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THE SEA SCOUT EXPERIMENTS, OCTOBER 1973

CLAES KÄLLSTRÖM

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

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Claes Källström

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1. INTRODUCTION

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

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

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

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

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

2. MEASUREMENT EQUIPMENT

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

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

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

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

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

3. THE AUTOPILOT

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

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

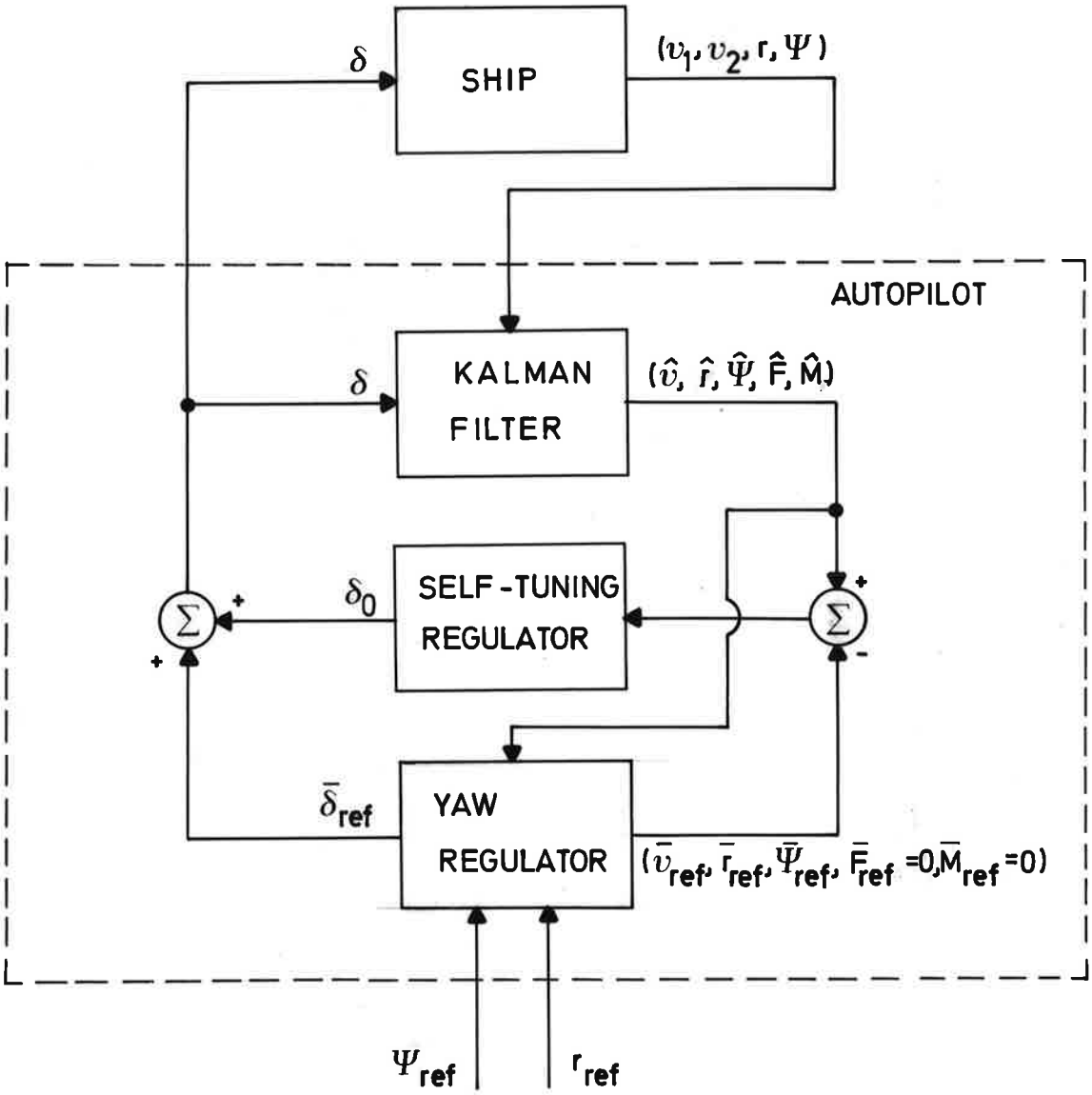

Fig. 3.1. Schematic diagram of the autopilot. r_{ref} is the reference value of the yaw angular velocity during the yaw. For course keeping only, $\bar{\delta}_{ref} = \bar{v}_{ref} = \bar{r}_{ref} = 0$ and $\bar{\Psi}_{ref} = \Psi_{ref}$.

3.1 The Kalman filter.

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

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

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

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

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

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))

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

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

$$\begin{aligned}\psi(t+1) - \psi(t) = {} & b_1\delta(t) + b_2\delta(t-1) + d_1v(t) + d_2r(t) + d_3F(t) + \\ & + d_4M(t) + e(t+1)\end{aligned} \tag{3.4}$$

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

$$\Sigma(\psi(t) - \bar{\psi}_{ref})^2 \tag{3.5}$$

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

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

$$+ d_3 F(t) + d_4 M(t)] \qquad (3.6)$$

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

$$\Psi(t+3) - \Psi(t) = b_1\delta(t) + b_2\delta(t-1) + d_1 v(t) + d_2 r(t) + d_3 F(t) +$$

$$+ d_4 M(t) + e(t+3) \qquad (3.8)$$

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 sta-

tionary 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.

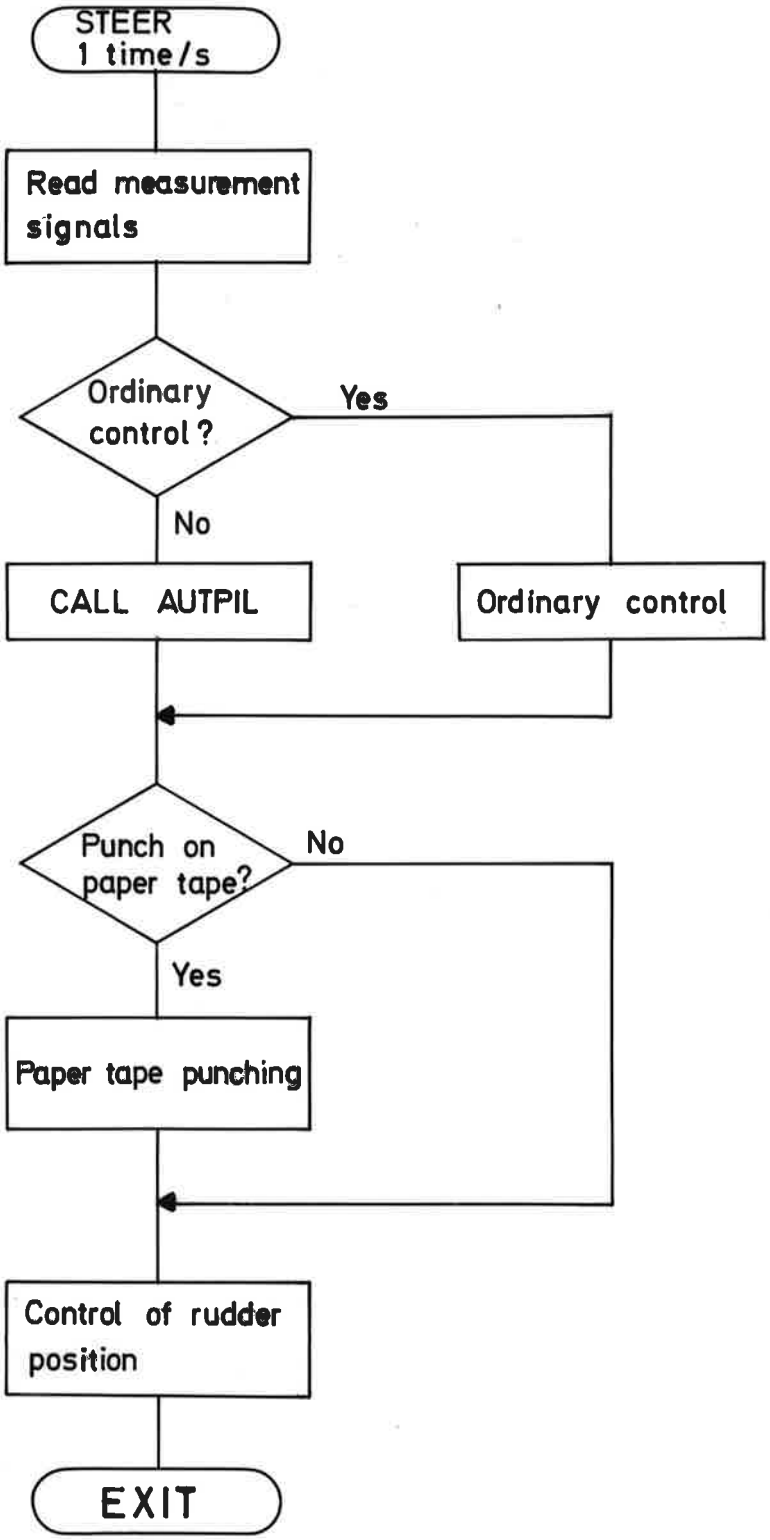

Fig. 4.1. Flow chart of the real time program STEER. The subroutine AUTPIL is the administration routine for the experiments.

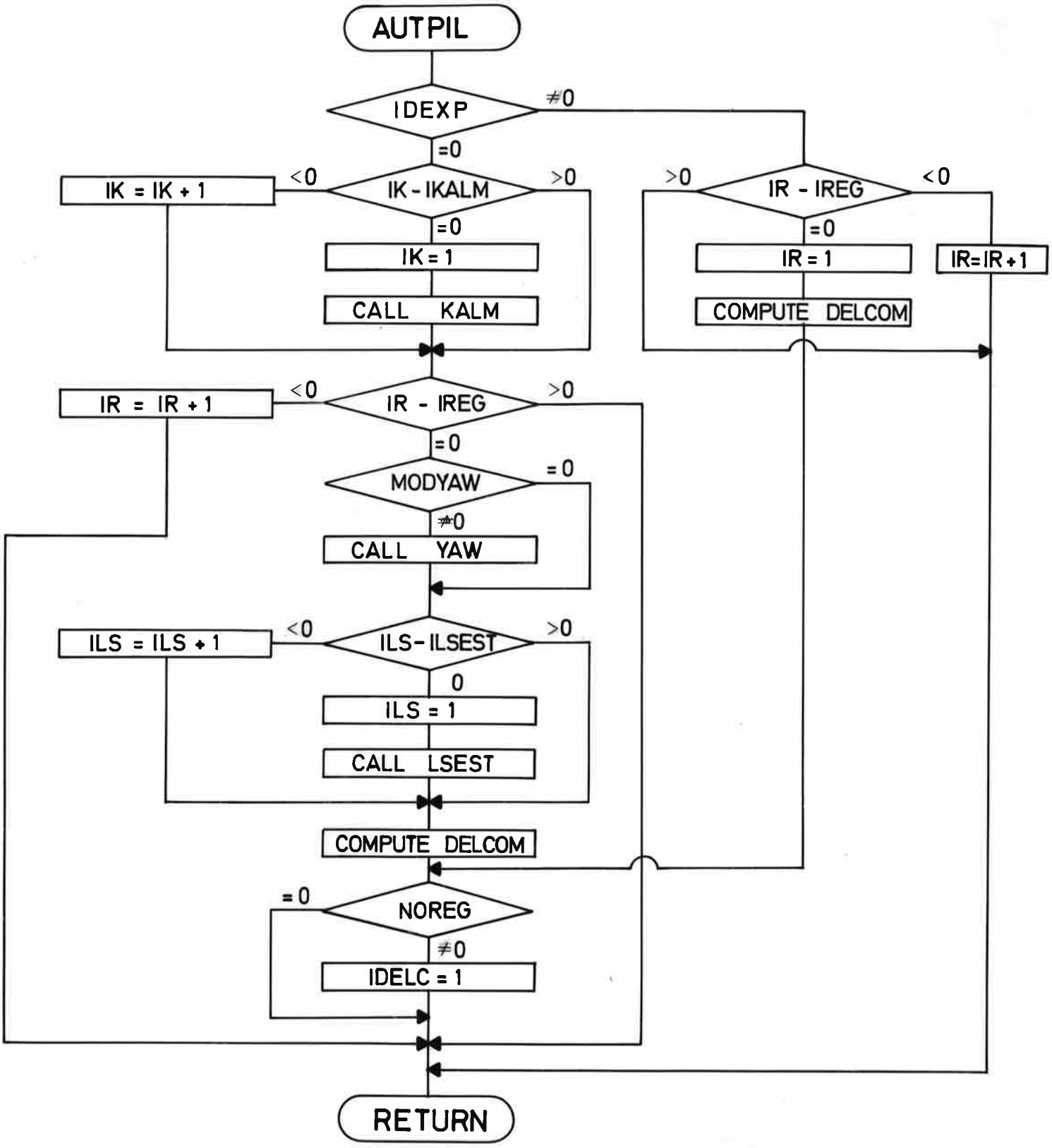

Fig. 4.2. Flow chart of subroutine AUTPIL.

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°.

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

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

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

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

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

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

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

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

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

6. CONCLUSIONS

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

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

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

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

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

ACKNOWLEDGEMENTS

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

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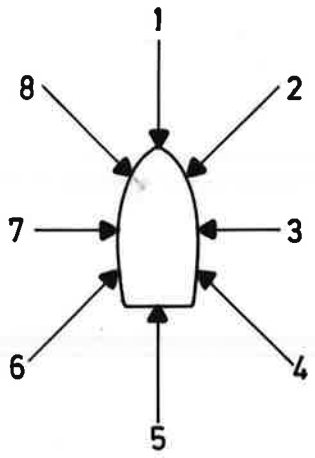
APPENDIX A

