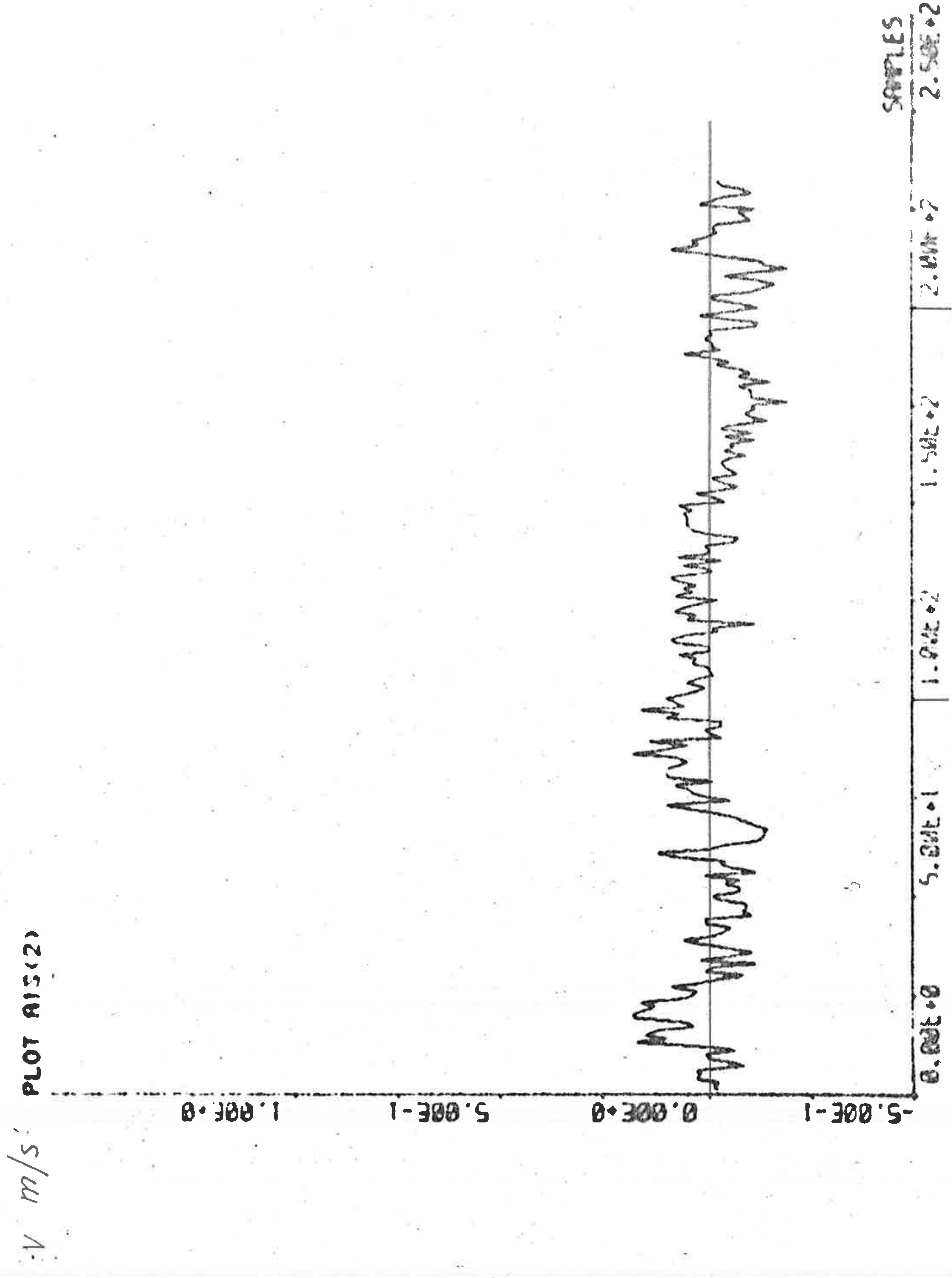

PLOT A1B(3)
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
V_1 knots


PLOT A1B(4)
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_z knots

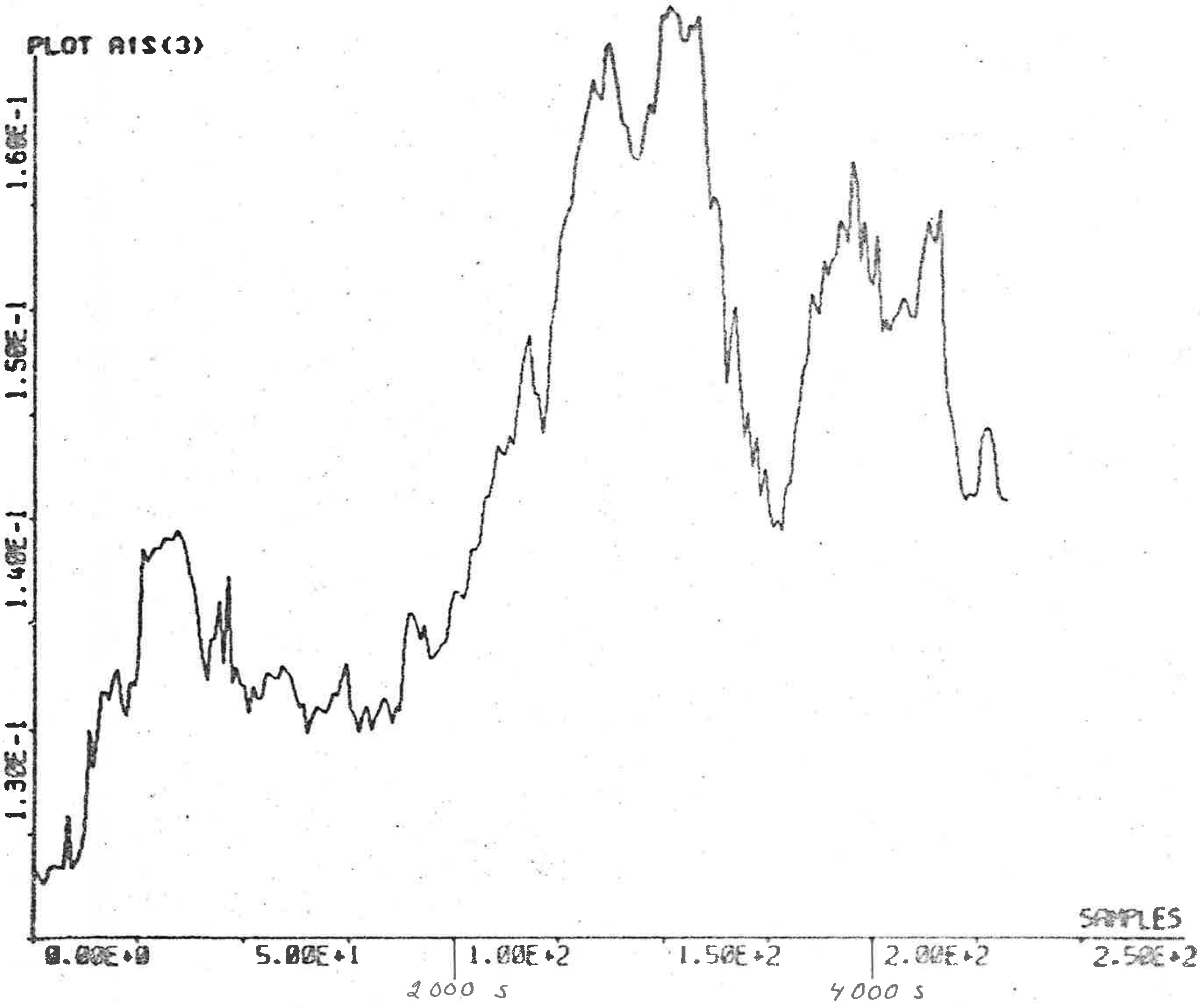

PLOT A1B(S)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
r degr/s

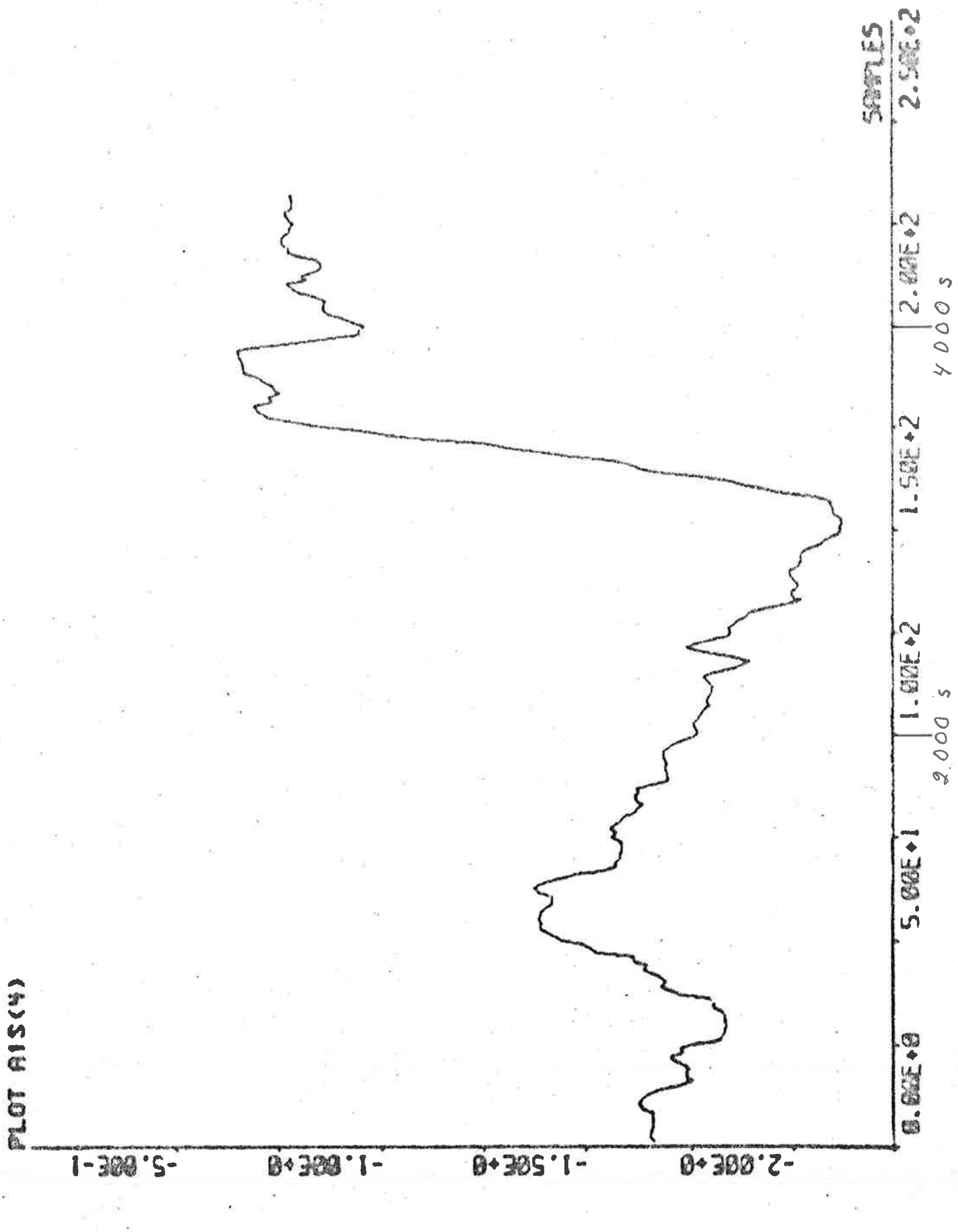

PLOT A1B(6)
1.41E+2
1.42E+2
1.43E+2
1.44E+2
ψ degr
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
141.5°
142.0°
142.5°


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

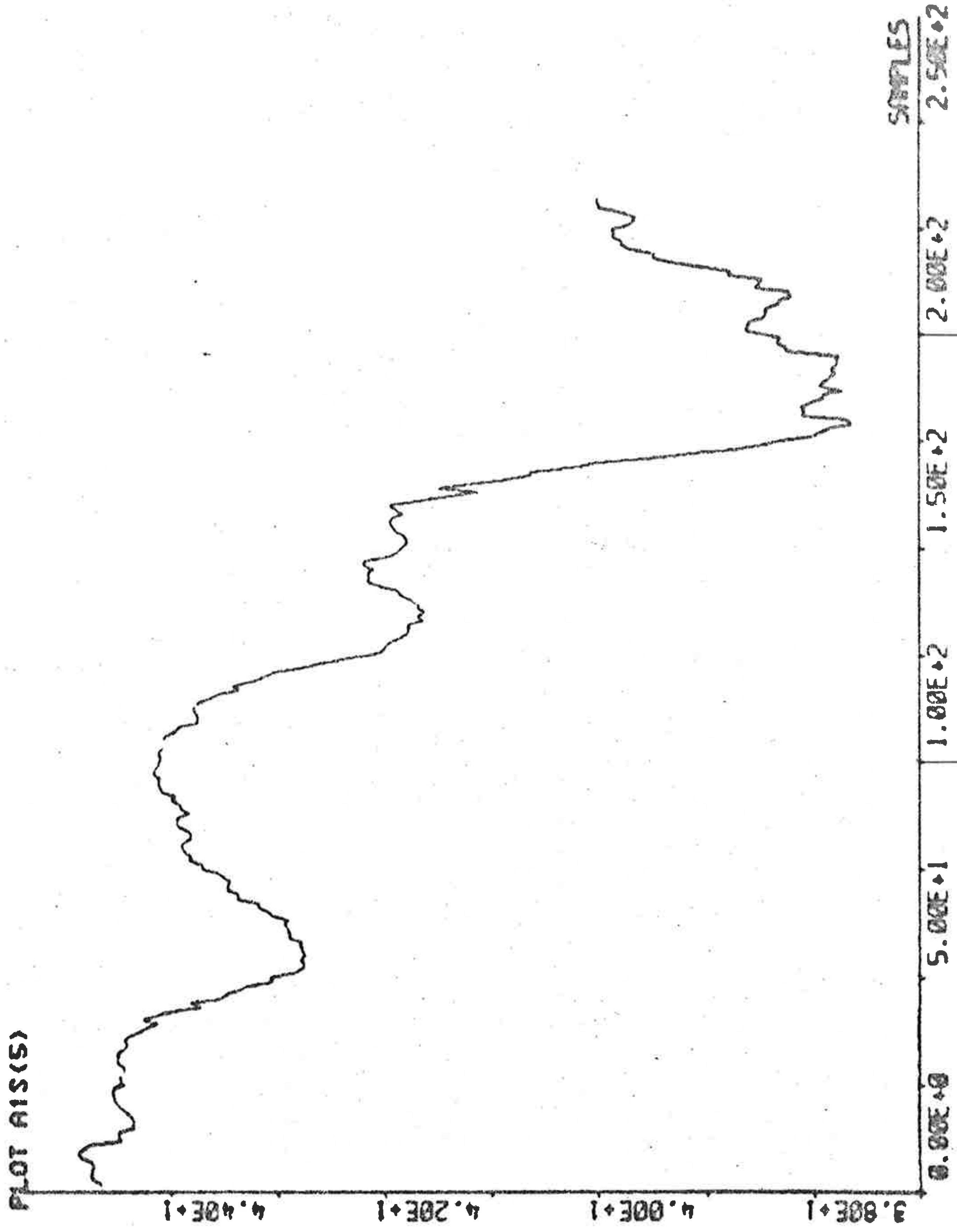

PLOT AIS(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
V m/s

b2


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


PLOT A1S(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


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

d2

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:

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

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

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:

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

Regulator:

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

Final values:

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

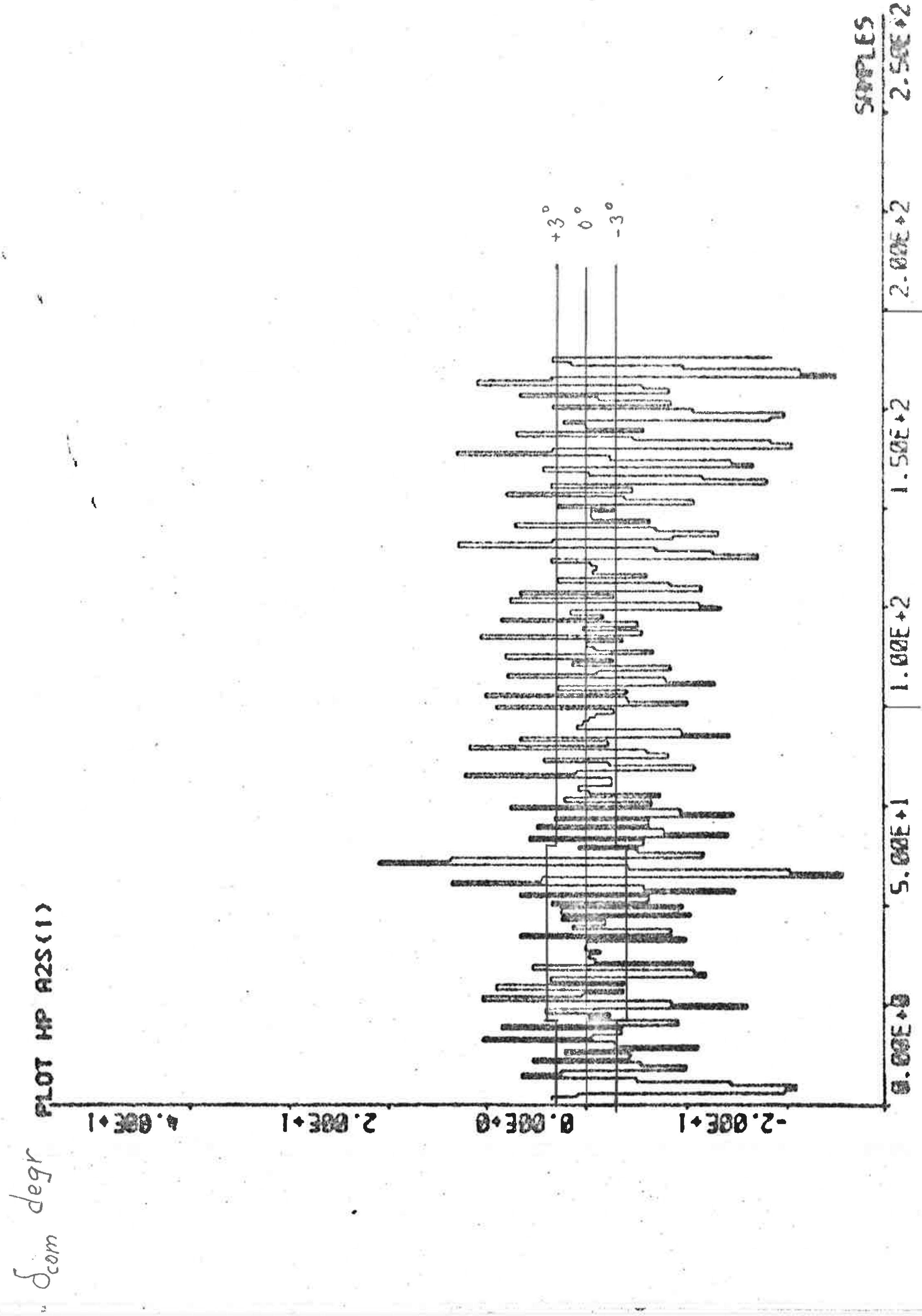
Regulator:

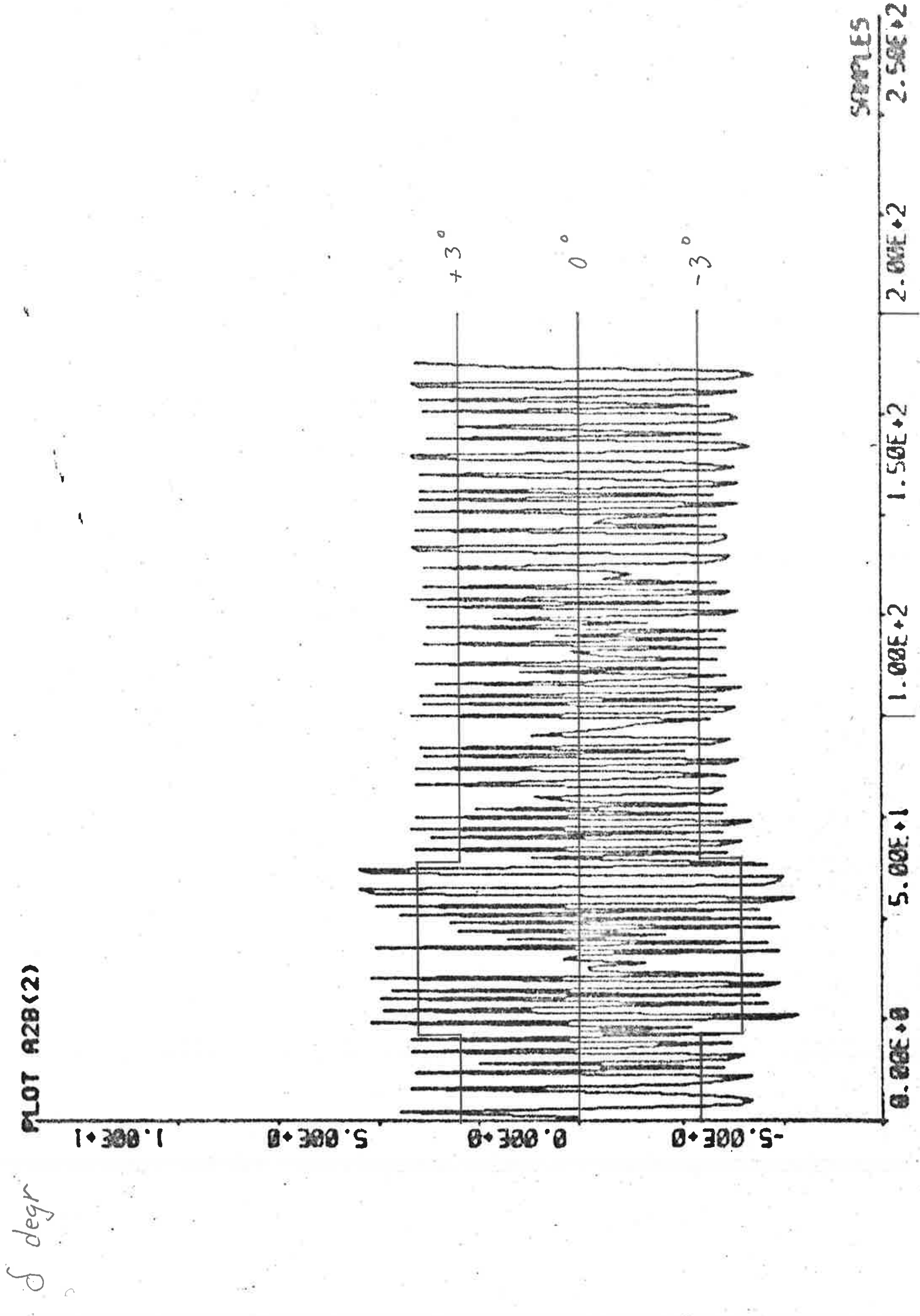
$$\delta(t) = -18.5529(\Psi(t) - \Psi_{ref}) - 1.3395\delta(t-1) - 2.5566v(t) -$$

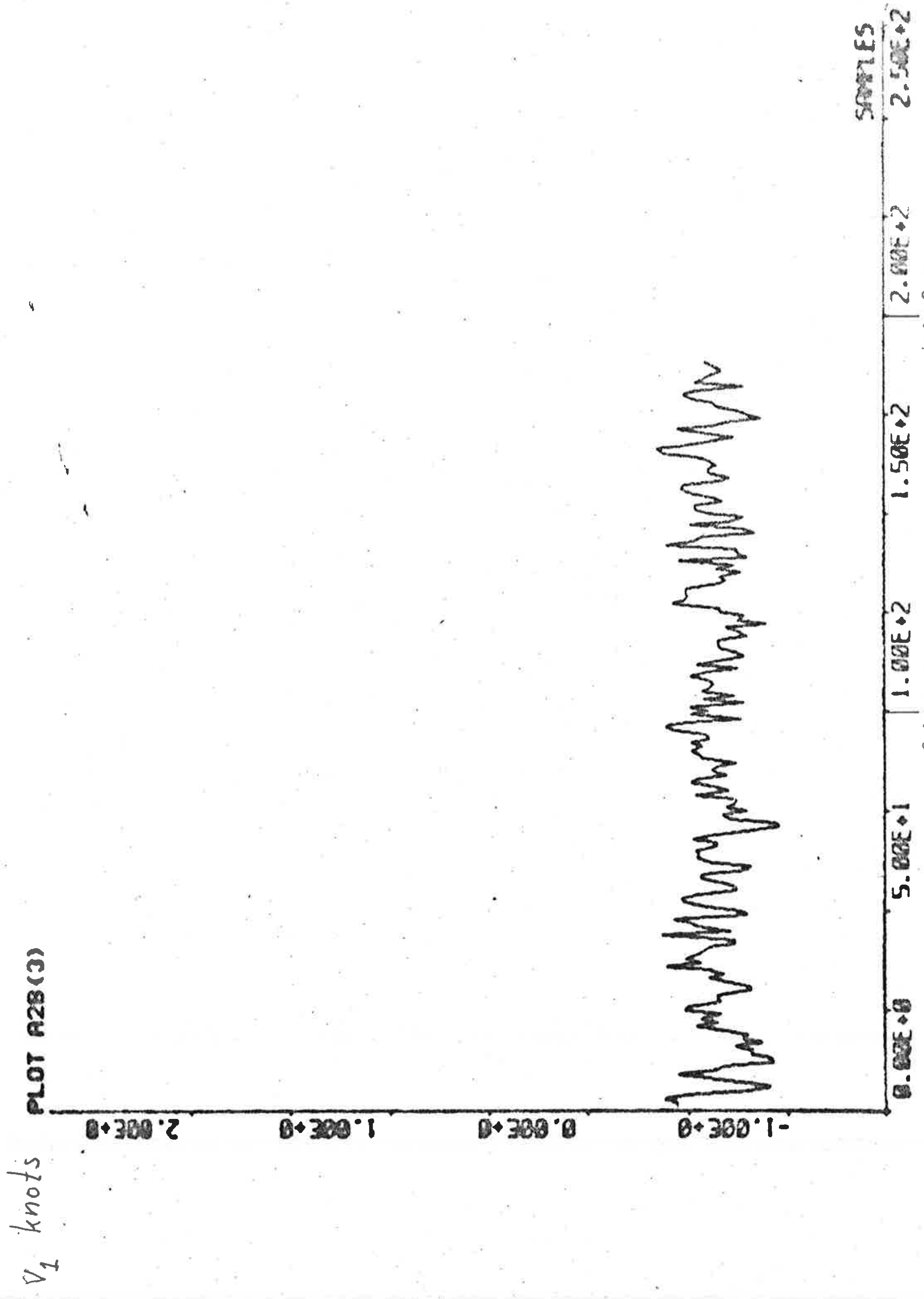
$$- 189.0724r(t)$$

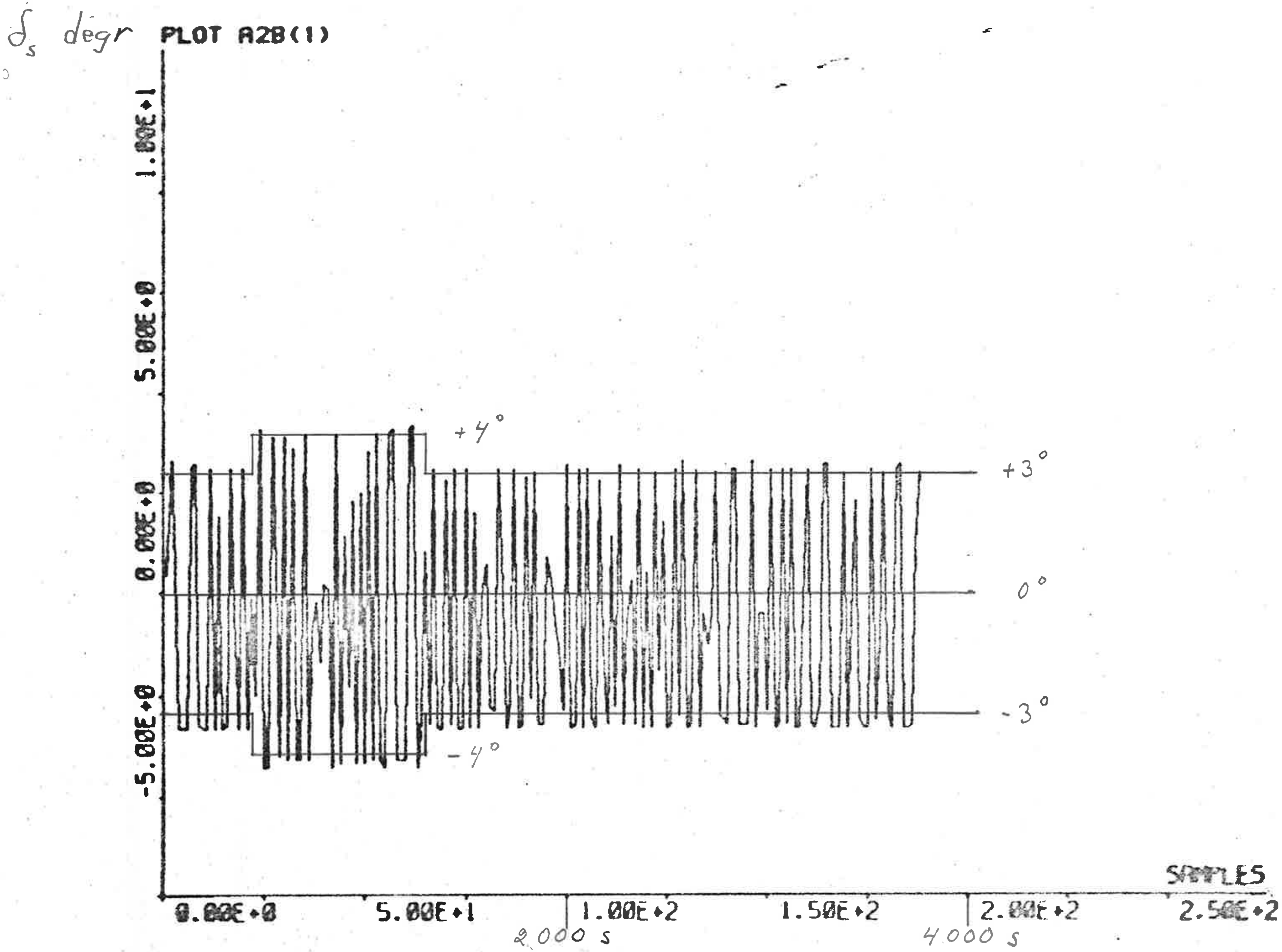
Statistics:

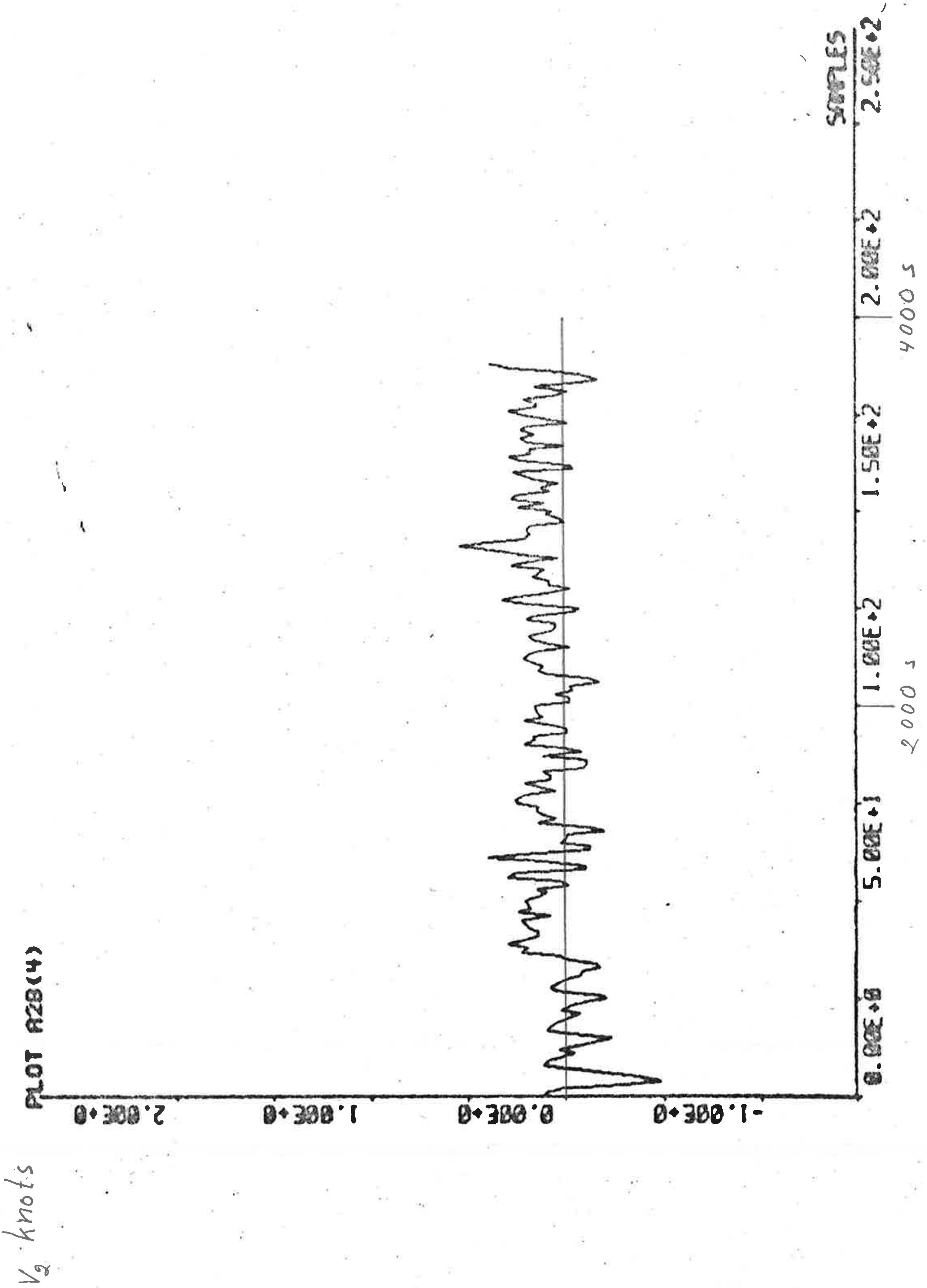
		Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-2.93	8.50	-25.8	21.0
δ_s	degr	-0.75	2.93	-4.3	4.2
δ	degr	0.67	3.50	-5.4	5.5
v_1	knots	-0.633	0.125	-0.96	-0.35
v_2	knots	0.078	0.145	-0.48	0.54
r	degr/s	0.0072	0.0278	-0.072	0.100
Ψ	degr	142.170	0.440	140.98	144.32
u	knots	16.743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

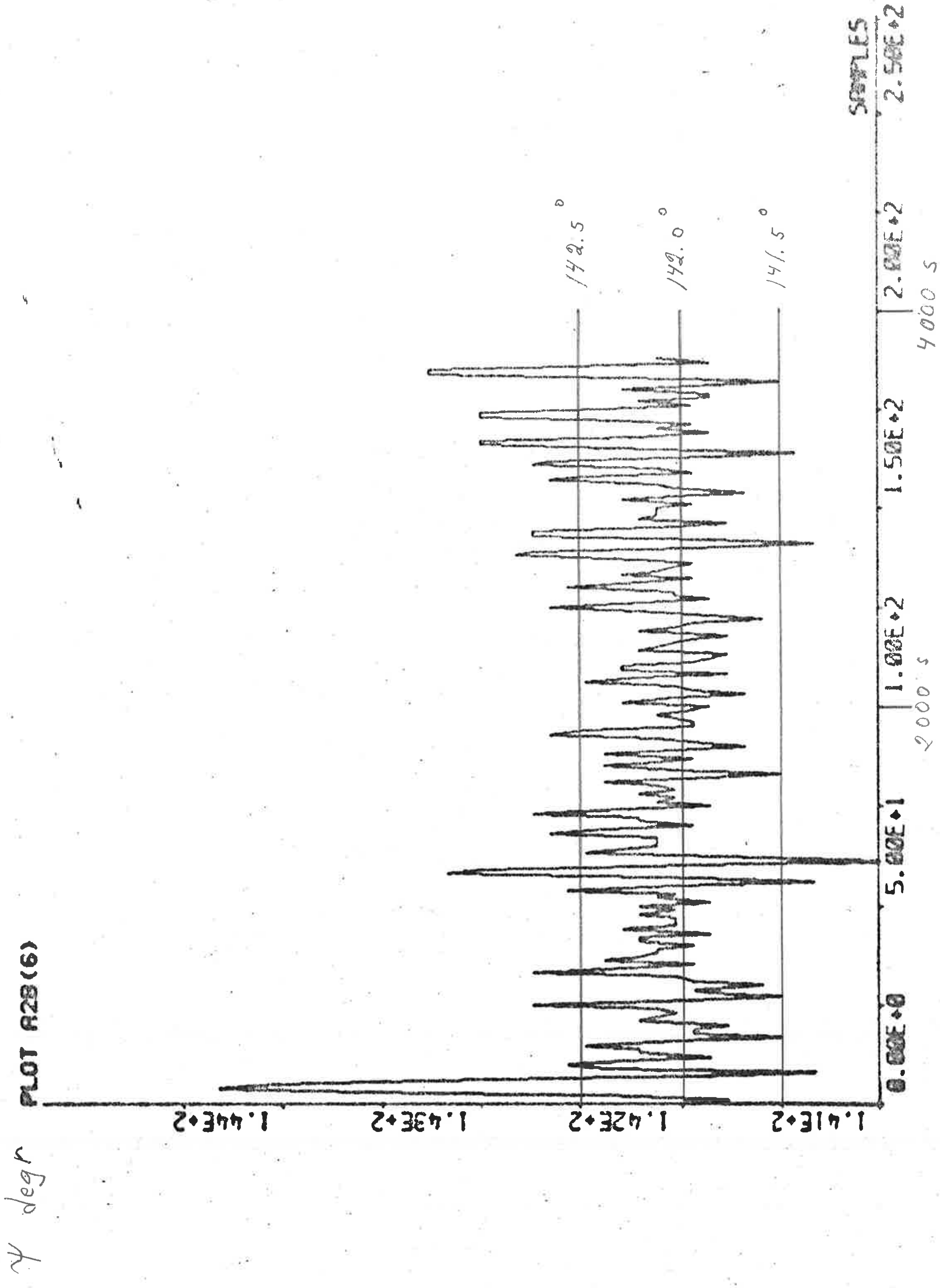

PLOT HP A2S(1)
4.00E+1
2.00E+1
0.00E+0
-2.00E+1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δ_{com} degr

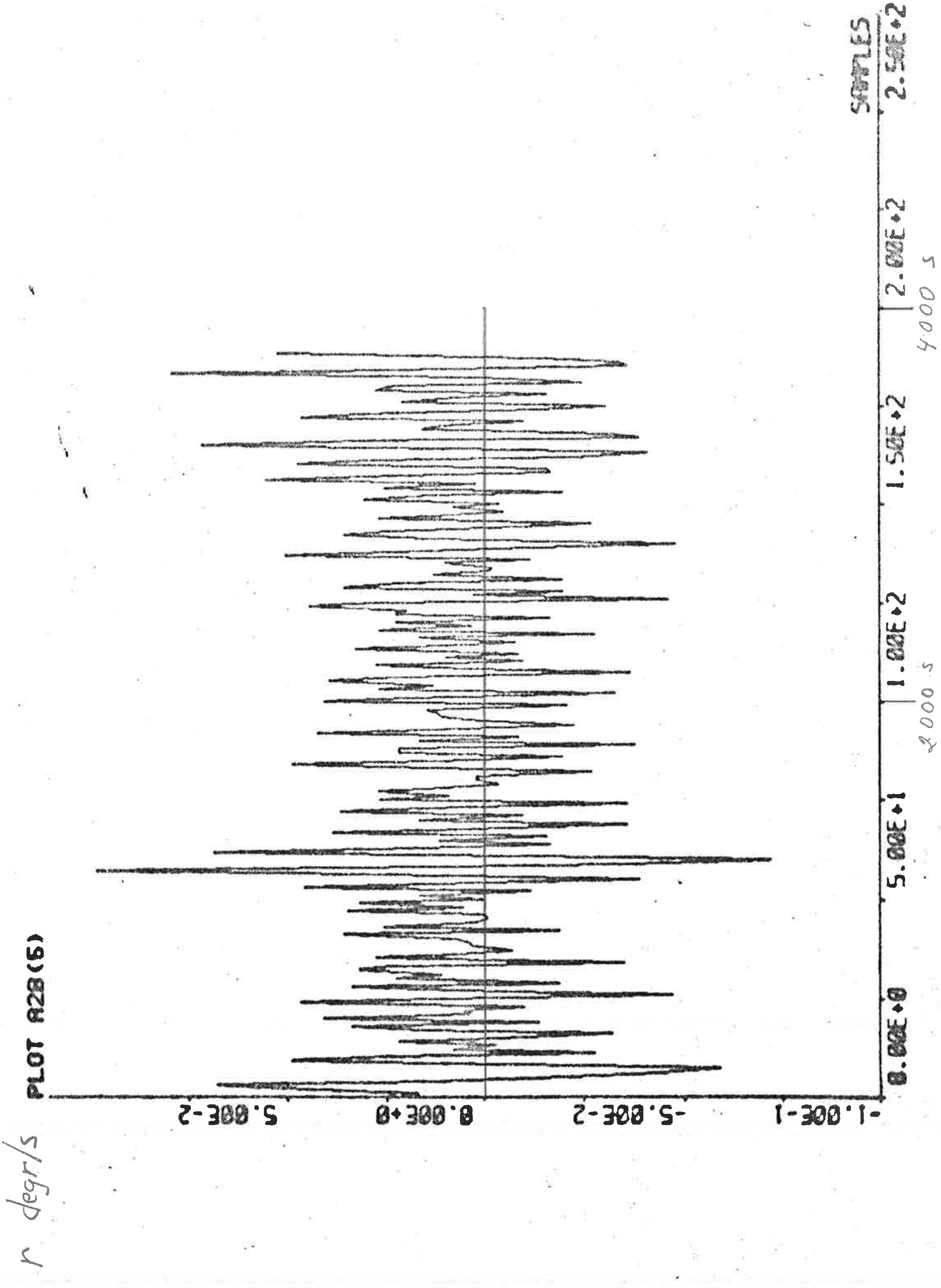

PLOT A2B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δ degr

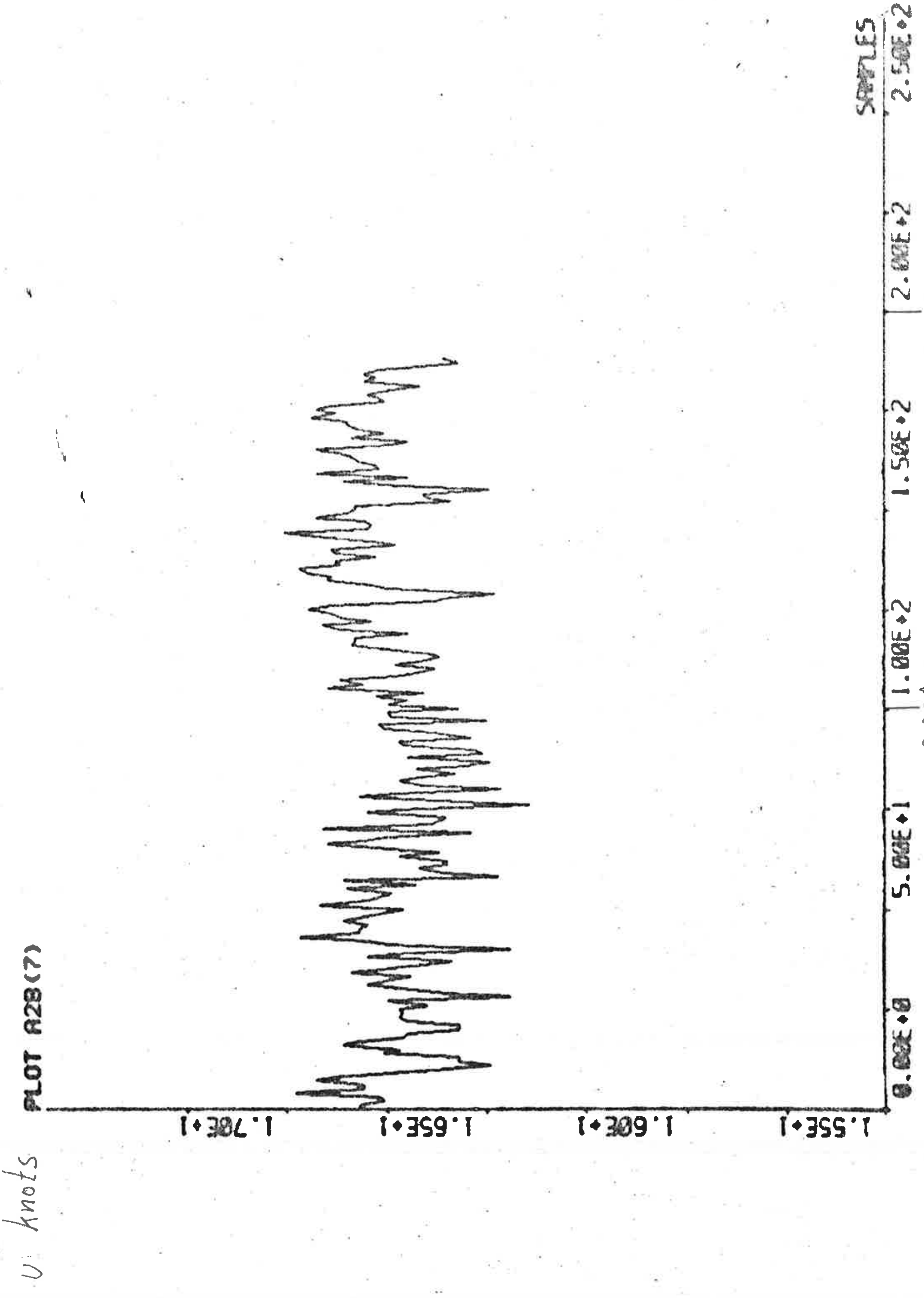

PLOT A2B(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
V1 knots

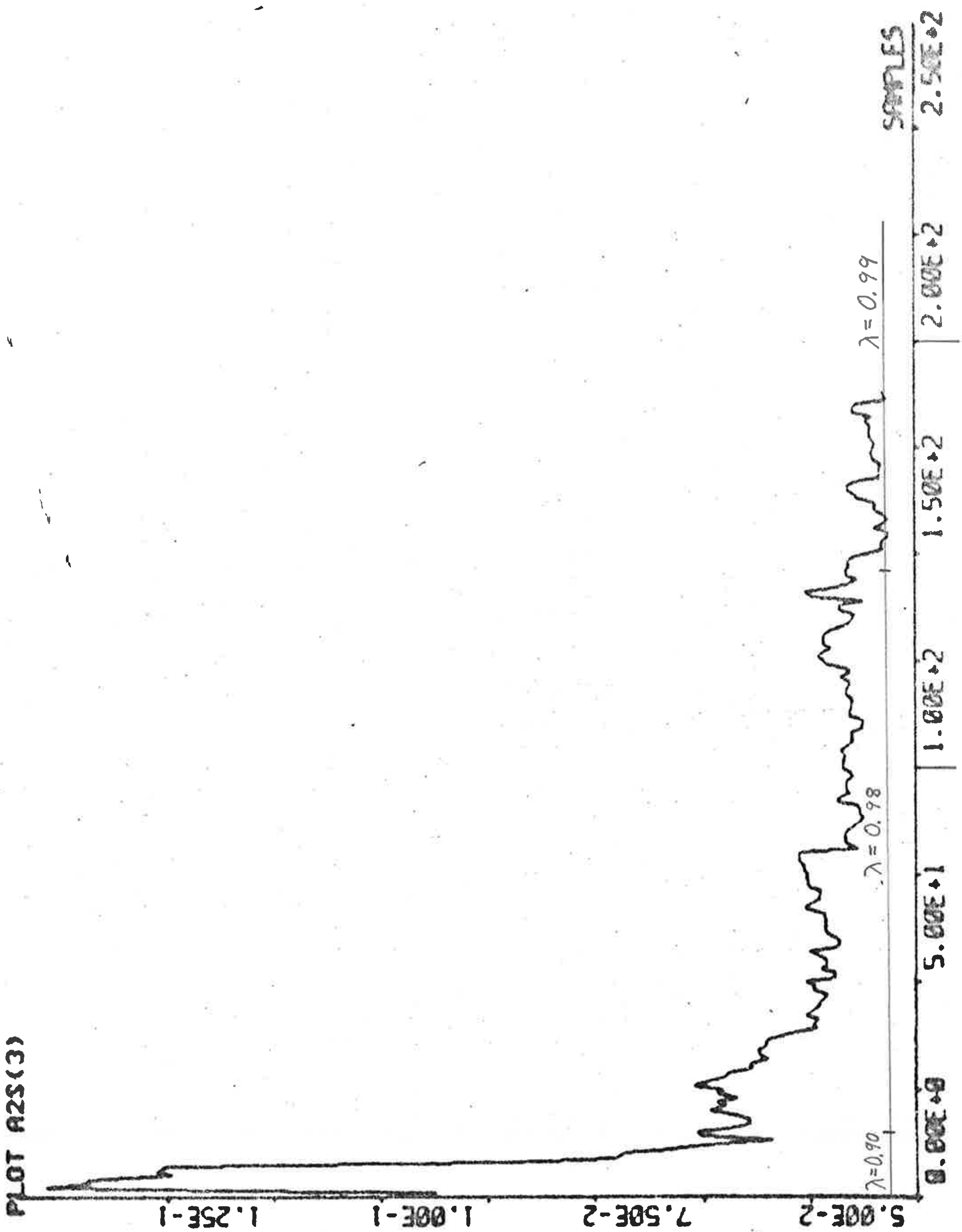

δ_s degr
PLOT A2B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+4°
-4°
+3°
0°
-3°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s


PLOT A2B(4)
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_2 knots

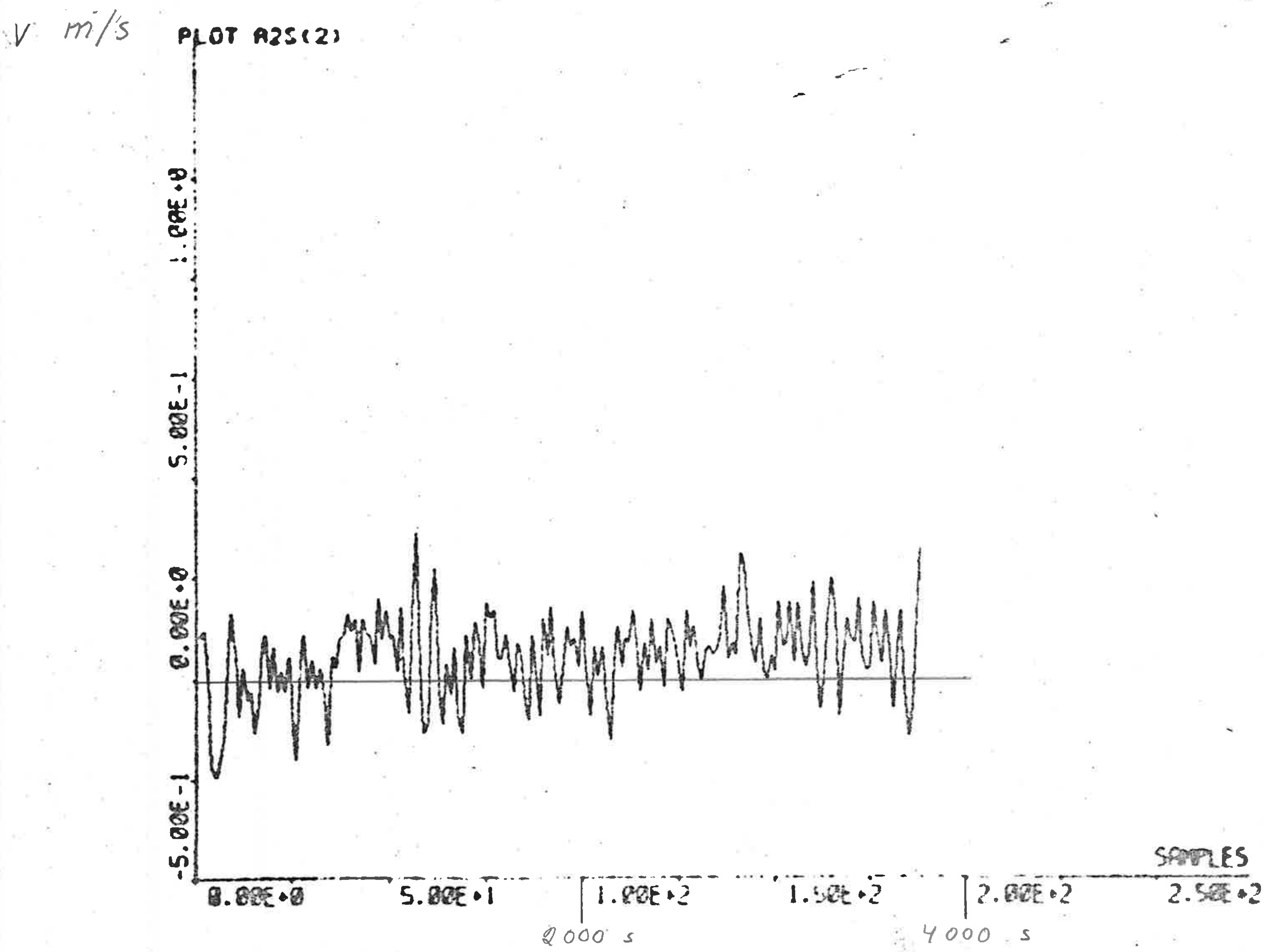

PLOT A2B(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
ψ degr
142.5°
142.0°
141.5°
0.00E+0
5.00E+1
1.00E+2
2000 s
1.50E+2
2.00E+2
4000 s
2.50E+2
SAMPLES


PLOT A2B(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-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s

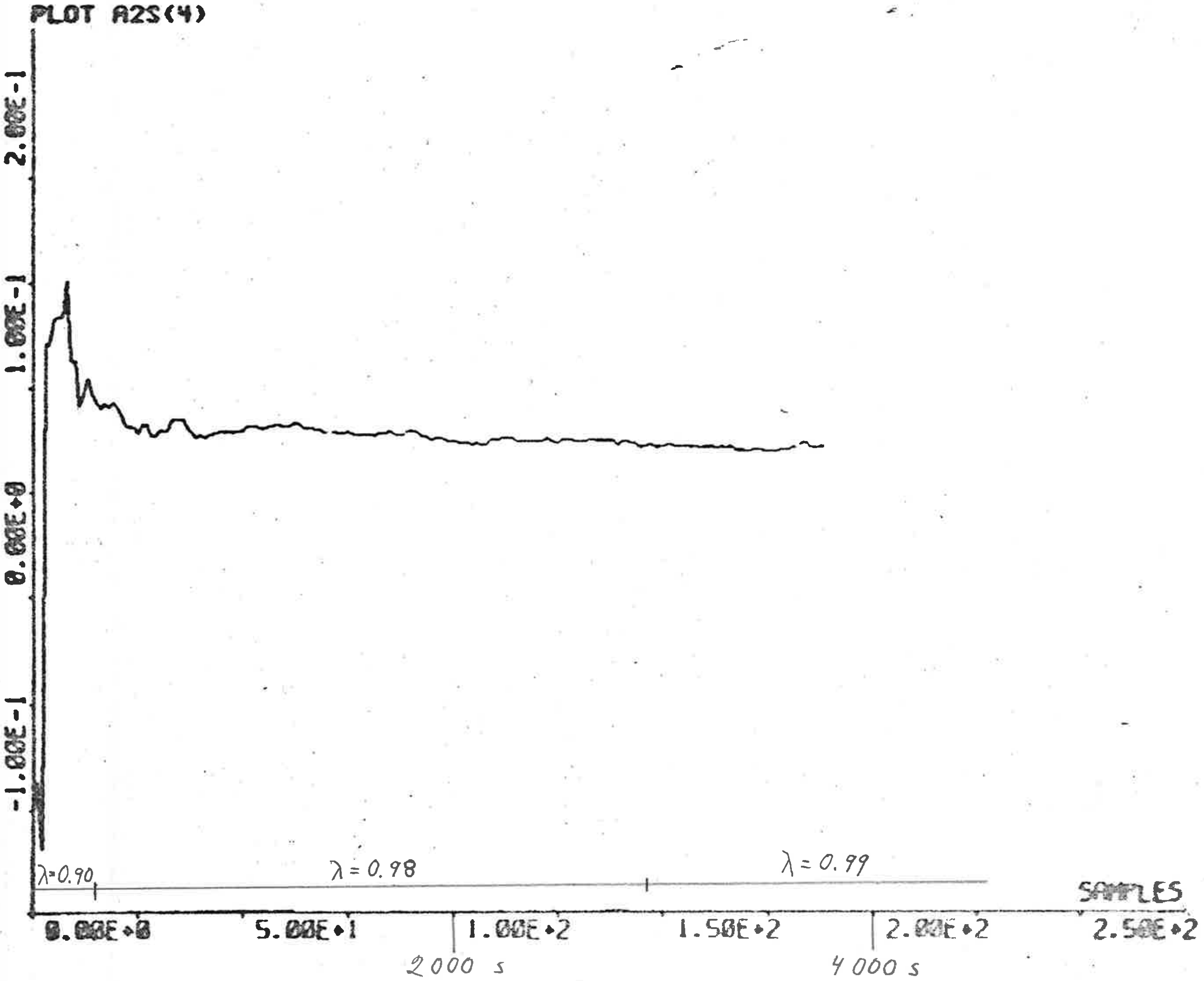

PLOT A2B(7)
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
1.55E+1
1.60E+1
1.65E+1
1.70E+1
U: knots

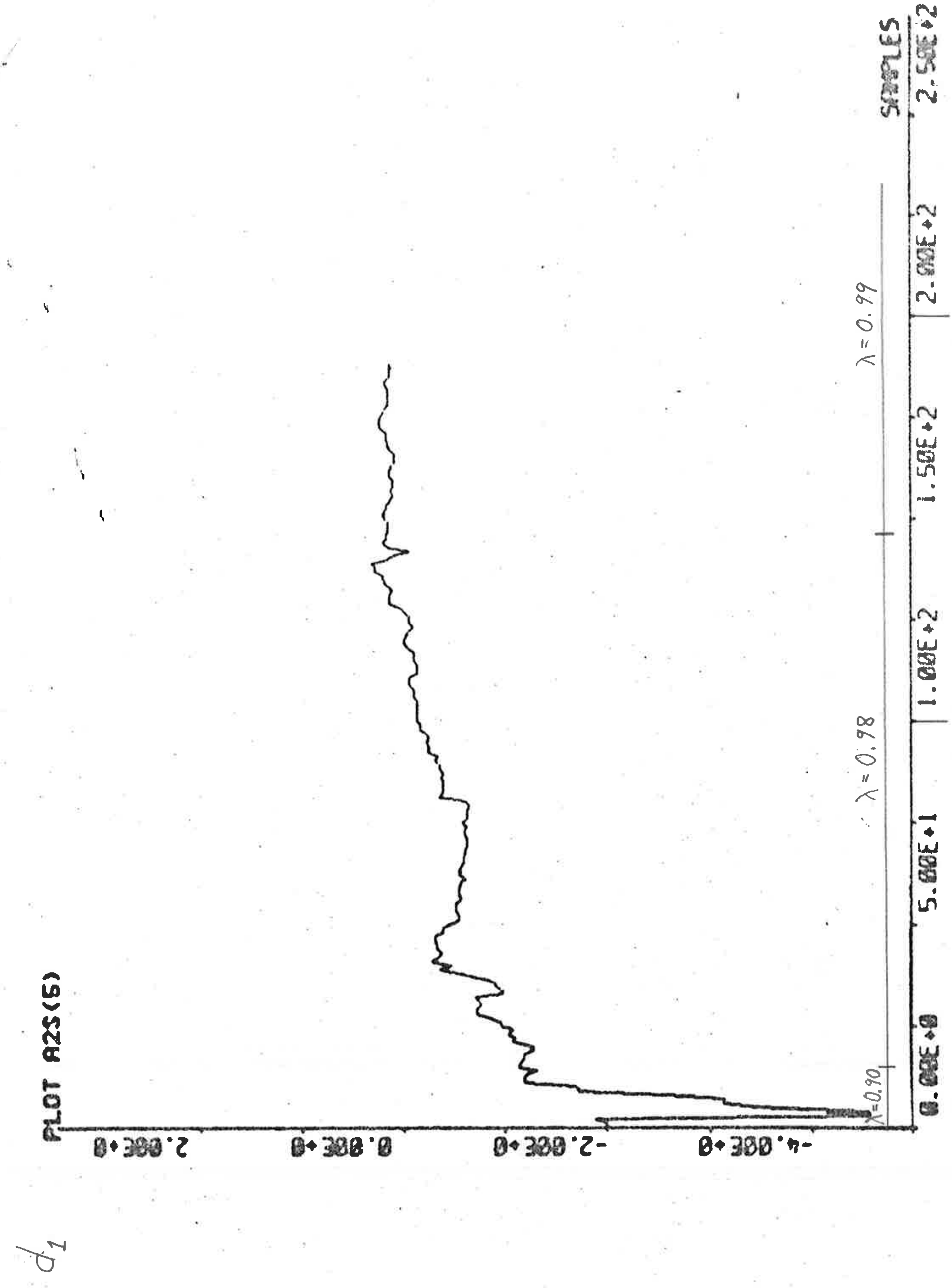

PLOT A2S(3)
1.25E-1
1.00E-1
7.50E-2
5.00E-2
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.90
λ=0.98
λ=0.99
2000 s
4000 s

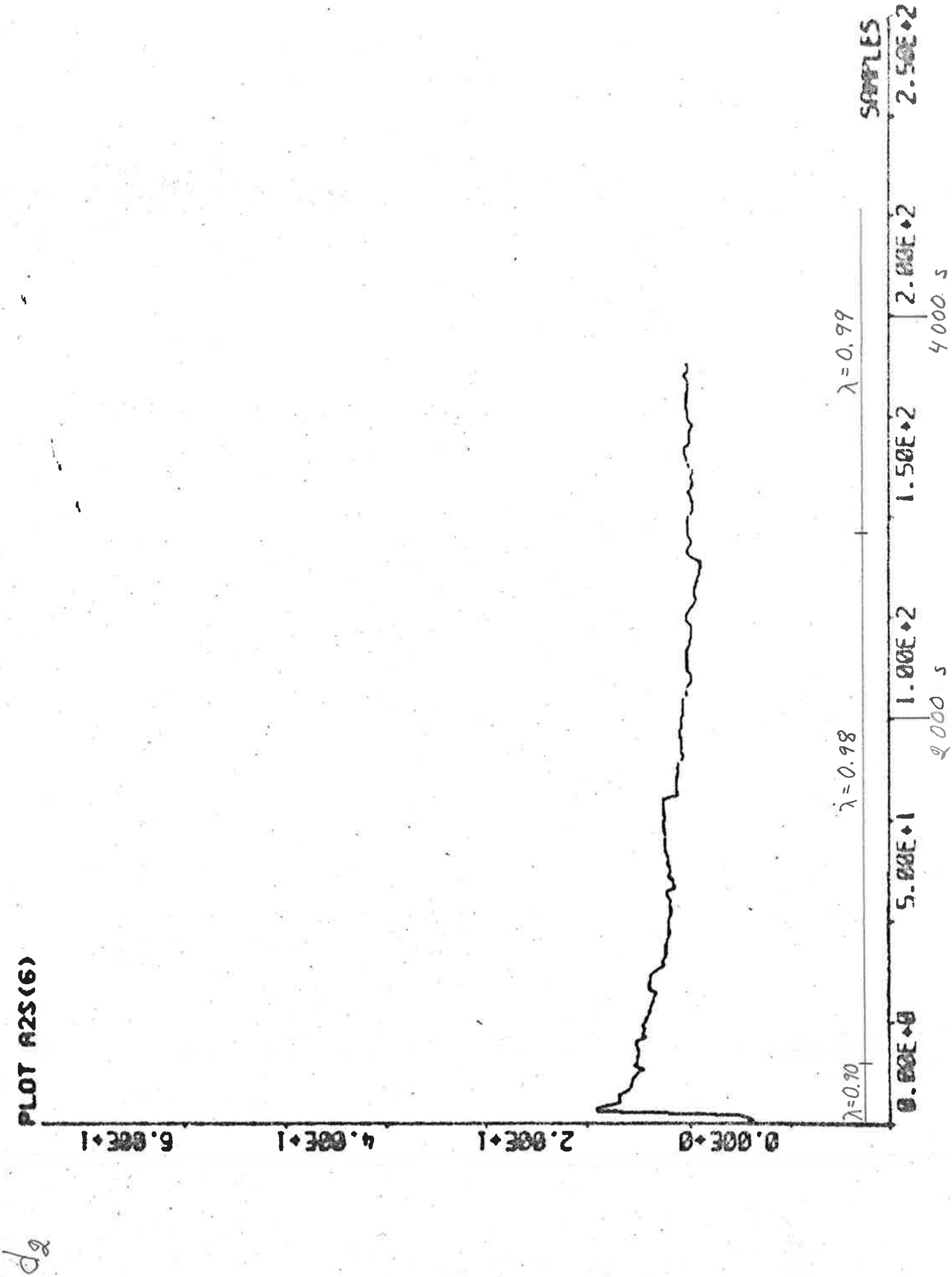
b1


V m/s
PLOT A2S(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s

b2


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


PLOT A2S(S)
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:

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

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

Regulator:

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

Sampling interval: 30 s
Forgetting factor λ: 0.98 (0 - 3150 s)
0.99 (3150 - 4440 s)
Rudder limits: ±3°
$\Psi_{ref} = 142^{\circ}$

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:

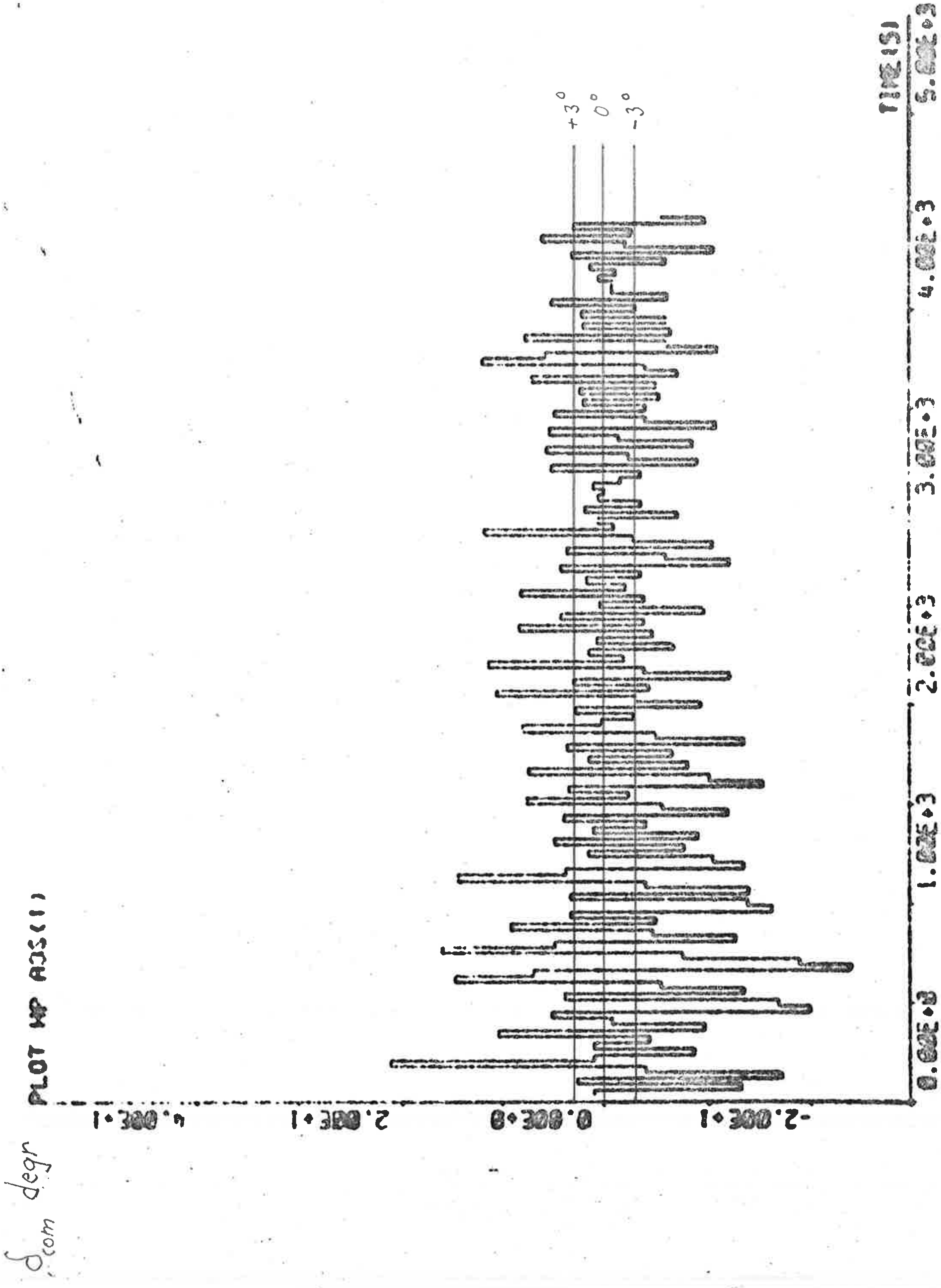
$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1243 \\ 0.1252 \\ 0.1451 \\ 11.1929 \end{bmatrix} \qquad P = \begin{bmatrix} 0.003153 & & & \\ -0.0004958 & 0.002615 & & \\ -0.01788 & 0.007169 & 0.9782 & \\ 0.3555 & -0.2717 & -5.138 & 78.06 \end{bmatrix}$$

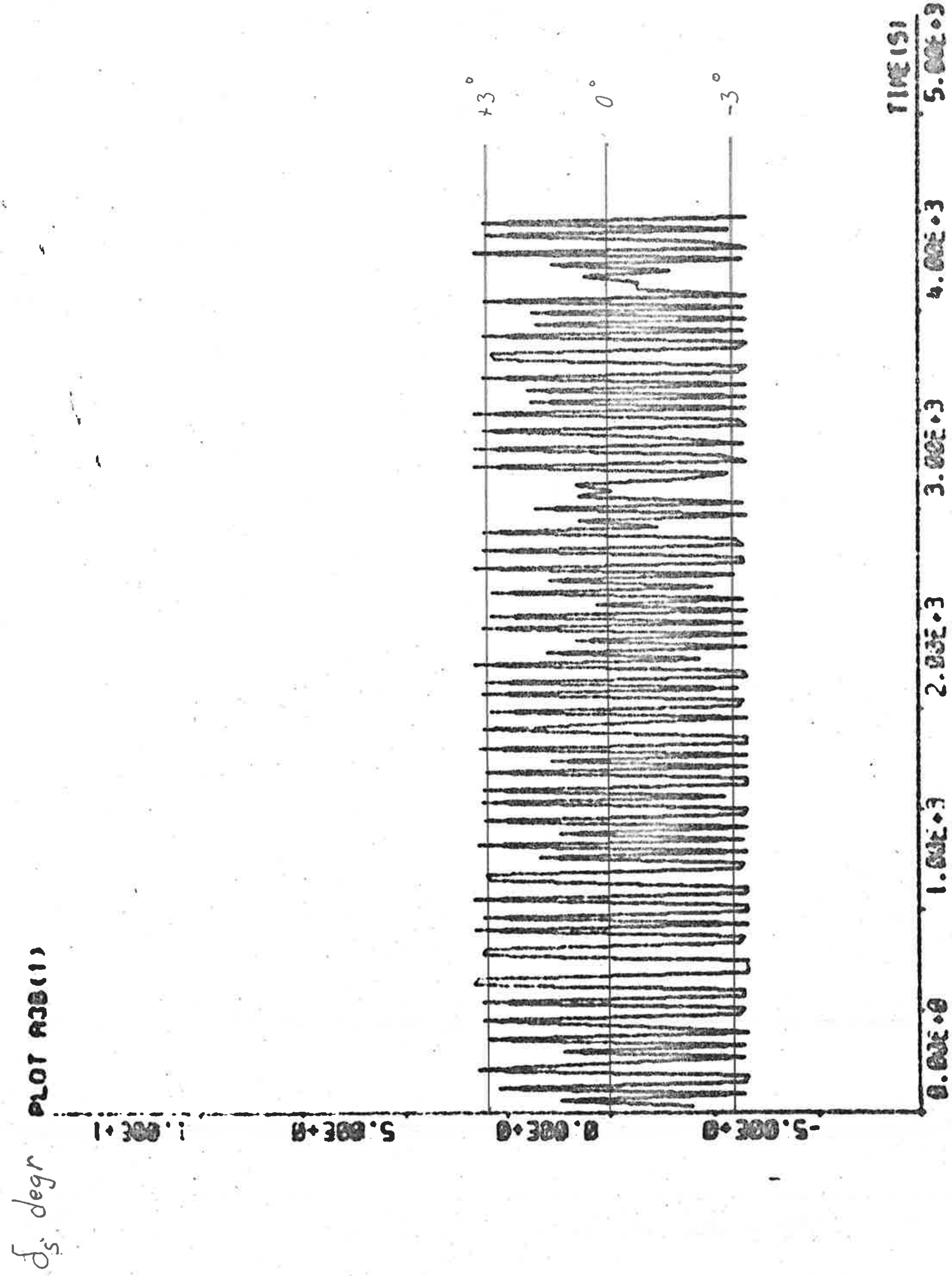
Regulator:

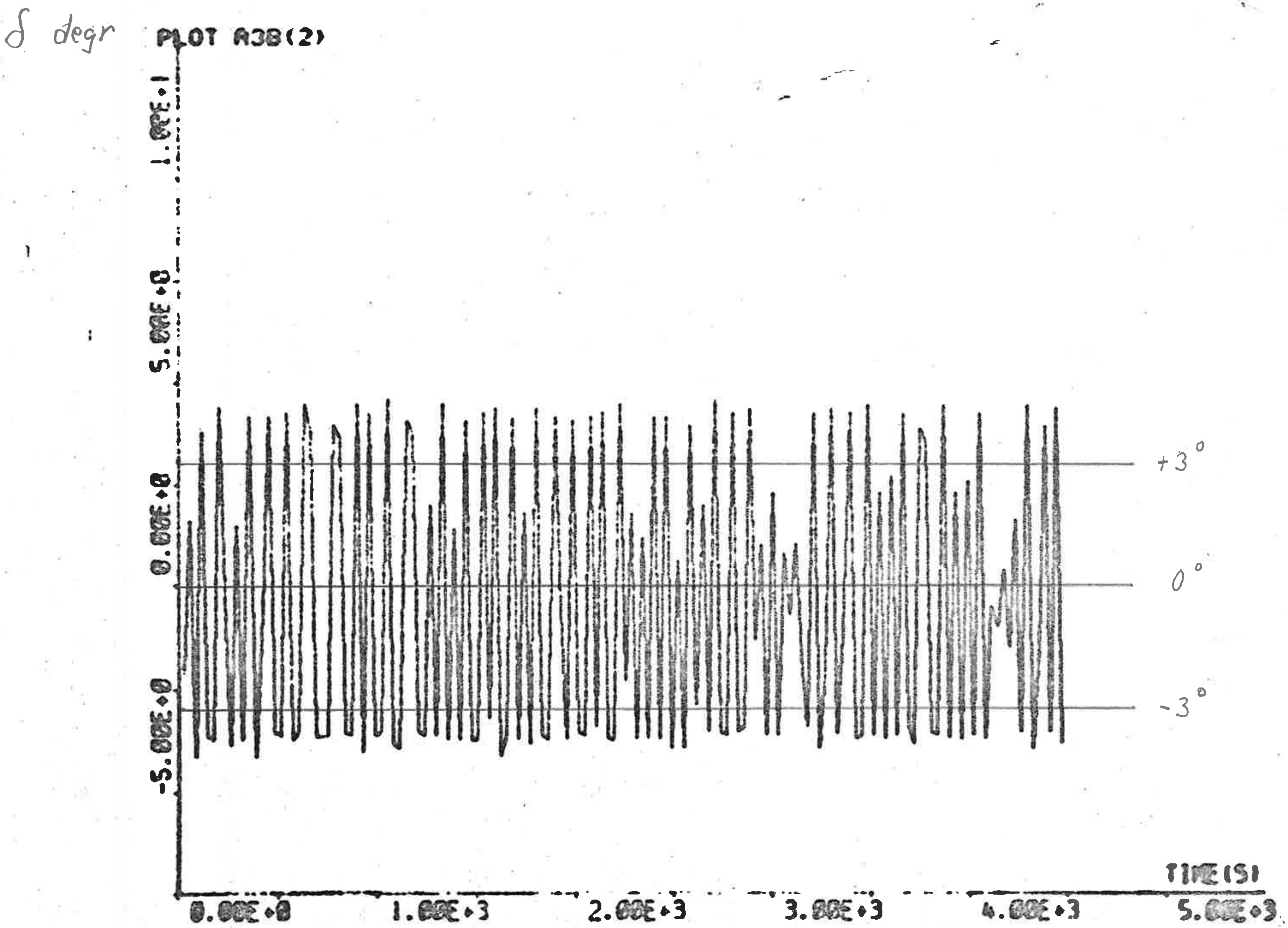
$$\delta(t) = -8.0451(\Psi(t) - \Psi_{ref}) - 1.0072\delta(t-1) - 1.1673v(t) - 90.0475r(t)$$

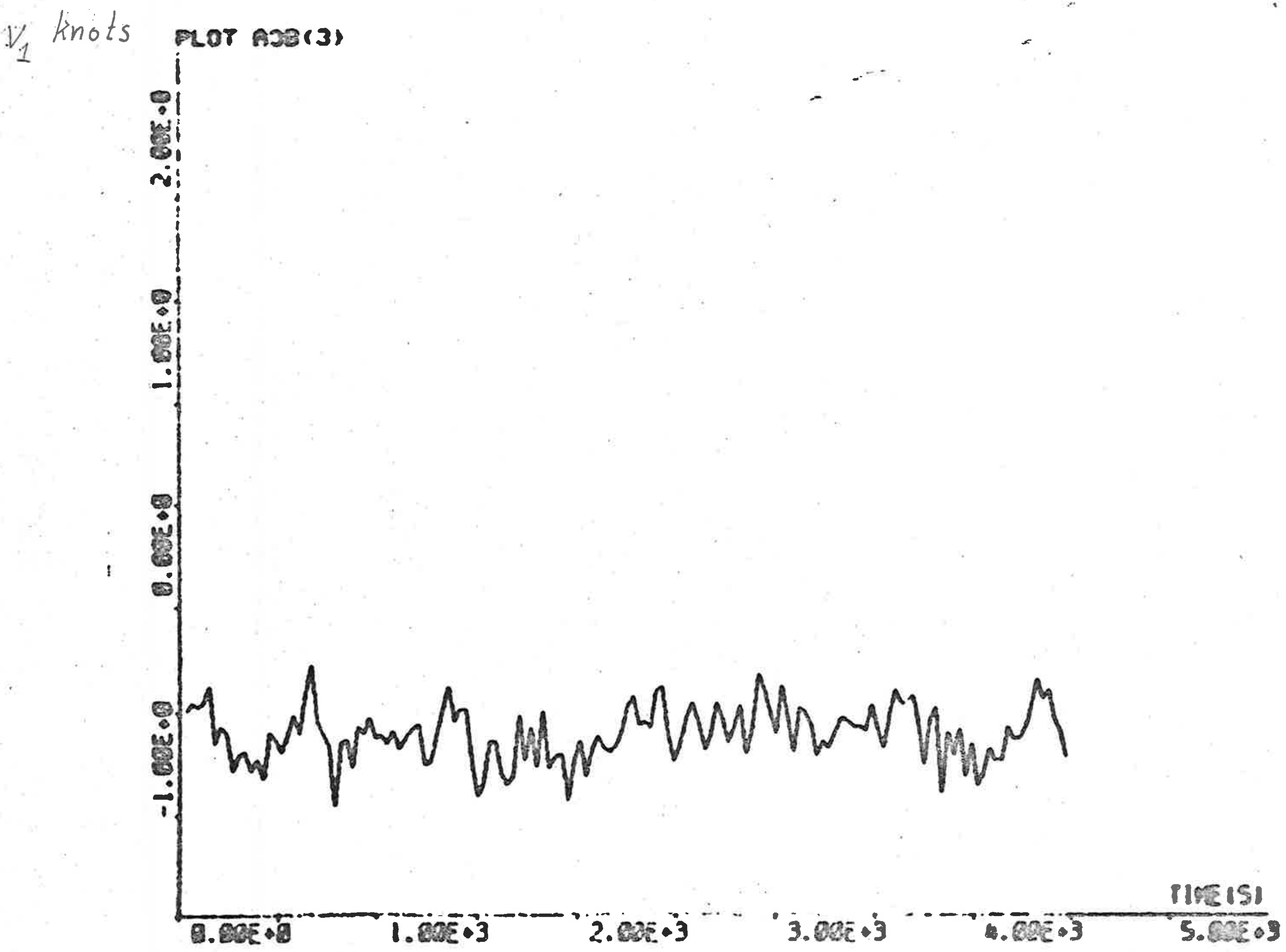
Statistics:

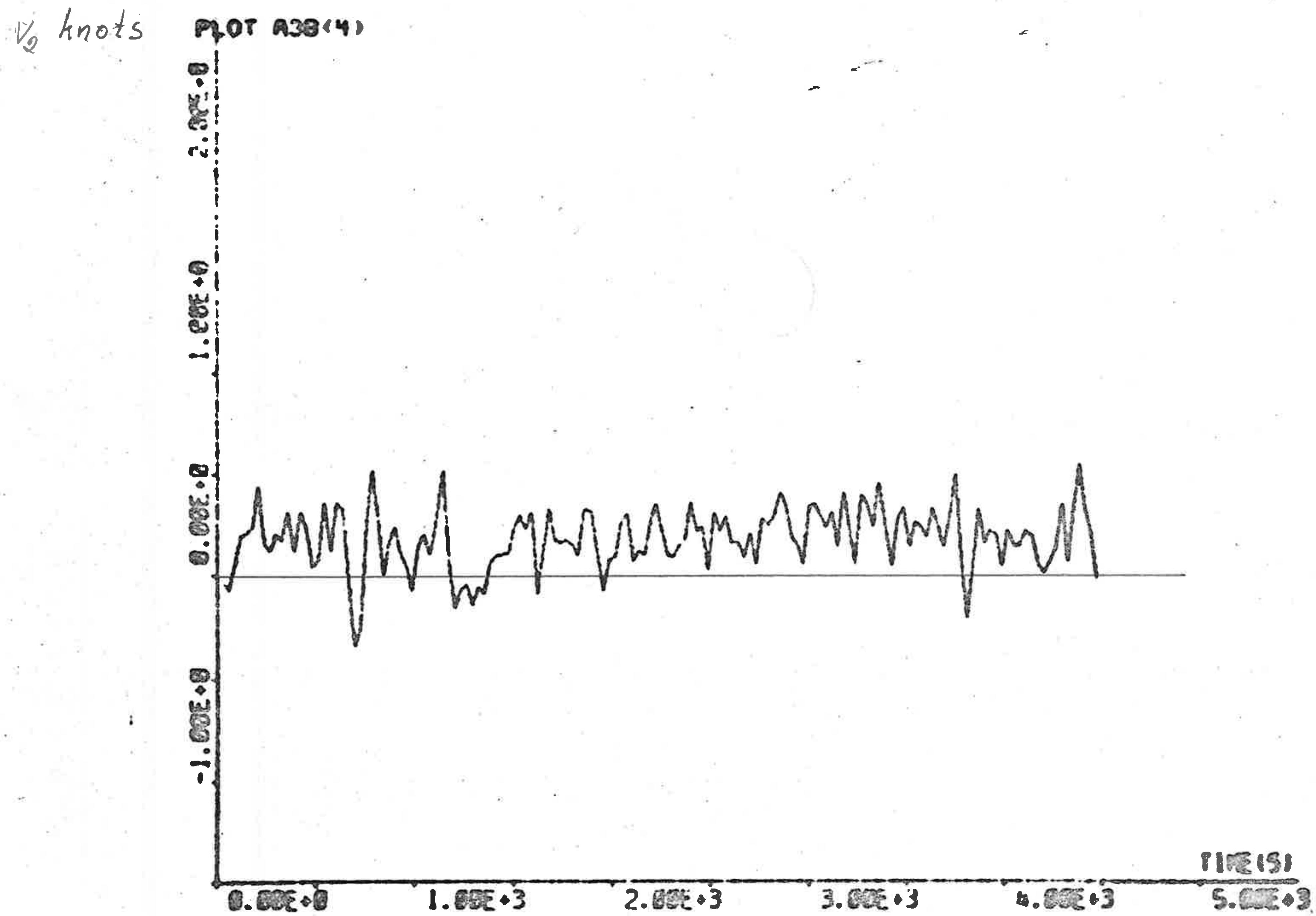
		Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-2.05	7.66	-24.2	21.1
δ_s	degr	-0.63	2.81	-3.3	3.3
δ	degr	-0.47	3.48	-4.1	4.6
v_1	knots	-0.605	0.129	-0.95	-0.28
v_2	knots	0.177	0.151	-0.34	0.55
r	degr/s	0.0076	0.0347	-0.063	0.097
Ψ	degr	142.147	0.522	140.71	143.88
u	knots	16.640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

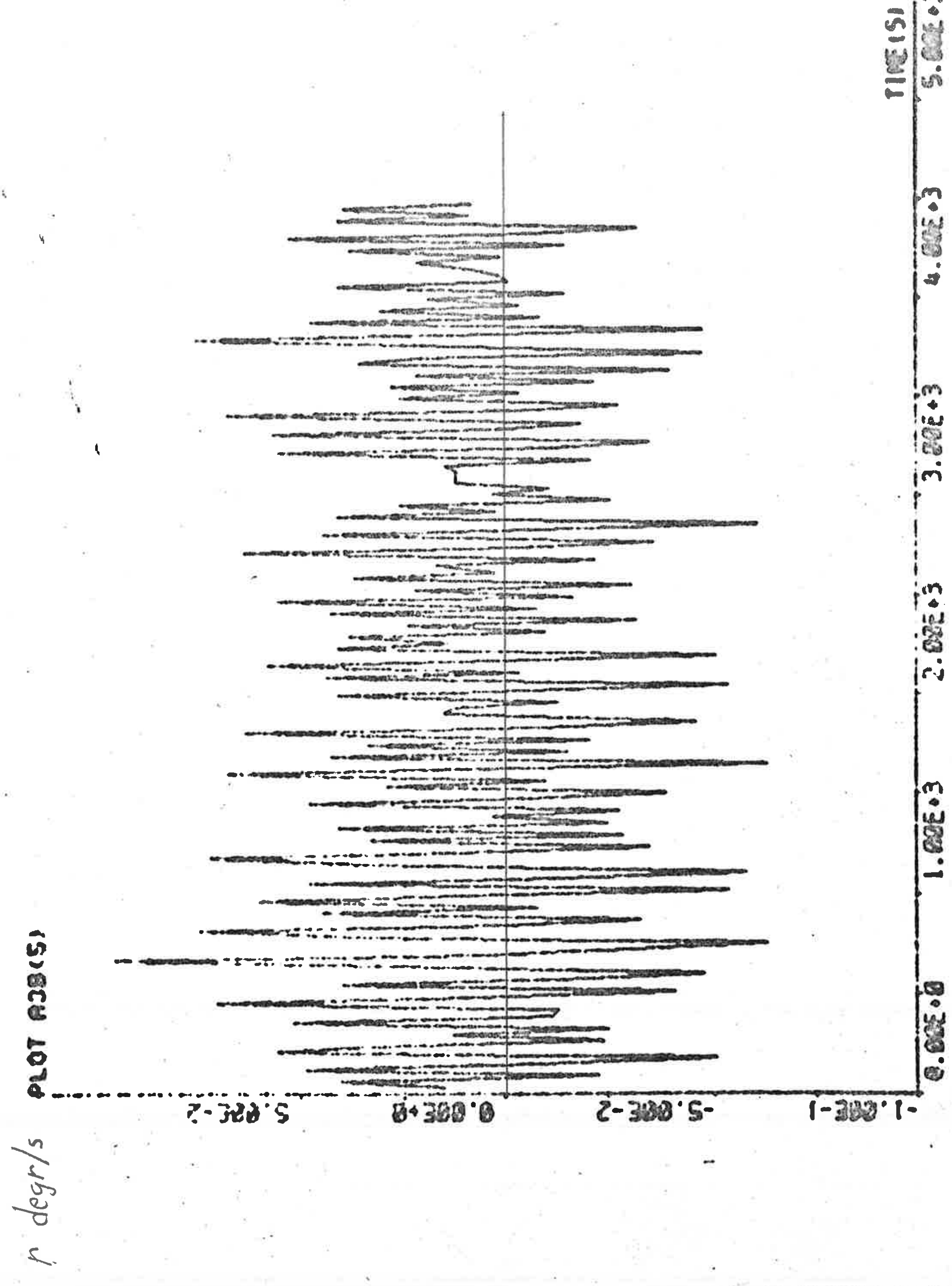

PLOT XP ADS(1)
-2.00E+1
0.00E+0
2.00E+1
4.00E+1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
+3°
0°
-3°
δ_{com} degr

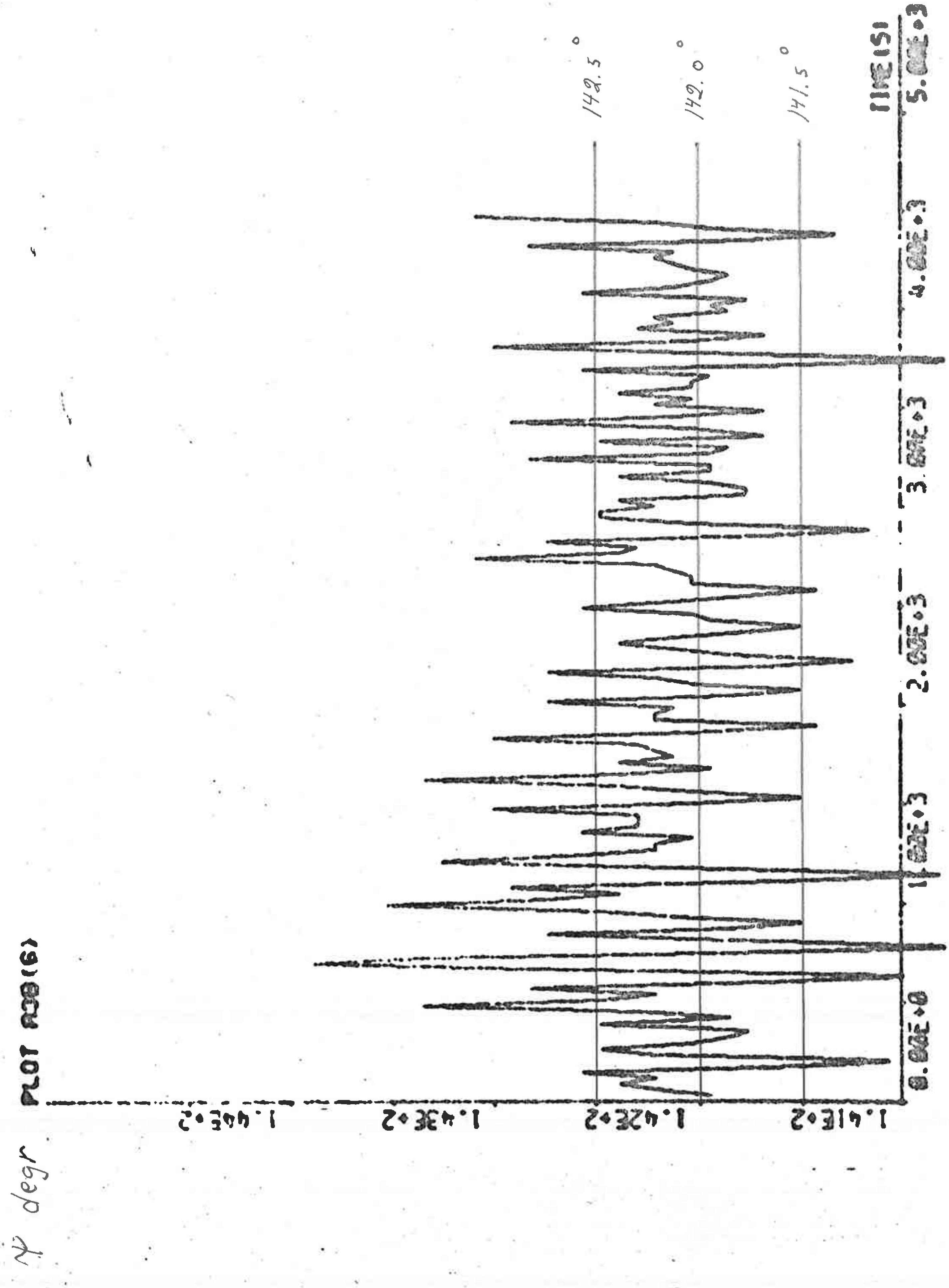

PLOT A3B(1)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
+3°
0°
-3°
δ_s degr

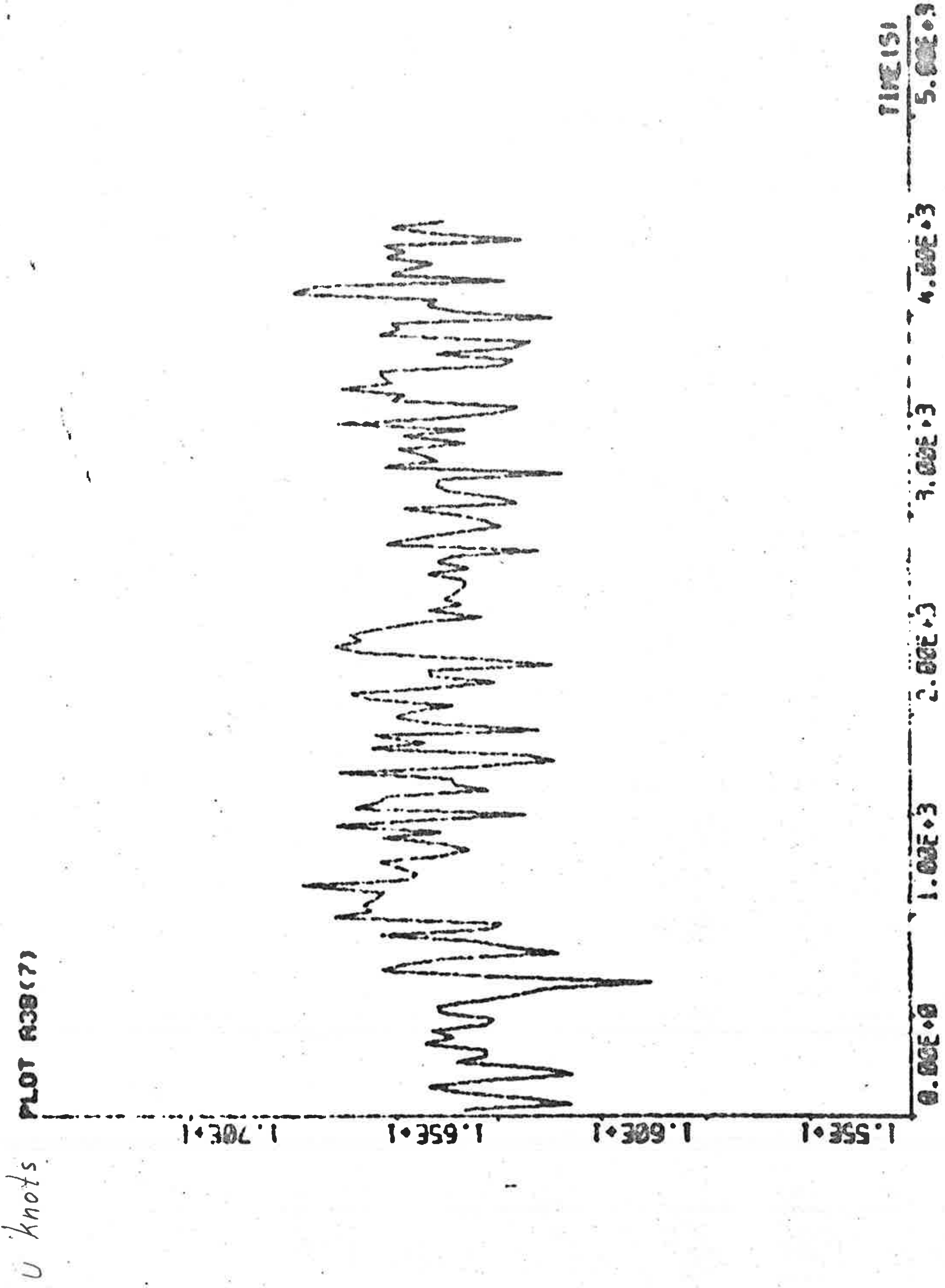

δ degr
PLOT A38(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

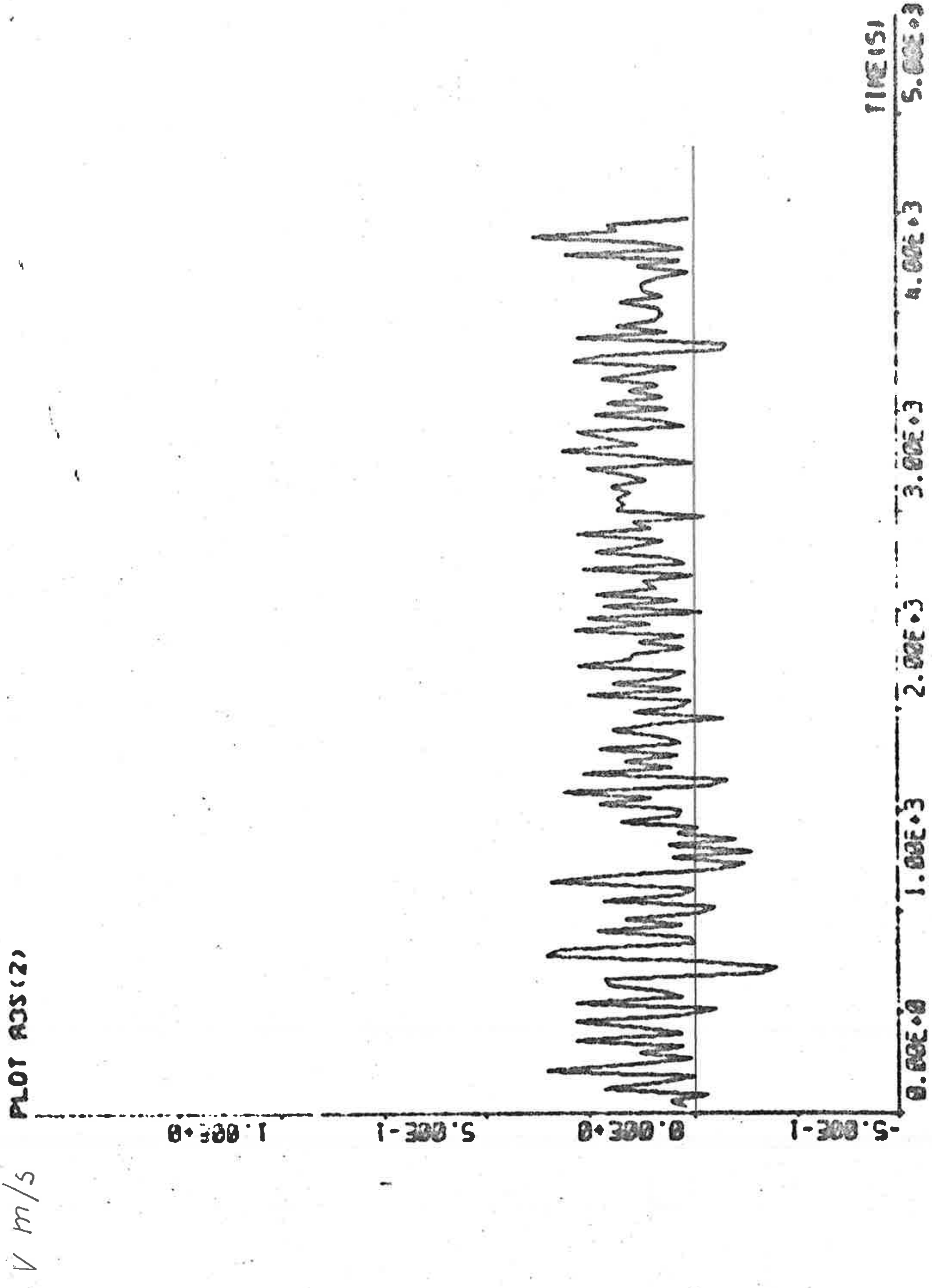

V_1 knots
PLOT A3B(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)


V_g knots
PLOT A38(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)

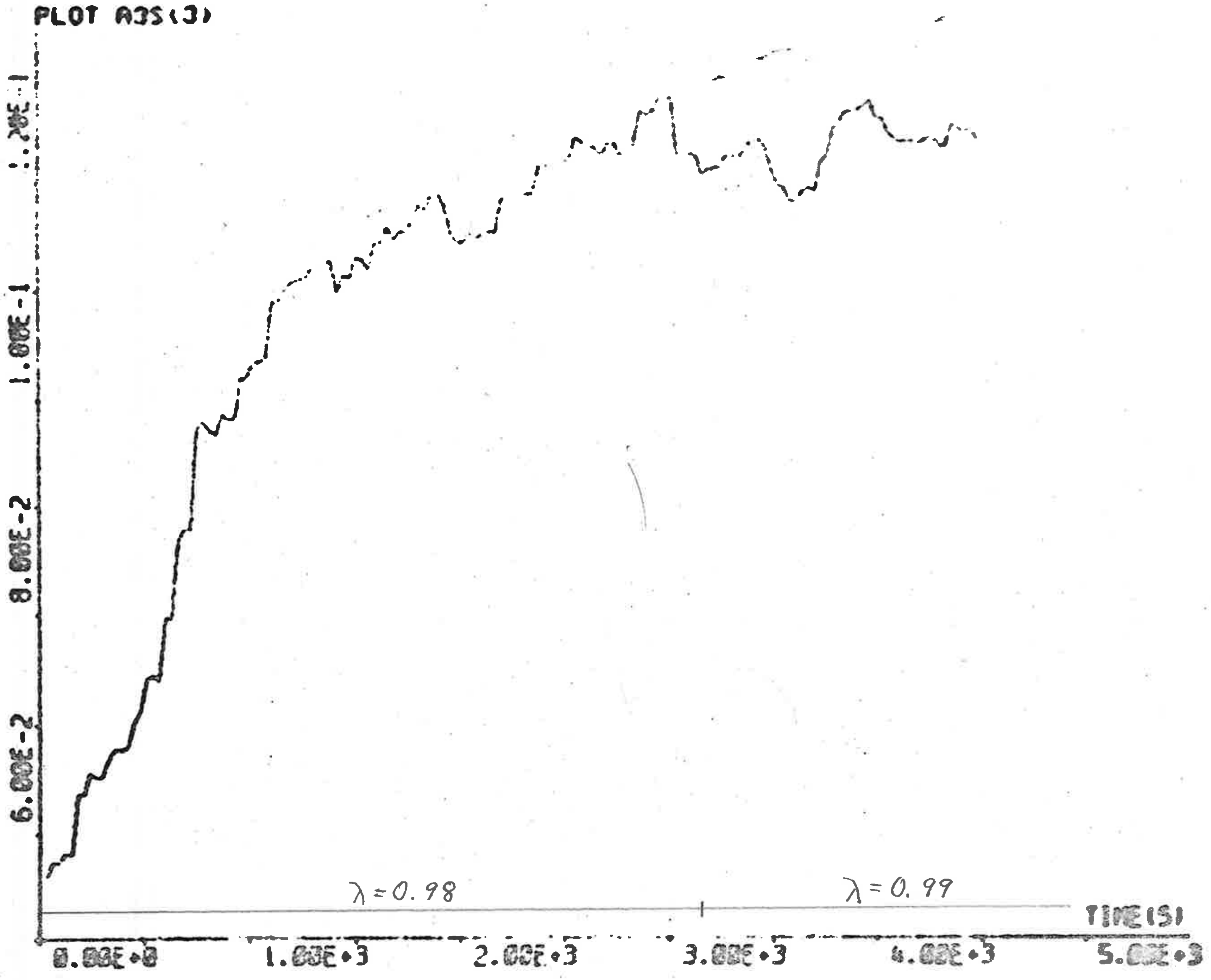

PLOT A3B(S)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
r degr/s

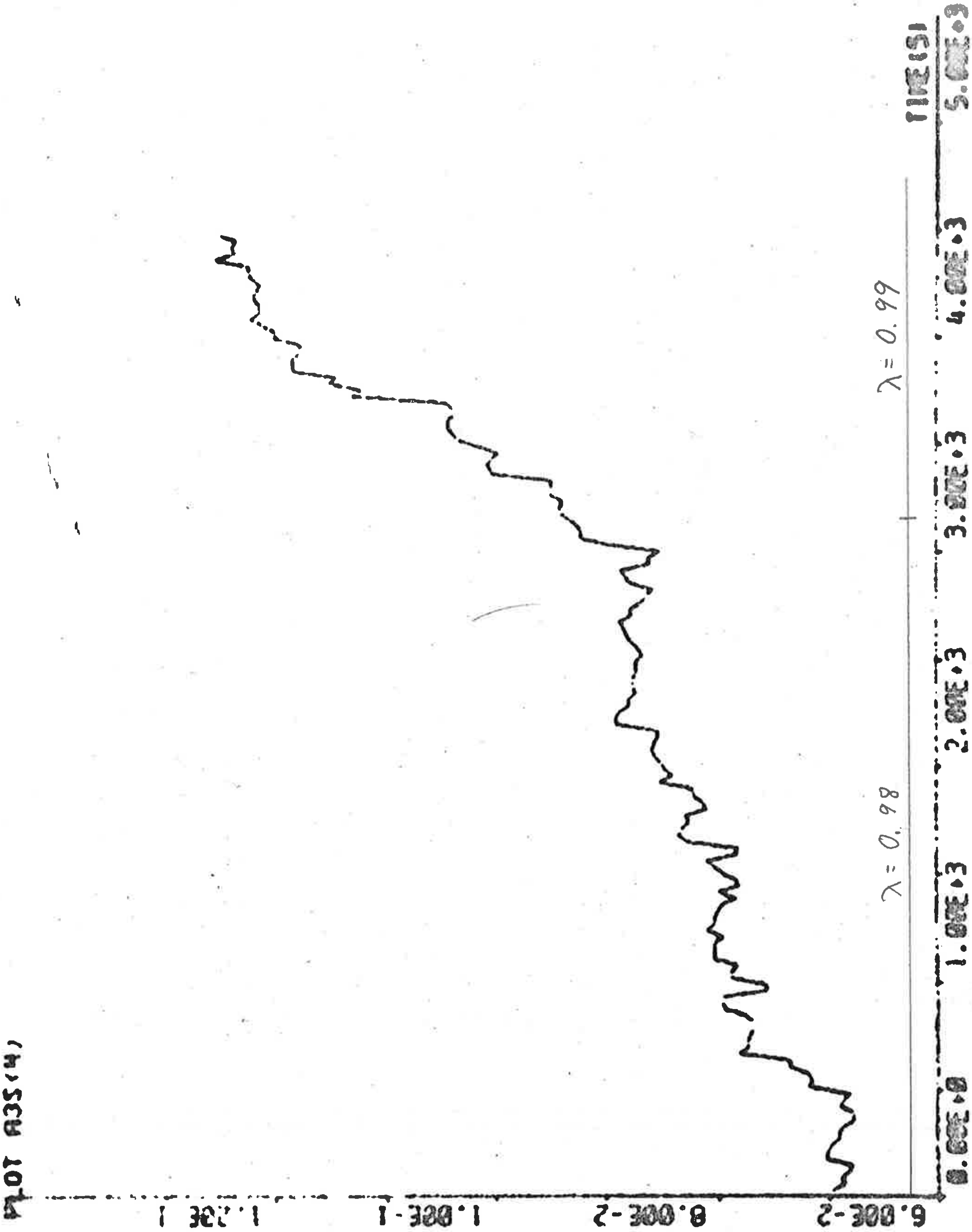

PLOT A3B(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
142.5°
142.0°
141.5°
ψ degr


PLOT A38(7)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.55E+1
1.60E+1
1.65E+1
1.70E+1
U knots

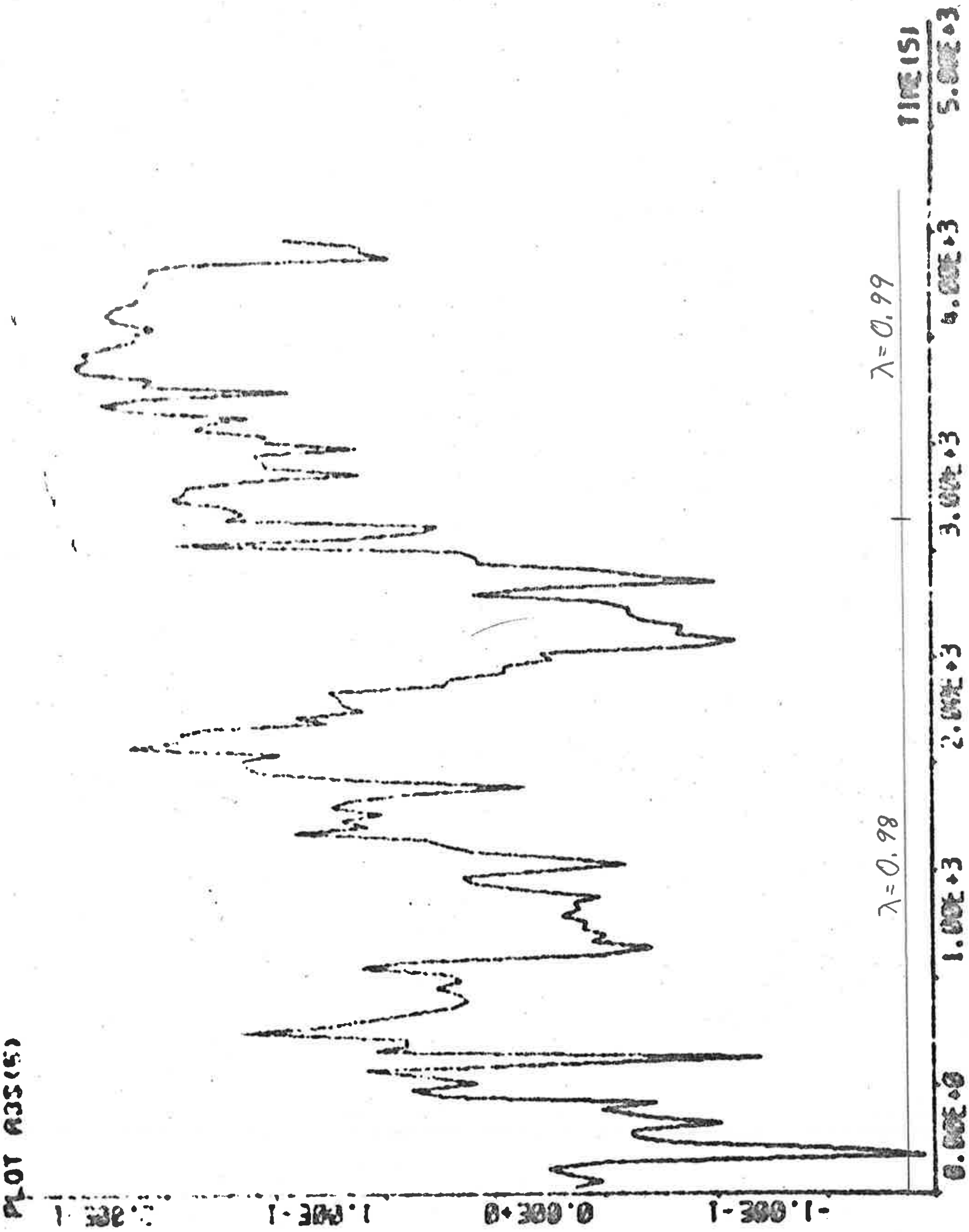

PLOT A3S(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
V m/s

b_1

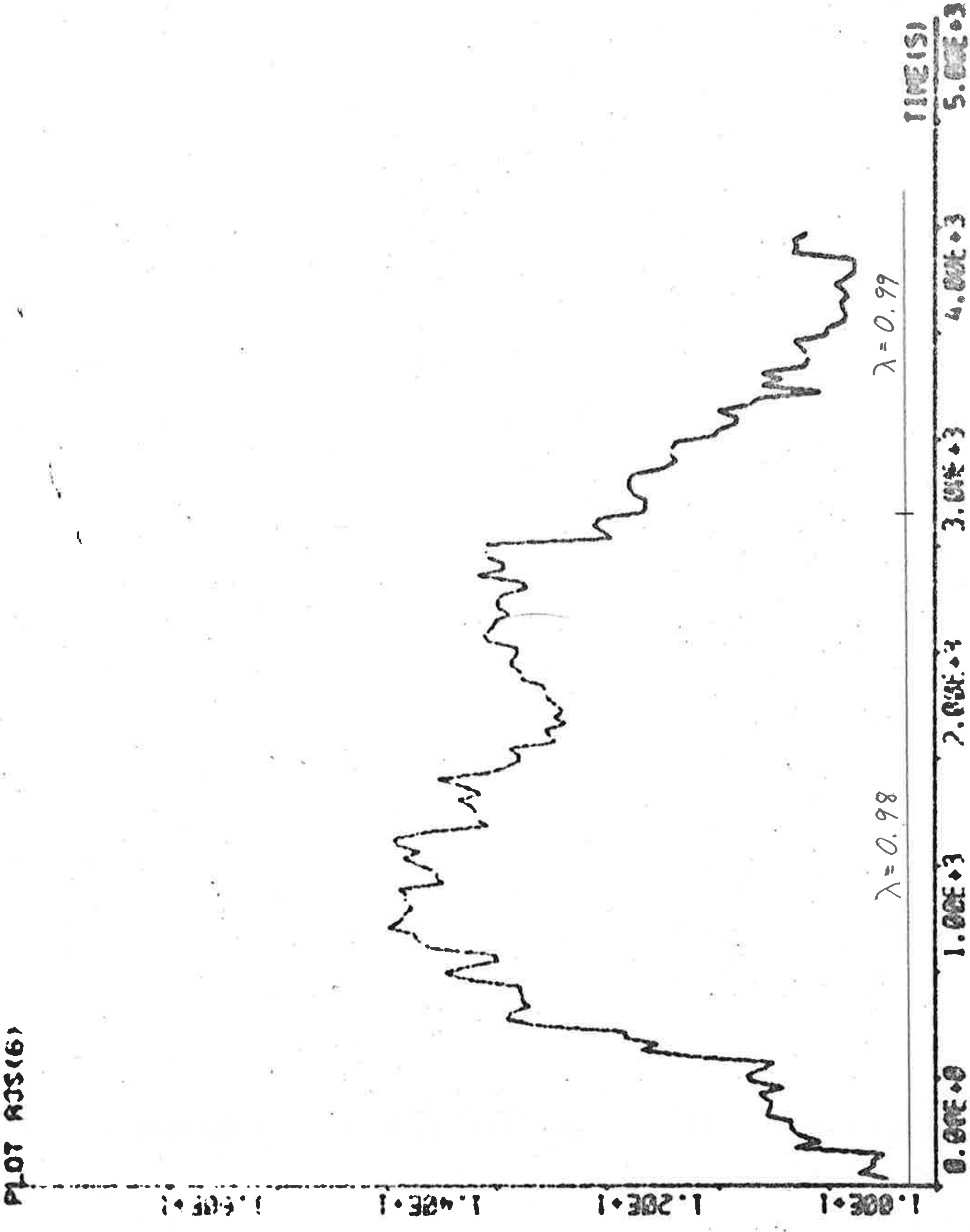

PLOT A3S(3)
1.20E-1
1.00E-1
8.00E-2
6.00E-2
λ = 0.98
λ = 0.99
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


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


PLOT R3S(5)
TIME (S)
2.000E-1
1.000E-1
0.000E+0
-1.000E-1
0.000E+0
1.000E+3
2.000E+3
3.000E+3
4.000E+3
5.000E+3
λ = 0.98
λ = 0.99

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
1.000E+1
1.200E+1
1.400E+1
1.600E+1
λ = 0.98
λ = 0.99

d_2

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:

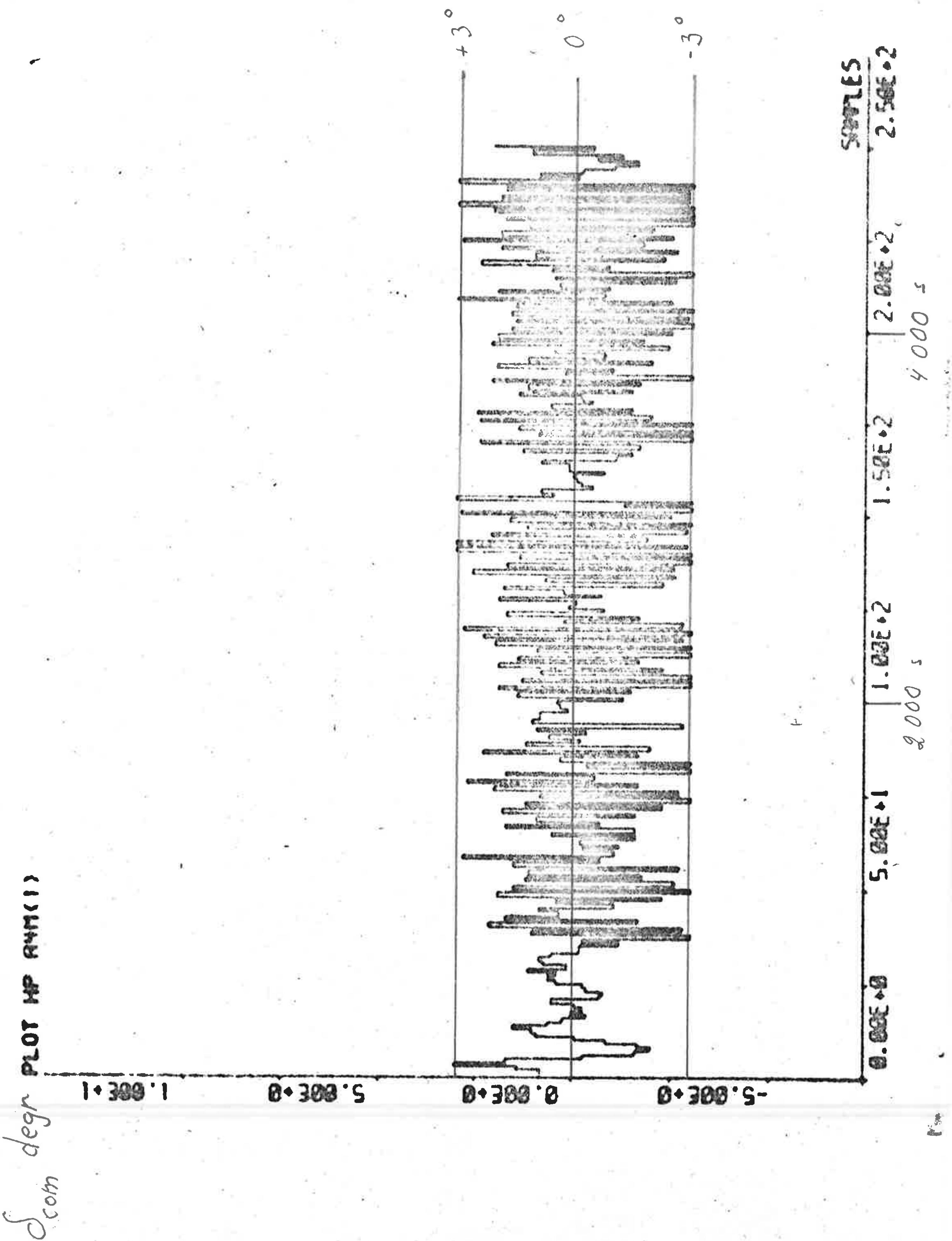
$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix} = \begin{bmatrix} 0.1199 \\ 0.1598 \\ 1.9656 \\ -1.7123 \\ -18.5008 \\ 2.3772 \end{bmatrix} \qquad P \text{ unknown}$$

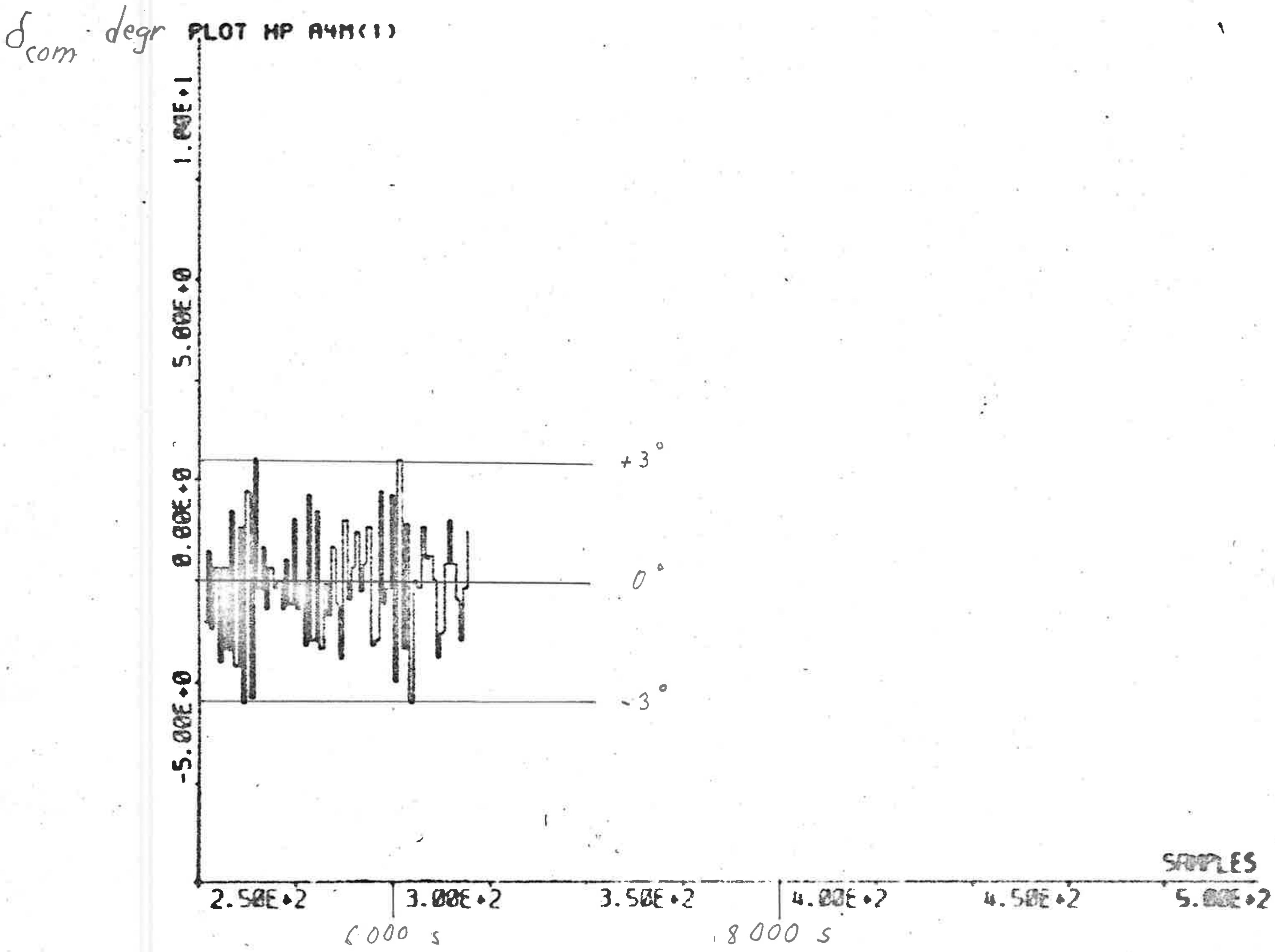
Regulator:

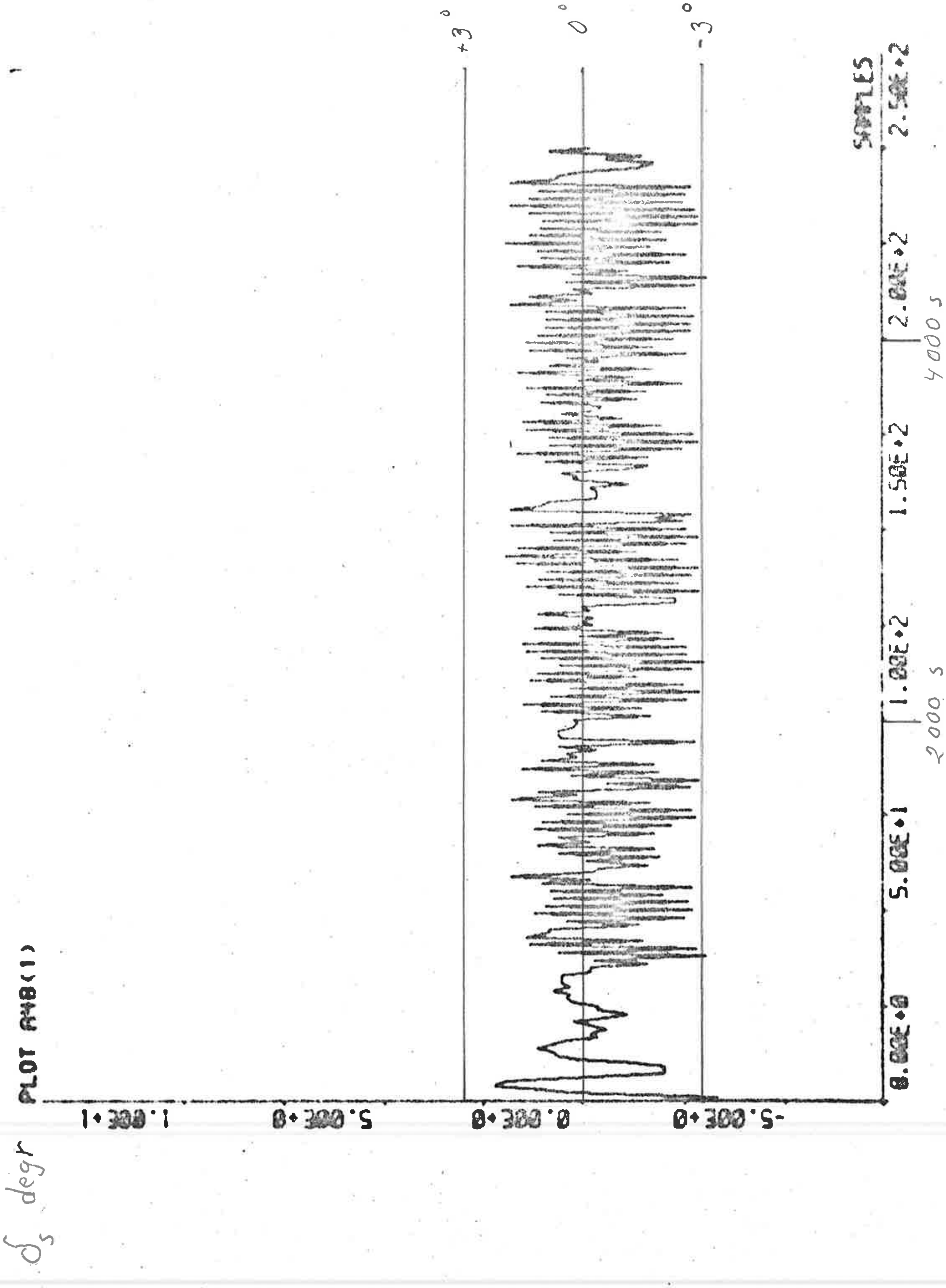
$$\delta(t) = -8.3403(\Psi(t) - \Psi_{ref}) - 1.3328\delta(t-1) - 16.3937\hat{v}(t) + $$
$$+ 14.2811\hat{r}(t) + 154.3019\hat{F}(t) - 19.8265\hat{M}(t)$$

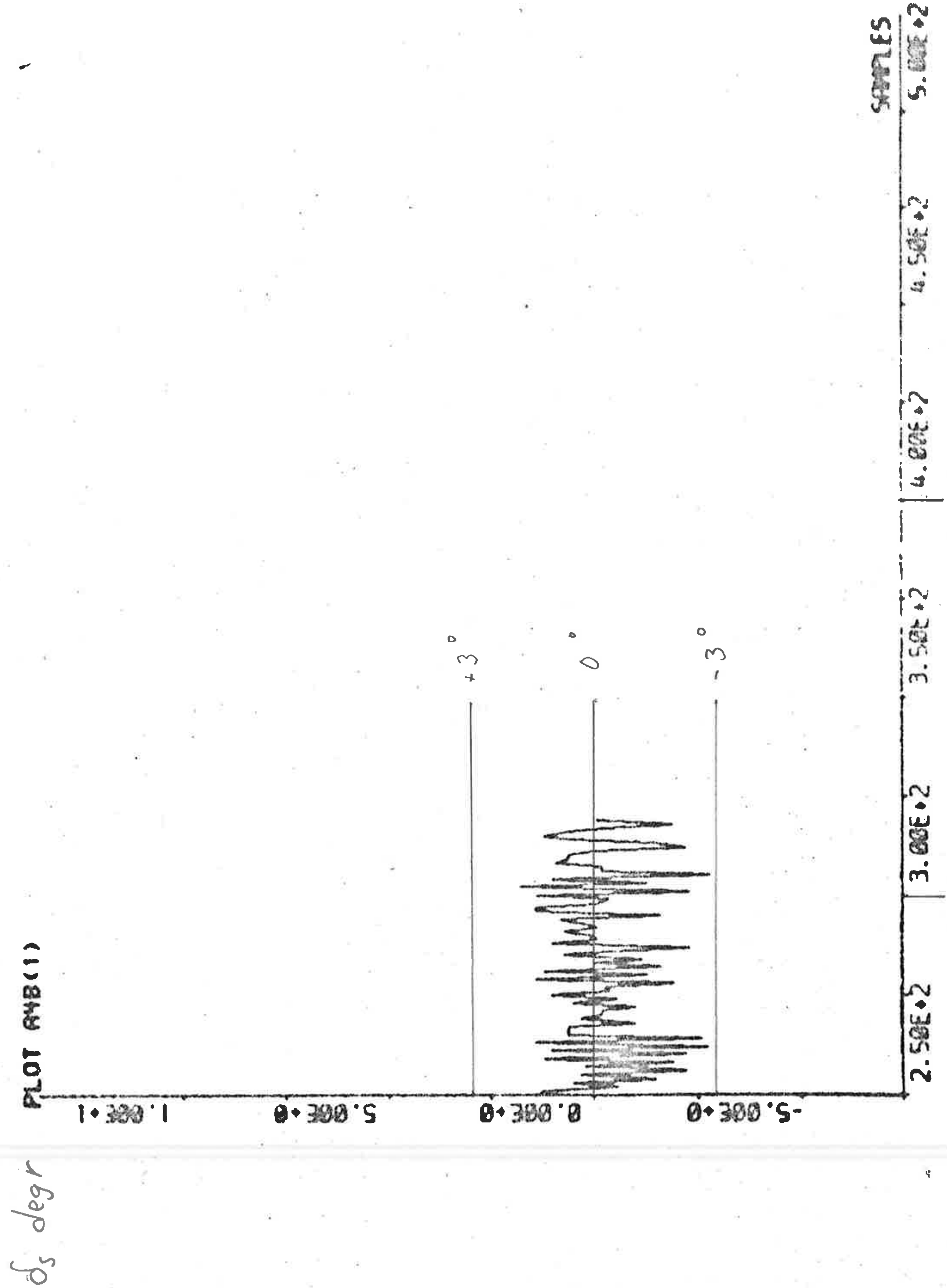
Statistics:

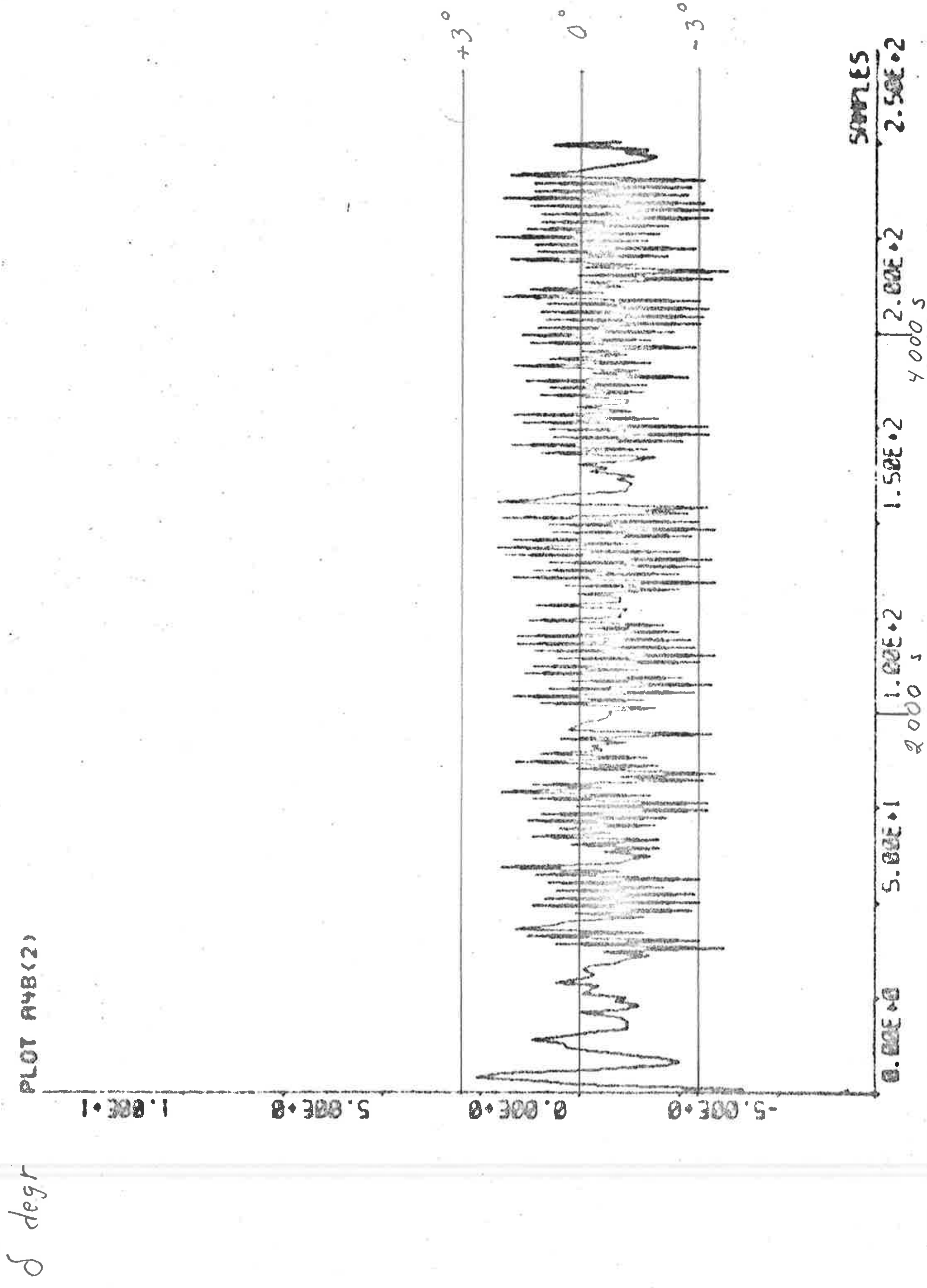
		0 - 6360 s (all data)				4000 - 6360 s			
		Mean value	Standard deviation	Minimum value	Maximum value	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	-0.18	1.73	-3.0	3.0	-0.17	1.73	-3.0	3.0
δ_s	degr	-0.38	1.47	-3.3	2.2	-0.33	1.45	-3.1	1.9
δ	degr	-0.65	1.58	-4.1	2.6	-0.63	1.55	-3.7	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

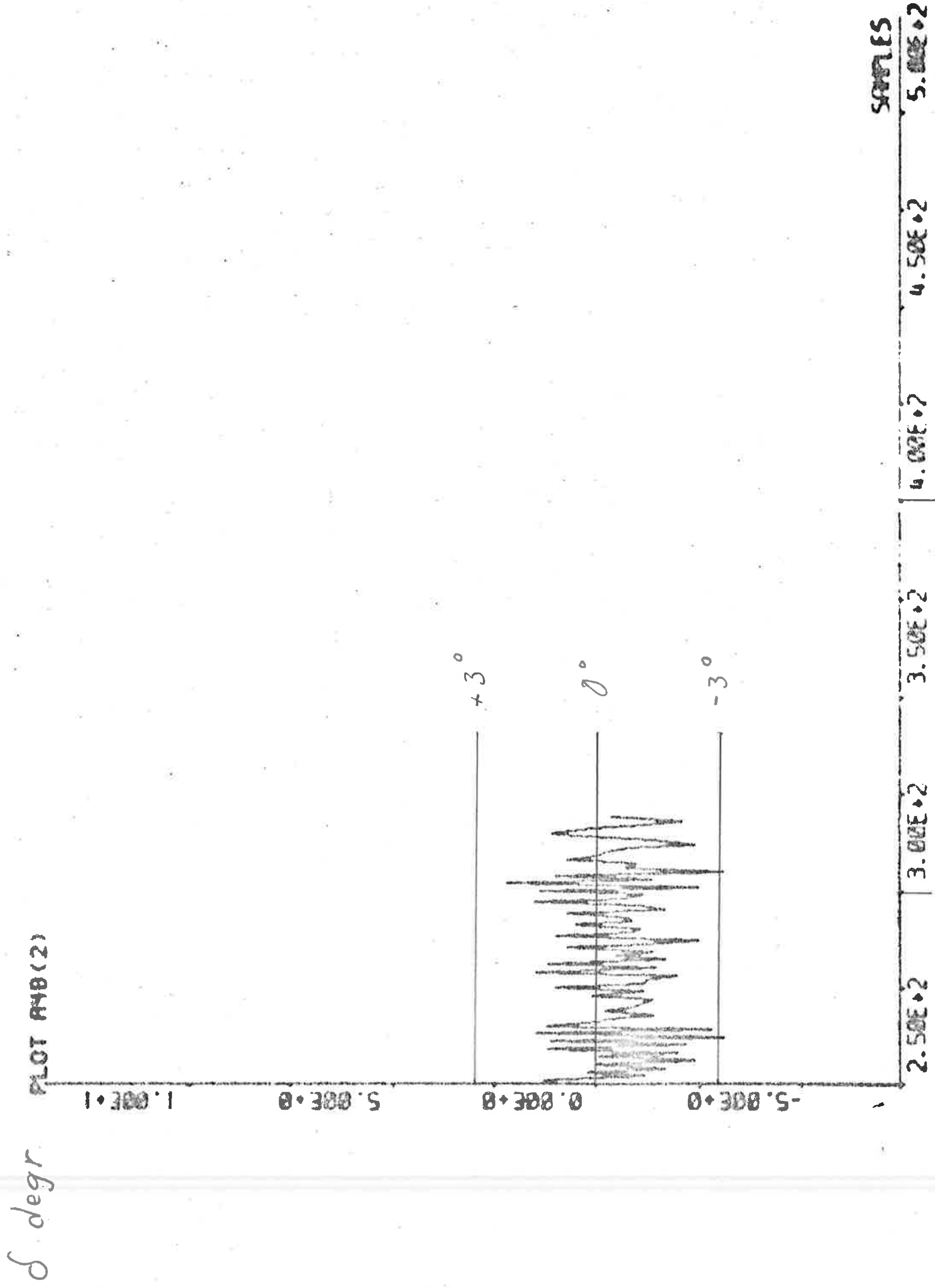

PLOT HP R4M(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
+3°
0°
-3°
2000 s
4000 s
δcom degr

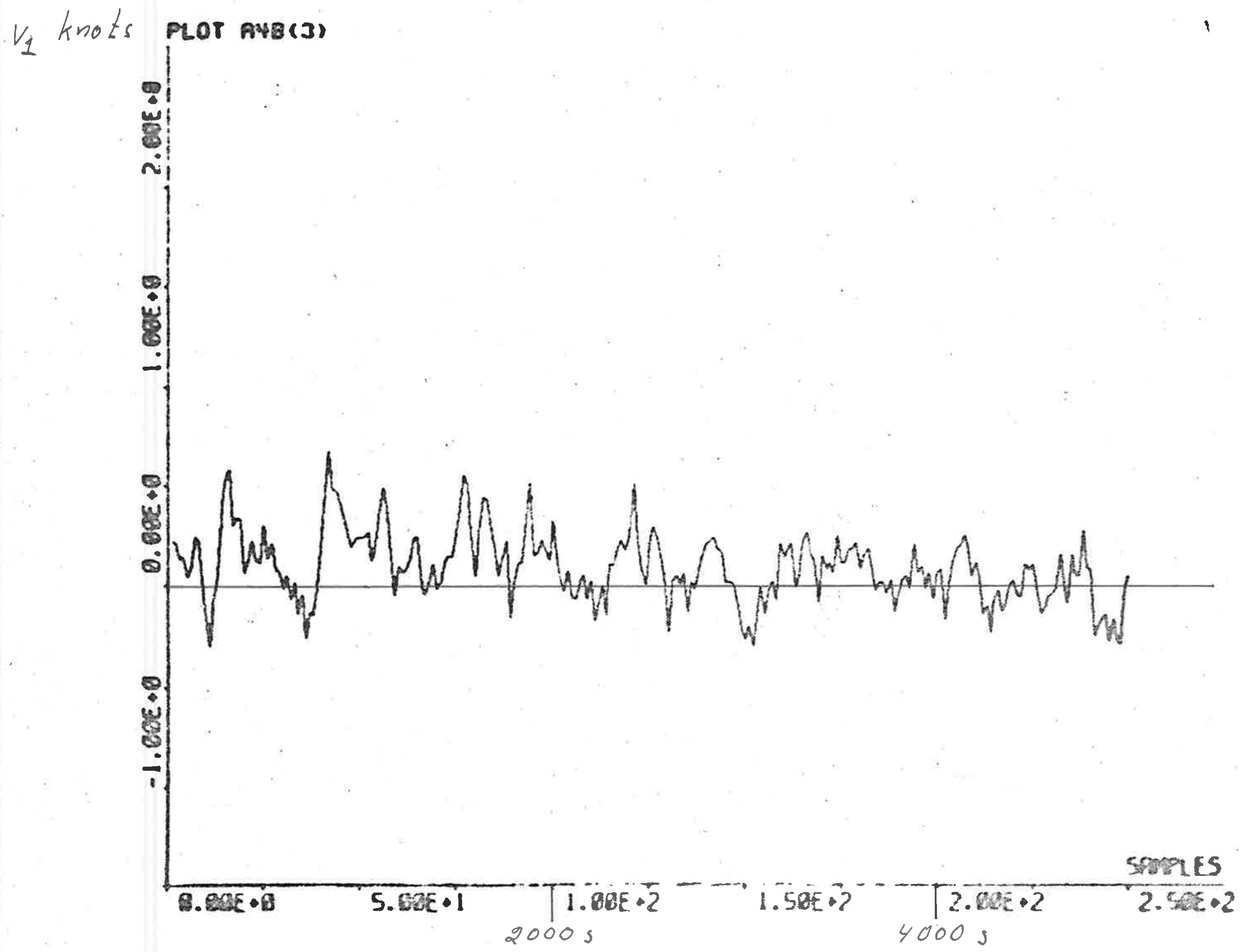

δ_{com} · degr
PLOT HP A4M(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

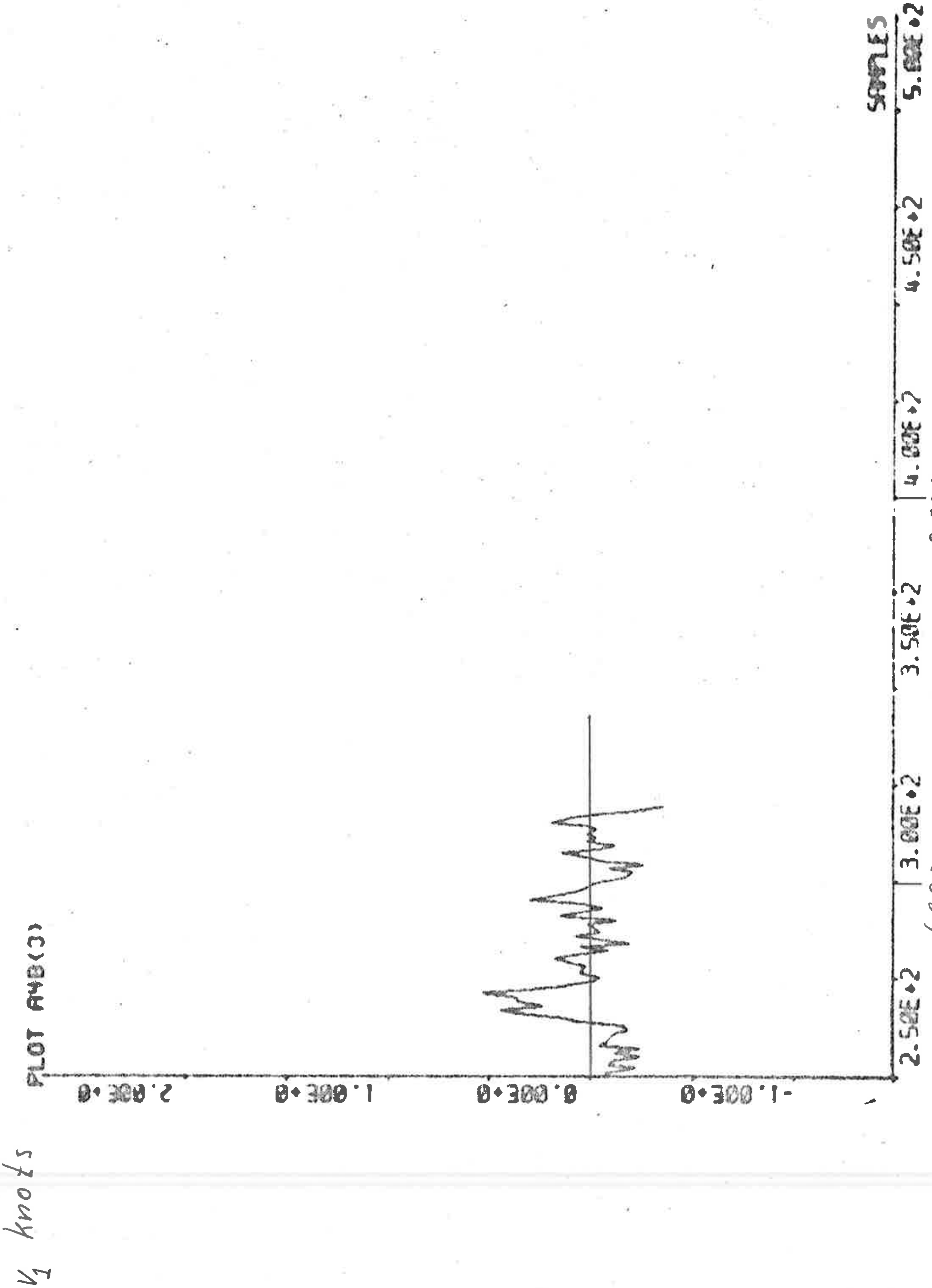

PLOT A+B(1)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
δ_s degr

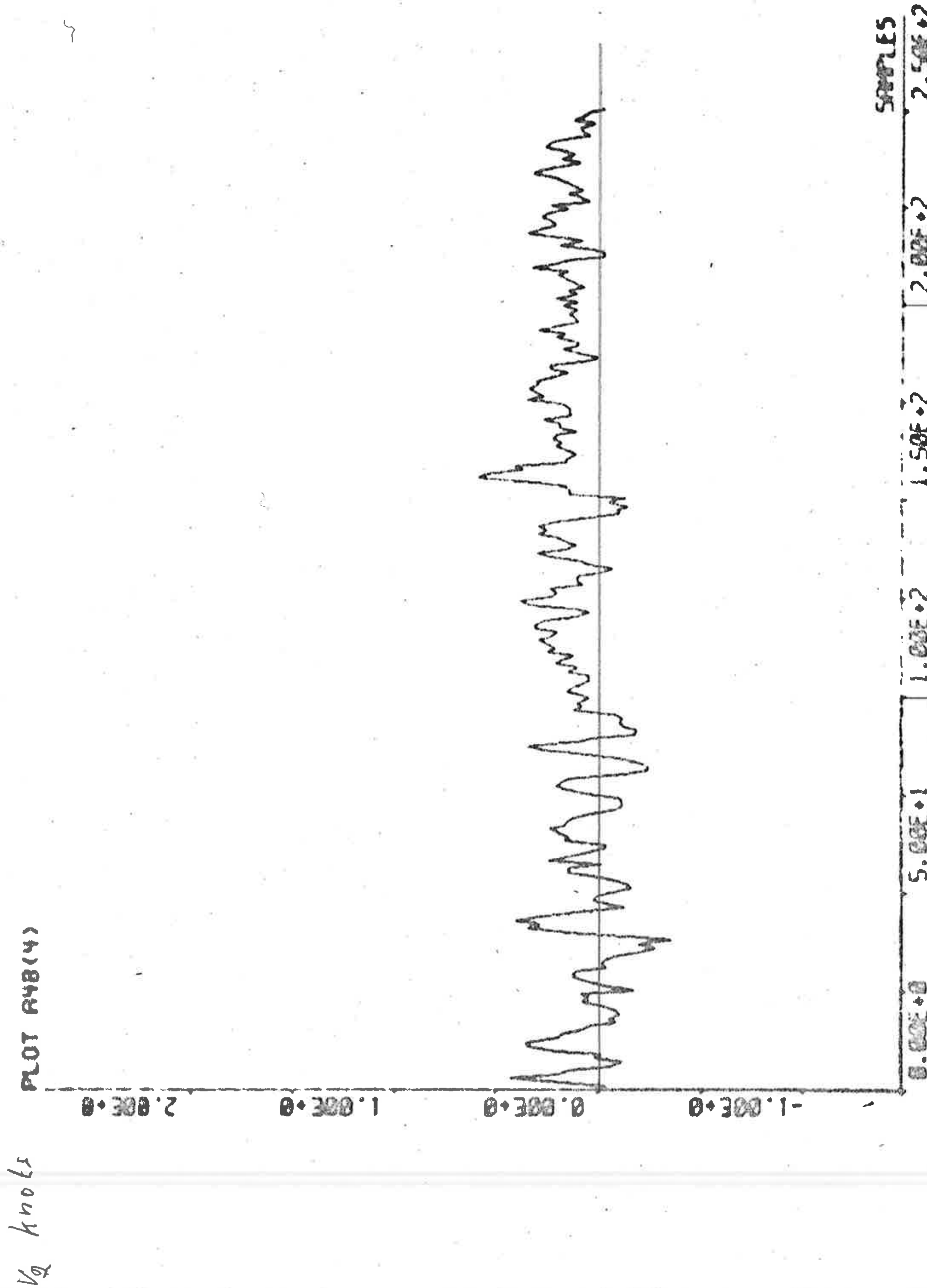

PLOT AYB(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
SAMPLES
+3°
0°
-3°
6000 s
8000 s
δs degr

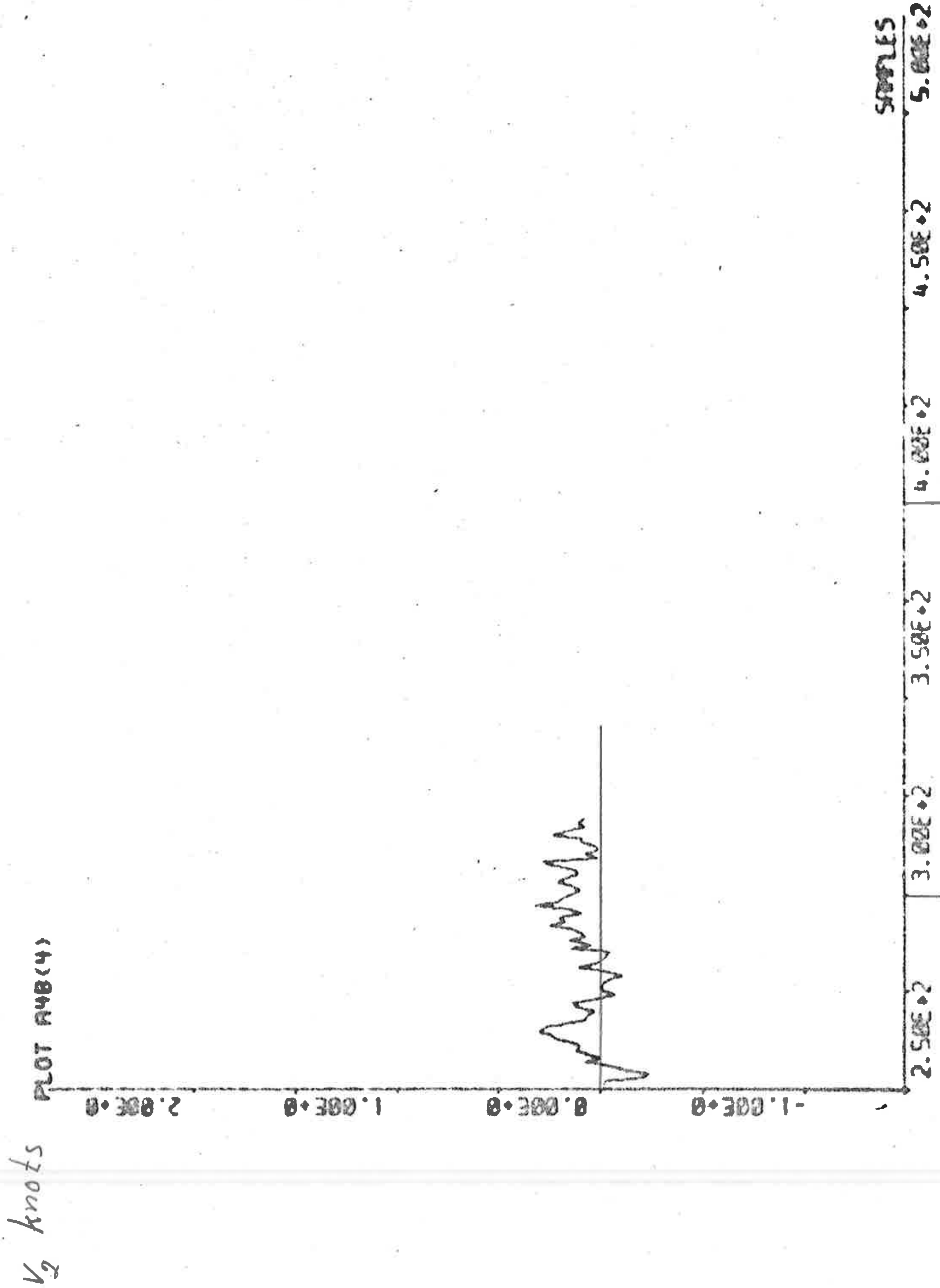

PLOT A4B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr
+3°
0°
-3°
0.00E+0
5.00E+1
1.00E+2
2000 s
1.50E+2
2.00E+2
4000 s
2.50E+2
SAMPLES

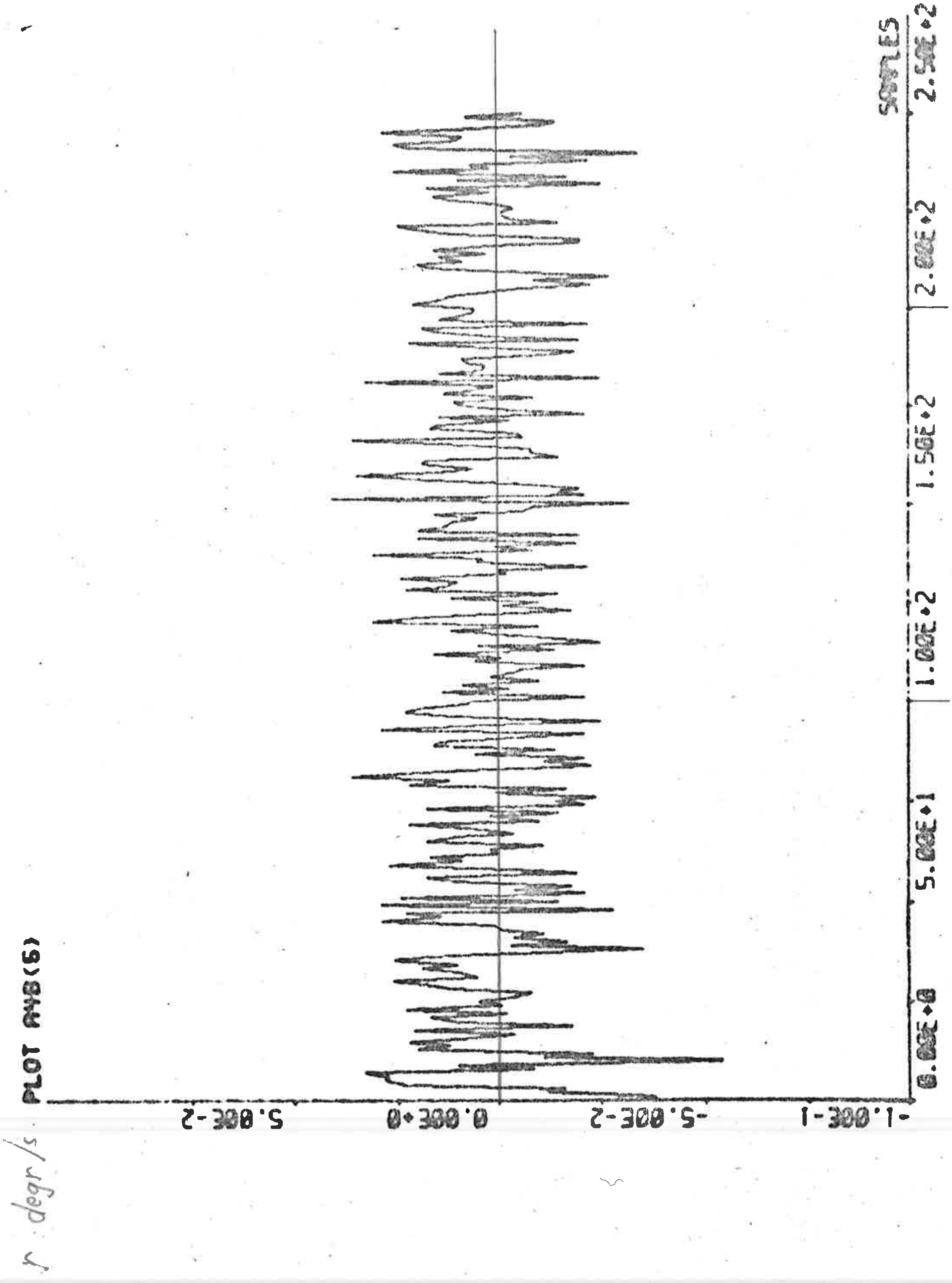

PLOT A4B(2)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
+3°
0°
-3°
6000 s
8000 s
δ degr

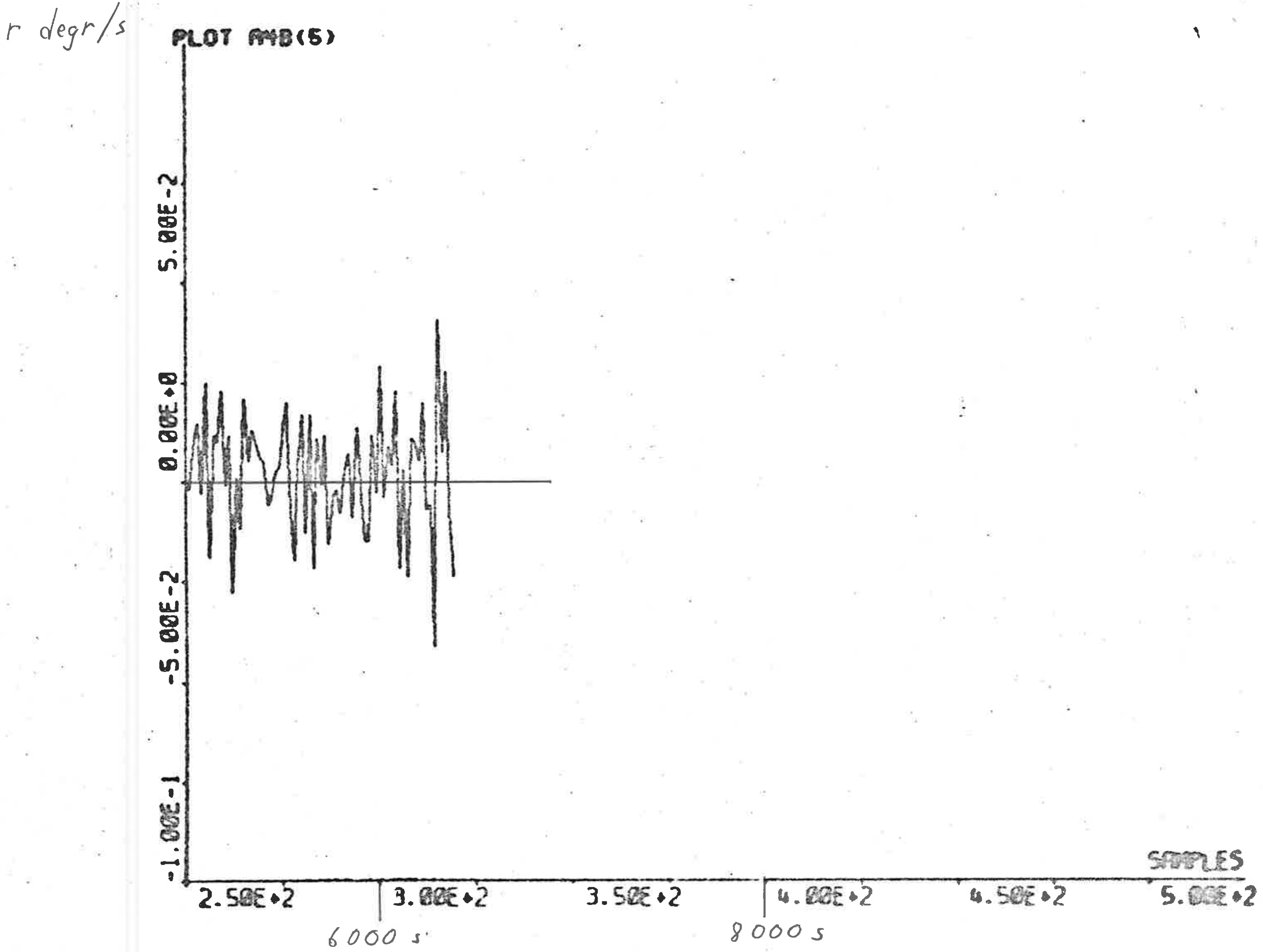

V1 knots
PLOT AVB(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

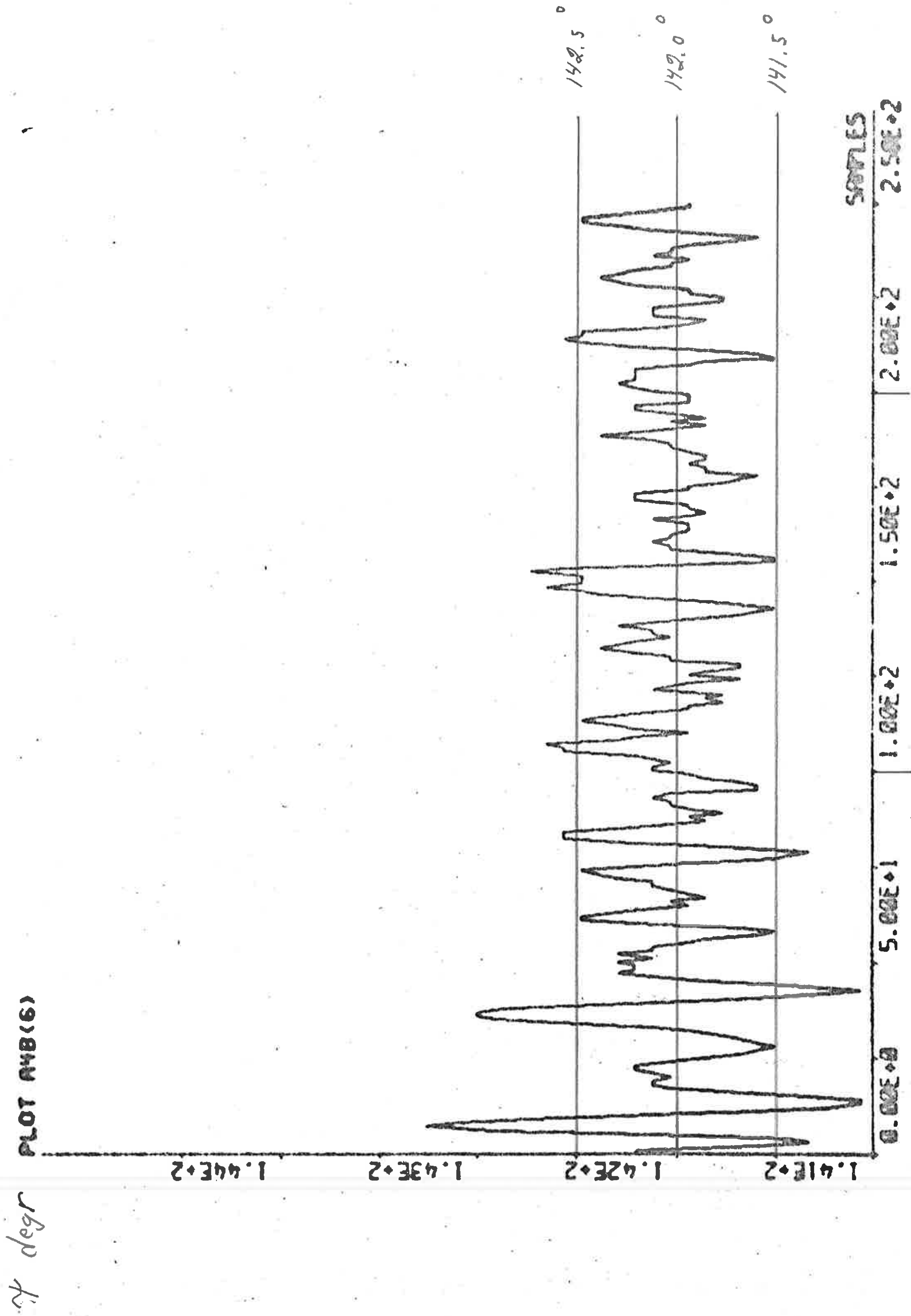

PLOT A4B(3)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_1 knots

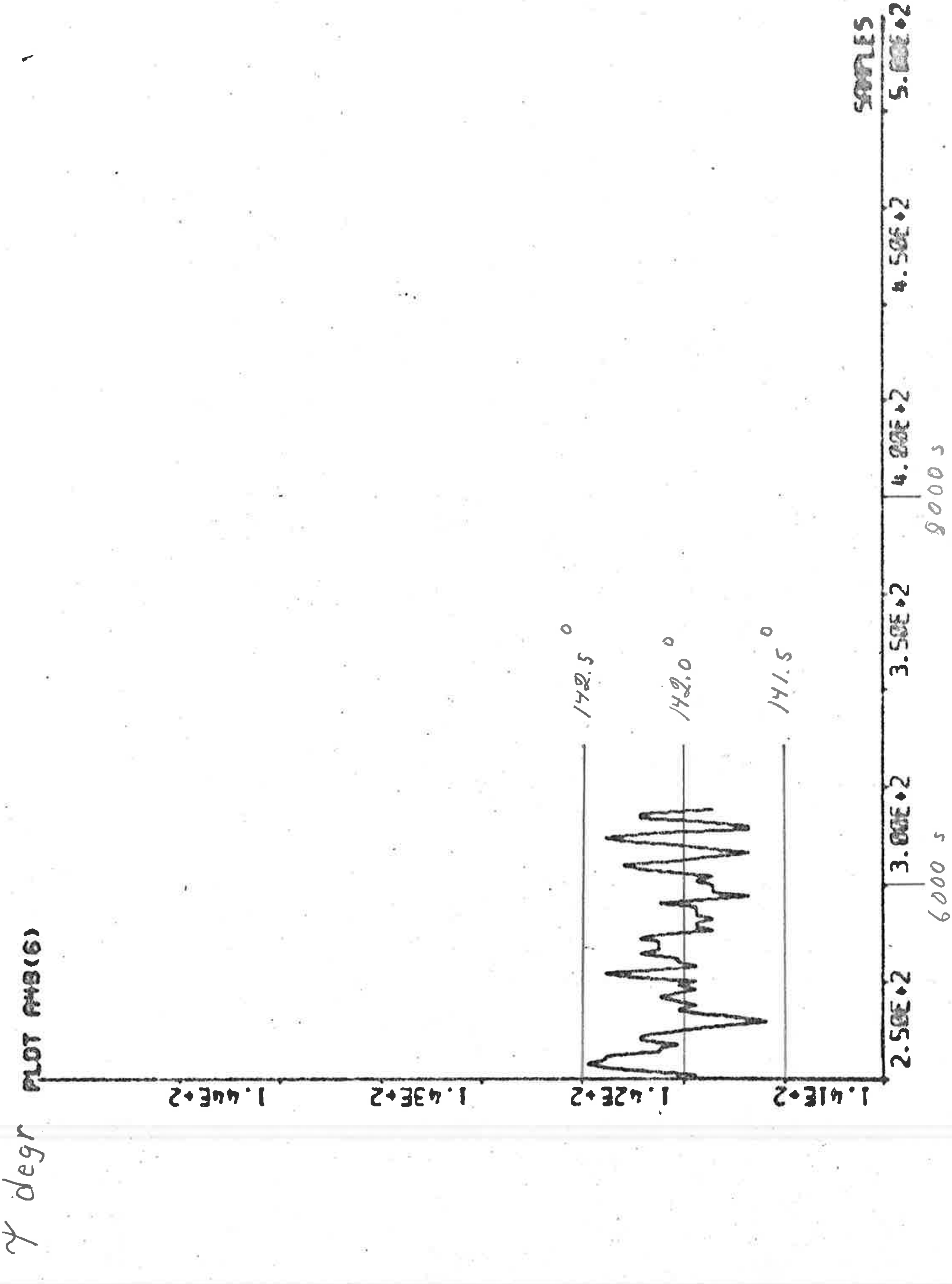

PLOT A4B(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
V_2 knots

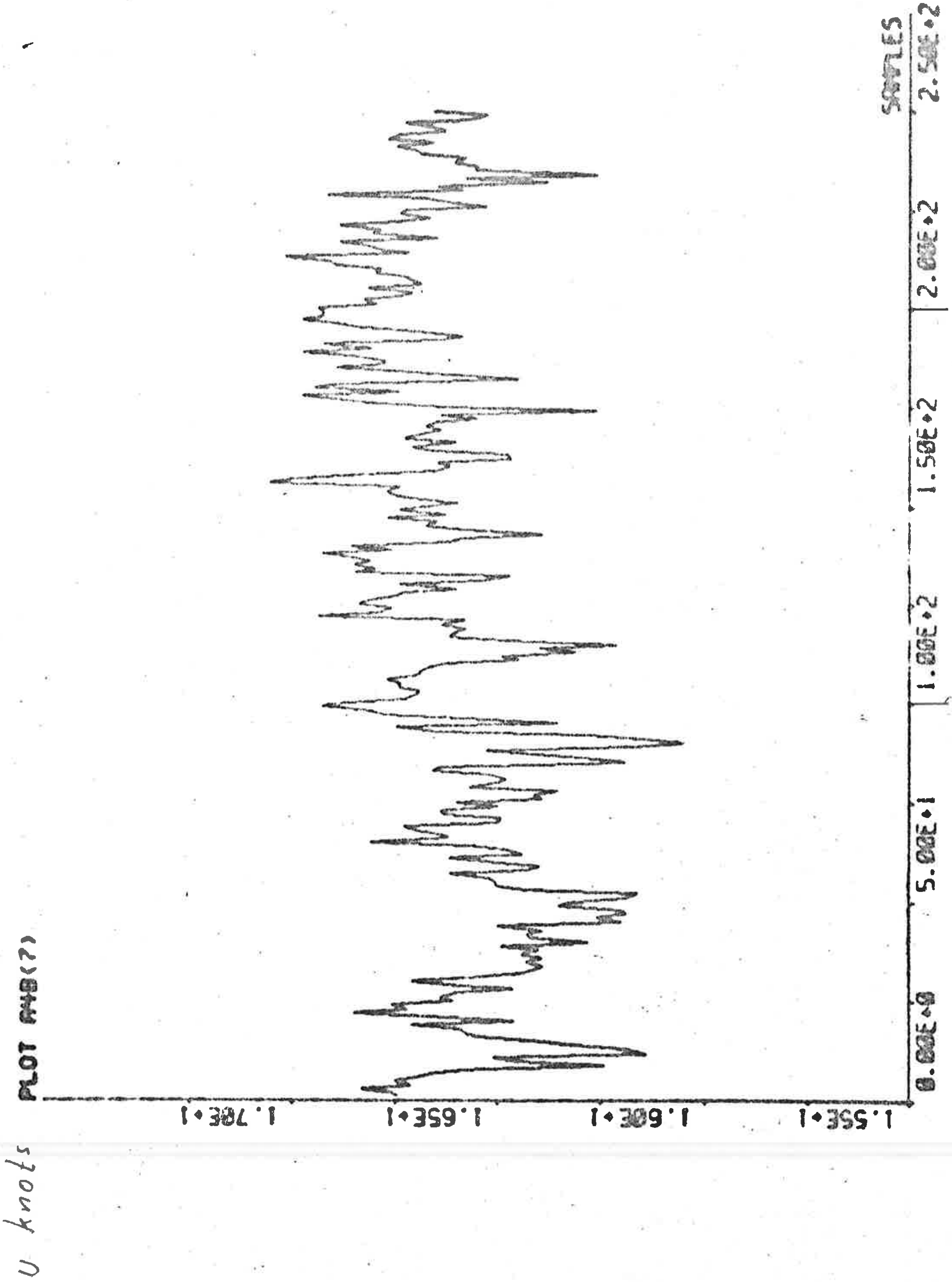

PLOT A4B(4)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
6000 s
8000 s
V_z knots