NOTATIONS

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

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

The wind direction related to the ship is expressed as:



```
001           SUBROUTINE AUTPIL
002     C
003     C     ADMINISTRATION SUBROUTINE FOR CONTROL
004     C     OF A SHIP.
005     C     REGULATOR 1.
006     C
007     C     AUTHOR, C.KALLSTROM 1973-09-22.
008     C
009     C     SUBROUTINE REQUIRED
010     C           KALM
011     C           YAW
012     C           LSEST
013     C
014           COMMON/DATA/ IDUM1(4),DELTA,Z(4),IDUM2(9),PSIREF,
015          1MODYAW,RREF,ISTBD,IPORT,IDELC,DELCOM,X(5),TH(6),
016          2REF(4),IFLAG,INAUT,IP,IPRINT,IDEXP,IR,IREG,NOREG,
017          3DELAMP,IK,IKALM,NX,NY,XKAL(5),IDUM3(258),AM(5,4),
018          4AXKAL(5,5),PSIMAX,PSIRFO,PSIDIF,IYAW,IDUM4(3),RL,RL1,
019          5IDUM5(162),ILS,ILSEST,PSIERR,VAL(7),IDUM6(93),S1,
020          6IDUM7(9)
021     C
022     C     INITIALIZING IF INAUT=1.
023     C
024           IF(INAUT) 20,20,10
025     10    INAUT=0
026           PSIRFO=PSIREF
027           IYAW=0
028           RL=RL1
029           DO 12 I=1,7
030     12    VAL(I)=0.
031           REF(1)=0.
032           REF(2)=0.
033           REF(3)=PSIREF
034           REF(4)=0.
035     C
036     C     IF IDEXP=1, COMPUTE DELCOM FOR IDENTIFICATION
037     C     EXPERIMENT.
038     C
039     20    IF(IDEXP) 40,40,22
040     22    IF(IR-IREG) 36,24,999
041     24    IR=1
042           IF(ISTBD+IPORT-1) 34,26,32
043     26    IF(ISTBD) 30,30,28
044     28    DELCOM=DELAMP
045           GO TO 34
046     30    DELCOM=-DELAMP
047           GO TO 34
048     32    DELCOM=0.
049     34    ISTBD=0
050           IPORT=0
051           GO TO 990
052     C
053     36    IR=IR+1
054           GO TO 999
055     C
056     C     CALL KALM IF IK=IKALM.
057     C
058     40    IF(IK-IKALM) 50,42,60
059     42    IK=1
060     C
061           CALL KALM
062     C
063           DO 48 I=1,5
```

```
064             S1=0.
065             DO 44 J=1,4
066         44  S1=S1+AM(I,J)*Z(J)
067             DO 46 J=1,5
068         46  S1=S1+AXKAL(I,J)*XKAL(J)
069         48  X(I)=S1
070             GO TO 60
071         C
072         50  IK=IK+1
073         C
074         C   IF IR=IREG AND MODYAW=1, COMPUTE SET POINT VALUES.
075         C
076         60  IF(IR-IREG) 92,62,999
077         62  IR=1
078             IF(MODYAW) 72,72,64
079         64  S1=PSIREF-PSIRFO
080             IF(S1 .LE. -180.) S1=S1+360.
081             IF(S1 .GT. 180.) S1=S1-360.
082             IF(ABS(S1)-PSIMAX) 68,68,74
083         68  IF(IYAW) 76,70,76
084         70  MODYAW=0
085         72  REF(1)=0.
086             REF(2)=0.
087             REF(3)=PSIREF
088             REF(4)=0.
089             GO TO 78
090         C
091         74  IYAW=0
092         C
093         76  CALL YAW
094         C
095         78  PSIRFO=PSIREF
096         C
097         C   UPDATE THE LEAST SQUARES ESTIMATES, IF ILS=ILSEST.
098         C
099             PSIERR=X(3)-REF(3)
100             IF(PSIERR .LE. -180.) PSIERR=PSIERR+360.
101             IF(PSIERR .GT. 180.) PSIERR=PSIERR-360.
102         C
103             IF(ILS-ILSEST) 82,80,84
104         80  ILS=1
105             IF(IDELC+1) 81,84,81
106         C
107         81  CALL LSEST
108         C
109             GO TO 84