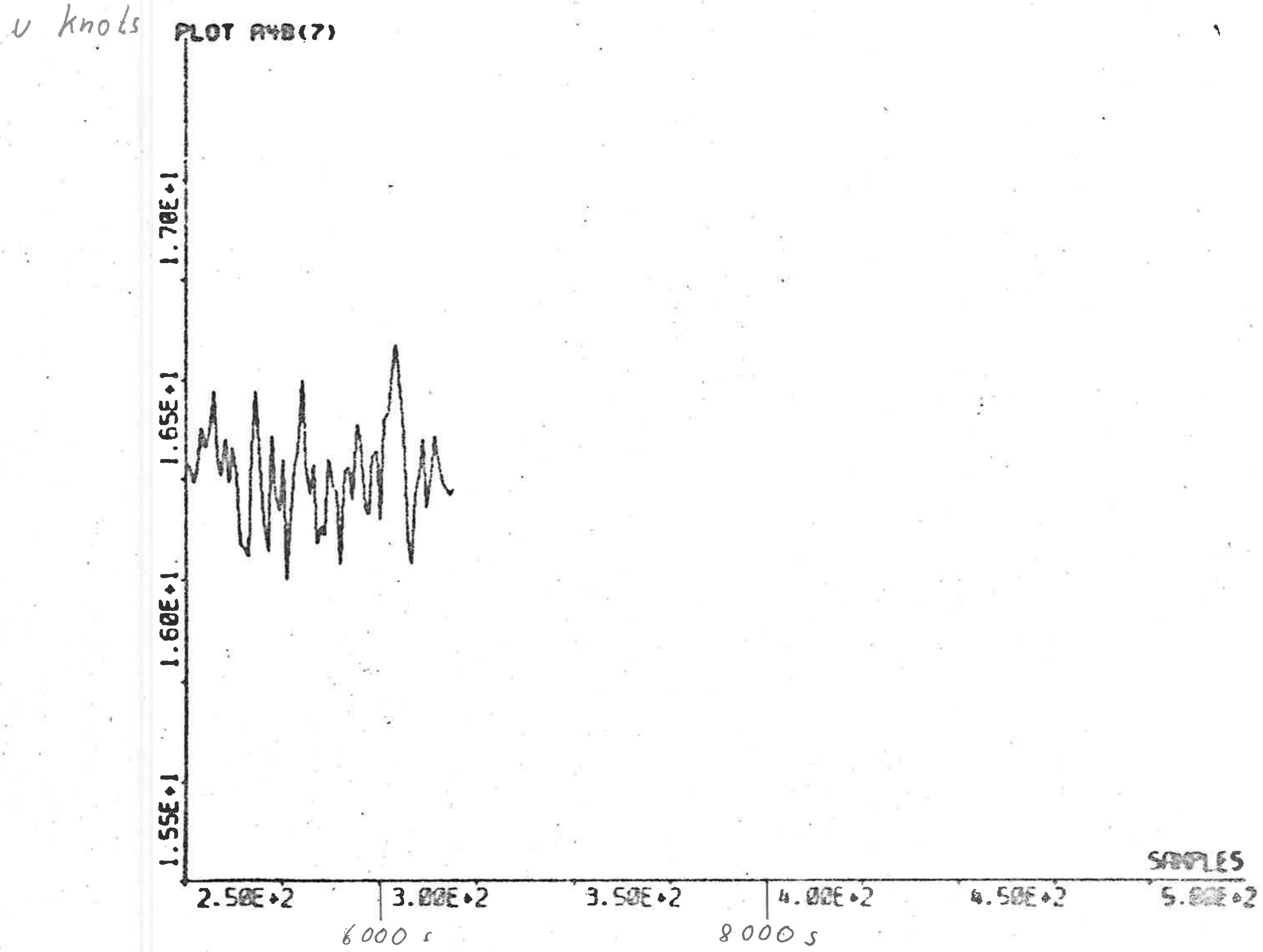

PLOT AYB(5)
-1.00E-1
-5.00E-2
0.00E+0
5.00E-2
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
r degr/s

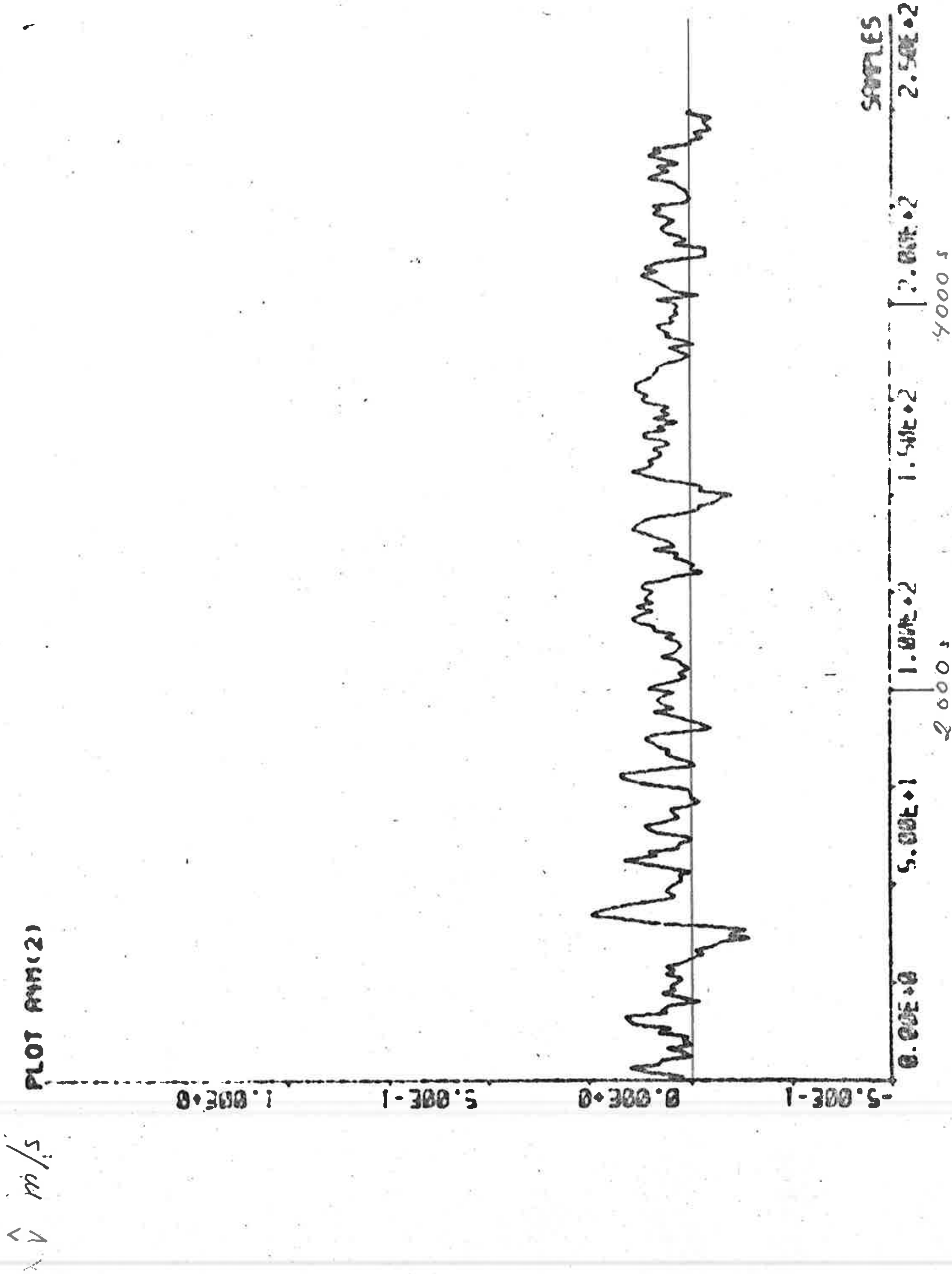

r degr/s
PLOT AMB(5)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

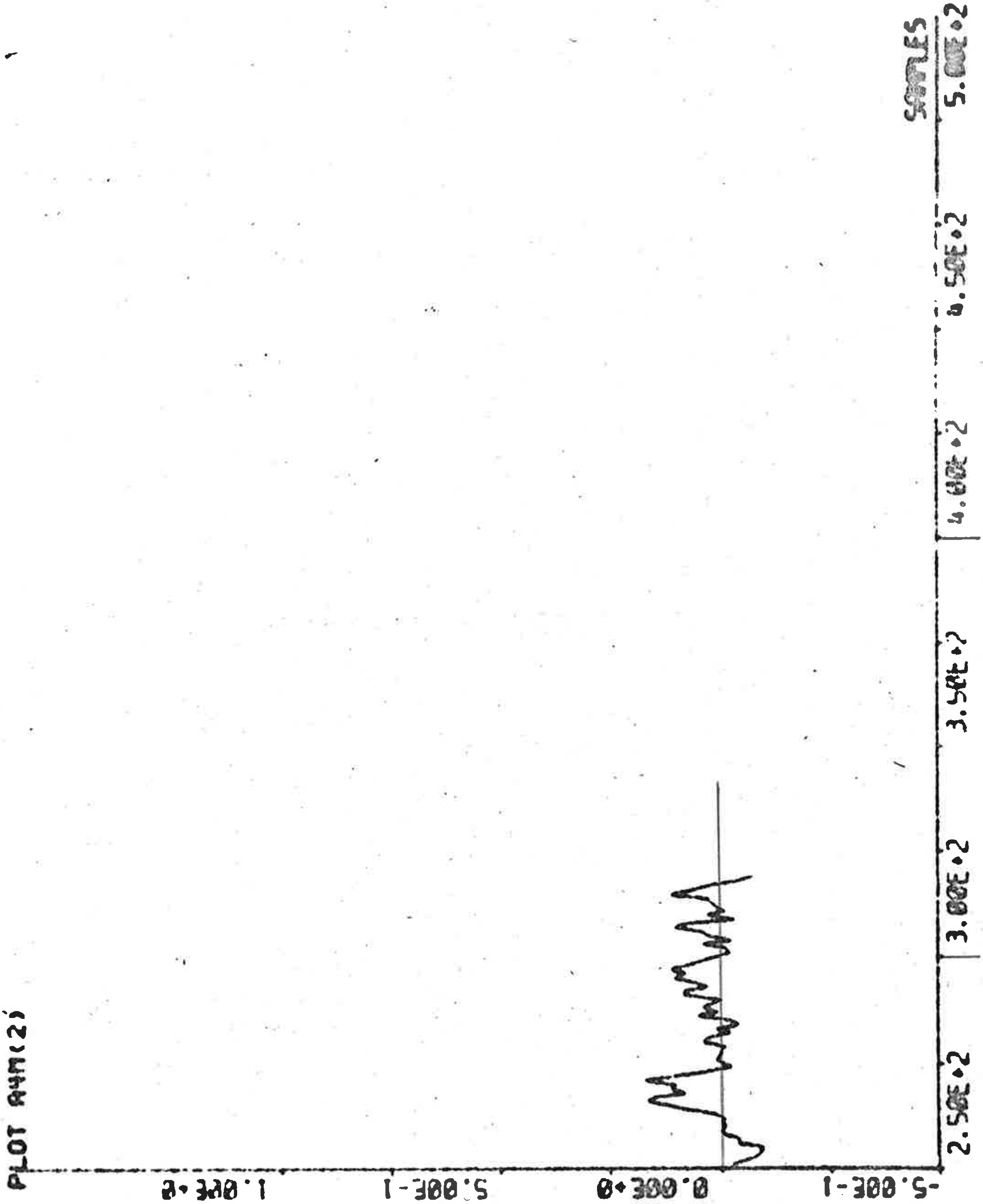

PLOT AVB(6)
1.41E+2
1.42E+2
1.43E+2
1.44E+2
x degr
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
142.5°
142.0°
141.5°


PLOT AHB(6)
1.41E+2
1.42E+2
1.43E+2
1.44E+2
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
SAMPLES
142.5°
142.0°
141.5°
6000 s
9000 s
Y degr

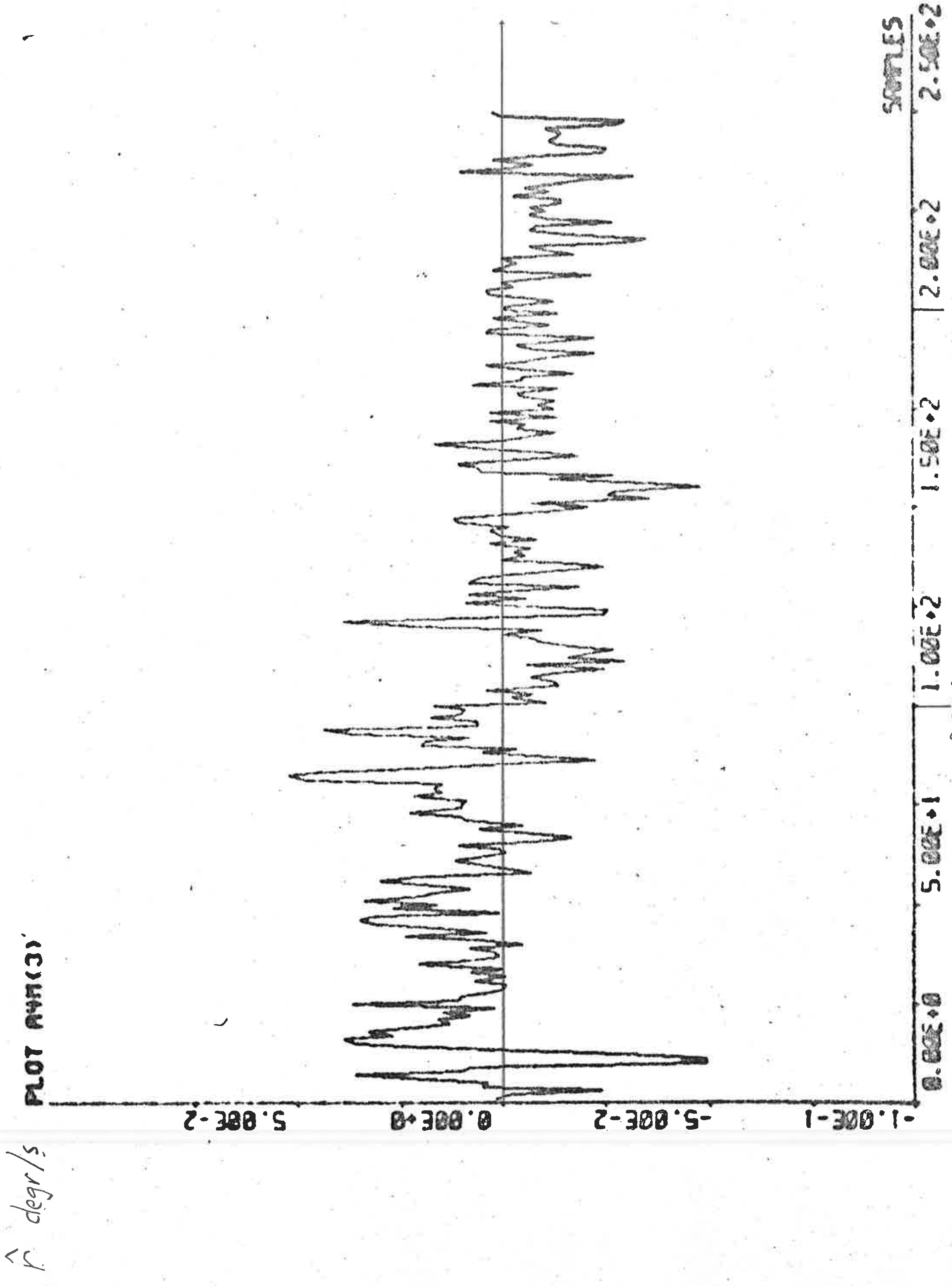

PLOT A4B(7)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
1.55E+1
1.60E+1
1.65E+1
1.70E+1
U knots

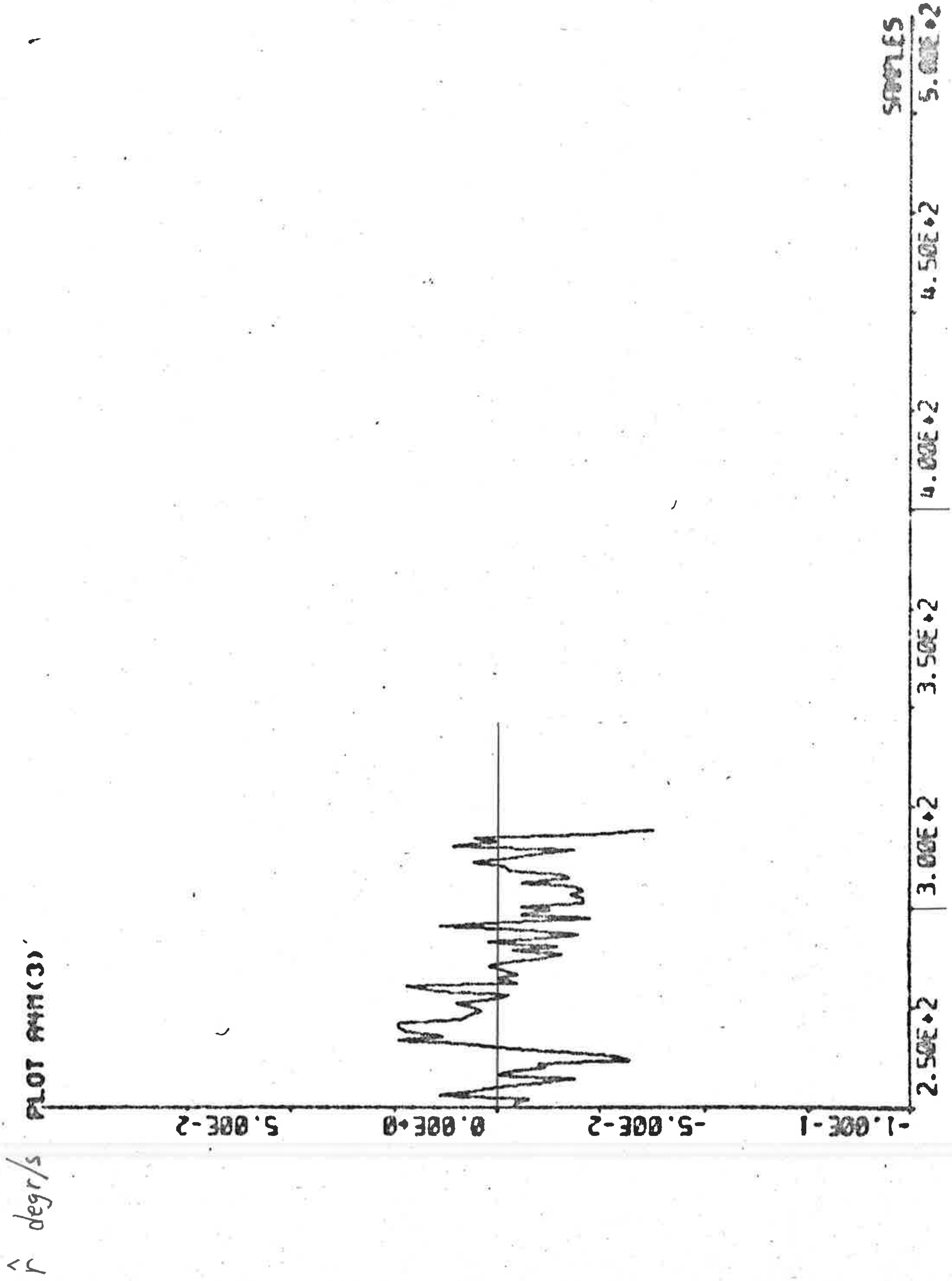

v knots
PLOT A+B(7)
1.70E+1
1.65E+1
1.60E+1
1.55E+1
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

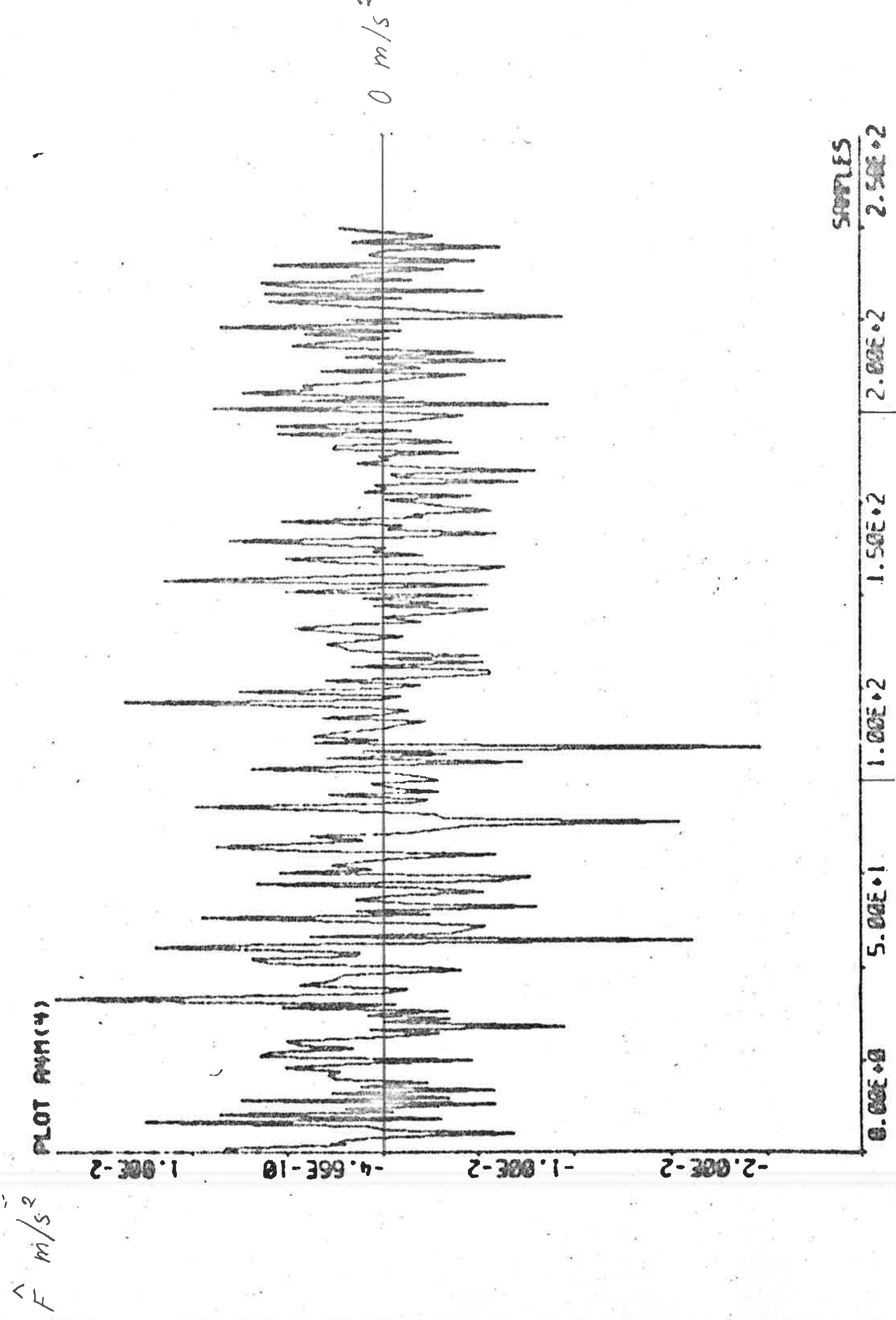

PLOT AMR(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
m/s

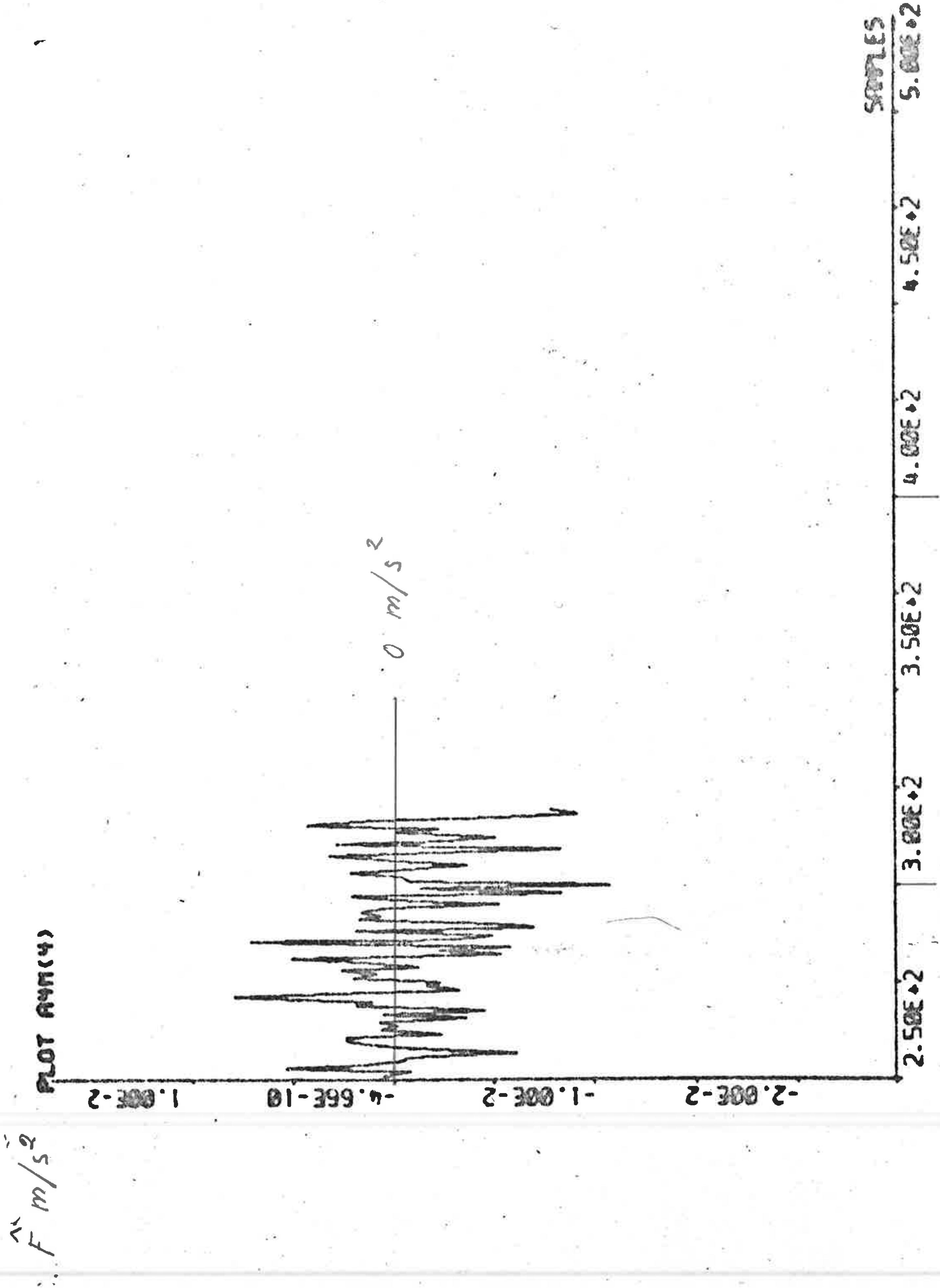

PLOT A4M(2)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
-5.00E-1
0.00E+0
5.00E-1
1.00E+0
6000 s
8000 s

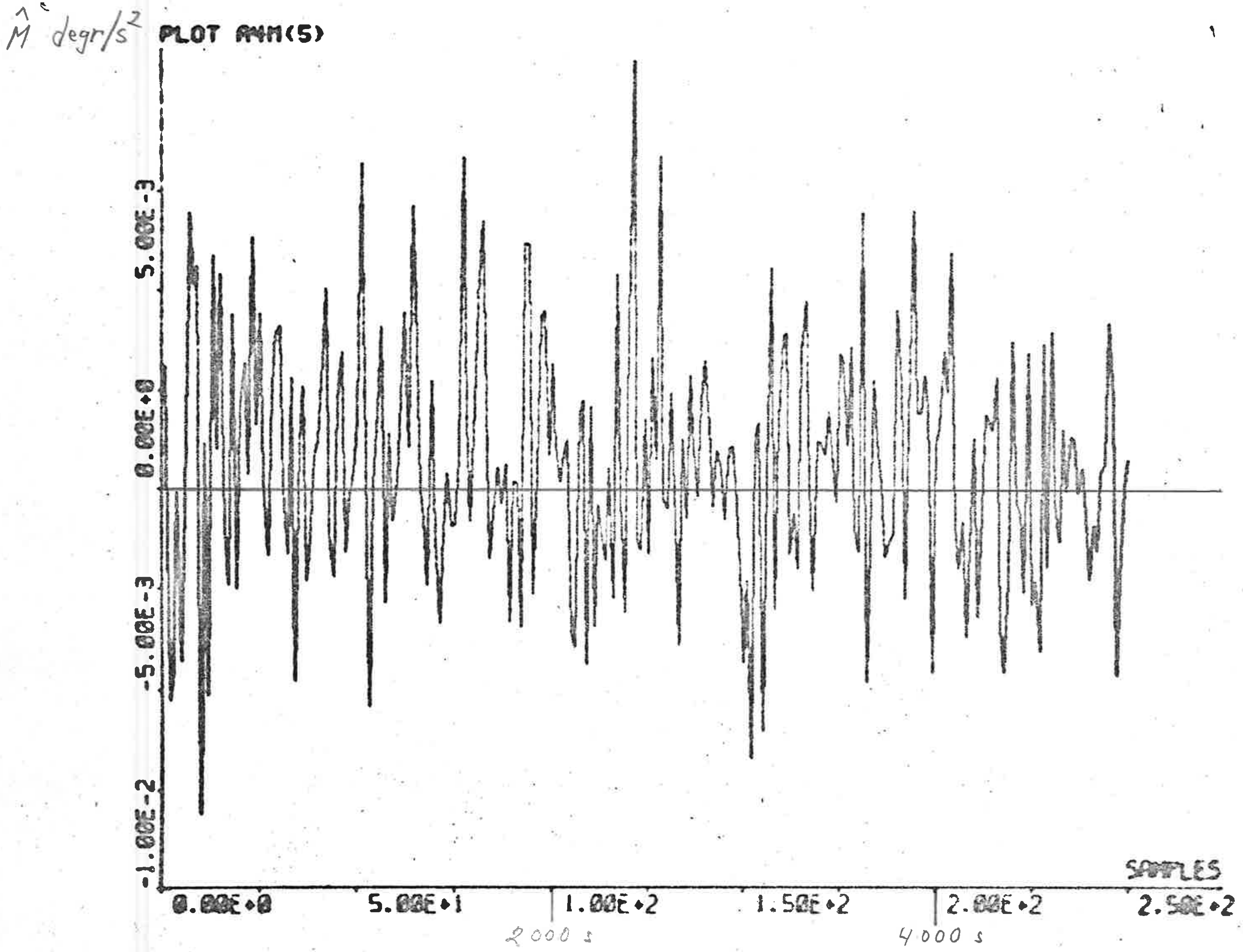
S/W 4

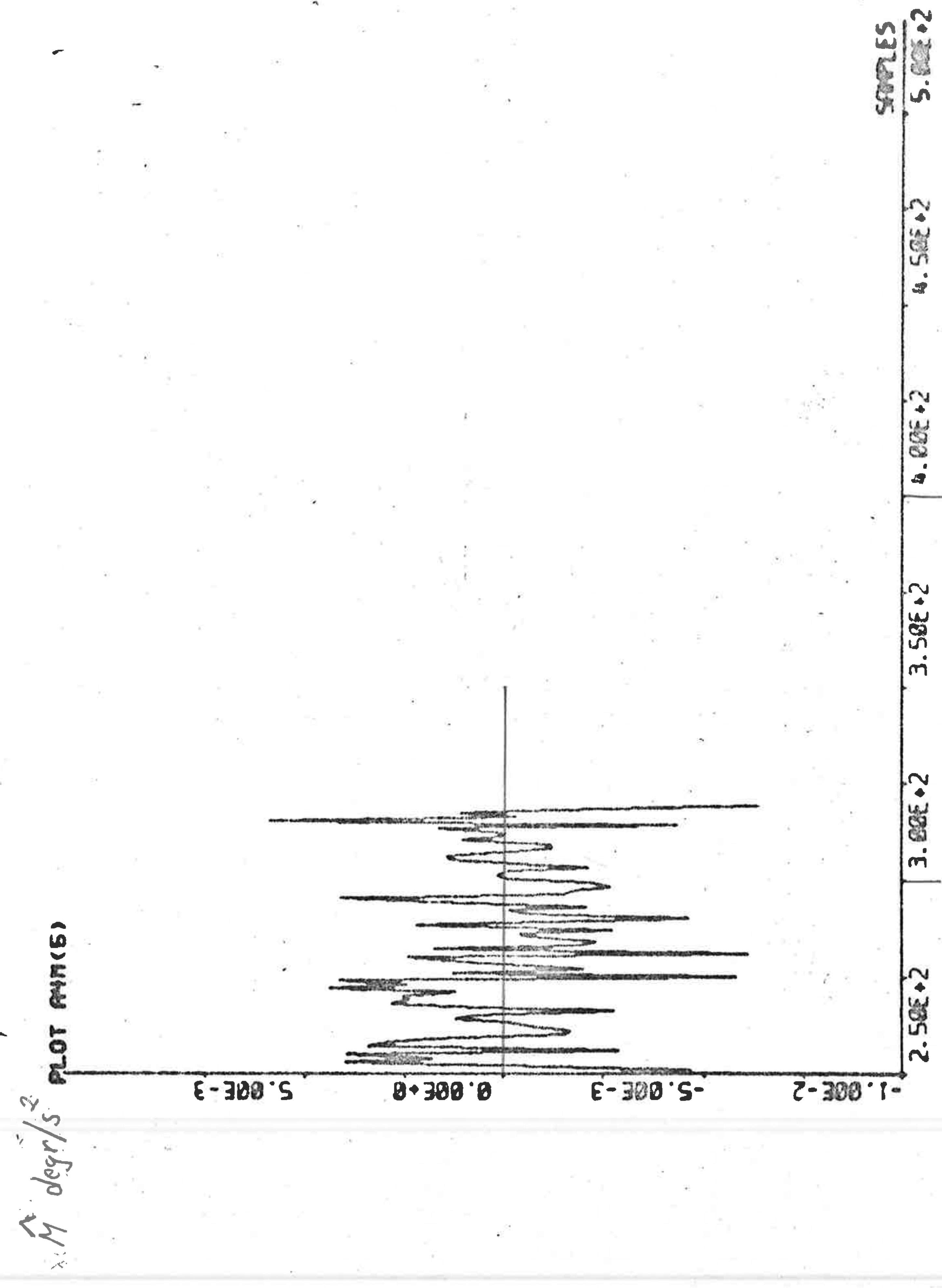

PLOT AYMT(3)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
r̂ degr/s

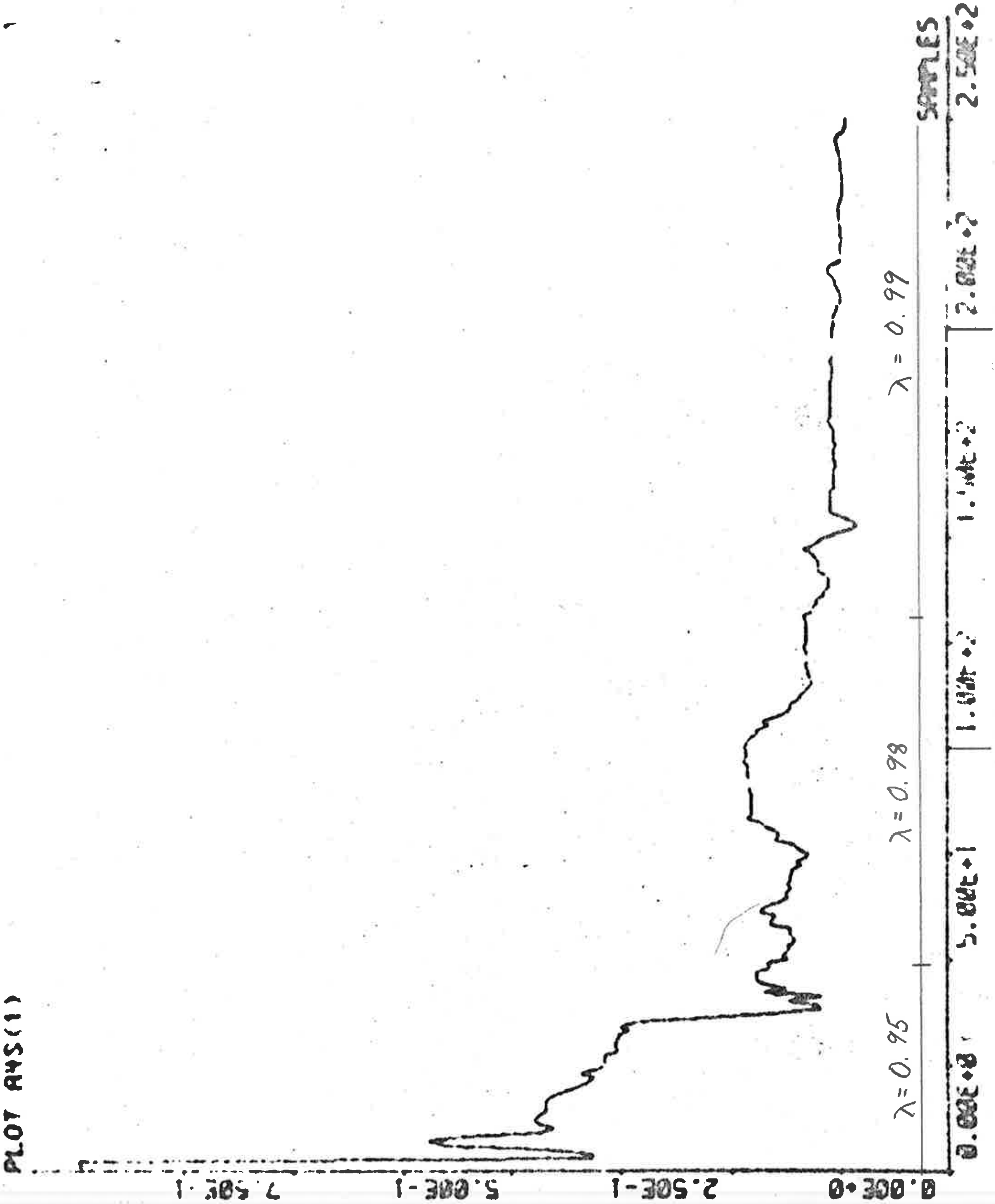

PLOT AHM(3)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
2.50E+2
3.00E+2
6000 s
3.50E+2
4.00E+2
8000 s
4.50E+2
5.00E+2
SAMPLES
$\hat{r}$ degr/s


PLOT AVA(4)
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s
0 m/s²
F̂ m/s²

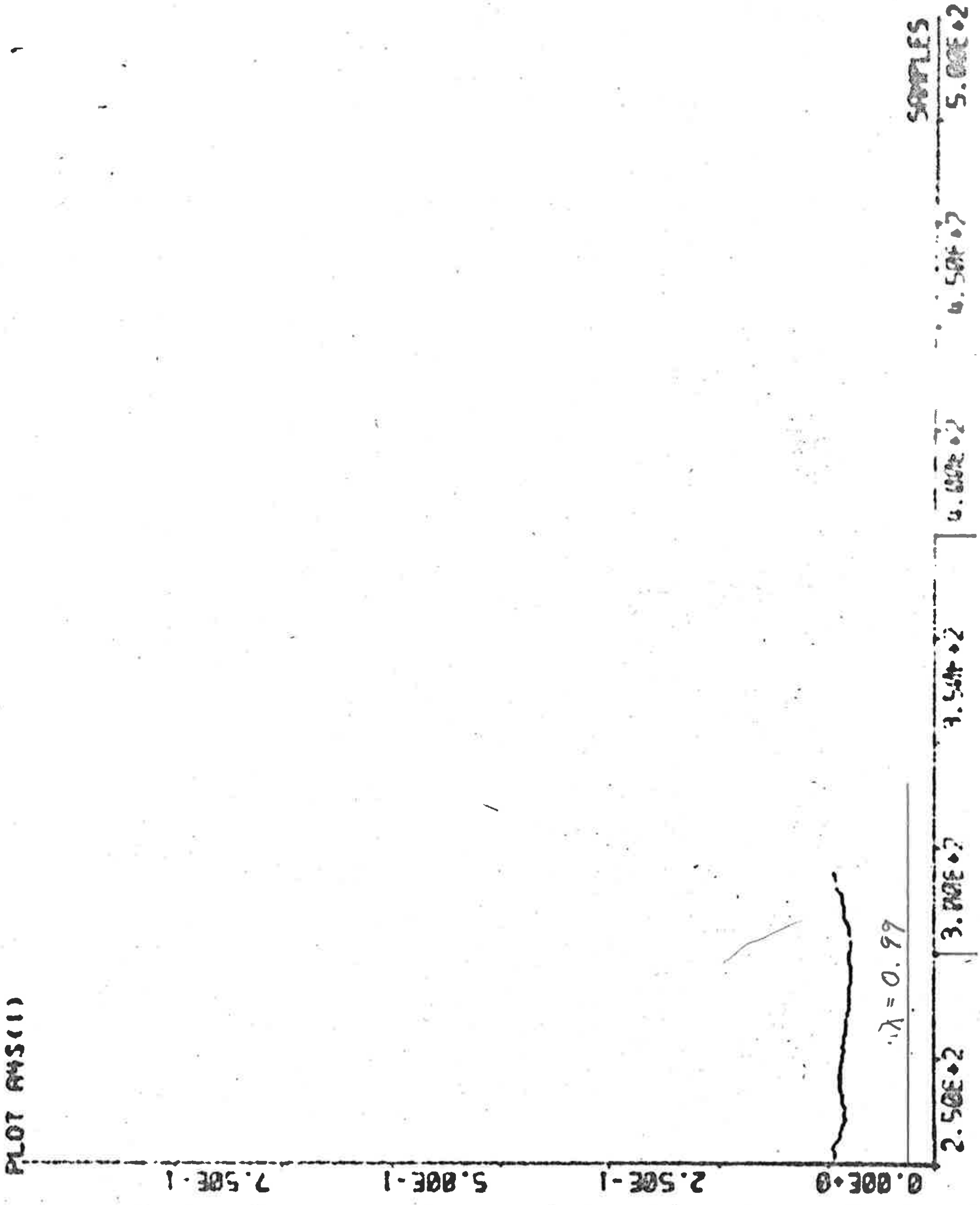

PLOT A4M(4)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
0 m/s²
6000 s
8000 s
F̂ m/s²


$\hat{M}$ degr/s^2
PLOT AMM(5)
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

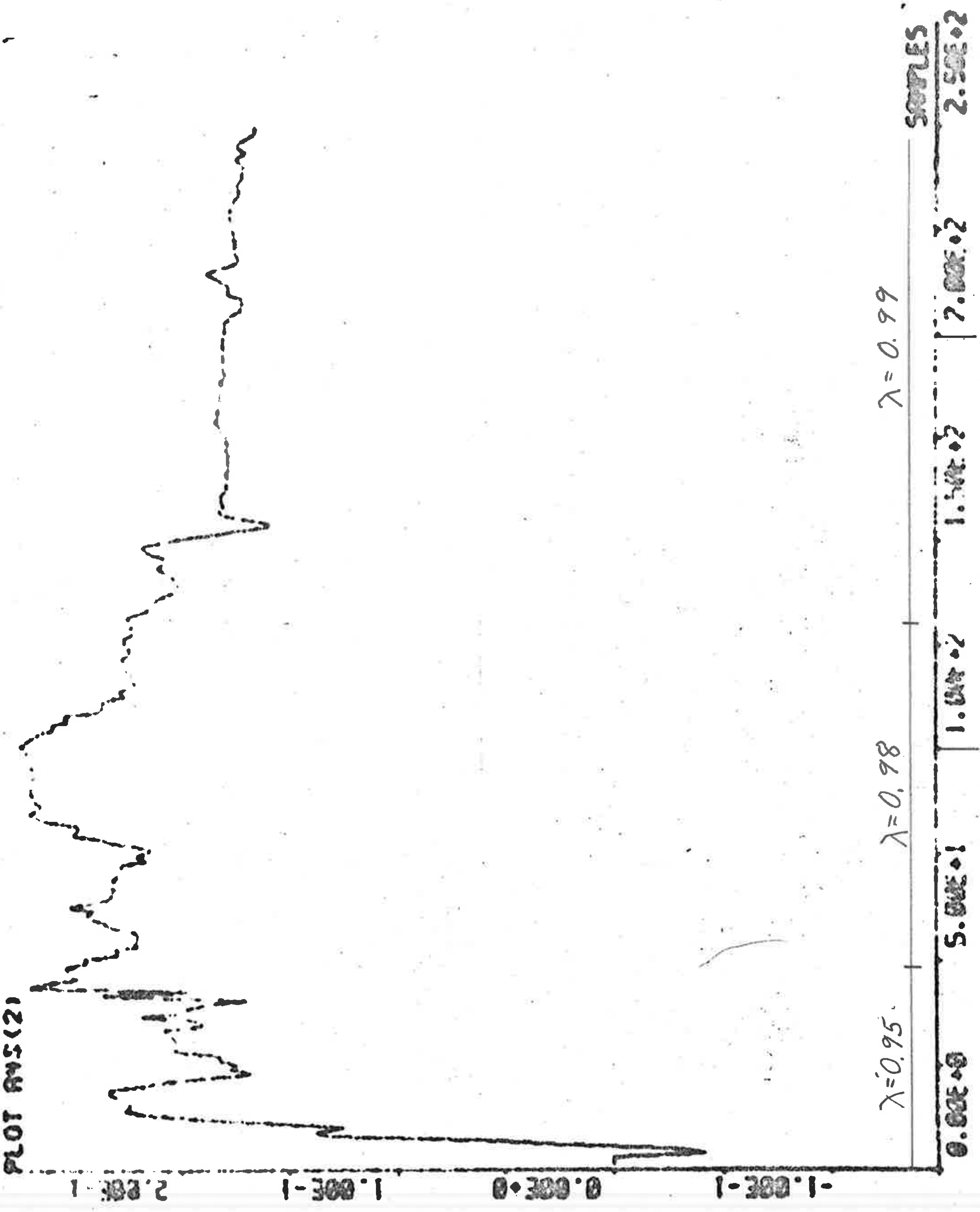

PLOT AMM(5)
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
6000 s
8000 s
M degr/s²


PLOT AHS(1)
0.000E+0
2.50E-1
5.00E-1
7.50E-1
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

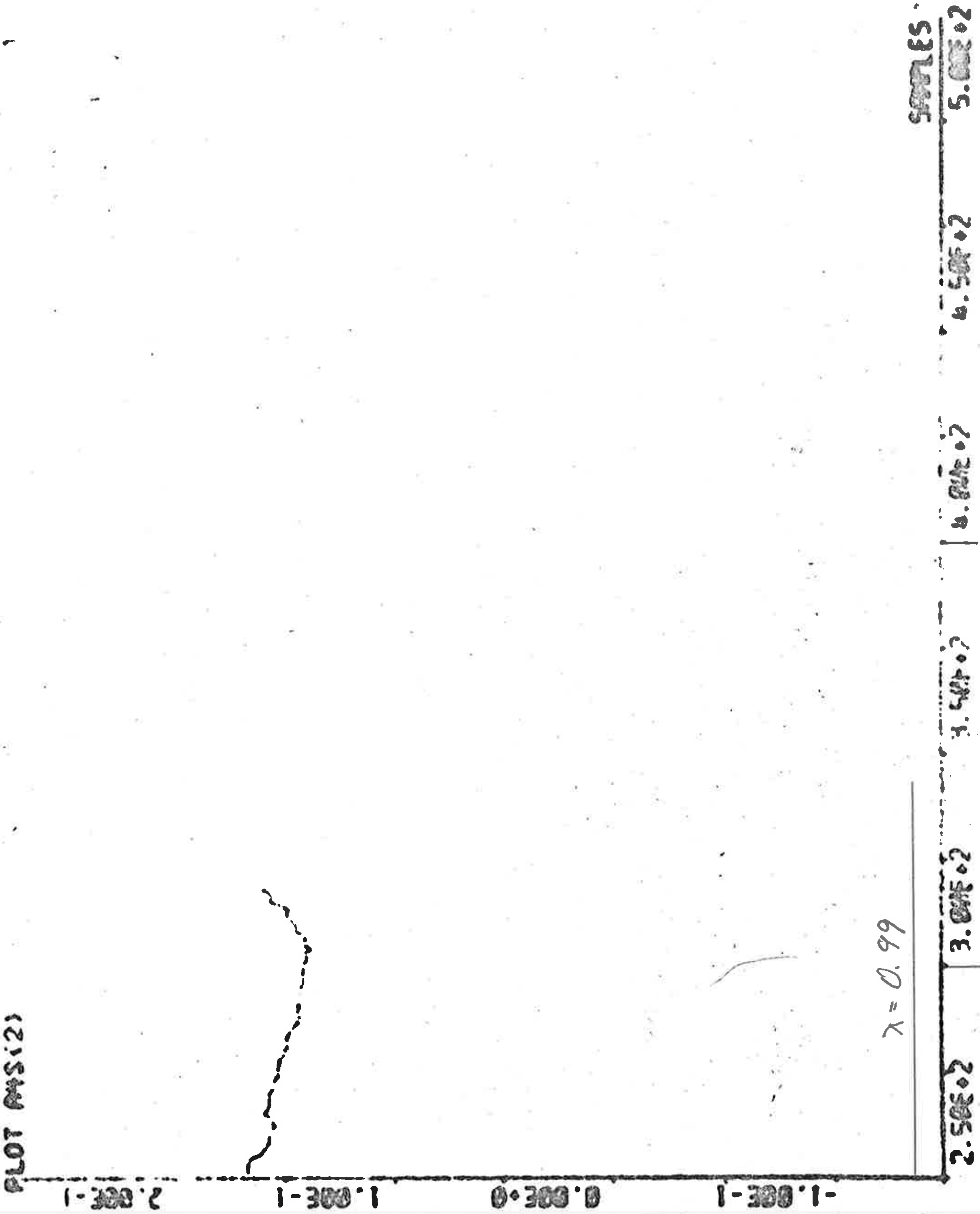
b1


PLOT RMS(1)
0.00E+0
2.50E-1
5.00E-1
7.50E-1
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
SAMPLES
λ = 0.99
6000 s
8000 s

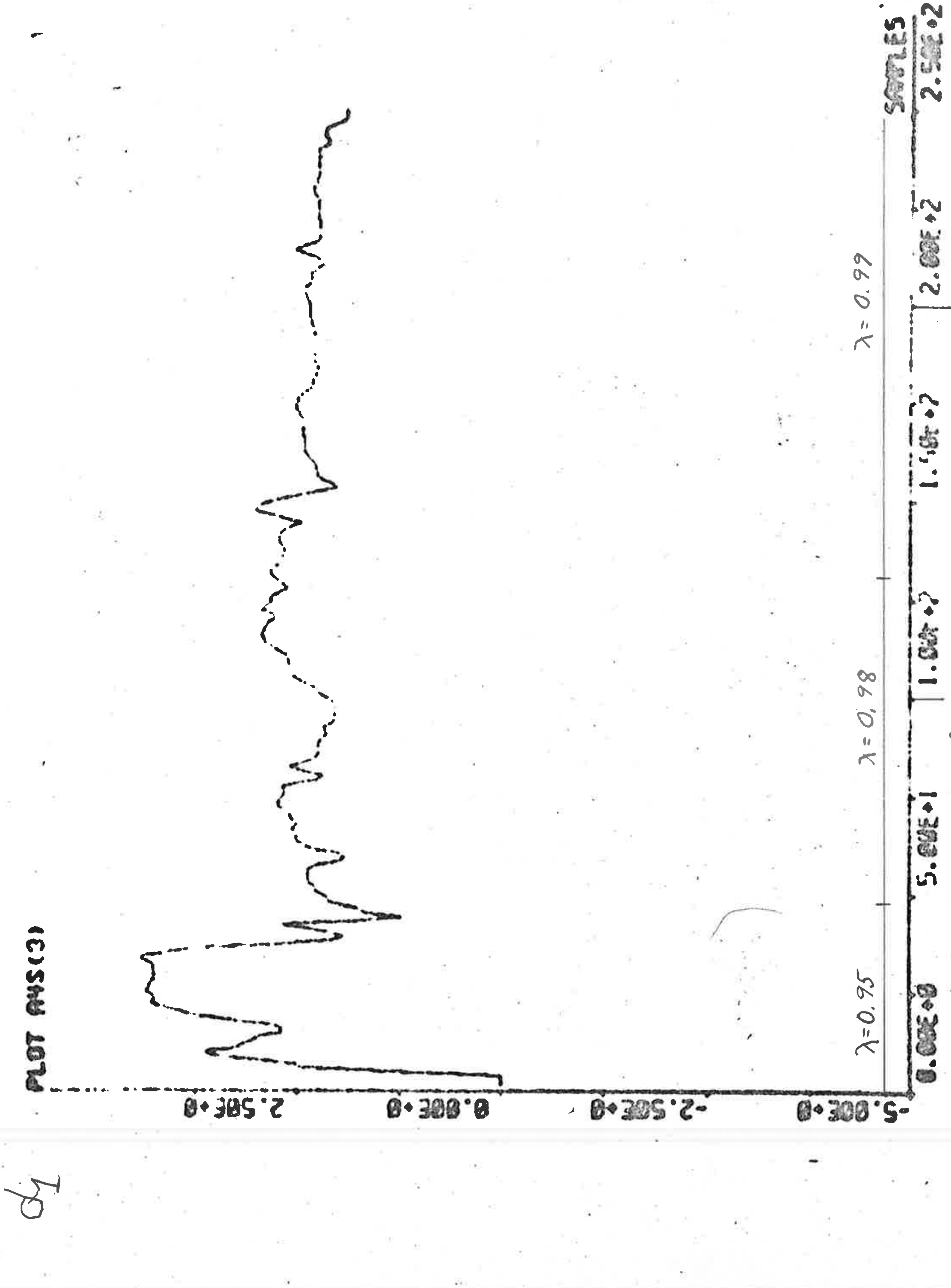
b1


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

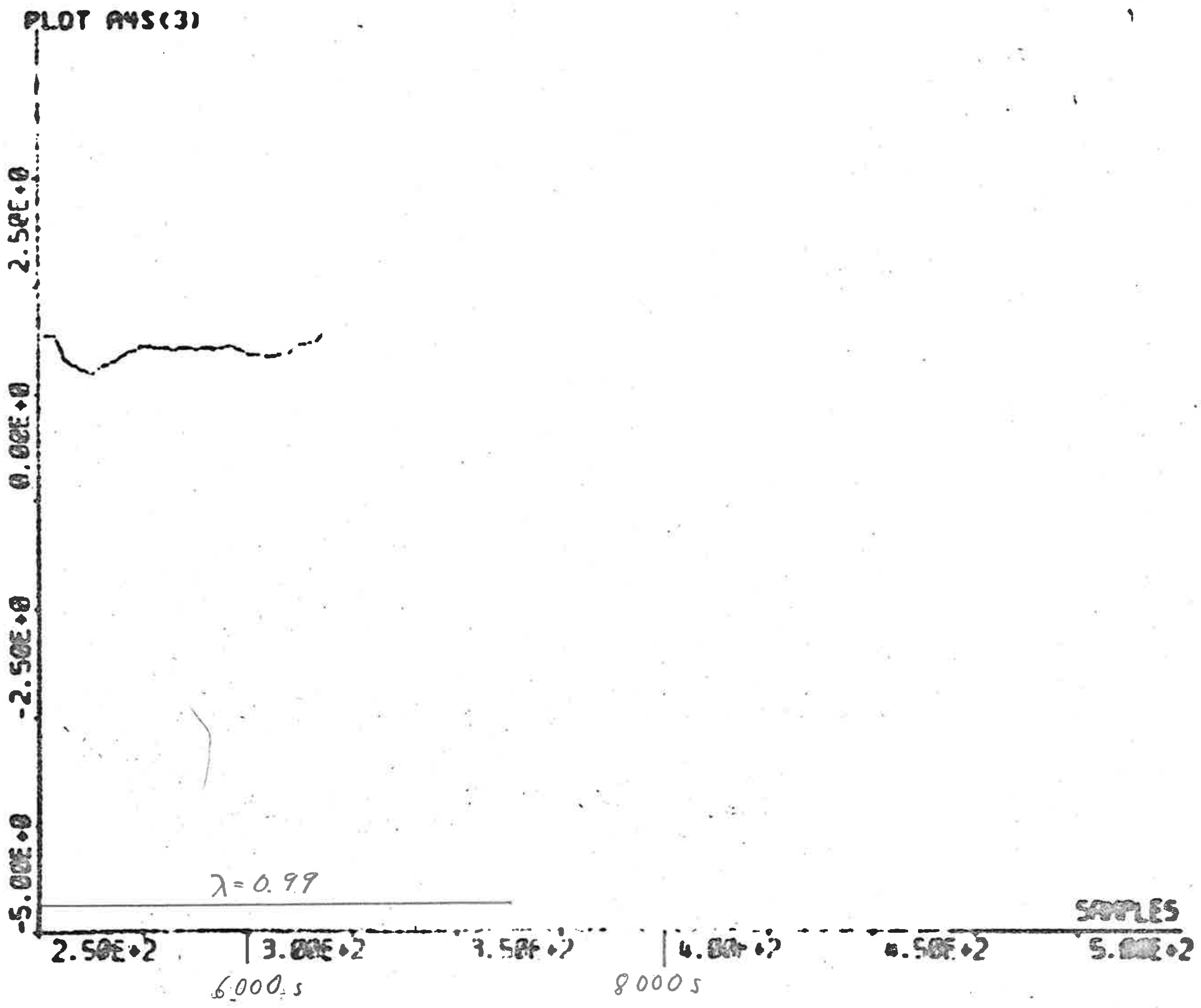
b2


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

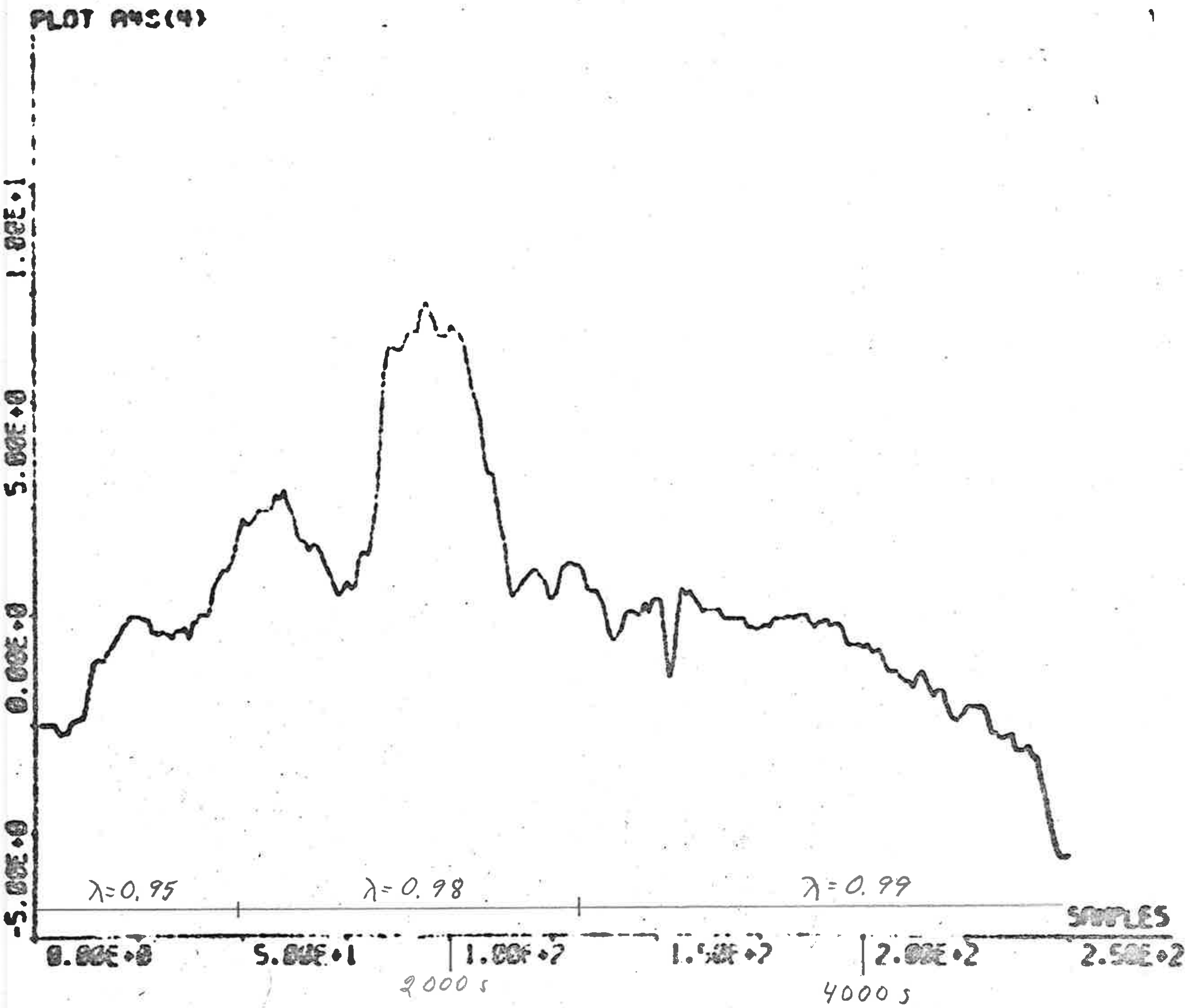
b2

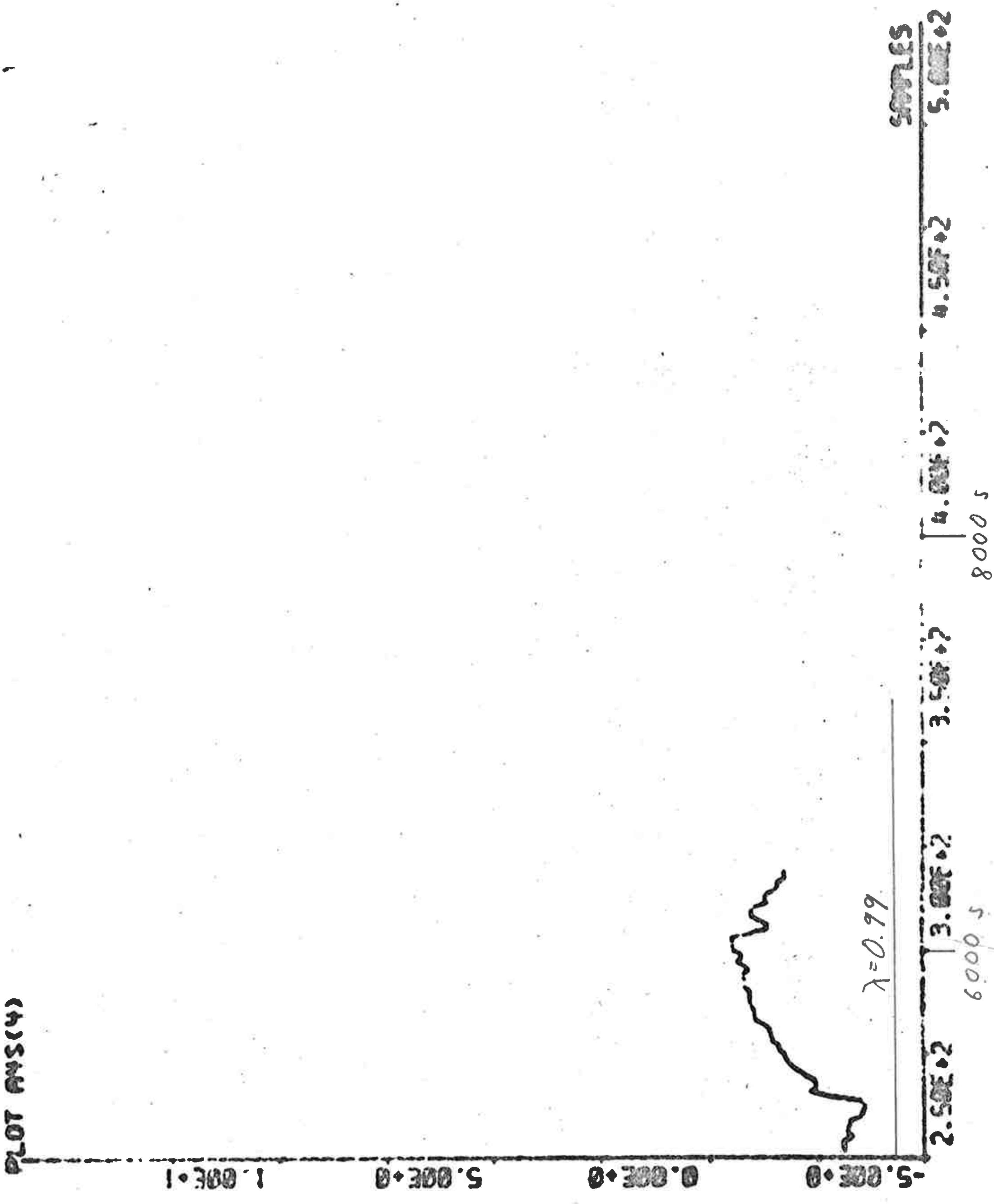

PLOT ANS(3)
2.50E+0
0.00E+0
-2.50E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s
Ip

d_1


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

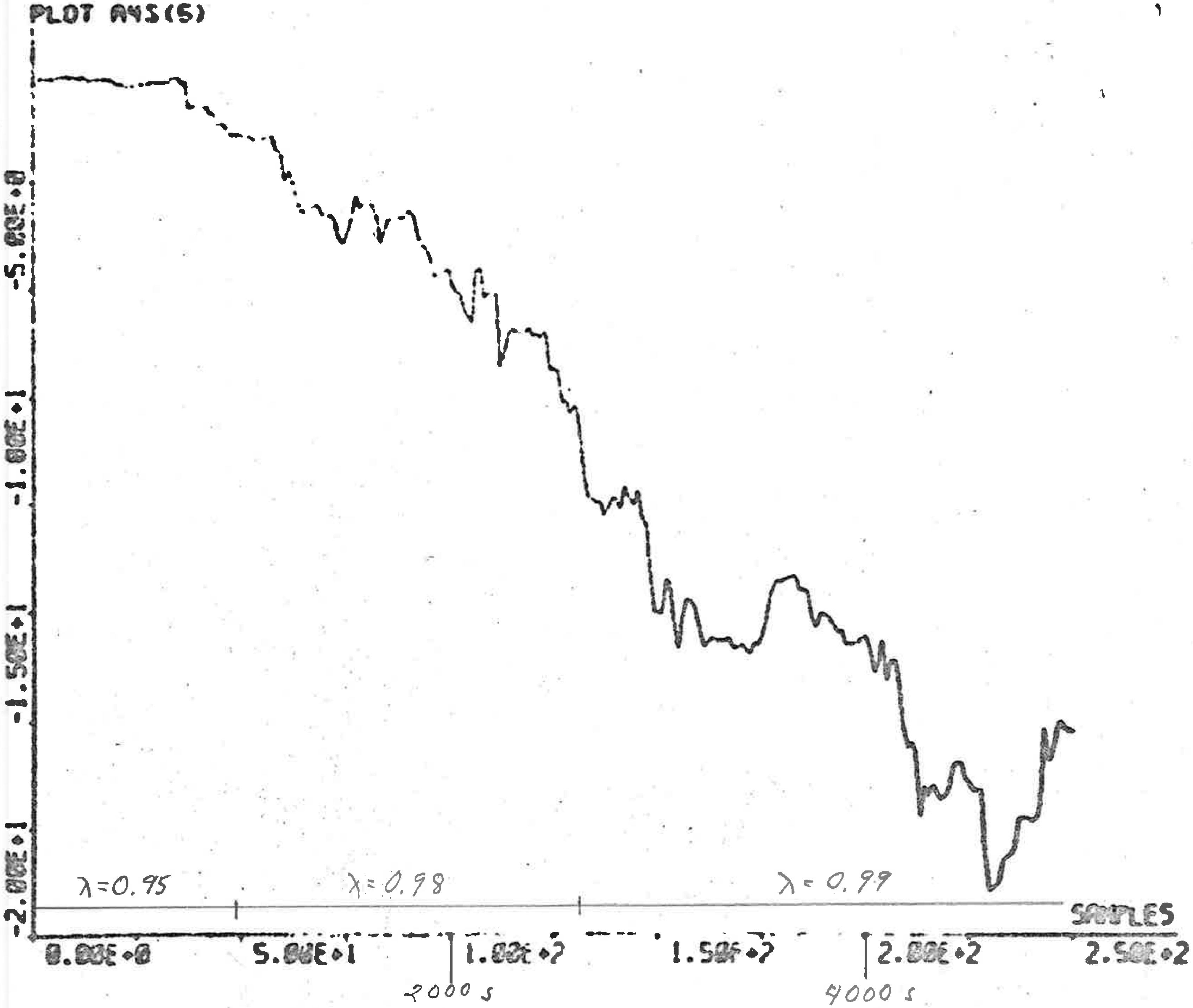
d_2


PLOT A*S(4)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
λ=0.95
λ=0.98
λ=0.99
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

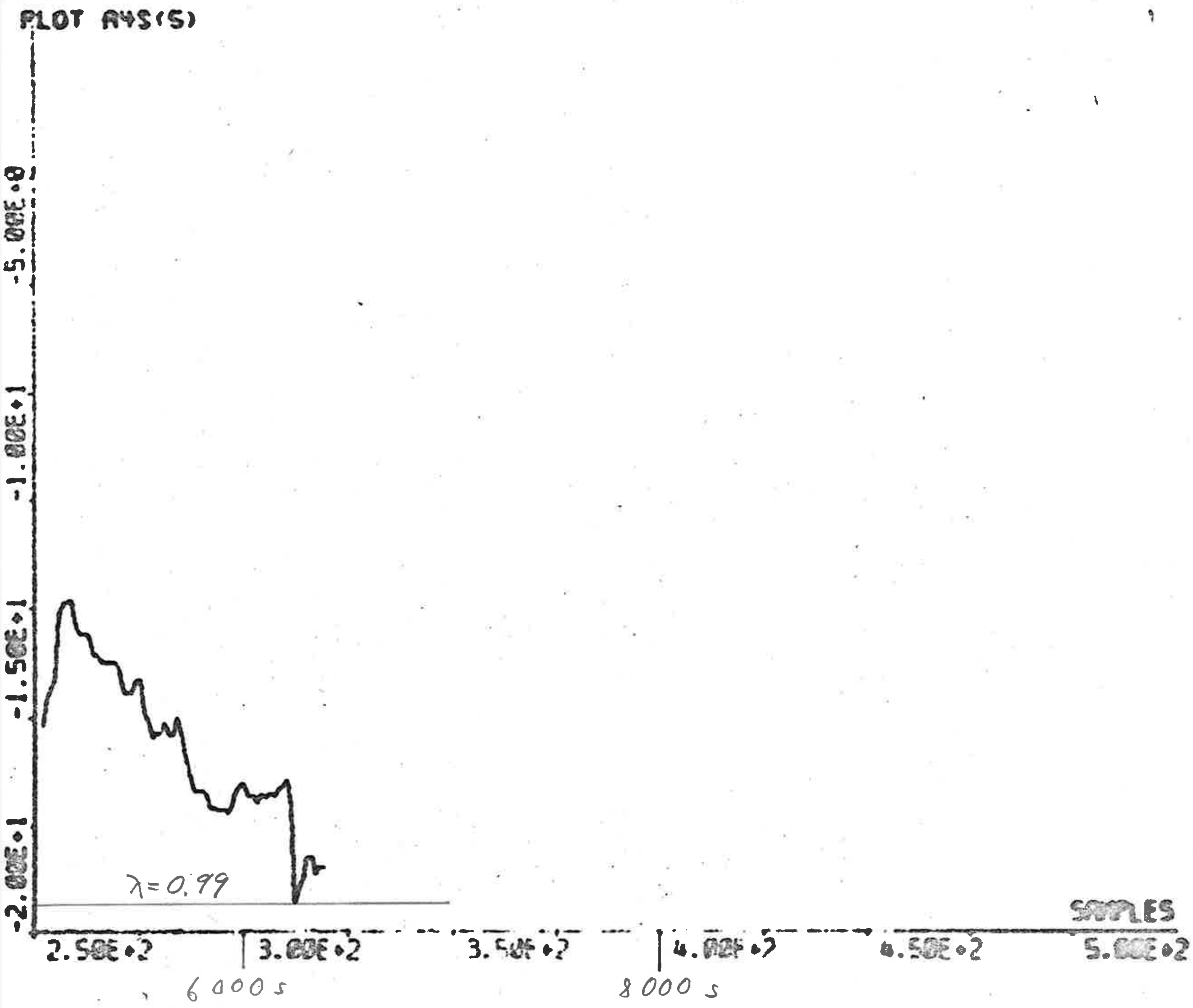

PLOT ANS(4)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
SAMPLES
λ=0.99
6000 s
8000 s

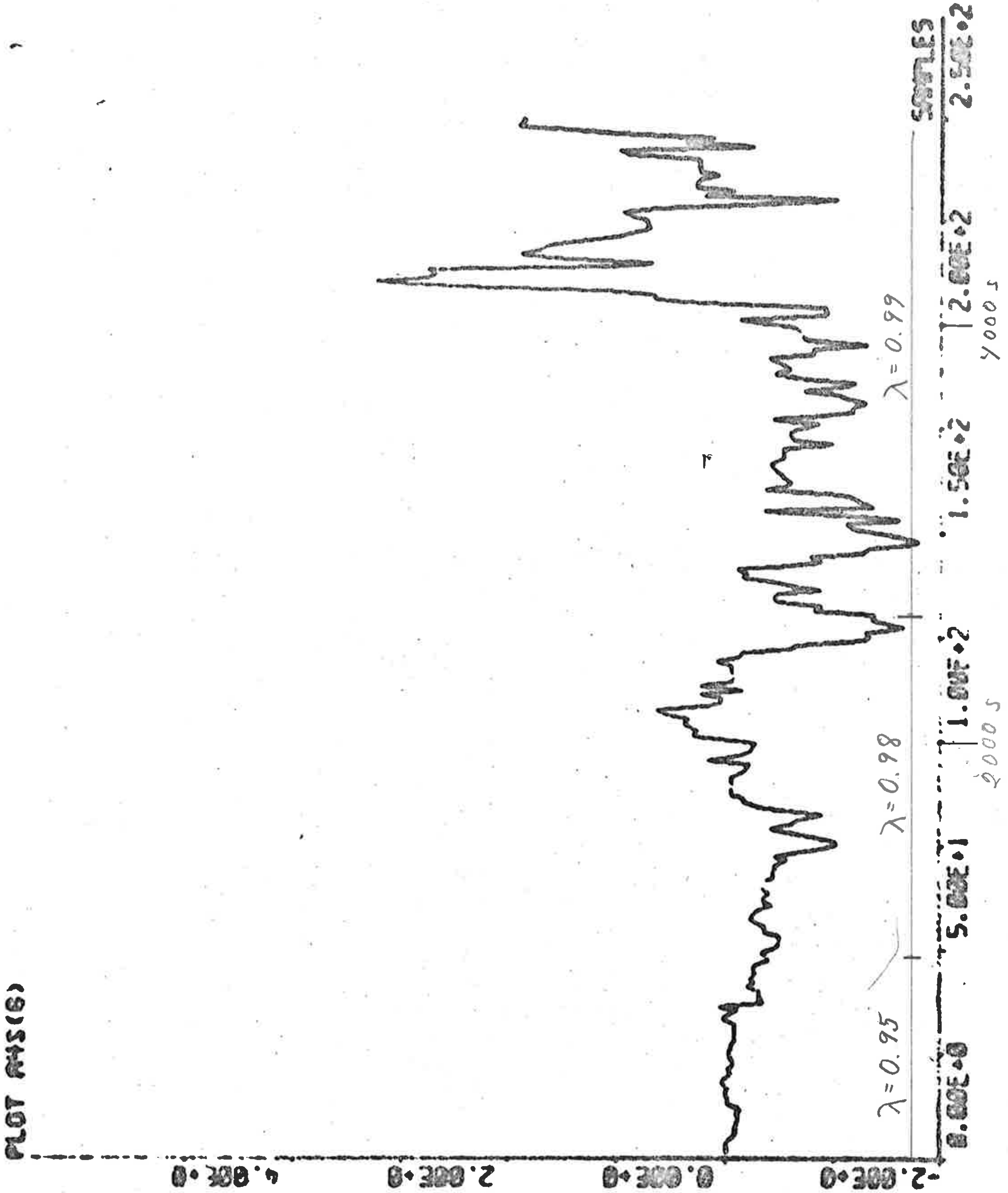
d2

d_3

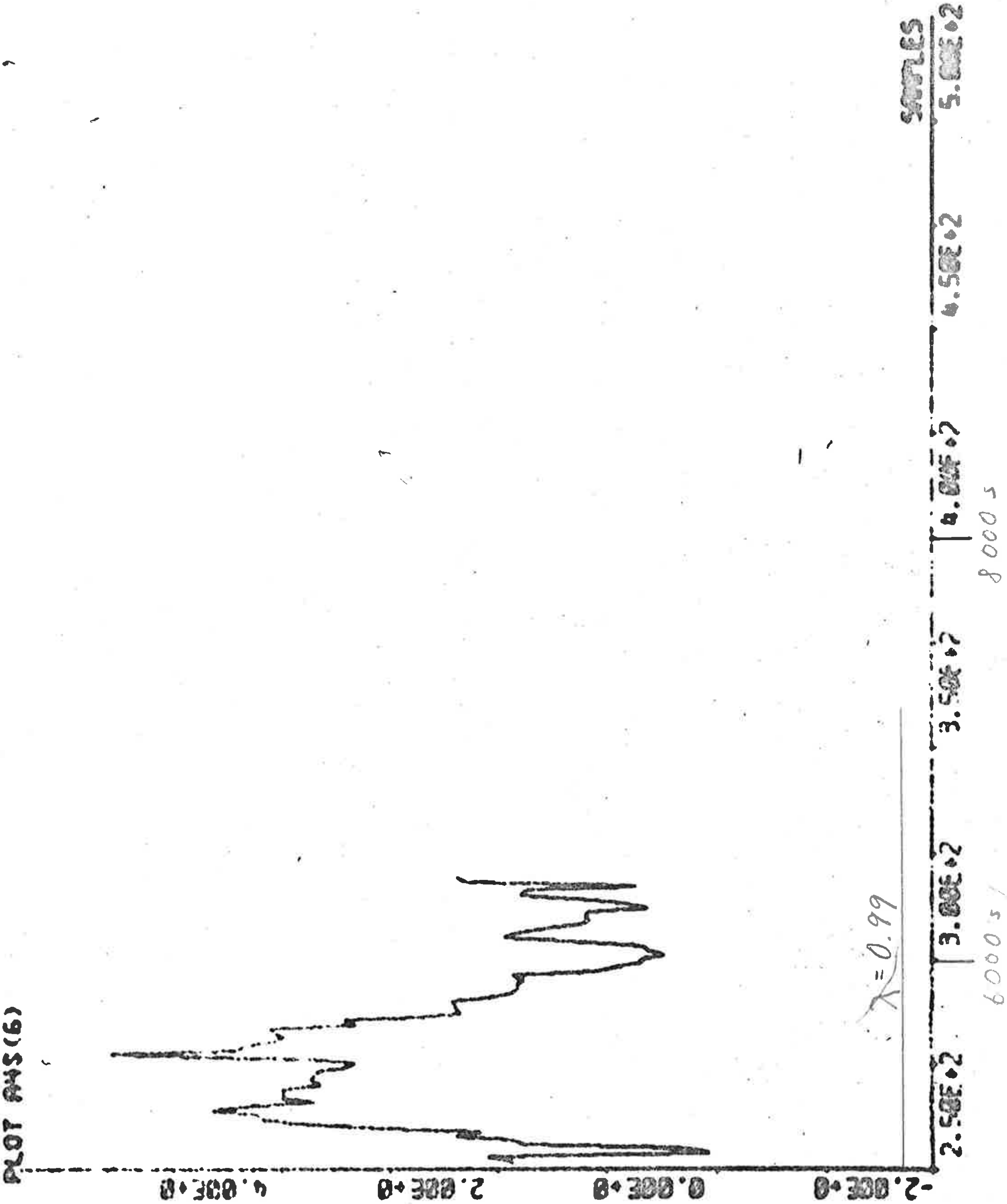

PLOT AVS(S)
-5.00E+0
-1.00E+1
-1.50E+1
-2.00E+1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s

d3


PLOT AYS(S)
-5.00E+0
-1.00E+1
-1.50E+1
-2.00E+1
λ=0.99
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s


PLOT AMS(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

d4


PLOT ABS(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:

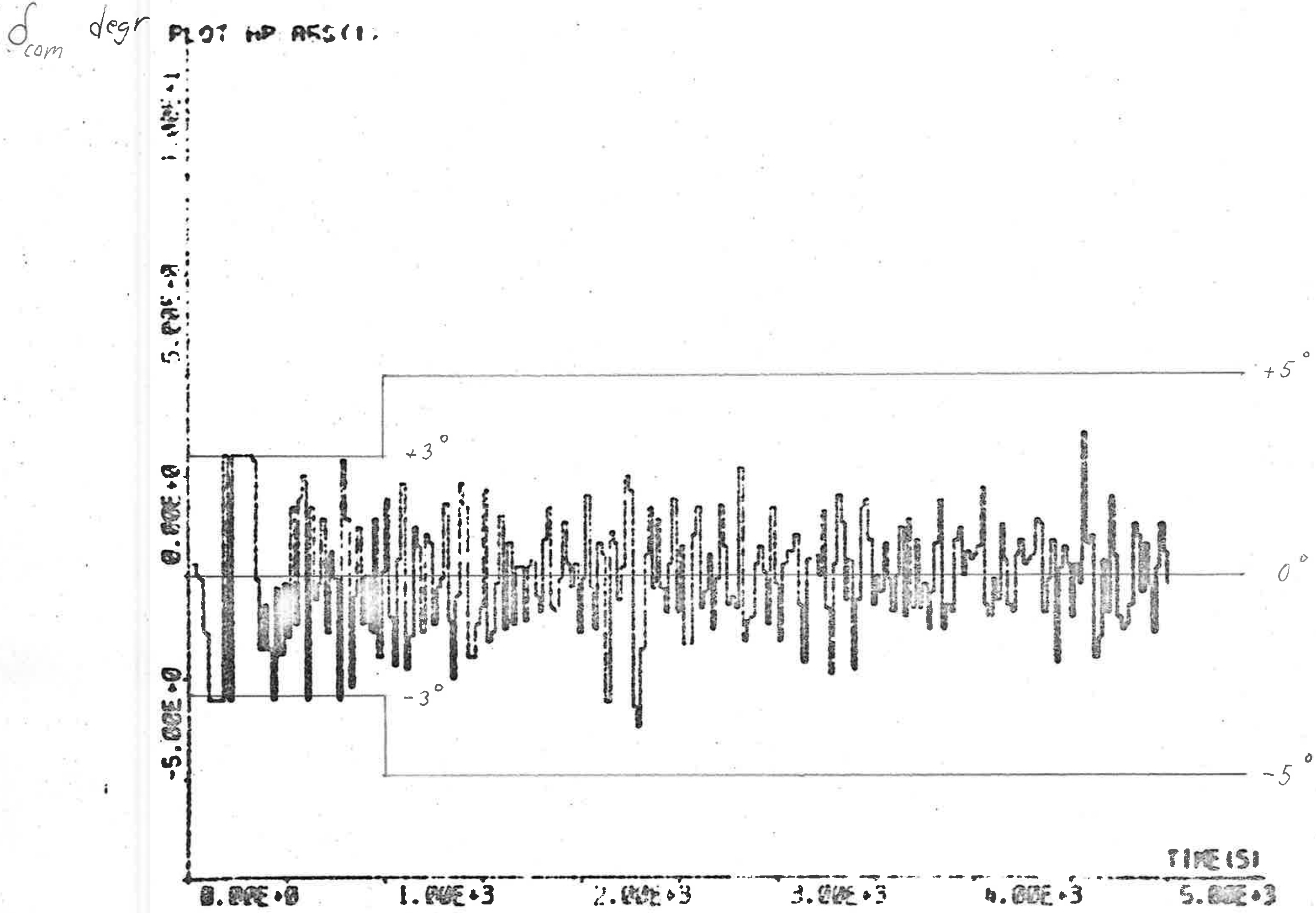
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.3544 \\ 0.0249 \\ 14.1280 \end{bmatrix} \qquad P = \begin{bmatrix} 0.02550 & & \\ -0.01440 & 0.01420 & \\ 1.413 & -0.9150 & 102.4 \end{bmatrix}$$

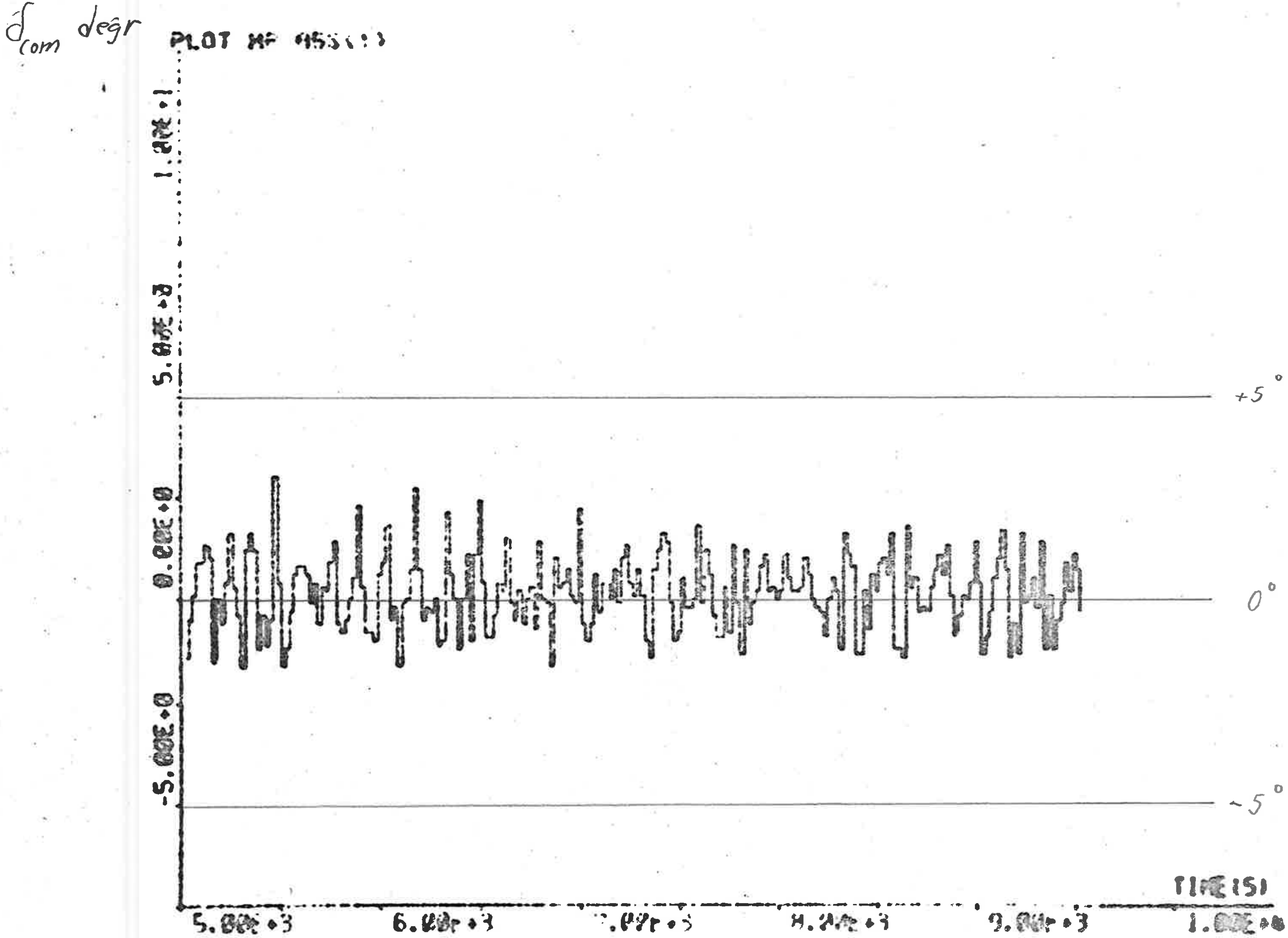
Regulator:

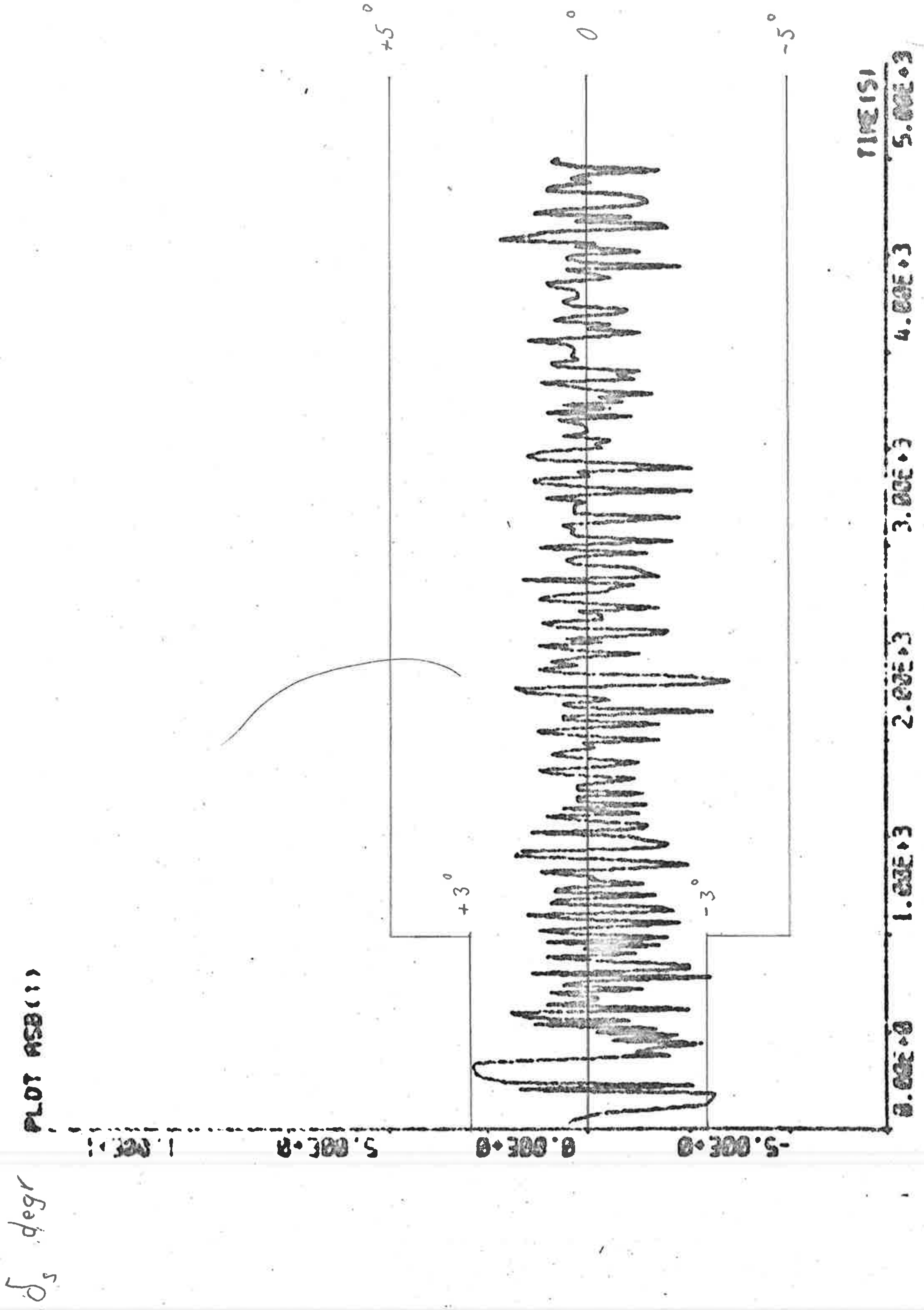
$$\delta(t) = -2.8217(\Psi(t) - \Psi_{ref}) - 0.0703\delta(t-1) - 39.8646r(t)$$

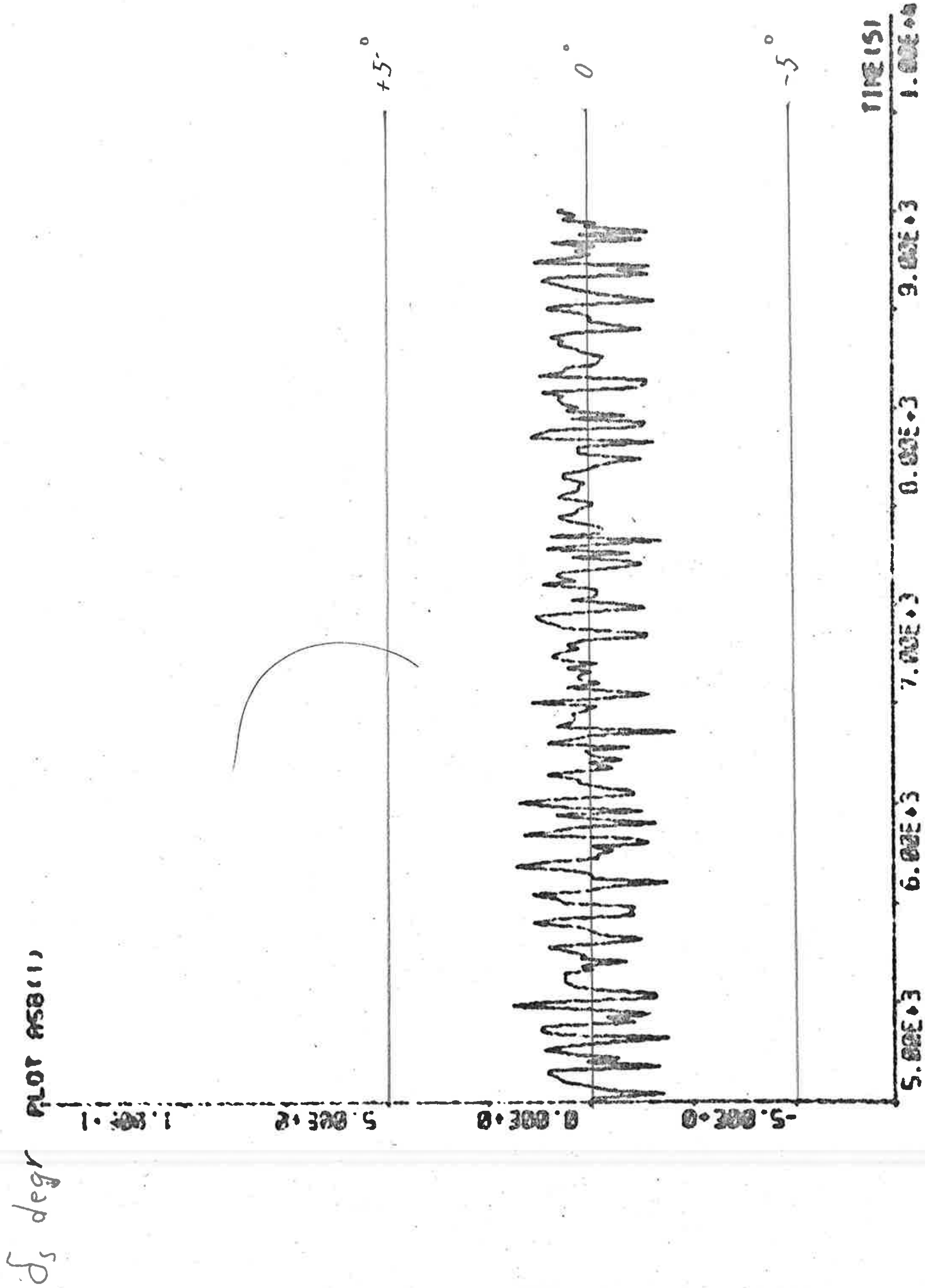
Statistics:

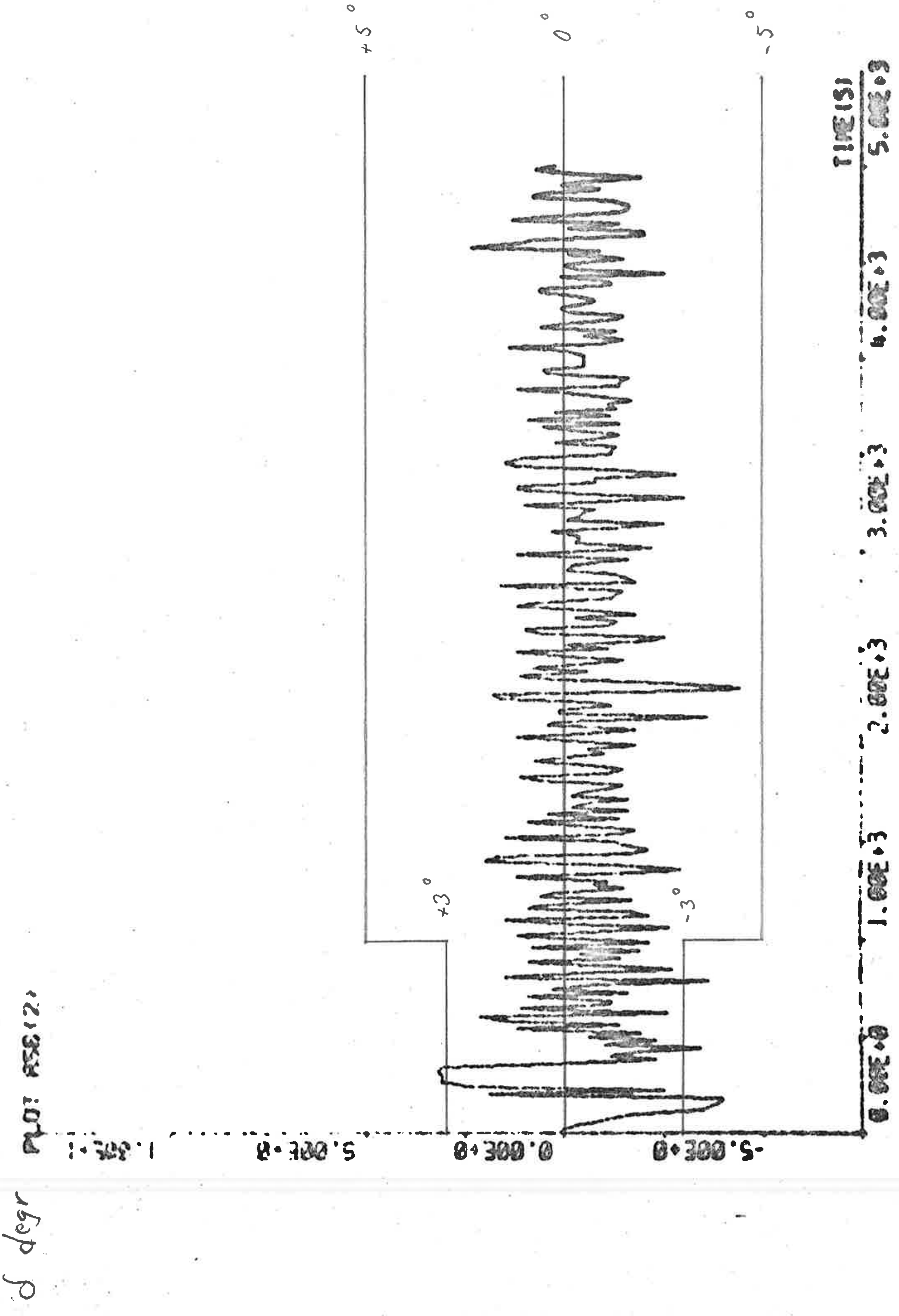
		0 - 9500 s (all data)				5000 - 9500 s			
		Mean value	Standard deviation	Minimum value	Maximum value	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com}	degr	0.06	1.21	-3.7	3.6	0.15	0.91	-1.6	3.0
δ_s	degr	-0.10	1.11	-3.5	2.9	0.02	0.85	-2.1	1.9
δ	degr	-0.49	1.18	-4.4	3.2	-0.42	0.90	-2.2	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

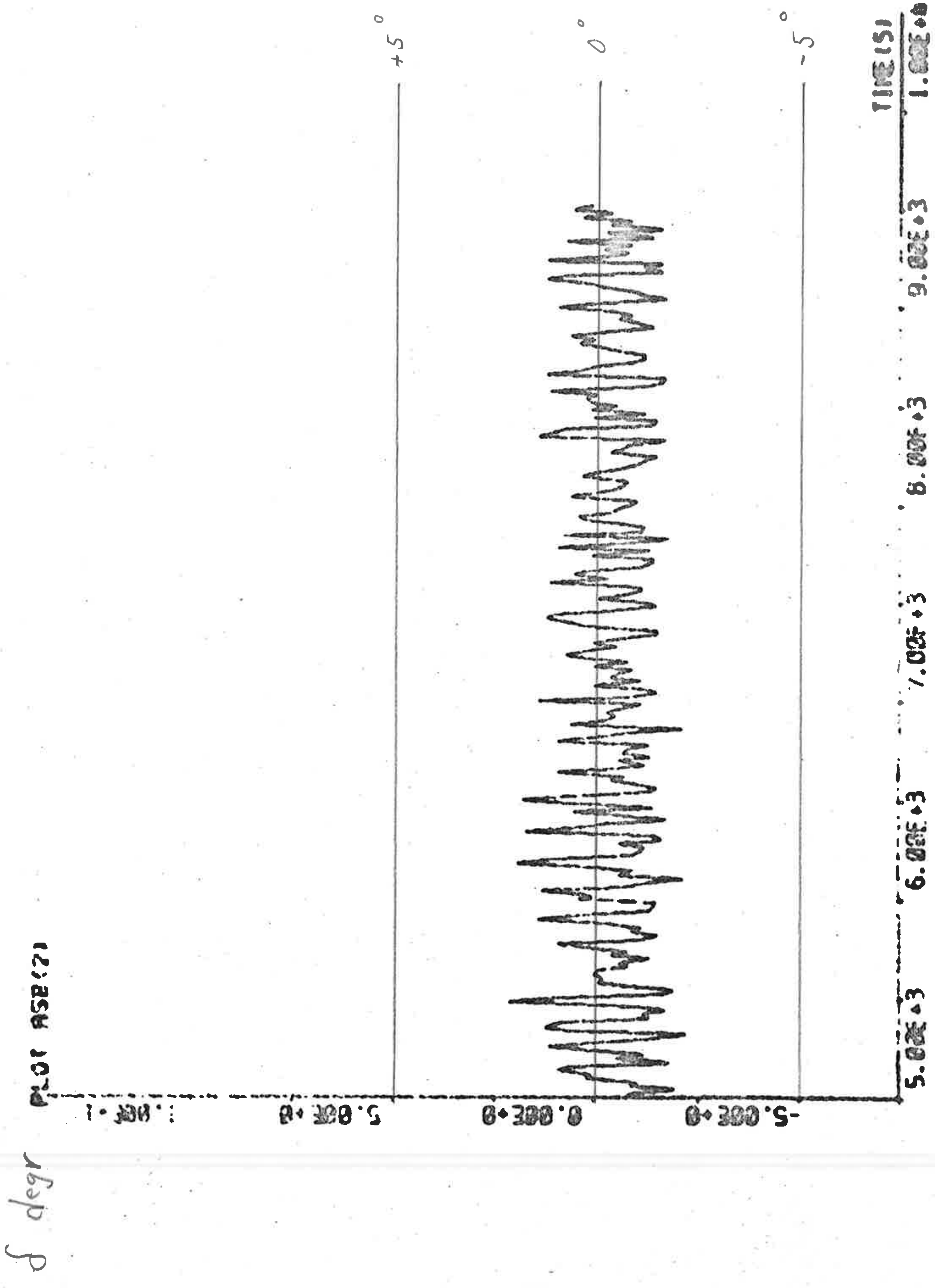

δcom degr
PLOT HP RES(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+5°
+3°
0°
-3°
-5°
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

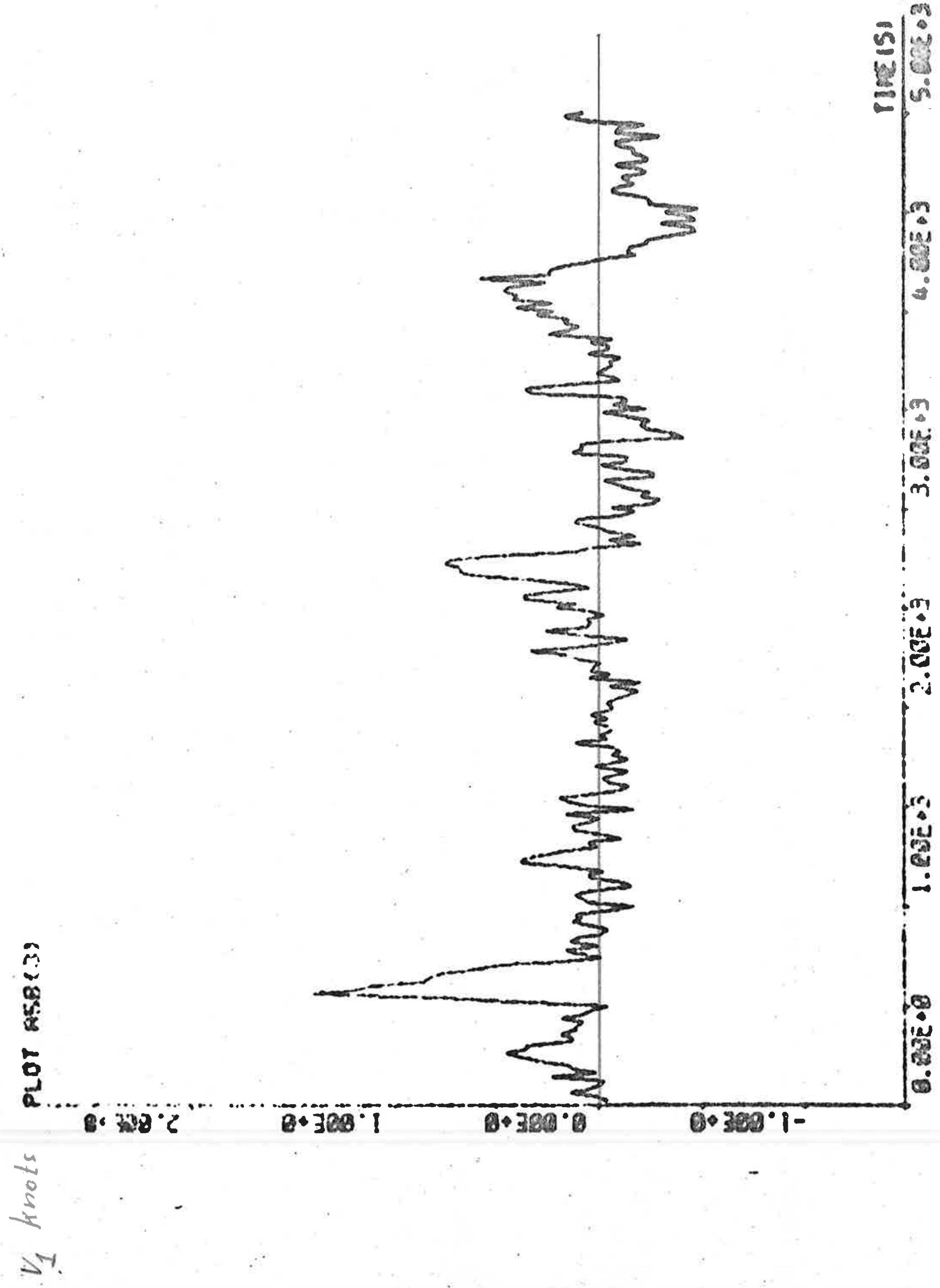

δ_{com} degr
PLOT OF 455(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+5°
0°
-5°
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4

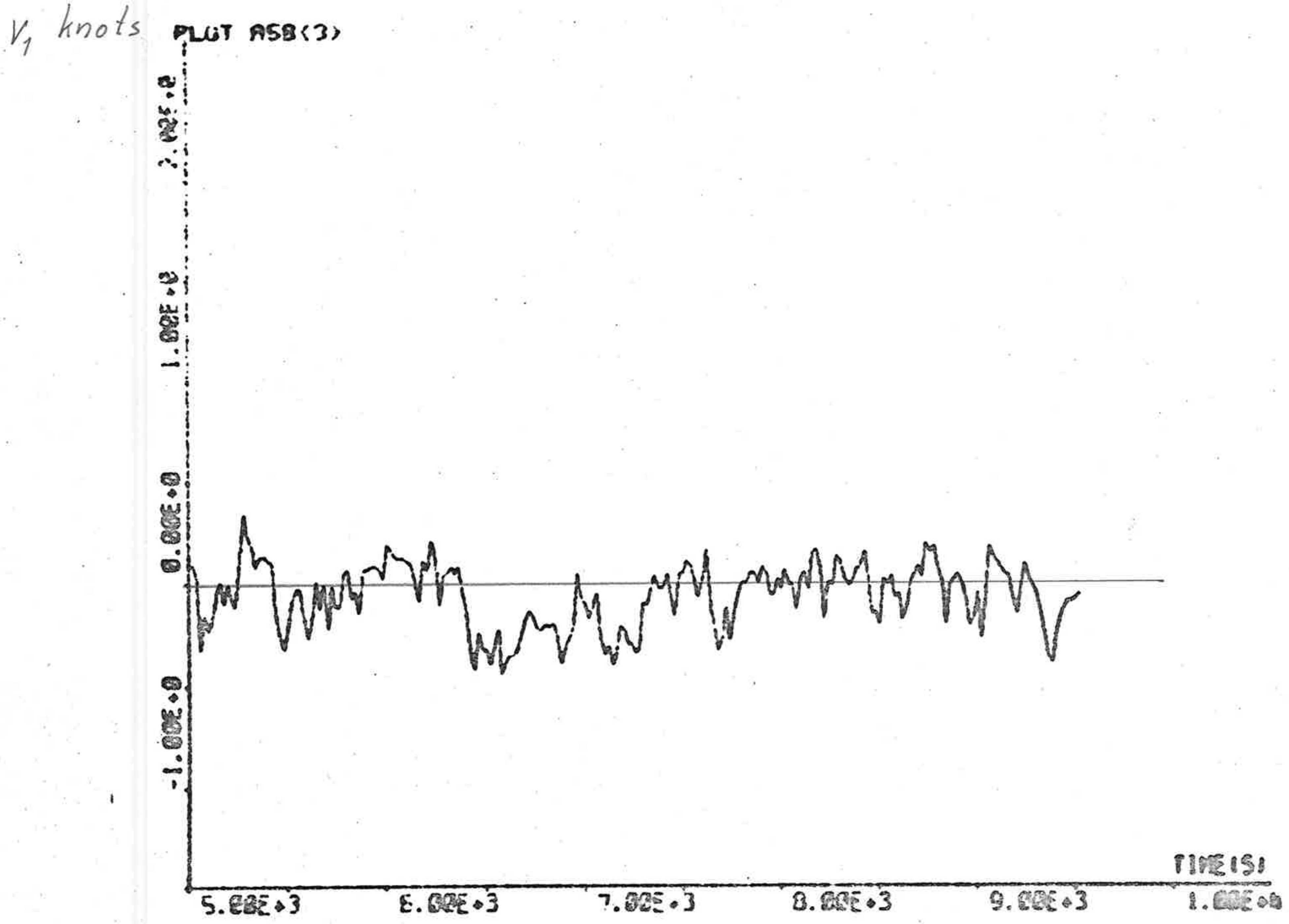

PLOT ASB(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+5°
0°
-5°
+3°
-3°
δs degr


PLOT ASB(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
+5°
0°
-5°
δs degr

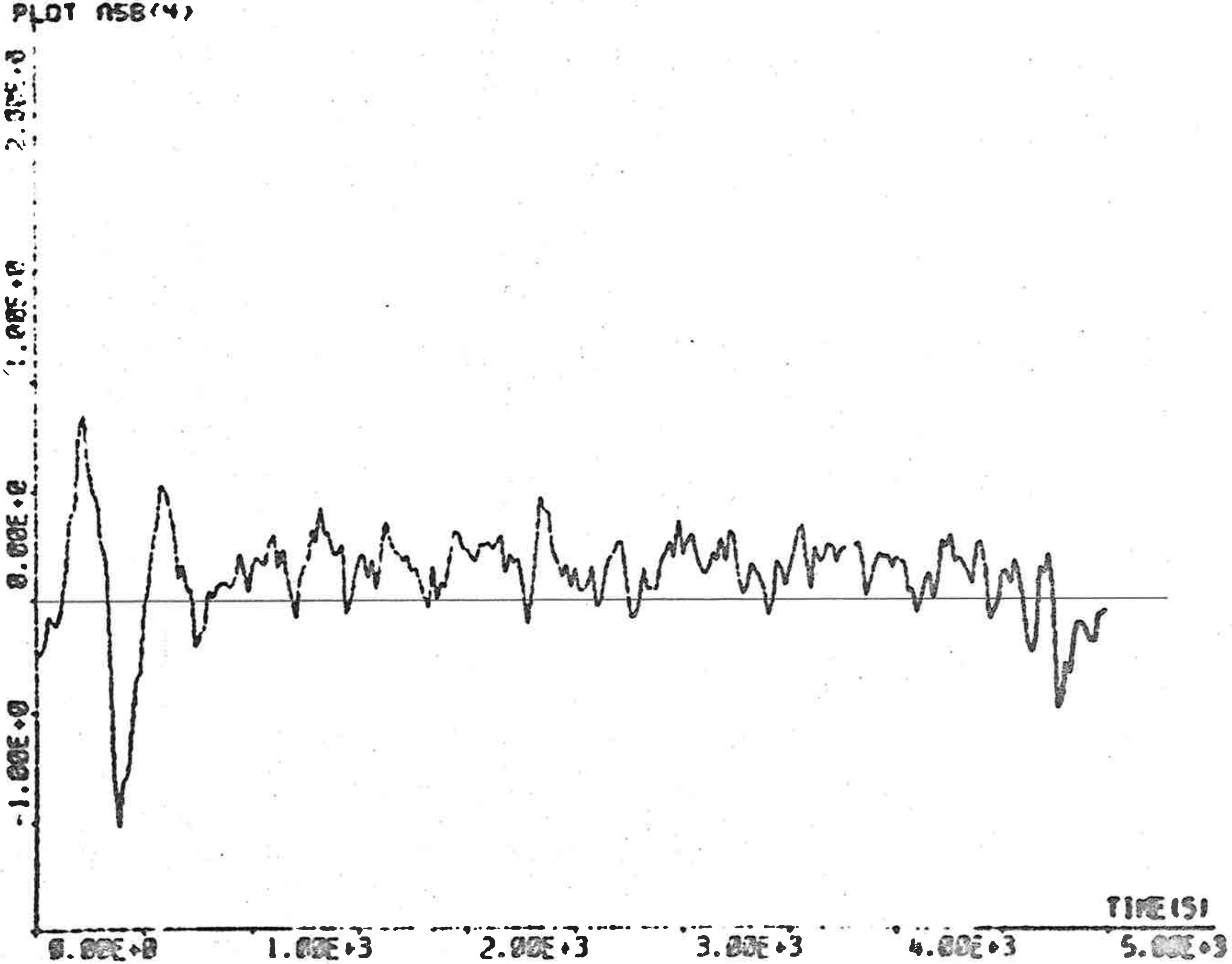

PLOT ASE(2)
1.00E-1
5.00E-2
0.00E+0
-5.00E-2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
+5°
0°
-5°
+3°
-3°
δ degr

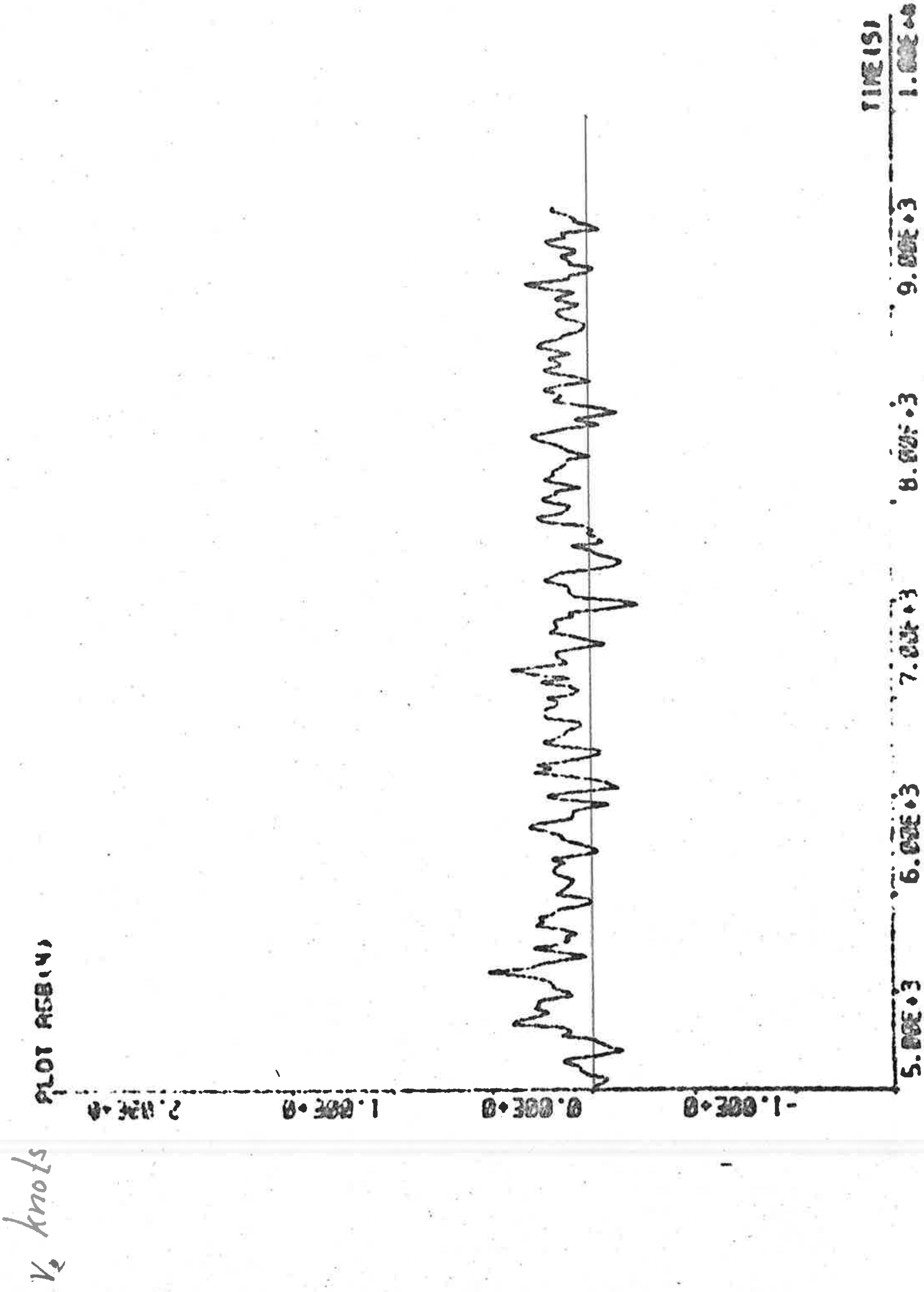

PLOT ASB(2)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
+5°
0°
-5°
δ degr

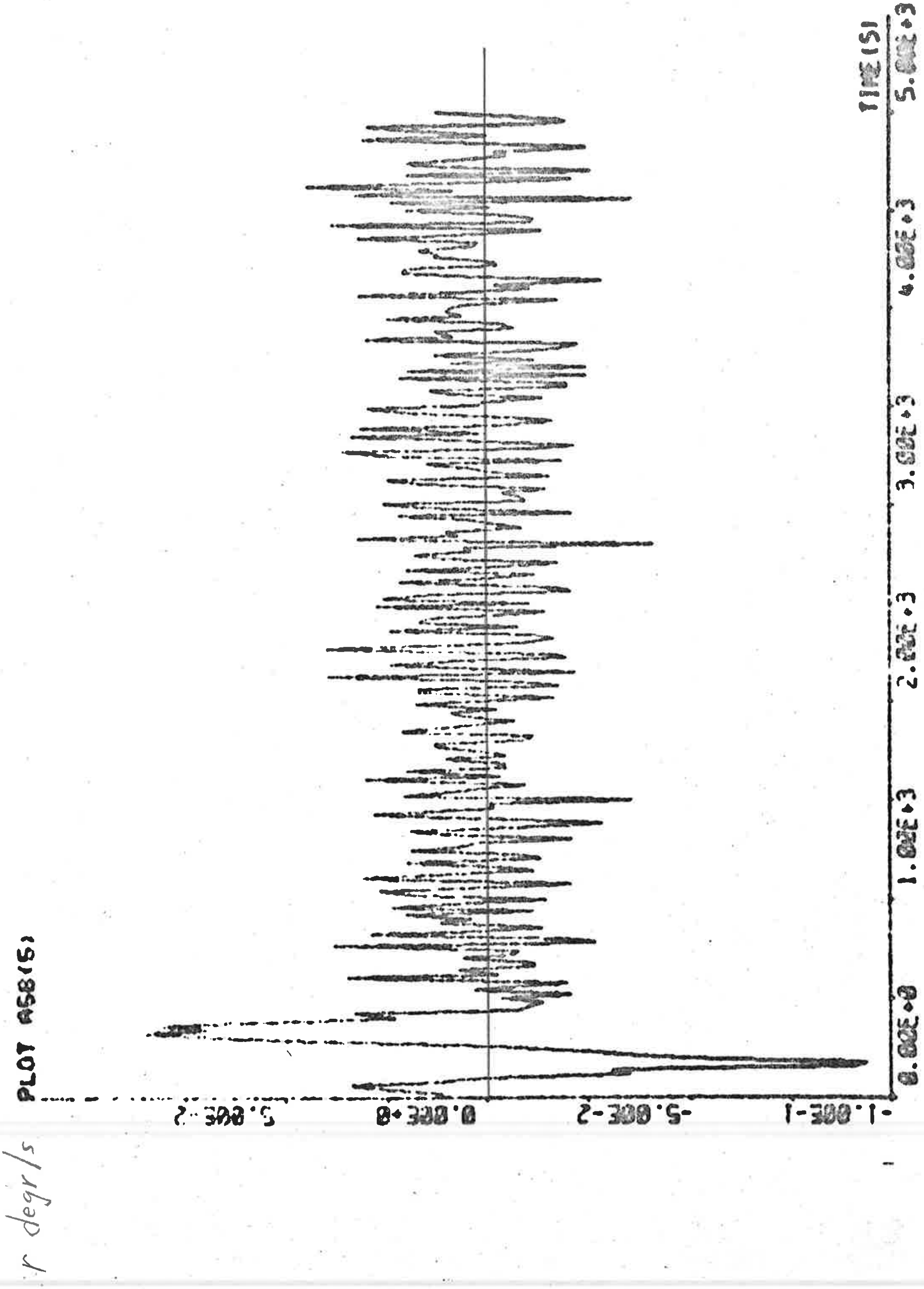

PLOT ASB(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_1 knots
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)


V_1 knots
PLOT ASB(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4

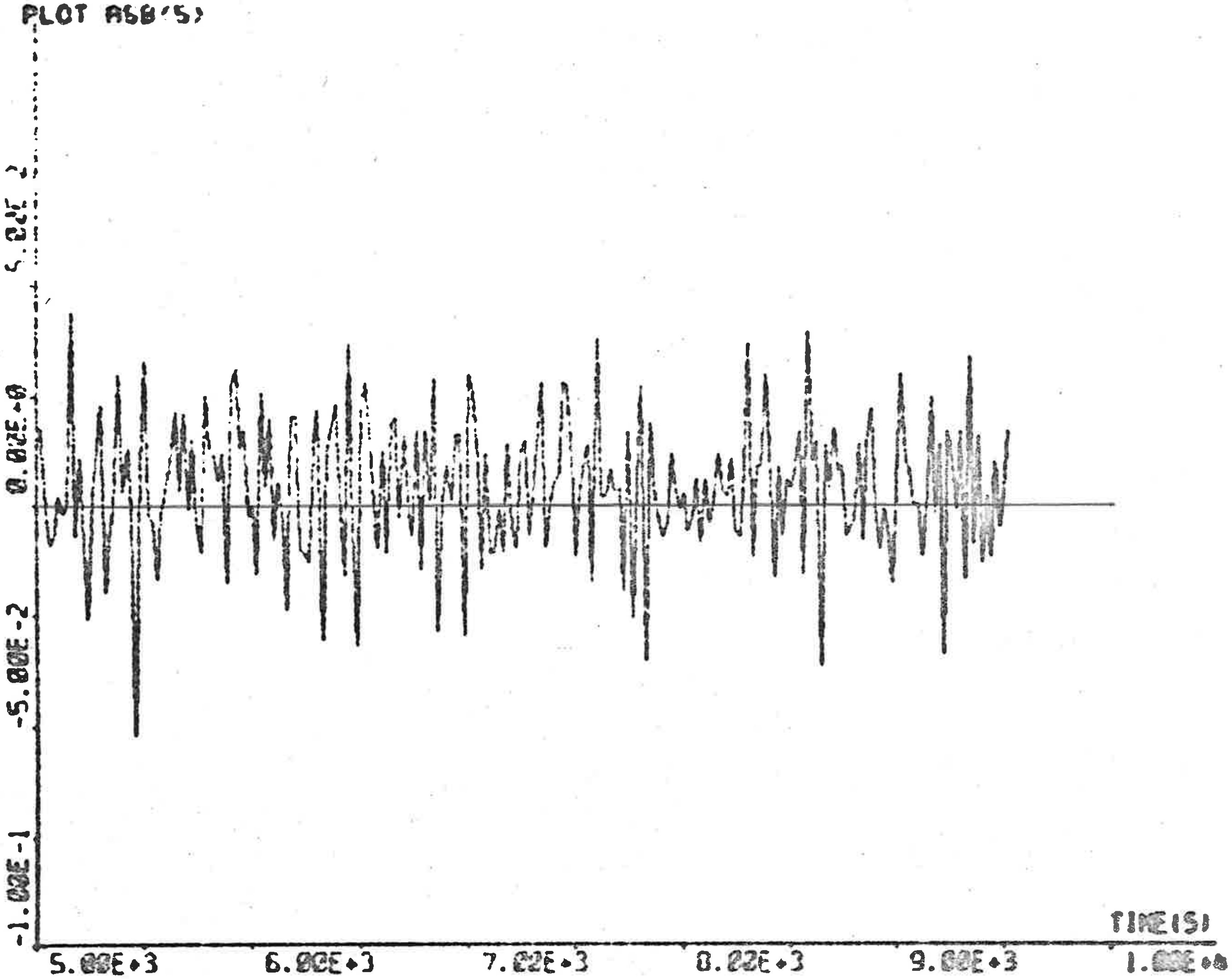
V_g knots

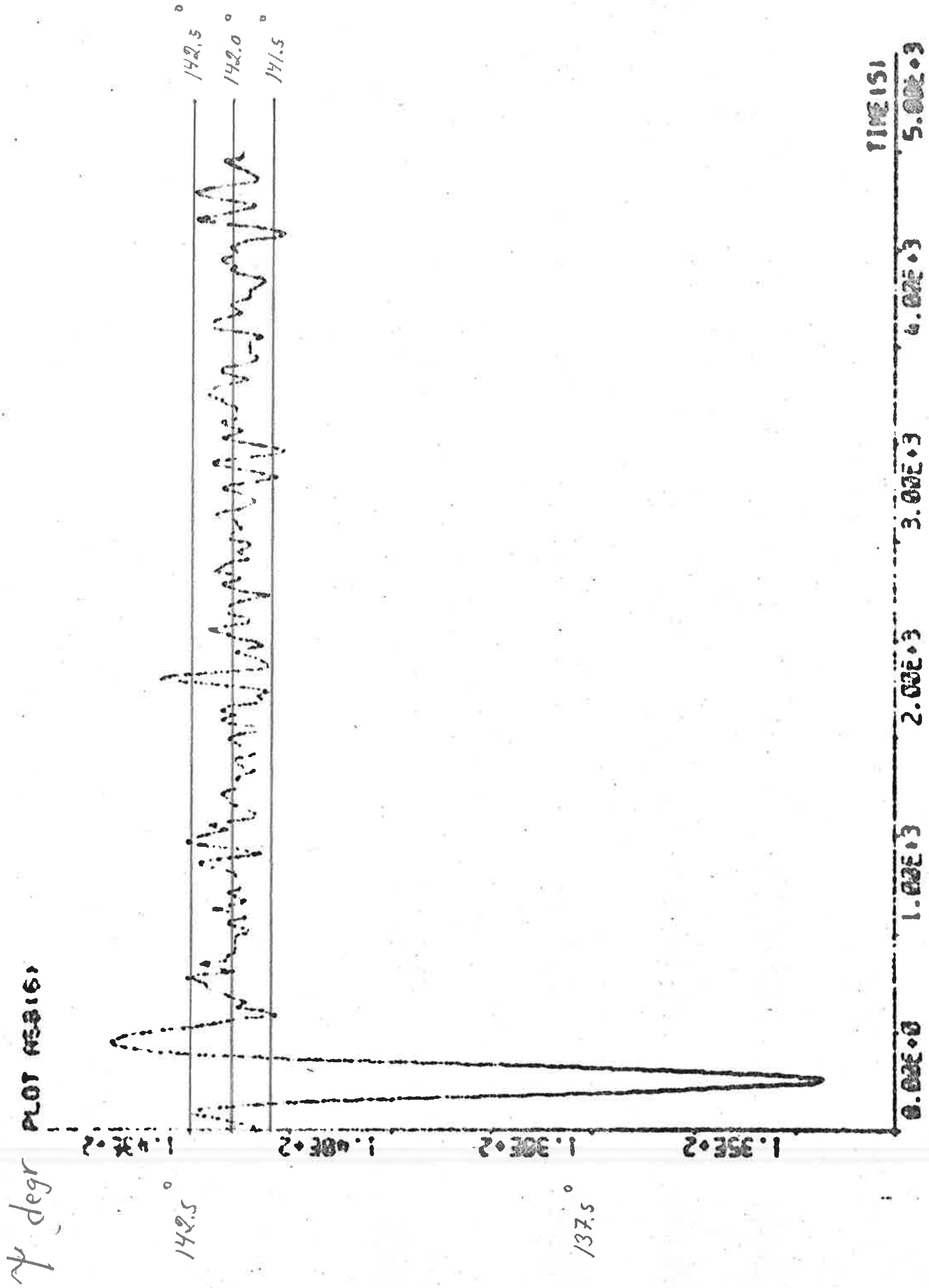

PLOT ASB(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

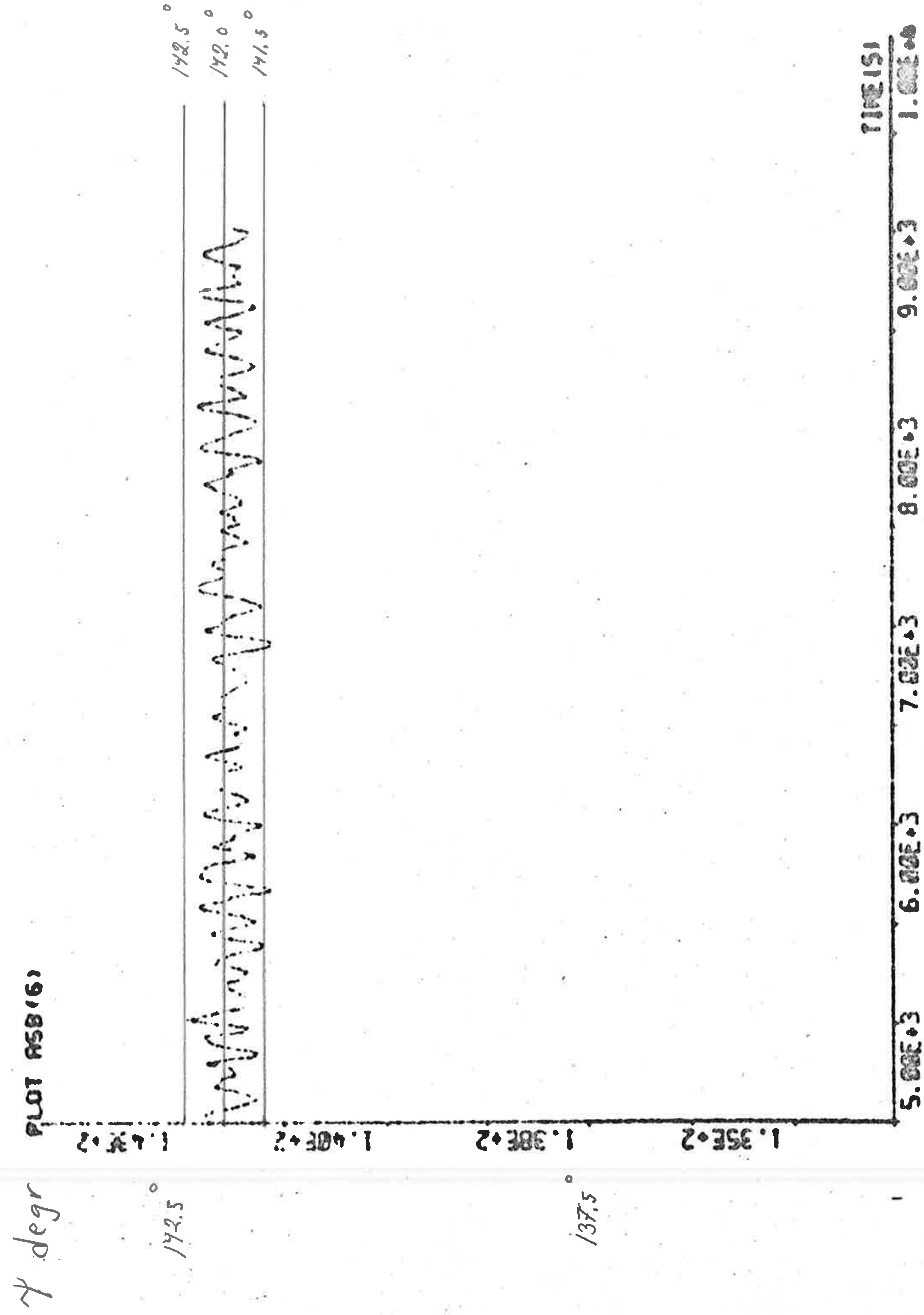

PLOT ASB(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)
V_2 knots

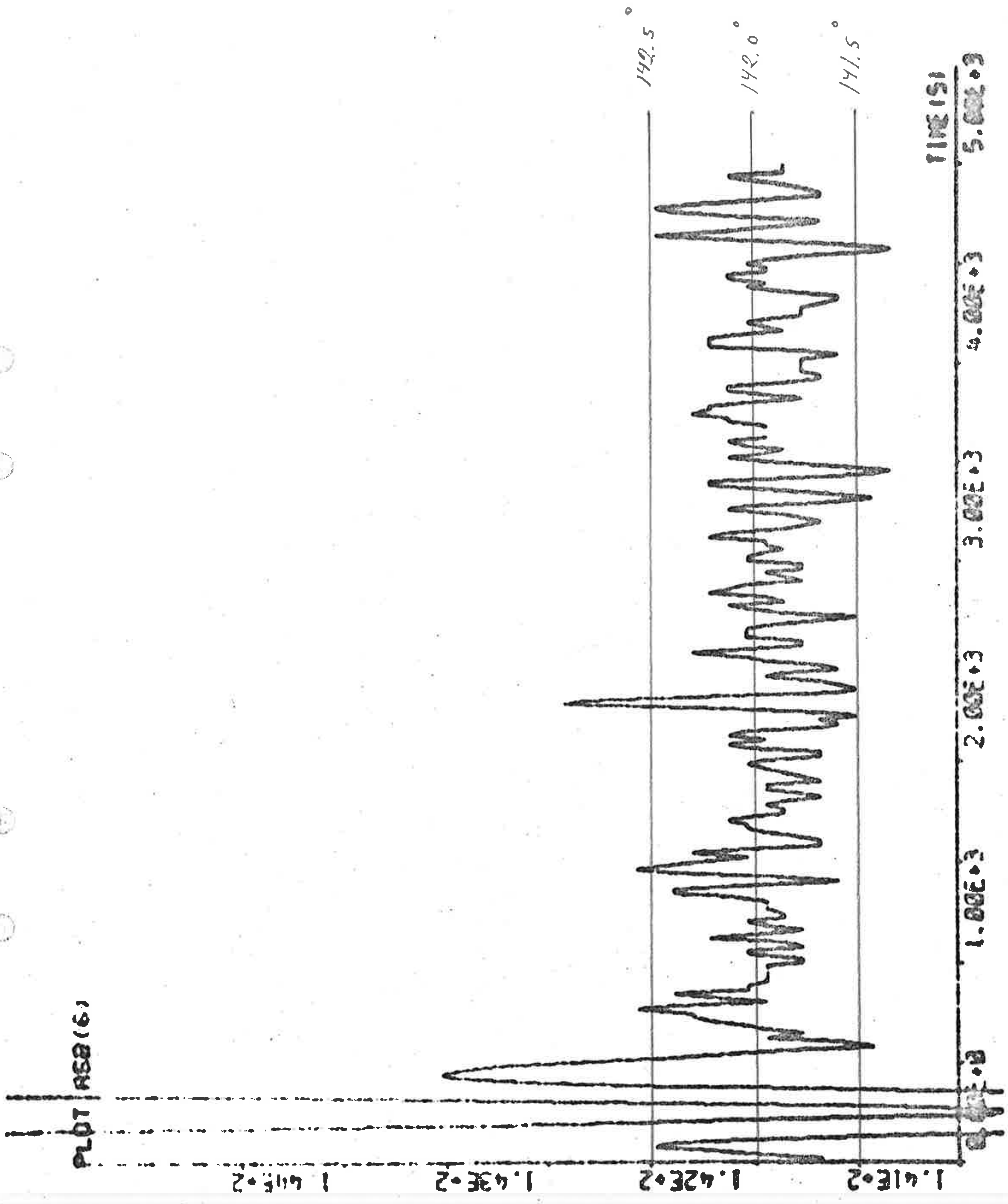

PLOT A58(S)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
r degr/s

r degr/s

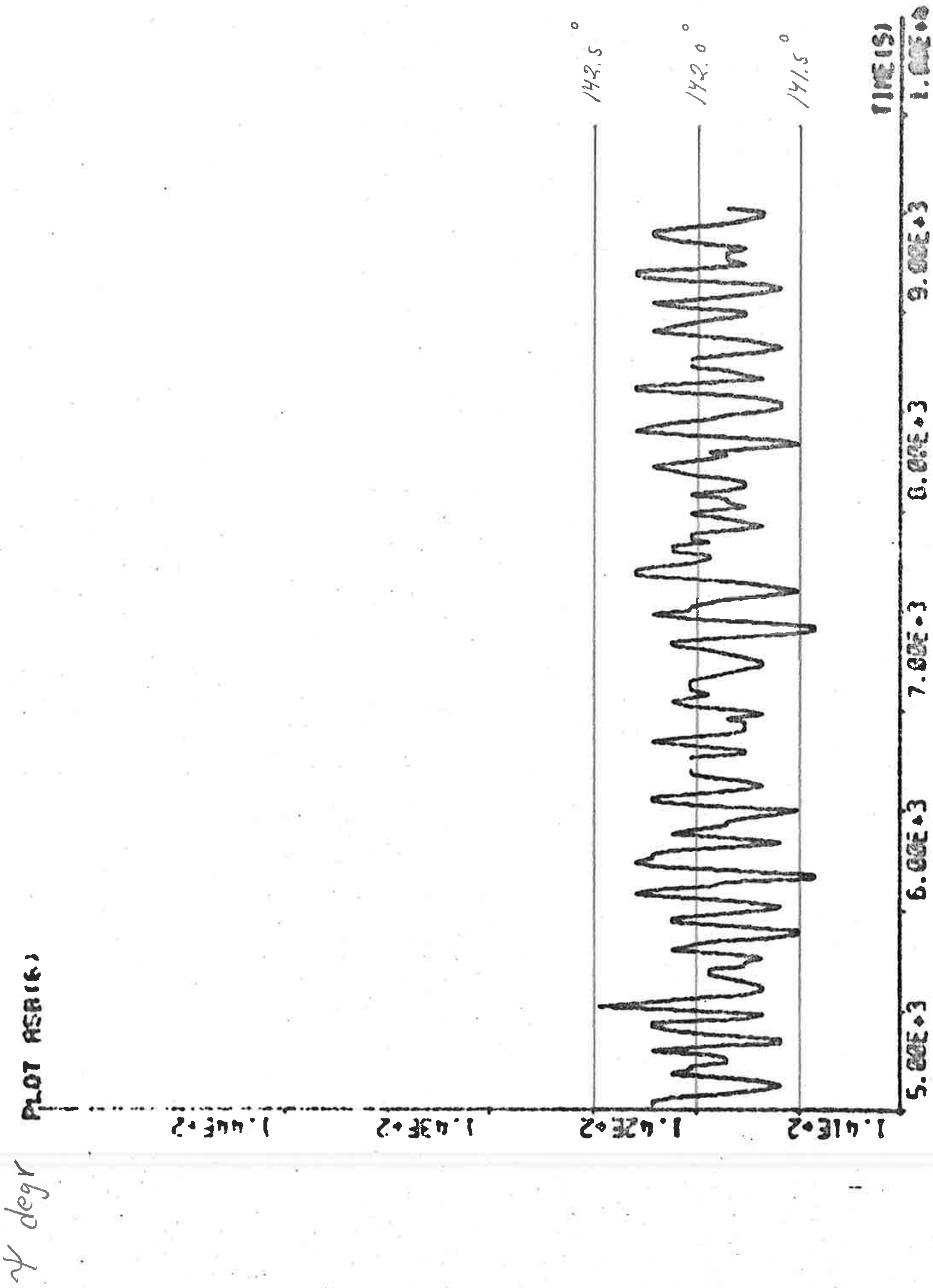

PLOT ASB(5)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4

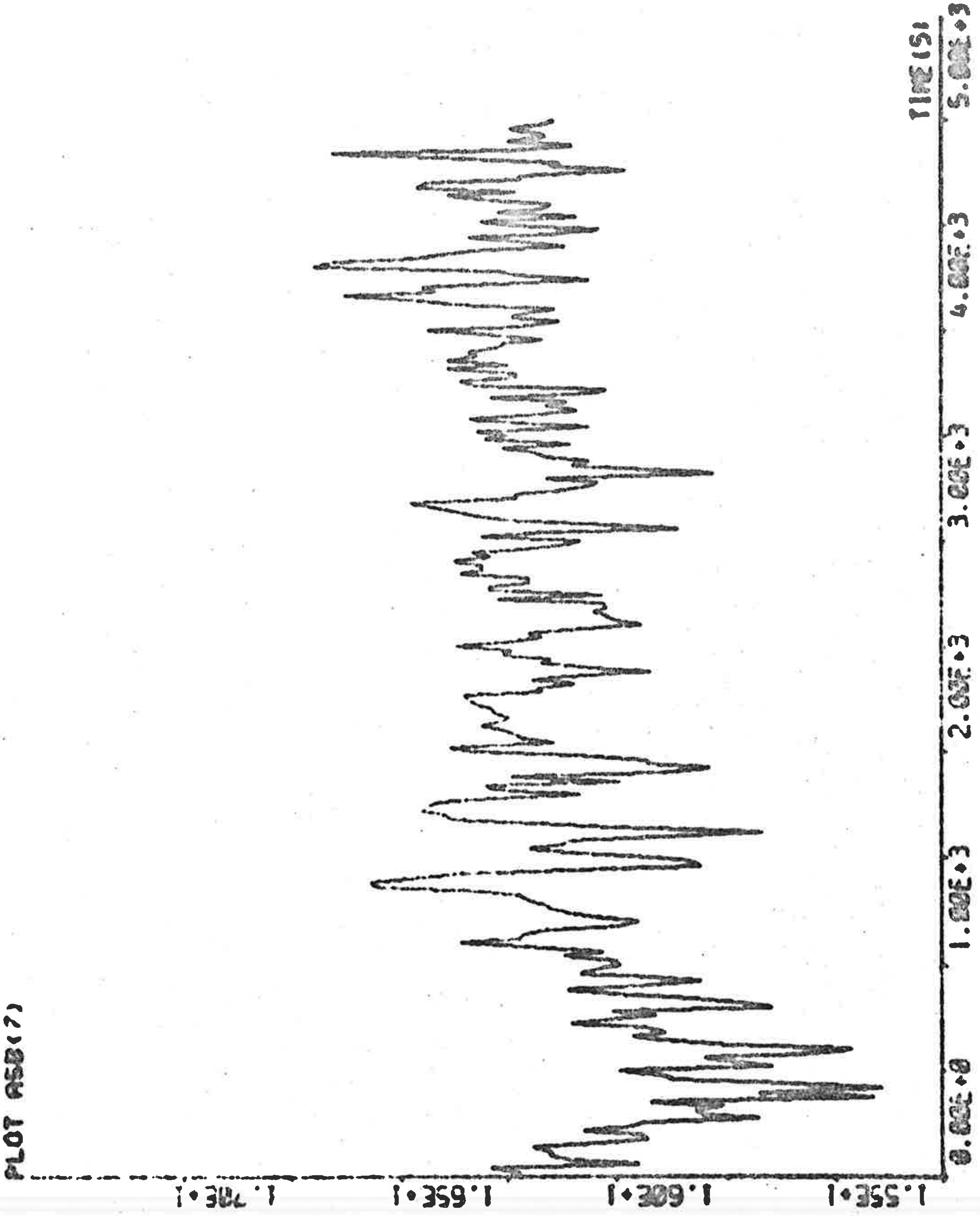

PLOT A53(6)
1.43E+2
1.40E+2
1.38E+2
1.35E+2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
142.5°
142.0°
141.5°
142.5°
137.5°
ψ degr


PLOT ASB(6)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.4E+2
1.40E+2
1.38E+2
1.35E+2
142.5°
142.0°
141.5°
T degr
142.5°
137.5°


142.5°
142.0°
141.5°
TIME (S)
5.00E+3
4.00E+3
3.00E+3
2.00E+3
1.00E+3
0.0
PLOT
ASB(6)
1.41E+2
1.42E+2
1.43E+2
1.44E+2

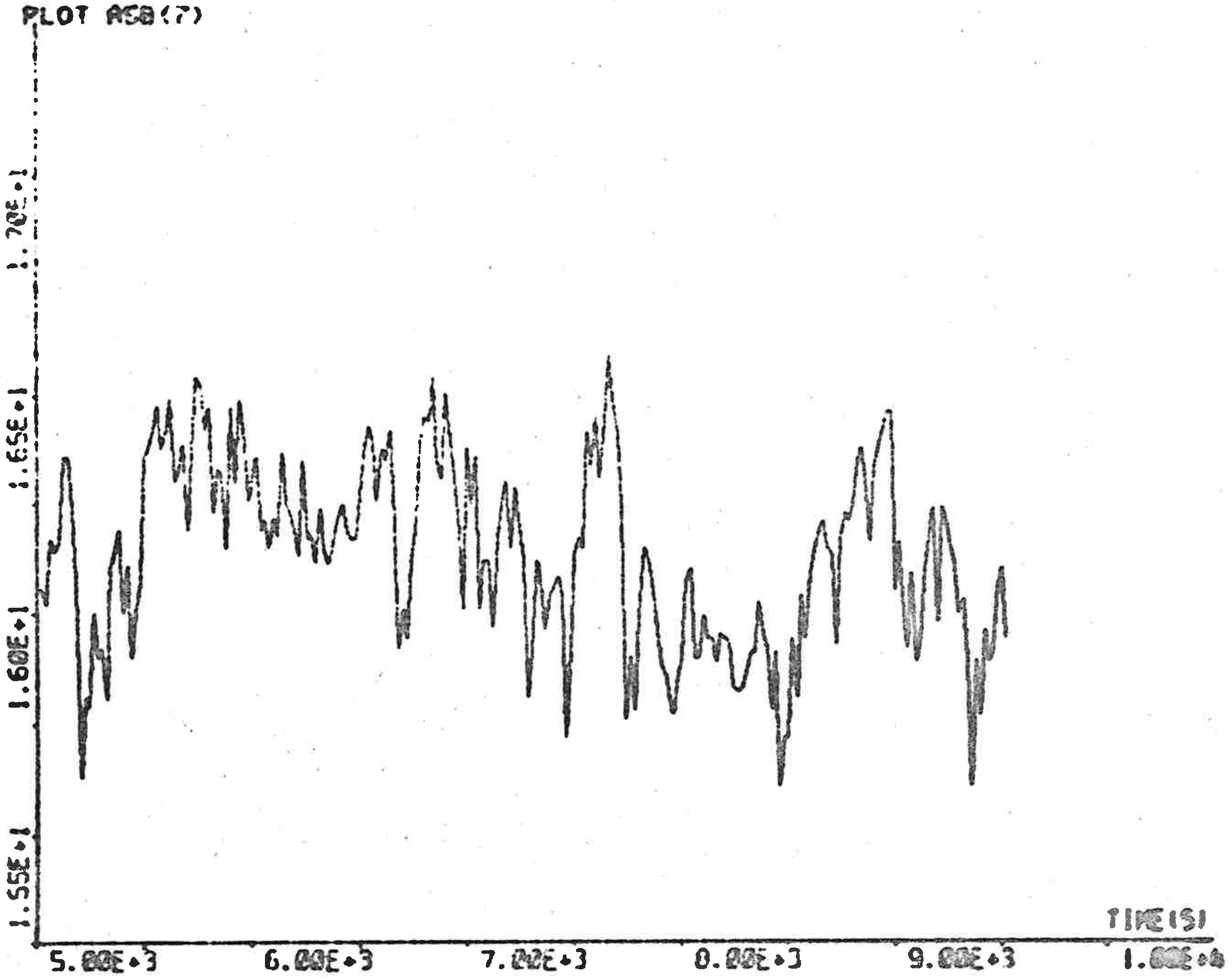
14 degr

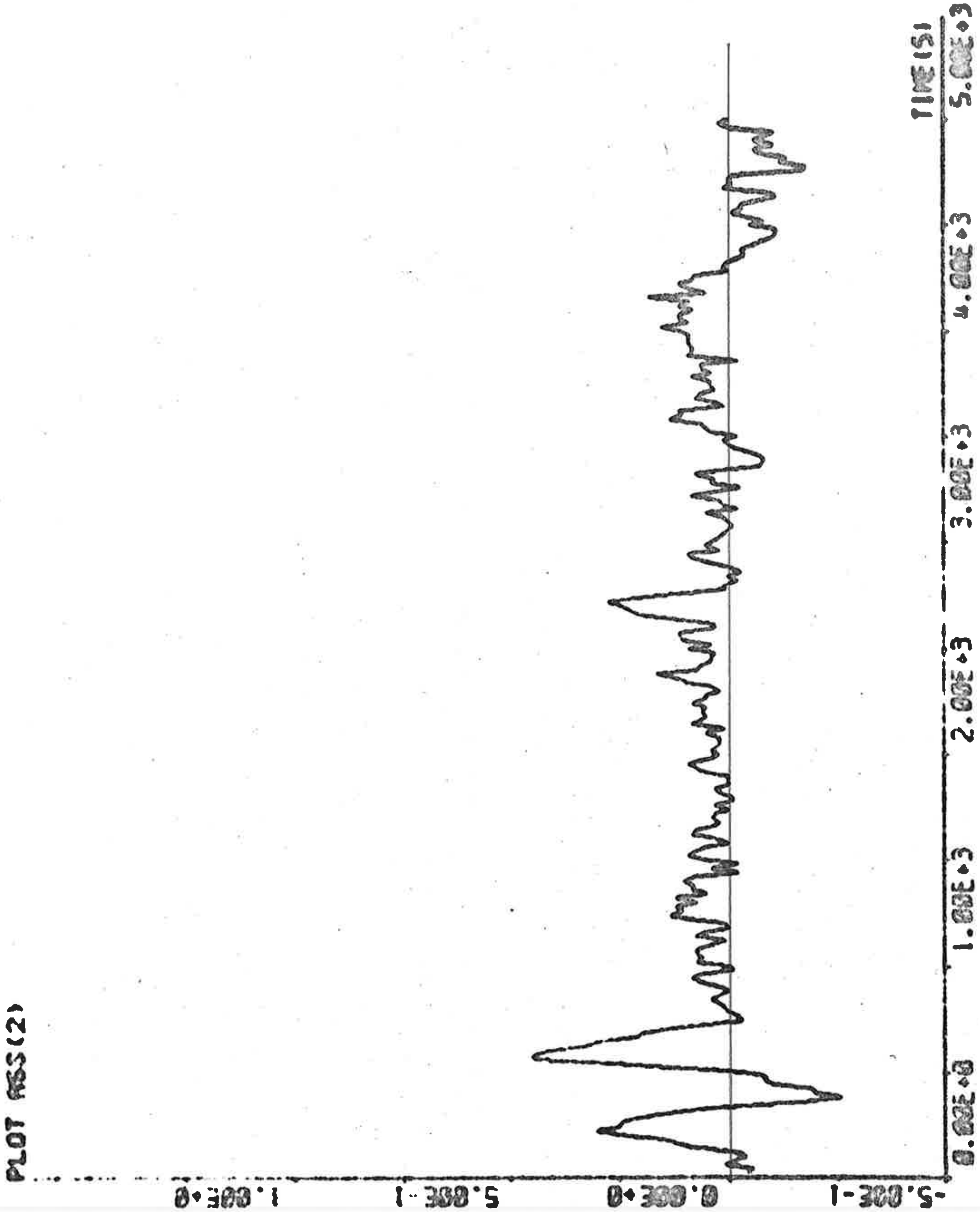

PLOT ASR(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME (S)
142.5°
142.0°
141.5°
ψ degr

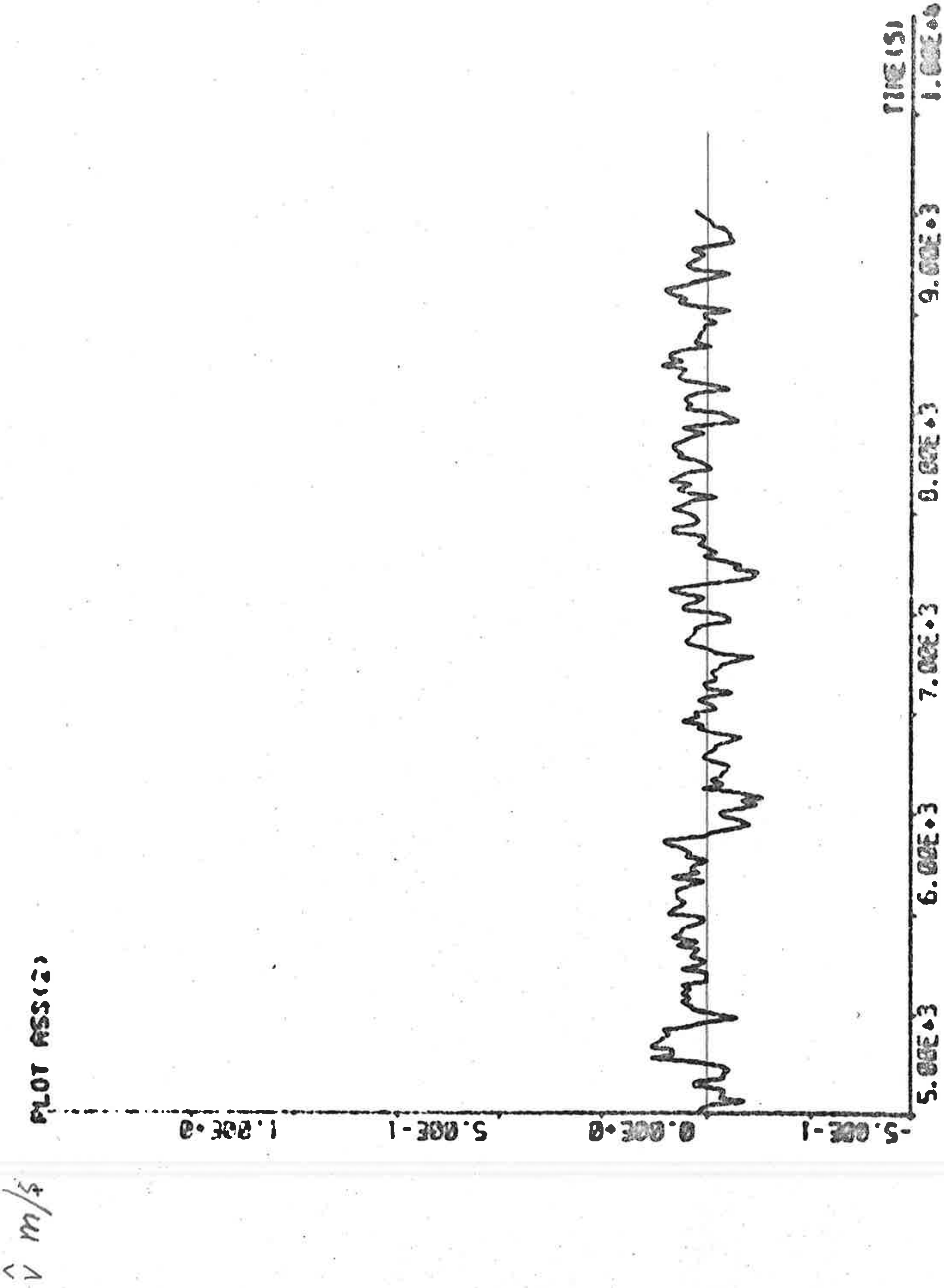

PLOT ASB(7)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.55E+1
1.60E+1
1.65E+1
1.70E+1

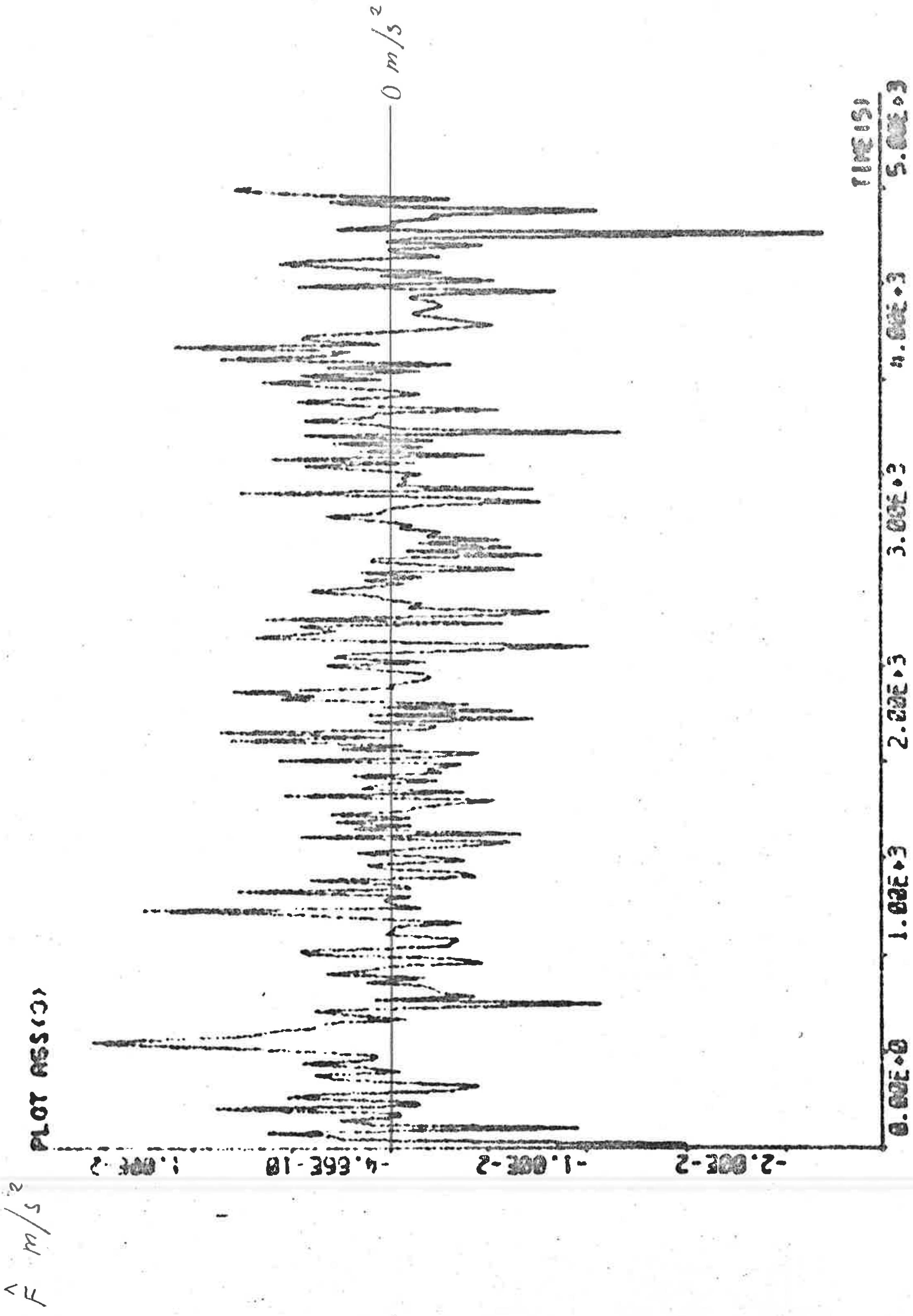
u knots

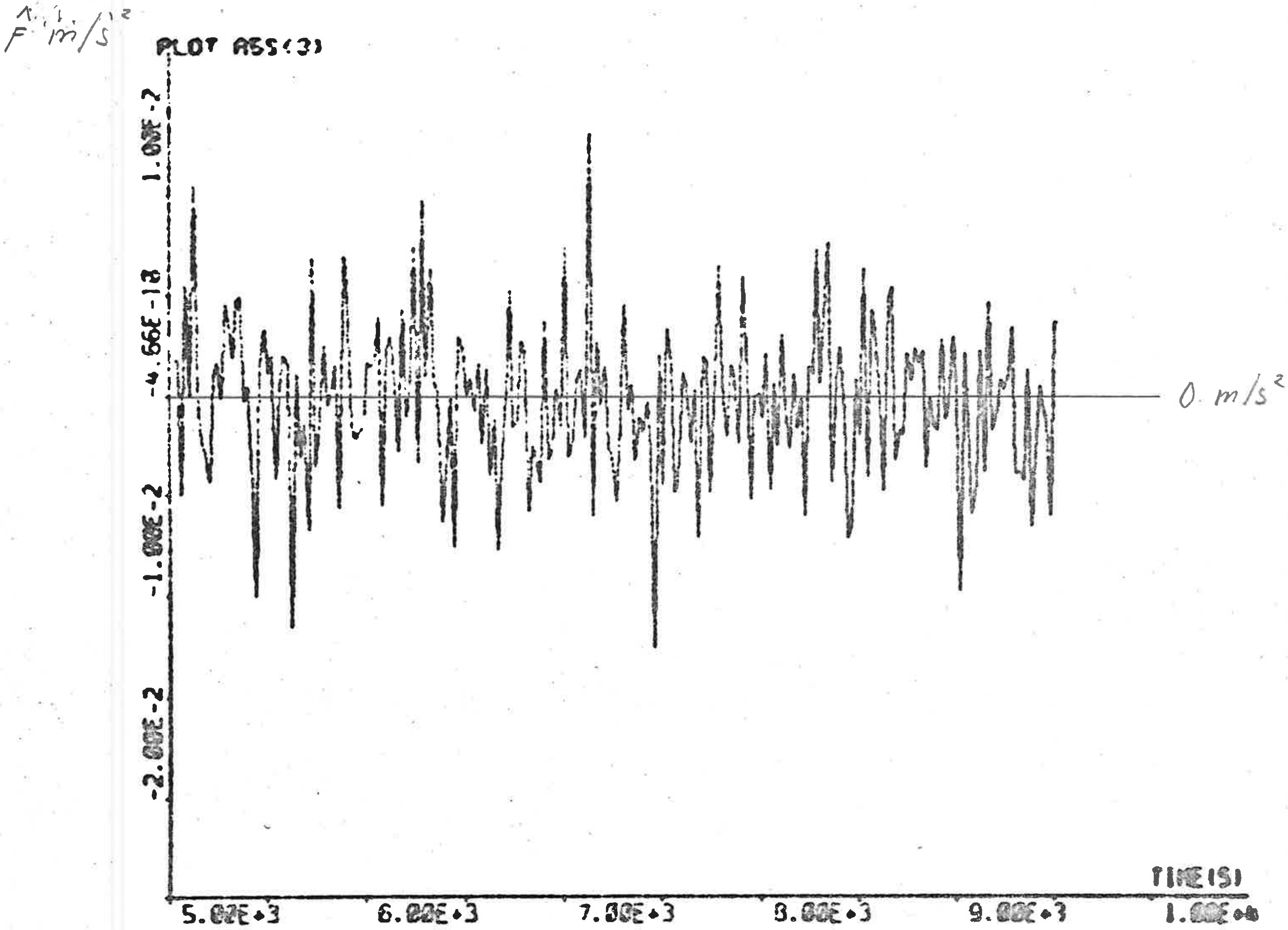
u knots

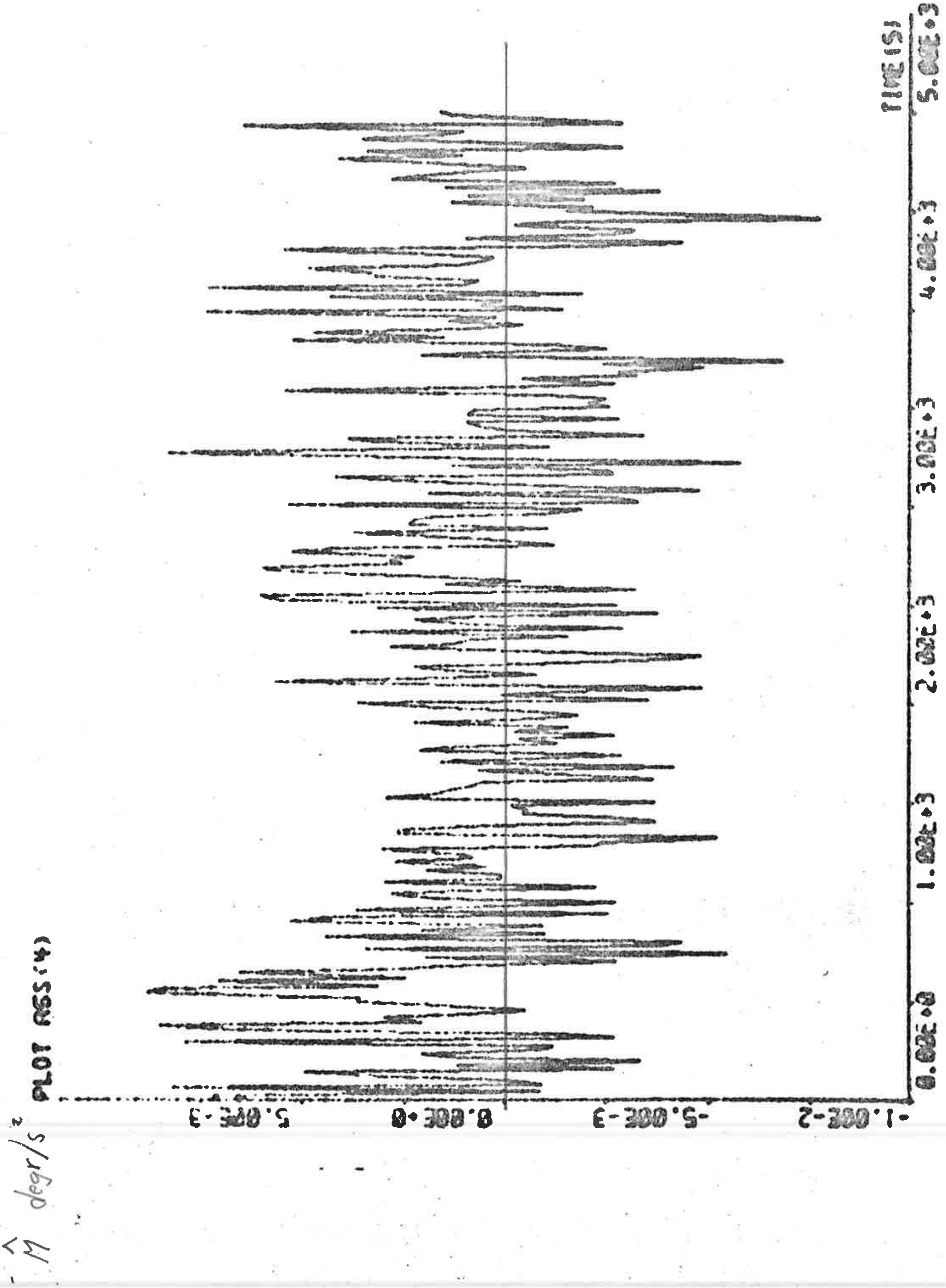

PLOT ASB(7)
1.70E+1
1.65E+1
1.60E+1
1.55E+1
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

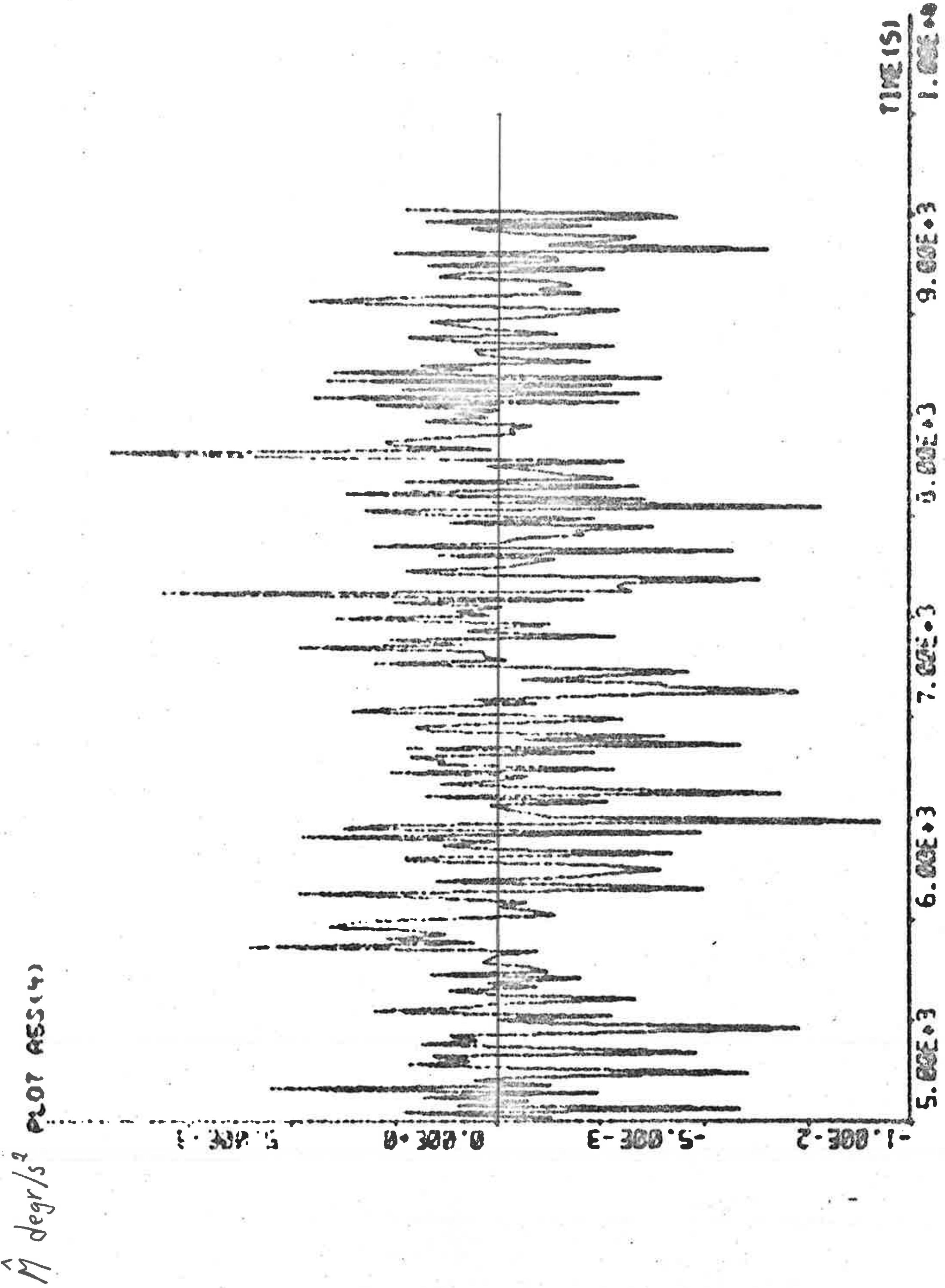

PLOT RES(2)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+0
5.00E-1
0.00E+0
-5.00E-1