110         82  ILS=ILS+1
111         84  VAL(2)=VAL(1)
112             VAL(3)=X(1)-REF(1)
113             VAL(4)=X(2)-REF(2)
114             VAL(5)=X(4)
115             VAL(6)=X(5)
116             VAL(7)=PSIERR
117             IF(IDELC .EQ. -1) VAL(7)=0.
118         C
119         C   COMPUTE NEW CONTROL SIGNAL.
120         C
121             S1=PSIERR
122             DO 90 I=2,6
123         90  S1=S1+TH(I)*VAL(I)
124             VAL(1)=-S1/TH(1)
125             DELCOM=REF(4)+VAL(1)
126             GO TO 990
127         C
```

```
128       92      IR=IR+1
129               GO TO 999
130       C
131       990     IF(NOREG) 999,999,992
132       992     IDELC=1
133       C
134       999     RETURN
135               END
```

```
001             SUBROUTINE AUTPIL
002       C
003       C     ADMINISTRATION SUBROUTINE FOR CONTROL
004       C     OF A SHIP.
005       C     REGULATOR 2.
006       C
007       C     AUTHOR, C.KALLSTROM 1973-09-23.
008       C
009       C     SUBROUTINE REQUIRED
010       C           KALM
011       C           YAW
012       C           LSEST
013       C
014             DIMENSION VAL1(7),VAL2(7)
015       C
016             COMMON/DATA/ IDUM1(4),DELTA,Z(4),IDUM2(9),PSIREF,
017            1MODYAW,RREF,ISTBD,IPORT,IDELC,DELCOM,X(5),TH(6),
018            2REF(4),IFLAG,INAUT,IP,IPRINT,IDEXP,IR,IREG,NOREG,
019            3DELAMP,IK,IKALM,NX,NY,XKAL(5),IDUM3(258),AM(5,4),
020            4AXKAL(5,5),PSIMAX,PSIRFO,PSIDIF,IYAW,IDUM4(3),RL,RL1,
021            5IDUM5(162),ILS,ILSEST,PSIERR,VAL(7),IDUM6(93),S1,
022            6IDUM7(9)
023       C
024       C     INITIALIZING IF INAUT=1.
025       C
026             IF(INAUT) 20,20,10
027       10    INAUT=0
028             PSIRFO=PSIREF
029             IYAW=0
030             RL=RL1
031             DO 12 I=1,7
032             VAL1(I)=0.
033             VAL2(I)=0.
034       12    VAL(I)=0.
035             REFDO=0.
036             REF(1)=0.
037             REF(2)=0.
038             REF(3)=PSIREF
039             REF(4)=0.
040       C
041       C     IF IDEXP=1, COMPUTE DELCOM FOR IDENTIFICATION
042       C     EXPERIMENT.
043       C
044       20    IF(IDEXP) 40,40,22
045       22    IF(IR-IREG) 36,24,999
046       24    IR=1
047             IF(ISTBD+IPORT-1) 34,26,32
048       26    IF(ISTBD) 30,30,28
049       28    DELCOM=DELAMP
050             GO TO 34
051       30    DELCOM=-DELAMP
052             GO TO 34
053       32    DELCOM=0.
054       34    ISTBD=0
055             IPORT=0
056             GO TO 990
057       C
058       36    IR=IR+1
059             GO TO 999
060       C
061       C     CALL KALM IF IK=IKALM.
062       C
063       40    IF(IK-IKALM) 50,42,60
```

```
064      42     IK=1
065      C
066             CALL KALM
067      C
068             DO 48 I=1,5
069             S1=0.
070             DO 44 J=1,4
071      44     S1=S1+AM(I,J)*Z(J)
072             DO 46 J=1,5
073      46     S1=S1+AXKAL(I,J)*XKAL(J)
074      48     X(I)=S1
075             GO TO 60
076      C
077      50     IK=IK+1
078      C
079      C      IF IR=IREG AND MODYAW=1, COMPUTE SET POINT VALUES.
080      C
081      60     IF(IR-IREG) 92,62,999
082      62     IR=1
083             IF(MODYAW) 72,72,64
084      64     S1=PSIREF-PSIRFO
085             IF(S1 .LE. -180.) S1=S1+360.
086             IF(S1 .GT. 180.) S1=S1-360.
087             IF(ABS(S1)-PSIMAX) 68,68,74
088      68     IF(IYAW) 76,70,76
089      70     MODYAW=0
090      72     REF(1)=0.
091             REF(2)=0.
092             REF(3)=PSIREF
093             REF(4)=0.
094             GO TO 78
095      C
096      74     IYAW=0
097      C
098      76     CALL YAW
099      C
100      78     PSIRFO=PSIREF
101      C
102      C      UPDATE THE LEAST SQUARES ESTIMATES, IF ILS=ILSEST.
103      C
104             PSIERR=X(3)-REF(3)
105             IF(PSIERR .LE. -180.) PSIERR=PSIERR+360.
106             IF(PSIERR .GT. 180.) PSIERR=PSIERR-360.
107      C
108             IF(ILS-ILSEST) 82,80,84
109      80     ILS=1
110      C
111      81     CALL LSEST
112      C
113             GO TO 84
114      82     ILS=ILS+1
115      84     DO 100 I=1,7
116             VAL(I)=VAL2(I)
117      100    VAL2(I)=VAL1(I)
118             VAL2(1)=DELTA-REFDO
119             VAL1(2)=VAL2(1)
120             VAL1(3)=X(1)-REF(1)
121             VAL1(4)=X(2)-REF(2)
122             VAL1(5)=X(4)
123             VAL1(6)=X(5)
124             VAL1(7)=PSIERR
125      C
126      C      COMPUTE NEW CONTROL SIGNAL.
127      C
```

```
128             S1=PSIERR
129             DO 90 I=2,6
130       90    S1=S1+TH(I)*VAL1(I)
131             VAL1(1)=-S1/TH(1)
132             DELCOM=REF(4)+VAL1(1)
133             REFDO=REF(4)
134             GO TO 990
135       C
136       92    IR=IR+1
137             GO TO 999
138       C
139       990   IF(NOREG) 999,999,992
140       992   IDELC=1
141       C
142       999   RETURN
143             END
```

```
001             SUBROUTINE KALM
002       C
003       C     SUBROUTINE TO COMPUTE THE STATE ESTIMATE
004       C     X(T/T)=X(T/T-1)+AK*EPS
005       C     WHERE
006       C     X(T/T-1)=FIKAL*X(T-1/T-1)+GAMKAL*DELTA(T-1)
007       C     EPS=EKAL*Z(T)-CKAL*X(T/T-1).
008       C
009       C     AUTHOR, C.KALLSTROM 1973-09-13.
010       C
011       C     SUBROUTINE REQUIRED
012       C           NONE
013       C
014             COMMON/DATA/ IDUM1(4),DELTA,Z(4),IDUM2(80),NX,NY,XKAL(5),
015            1FIKAL(5,5),GAMKAL(5),CKAL(4,5),EKAL(4,4),AK(5,4),IDUM3(405),
016            2SL(5),X1(5),S1,IDUM4(9)
017       C
018       C     COMPUTE X(T/T-1)=FIKAL*X(T-1/T-1)+GAMKAL*DELTA(T-1)
019       C     AND STORE THE RESULT IN X1.
020       C
021             DO 12 I=1,NX
022             S1=GAMKAL(I)*DELTA
023             DO 10 J=1,NX
024       10    S1=S1+FIKAL(I,J)*XKAL(J)
025       12    X1(I)=S1
026       C
027       C     COMPUTE EPS=EKAL*Z-CKAL*X(T/T-1) AND STORE
028       C     THE RESULT IN SL.
029       C
030             DO 24 I=1,NY
031             S1=0.
032             DO 20 J=1,4
033       20    S1=S1+EKAL(I,J)*Z(J)
034             DO 22 J=1,NX
035       22    S1=S1-CKAL(I,J)*X1(J)
036       24    SL(I)=S1
037       C
038             IF(SL(NY) .LE. -180.) SL(NY)=SL(NY)+360.
039             IF(SL(NY) .GT. 180.) SL(NY)=SL(NY)-360.
040       C
041       C     COMPUTE X(T/T)=X(T/T-1)+AK*EPS AND STORE
042       C     THE RESULT IN XKAL.
043       C
044             DO 32 I=1,NX
045             S1=X1(I)
046             DO 30 J=1,NY
047       30    S1=S1+AK(I,J)*SL(J)
048       32    XKAL(I)=S1
049       C
050             IF(XKAL(3) .LT. 0.) XKAL(3)=XKAL(3)+360.
051             IF(XKAL(3) .GE. 360.) XKAL(3)=XKAL(3)-360.