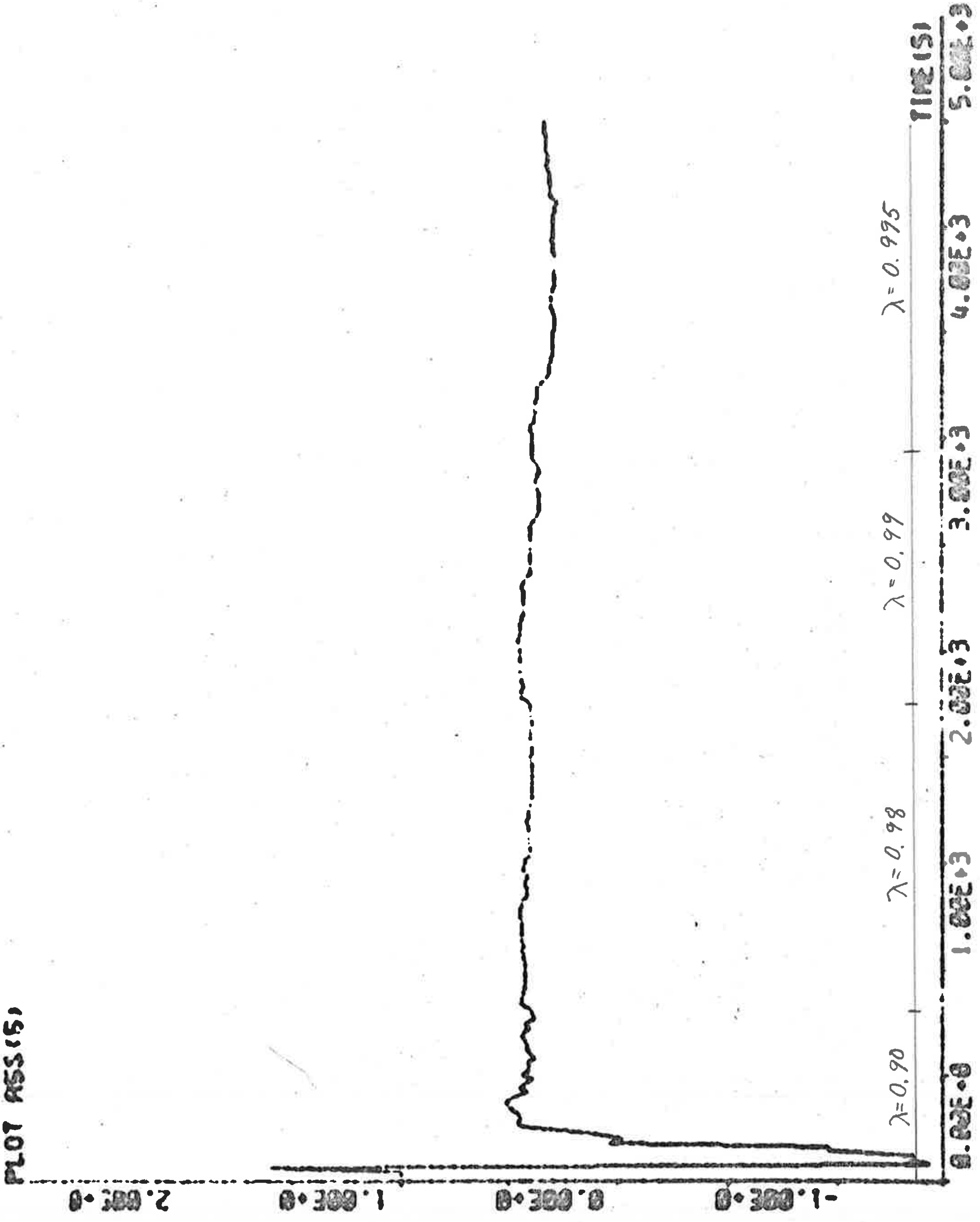

PLOT ASS(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)
v m/s


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


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

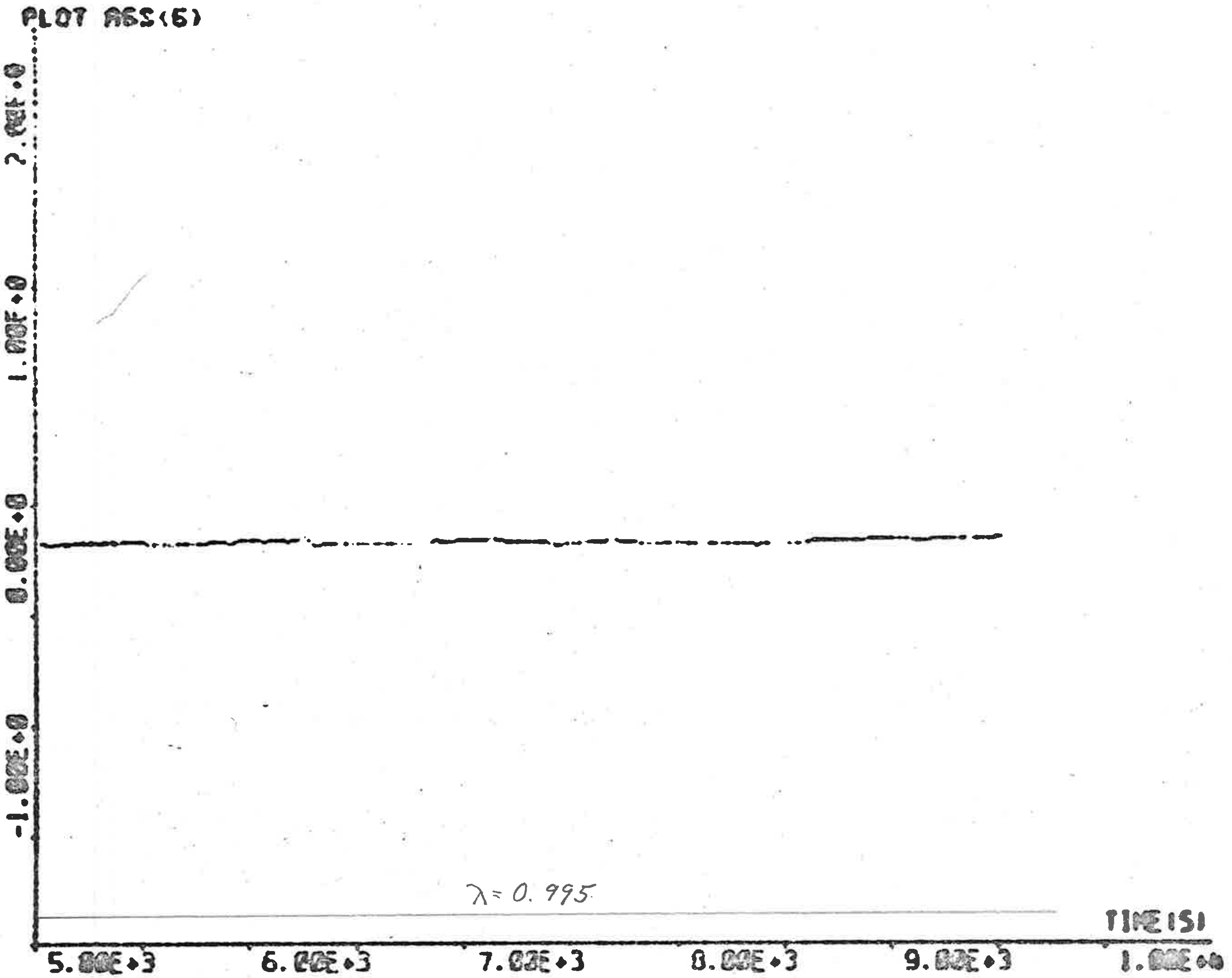

PLOT ASS(4)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
$\hat{M}$ degr/s^2

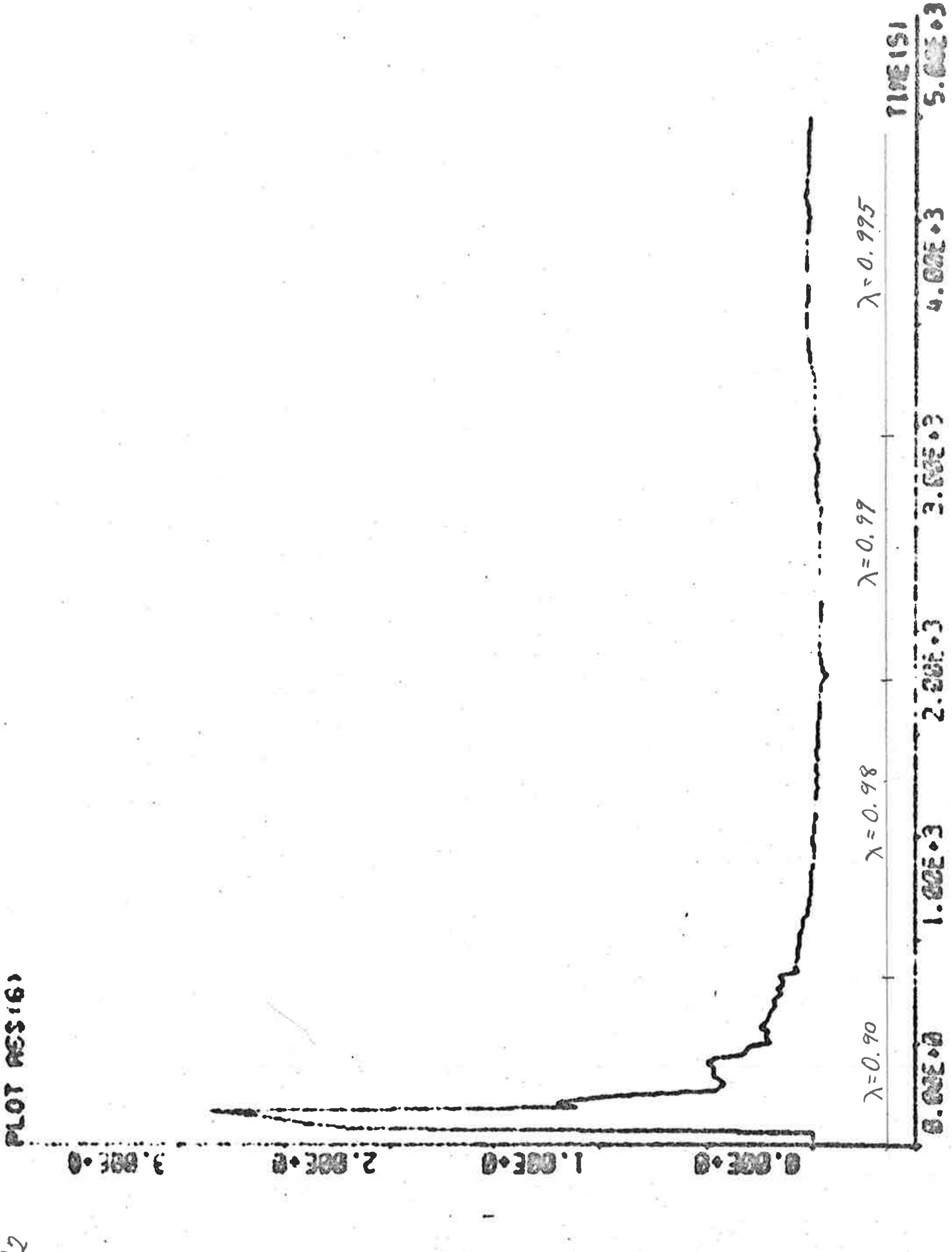

PLOT ASS(4)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E-2
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
M̂ degr/s²


PLOT ASS(5)
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
λ=0.90
λ=0.98
λ=0.99
λ=0.995

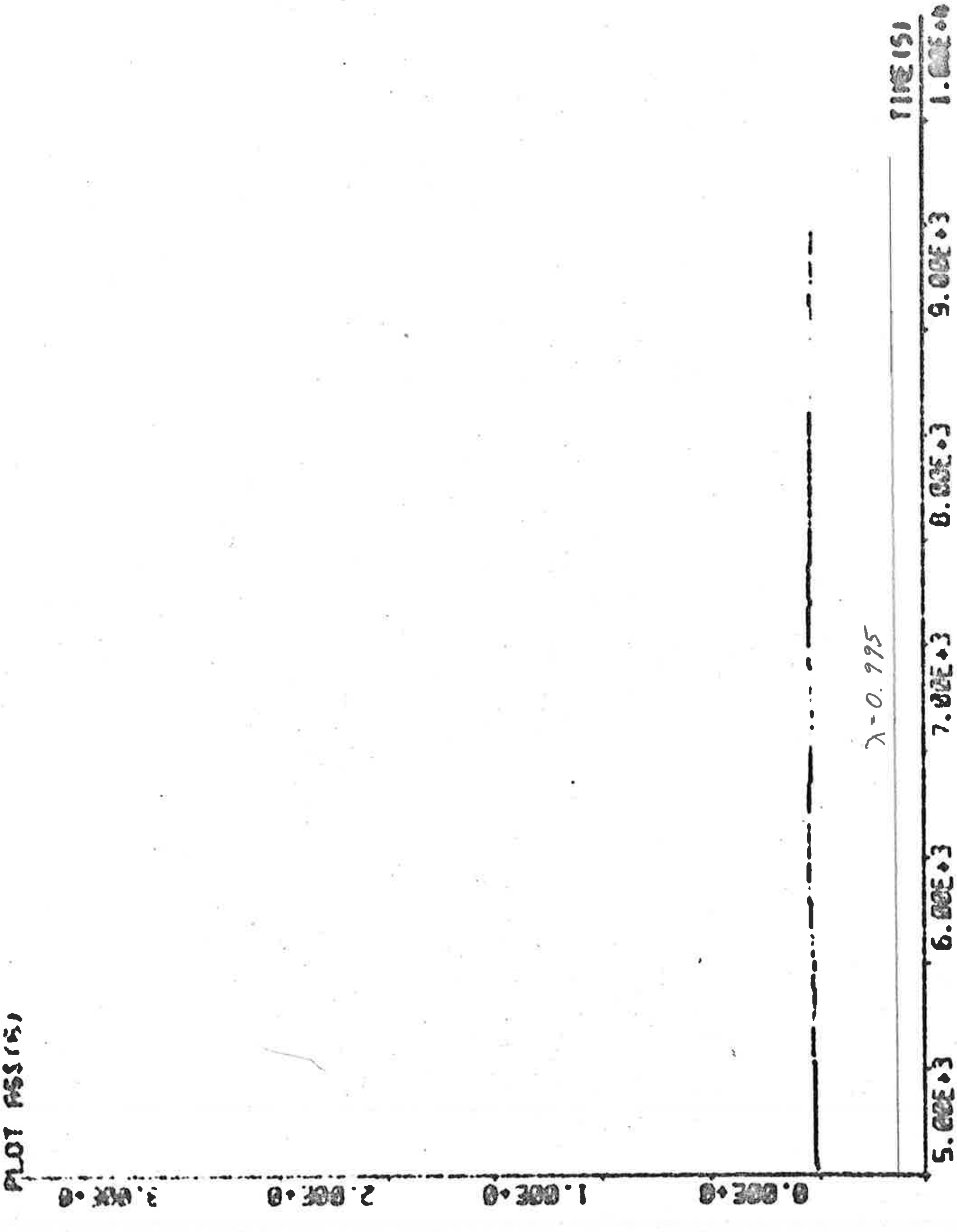
b1

b1

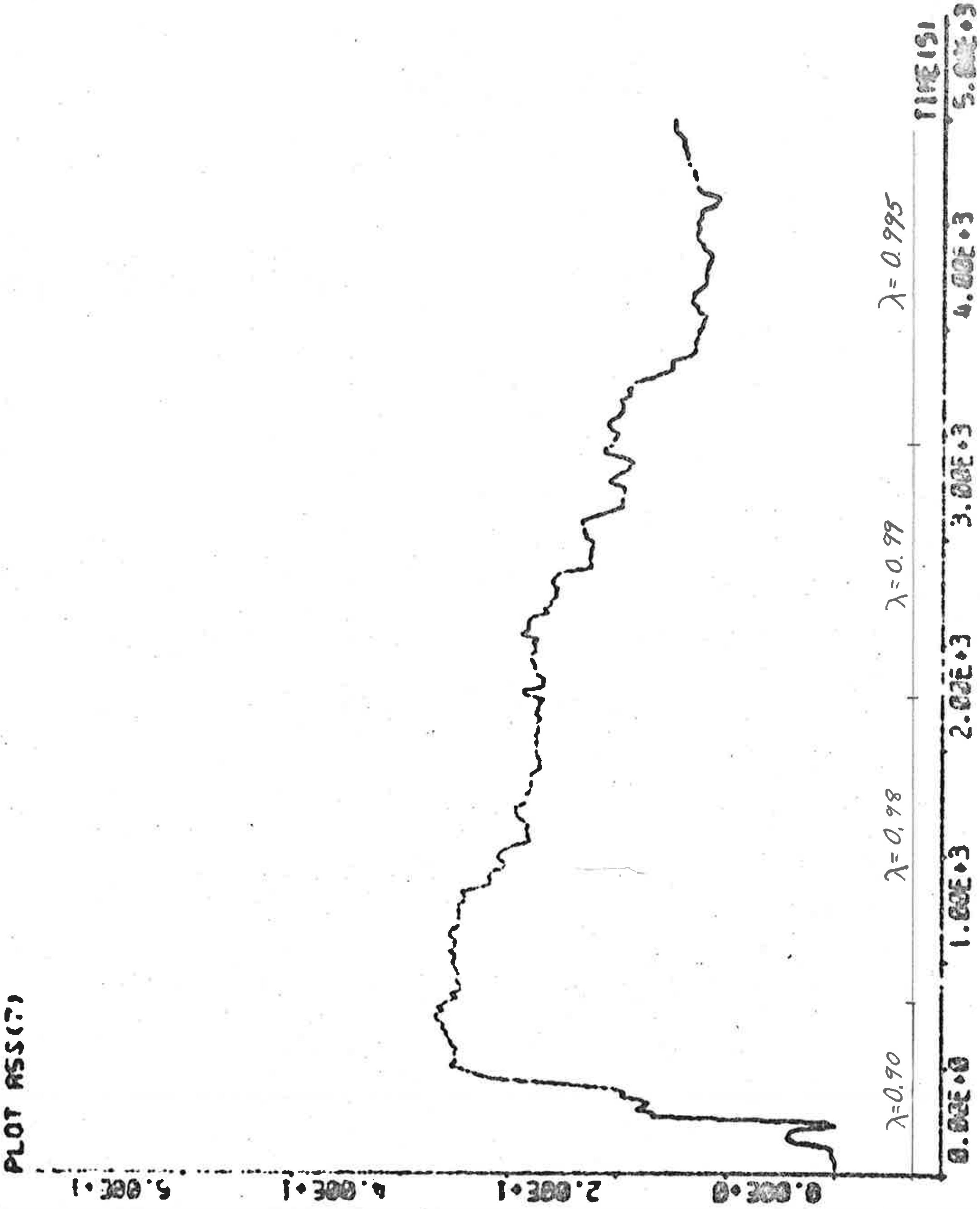

PLOT ABS(5)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
λ = 0.995
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4


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

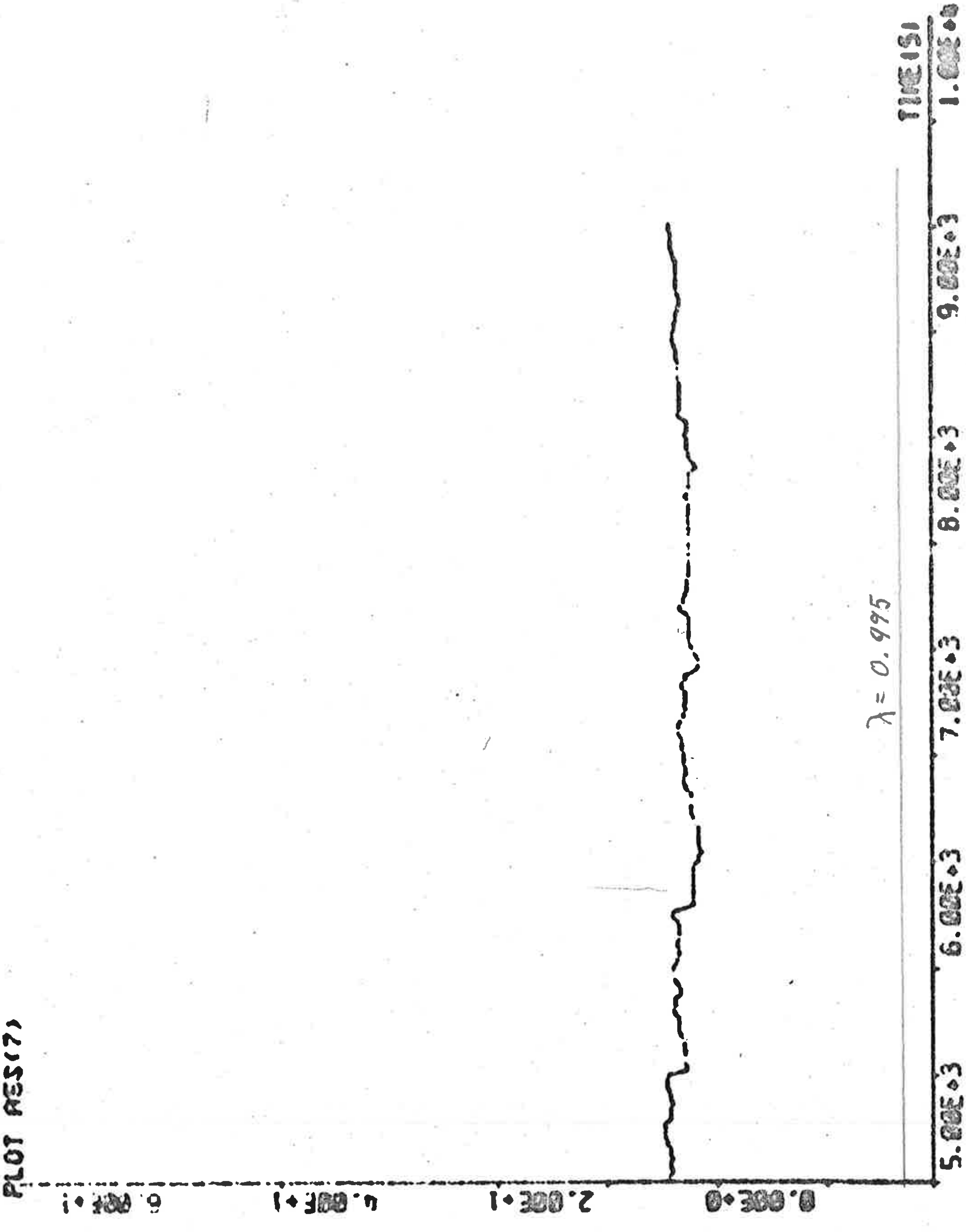
p_2


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

b2


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

d_2


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

d_2

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:

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

Regulator:

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

Sampling interval:	20 s	
Forgetting factor λ:	0.995	(0 - 3700 s)
	0.99	(3700 - 5360 s)
Rudder limits:	±10°	(0 - 3220 s)
	±10°, ±5°, ±3°	(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:

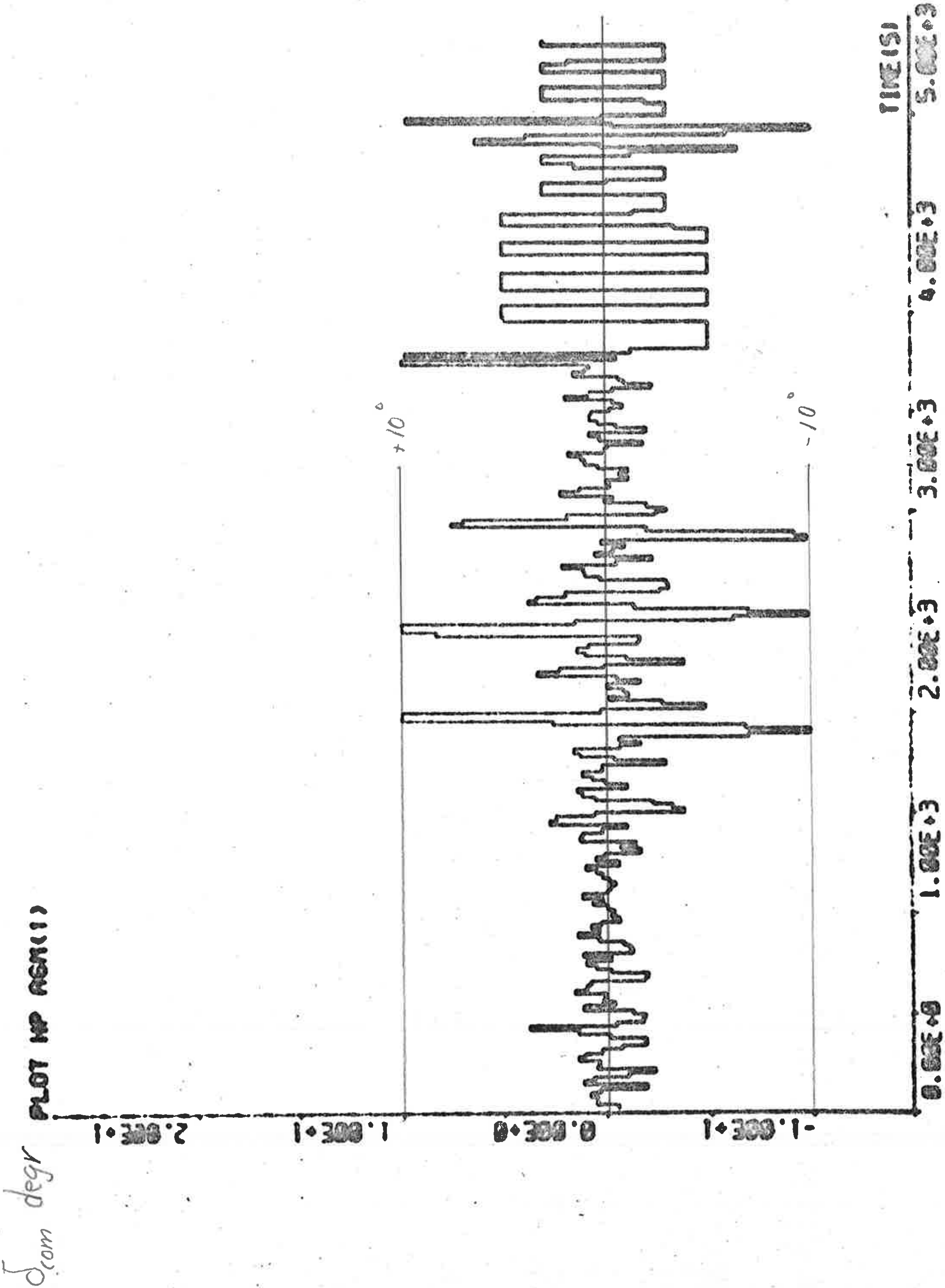
$$\delta(t) = -1.3837(\Psi(t) - \Psi_{ref}) + 0.3534\delta(t-1) - 52.9340r(t)$$

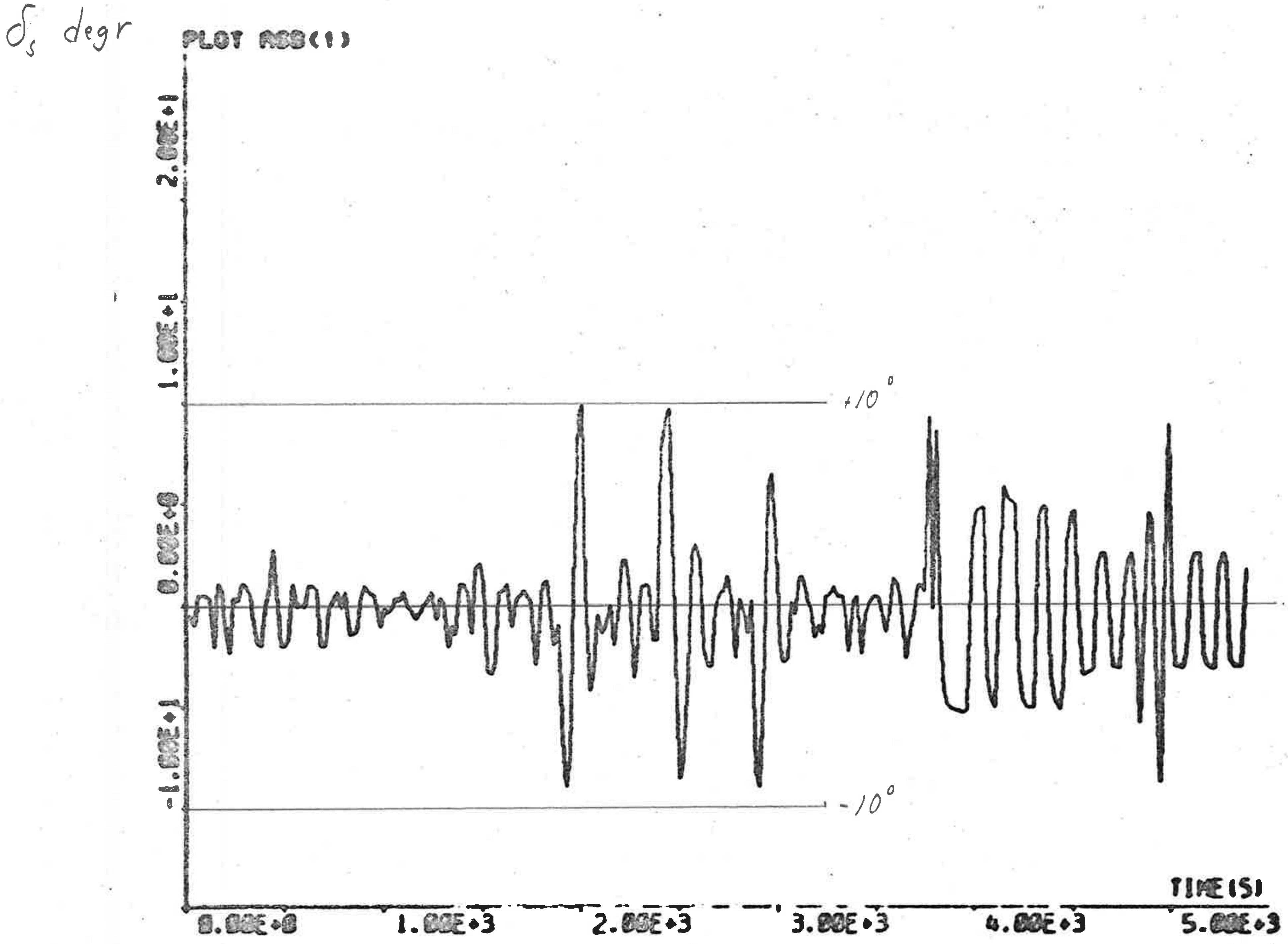
Final values:

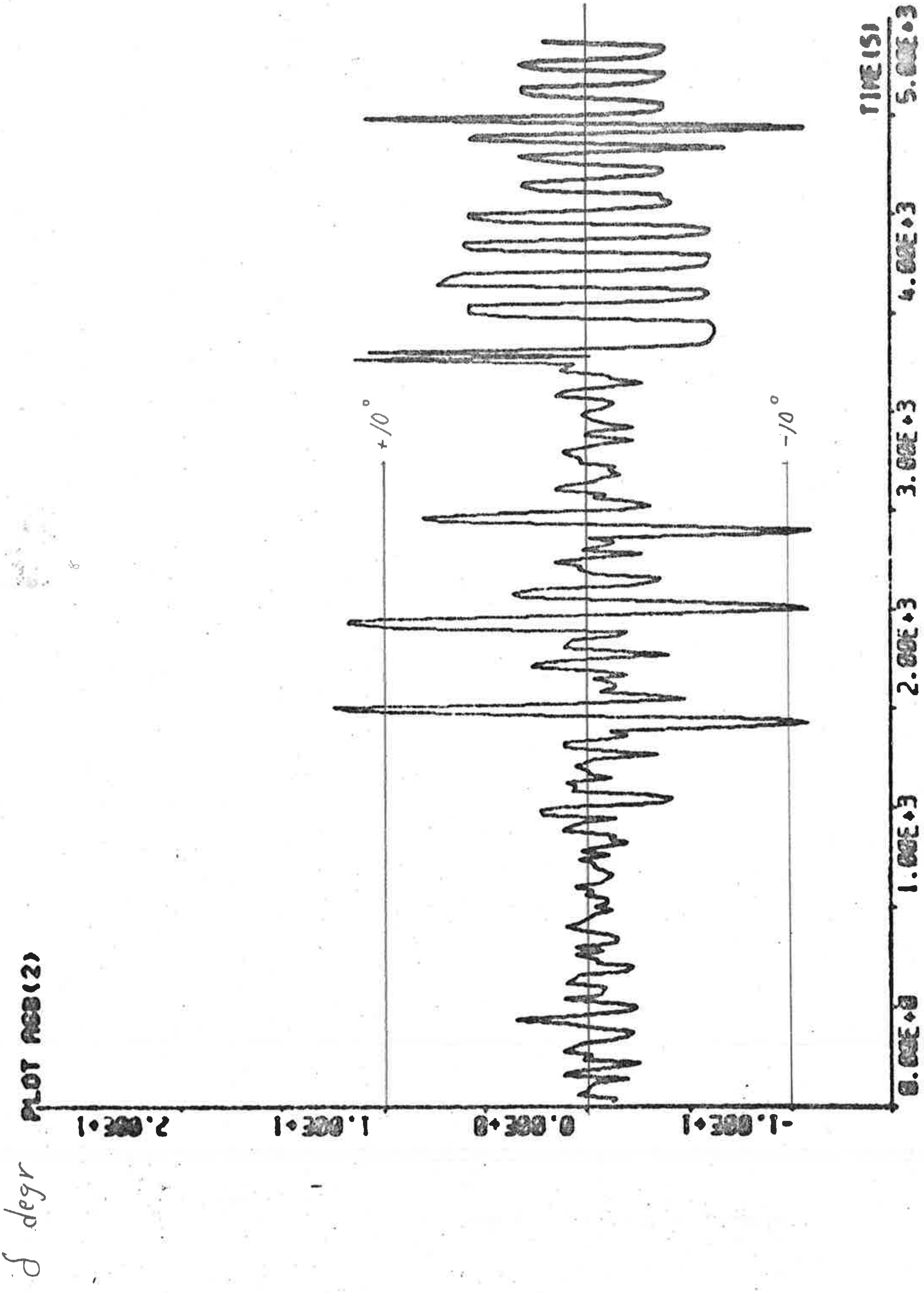
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.0925 \\ 0.0631 \\ 1.7870 \end{bmatrix} \qquad P = \begin{bmatrix} 0.0000154 & & \\ -0.0000017 & 0.0000511 & \\ 0.001778 & -0.006988 & 1.277 \end{bmatrix}$$

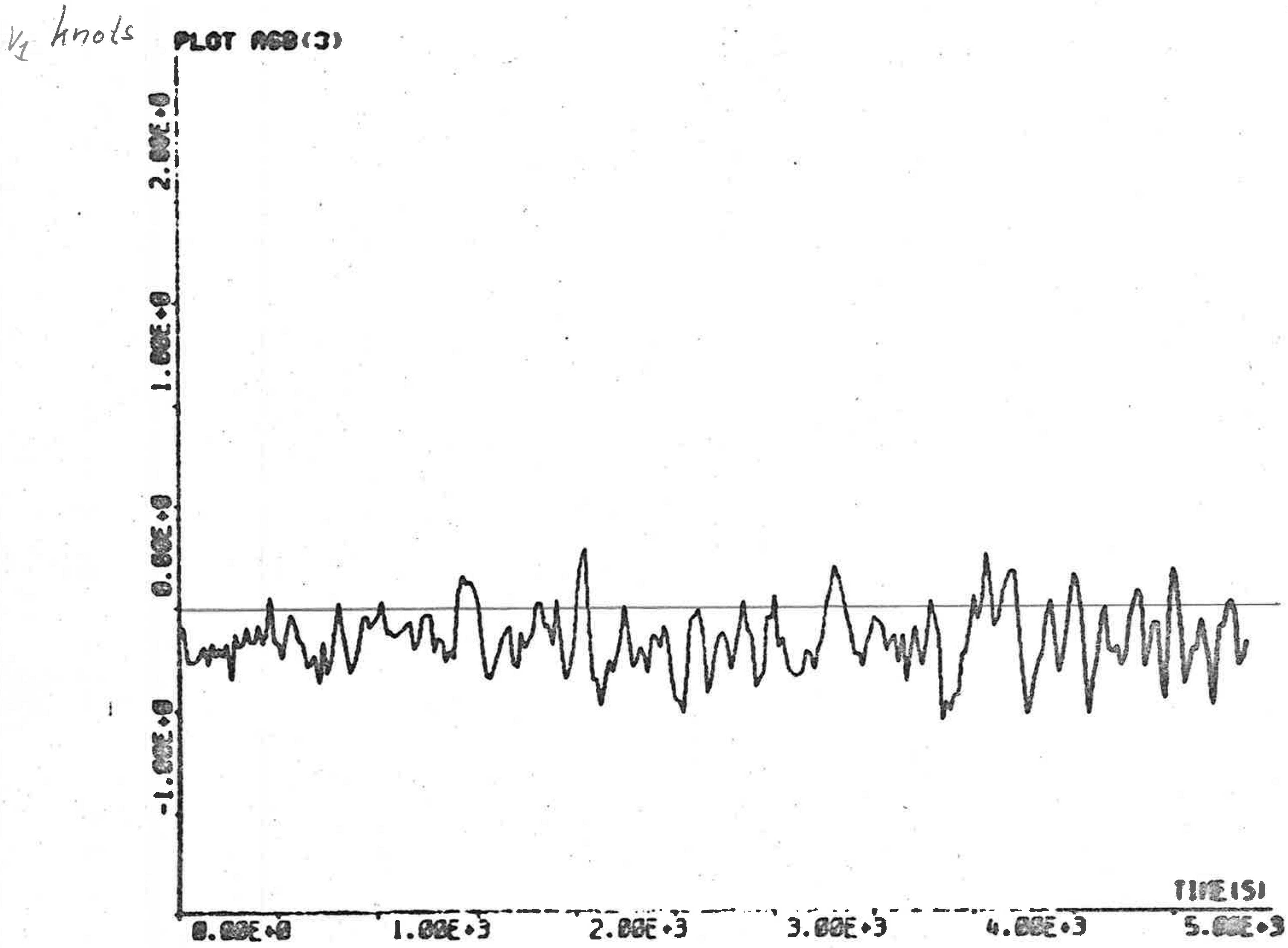
Regulator:

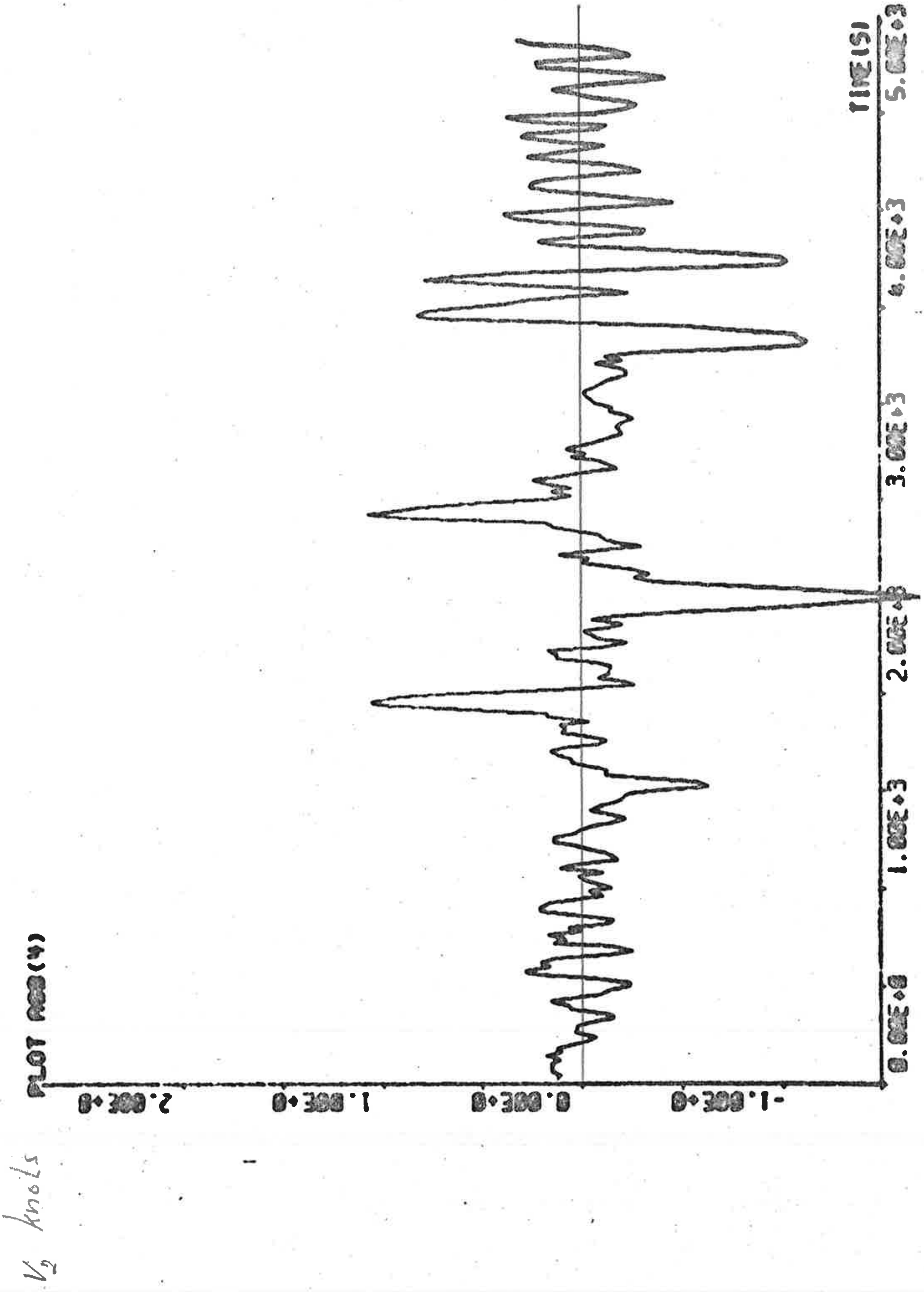
$$\delta(t) = -10.8108(\Psi(t) - \Psi_{ref}) - 0.6822\delta(t-1) - 19.3189r(t)$$

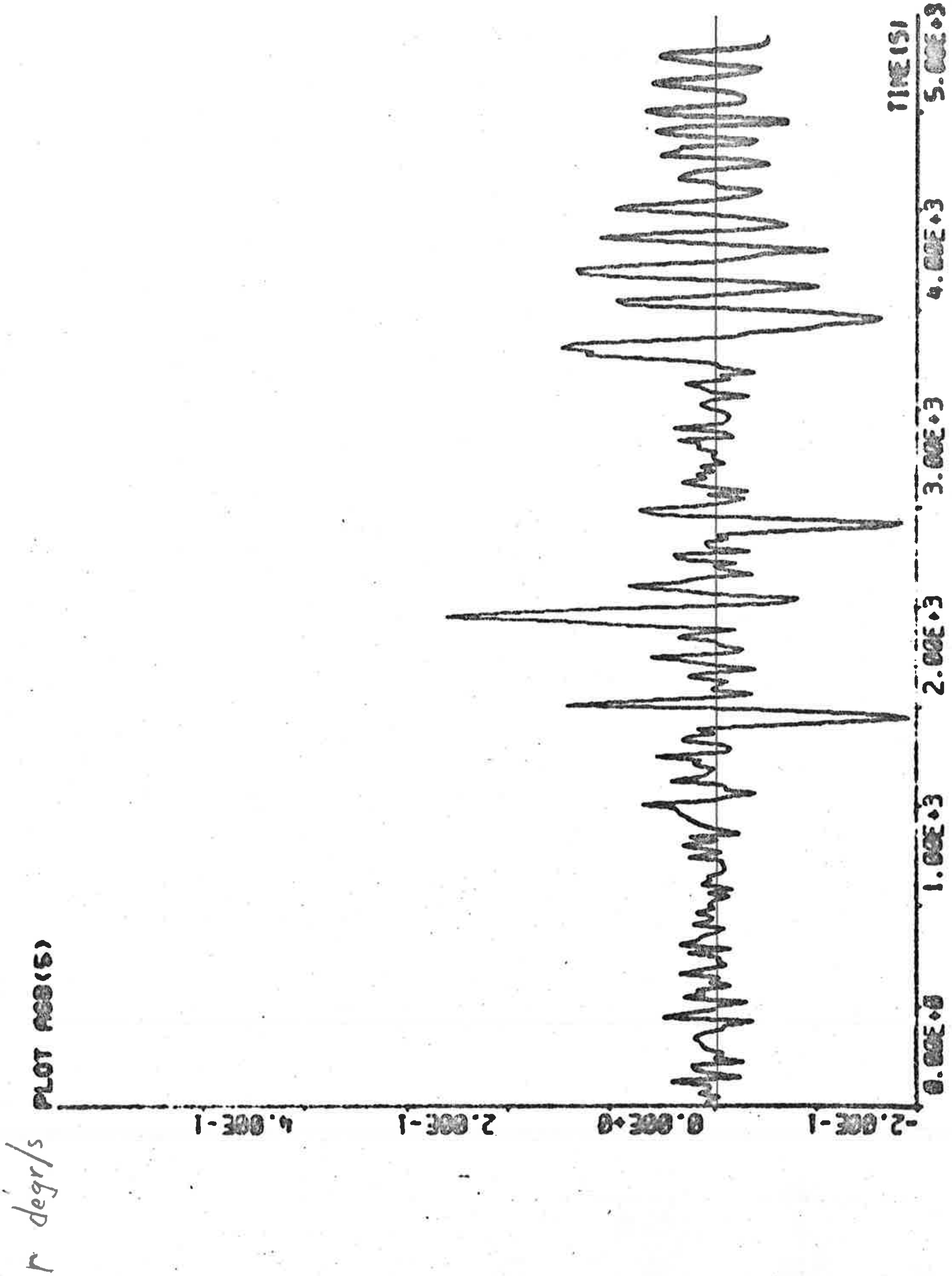

PLOT HP ASM(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
2.00E+1
1.00E+1
0.00E+0
-1.00E+1
+10°
-10°
δ_{com} degr

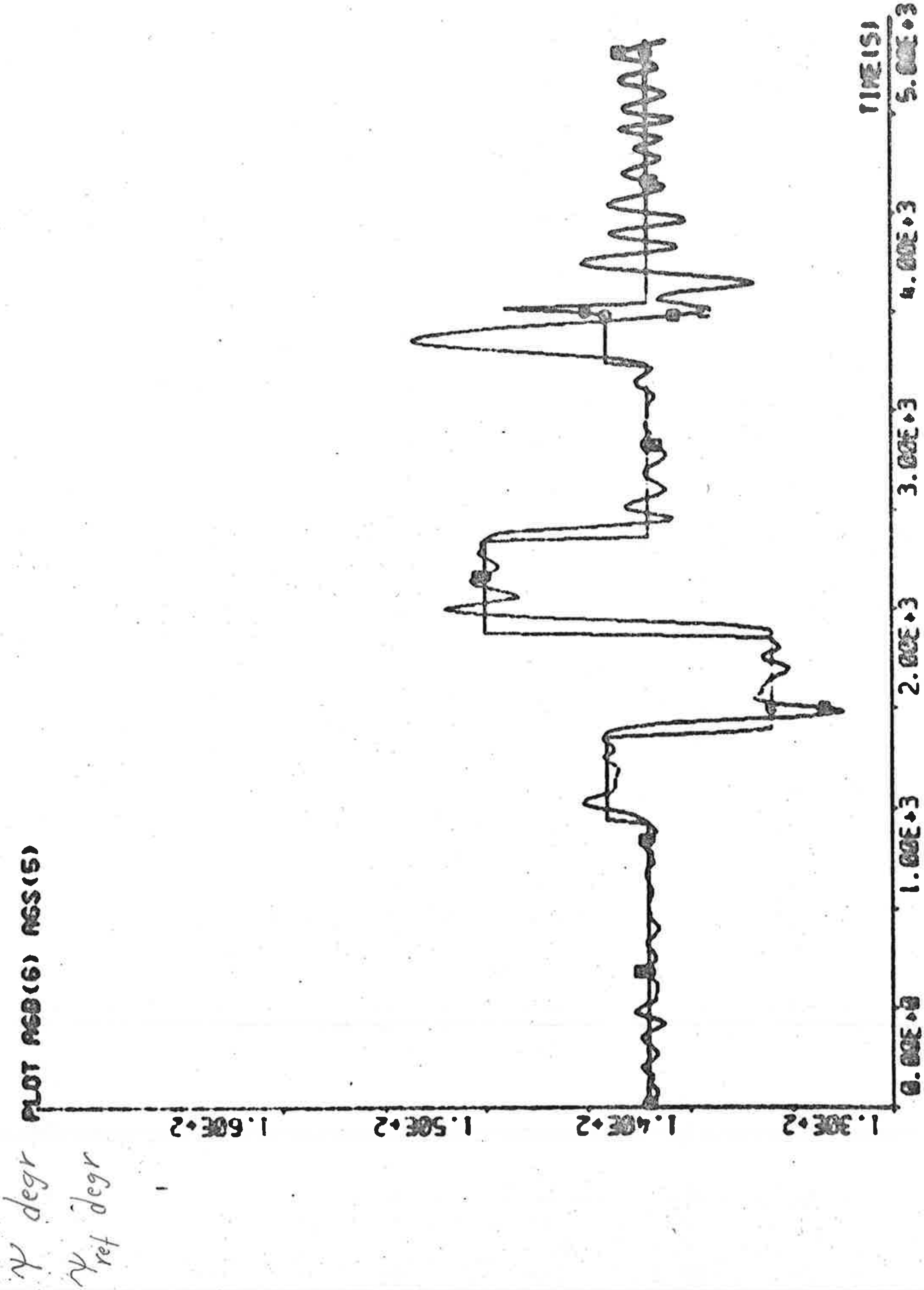

δ_s degr
PLOT ABS(1)
2.00E+1
1.00E+1
0.00E+0
-1.00E+1
+10°
-10°
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

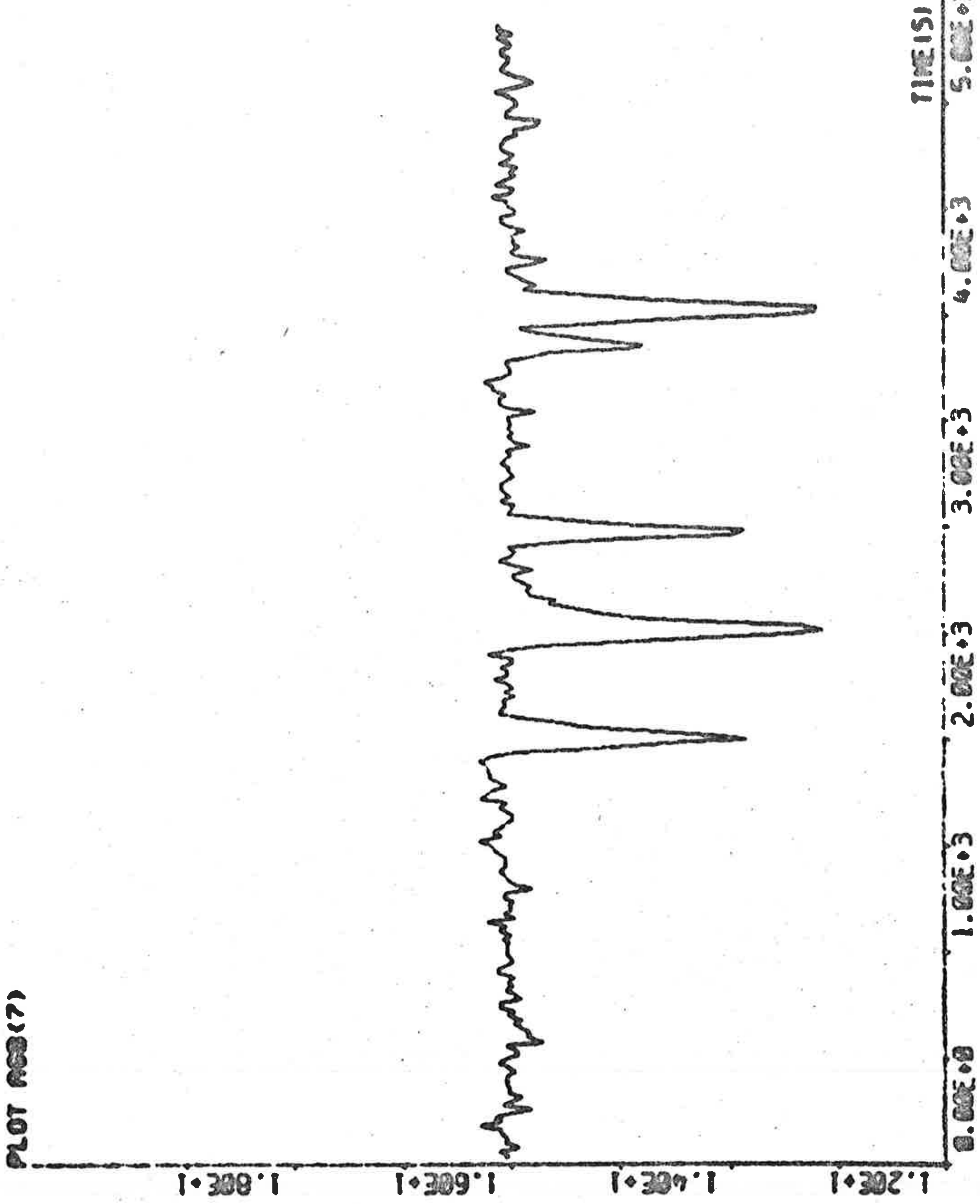

PLOT ASB(2)
2.00E+1
1.00E+1
0.00E+0
-1.00E+1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
+10°
-10°
δ degr


V_1 knots
PLOT AGB(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)

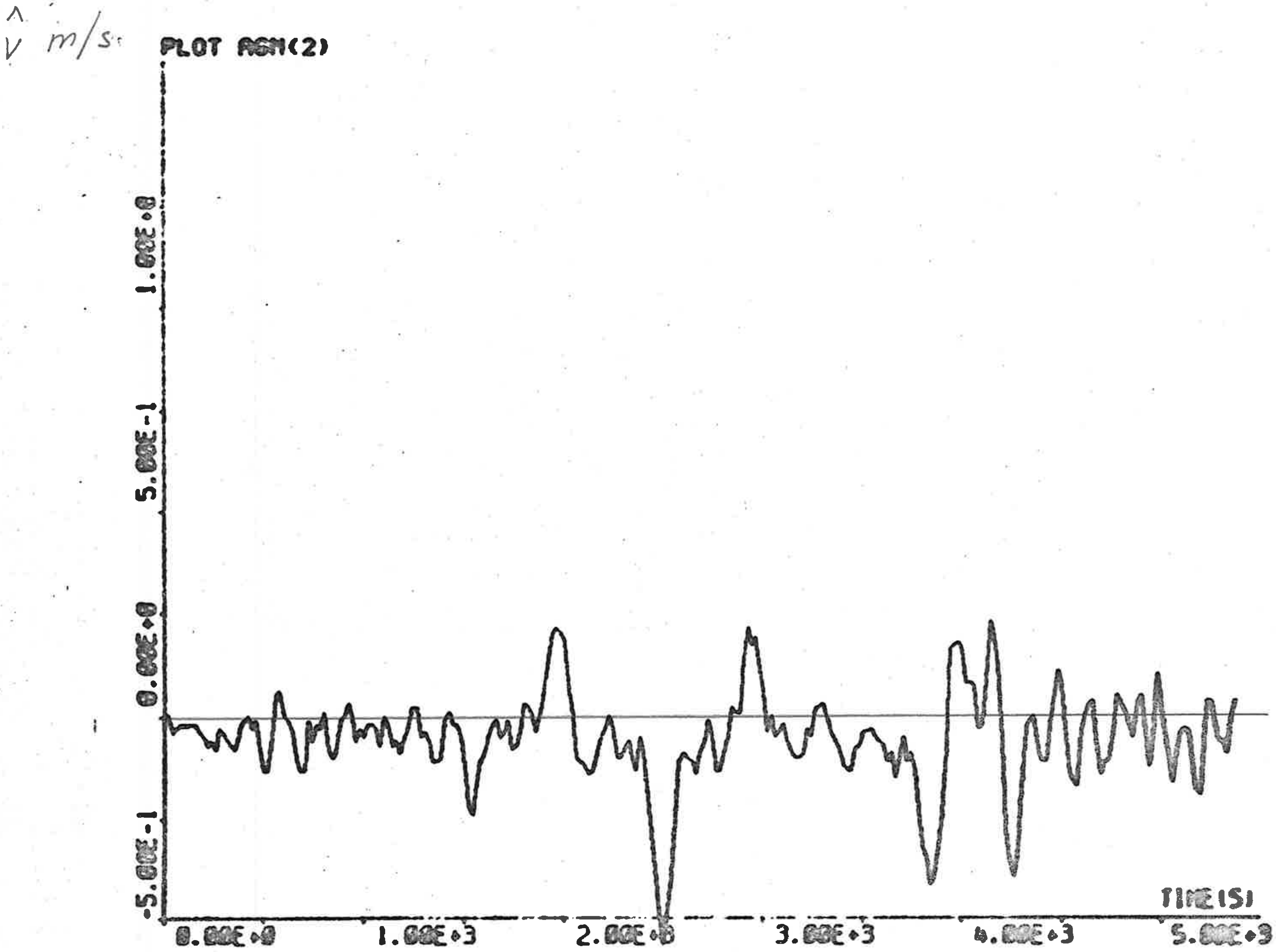

PLOT [illegible](4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
V_2 knots

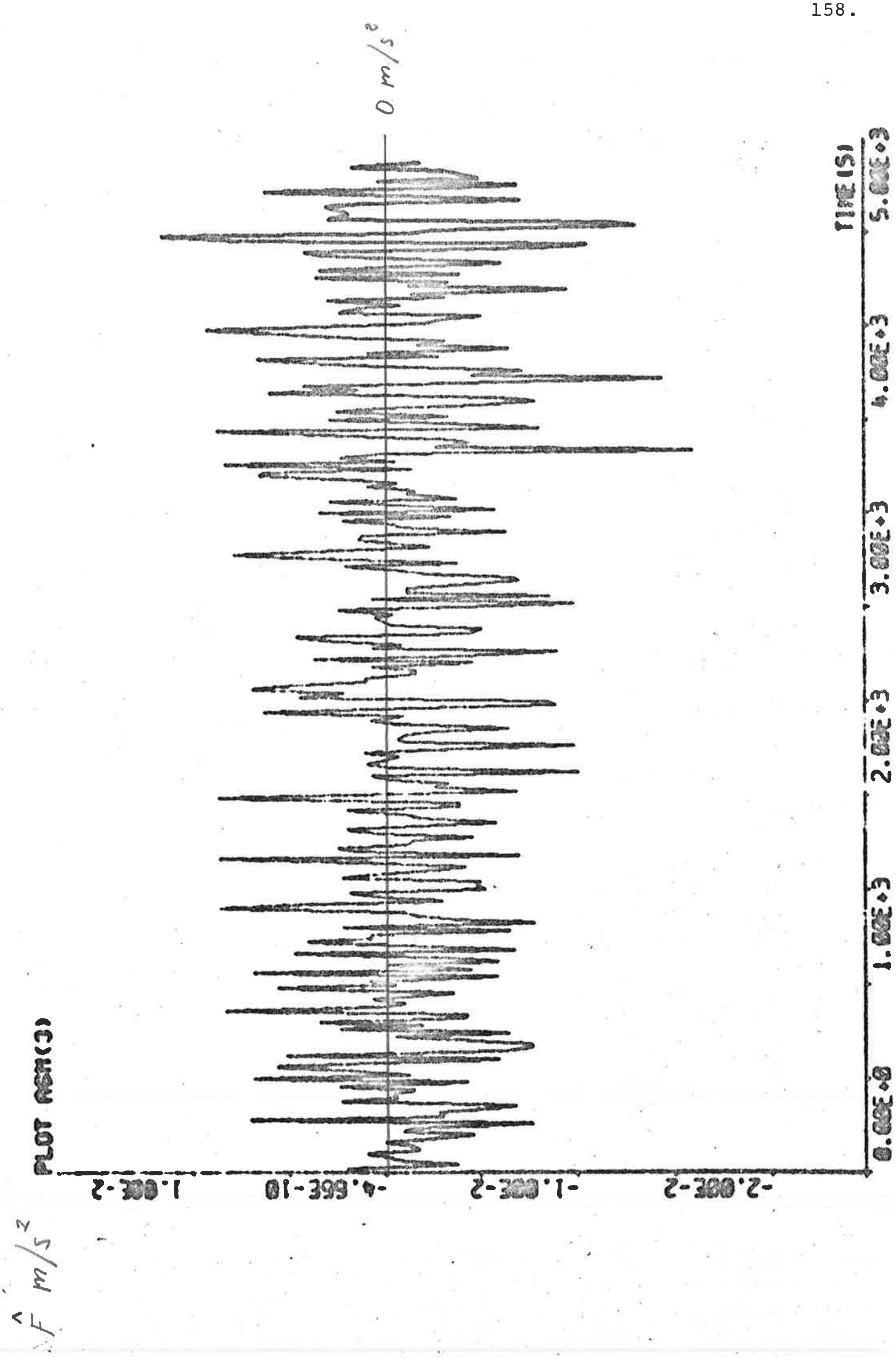

PLOT R00(5)
4.00E-1
2.00E-1
0.00E+0
-2.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
r degr/s

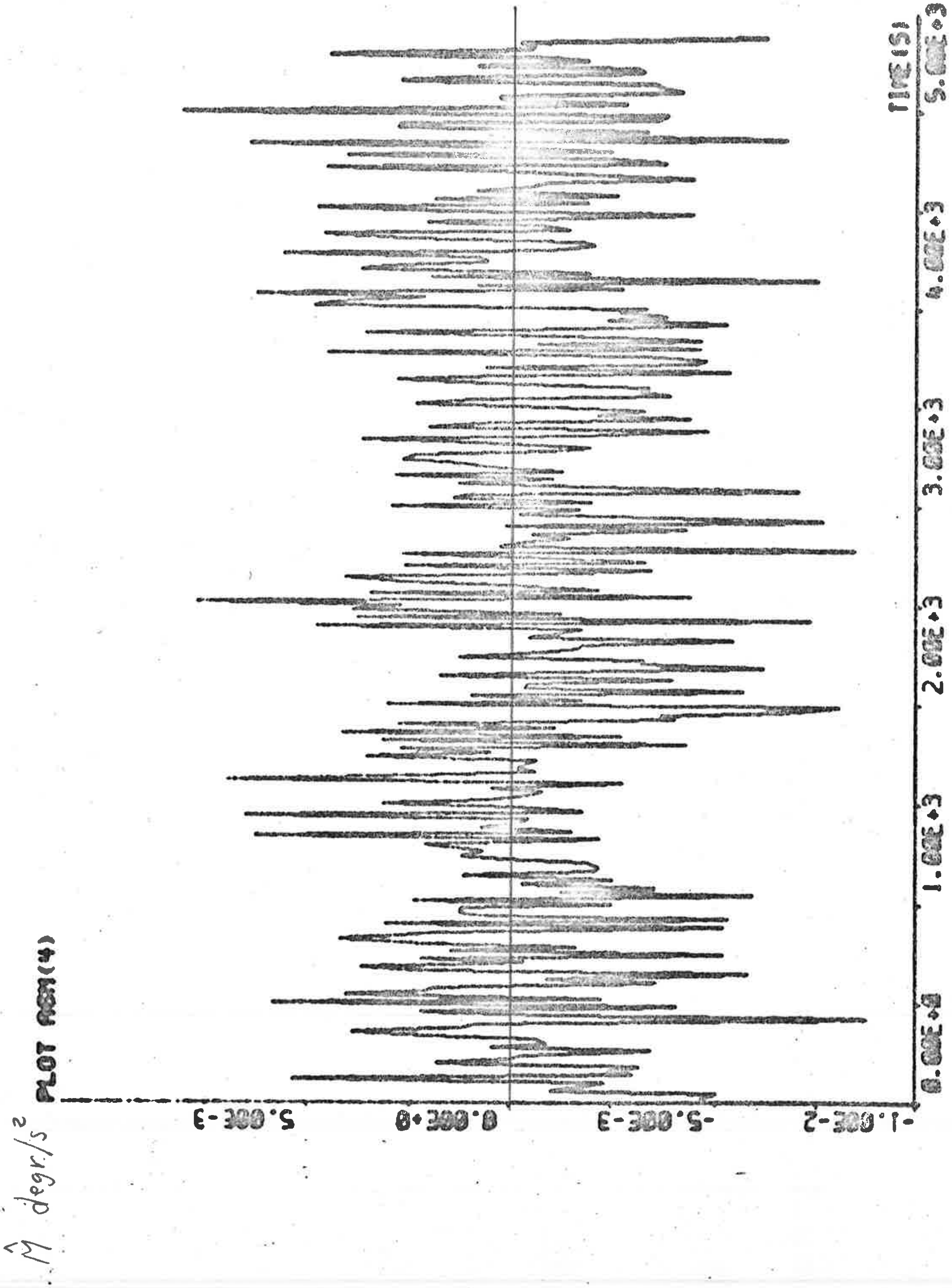

PLOT ASB(6) ASS(5)
1.60E+2
1.50E+2
1.40E+2
1.30E+2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
ψ degr
ψref degr


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

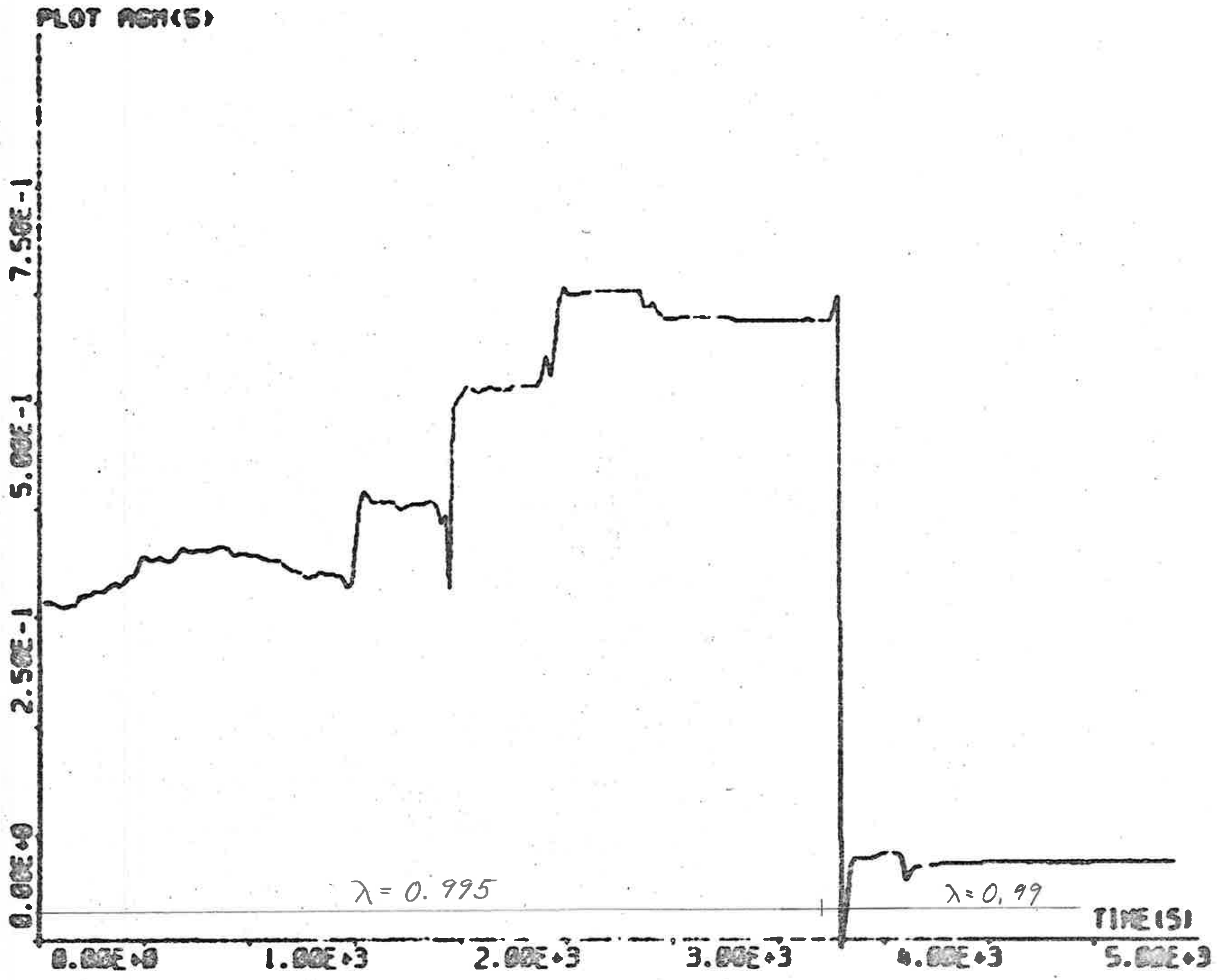
v knots

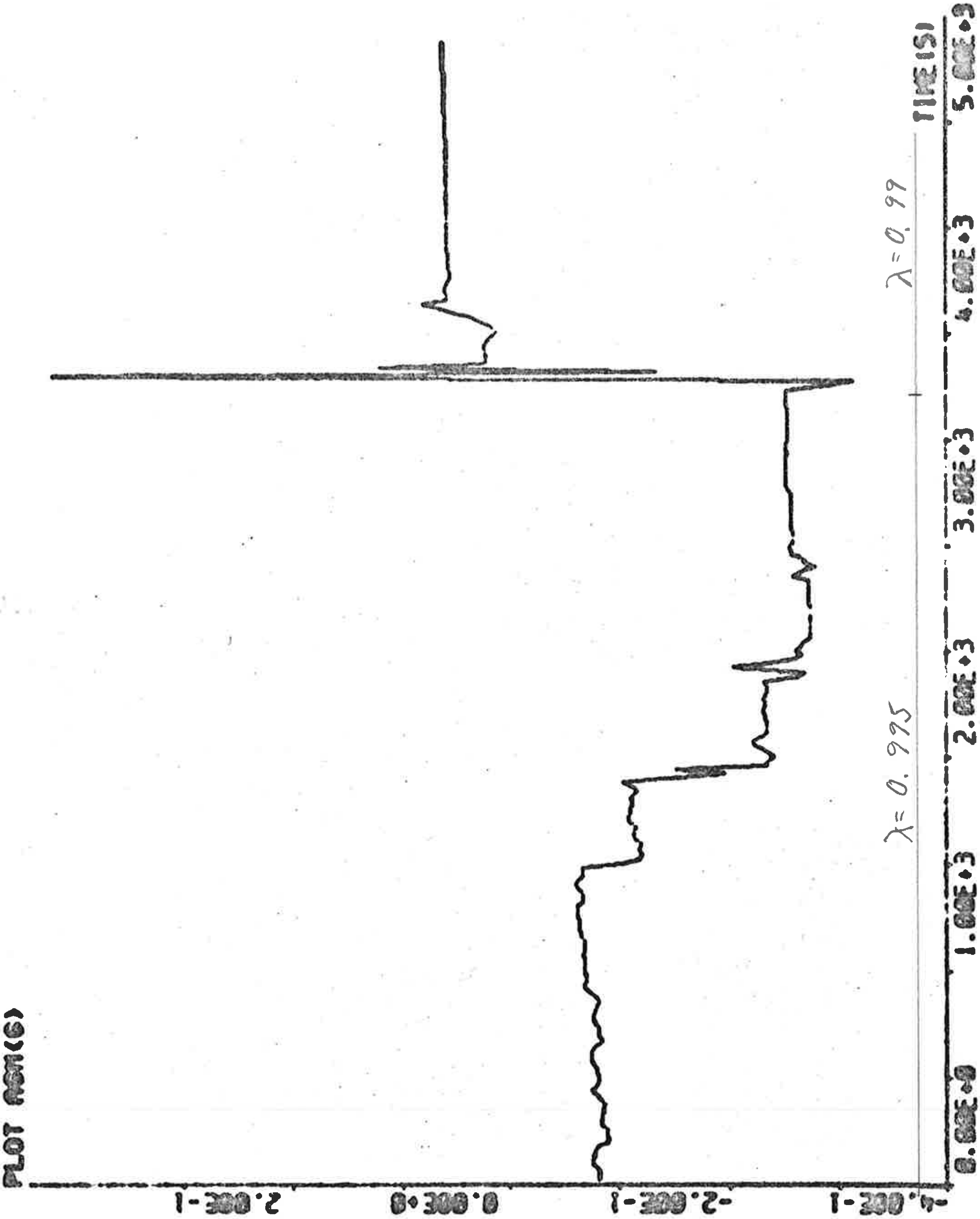

$\hat{v}$ m/s
PLOT ASM(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)


PLOT 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
-4.666E-10
-1.00E-2
-2.00E-2
0 m/s²
F̂ m/s²


PLOT ASM(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
M̂ degr./s²

b_1

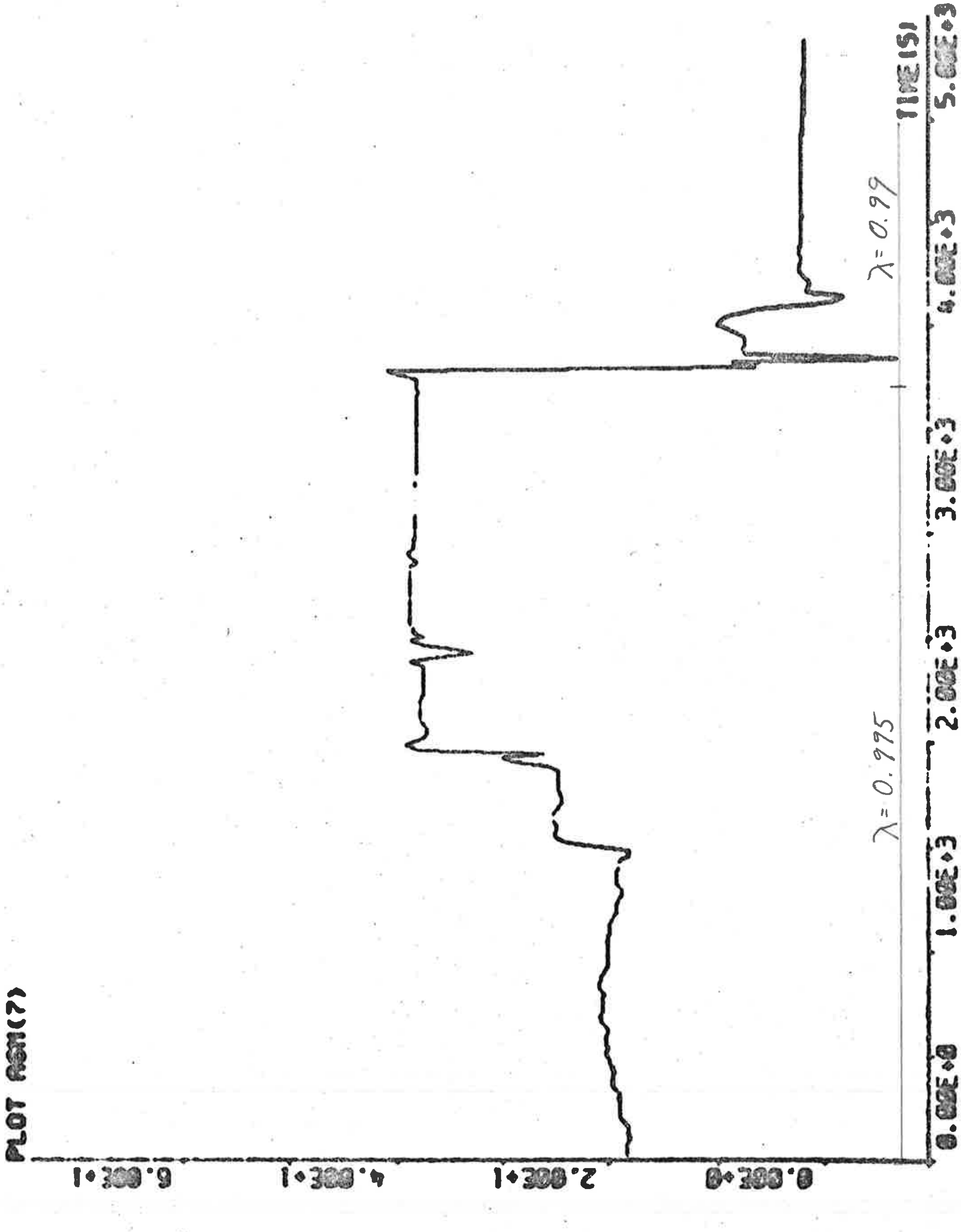

PLOT AGM(5)
7.50E-1
5.00E-1
2.50E-1
0.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
λ = 0.995
λ = 0.99



λ = 0.995

λ = 0.99

b2


PLOT RSM(7)
6.00E+1
4.00E+1
2.00E+1
0.00E+0
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

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:

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

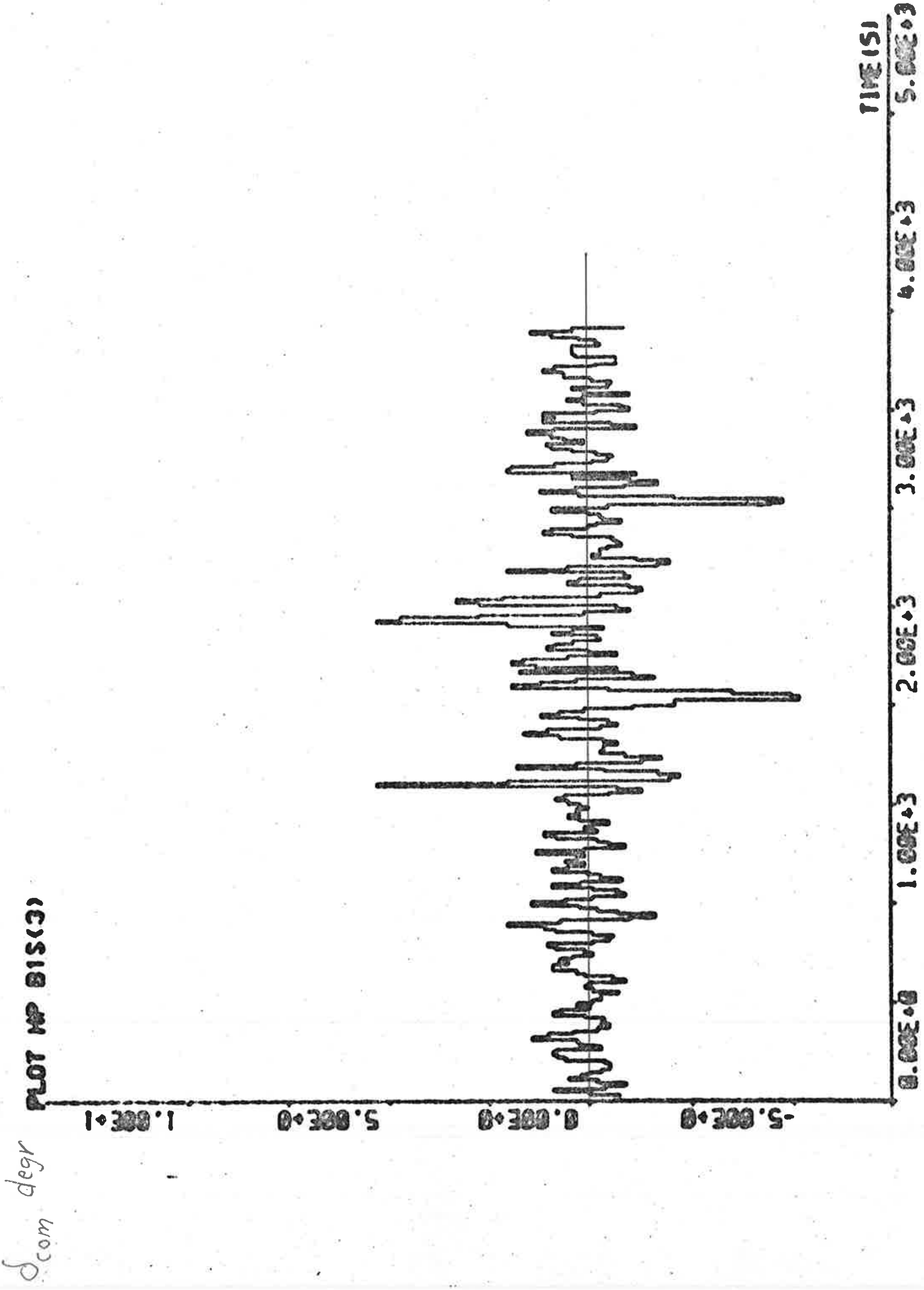
The parameters k_1 and k_2 were manually tuned for the actual weather disturbances:

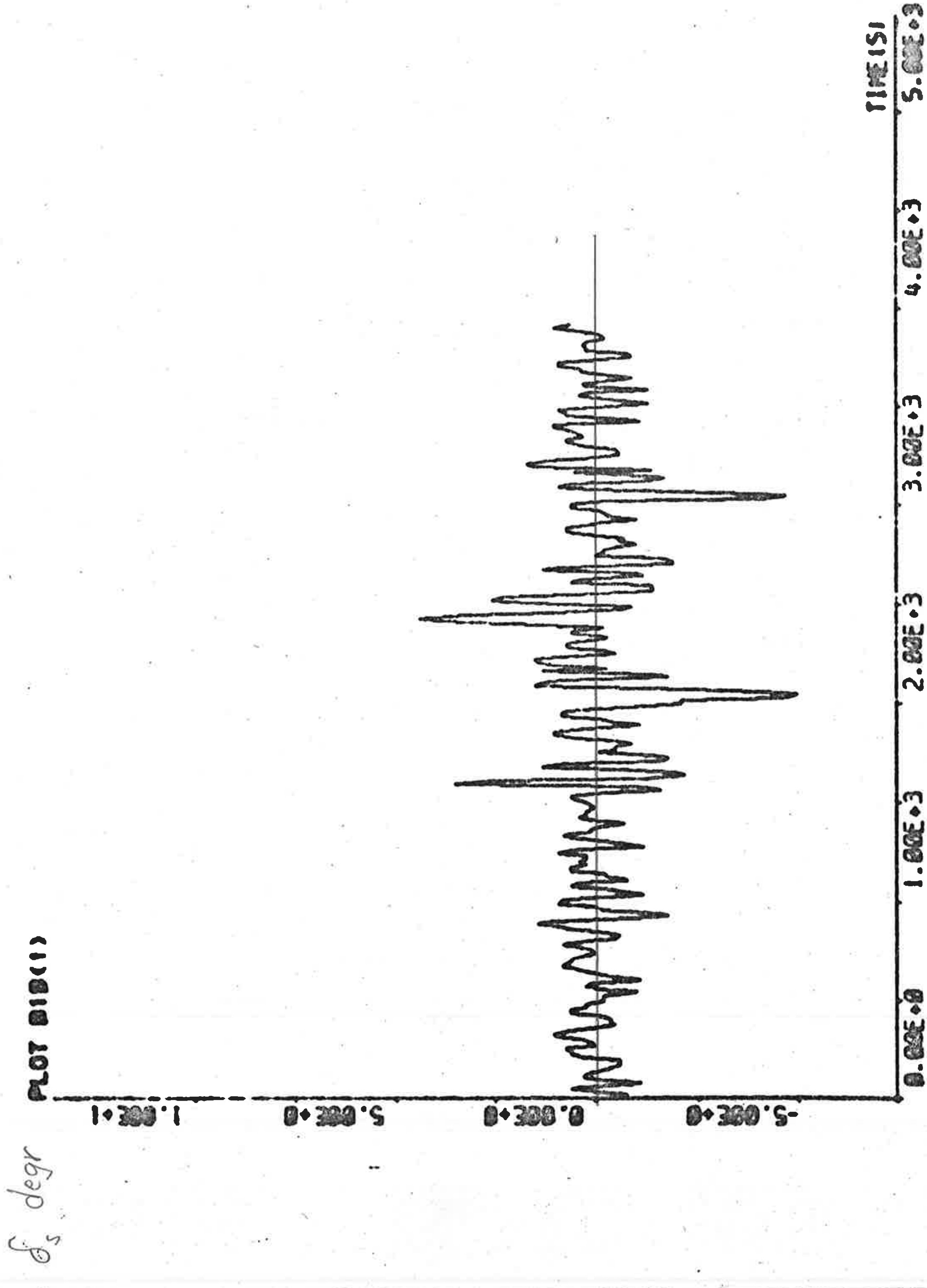
$k_1 = 1.5$
$k_2 = 80.0$

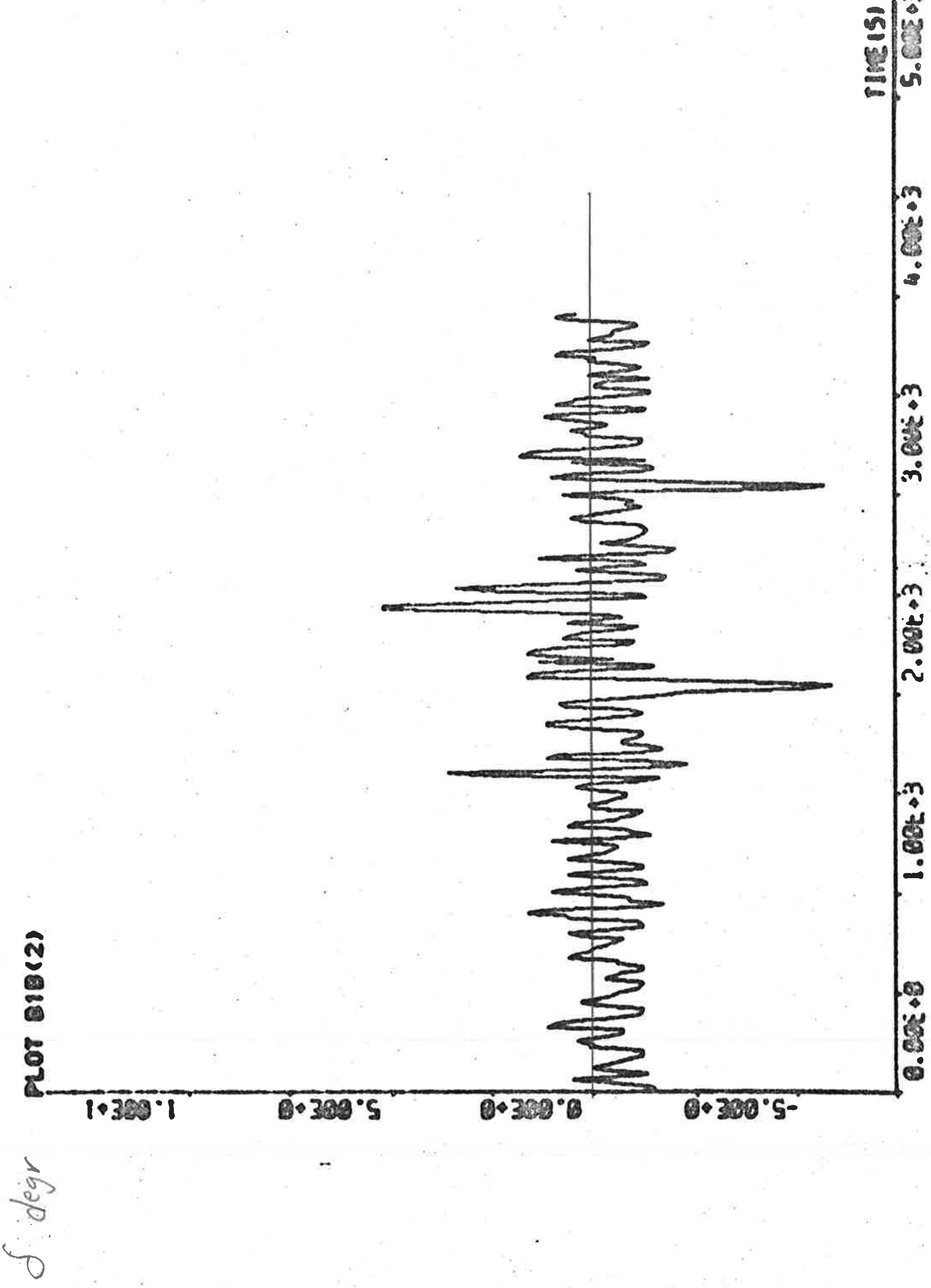
Sampling interval: 15 s
Rudder limits: ±15°
Maximum yaw rate r during yaws: 0.1 degr/s
Ψ_{ref}: 142°, 144°, 136°, 150°, 142°

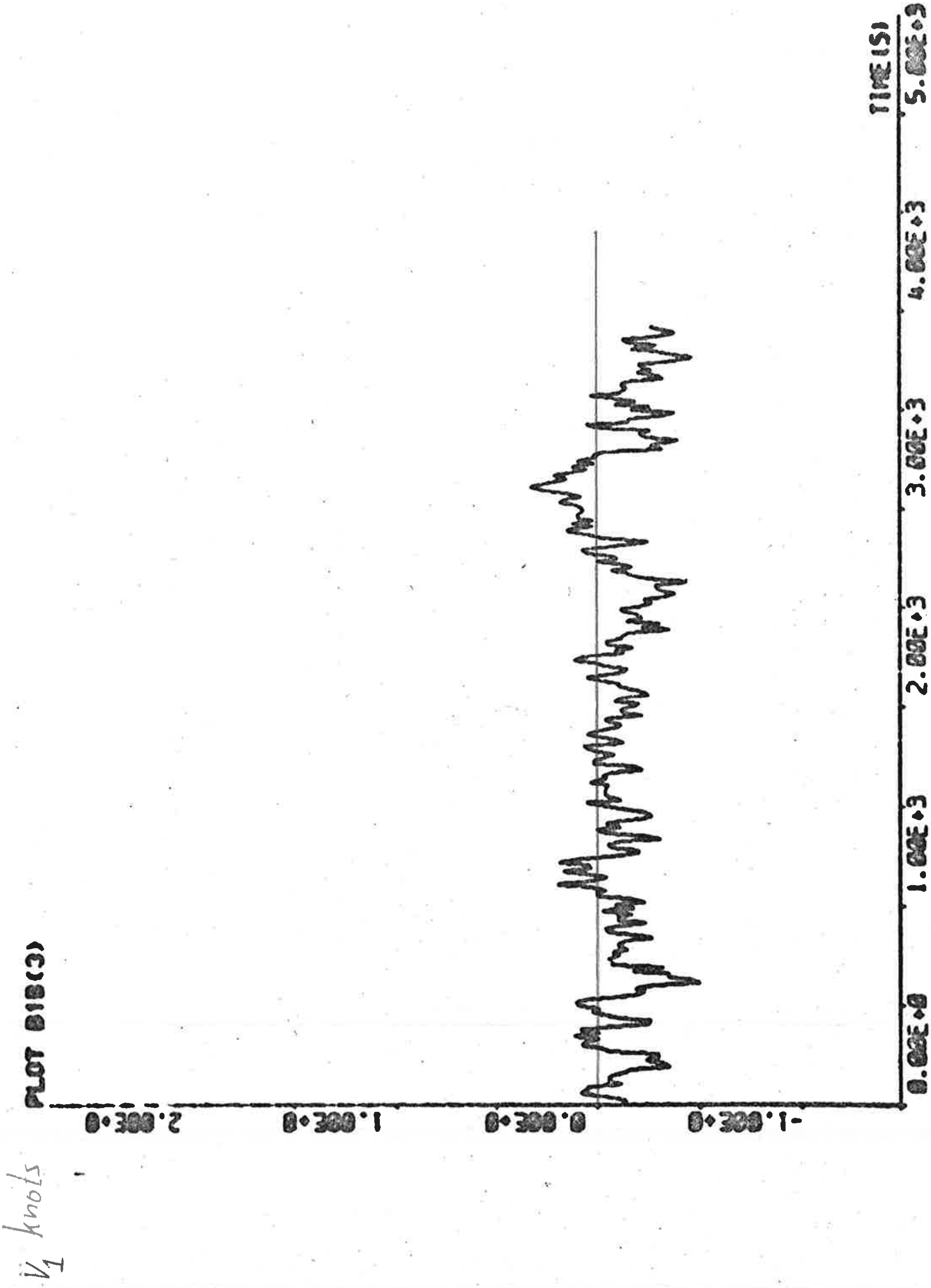
Statistics:

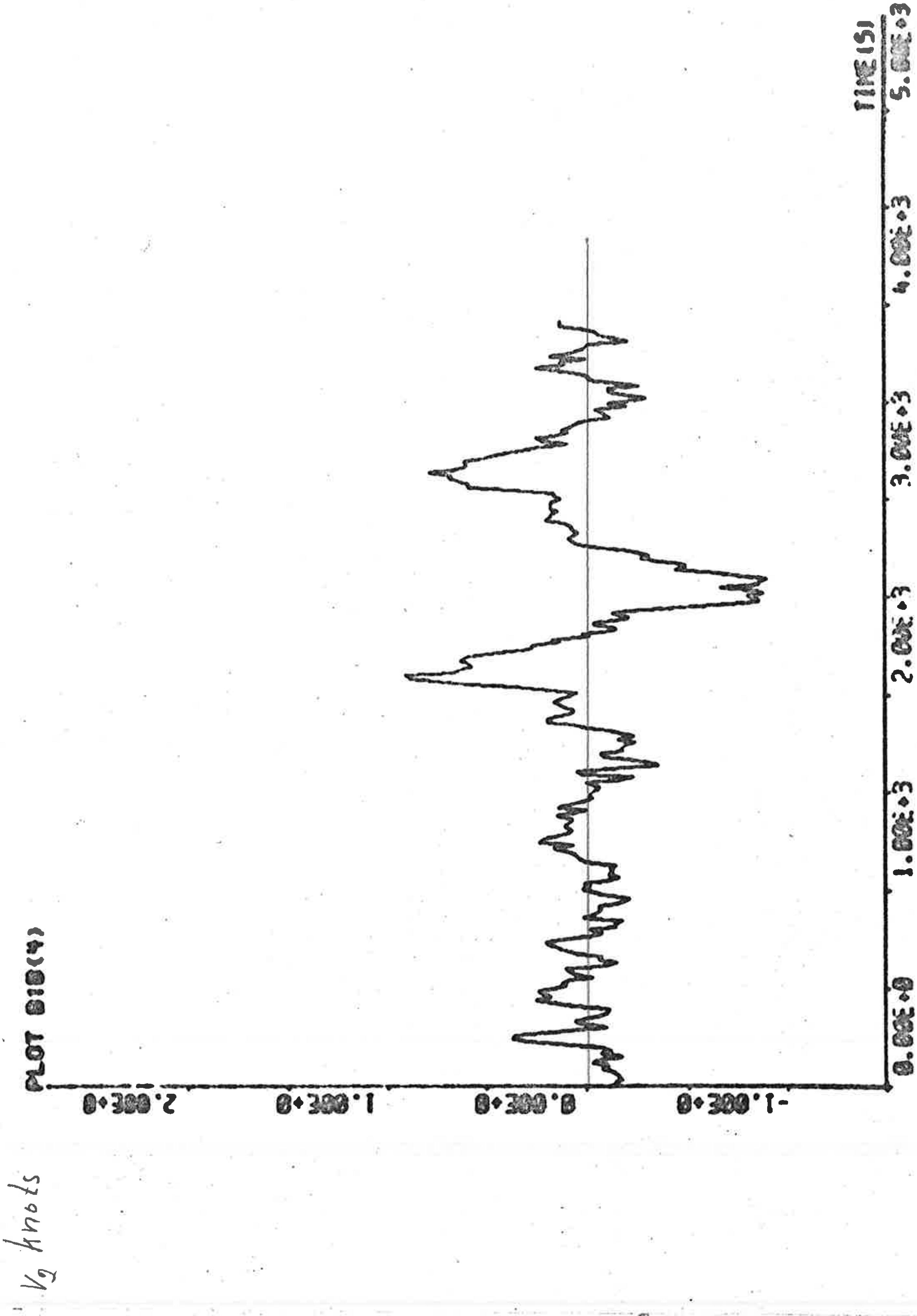
	0 - 1500 s			
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	0.13	0.63	-1.6	2.0
δ_s degr	0.05	0.58	-1.8	1.4
δ degr	-0.40	0.70	-1.7	1.6
v_1 knots	-0.102	0.135	-0.50	0.19
v_2 knots	0.014	0.128	-0.21	0.37
r degr/s	0.0030	0.0099	-0.021	0.030
Ψ degr	142.001	0.171	141.59	142.38
v knots	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

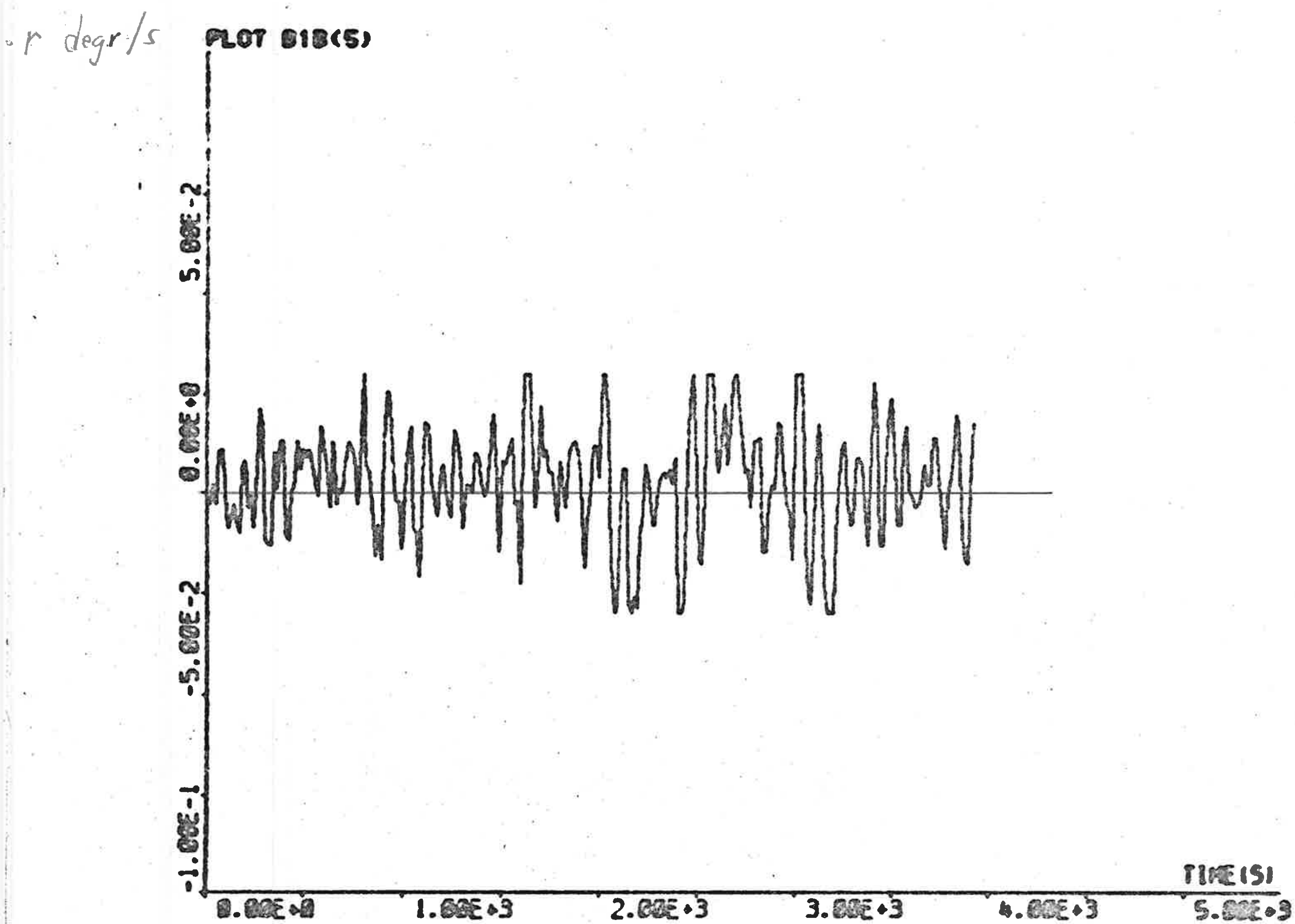

PLOT MP BIS(3)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)
δcom degr

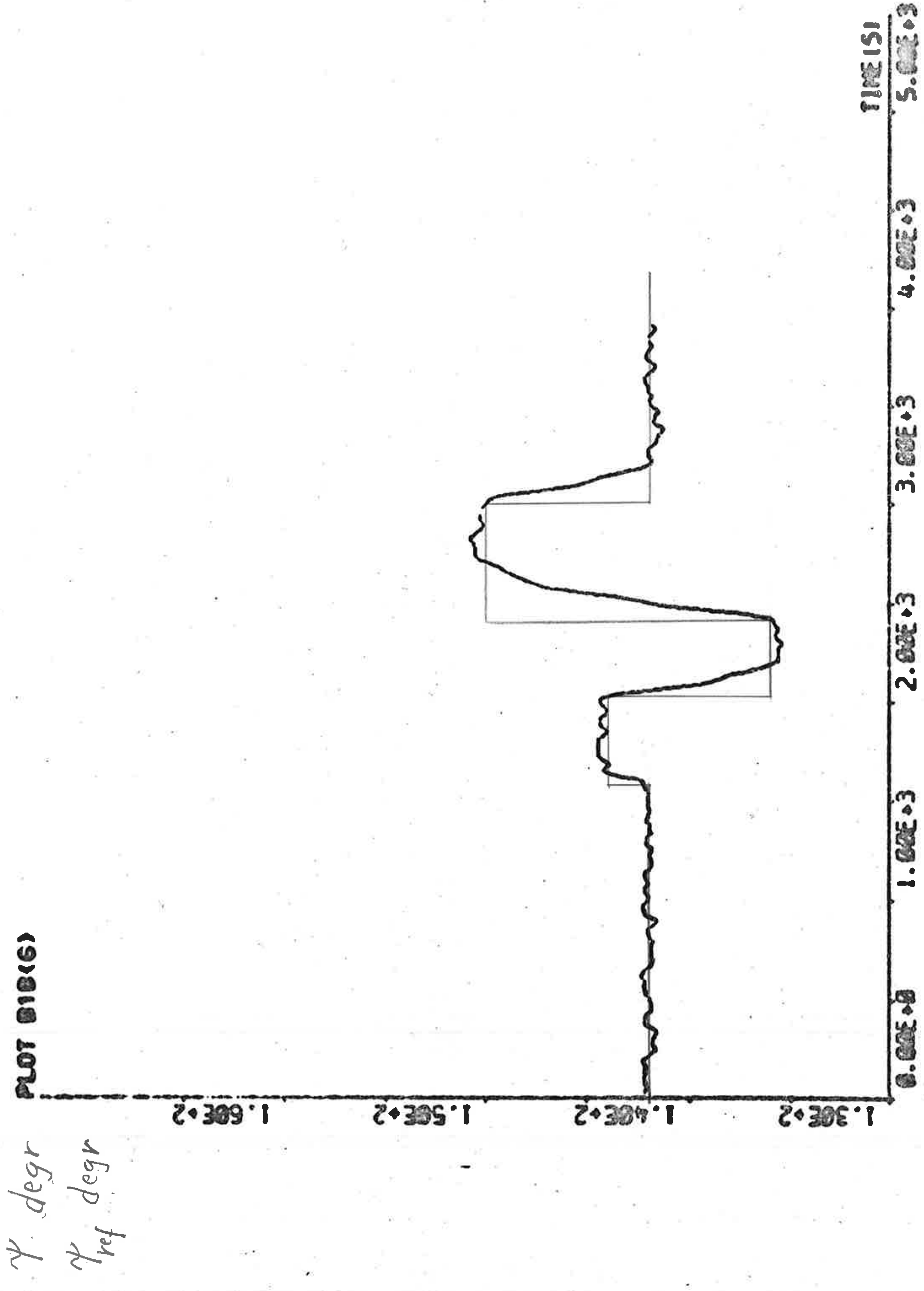

PLOT BIB(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
δs degr

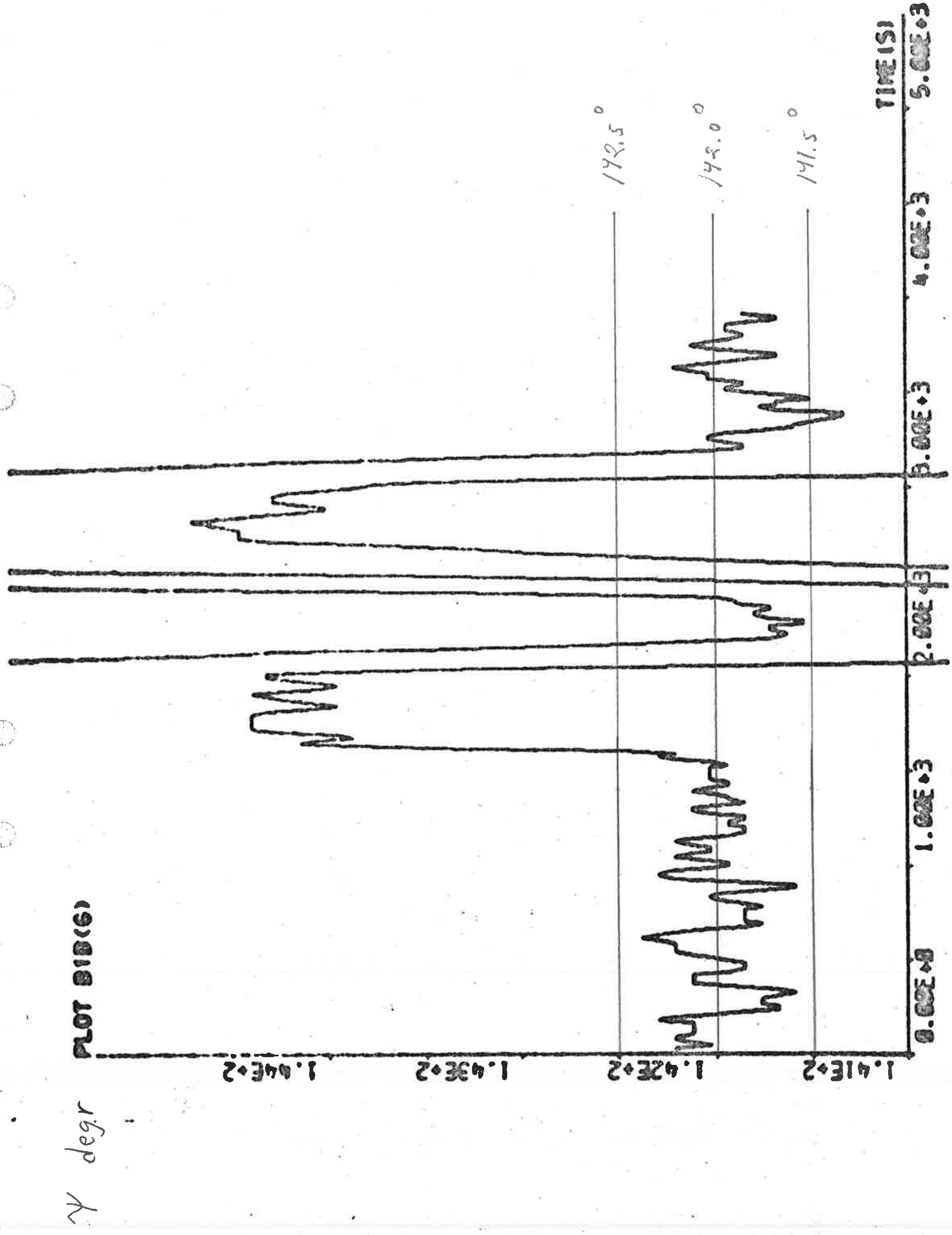

PLOT B1B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
δ degr

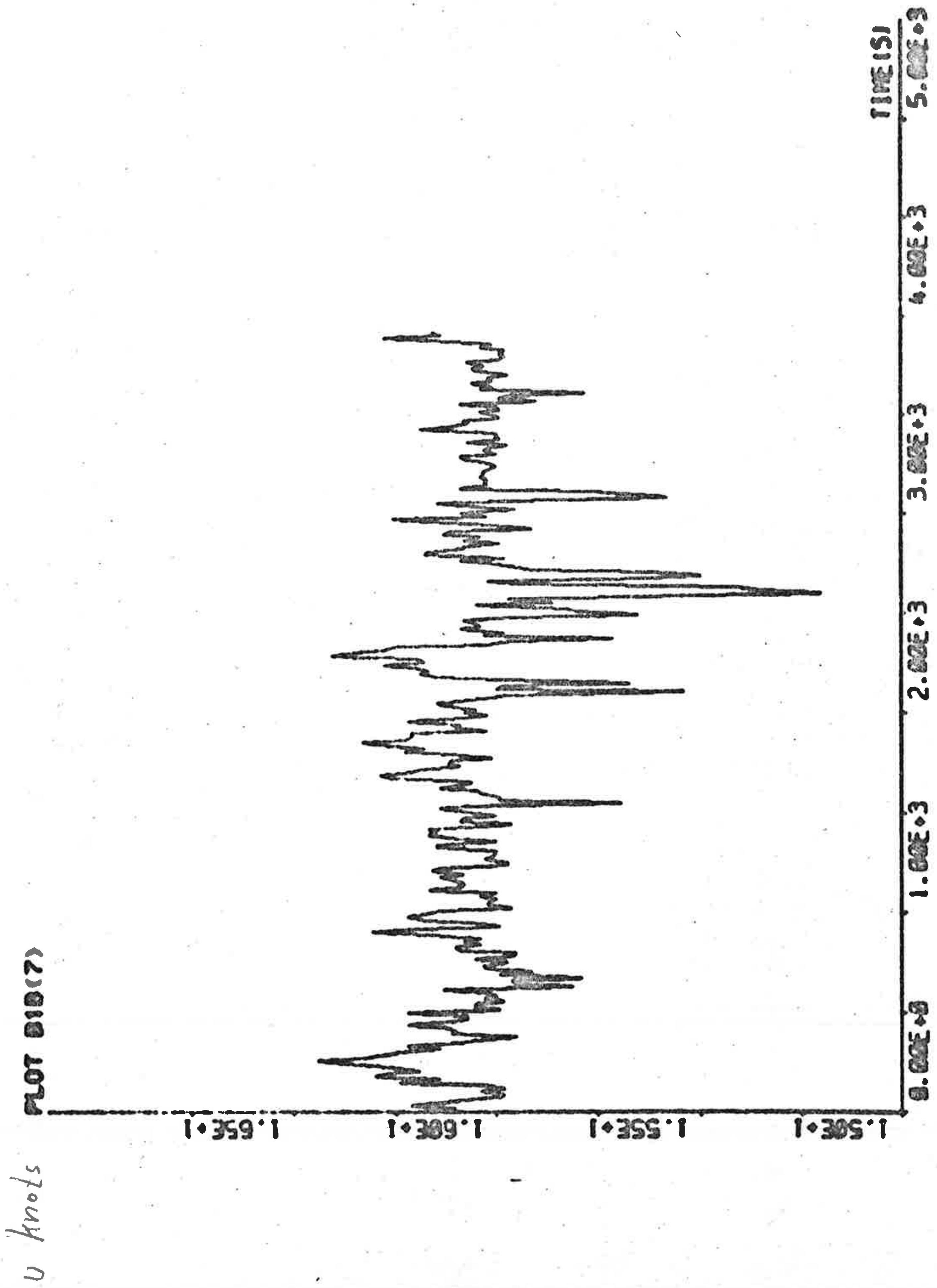

PLOT B1B(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)
V_1 knots

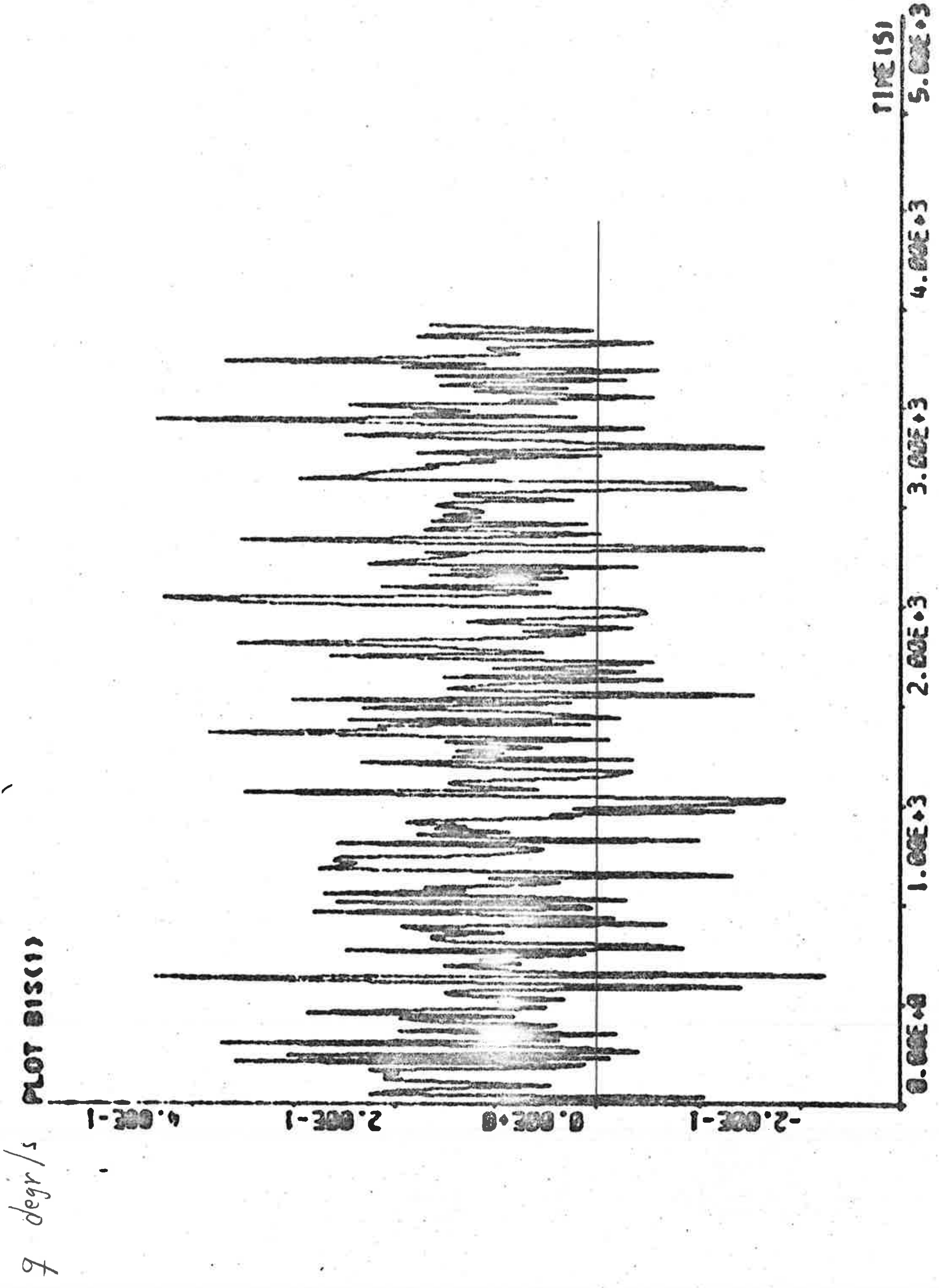

PLOT BIB(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)
Vg knots

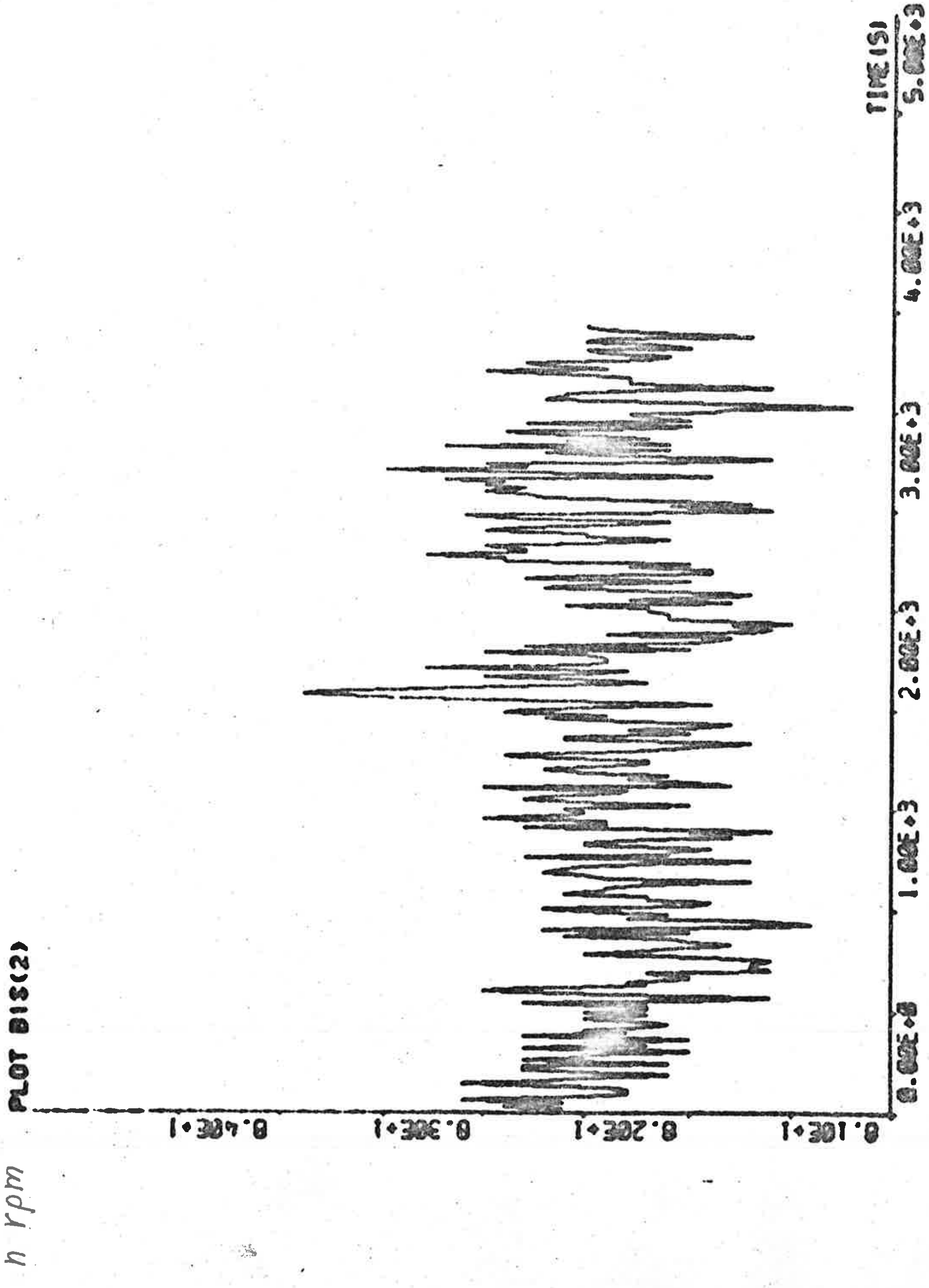

r degr/s
PLOT B1B(5)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


PLOT B18(6)
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
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°
γ degr


PLOT D1B(7)
1.65E+1
1.60E+1
1.55E+1
1.50E+1
0.00E+0
5.00E+2
1.00E+3
1.50E+3
2.00E+3
2.50E+3
3.00E+3
3.50E+3
4.00E+3
4.50E+3
5.00E+3
TIME(S)
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
q degr/s


PLOT BIS(2)
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
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:

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

Regulator:

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

Sampling interval 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:

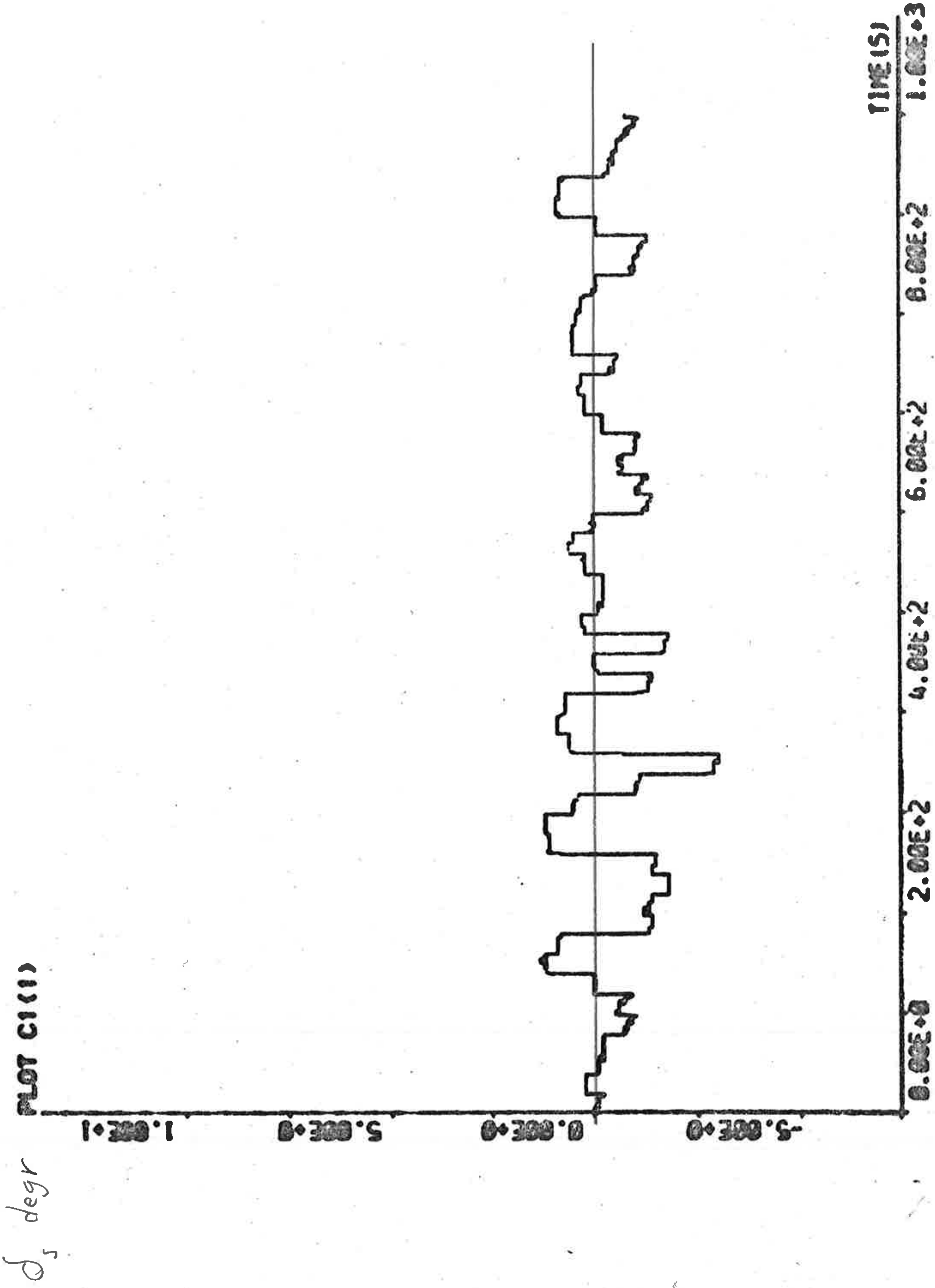
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.353 \\ 0.003 \\ 13.729 \end{bmatrix} \qquad P \text{ unknown}$$

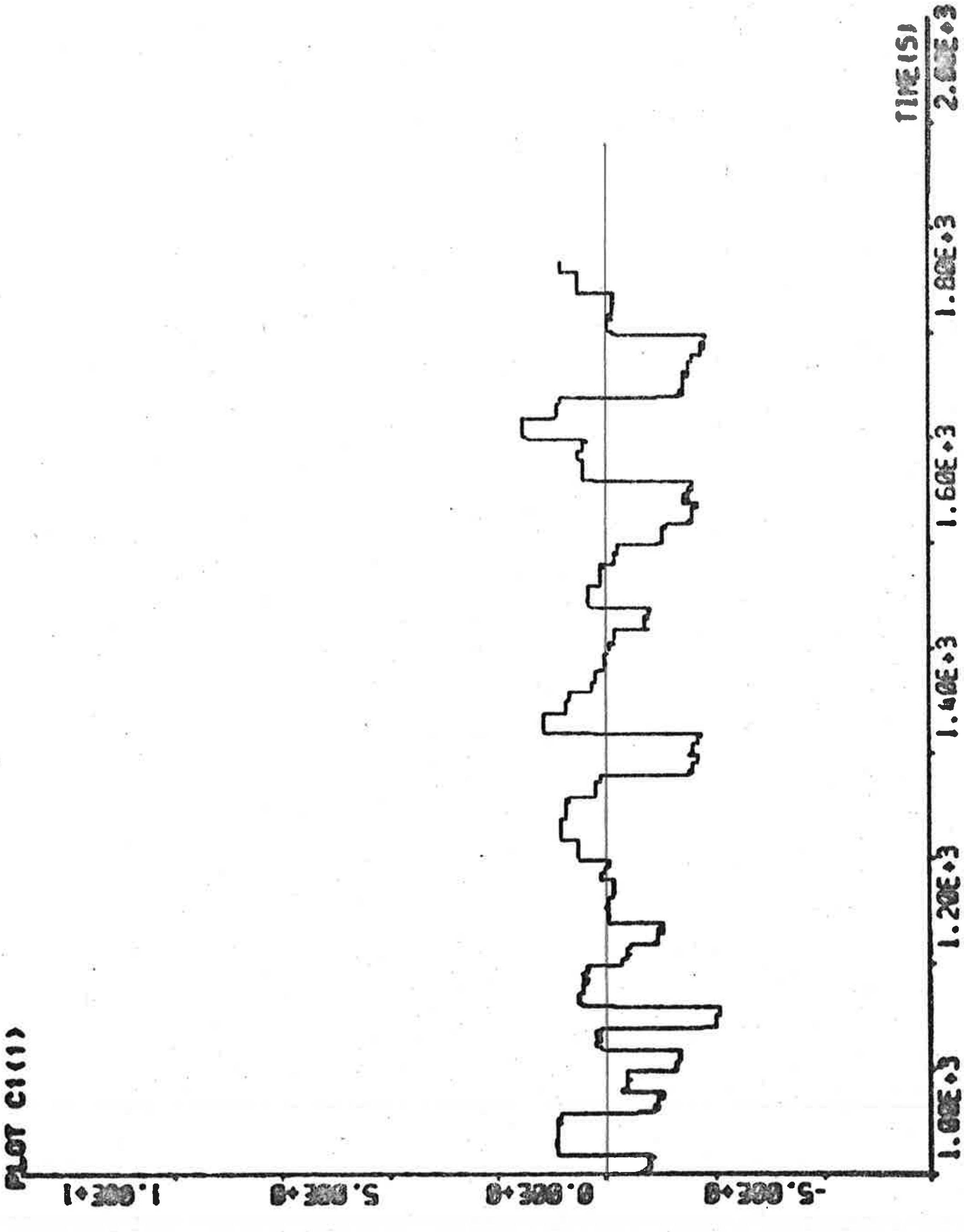
Regulator:

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

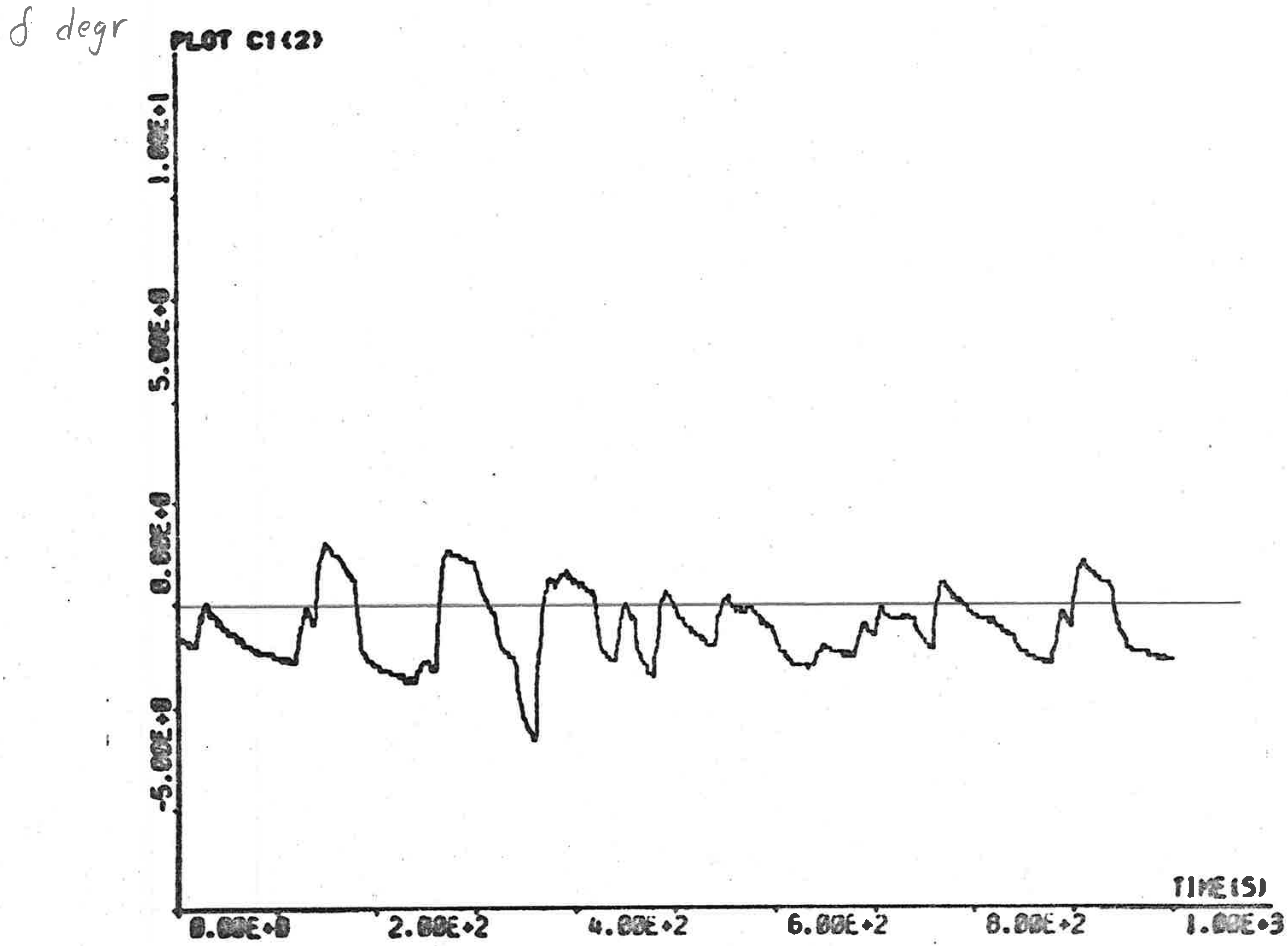
Statistics:

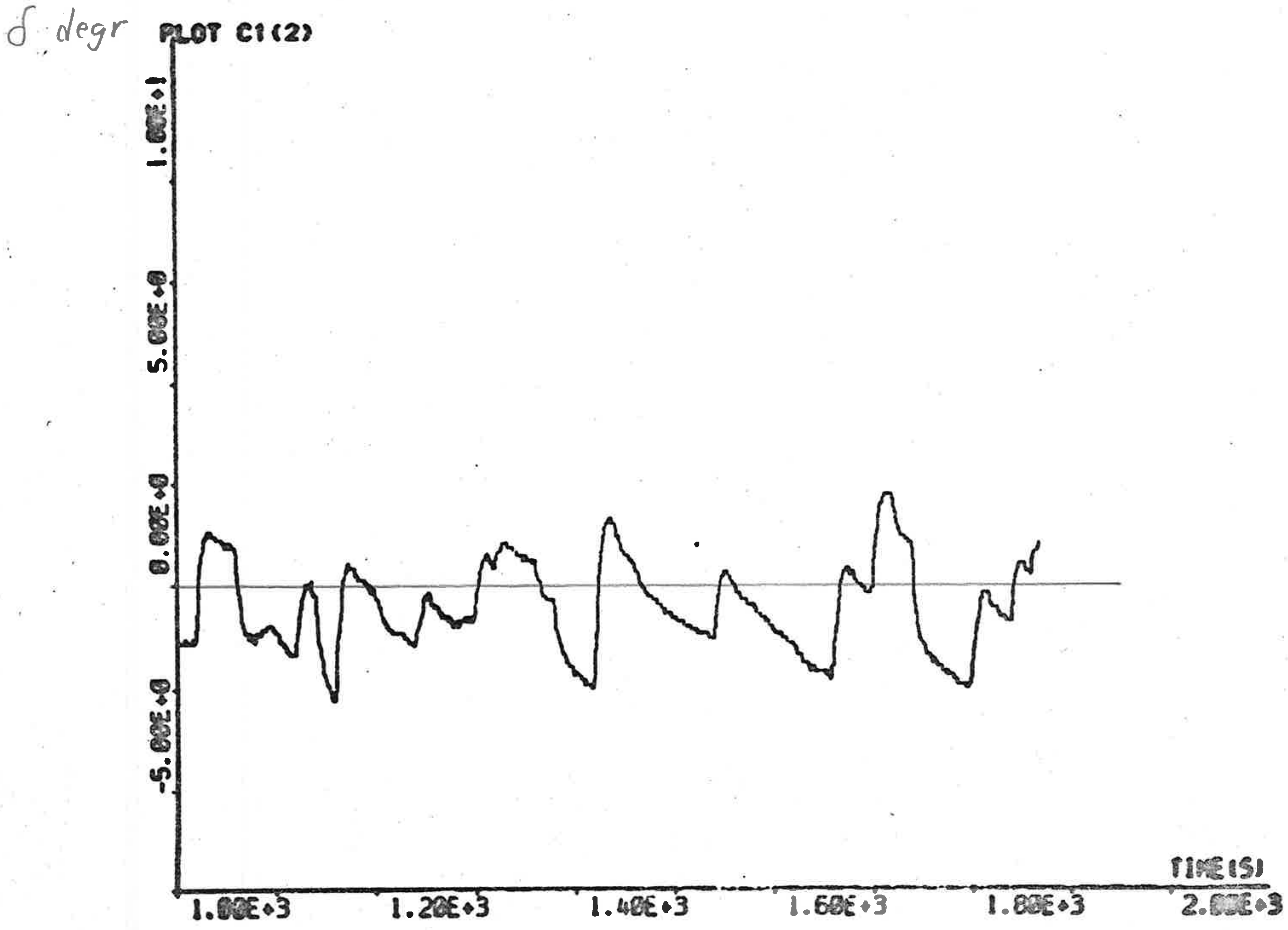
		Mean value	Standard deviation	Minimum value	Maximum value
δ_s	degr	-0.26	1.00	-3.0	1.9
δ	degr	-0.57	0.96	-3.3	2.2
v_1	knots	-0.129	0.145	-0.47	0.19
v_2	knots	0.036	0.119	-0.26	0.29
r	degr/s	0.0031	0.0171	-0.058	0.055
Ψ	degr	142.018	0.232	141.50	142.65
u	knots	16.036	0.136	15.47	16.30

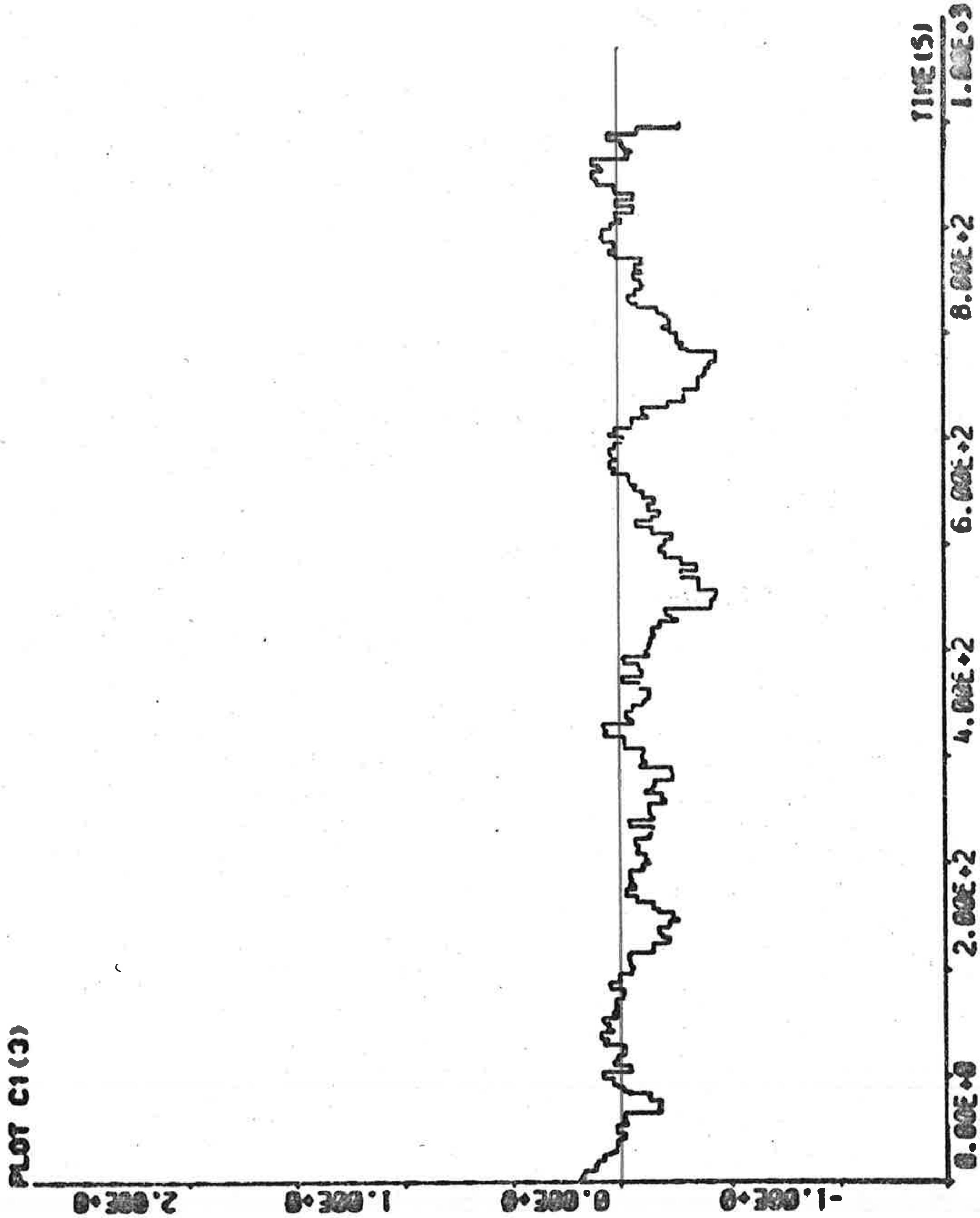

PLOT C1(1)
TIME (S)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ_s degr


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

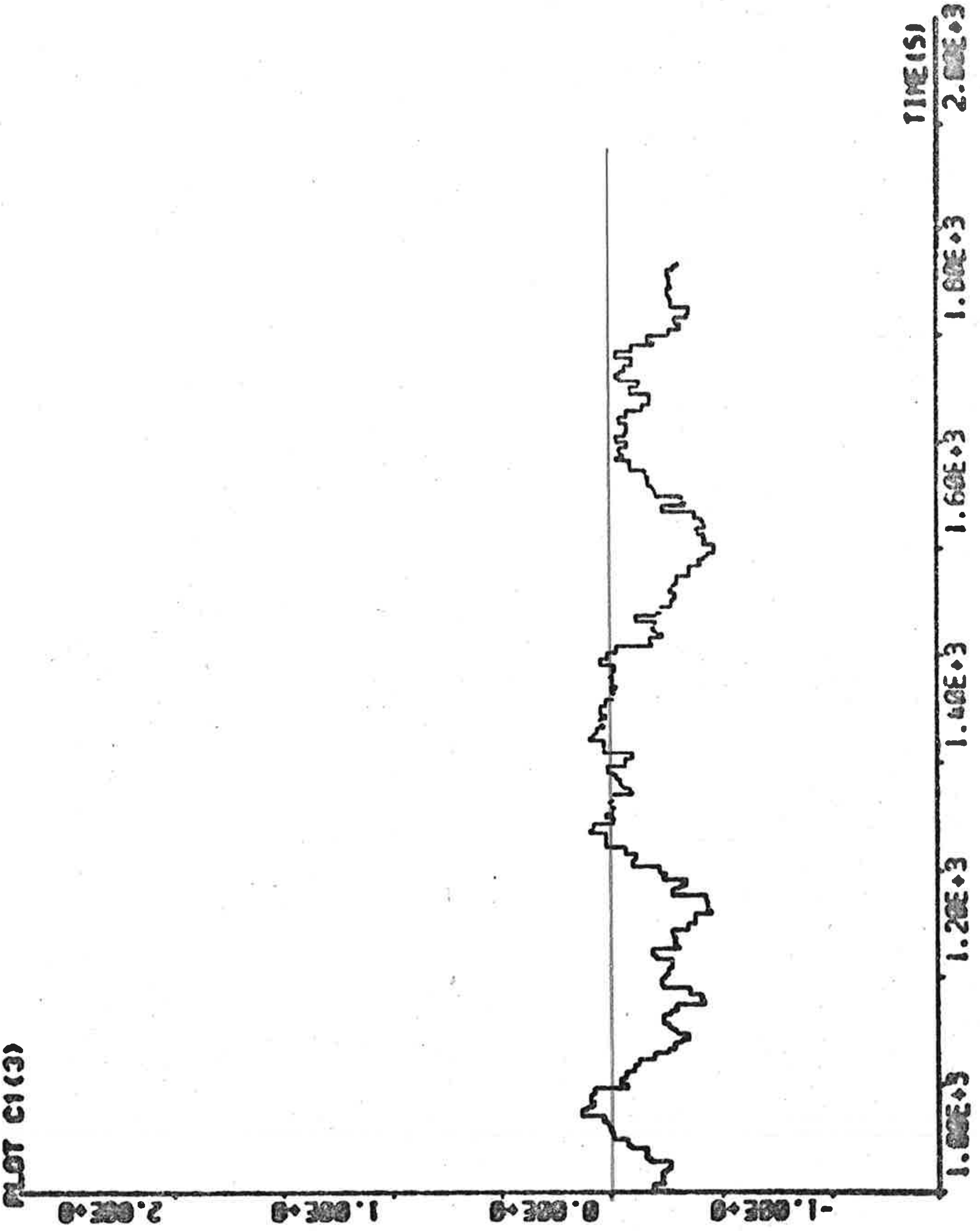
δ_s degr


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

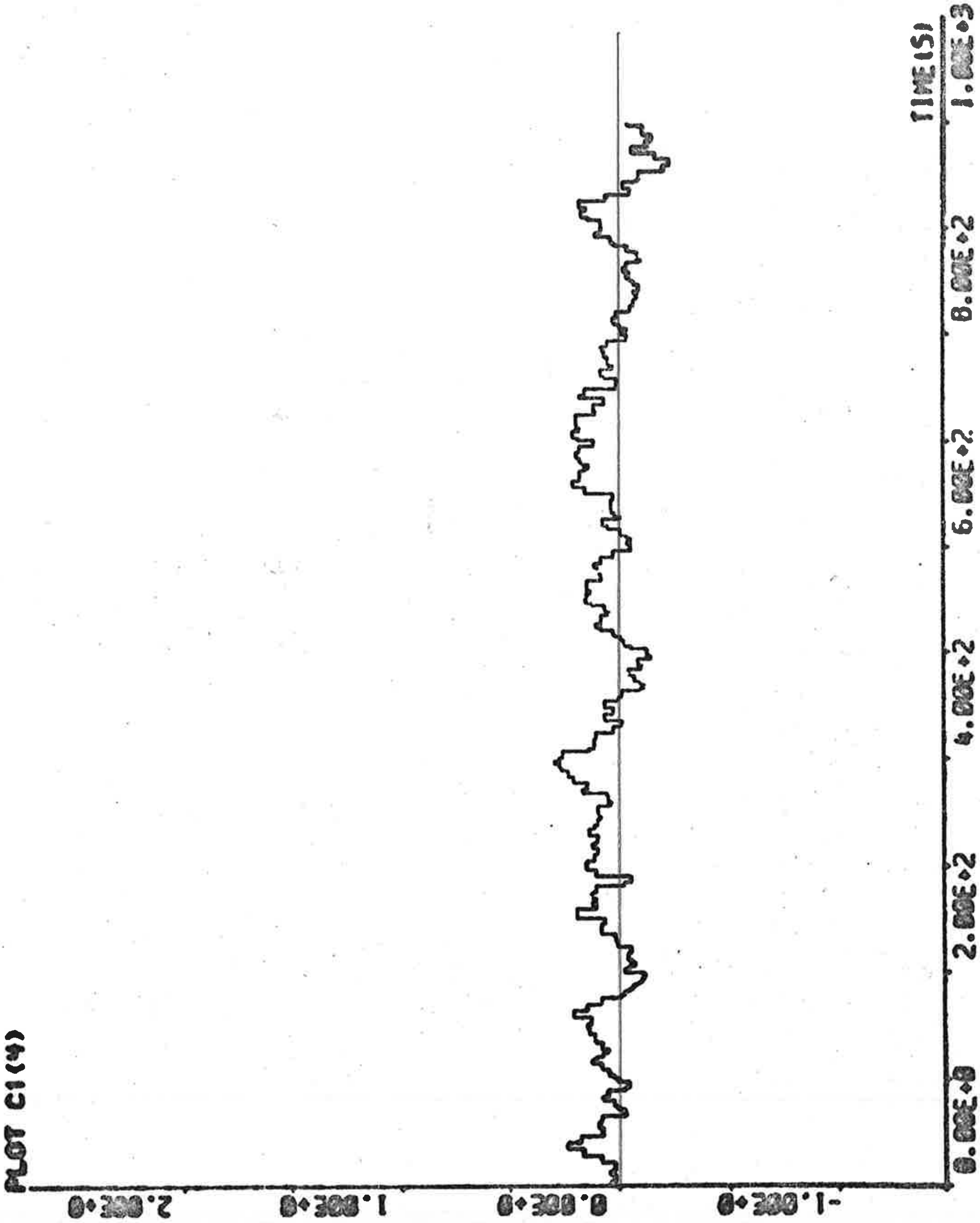

δ degr
PLOT C1(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3


PLOT C1 (3)
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

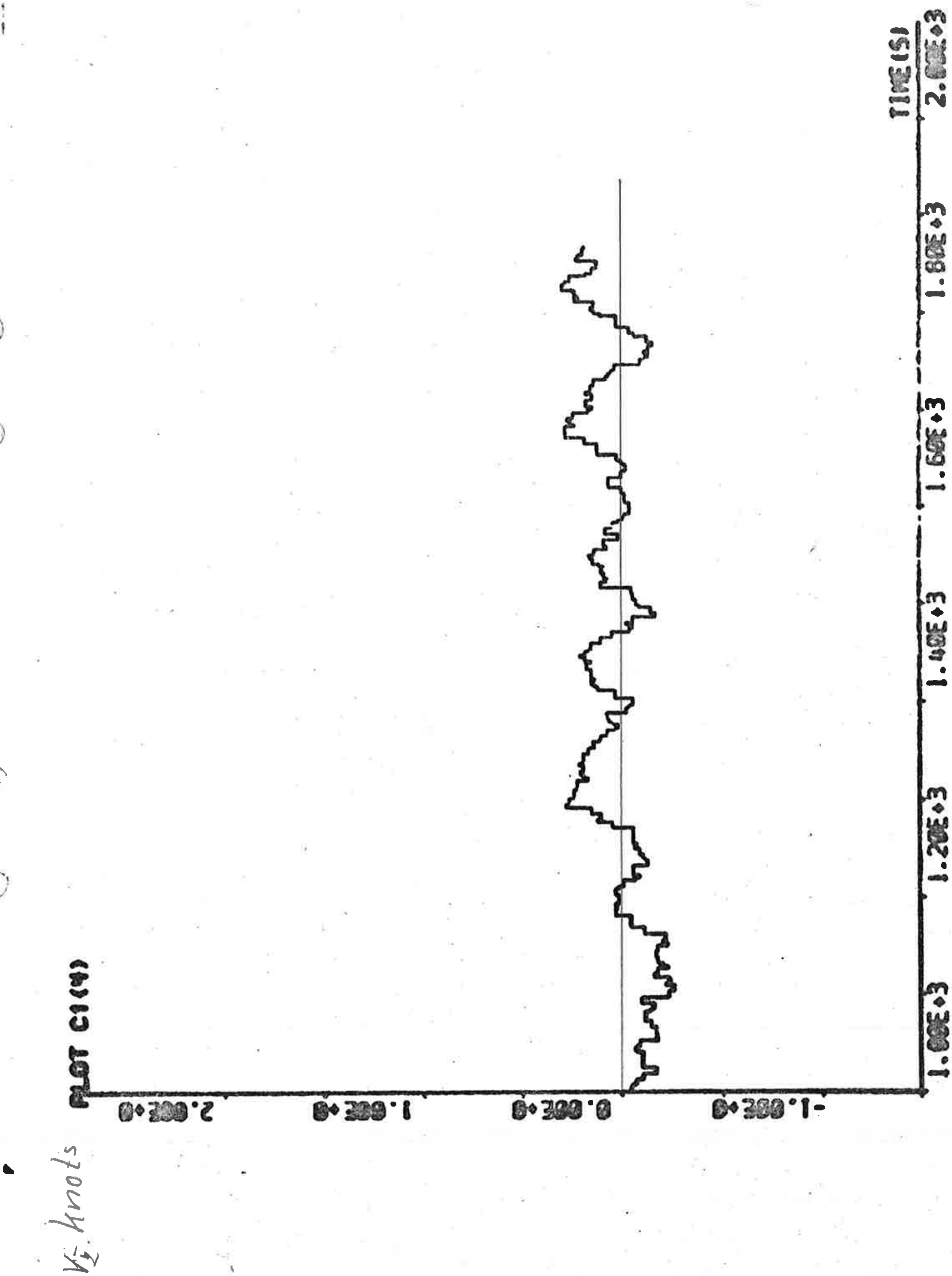
V_1 knots

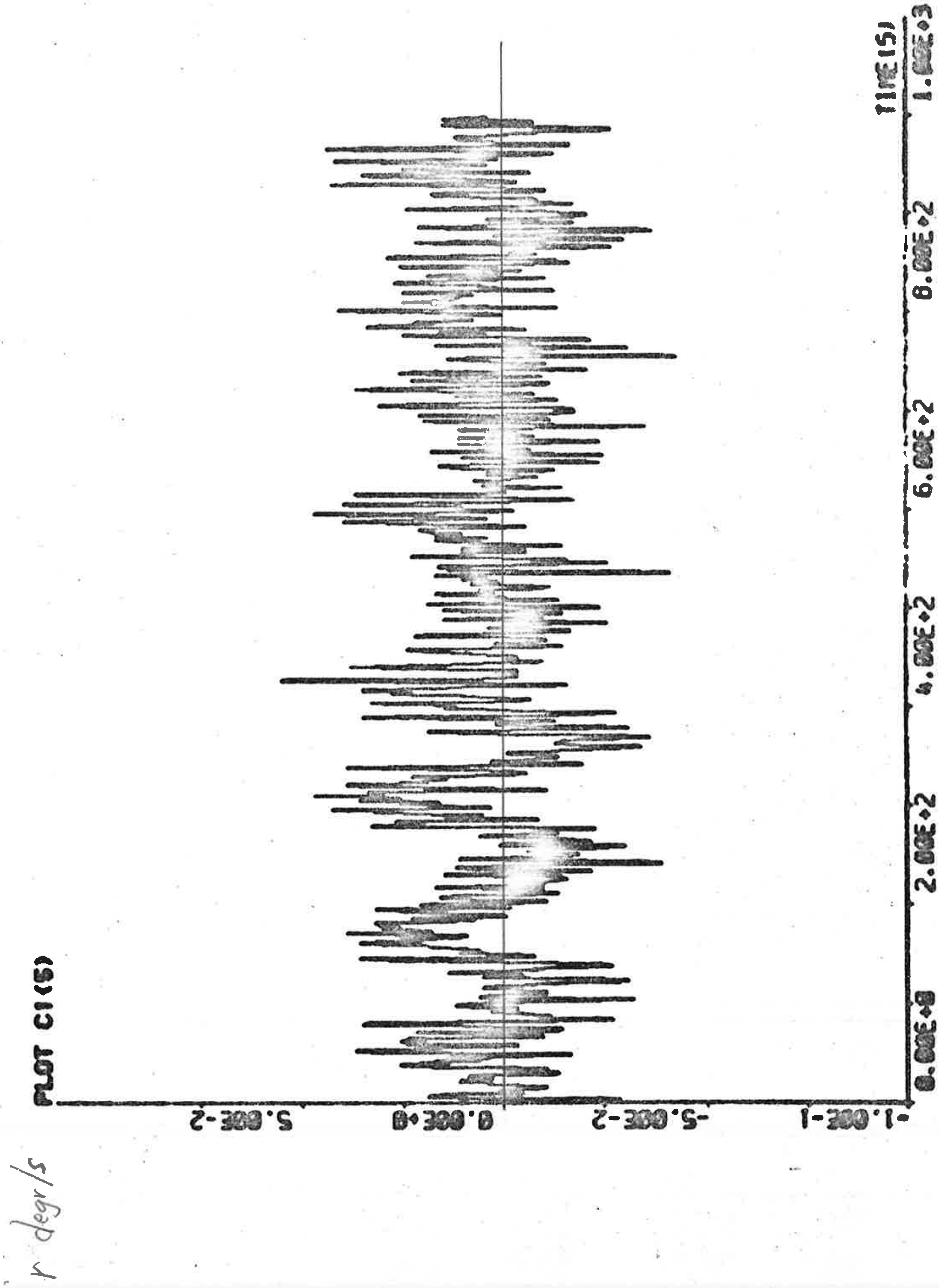

PLOT C1(3)
TIME(S)
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
-1.00E+0
0.00E+0
1.00E+0
2.00E+0

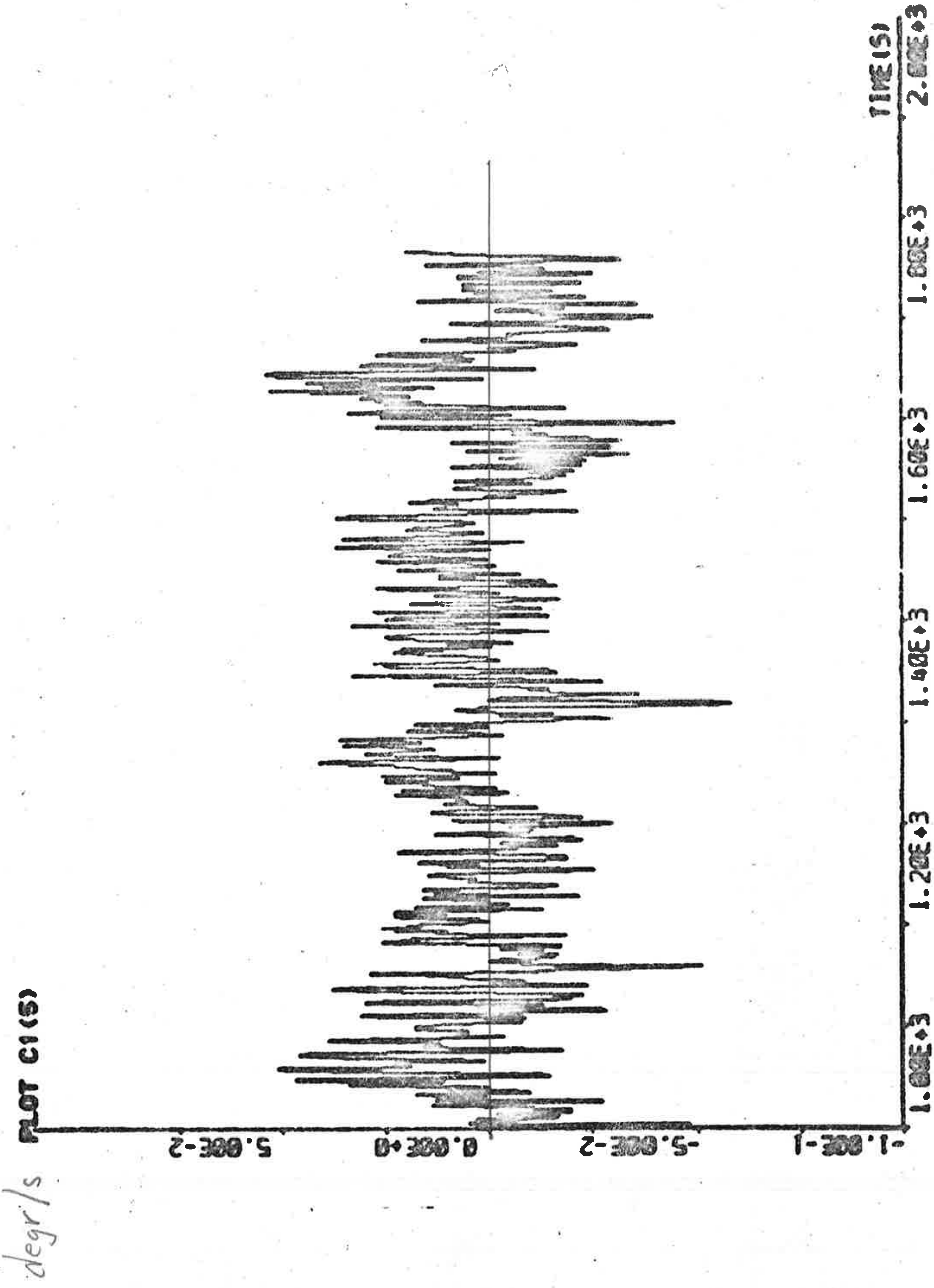
V_1 knots

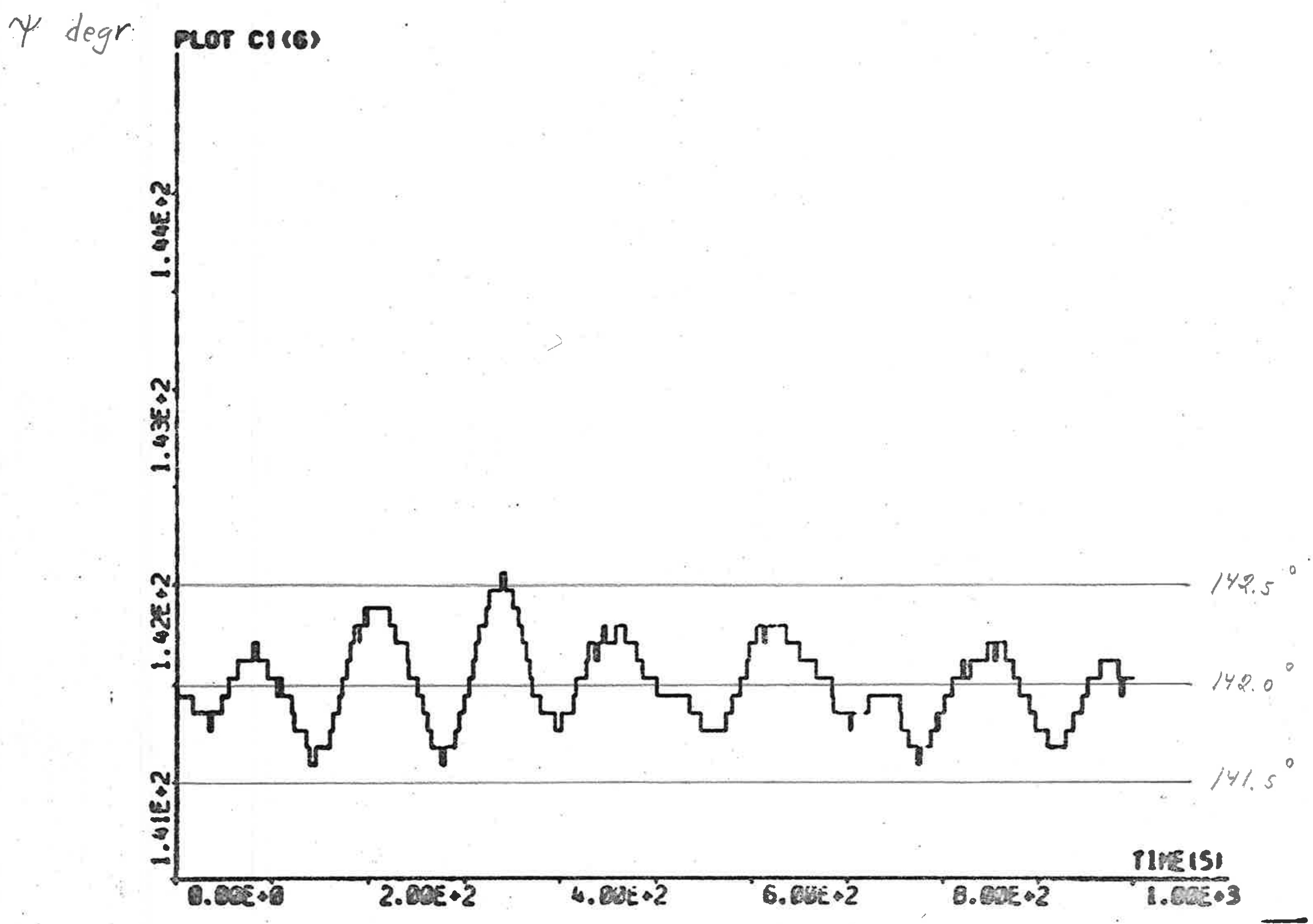

PLOT C1 (4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
TIME (S)

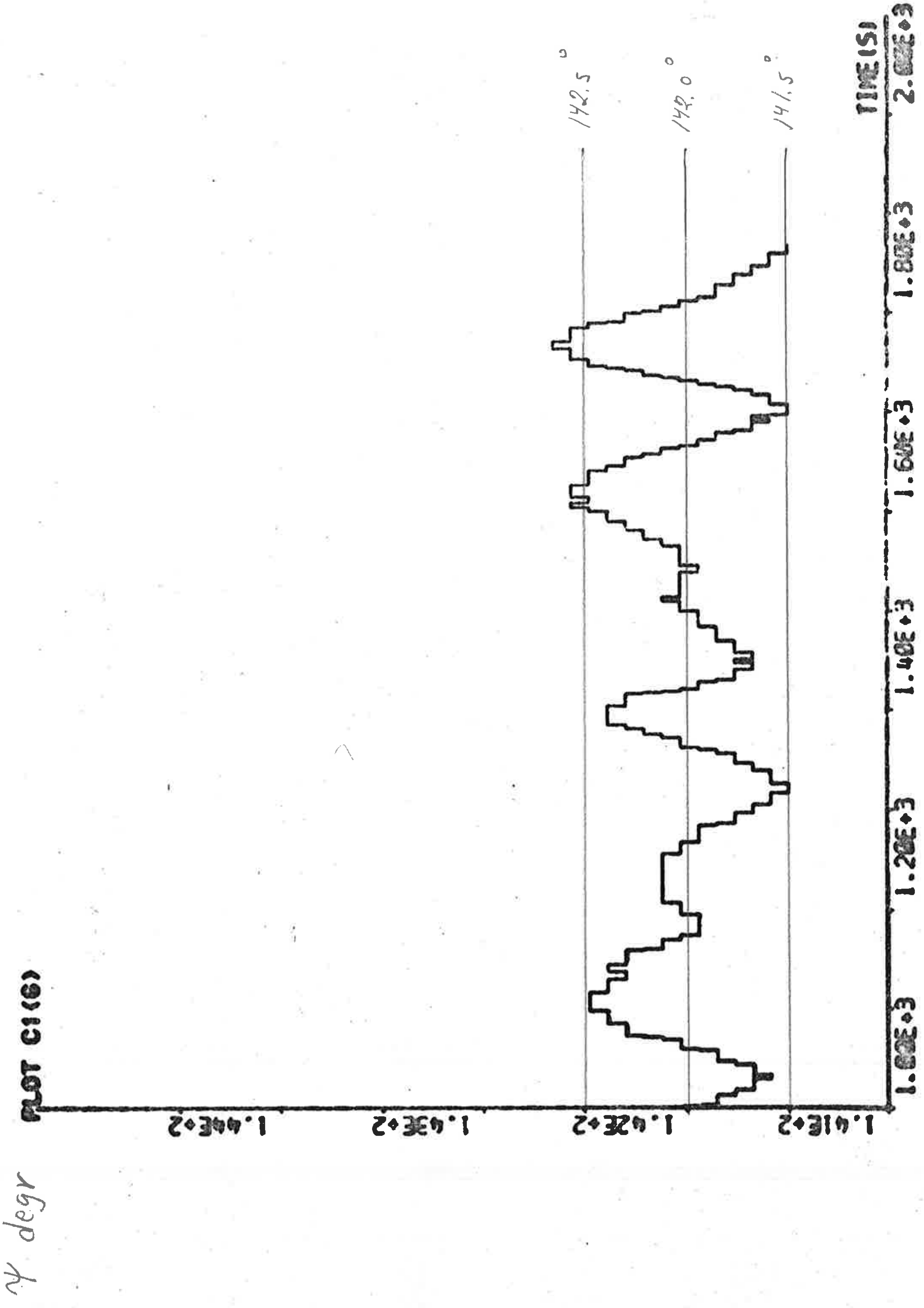
V_2 knots

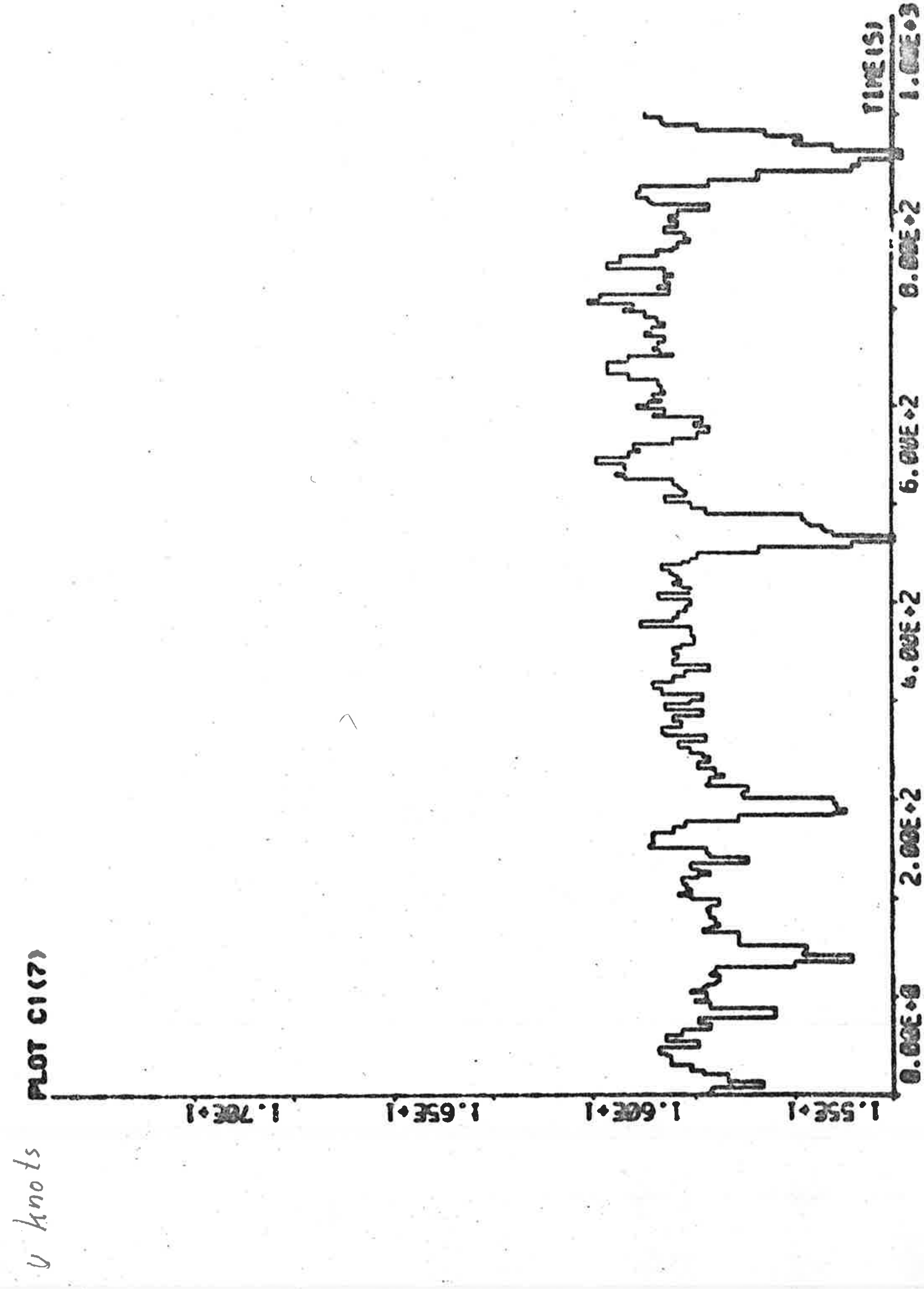

PLOT C1(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
TIME(S)
Vz knots

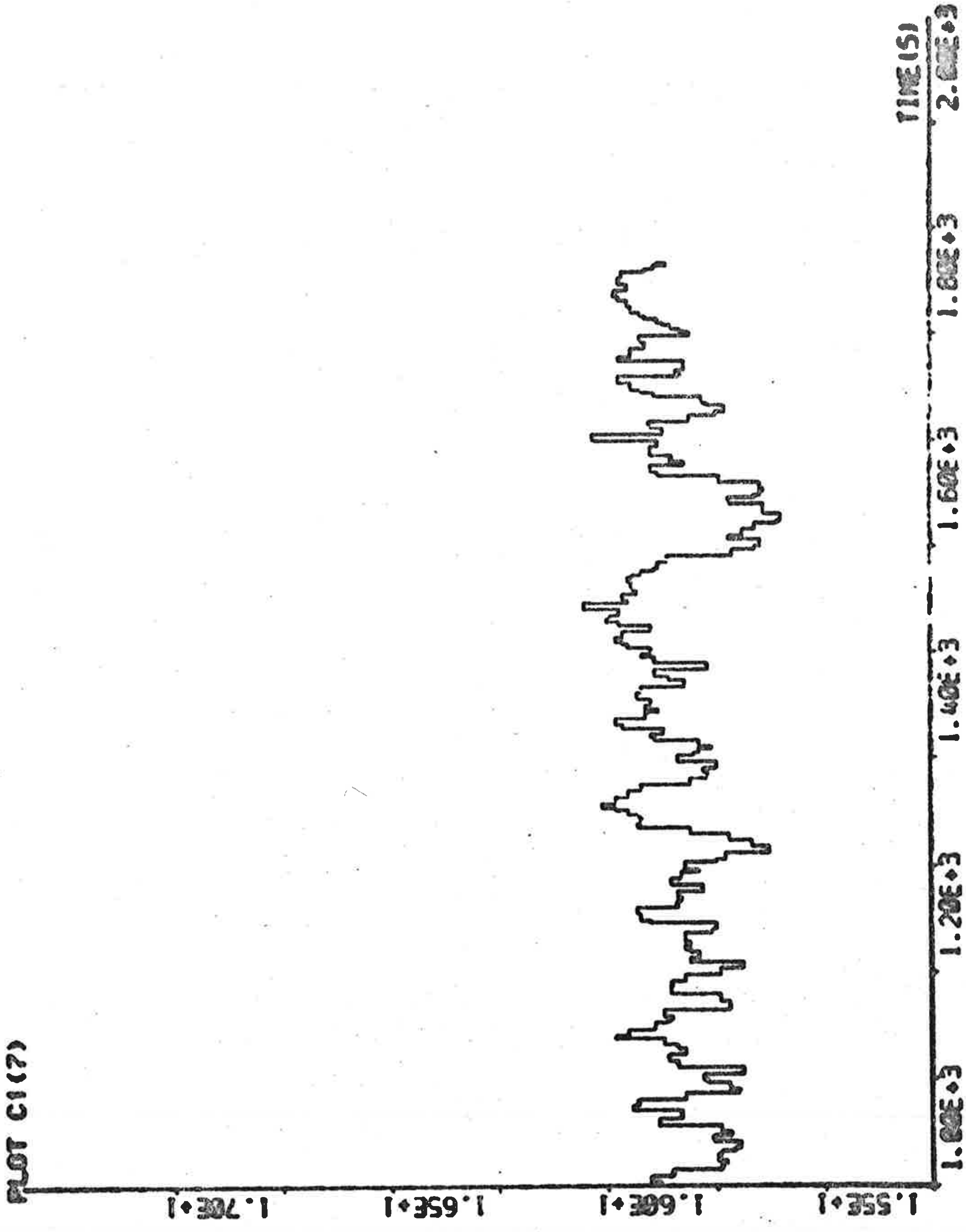

PLOT C1 (S)
TIME (S)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
0.00E+0
2.00E+2
4.00E+2
6.00E+2
6.00E+2
1.00E+3
r degr/s


PLOT C1(5)
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


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)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3


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


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)
1.70E+1
1.65E+1
1.60E+1
1.55E+1
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
TIME(S)

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.