052       C
053             RETURN
054             END
```

```
001             SUBROUTINE YAW
002       C
003       C     SUBROUTINE TO GENERATE SET POINT VALUES
004       C     DURING YAW.
005       C
006       C     AUTHOR, C.KALLSTROM 1973-09-21.
007       C
008       C     SUBROUTINE REQUIRED
009       C           NONE
010       C
011             COMMON/DATA/ IDUM1(28),PSIREF,MODYAW,RREF,IDUM2(6),
012            1X(5),TH(6),REF(4),IDUM3(6),IREG,IDUM4(422),PSIDIF,
013            2IYAW,KYAW,KKYAW,LYAW,RL,RL1,RL2,RNOM,VNOM,DELNOM,
014            3AYAW(2,3),CYAW,FIYAW(5,5),GAMYAW(5),REFN(4),REFNN(4),
015            4X2(5),IDUM5(89),SL(5),X1(5),S1,S2,S3,S4
016       C
017       C     COMPUTE PSIDIF=PSIREF-PSI.
018       C
019             PSIDIF=PSIREF-X(3)
020             IF(PSIDIF .LE. -180.) PSIDIF=PSIDIF+360.
021             IF(PSIDIF .GT. 180.) PSIDIF=PSIDIF-360.
022       C
023       C     INITIALIZE IF IYAW=0.
024       C
025             IF(IYAW) 20,10,90
026       10    IYAW=-1
027             KKYAW=KYAW
028             IF(PSIDIF .GE. 0.) RNOM=RREF
029             IF(PSIDIF .LT. 0.) RNOM=-RREF
030       C
031             RL=RL2
032       C
033             VNOM=AYAW(1,1)*RNOM+AYAW(1,2)*X(4)+AYAW(1,3)*X(5)
034             DELNOM=AYAW(2,1)*RNOM+AYAW(2,2)*X(4)+AYAW(2,3)*X(5)
035       C
036       C     TEST IF THE YAW IS TO BE TERMINATED.
037       C
038       20    IF(PSIDIF-FLOAT(3*IREG*KYAW)*CYAW*RNOM) 22,22,24
039       22    IF(RNOM) 30,80,80
040       24    IF(RNOM)80,80,30
041       C
042       C     IF IYAW=-3, JUMP TO THE STATIONARY PHASE.
043       C
044       30    IF(IYAW+2) 70,60,40
045       C
046       C     THE INITIAL PHASE.
047       C
048       40    DO 46 I=1,5
049             S1=0.
050             DO 44 J=1,5
051       44    S1=S1+FIYAW(I,J)*X(J)
052       46    SL(I)=S1
053       C
054             S1=VNOM
055             S2=RNOM
056             DO 48 J=1,5
057             S1=S1-FIYAW(1,J)*SL(J)
058       48    S2=S2-FIYAW(2,J)*SL(J)
059       C
060             S3=0.
061             S4=0.
062             DO 50 J=1,5
063             S3=S3+FIYAW(1,J)*GAMYAW(J)
```

```
064      50     S4=S4+FIYAW(2,J)*GAMYAW(J)
065      C
066             SL(1)=S3*GAMYAW(2)-S4*GAMYAW(1)
067             REF(4)=(S1*GAMYAW(2)-S2*GAMYAW(1))/SL(1)
068             REFN(4)=(-S4*S1+S2*S3)/SL(1)
069      C
070             REF(1)=X(1)
071             REF(2)=X(2)
072             REF(3)=X(3)
073      C
074             DO 54 I=1,5
075             S1=GAMYAW(I)*REF(4)
076             DO 52 J=1,5
077      52     S1=S1+FIYAW(I,J)*X(J)
078      54     SL(I)=S1
079      C
080             REFN(1)=SL(1)
081             REFN(2)=SL(2)
082             REFN(3)=SL(3)
083      C
084             DO 58 I=1,5
085             S1=GAMYAW(I)*REFN(4)
086             DO 56 J=1,5
087      56     S1=S1+FIYAW(I,J)*SL(J)
088      58     X2(I)=S1
089      C
090             IYAW=-2
091             GO TO 999
092      C
093      60     DO 62 I=1,4
094      62     REF(I)=REFN(I)
095      C
096             IYAW=-3
097             GO TO 999
098      C
099      C      THE STATIONARY PHASE.
100      C
101      70     REF(1)=VNOM
102             REF(2)=RNOM
103             REF(3)=X2(3)
104             REF(4)=DELNOM
105      C
106             DO 74 I=1,5
107             S1=GAMYAW(I)*DELNOM