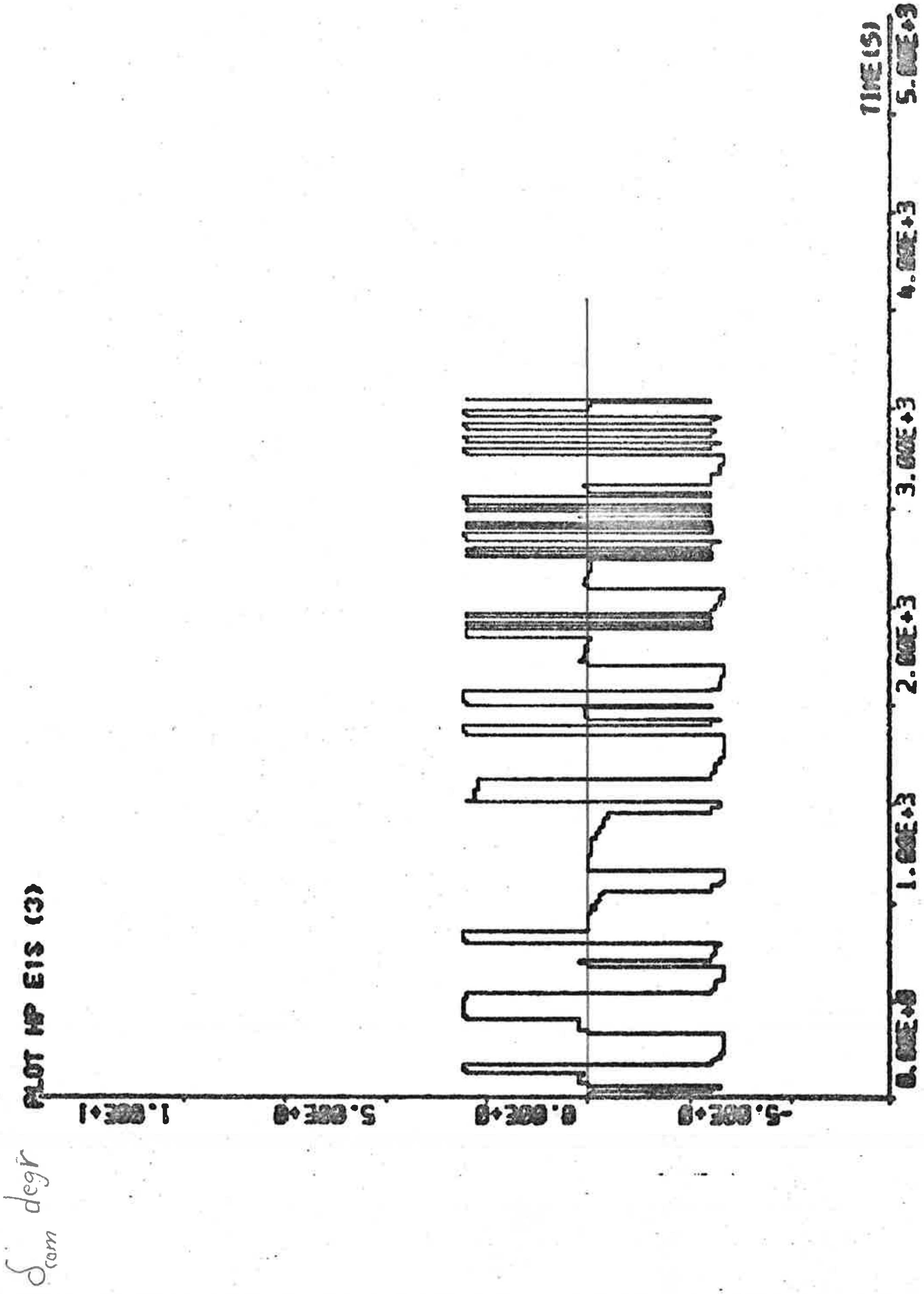
Calibration of the rudder servo:

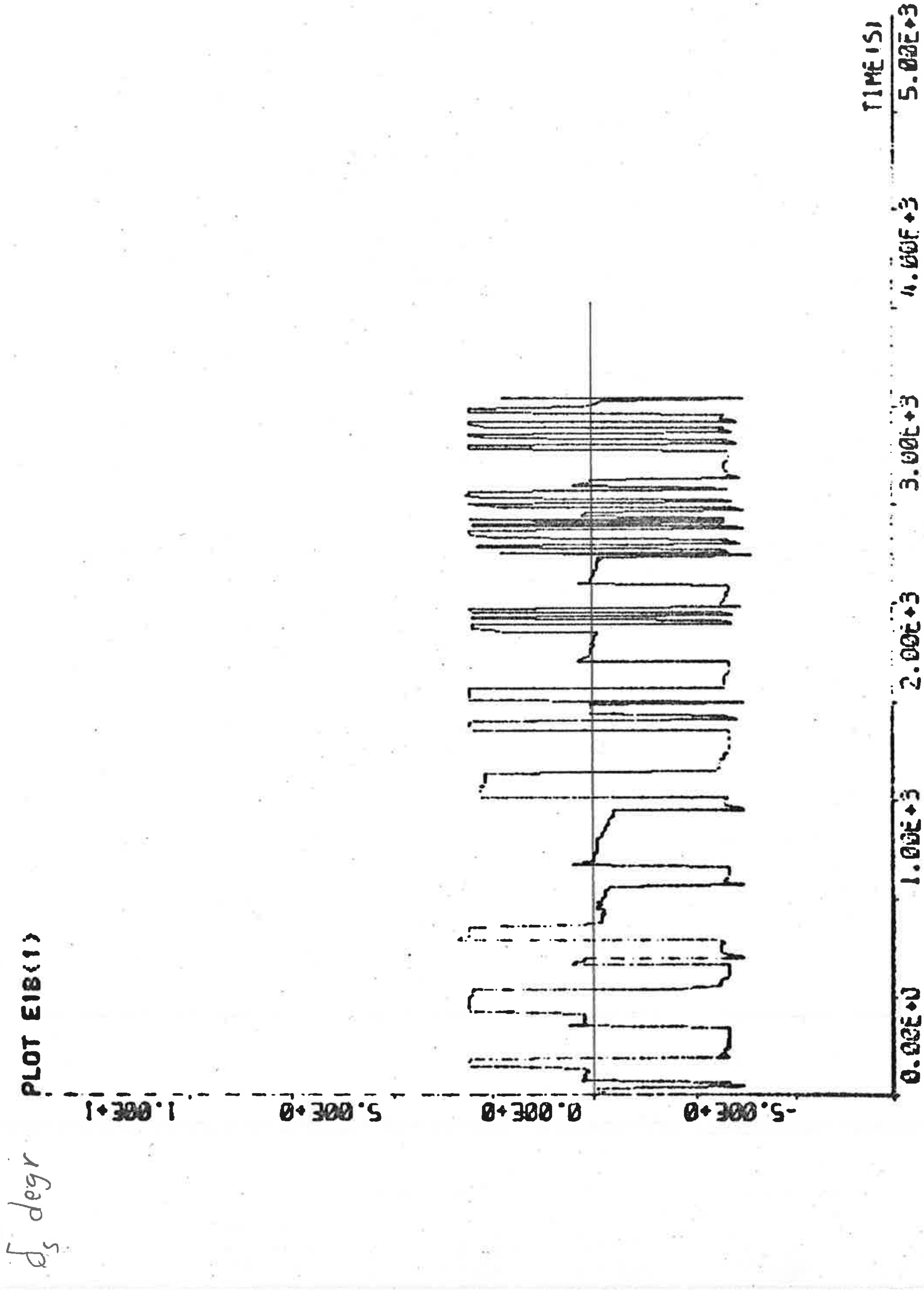
10 volts = 36.5°
-10 volts = -43.5°

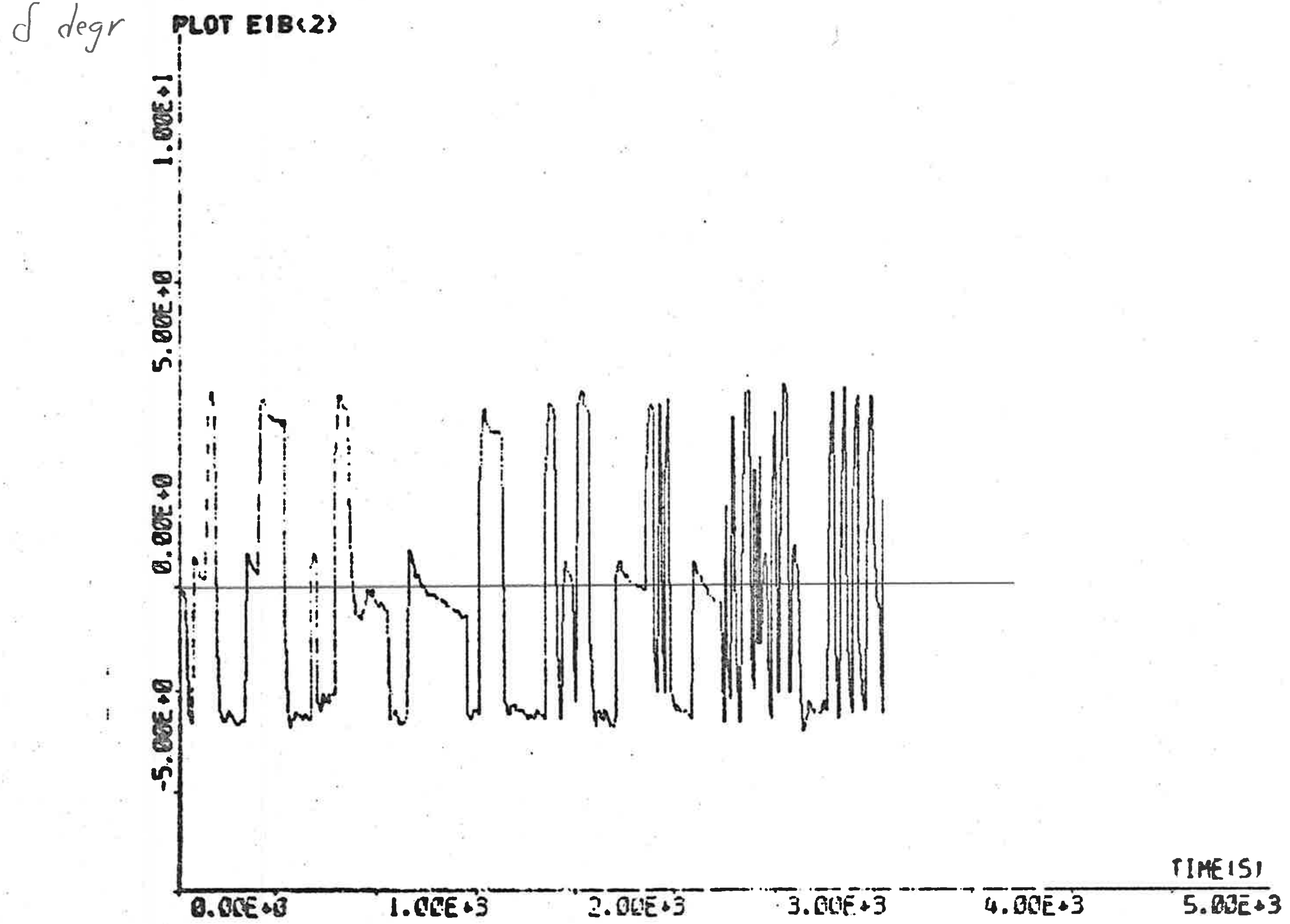
Sampling interval: 10 s
Rudder angles: +3°, 0°, -3°

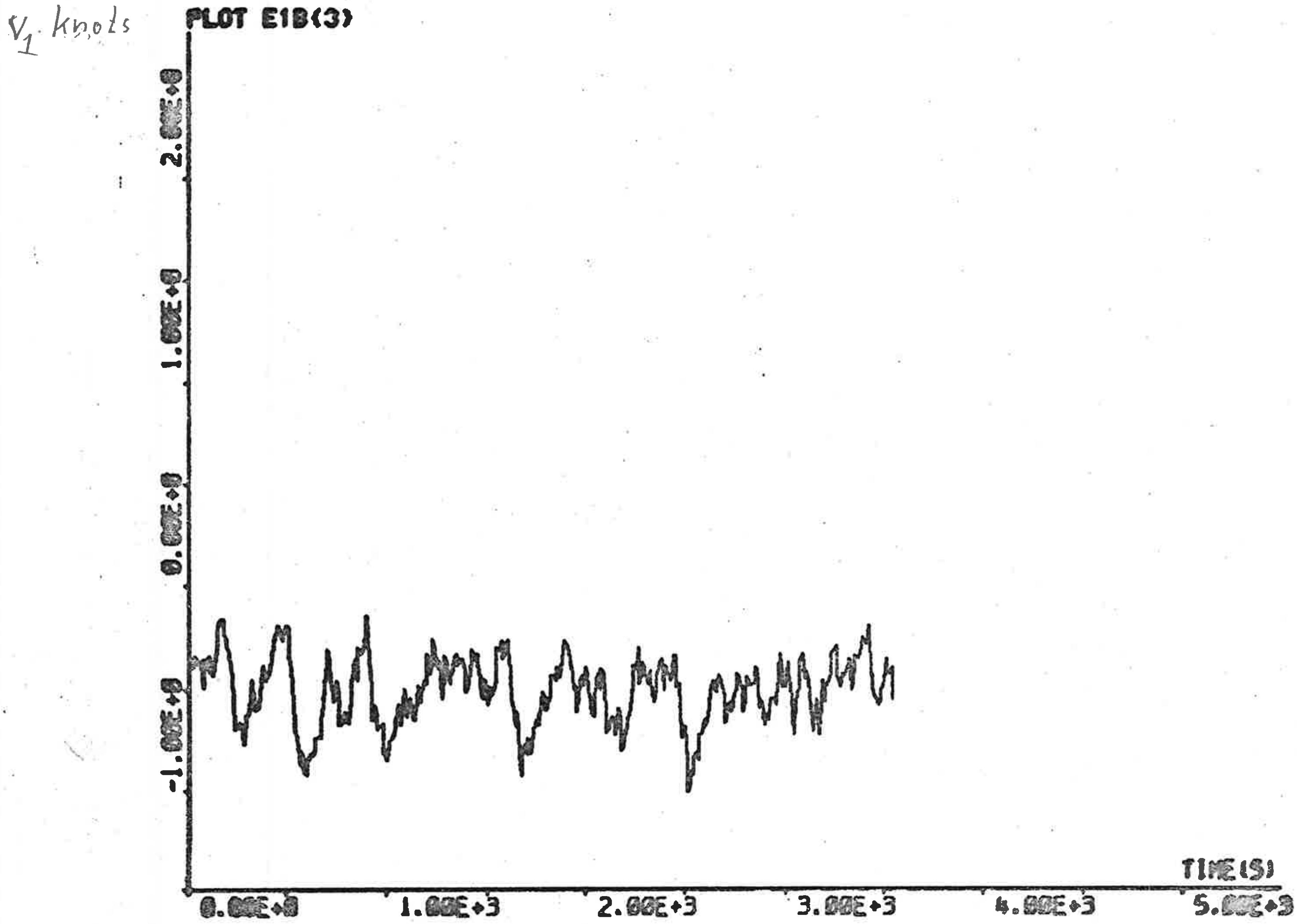
Statistics:

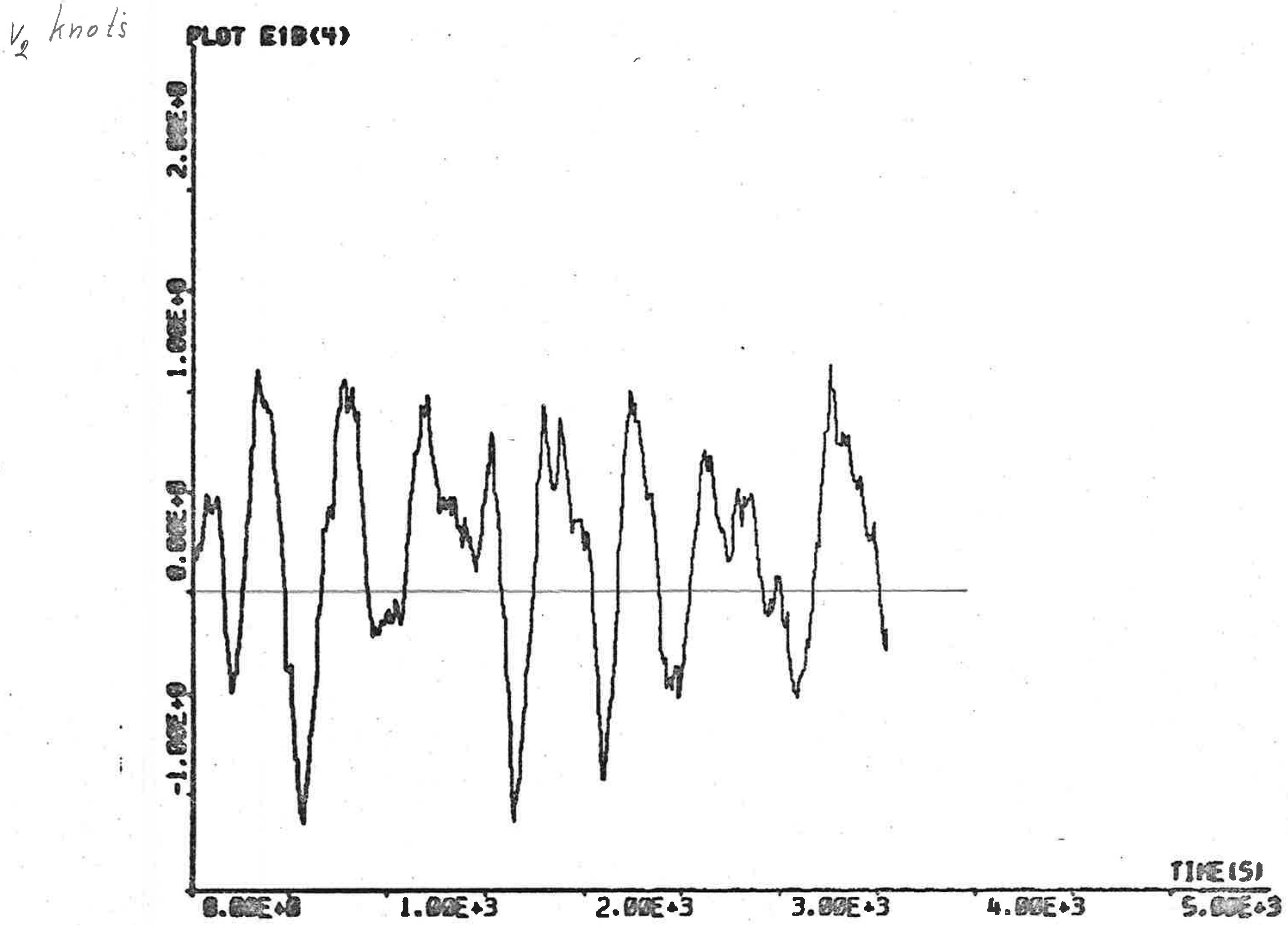
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.65	2.47	-3.3	3.1
δ_s degr	-0.72	2.50	-3.9	3.4
δ degr	-0.28	2.75	-3.5	5.0
v_1 knots	-0.506	0.164	-1.01	-0.14
v_2 knots	0.206	0.497	-1.15	1.13
r degr/s	0.0087	0.0549	-0.110	0.160
ψ degr	182.754	3.722	176.60	192.10
u knots	16.896	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

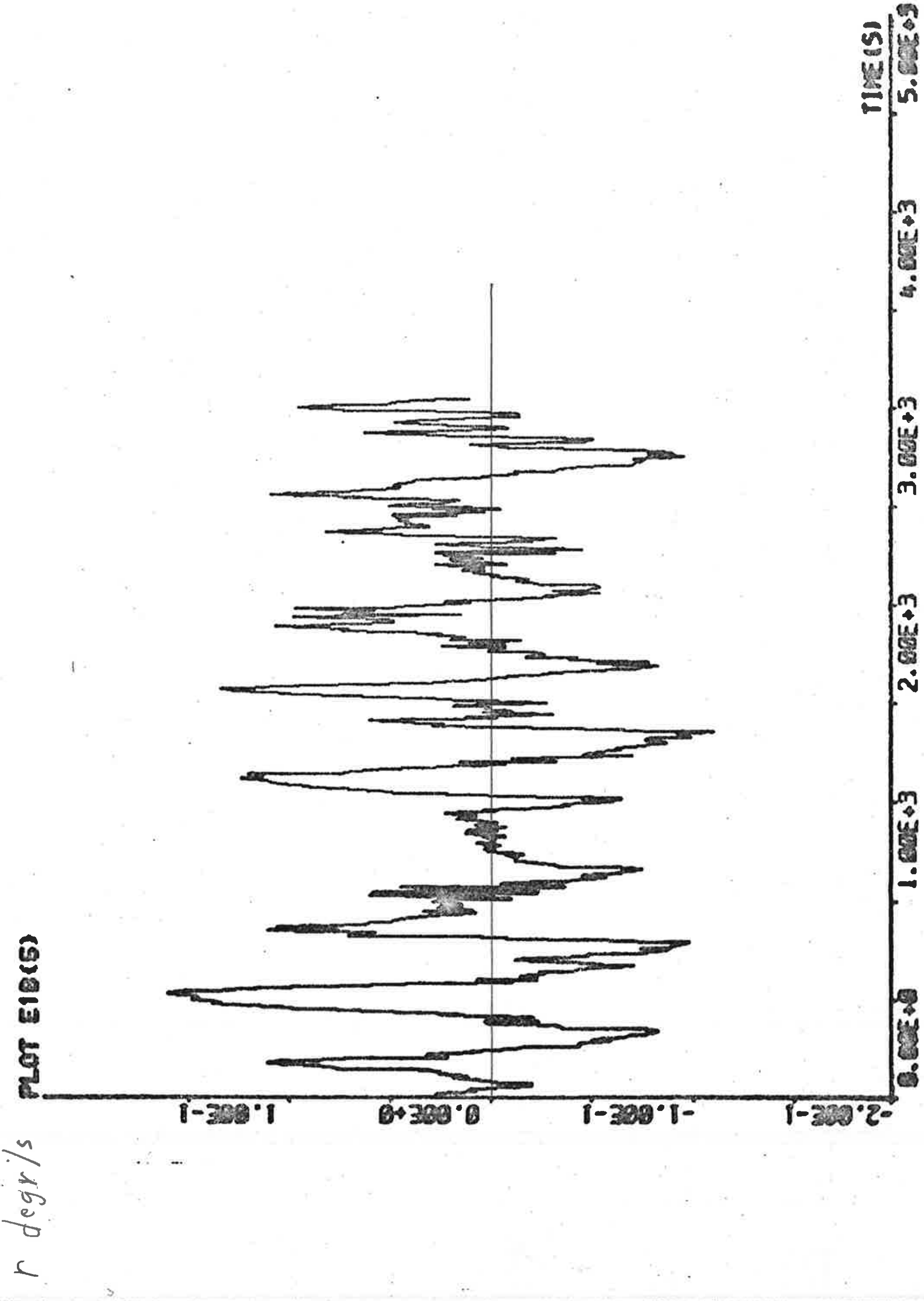

PLOT HP E1S (3)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ_{com} degr

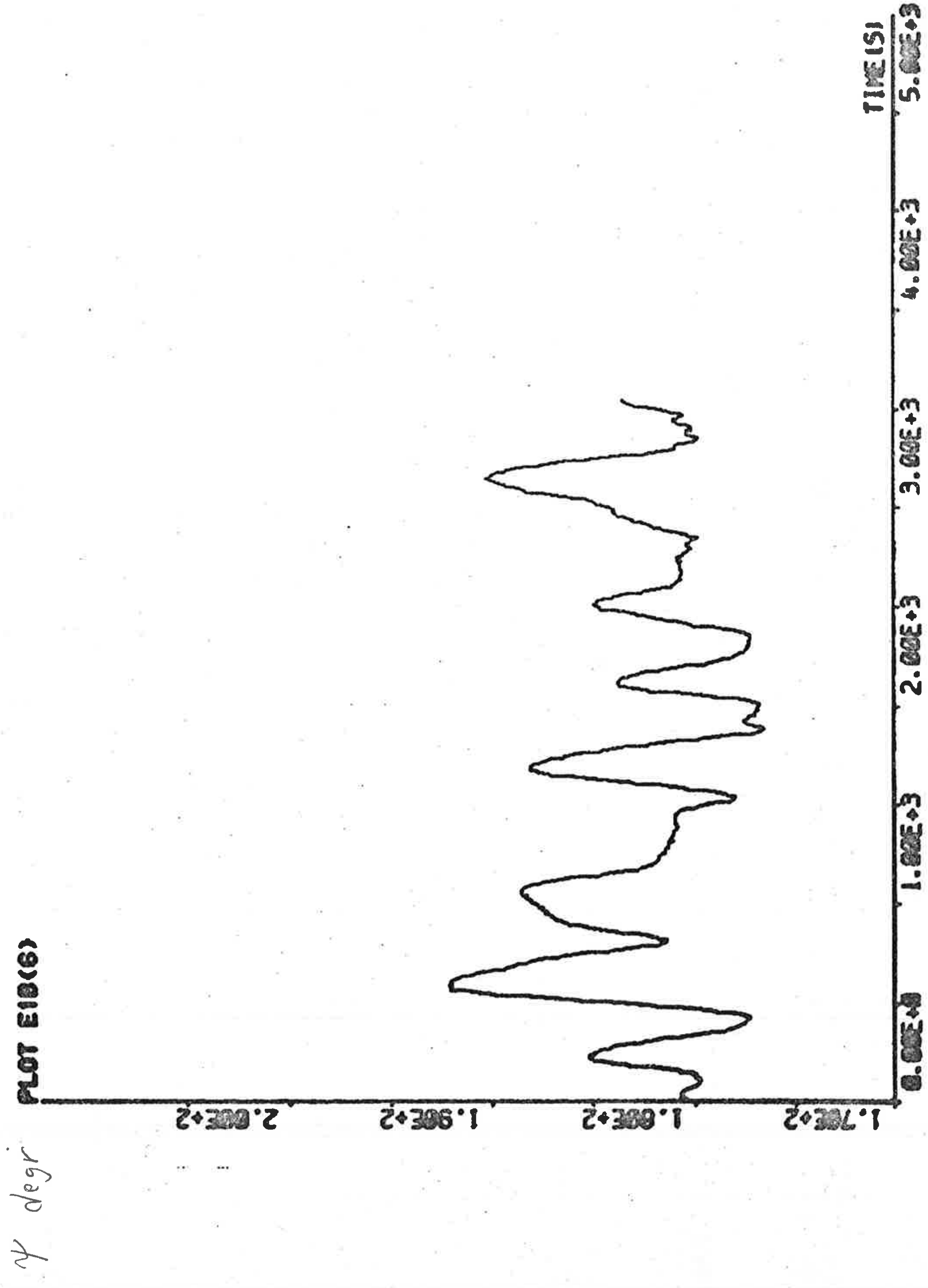

PLOT E18(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
δs degr

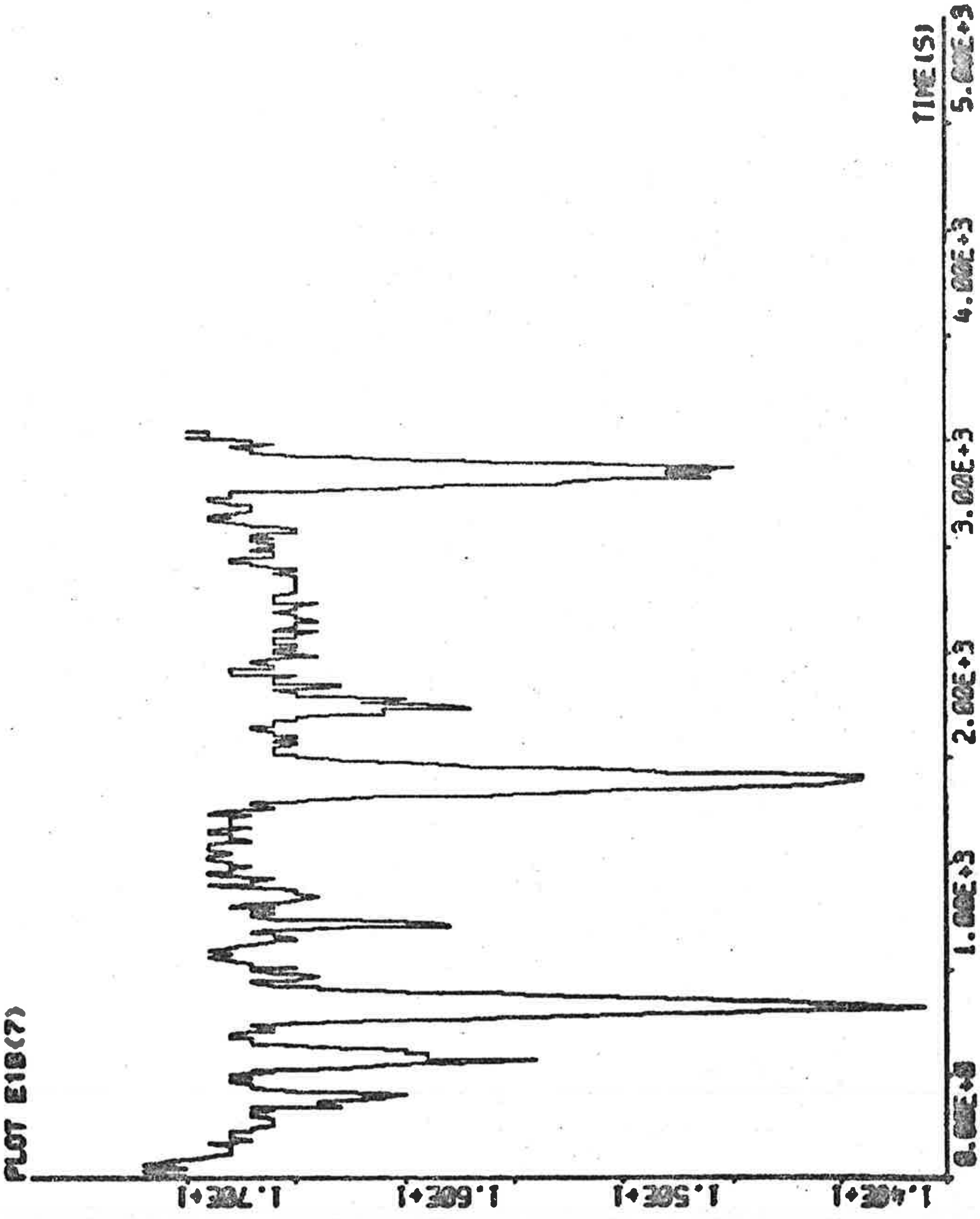

δ degr
PLOT E1B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


V_1 knots
PLOT E1B(3)
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


V_2 knots
PLOT E1B(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)

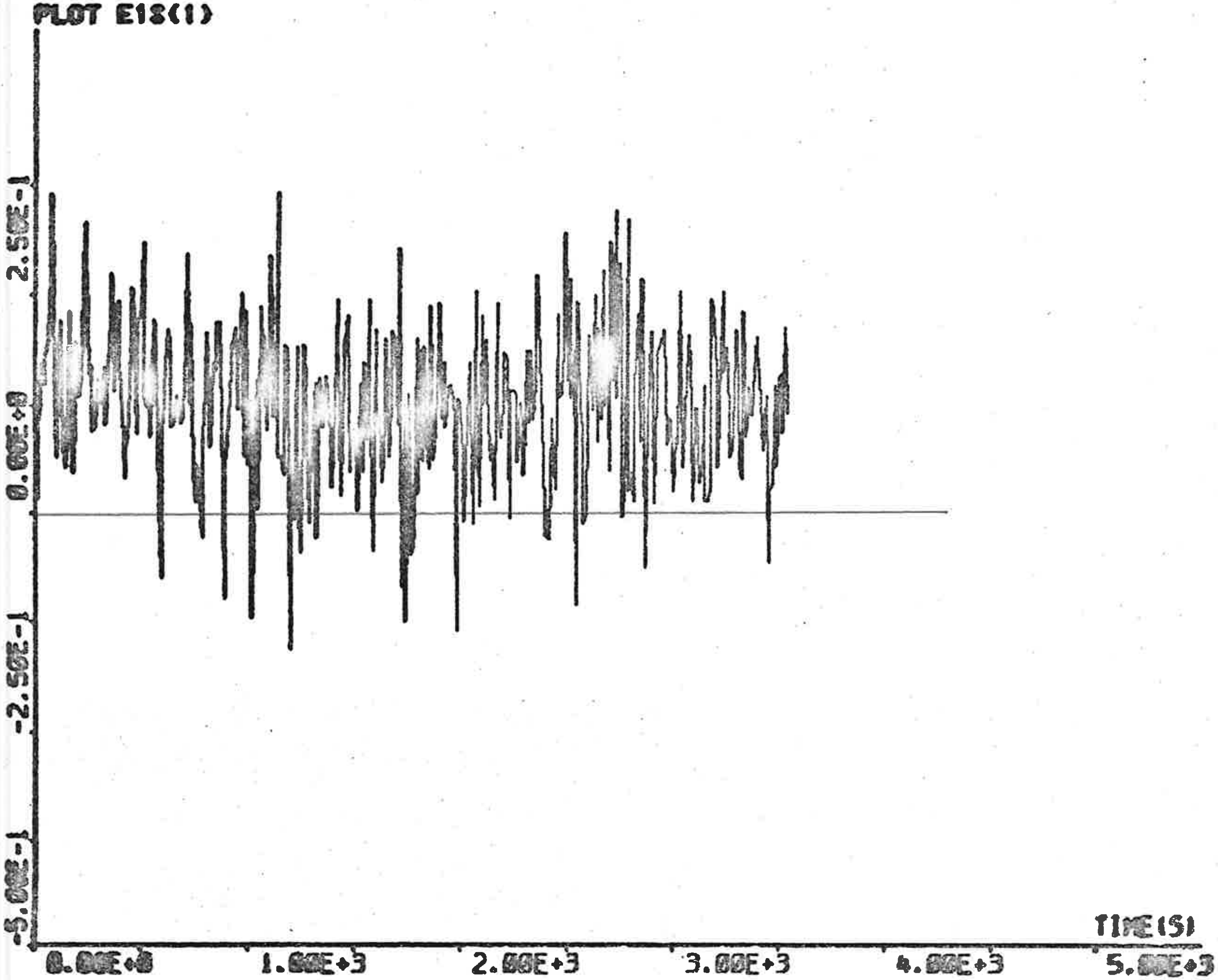

PLOT E10(5)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
r degr/s

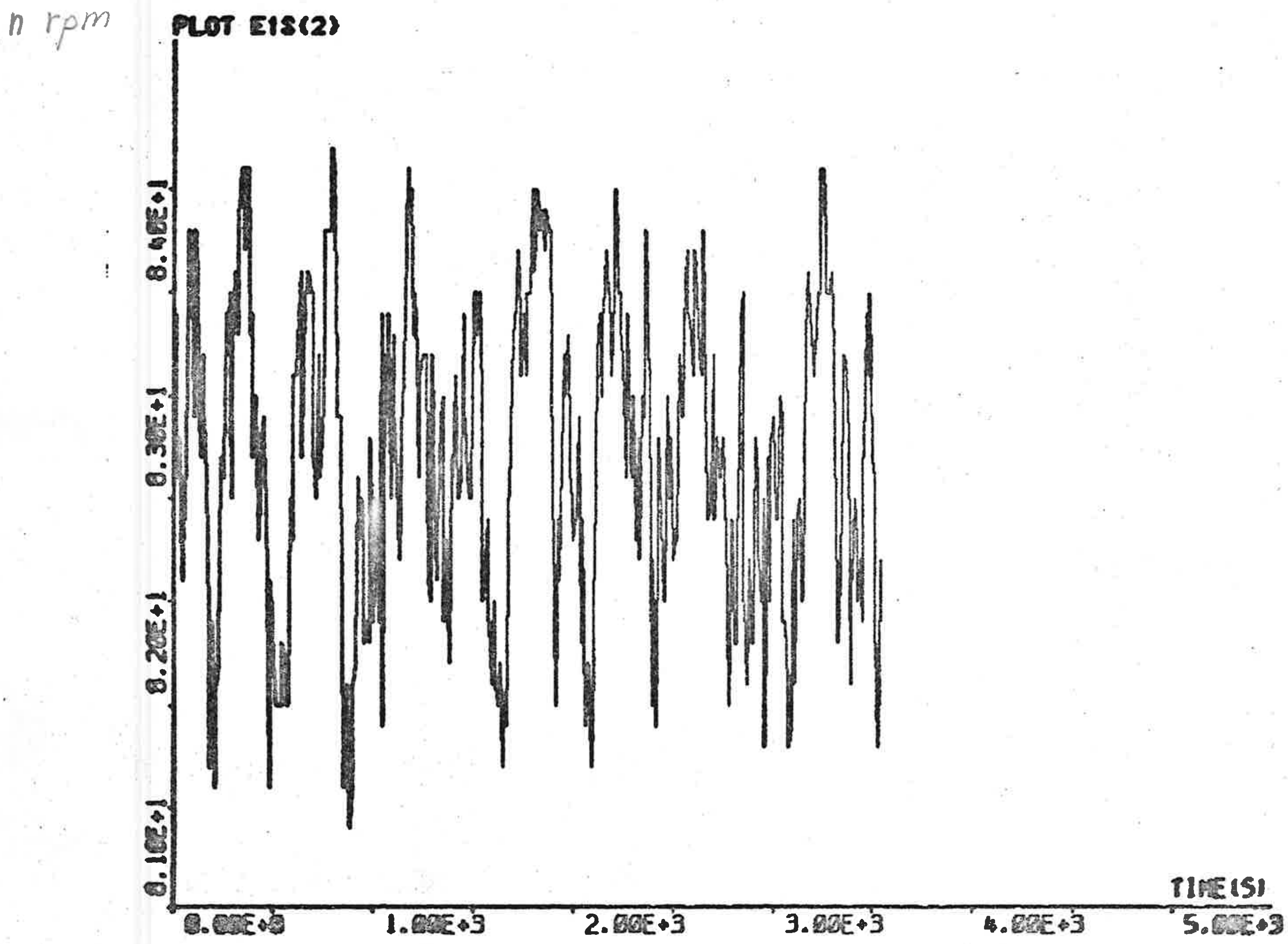

PLOT E18(6)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.70E+2
1.80E+2
1.90E+2
2.00E+2
ψ degr


PLOT E1B(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

v knots

9 degr/s


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


n rpm
PLOT E1S(2)
0.40E+1
0.30E+1
0.20E+1
0.10E+1
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

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°

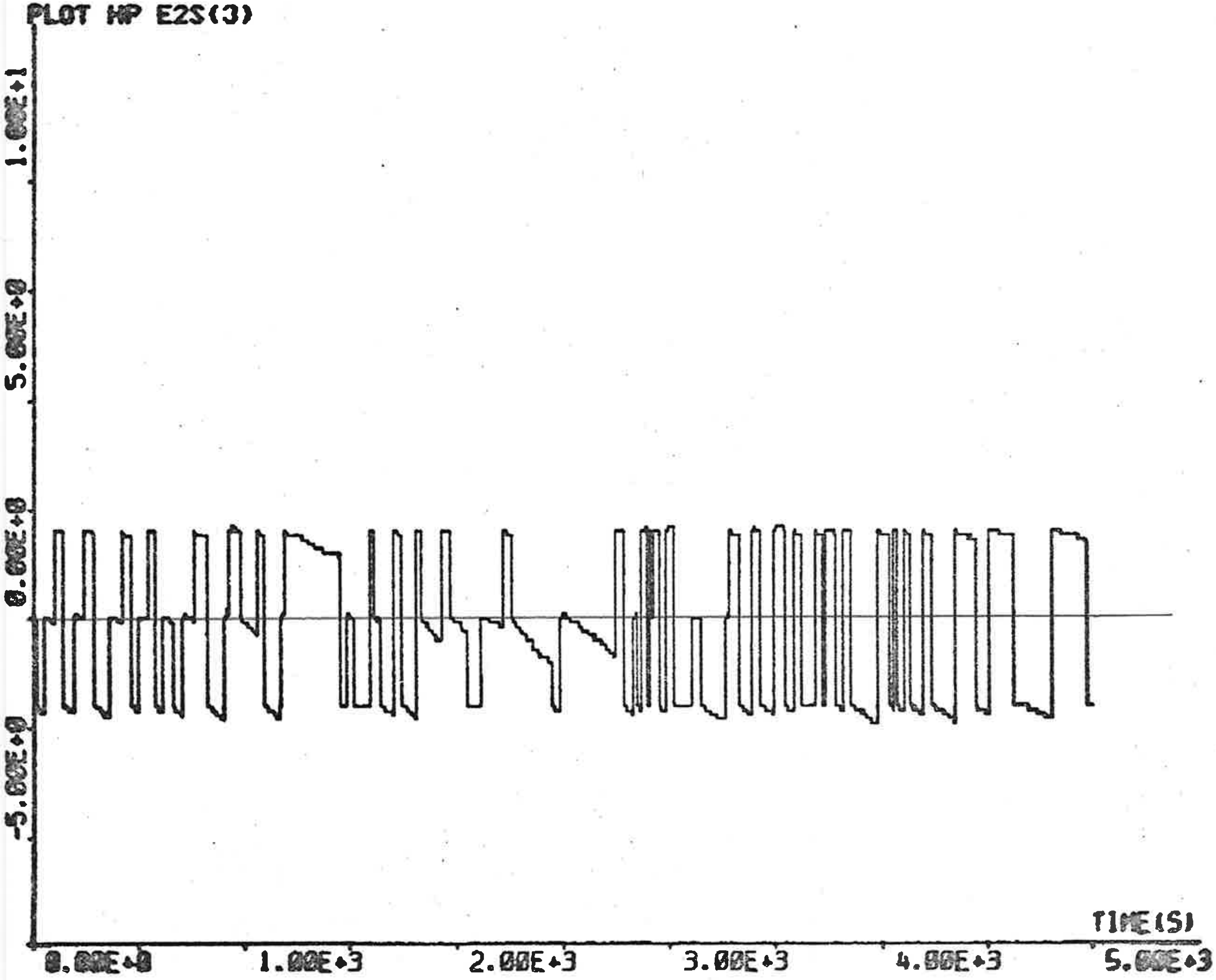
Sampling interval: 5 s

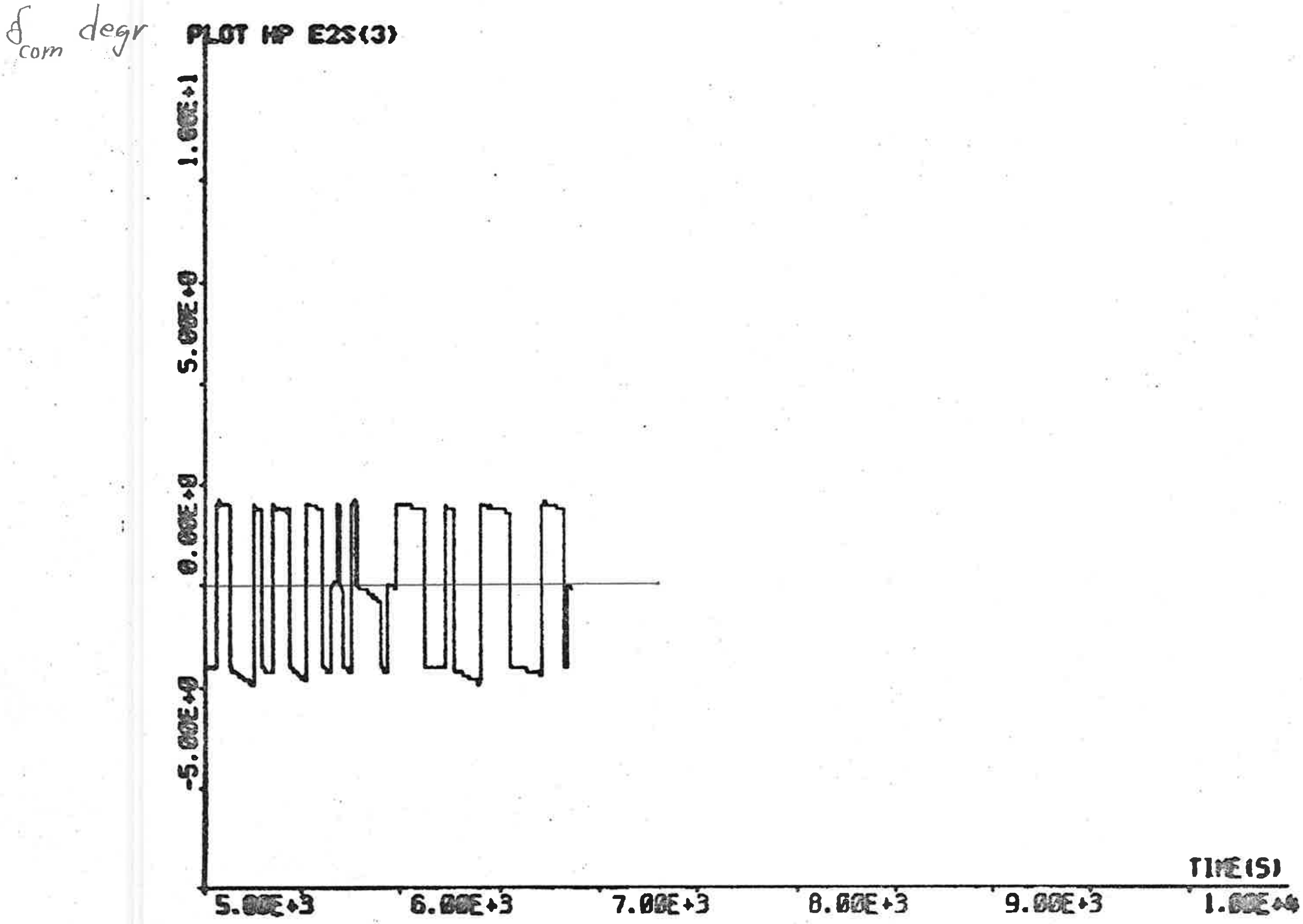
Rudder angles: +2°, 0°, -2°

Statistics:

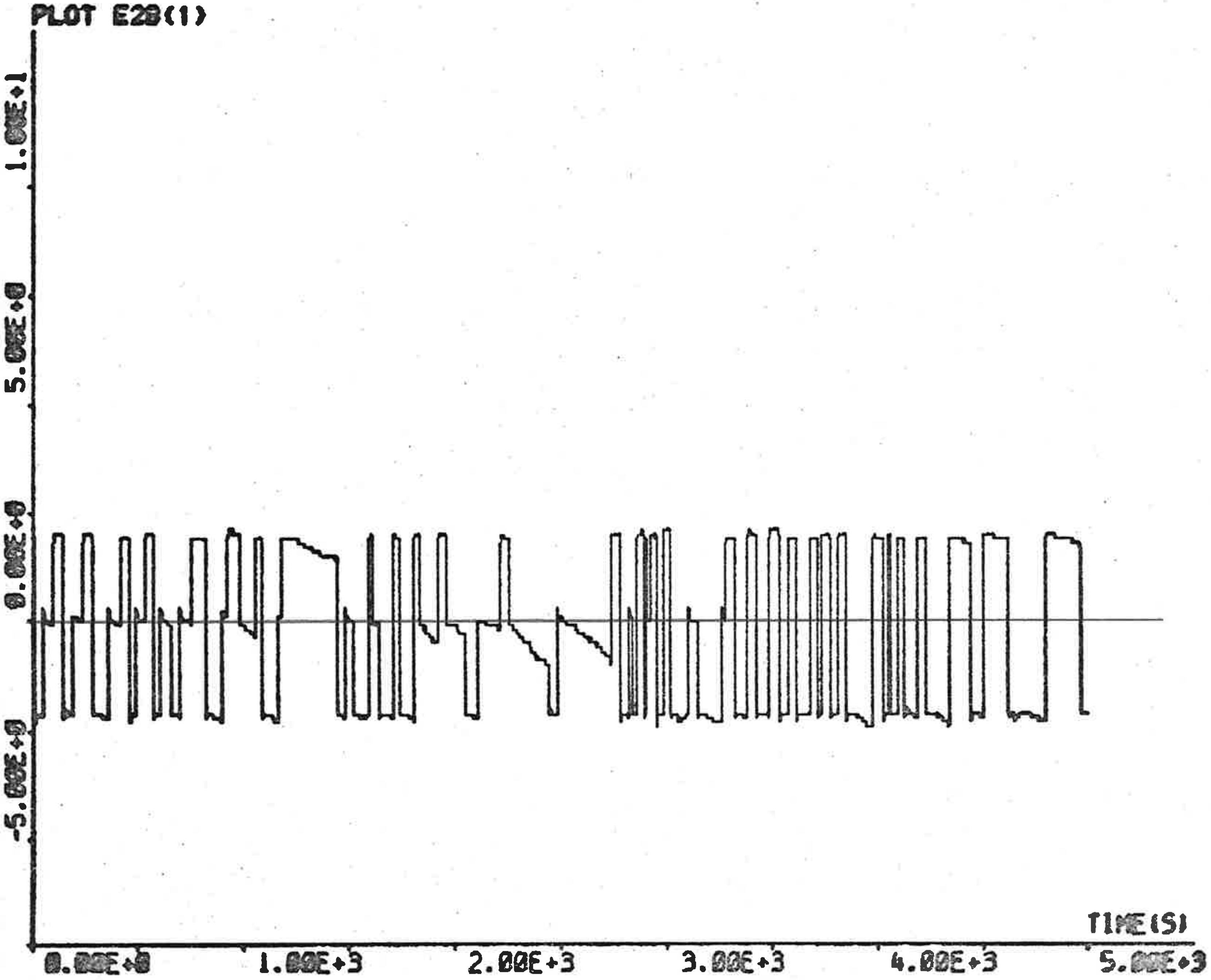
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.22	1.77	-2.4	2.1
δ_s degr	-0.24	1.79	-2.4	2.1
δ degr	-0.43	1.85	-2.9	2.5
v_1 knots	-0.567	0.146	-1.01	-0.16
v_2 knots	0.112	0.361	-1.01	1.12
r degr/s	0.0067	0.0383	-0.099	0.117
Ψ degr	145.572	6.290	137.64	159.96
u knots	16.742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

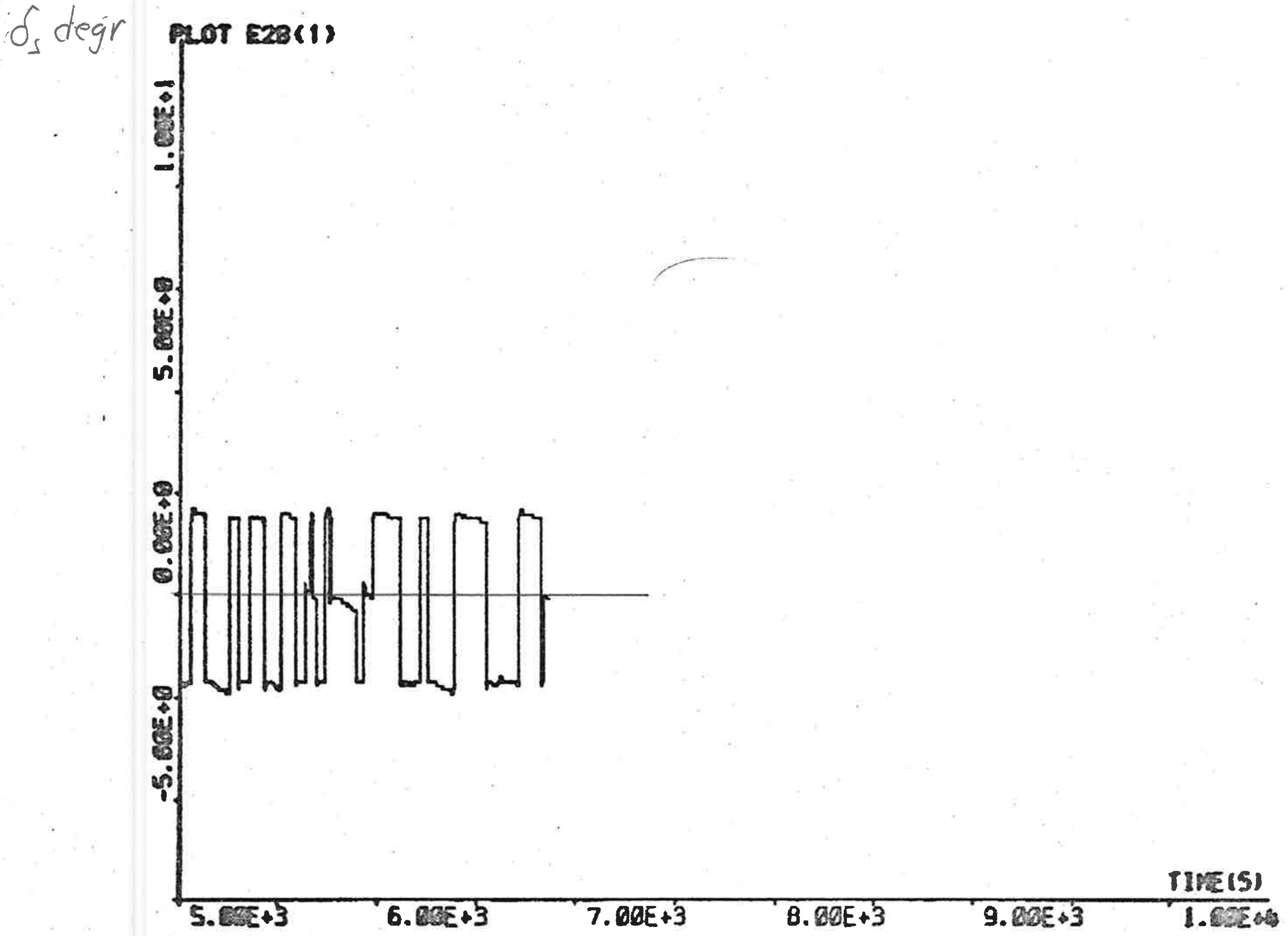
δ_{com} degr

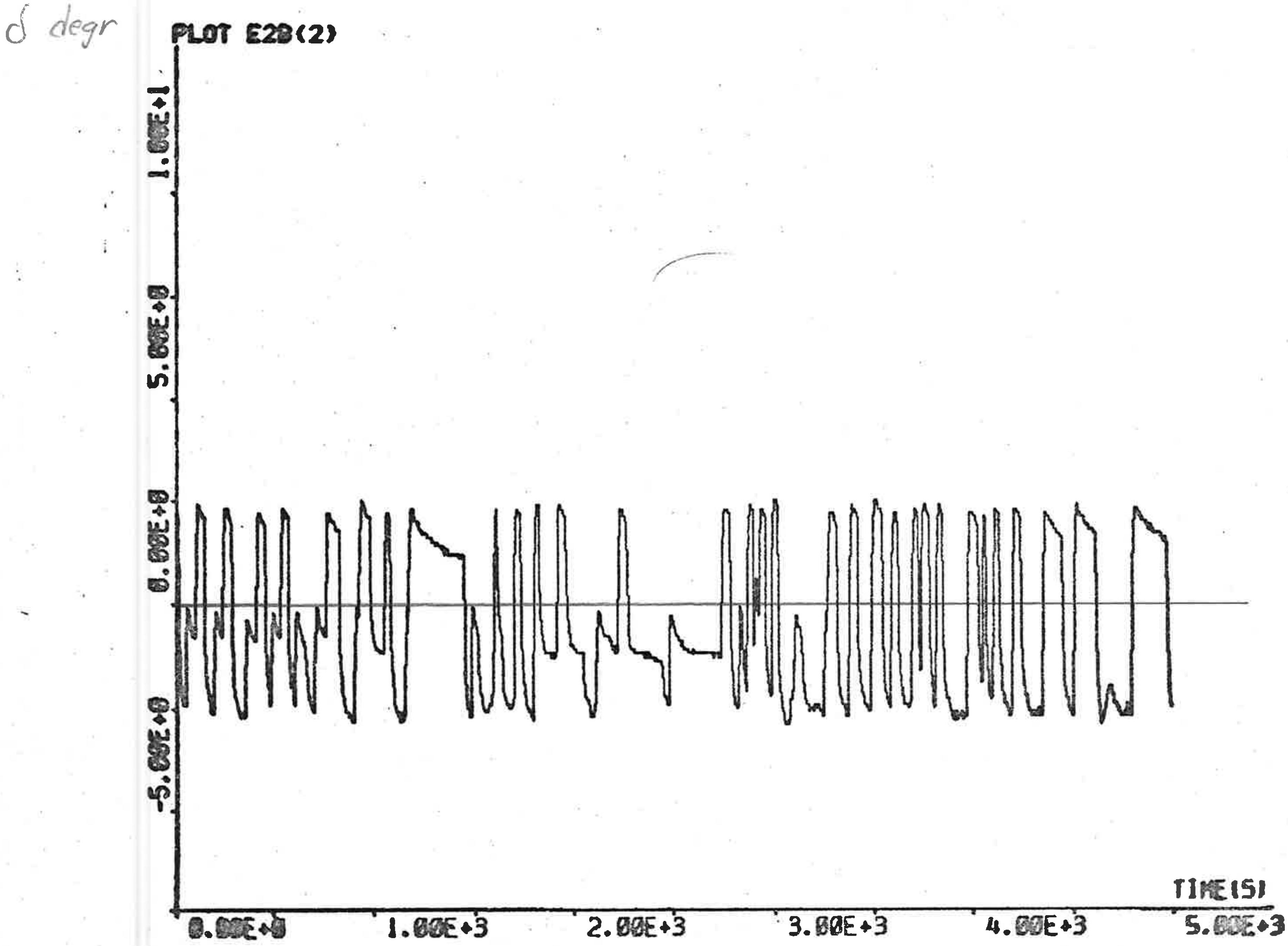


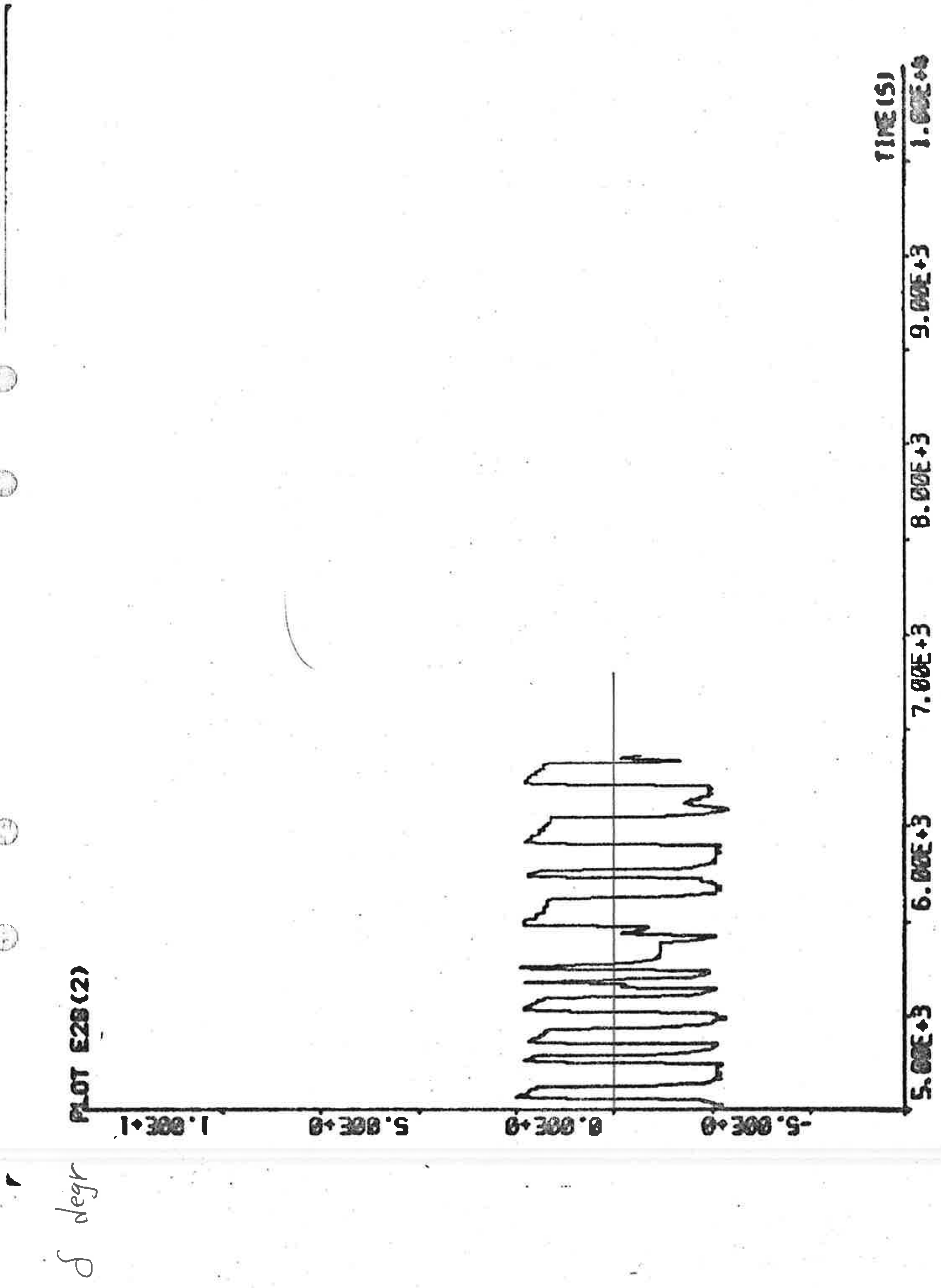

δ_{com} degr
PLOT HP E2S(3)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4

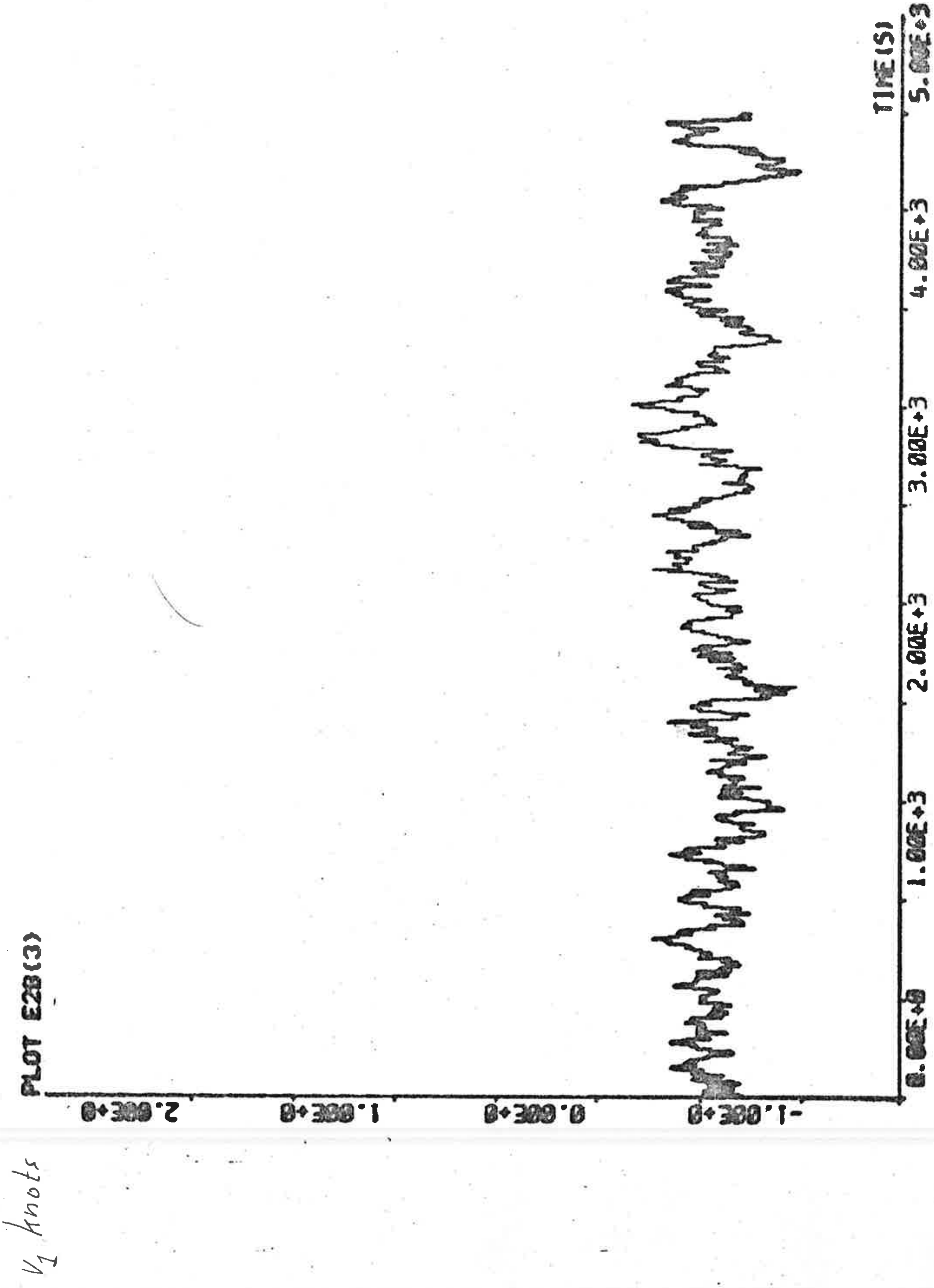
δ_s degr

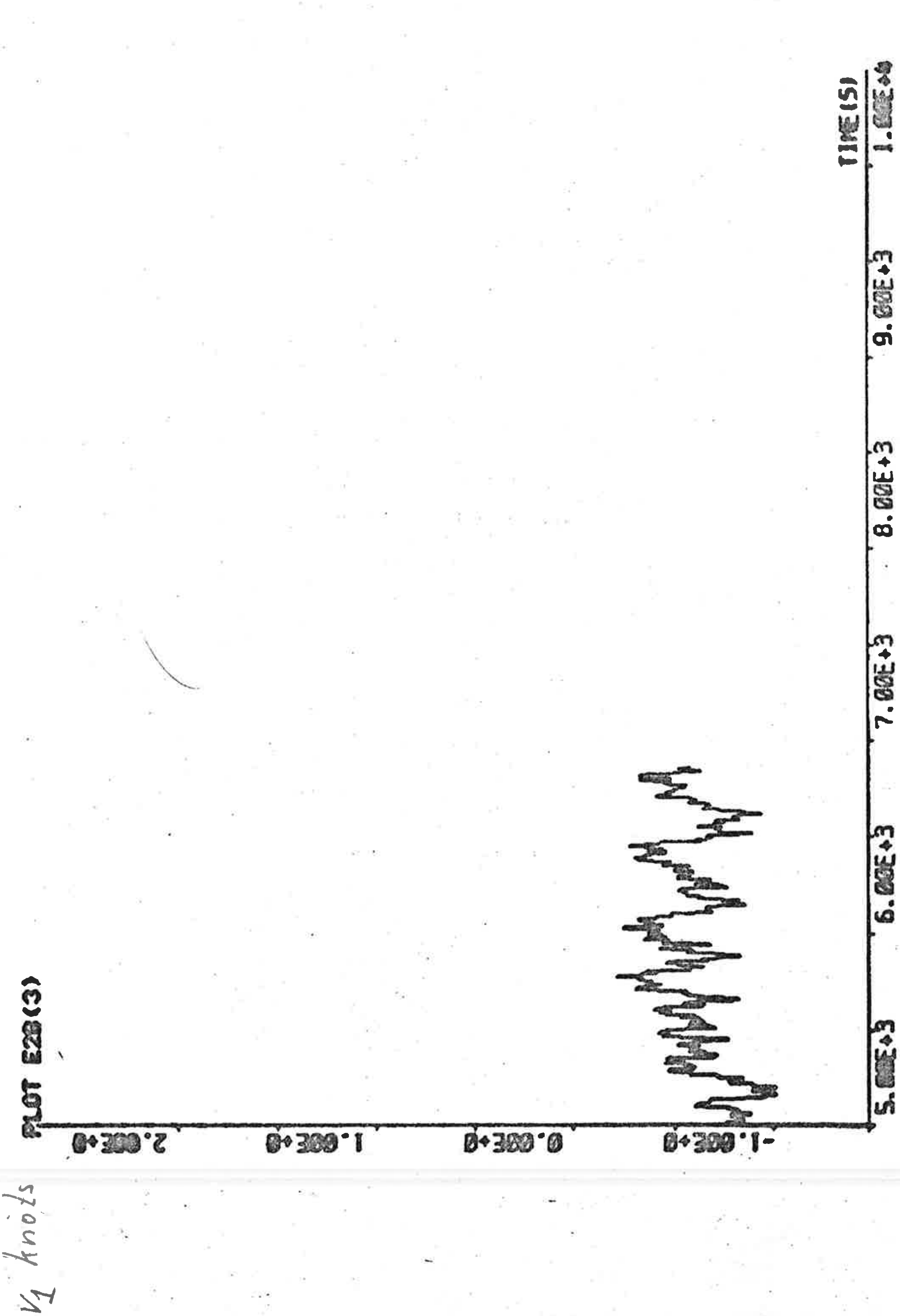

PLOT E28(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

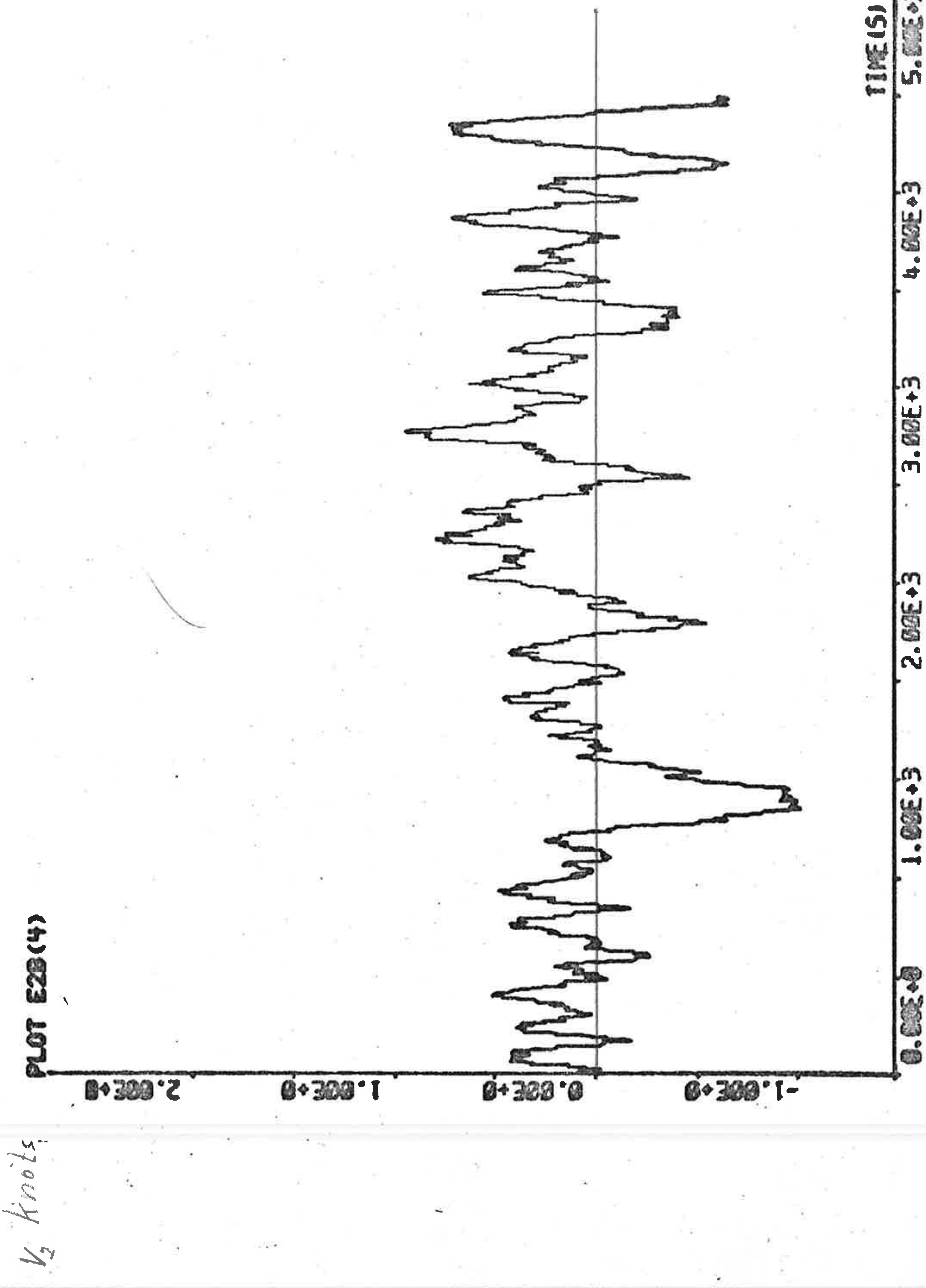

δ_s degr
PLOT E2B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4

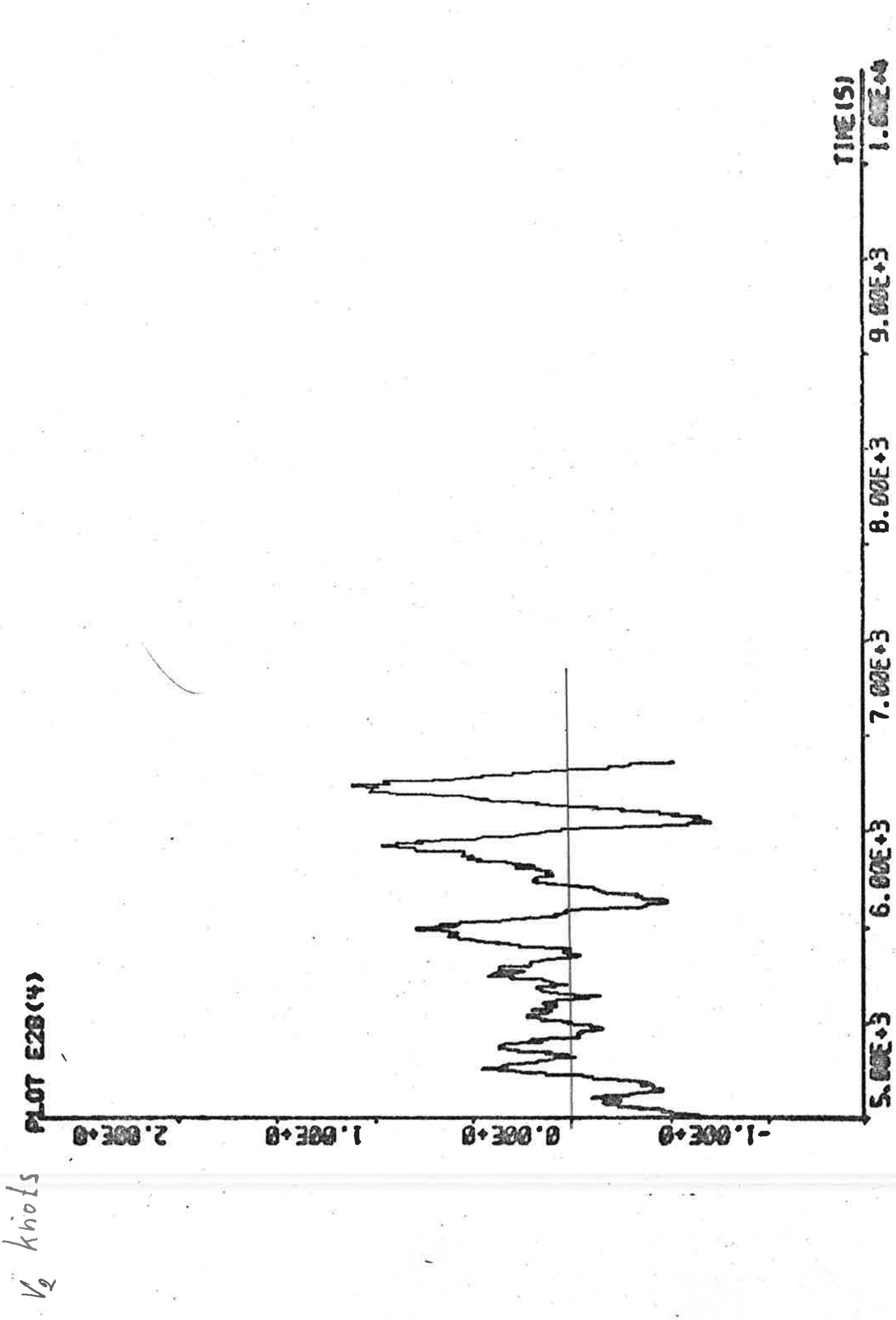

δ degr
PLOT E2B(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

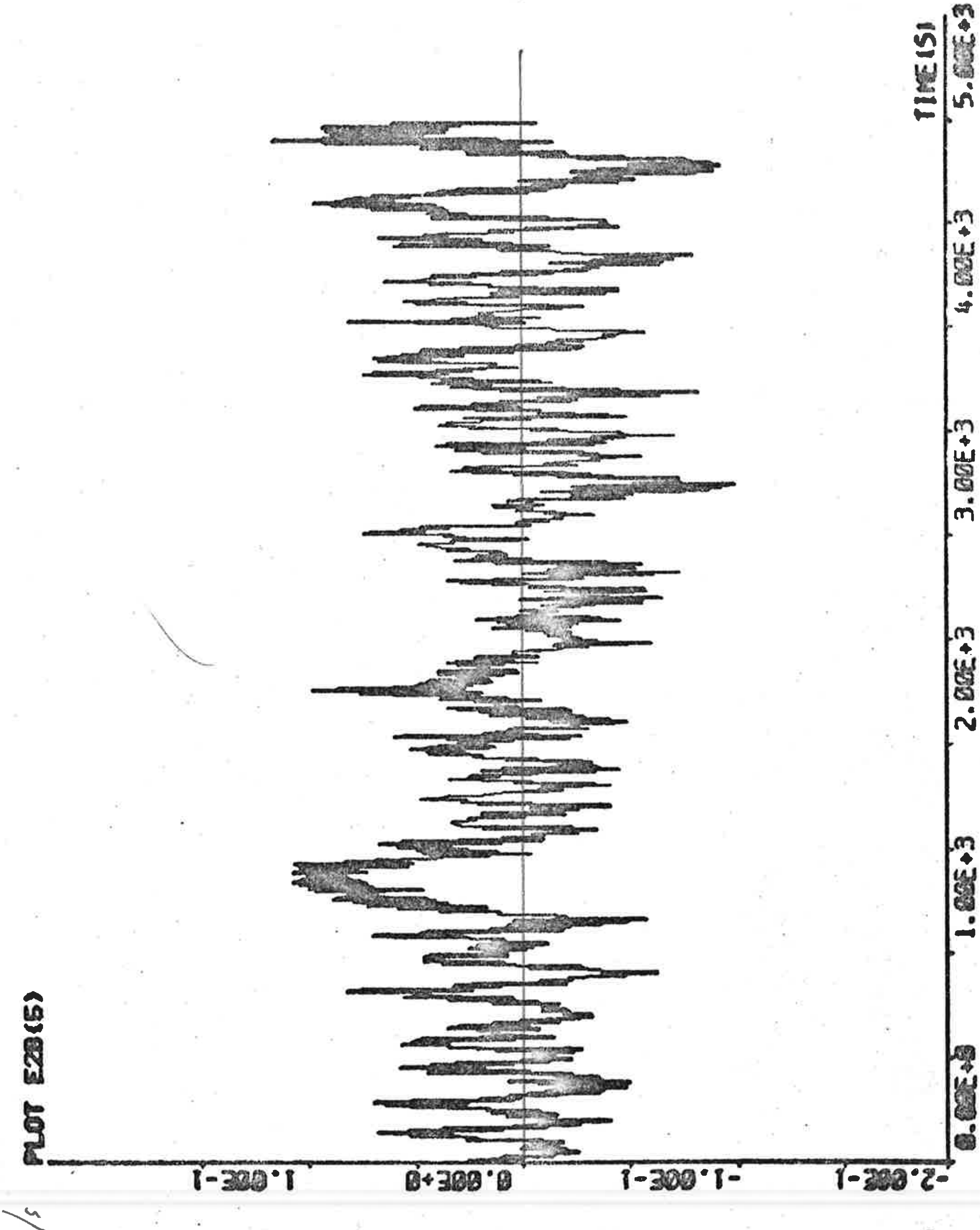

PLOT E28(2)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr


PLOT E2B(3)
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)
V_1 knots

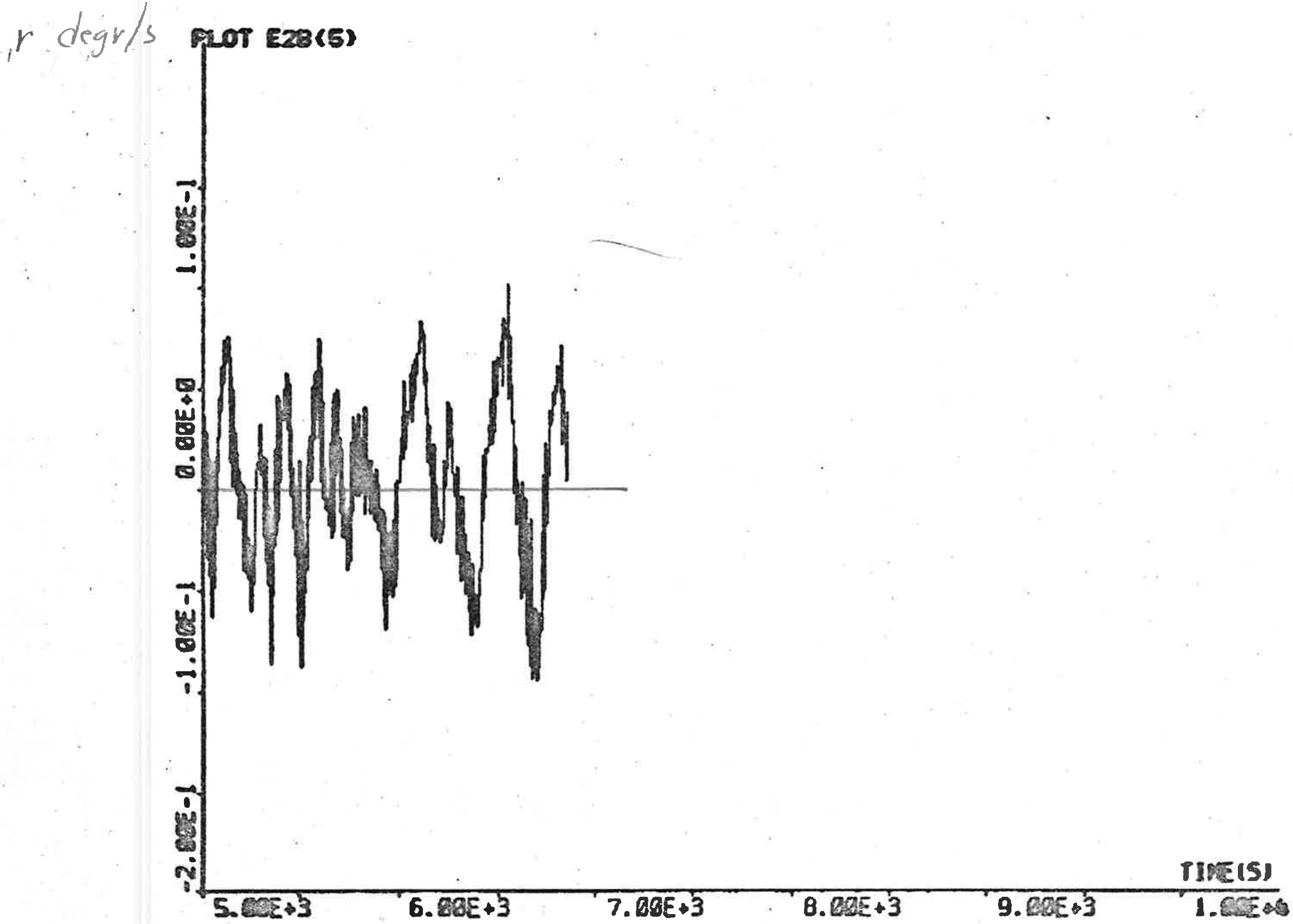

PLOT E2B(3)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
-1.00E+0
0.00E+0
1.00E+0
2.00E+0
V_1 knots

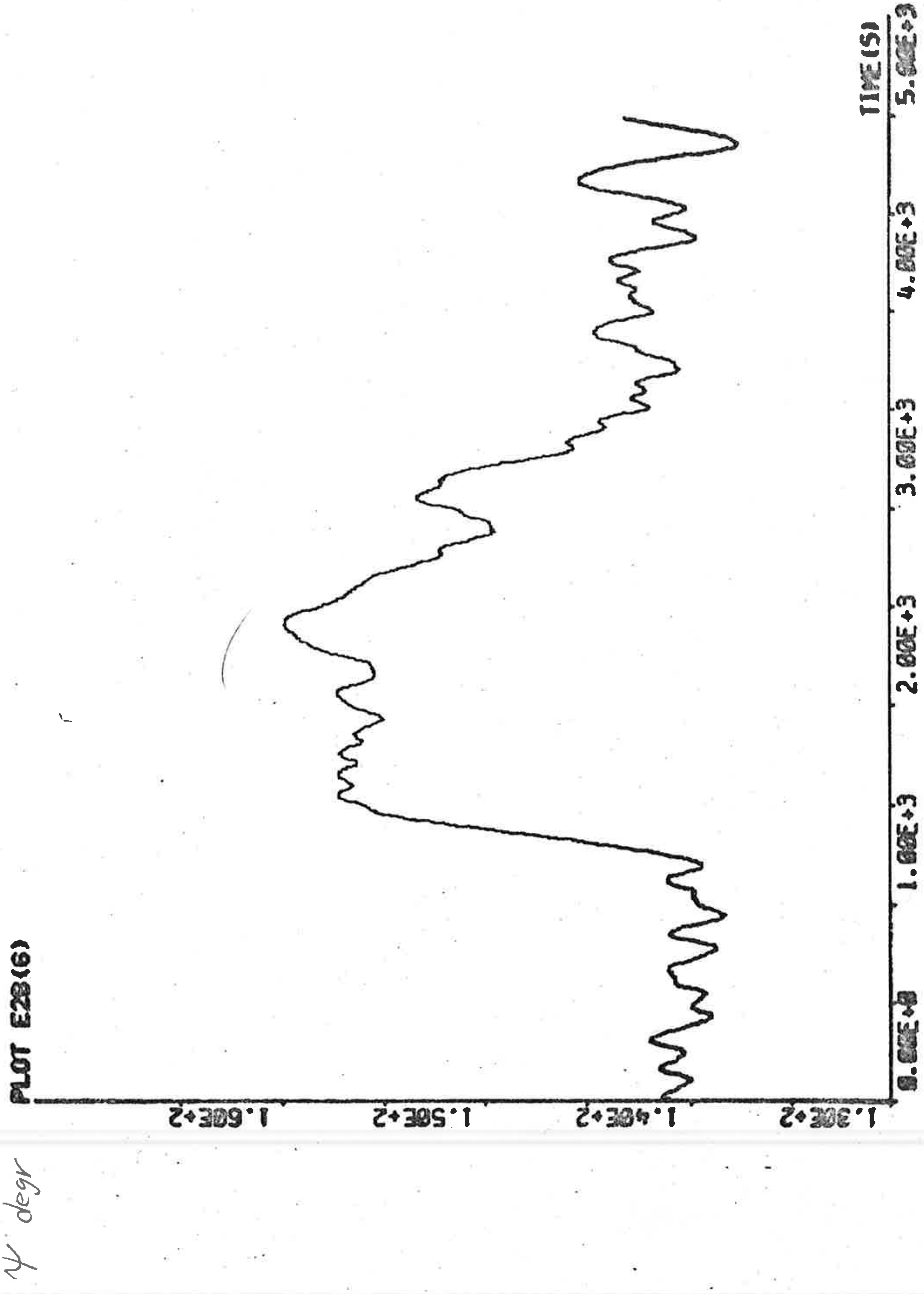

PLOT E2B(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
V_2 knots

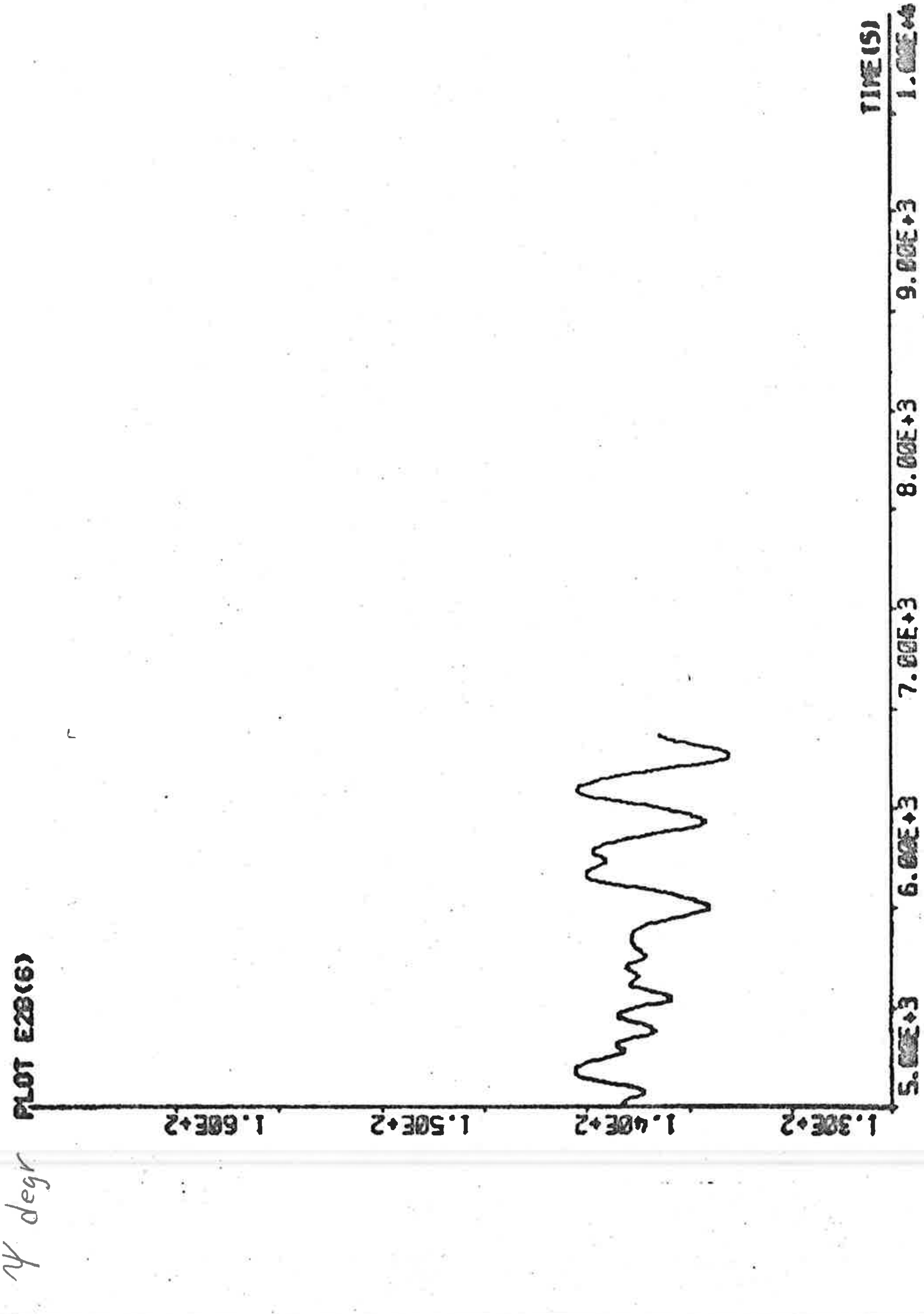

PLOT E2B(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)
V2 knots


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

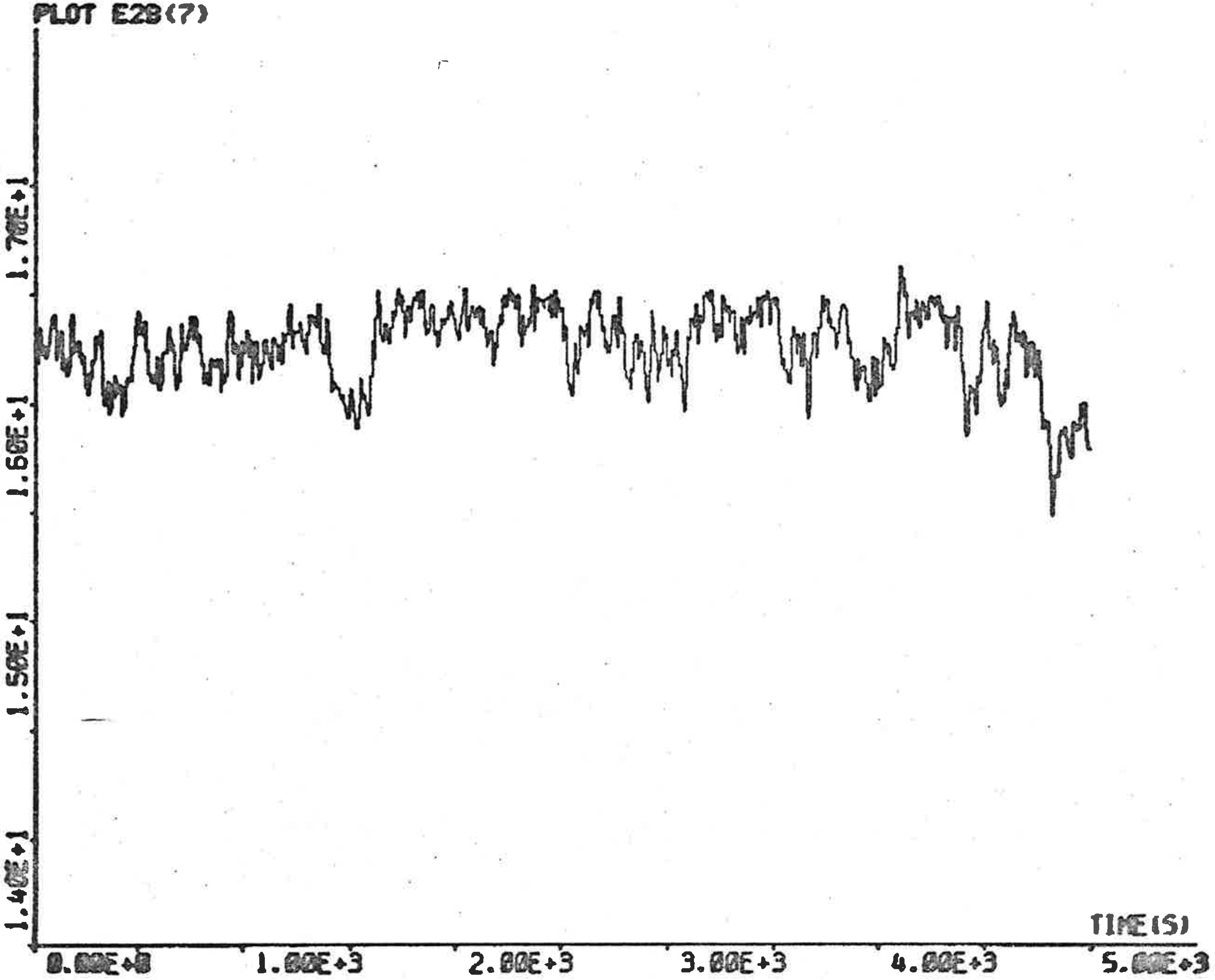
r degr/s

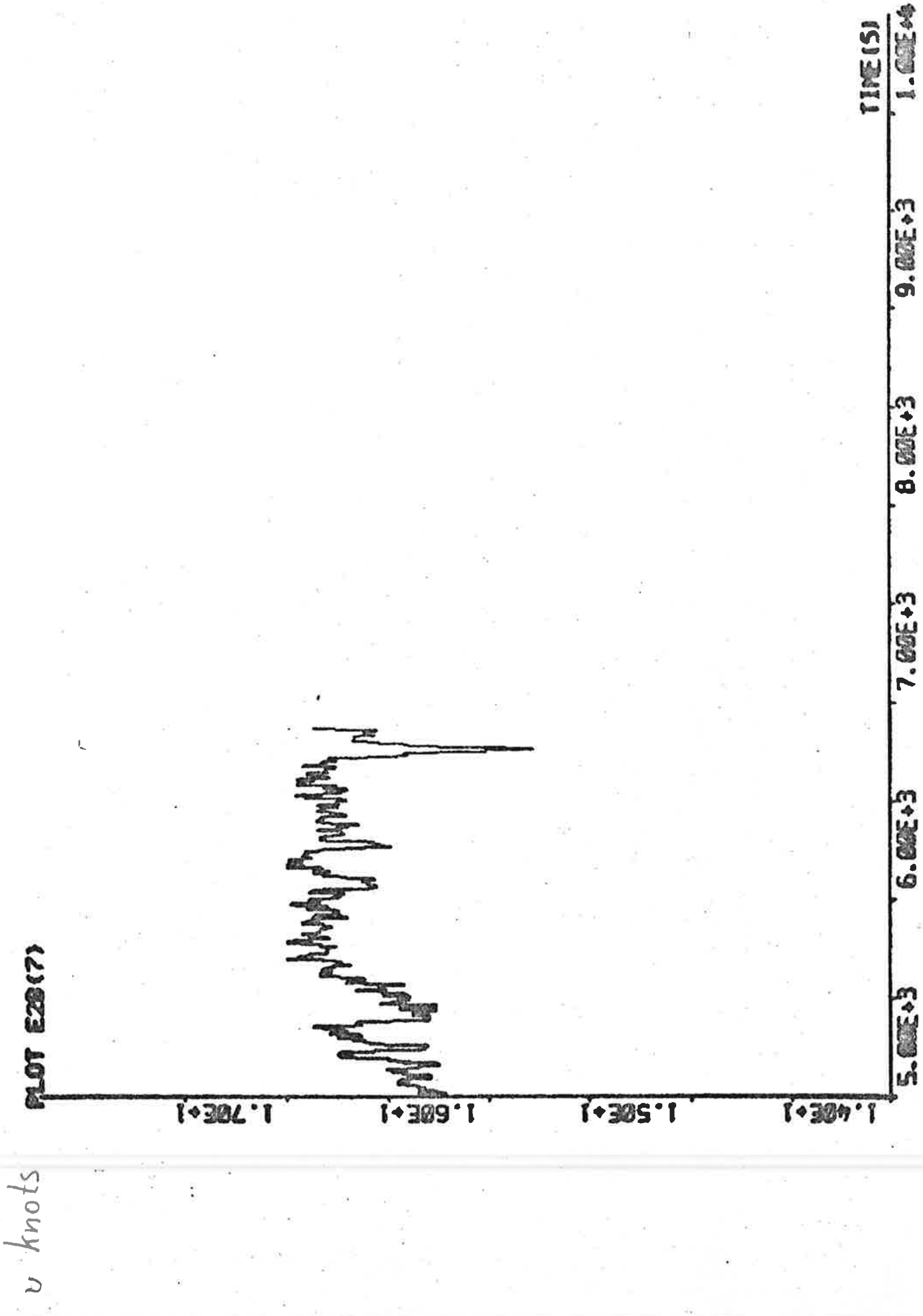

r degr/s
PLOT E28(5)
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4

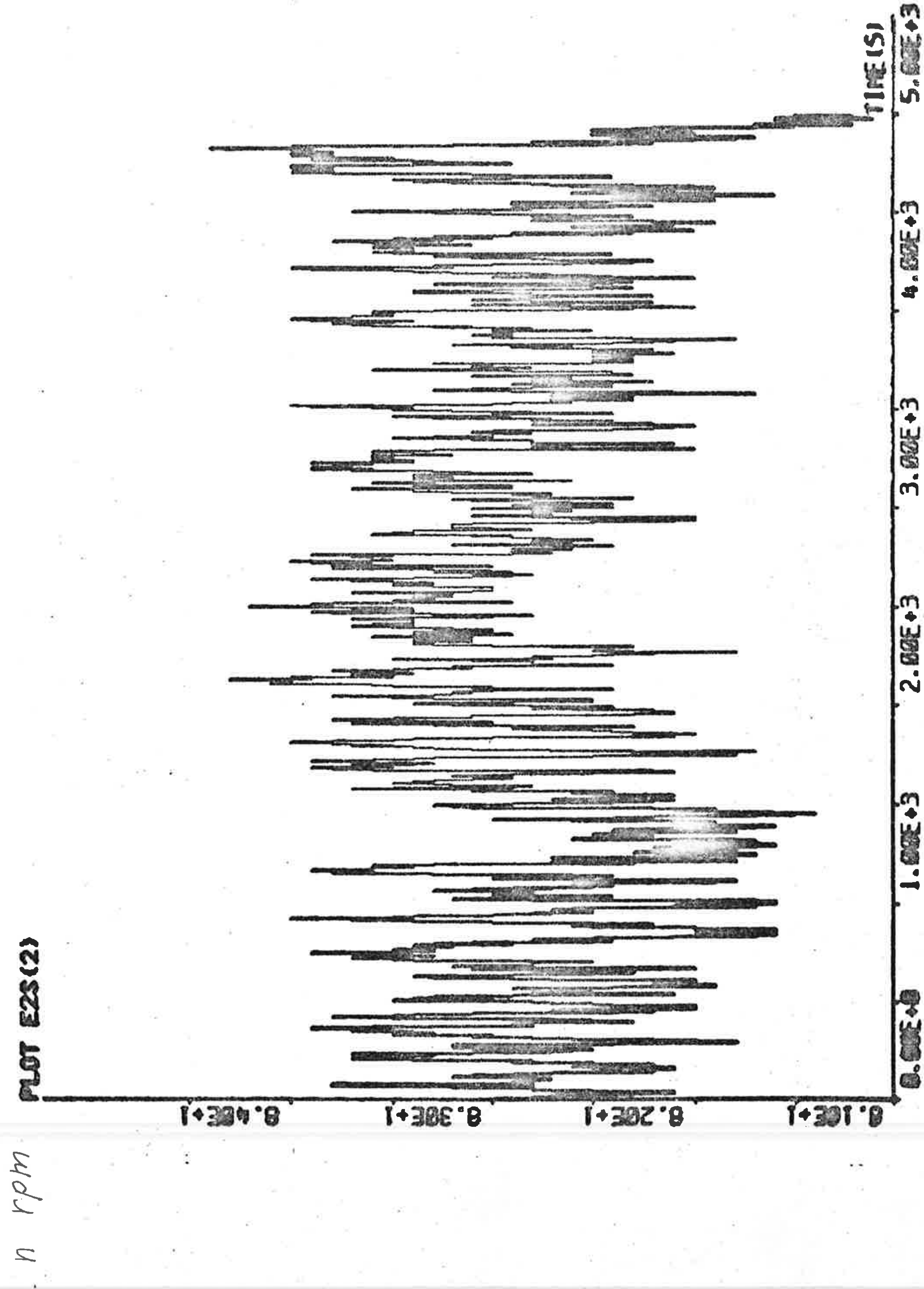

PLOT E28(6)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.30E+2
1.40E+2
1.50E+2
1.60E+2
ψ degr


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

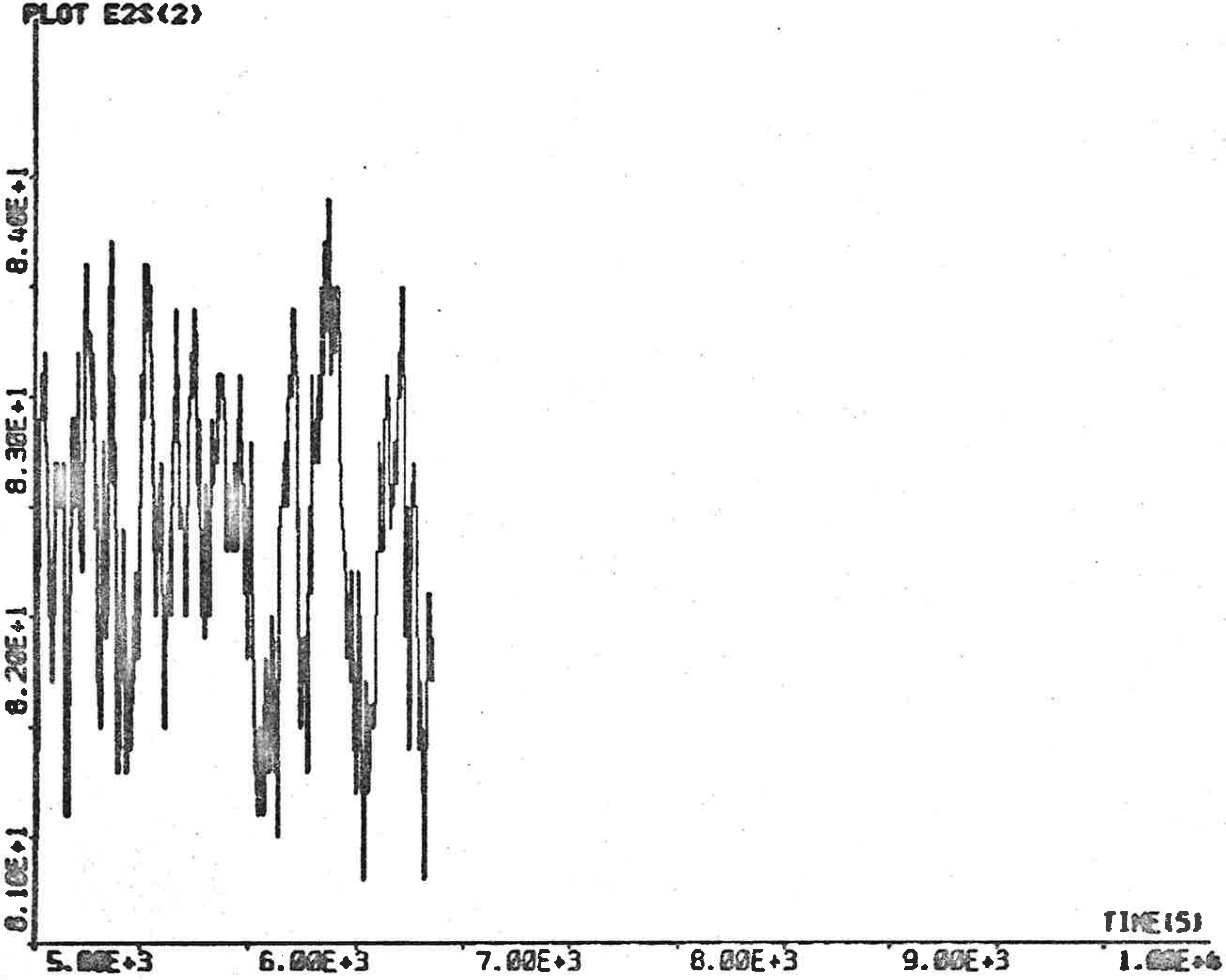
u knots


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


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


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

n rpm


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

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.

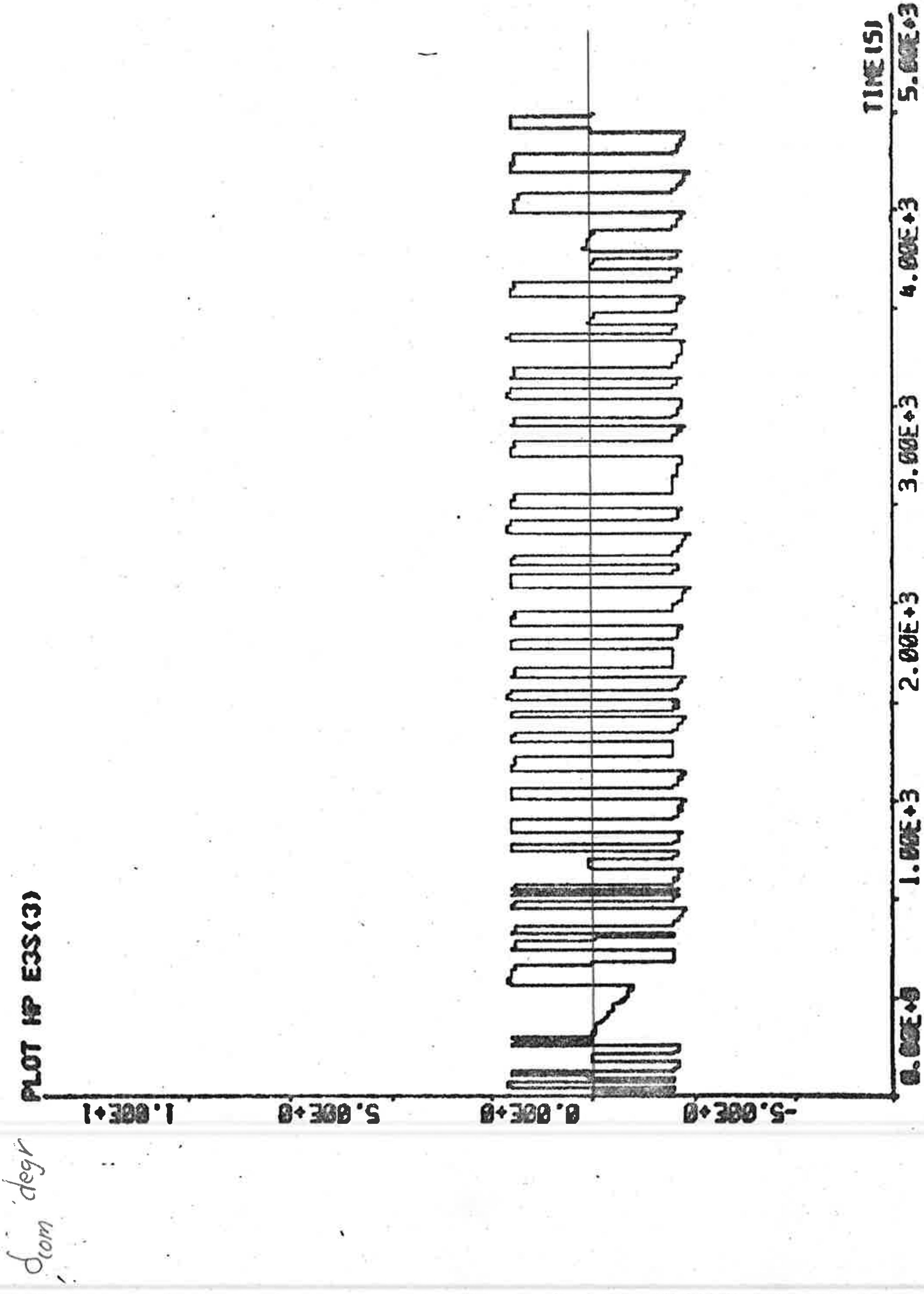
Calibration of the rudder servo:

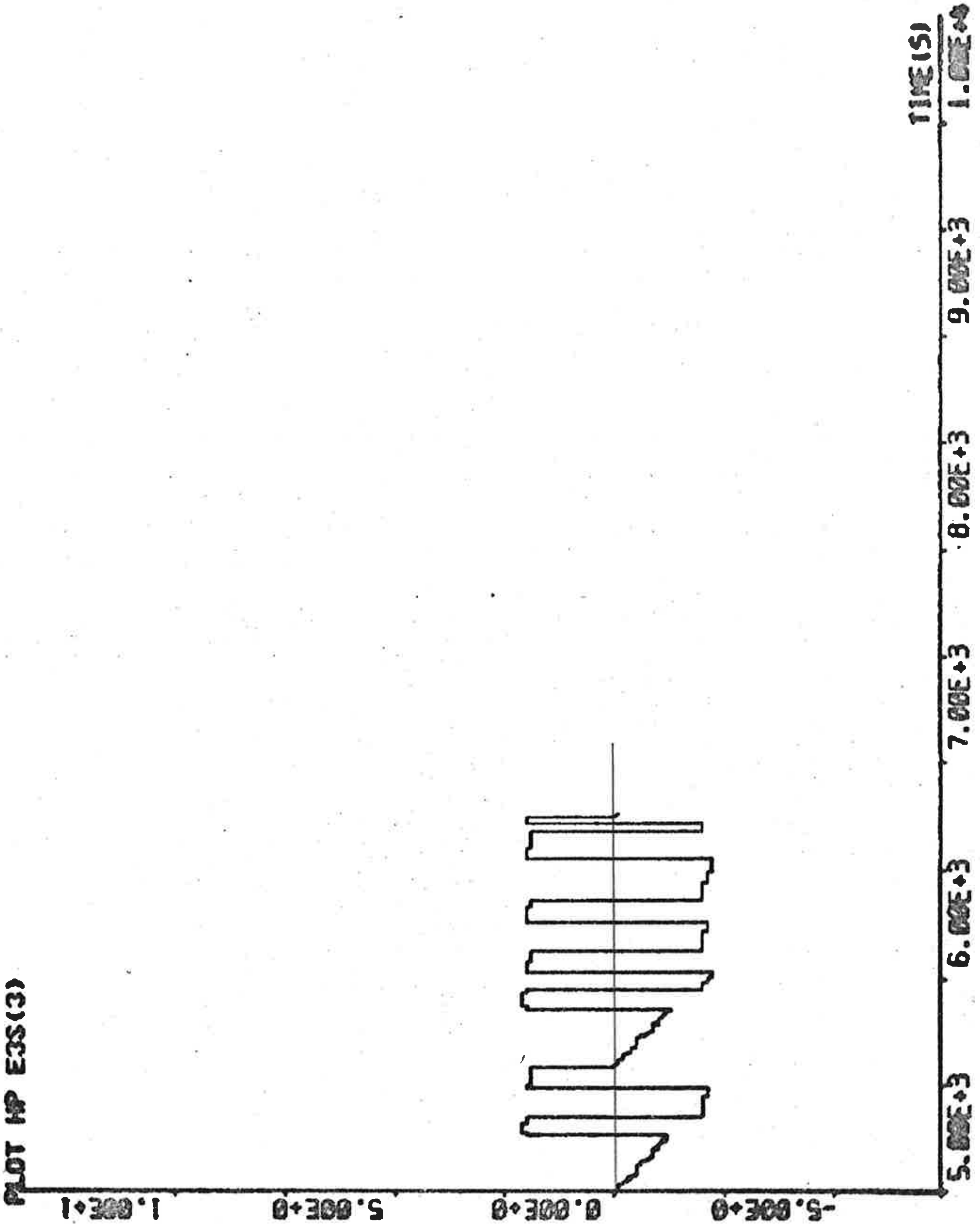
10 volts = 36.9°
-10 volts = -43.1°

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

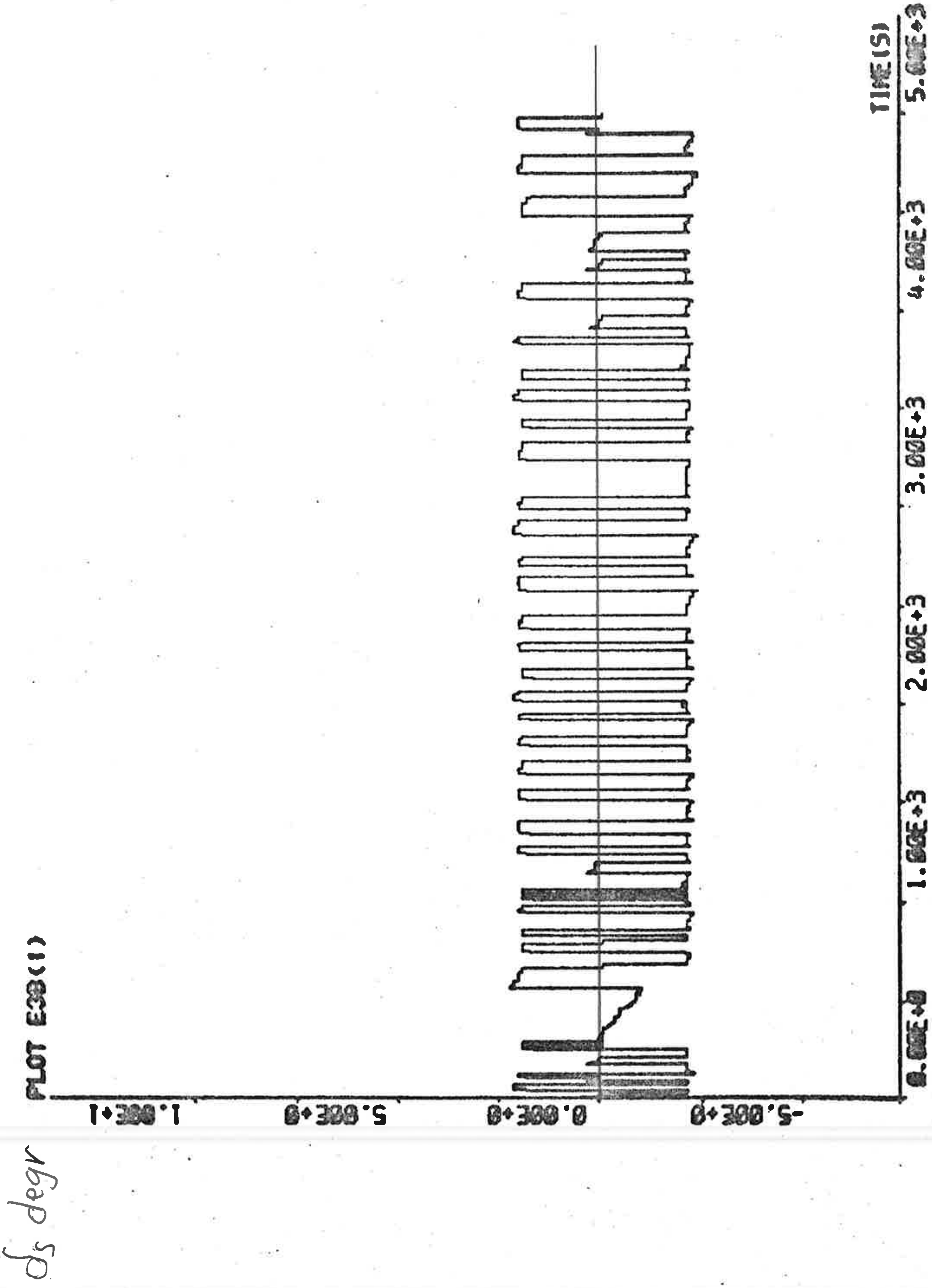
Statistics:

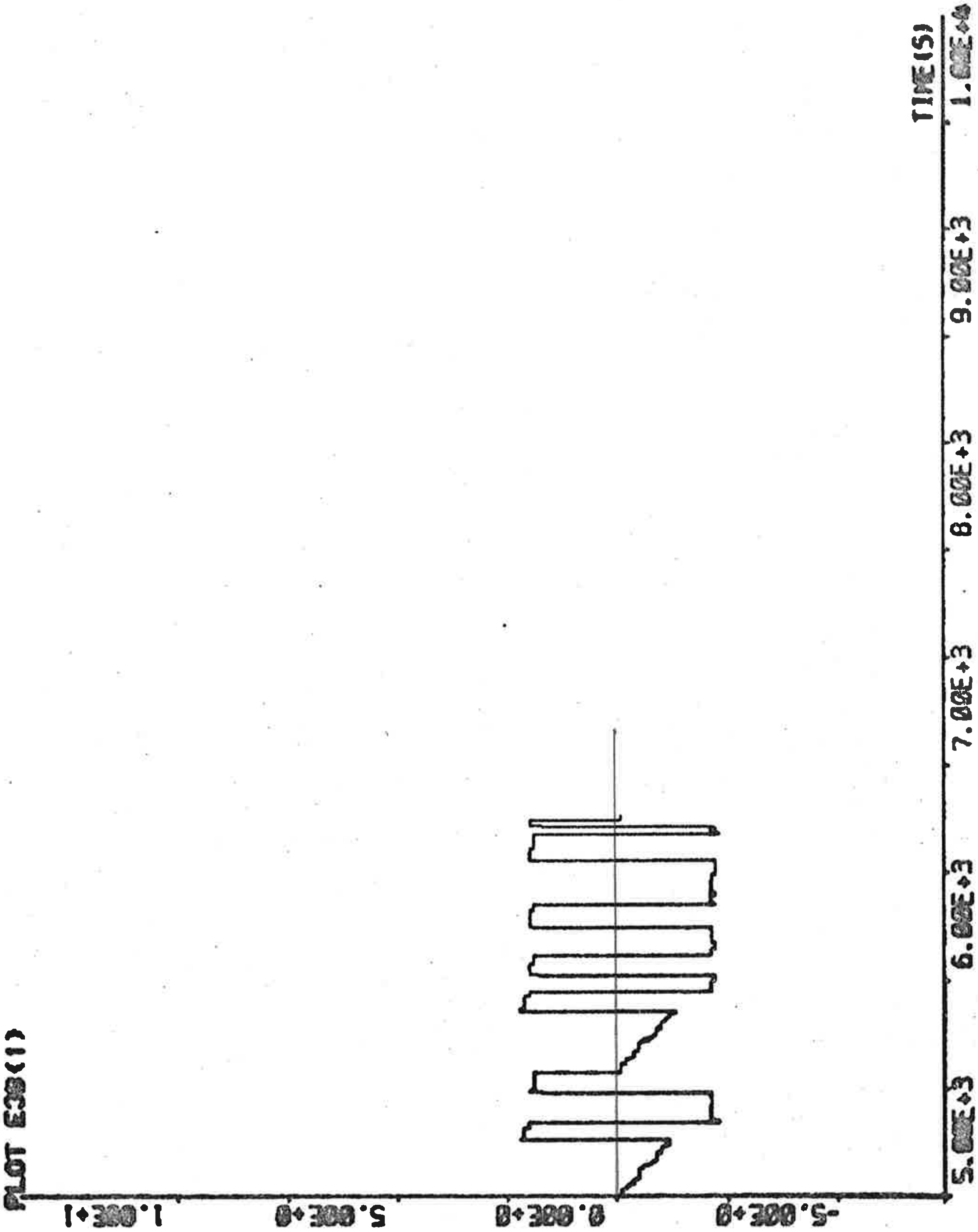
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.38	1.82	-2.4	2.1
δ_s degr	-0.40	1.84	-2.4	2.2
δ degr	-0.58	1.91	-2.8	2.6
v_1 knots	-0.677	0.156	-1.05	-0.25
v_2 knots	0.015	0.300	-0.99	0.77
r degr/s	0.0063	0.0372	-0.084	0.112
Ψ degr	142.136	1.838	137.20	147.57
u knots	16.816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


PLOT HP E3S(3)
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
δcom degr

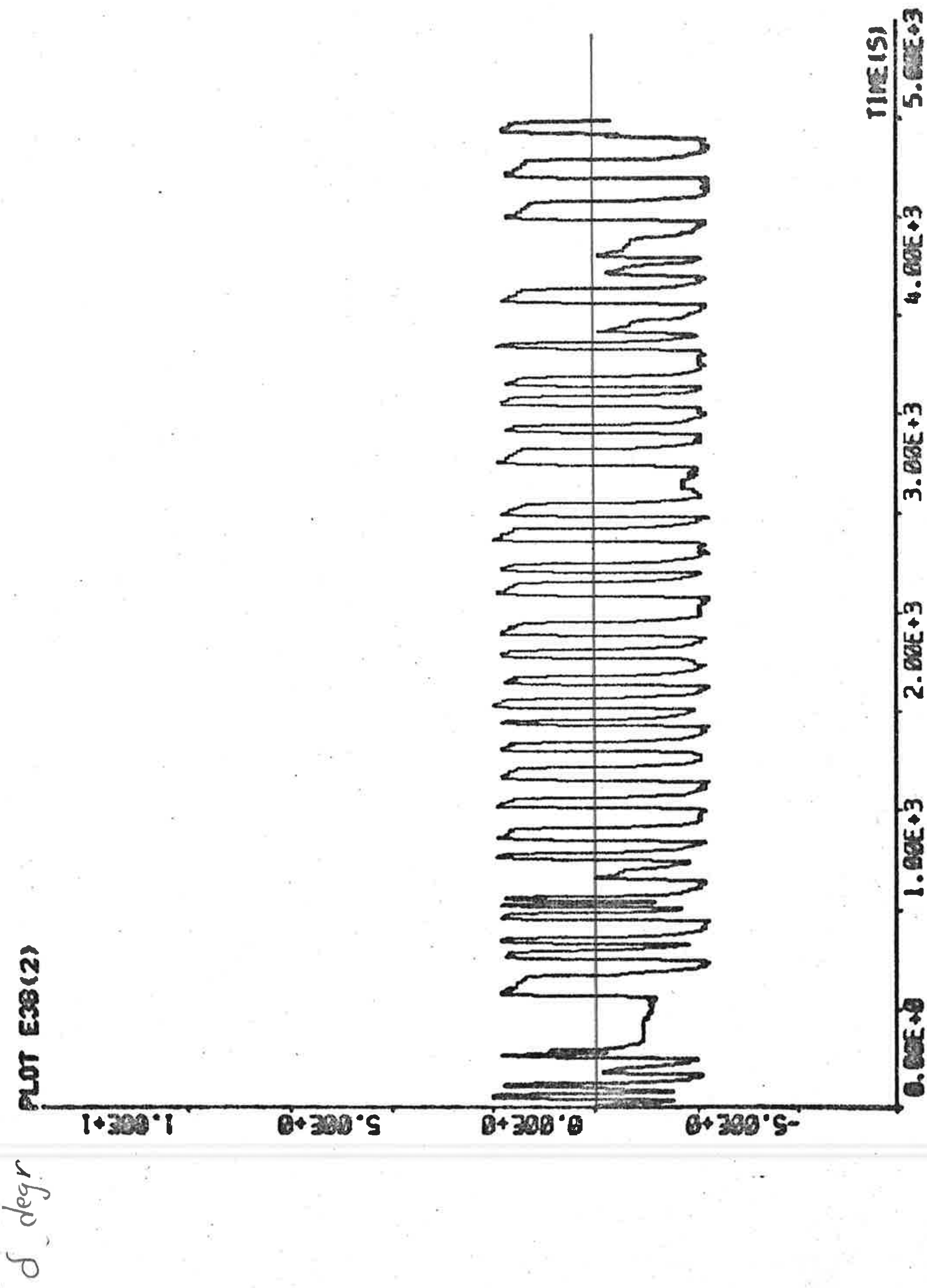


δ_{com} degr

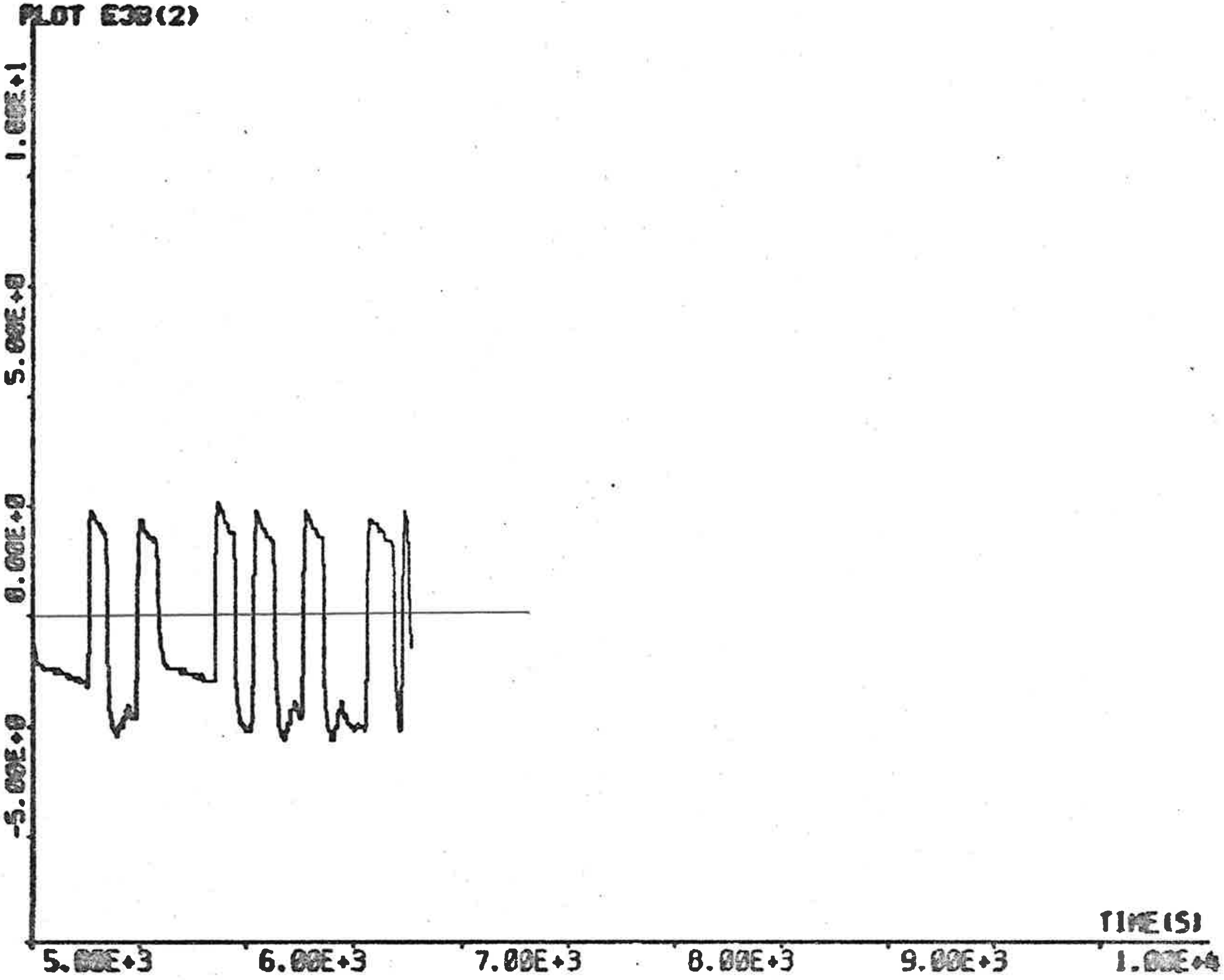

PLOT E3B(1)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
δs degr

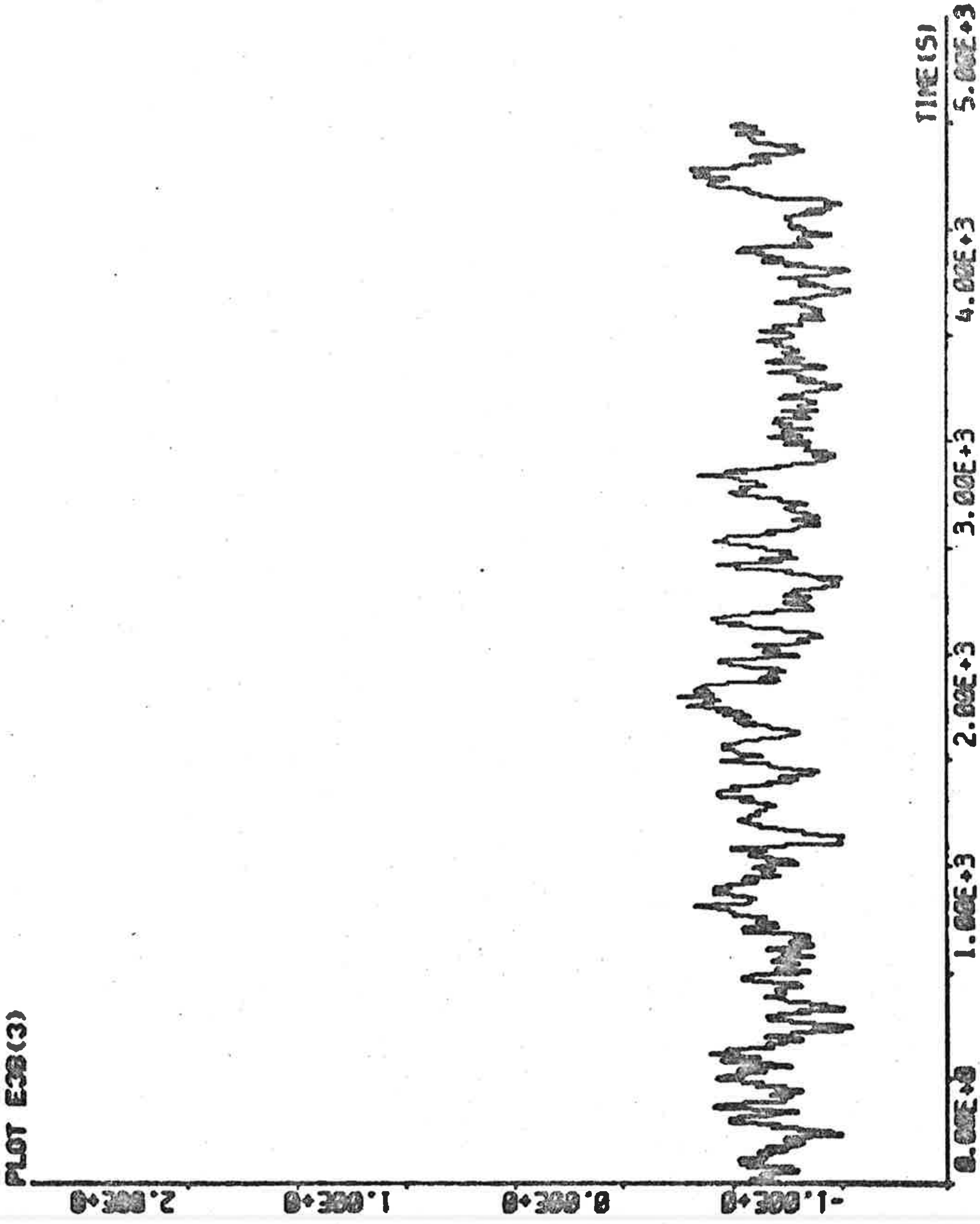

PLOT E3B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

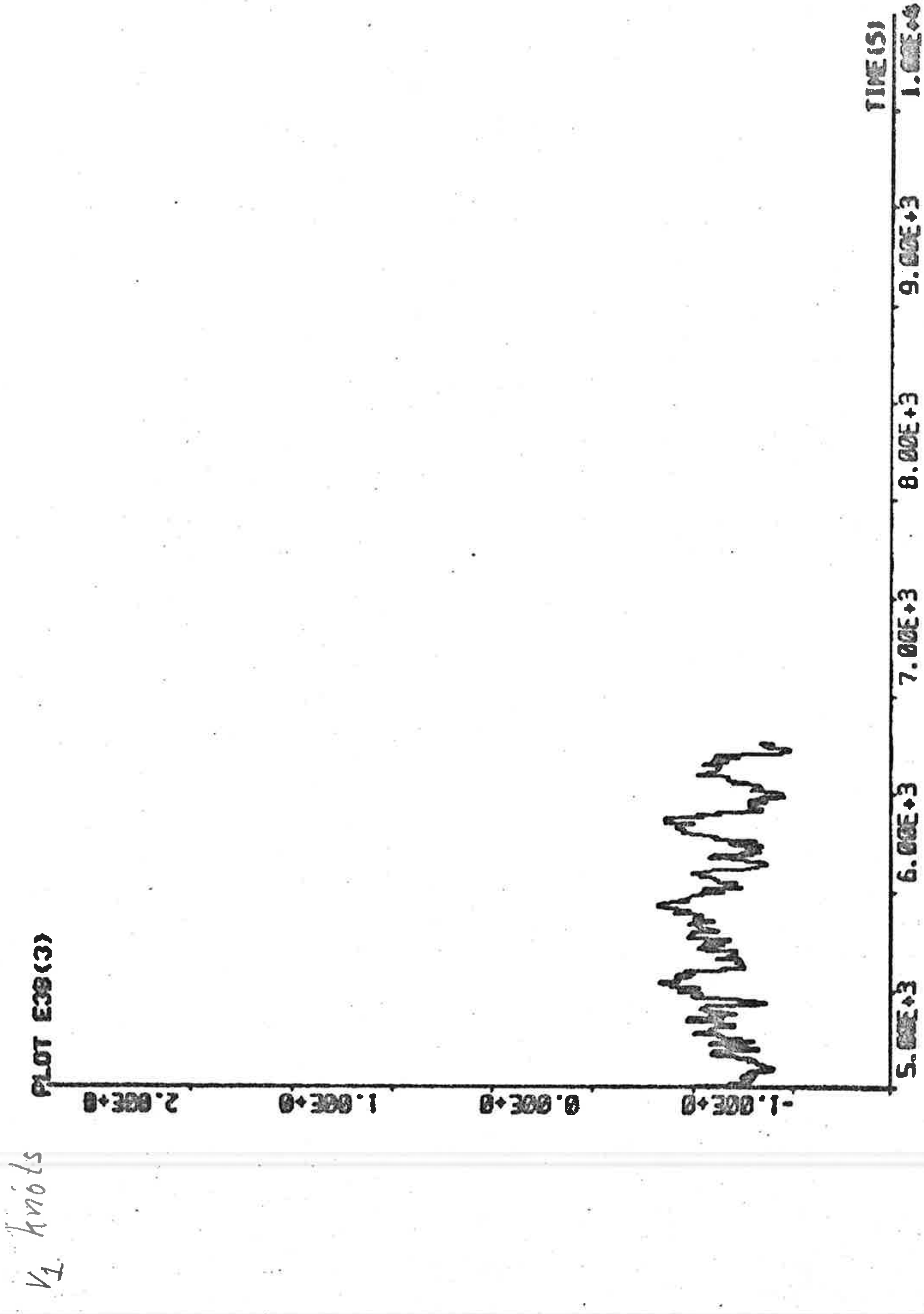
δ_s degr

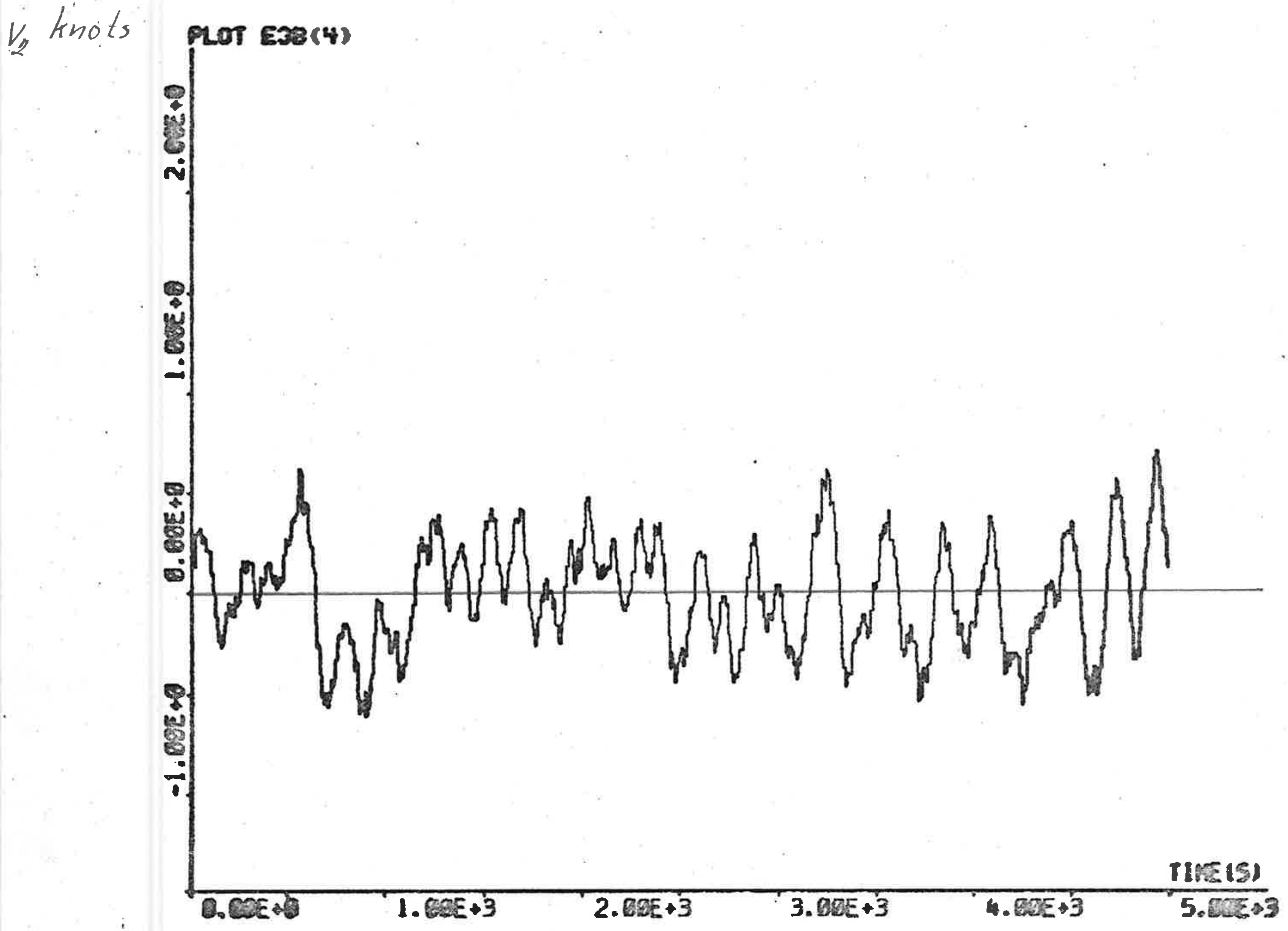

PLOT E3B(2)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr

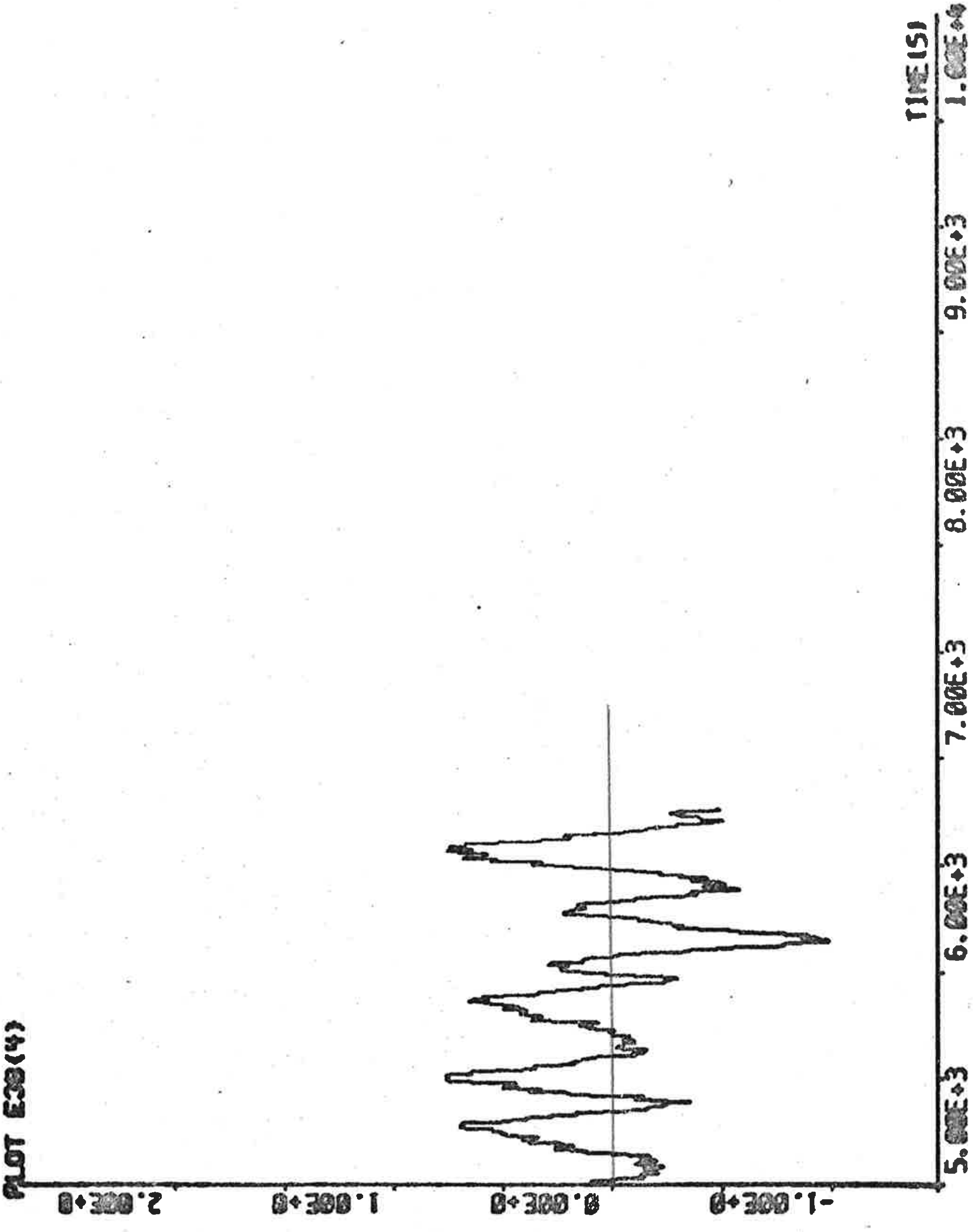
δ: degr


PLOT E3B(2)
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)

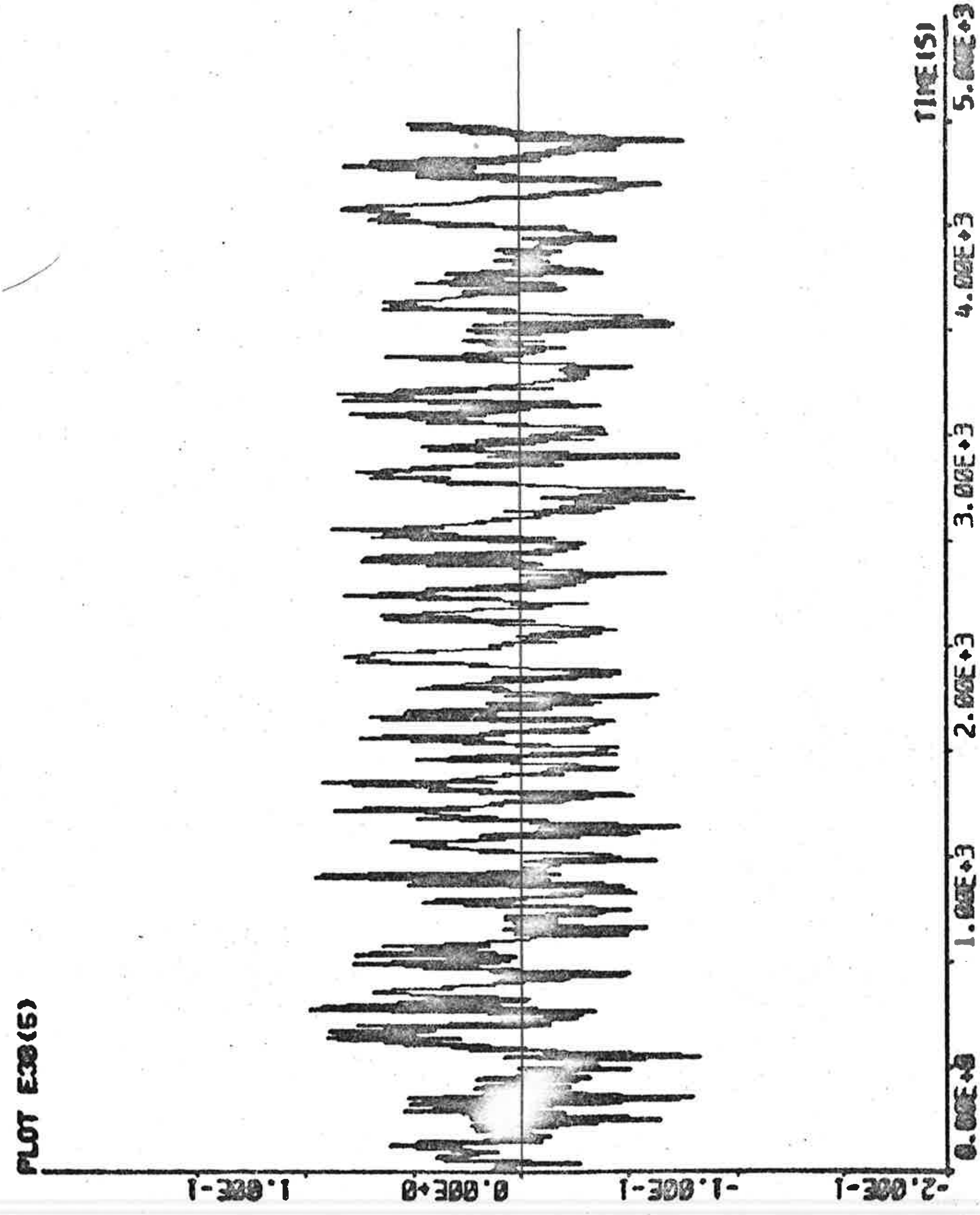

PLOT E3B(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)
V_1 knots


PLOT E38(3)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
V_1 knots

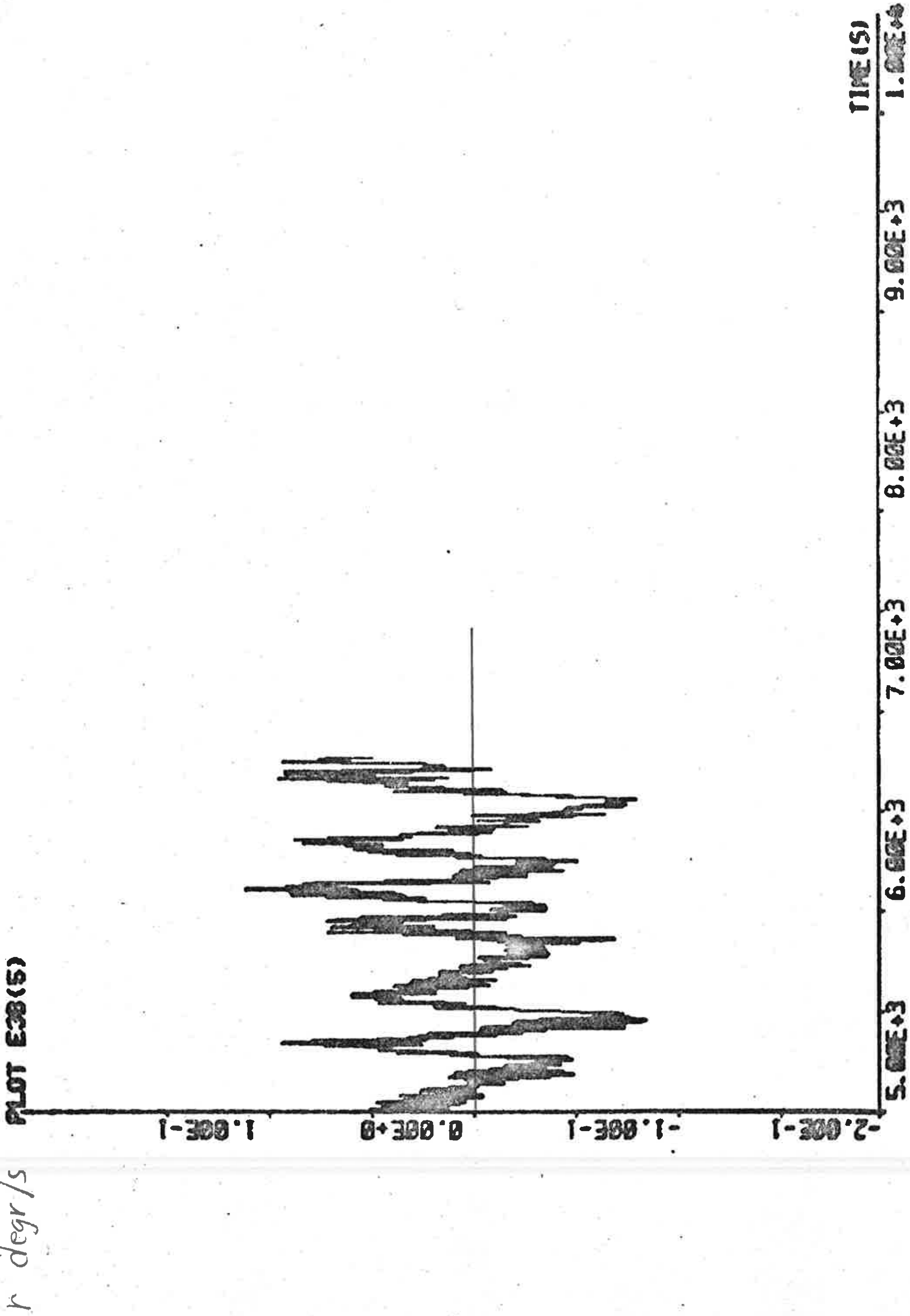

V_z knots
PLOT E38(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

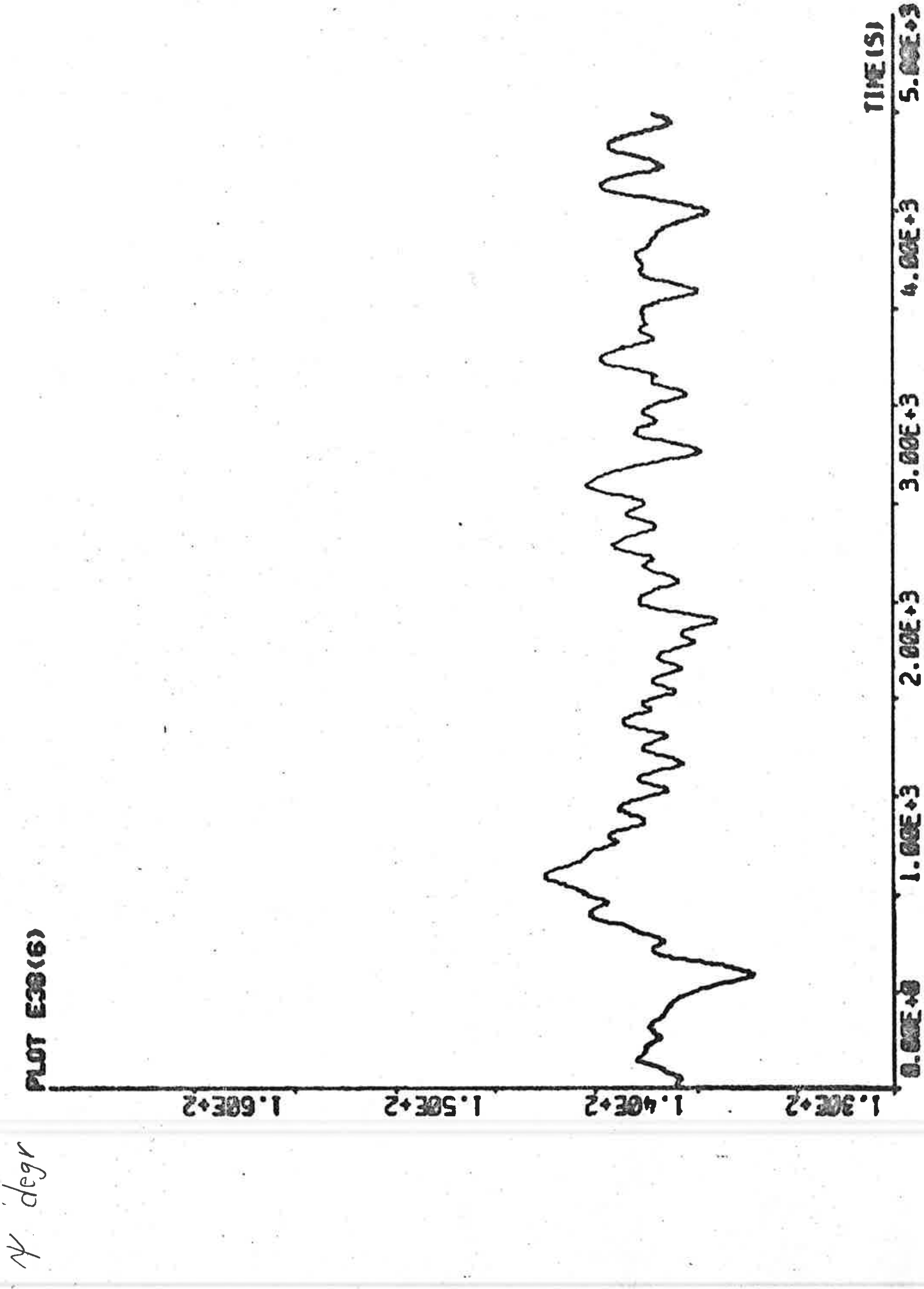

PLOT E38(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

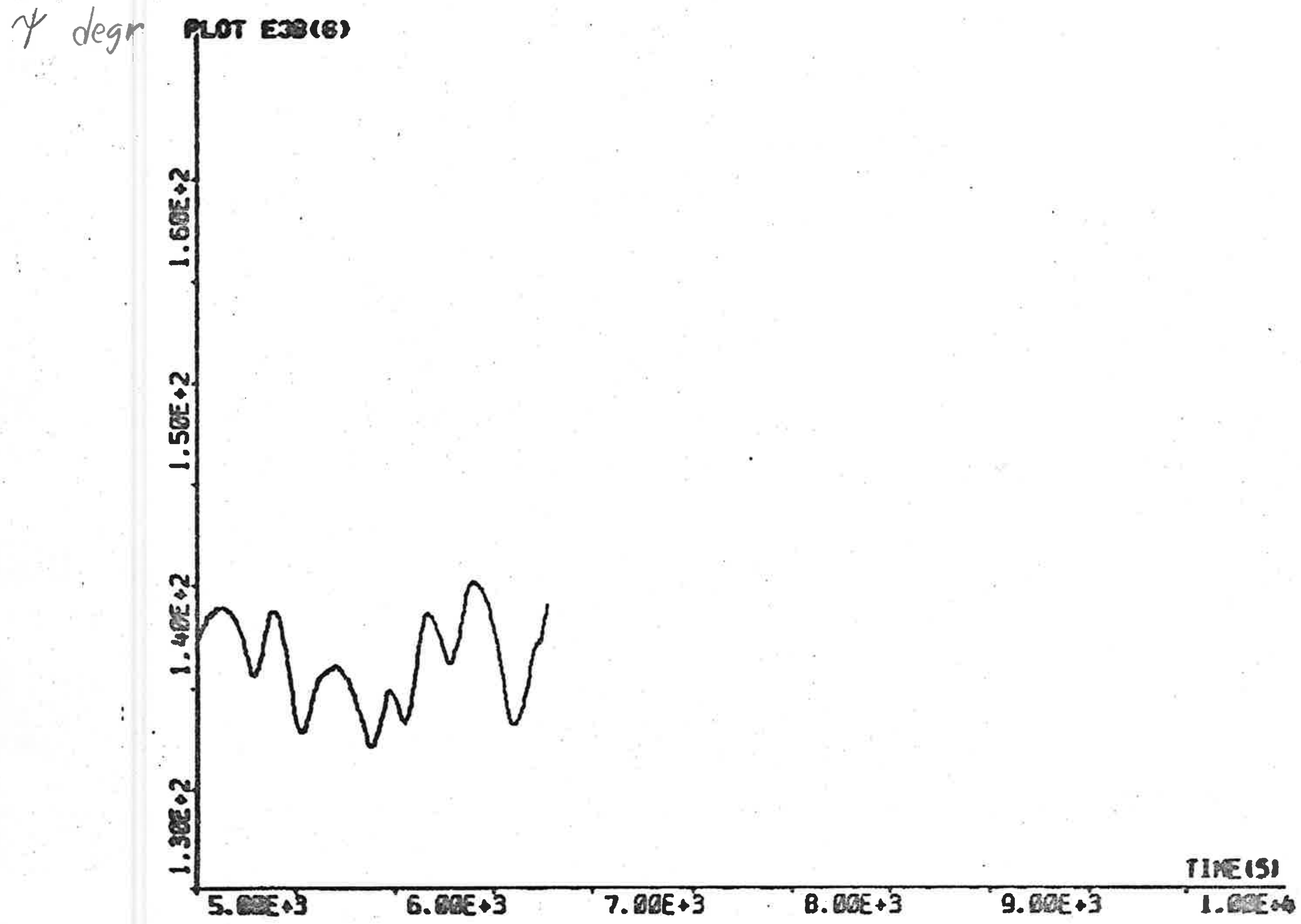
V_2 knots

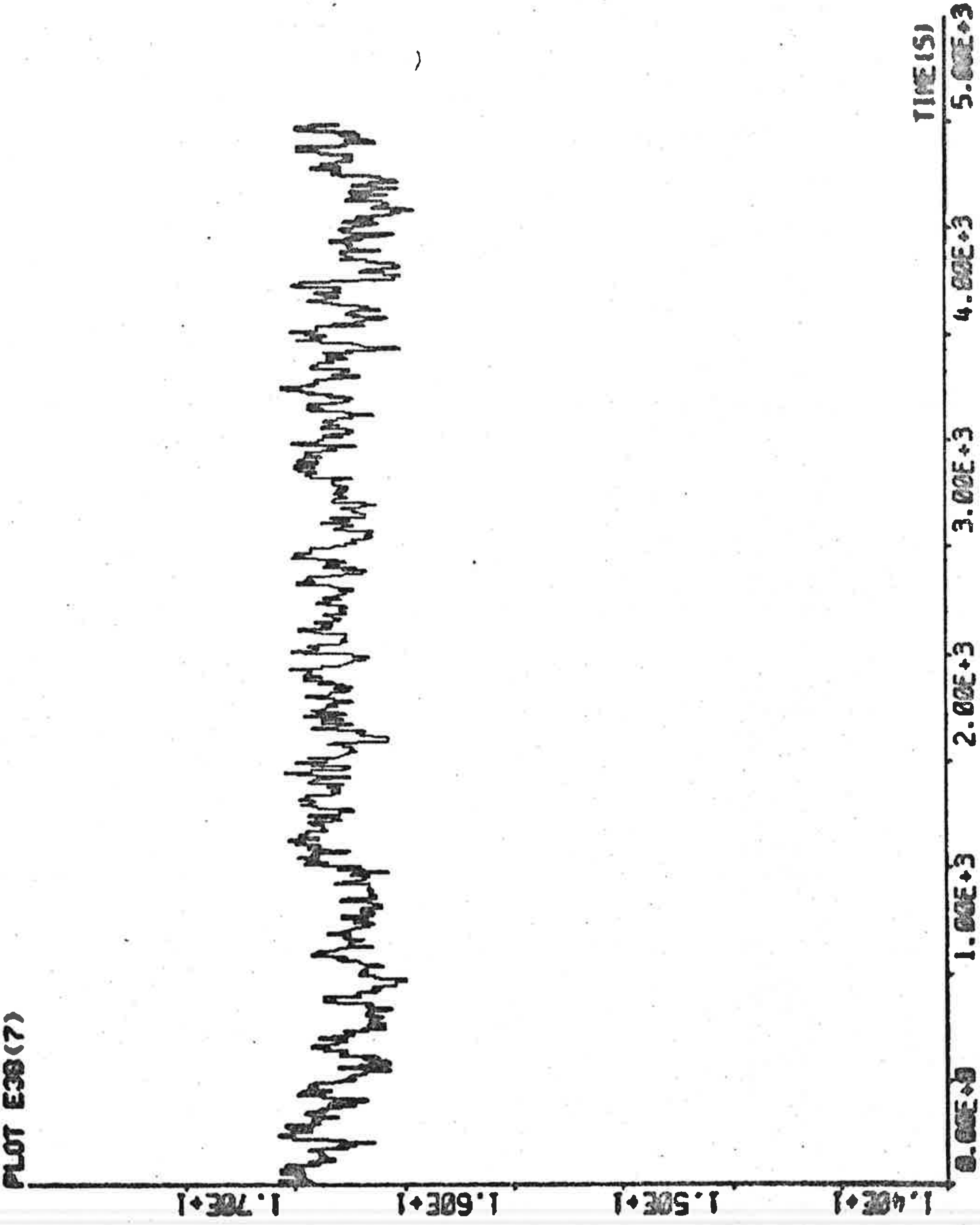

PLOT E30(5)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1

r degr/s

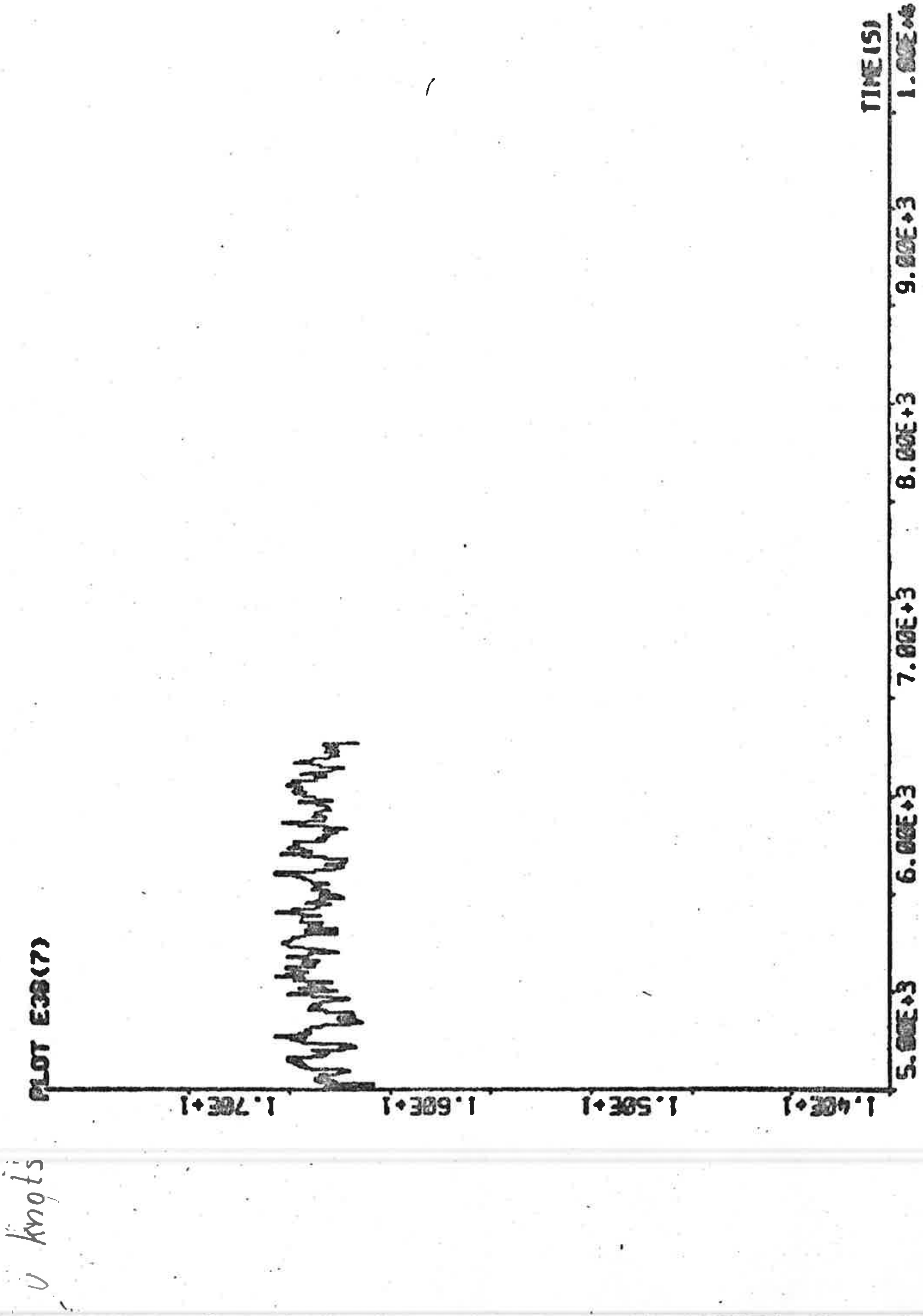

PLOT E3B(5)
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
r degr/s

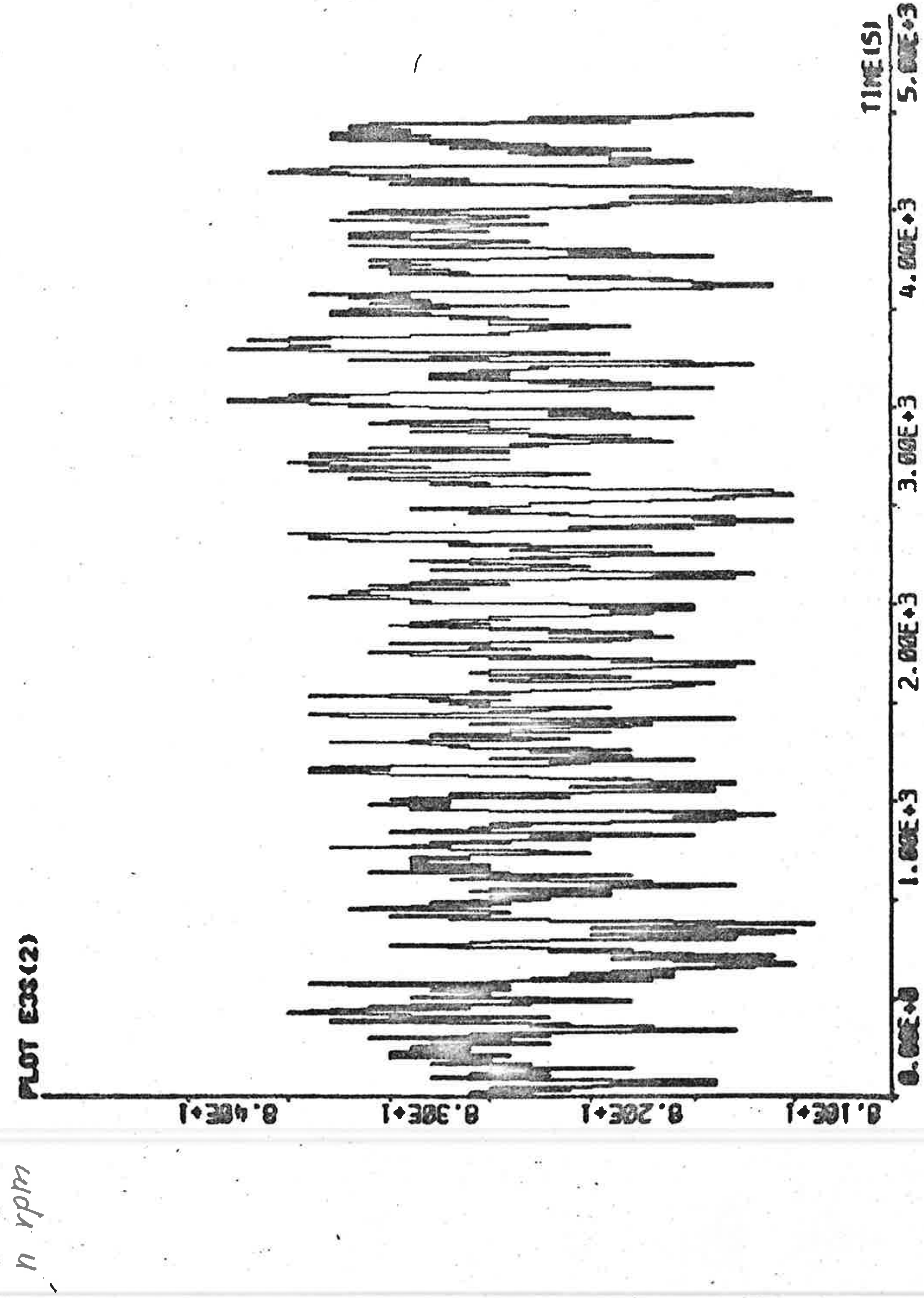

PLOT E38(6)
1.30E+2
1.40E+2
1.50E+2
1.60E+2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME (S)
ψ degr

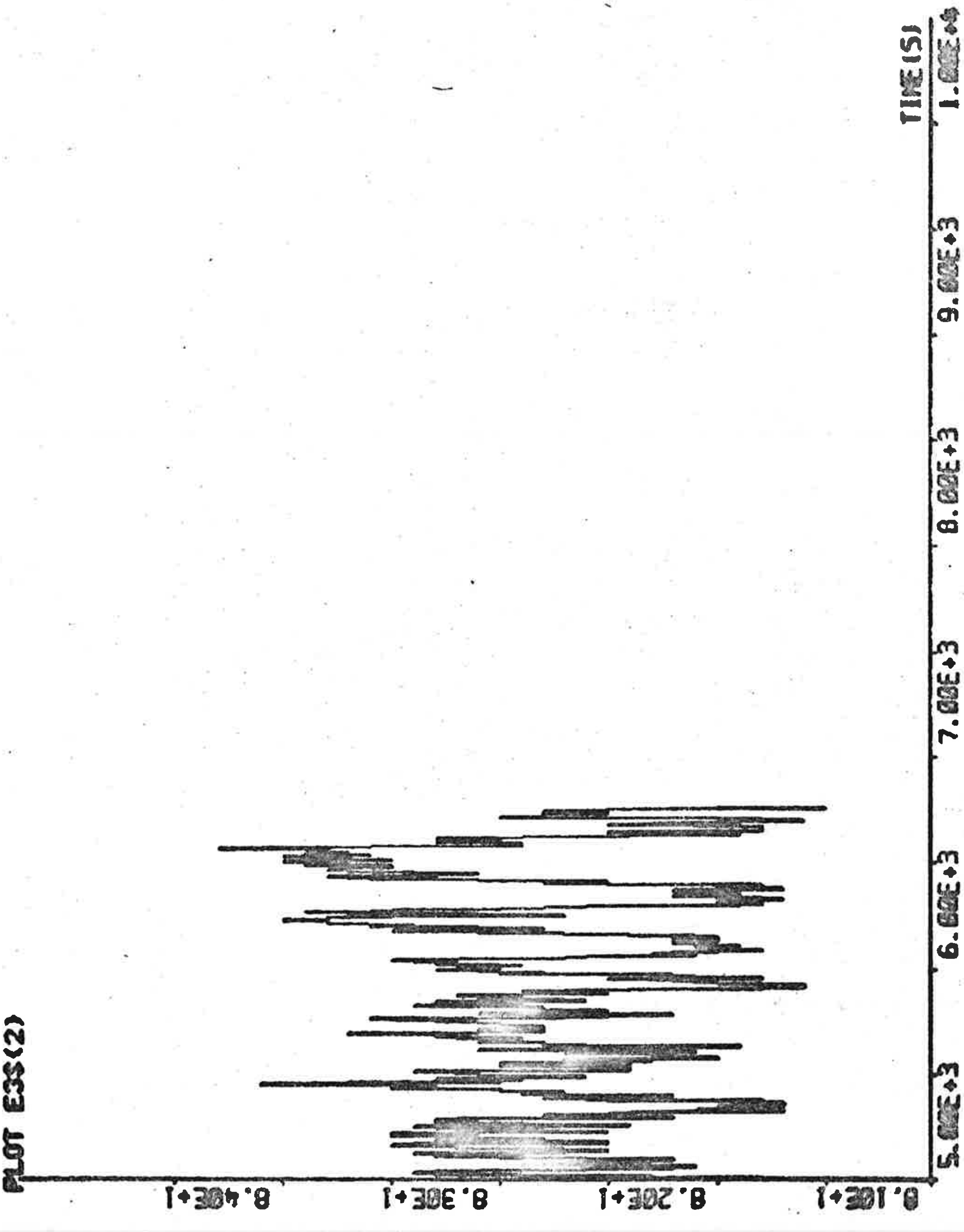

ψ degr
PLOT E33(6)
1.60E+2
1.50E+2
1.40E+2
1.30E+2
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4


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


PLOT E3S(2)
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
n rpm


PLOT E3S(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