108             DO 72 J=1,5
109      72     S1=S1+FIYAW(I,J)*X2(J)
110      74     SL(I)=S1
111      C
112             DO 76 I=1,5
113      76     X2(I)=SL(I)
114      C
115             IF(X2(3) .LT. 0.) X2(3)=X2(3)+360.
116             IF(X2(3) .GE. 360.) X2(3)=X2(3)-360.
117      C
118             GO TO 999
119      C
120      C      THE TERMINATING PHASE.
121      C
122      80     IF(IYAW+3) 82,82,84
123      82     IF(PSIDIF*RNOM) 84,84,86
124      84     KKYAW=1
125      C
126      86     IYAW=1
127             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)
```

```
192             REF(2)=X(2)
193             REF(3)=X(3)
194       C
195             DO 128 I=1,5
196             S1=GAMYAW(I)*REF(4)
197             DO 126 J=1,5
198       126   S1=S1+FIYAW(I,J)*X(J)
199       128   X1(I)=S1
200       C
201             REFN(1)=X1(1)
202             REFN(2)=X1(2)
203             REFN(3)=X1(3)
204       C
205             DO 132 I=1,3
206             S1=GAMYAW(I)*REFN(4)
207             DO 130 J=1,5
208       130   S1=S1+FIYAW(I,J)*X1(J)
209       132   REFNN(I)=S1
210       C
211             IYAW=2
212             GO TO 999
213       C
214       140   DO 142 I=1,4
215       142   REF(I)=REFN(I)
216             IYAW=3
217             GO TO 999
218       C
219       150   DO 152 I=1,4
220       152   REF(I)=REFNN(I)
221       C
222             IF(LYAW-KKYAW) 154,156,156
223       154   LYAW=LYAW+1
224             IYAW=1
225             GO TO 999
226       C
227       156   IYAW=0
228             MODYAW=0
229             RL=RL1
230       C
231       999   IF(REF(3) .LT. 0.) REF(3)=REF(3)+360.
232             IF(REF(3) .GE. 360.) REF(3)=REF(3)-360.
233             RETURN
234             END
```

```
001            SUBROUTINE LSEST
002      C
003      C     LEAST SQUARES IDENTIFICATION OF THE PARAMETERS
004      C     TH(1),...,TH(6) IN THE MODEL
005      C        PSI(T)-PSIREF(T)=PSI(T-1)-PSIREF(T-1)+
006      C        TH(1)*DELTA(T-1)+TH(2)*DELTA(T-2)+
007      C        TH(3)*(V(T-1)-VREF(T-1))+TH(4)*(R(T-1)-RREF(T-1))+
008      C        TH(5)*F(T-1)+TH(6)*M(T-1)+E(T).
009      C
010      C     AUTHOR, C.KALLSTROM 1973-09-20.
011      C
012      C     SUBROUTINE REQUIRED
013      C           NONE
014      C
015            COMMON/DATA/ IDUM1(56),TH(6),IDUM2(448),RL,IDUM3(167),
016           1PSIERR,VAL(7),COV(21),SL(10),S1,S2,S3,S4
017      C
018            S1=PSIERR-VAL(7)
019            DO 10 I=1,6
020      10    S1=S1-TH(I)*VAL(I)
021      C
022            DO 22 I=1,6
023            S2=0.
024            DO 20 J=1,6
025            L=I*(I-1)/2+J
026            IF(J .GT. I) L=J*(J-1)/2+I
027      20    S2=S2+COV(L)*VAL(J)
028      22    SL(I)=S2
029      C
030            S2=1.
031            DO 30 I=1,6
032      30    S2=S2+VAL(I)*SL(I)
033      C
034            DO 40 I=1,6
035      40    TH(I)=TH(I)+SL(I)*S1/S2
036      C
037            DO 50 I=1,6
038            DO 50 J=1,I
039            L=I*(I-1)/2+J
040      50    COV(L)=(COV(L)-SL(I)*SL(J)/S2)/RL
041      C
042            RETURN
043            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:

$$(\Psi(+1) - \Psi_{ref}) - (\Psi(t) - \Psi_{ref}) = 0.6\ \delta(t) + b_2\delta(t-1) + d_1 v(t) + d_2 r(t) + e(t+1)$$

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

Regulator:

$$\delta(t) = -\frac{1}{0.6}\left[(\Psi(t) - \Psi_{ref}) + b_2\delta(t-1) + d_1 v(t) + d_2 r(t)\right]$$

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

Initial values:

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

Regulator:

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

Final values:

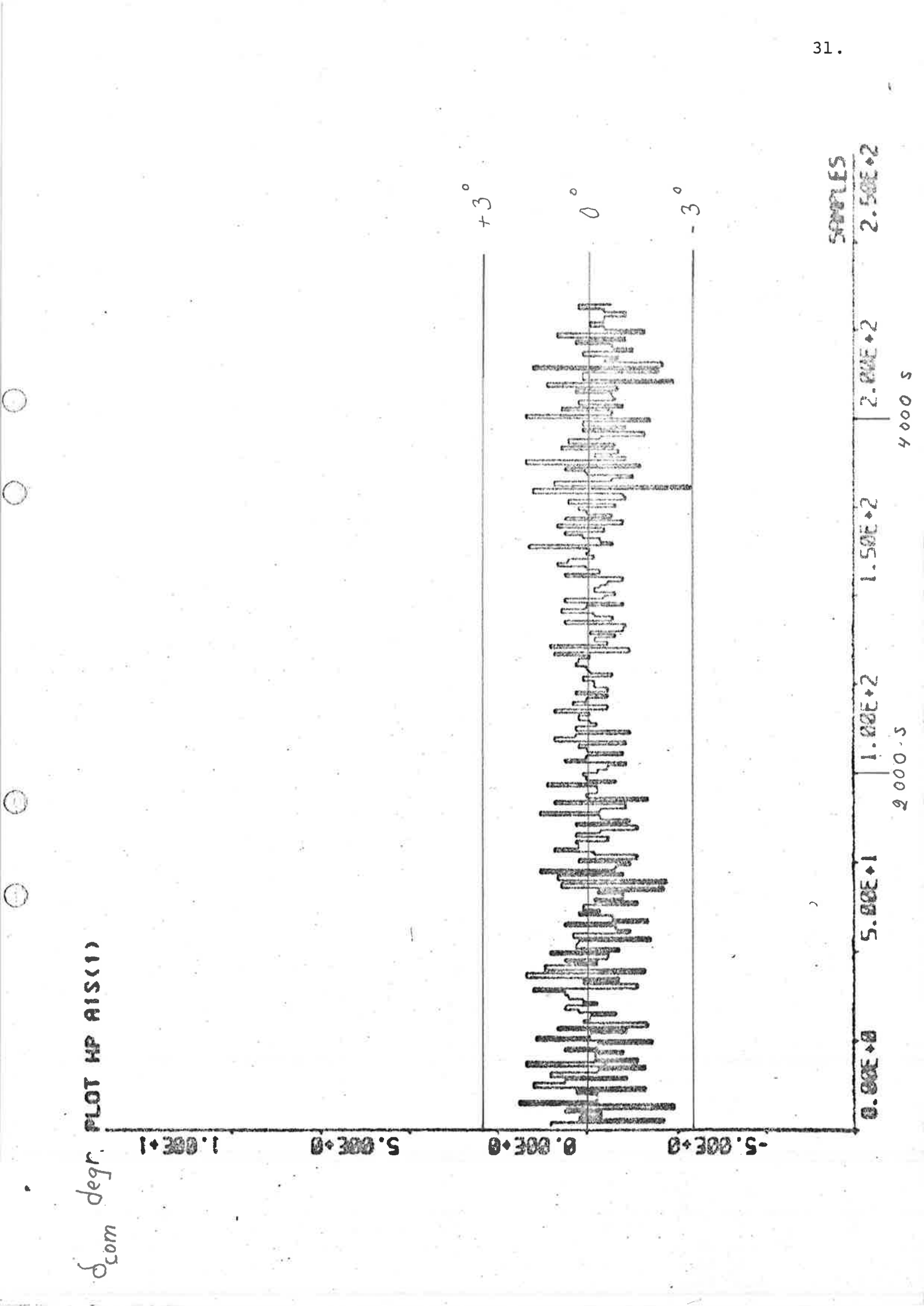
$$\begin{bmatrix} b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1459 \\ -0.7773 \\ 41.0180 \end{bmatrix} \qquad P = \begin{bmatrix} 0.01705 & & \\ -0.08942 & 2.249 & \\ -0.2811 & 0.6094 & 51.10 \end{bmatrix}$$

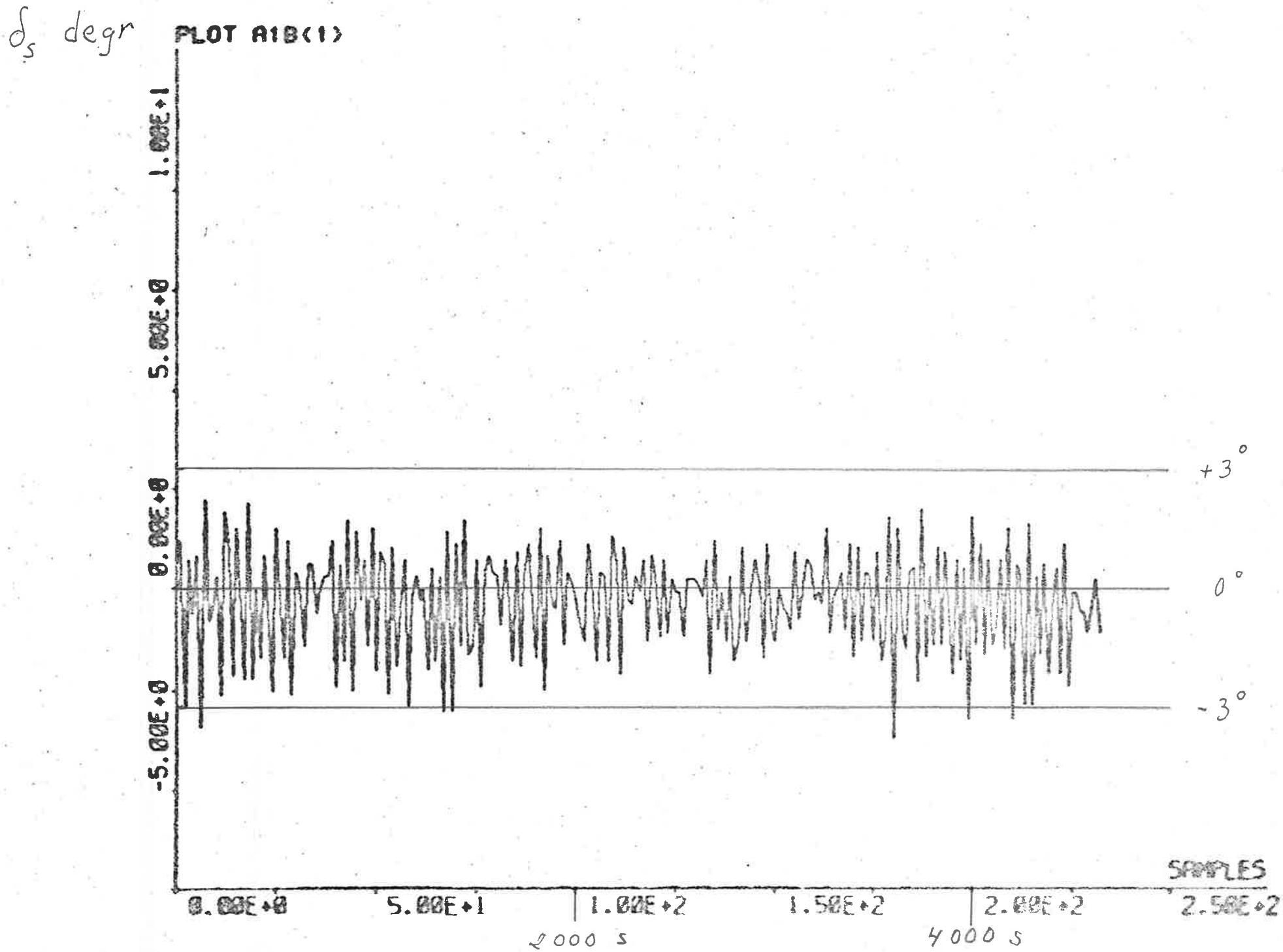
Regulator:

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

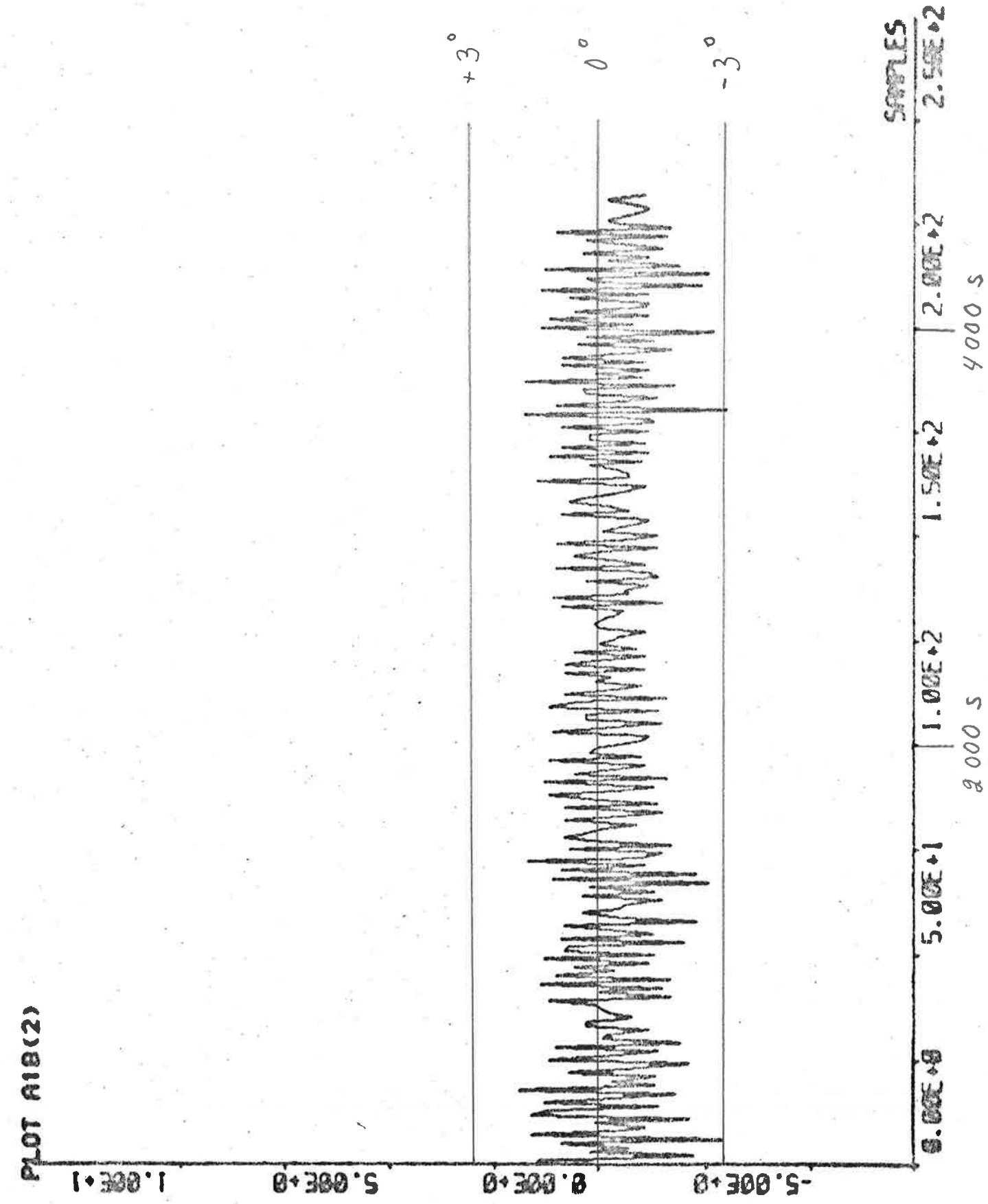
Statistics:

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


PLOT HP AIS(1)
δ_{com} degr.
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+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

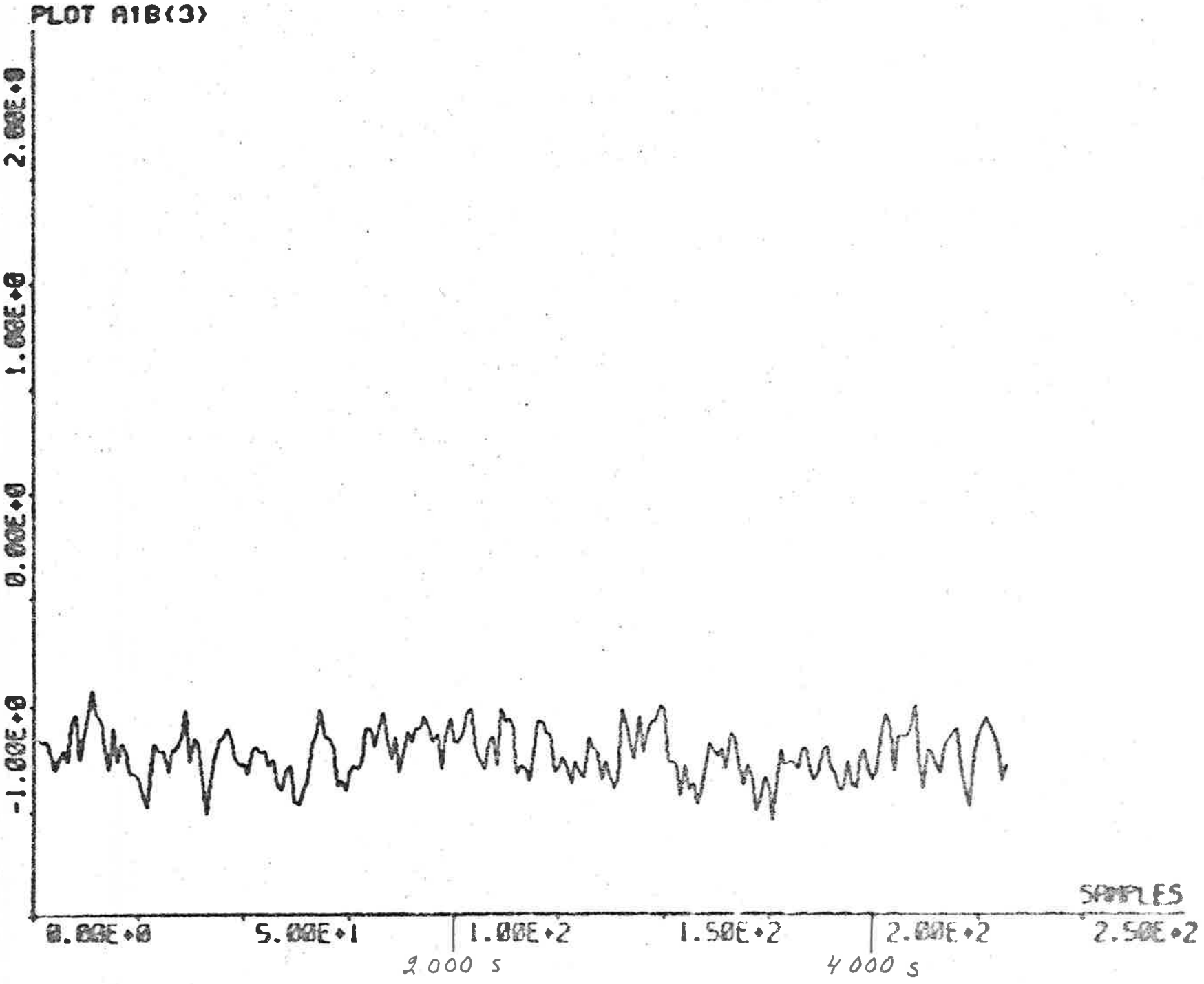


δ_s degr
PLOT A1B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

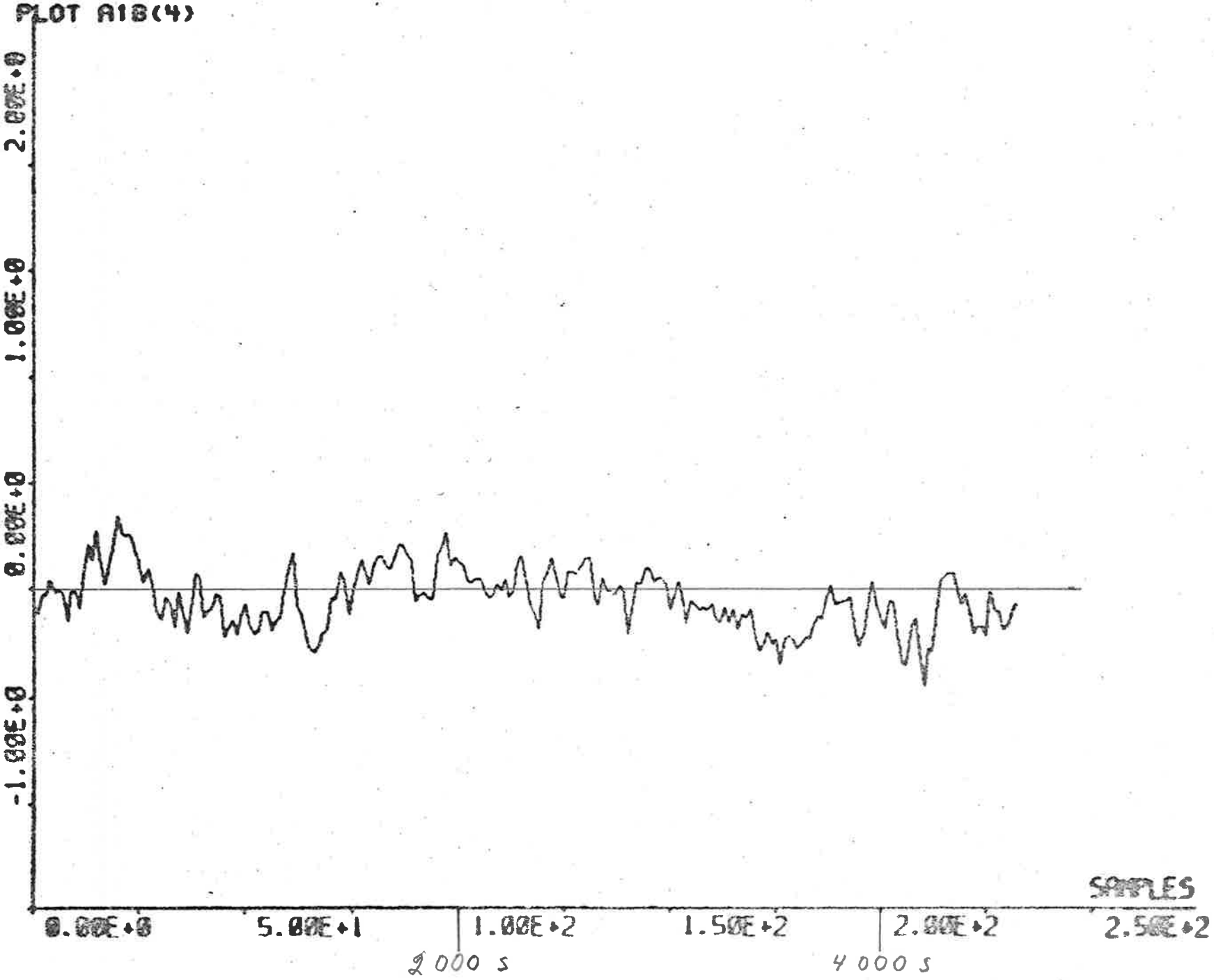

PLOT A18(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
8000 s
4000 s

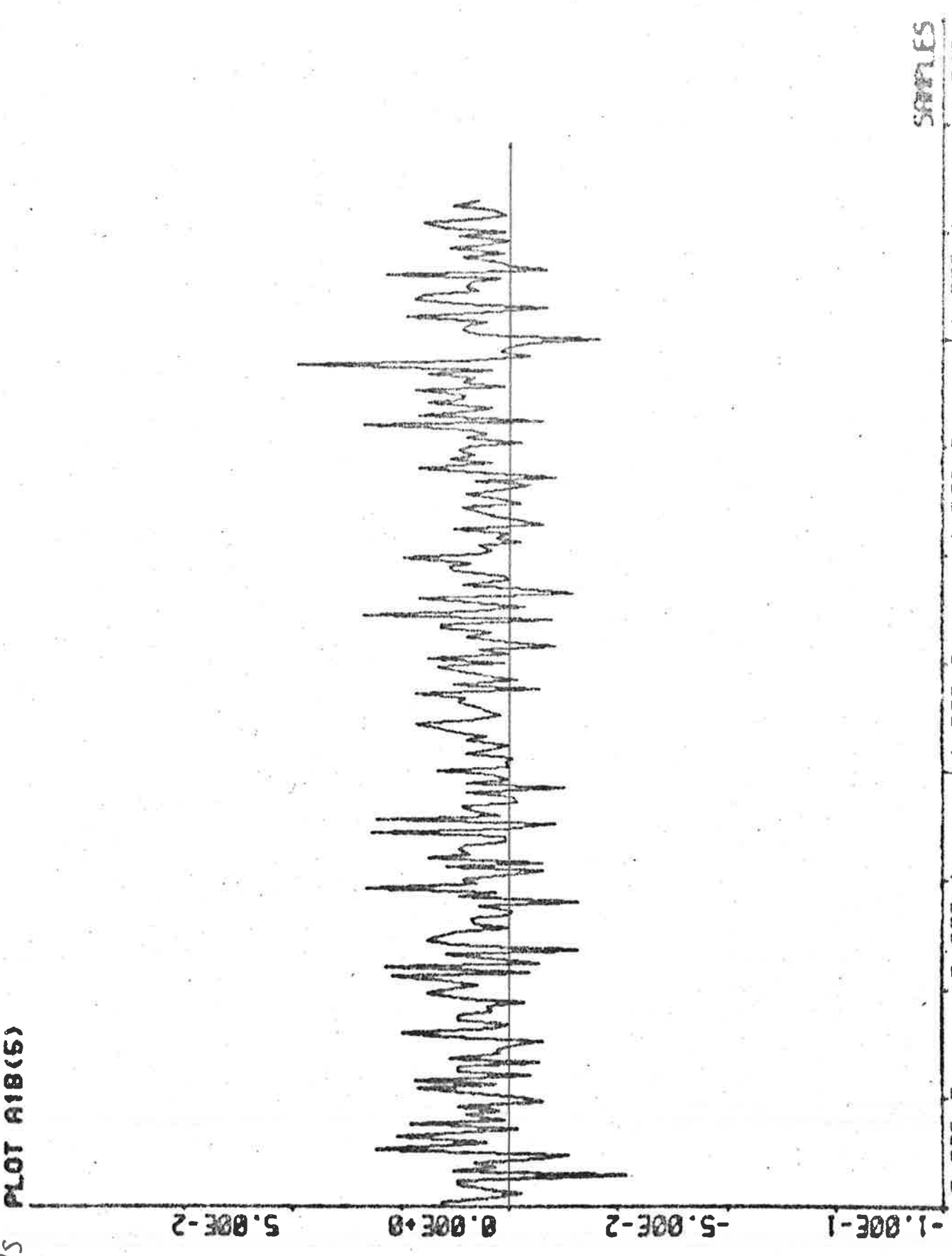
δ degr

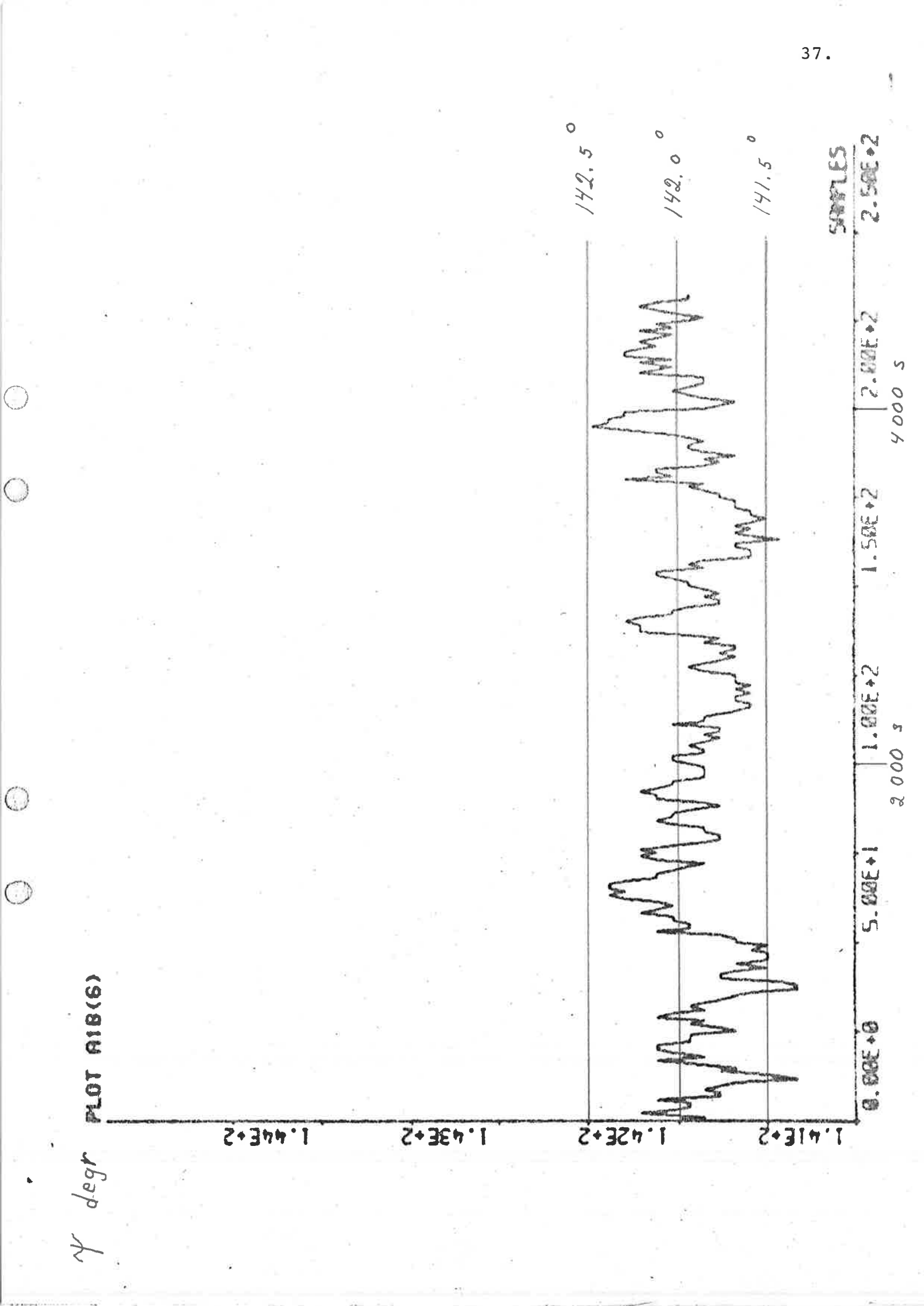
V_1 knots


PLOT A1B(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

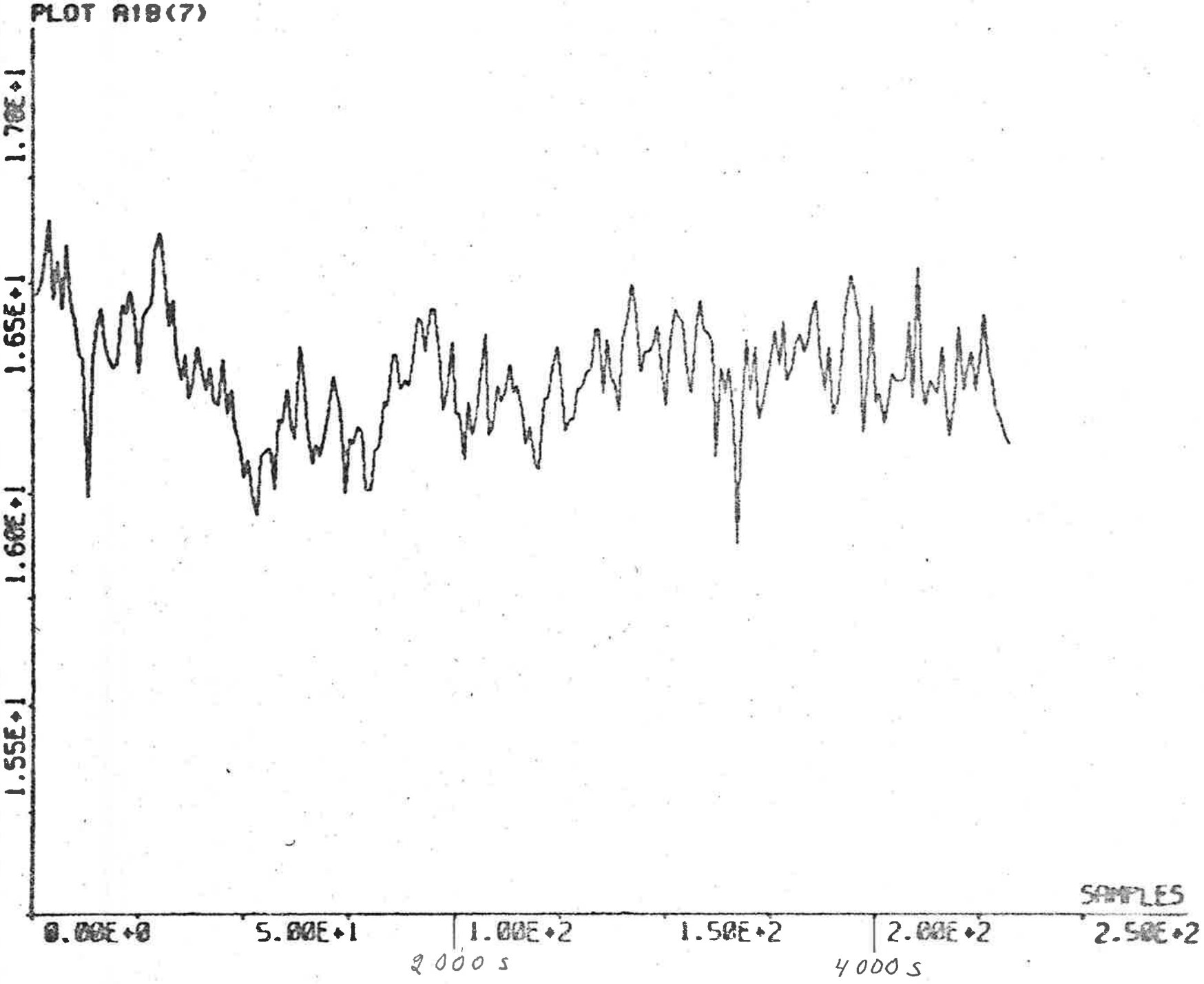
V_2 knots

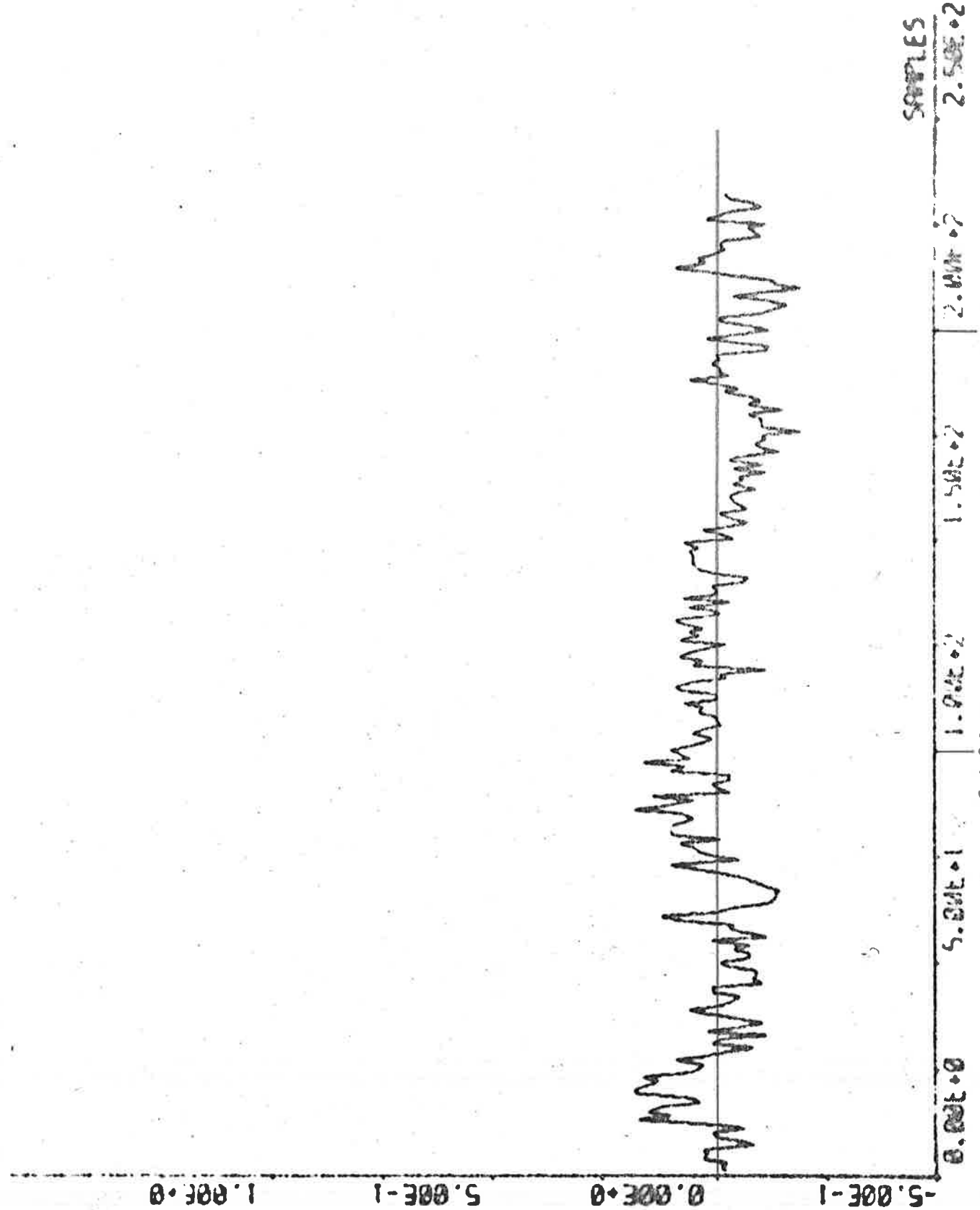

PLOT A18(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

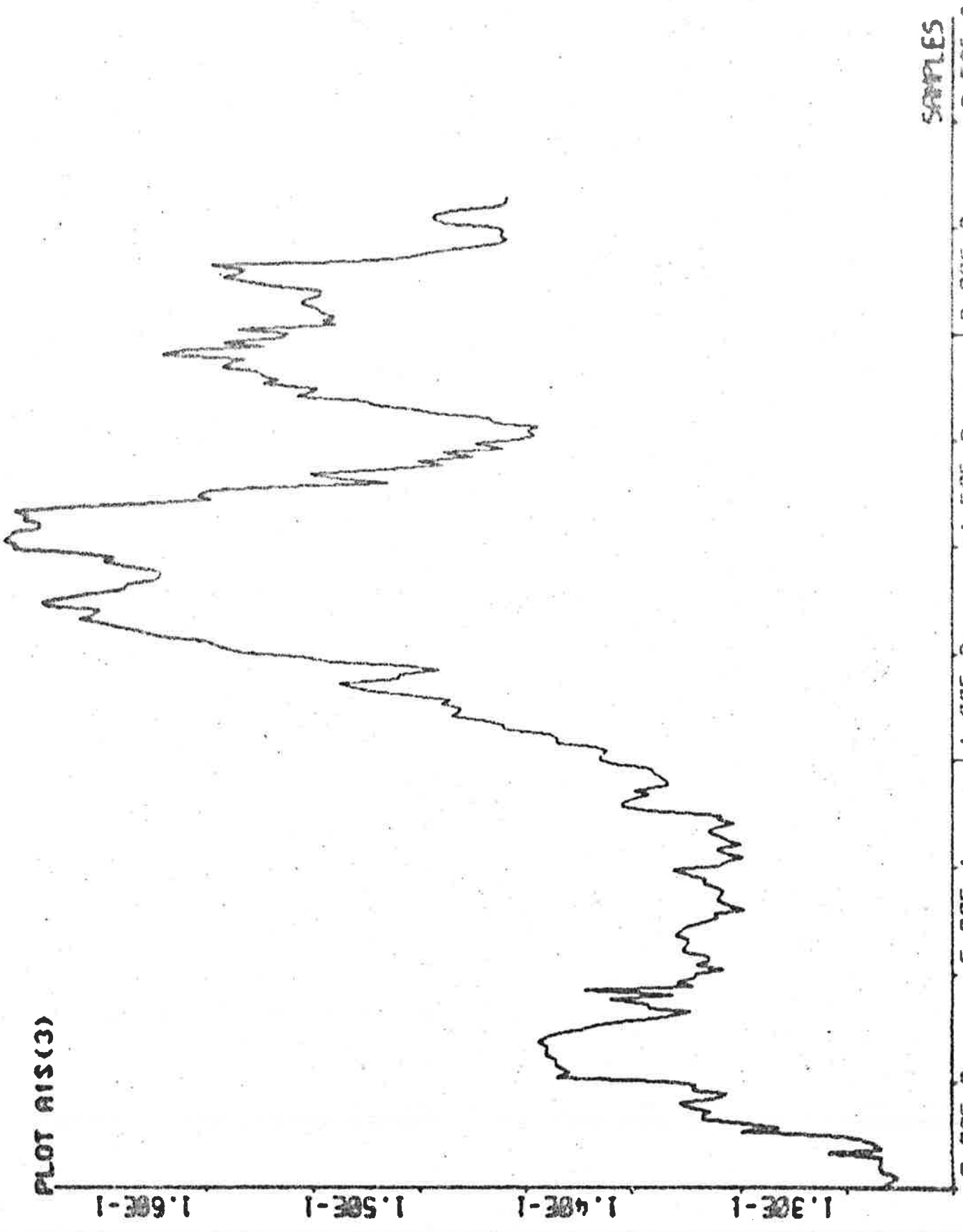

PLOT A1B(5)
r degr/s
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2 000 s
4000 s


γ degr
PLOT A1B(6)
1.4E+2
1.42E+2
1.43E+2
1.44E+2
142.5°
142.0°
141.5°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

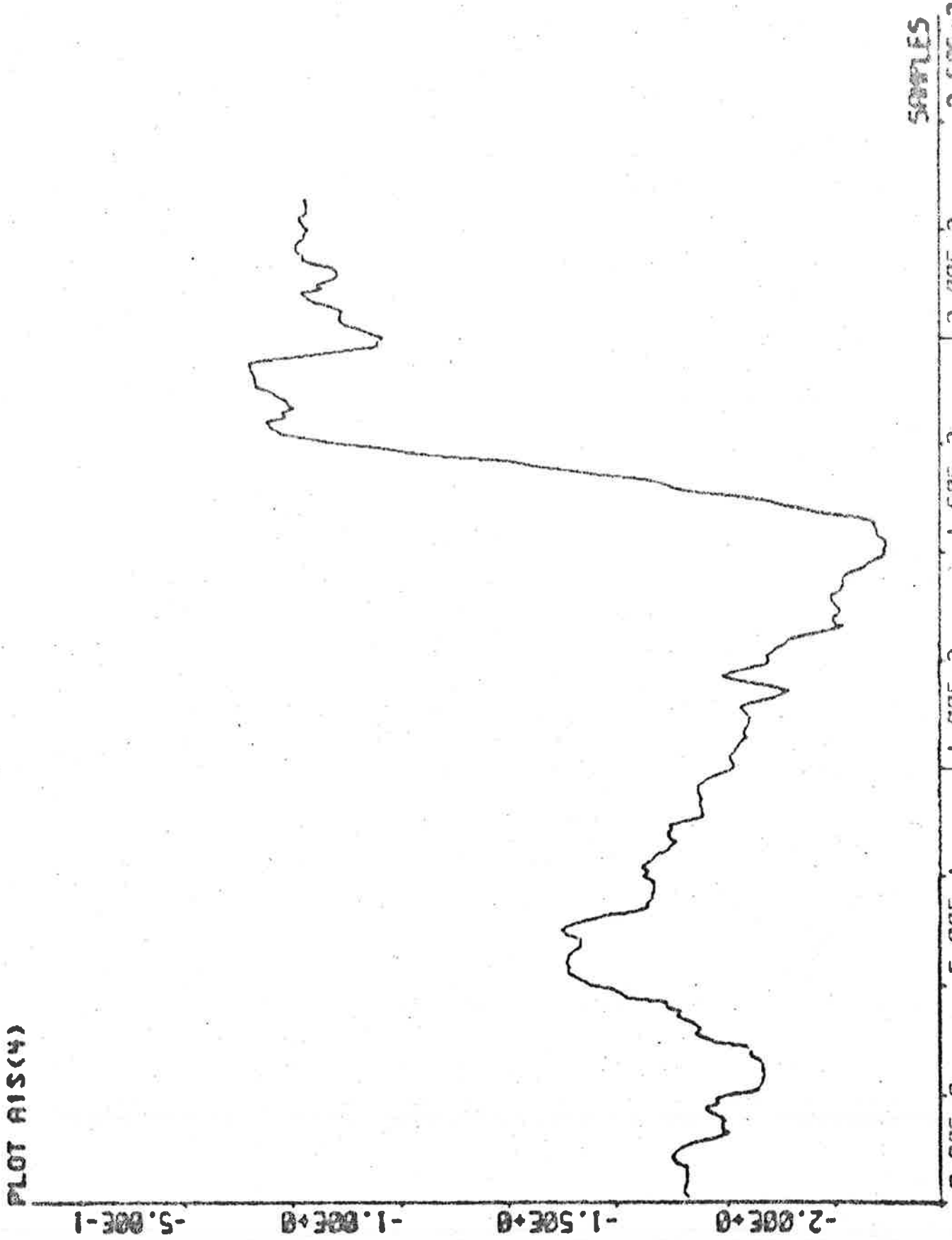
U knots


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

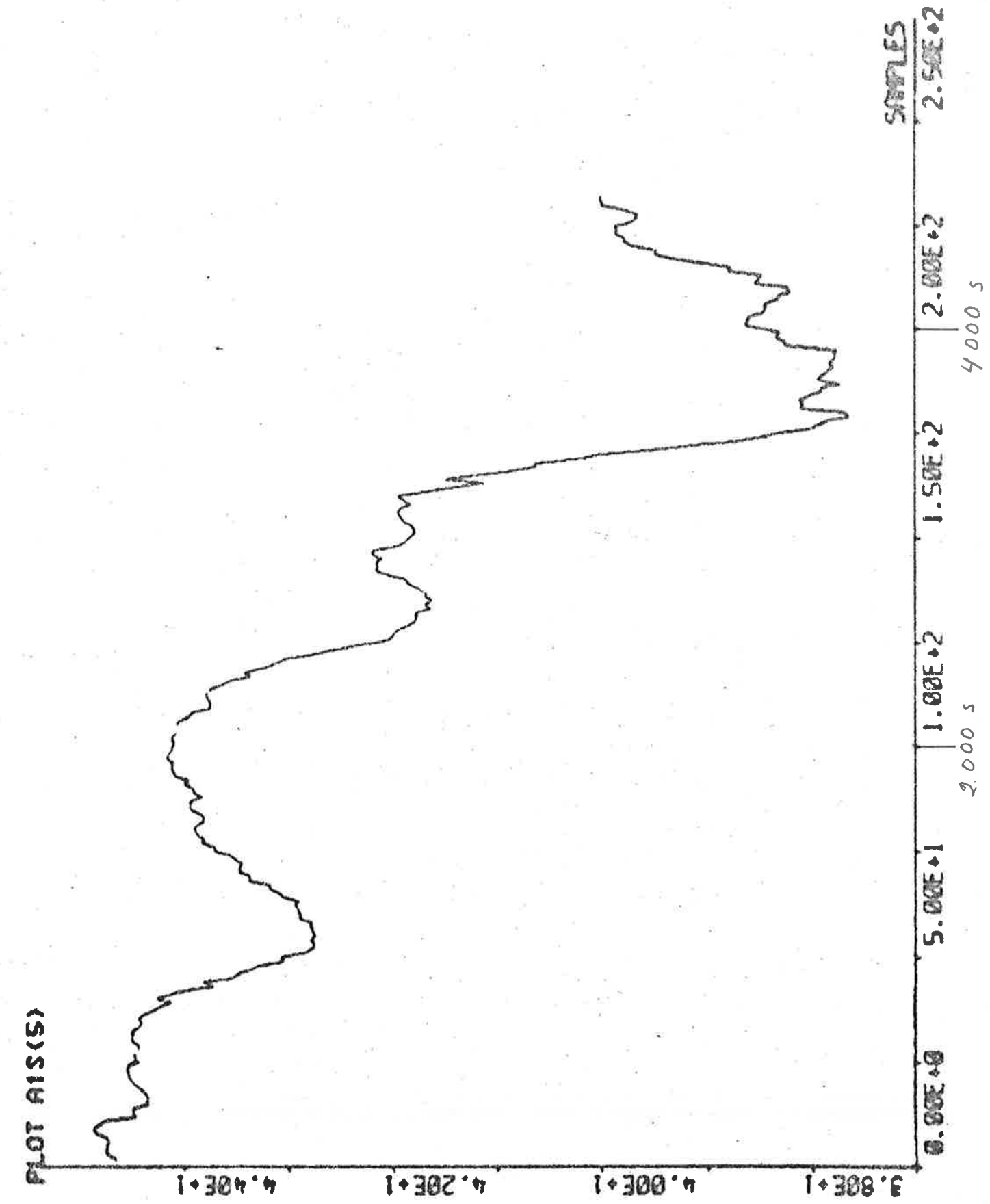

v m/s
PLOT A13(2)
1.00E-1
5.00E-1
0.000
-5.00E-1
0.00E+0
5.00E+1
1.00E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s


PLOT AIS(3)
1.68E-1
1.58E-1
1.48E-1
1.38E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
4000 s
4000 s

b2


PLOT AIS(4)
-2.000E+0
-1.500E+0
-1.000E+0
-5.000E-1
0.000E+0
5.000E+1
1.000E+2
1.500E+2
2.000E+2
2.500E+2
SAMPLES
2000 s
4000 s

d_1


PLOT A1S(S)
4.408E+1
4.207E+1
4.006E+1
3.805E+1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2.000 s
4.000 s

d_2

Experiment A2.

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

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

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

Model in the regulator:

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

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

Regulator:

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

Sampling interval: 20 s
Forgetting factor λ: 0.90 (0 - 300 s)
0.98 (300 - 2960 s)
0.99 (2960 - 3740 s)
Rudder limits: ± 3° (0 - 440 s)
± 4° (440 - 1300 s)
± 3° (1300 - 3740 s)
Ψ_{ref} = 142°

Intitial values:

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

Regulator:

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

Final values:

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

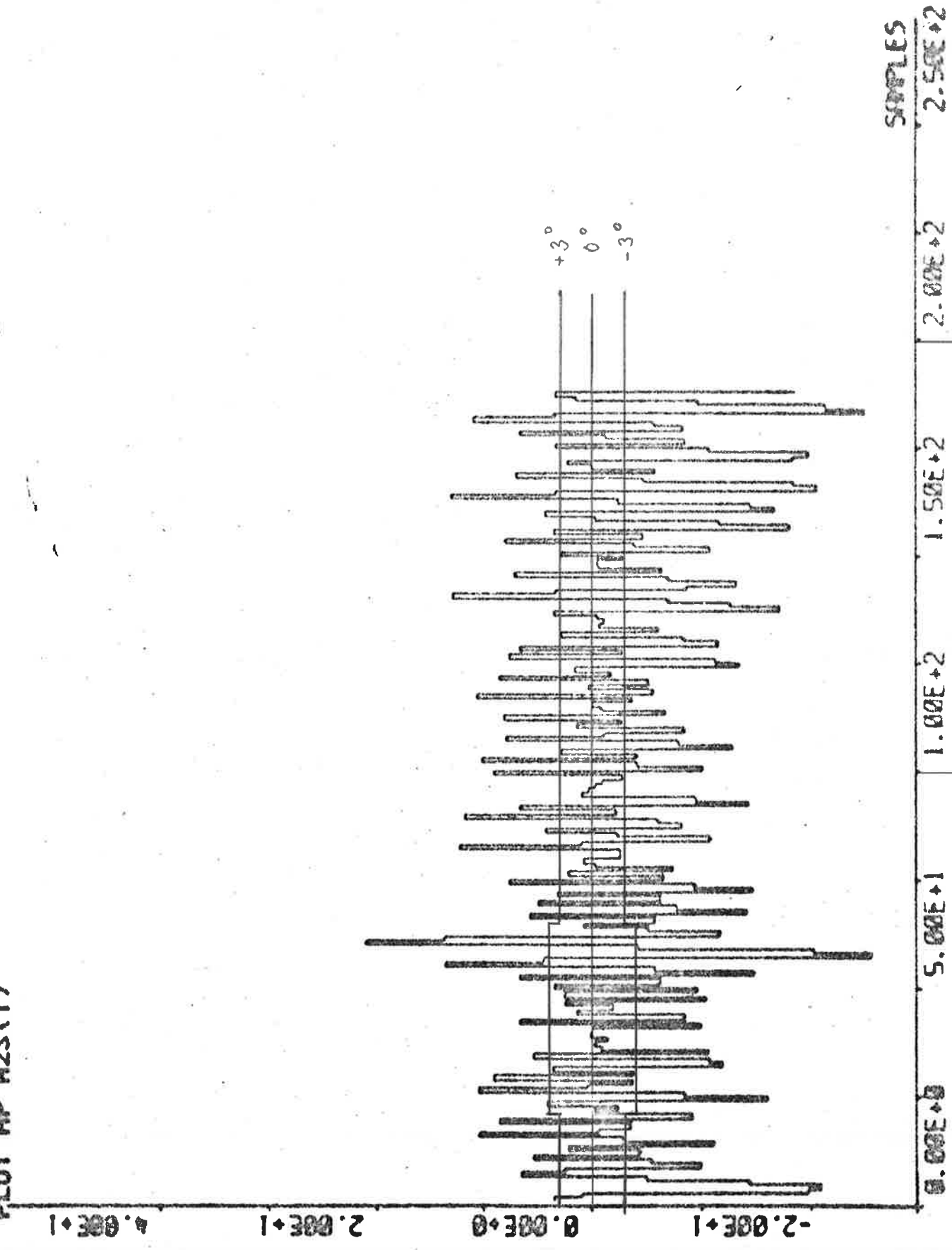
Regulator:

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

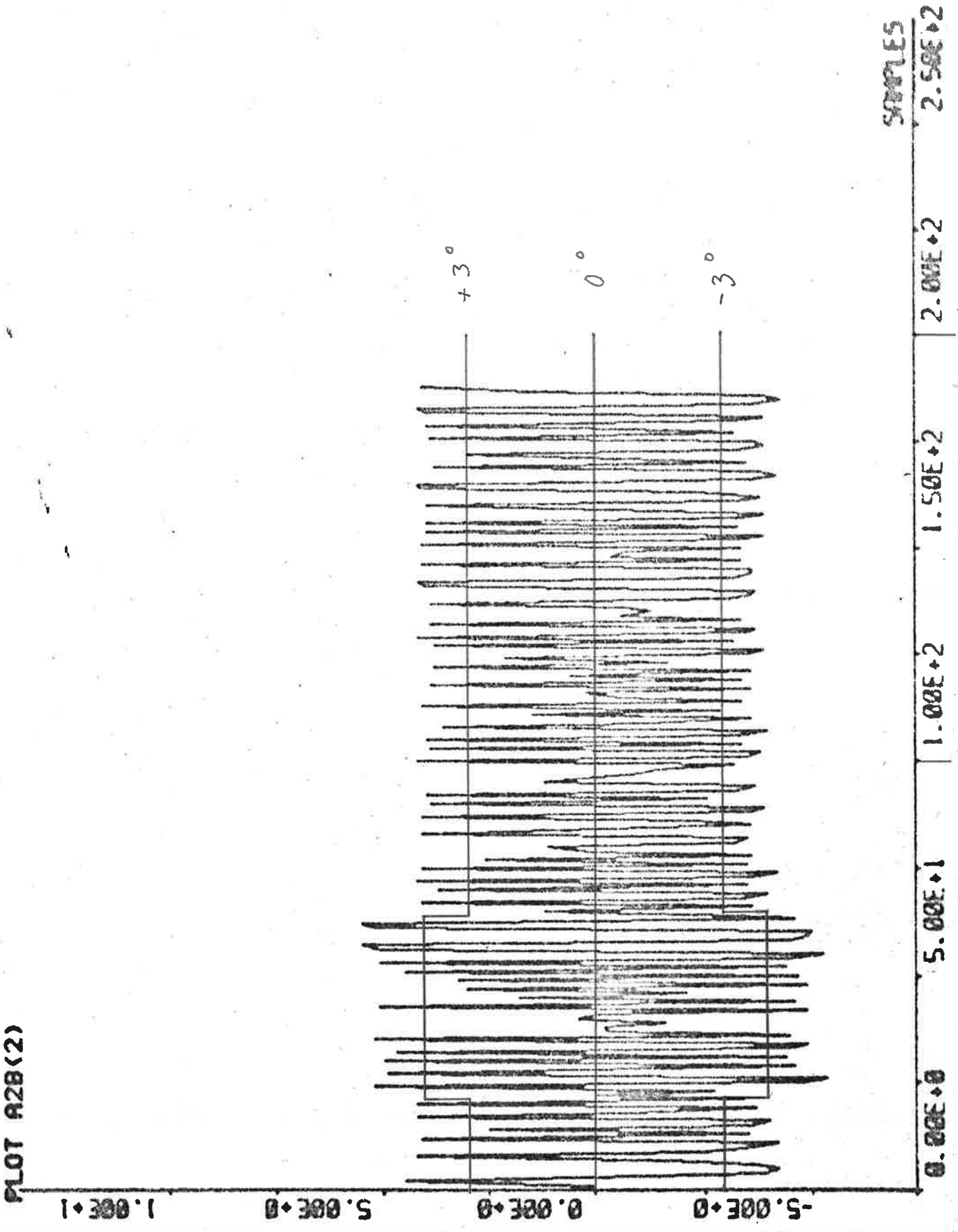
$$- 189.0724r(t)$$

Statistics:

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

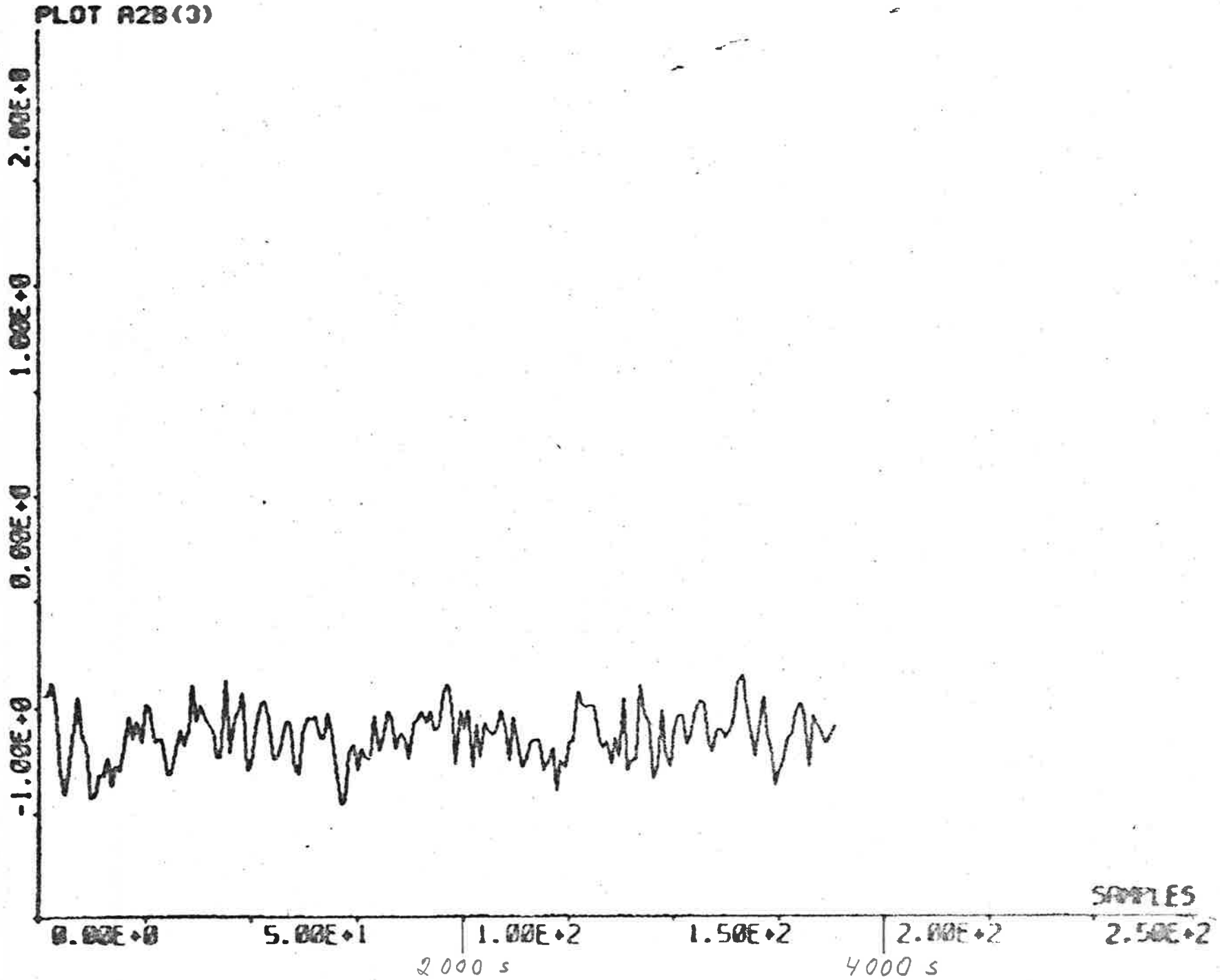


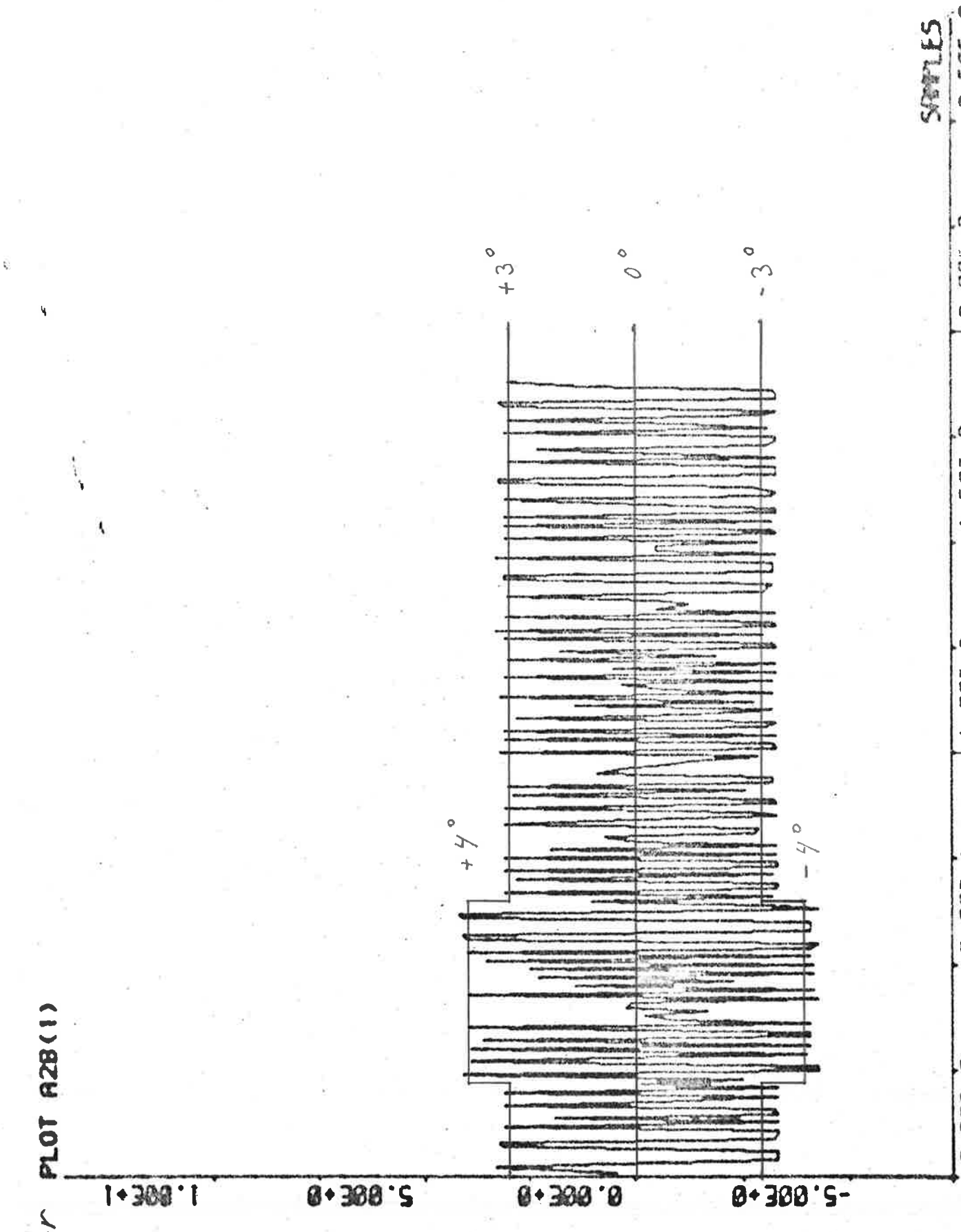
δ_{com} degr


PLOT A28(2)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
+3°
0°
-3°
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
2000 s
4000 s

δ degr

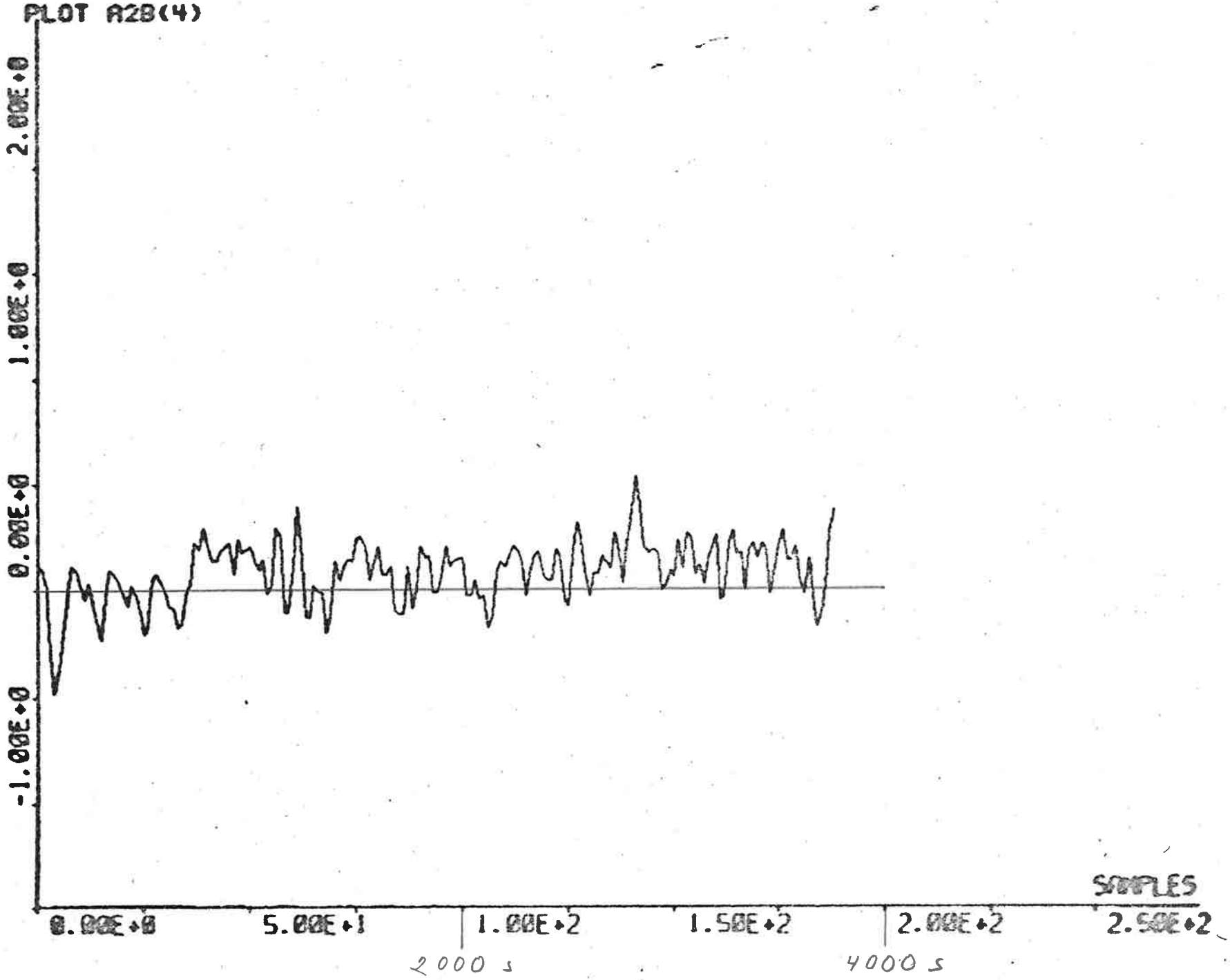
V_1 knots

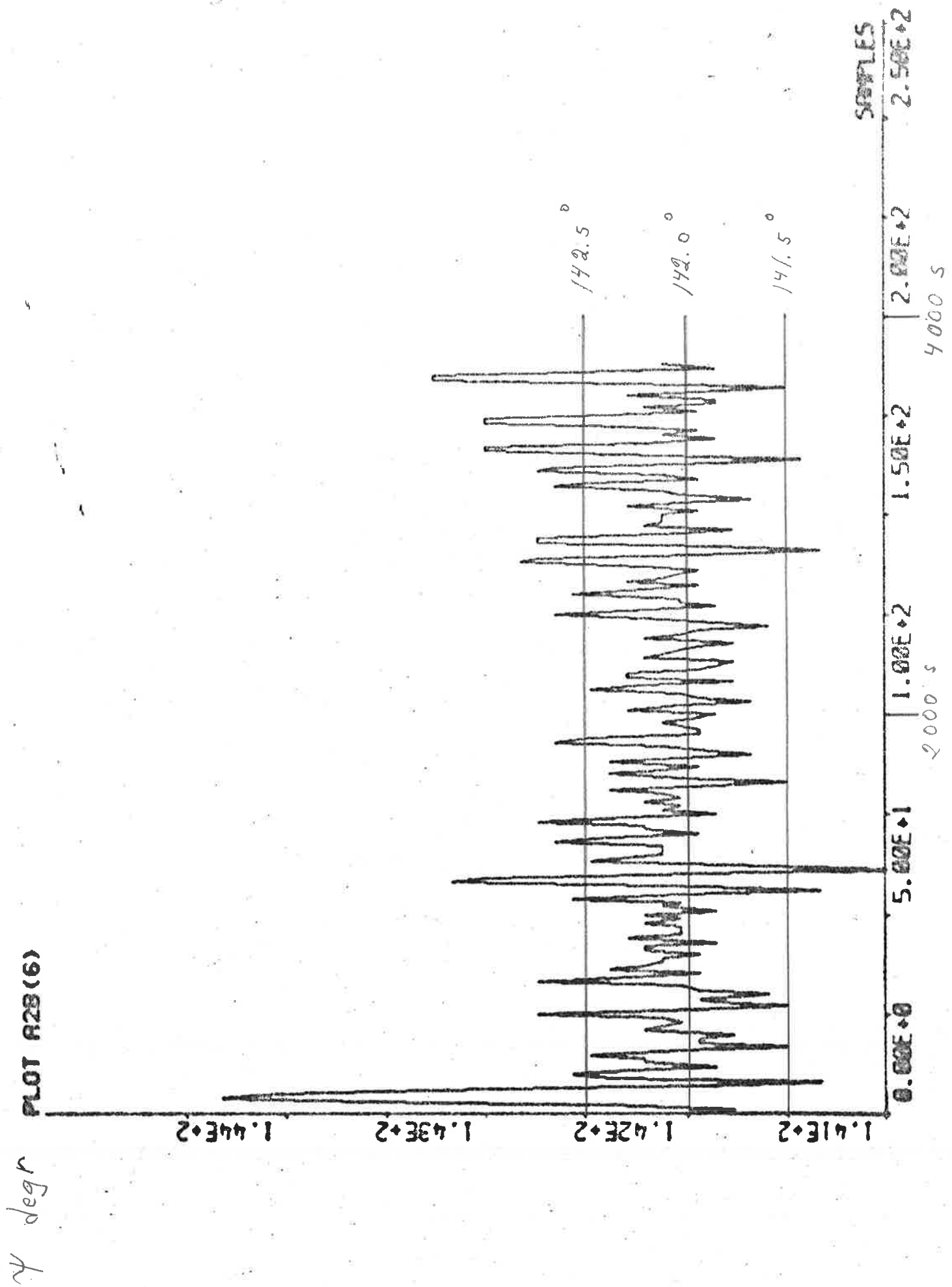

PLOT A28(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

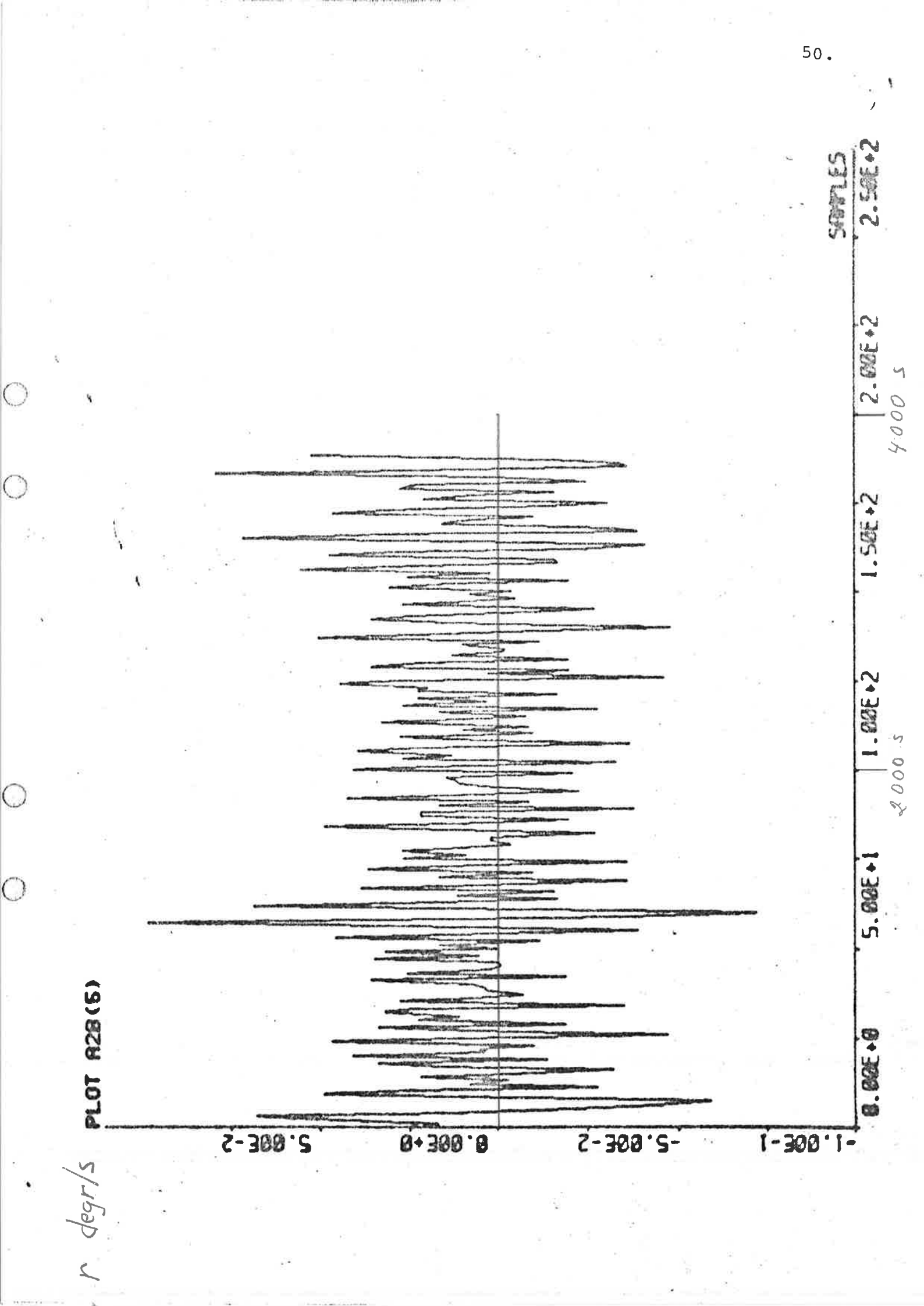

PLOT A2B(1)
SAMPLES
+3°
0°
-3°
+4°
-4°
1.300·1
5.300·0
0.300·0
-5.300·0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

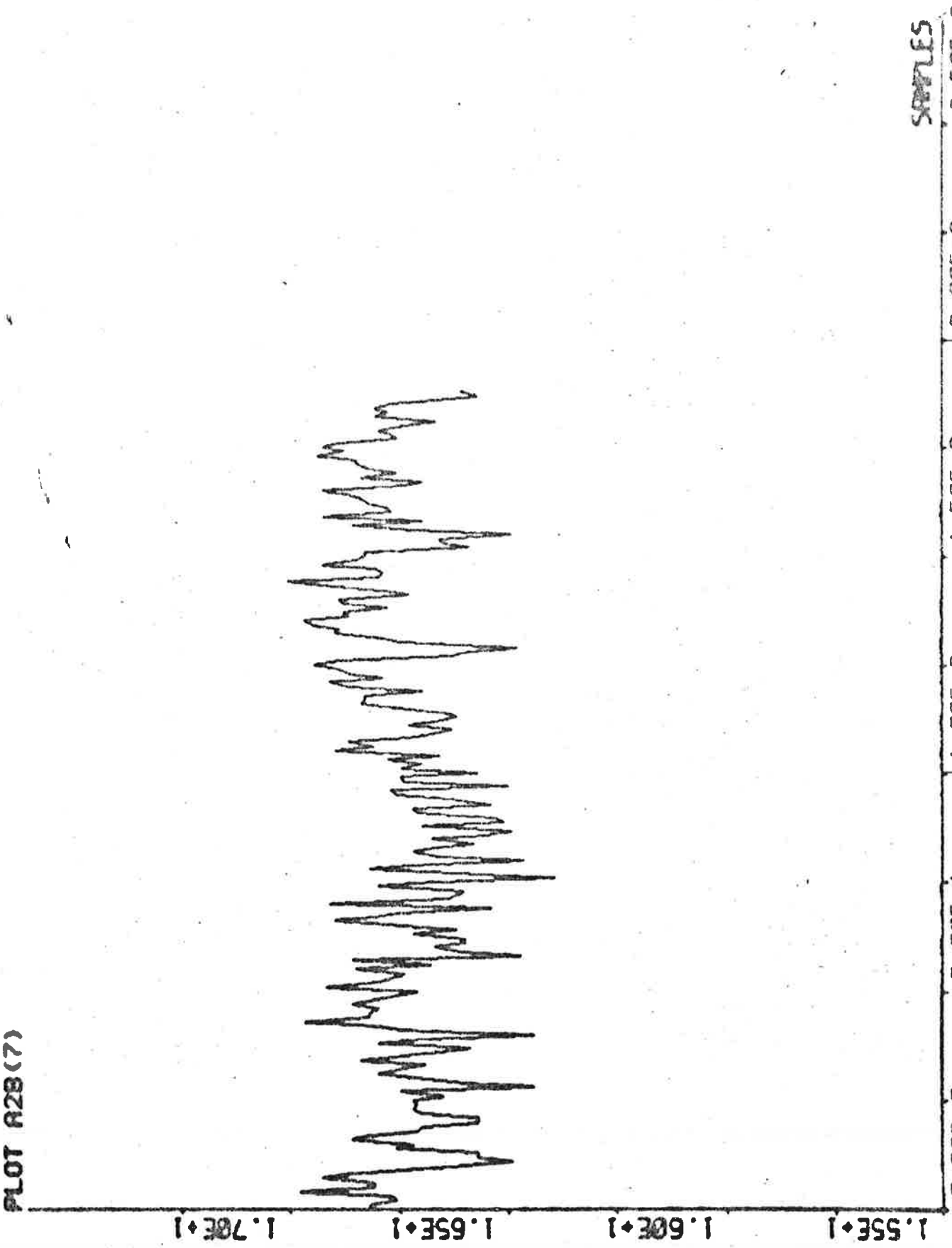
δ_s degr

V_2 knots

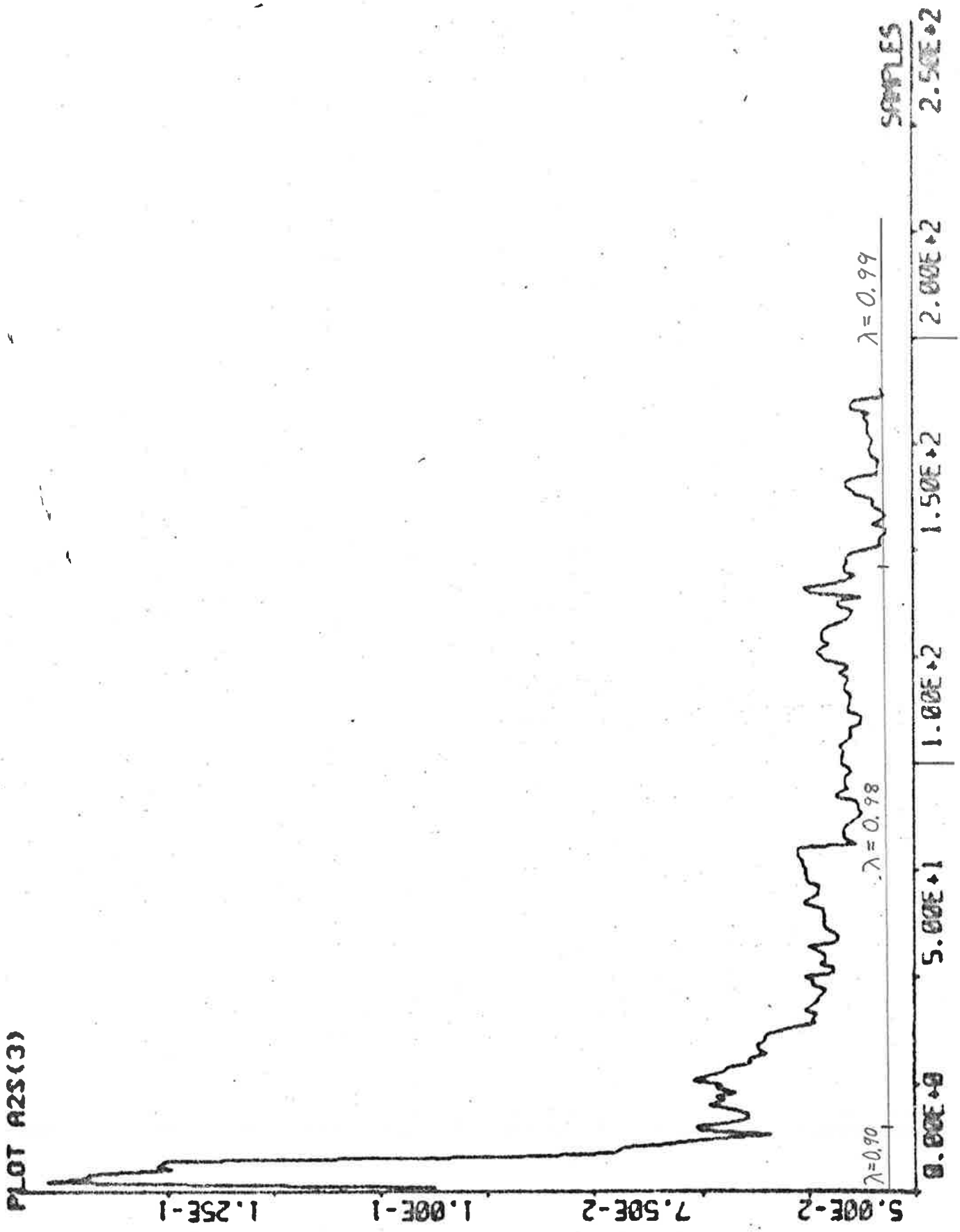

PLOT A2B(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s


PLOT R28(6)
ψ degr
1.41E+2
1.42E+2
1.43E+2
1.44E+2
142.5°
140.0°
141.5°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

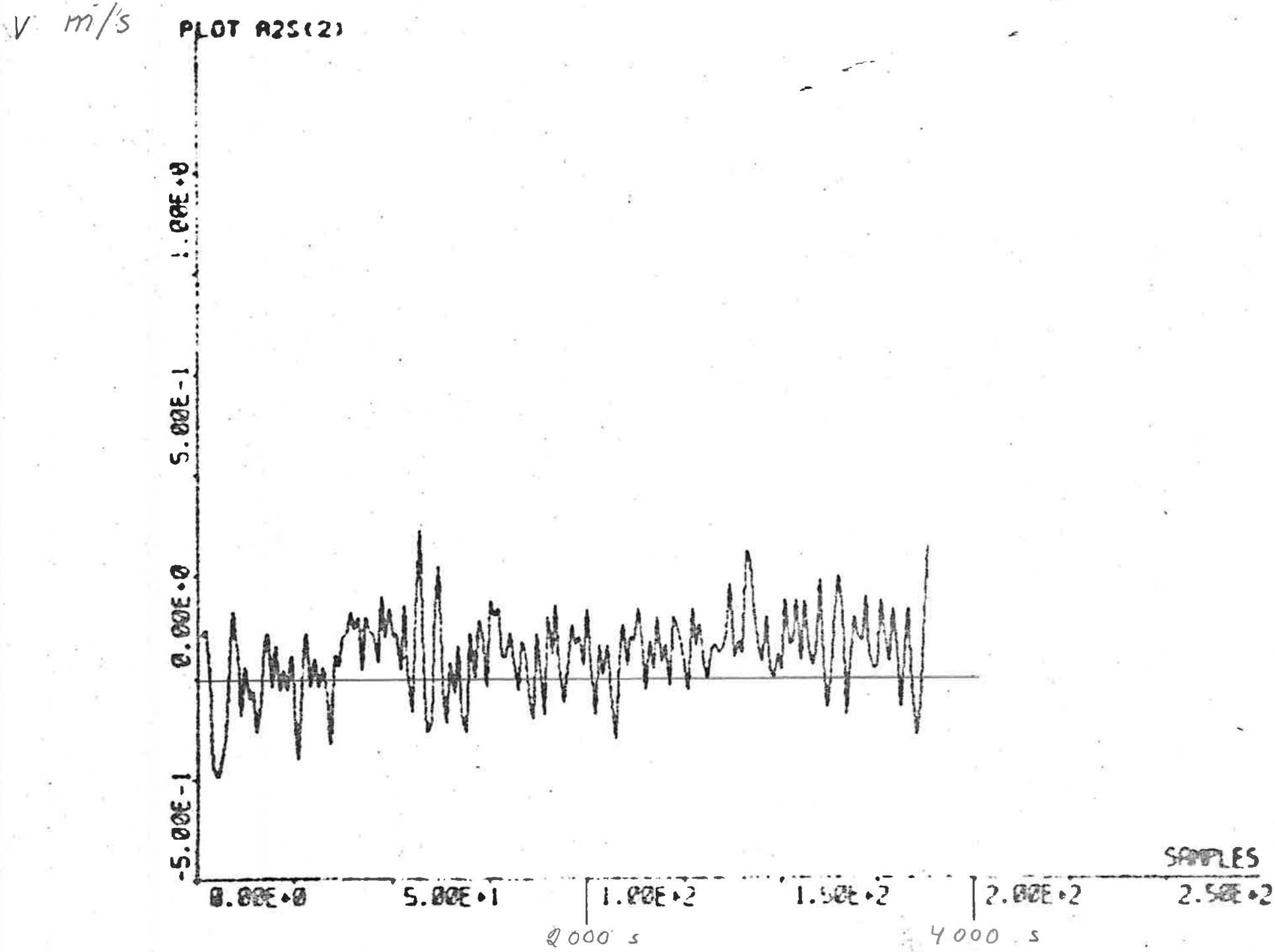

PLOT A28(5)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
-1.00E-1
-5.00E-2
0.00E+0
5.00E-2
r degr/s
4000 s
4000 s

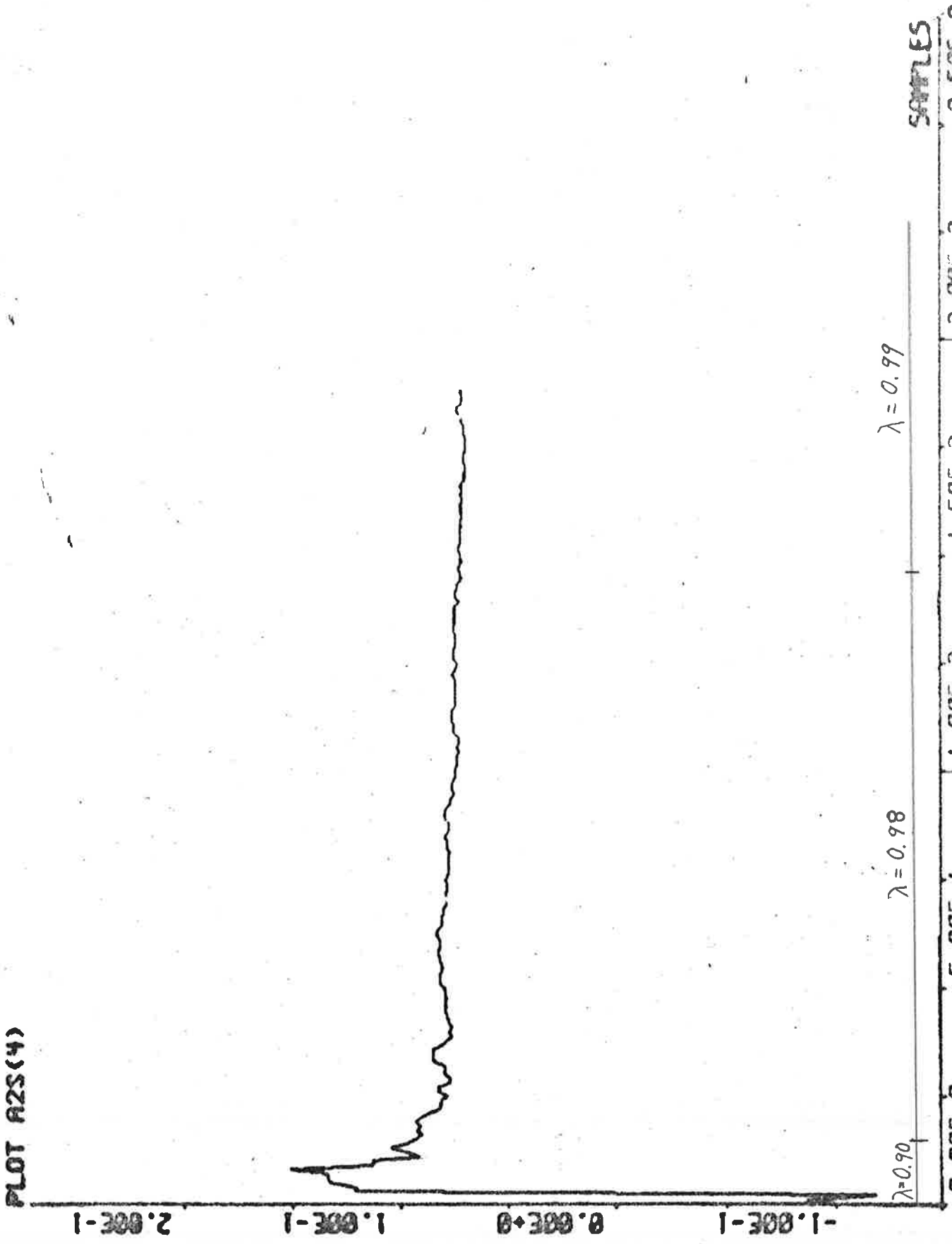

PLOT A23(7)
1.556+1
1.606+1
1.656+1
1.706+1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
2000 s
4000 s

U knots

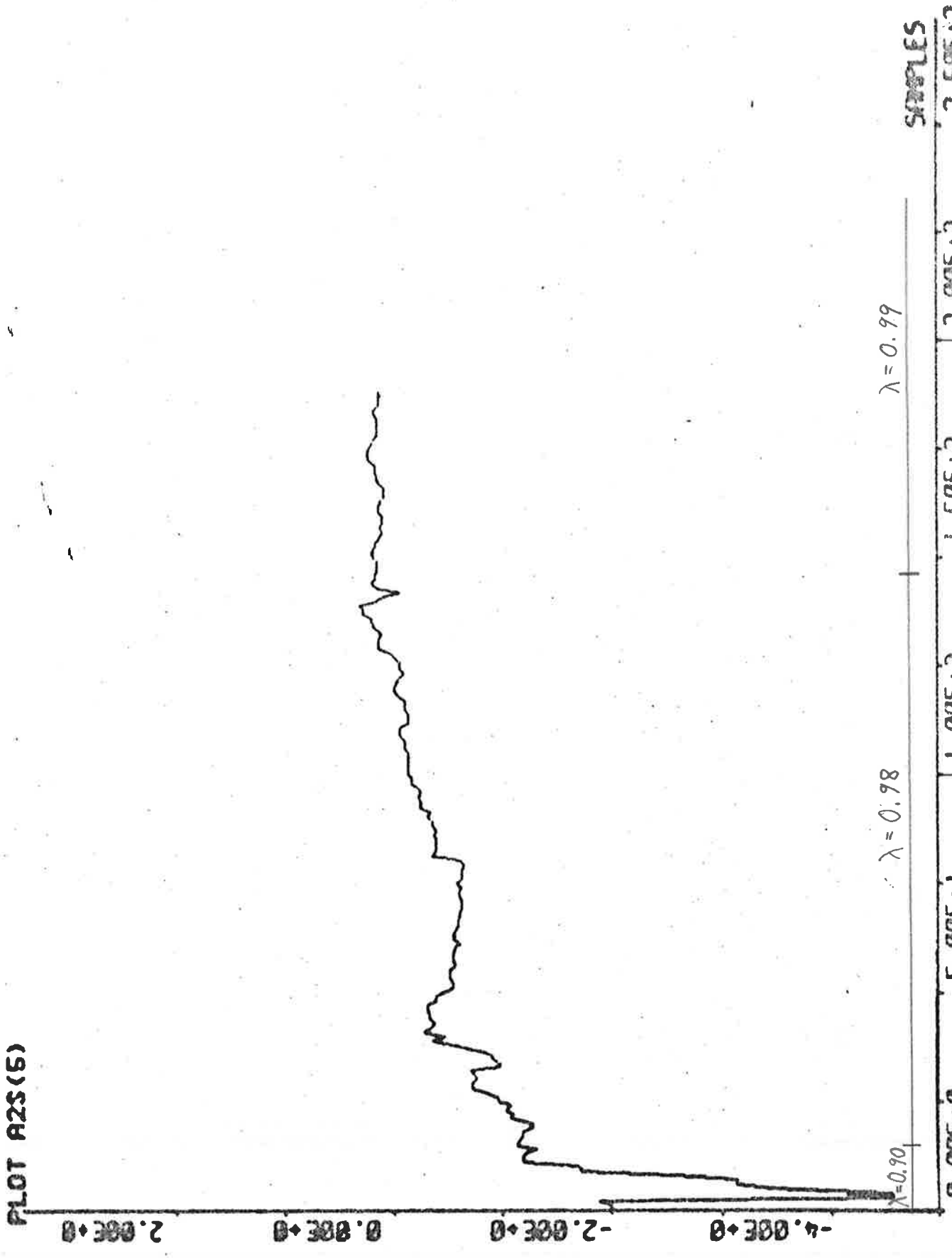

PLOT A2S(3)
5.00E-2
7.50E-2
1.00E-1
1.25E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.99
λ=0.98
λ=0.90
2000 s
4000 s

b_1

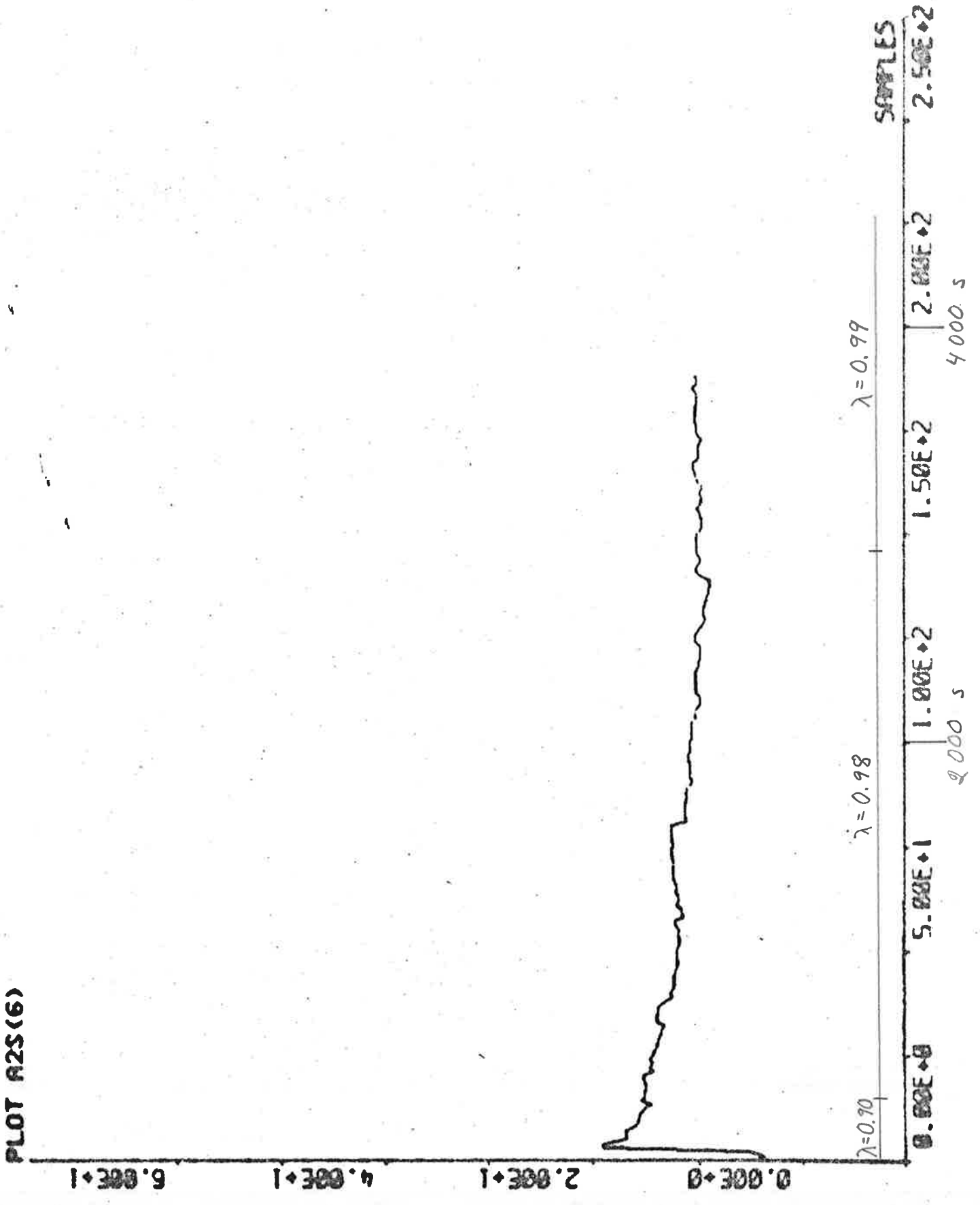

V m/s
PLOT A2S(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s


PLOT A2S(4)
1.300E-2
1.300E-1
0.300E+0
-1.300E-1
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
λ=0.90
λ=0.98
λ=0.99
2000 s
4000 s

b2


PLOT A2S(6)
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
λ=0.90
λ=0.98
λ=0.99
4000 s
4000 s

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:

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

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

Regulator:

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

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

Initial values:

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

Regulator:

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

Final values:

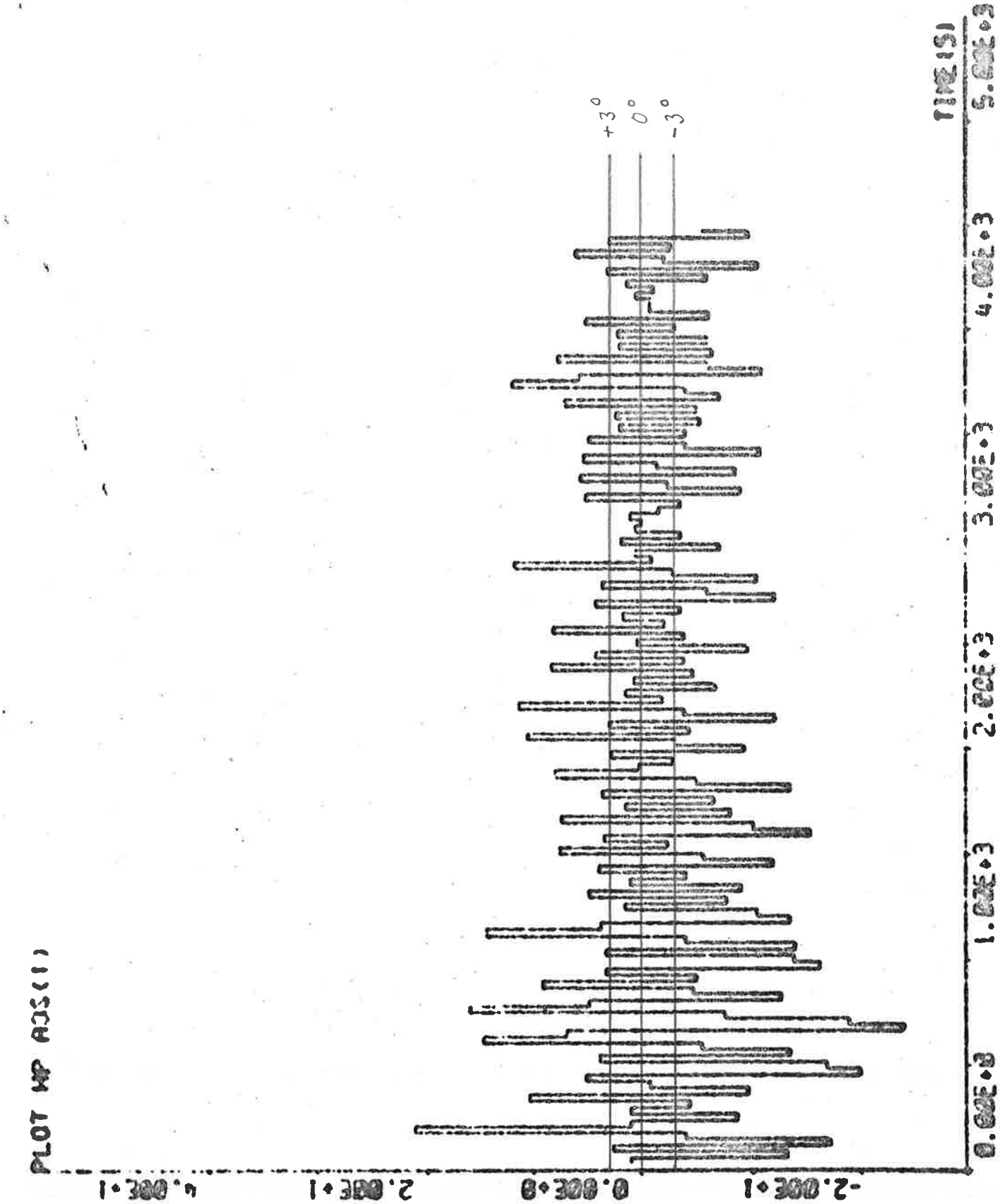
$$\begin{bmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.1243 \\ 0.1252 \\ 0.1451 \\ 11.1929 \end{bmatrix} \qquad P = \begin{bmatrix} 0.003153 & & & \\ -0.0004958 & 0.002615 & & \\ -0.01788 & 0.007169 & 0.9782 & \\ 0.3555 & -0.2717 & -5.138 & 78.06 \end{bmatrix}$$

Regulator:

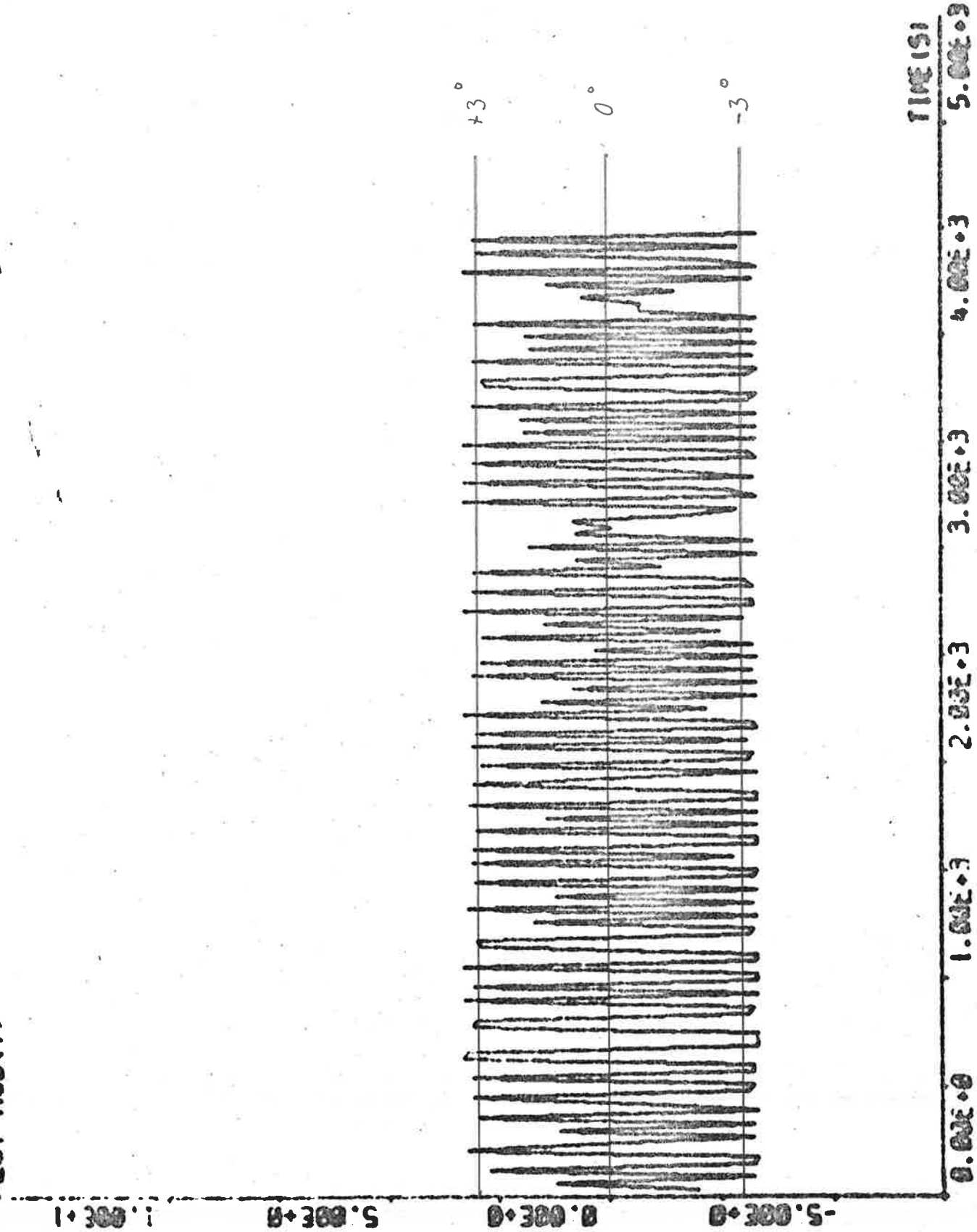
$$\delta(t) = -8.0451(\Psi(t) - \Psi_{ref}) - 1.0072\delta(t-1) - 1.1673v(t) - 90.0475r(t)$$

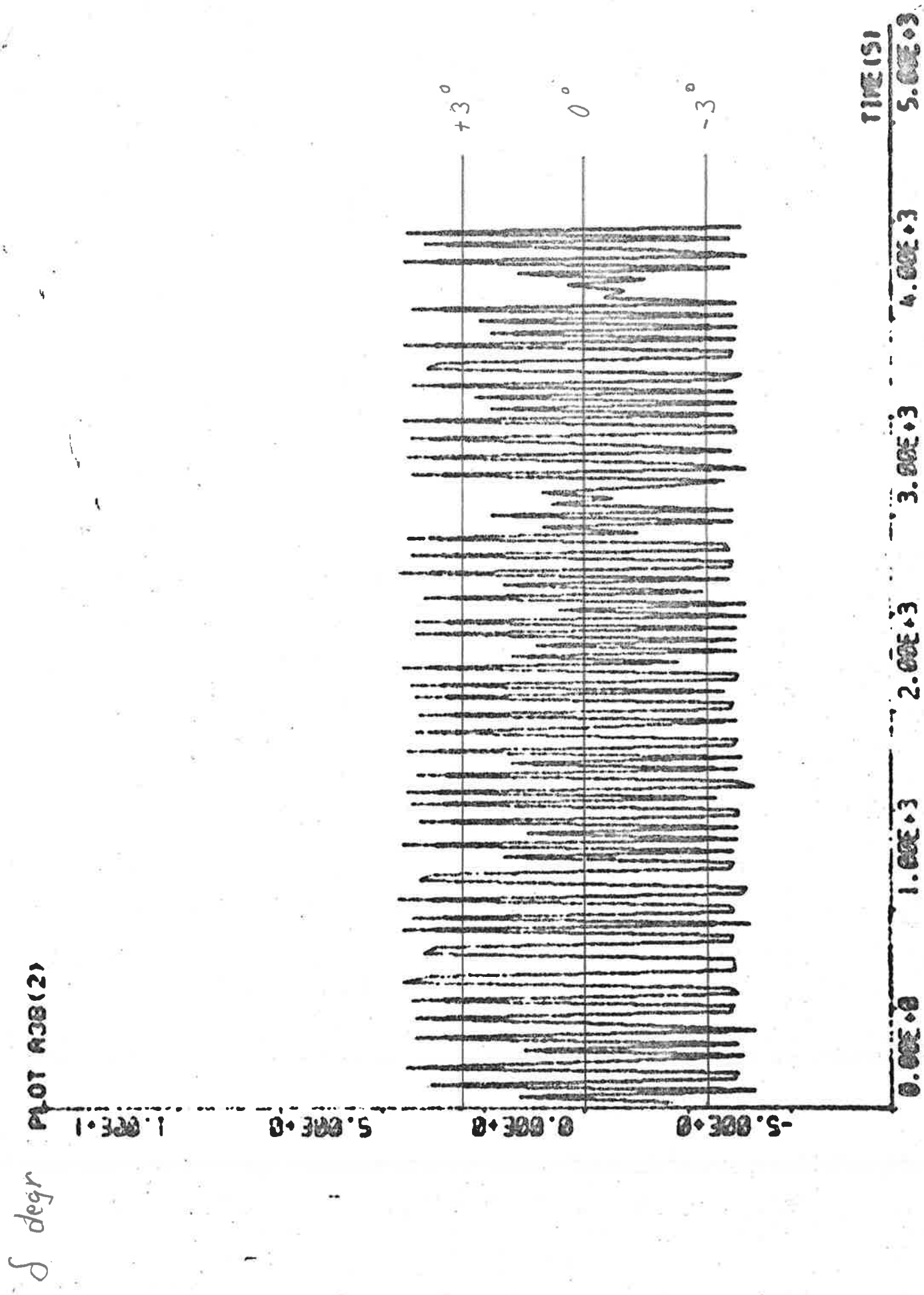
Statistics:

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

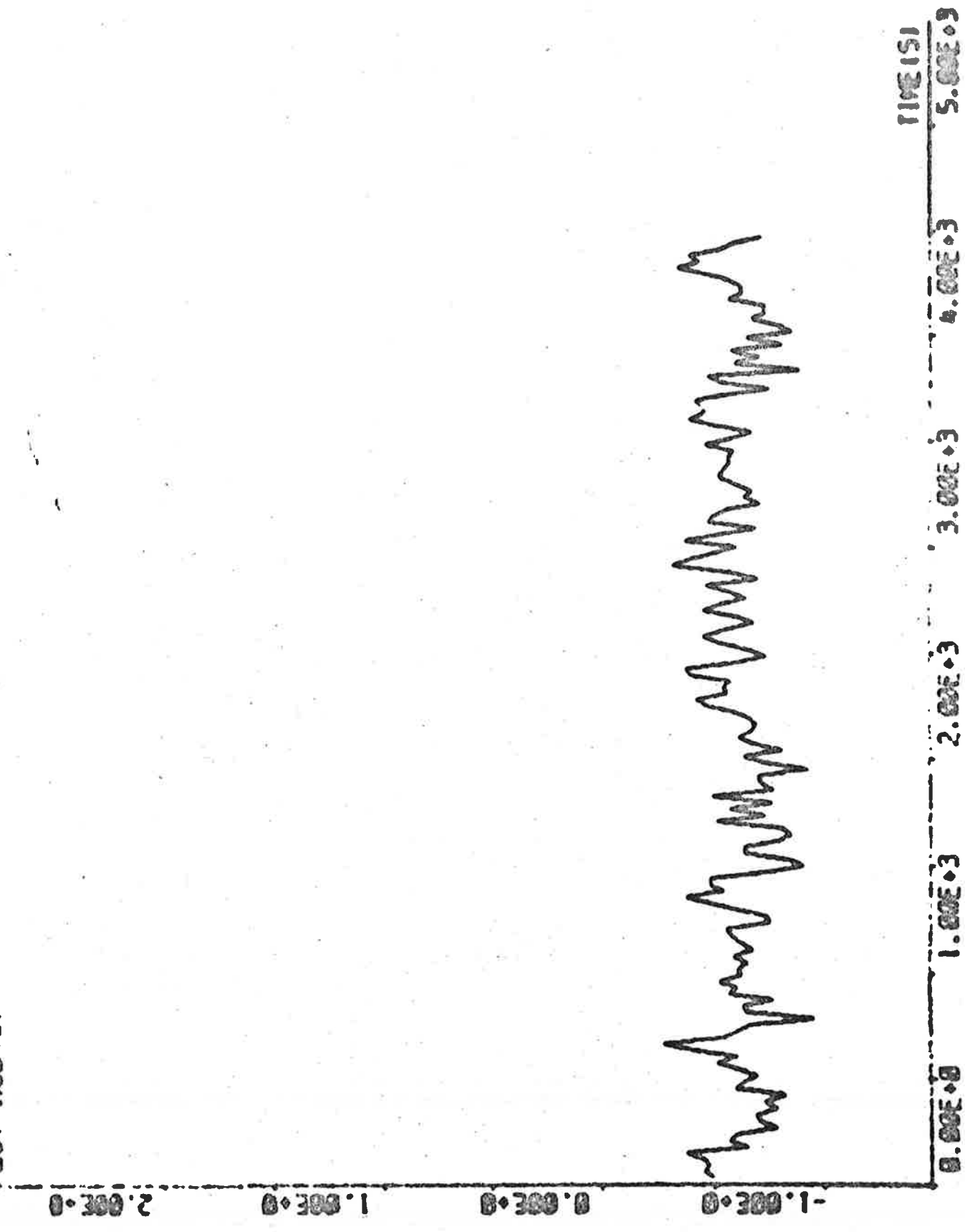


δ_{com} degr


PLOT A3B(1)
TIME(S)
+3°
0°
-3°
δs degr

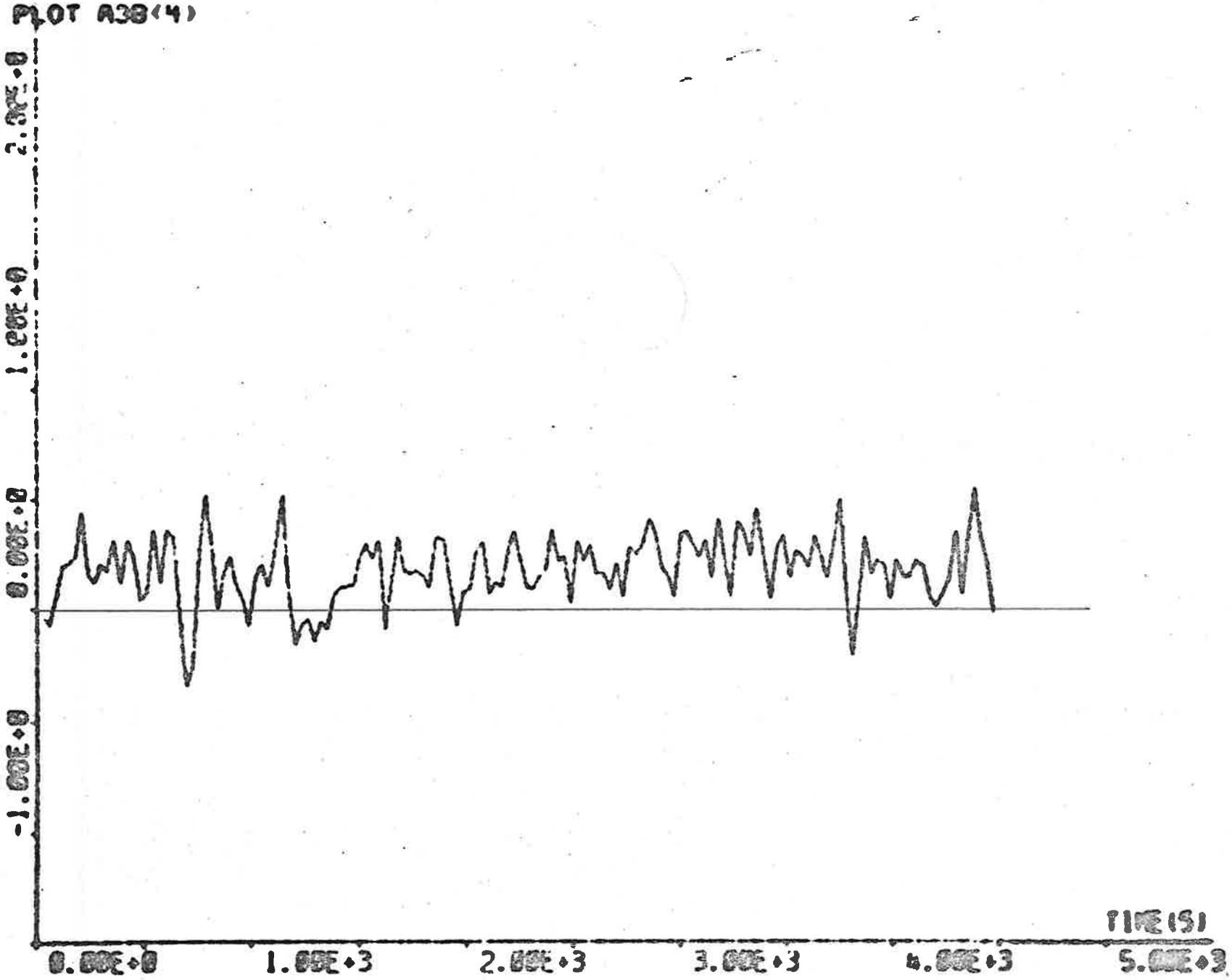

PLOT A3B(2)
TIME(S)
+3°
0°
-3°
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

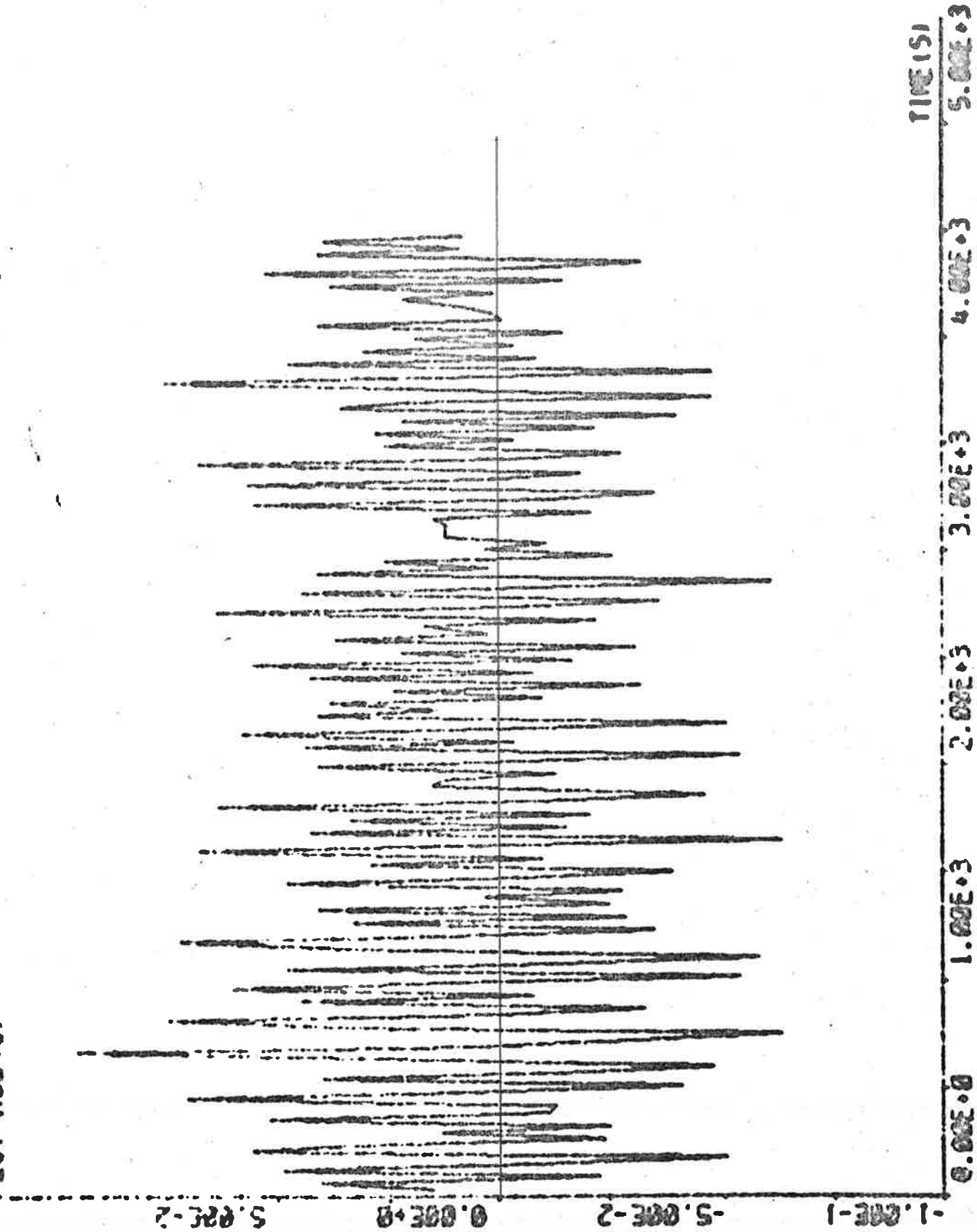
δ degr

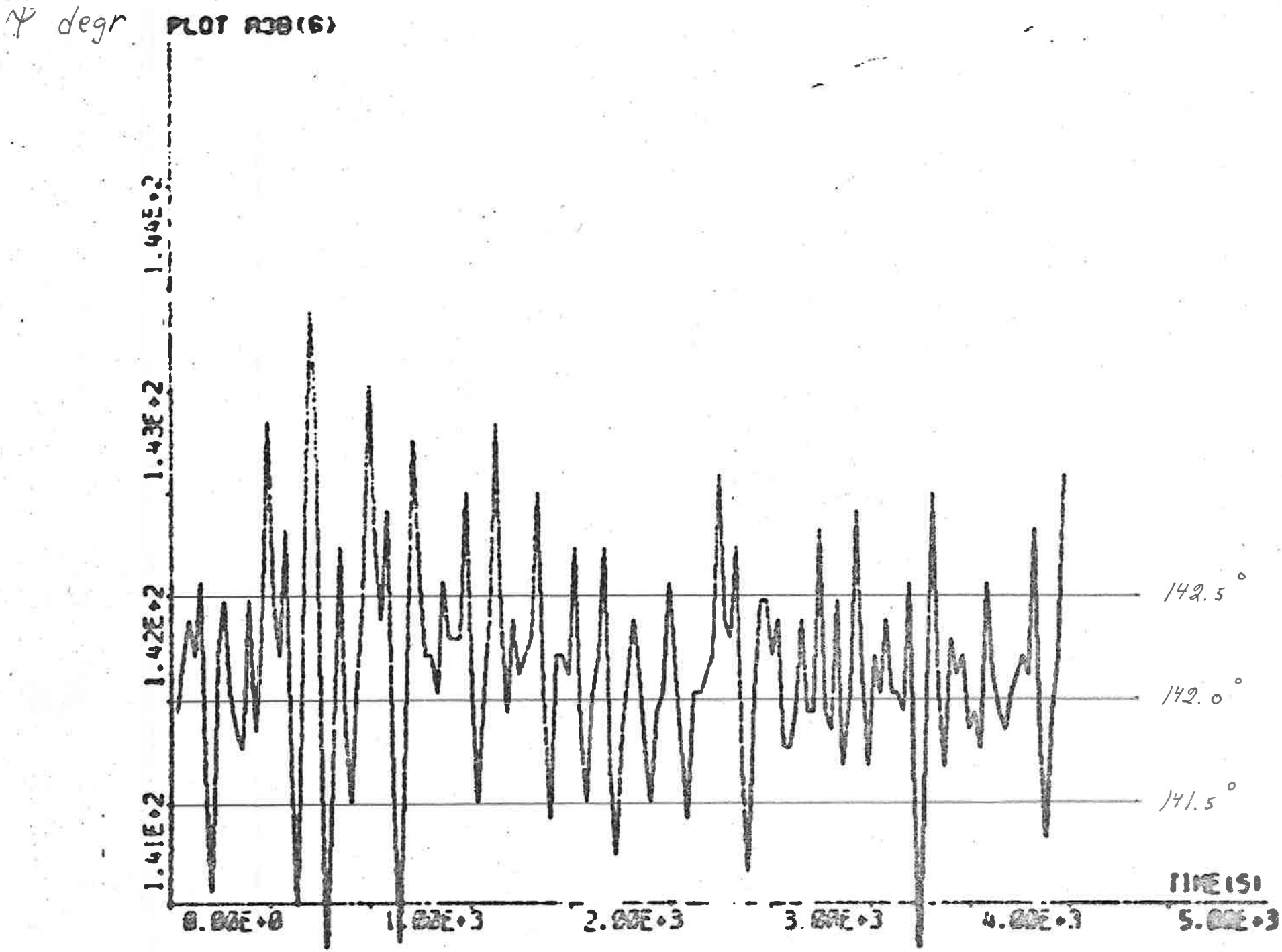

PLOT AC3(3)
2.00E-1
1.00E-1
0.00E+0
-1.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

V_1 knots

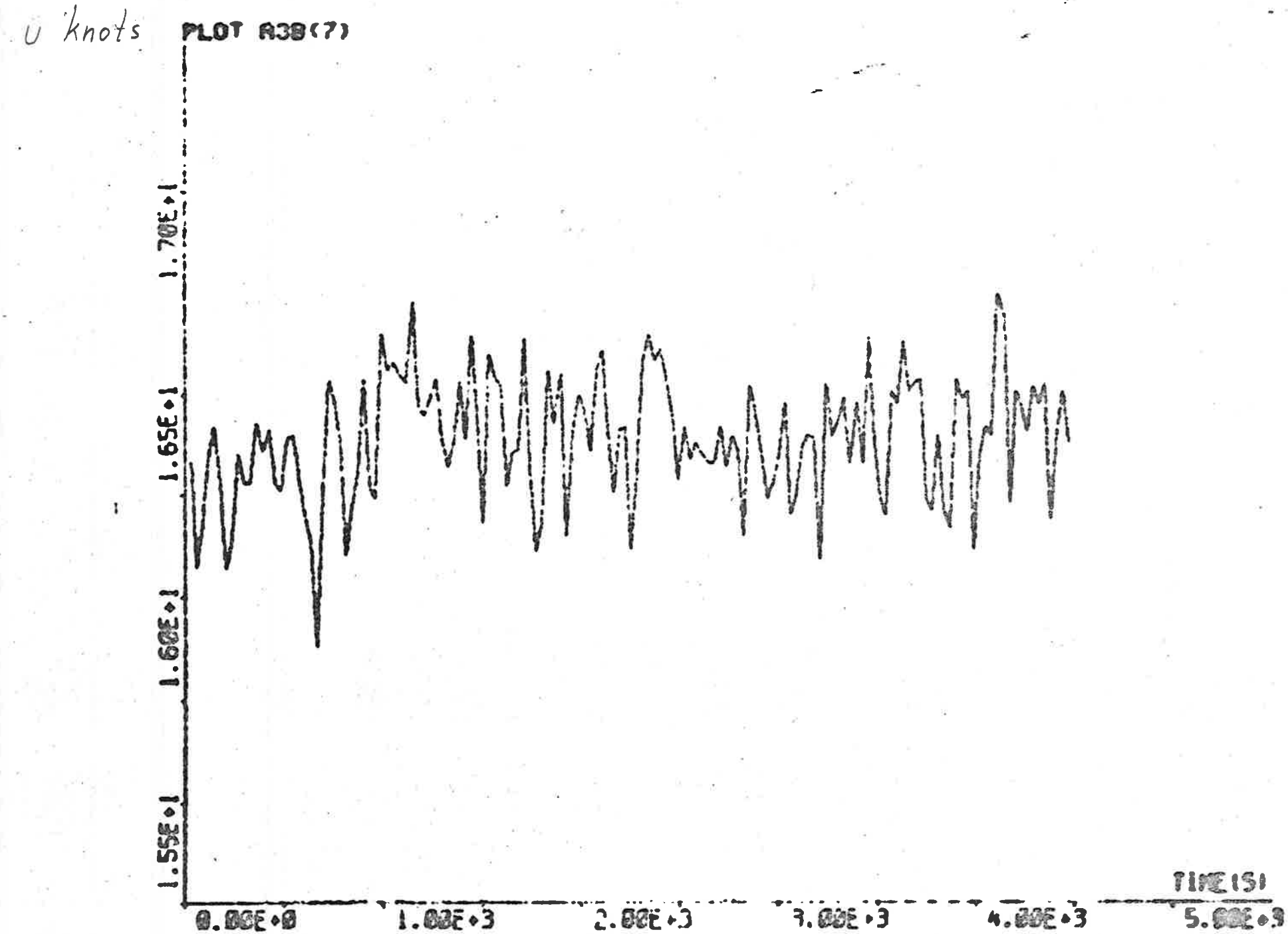
V_2 knots

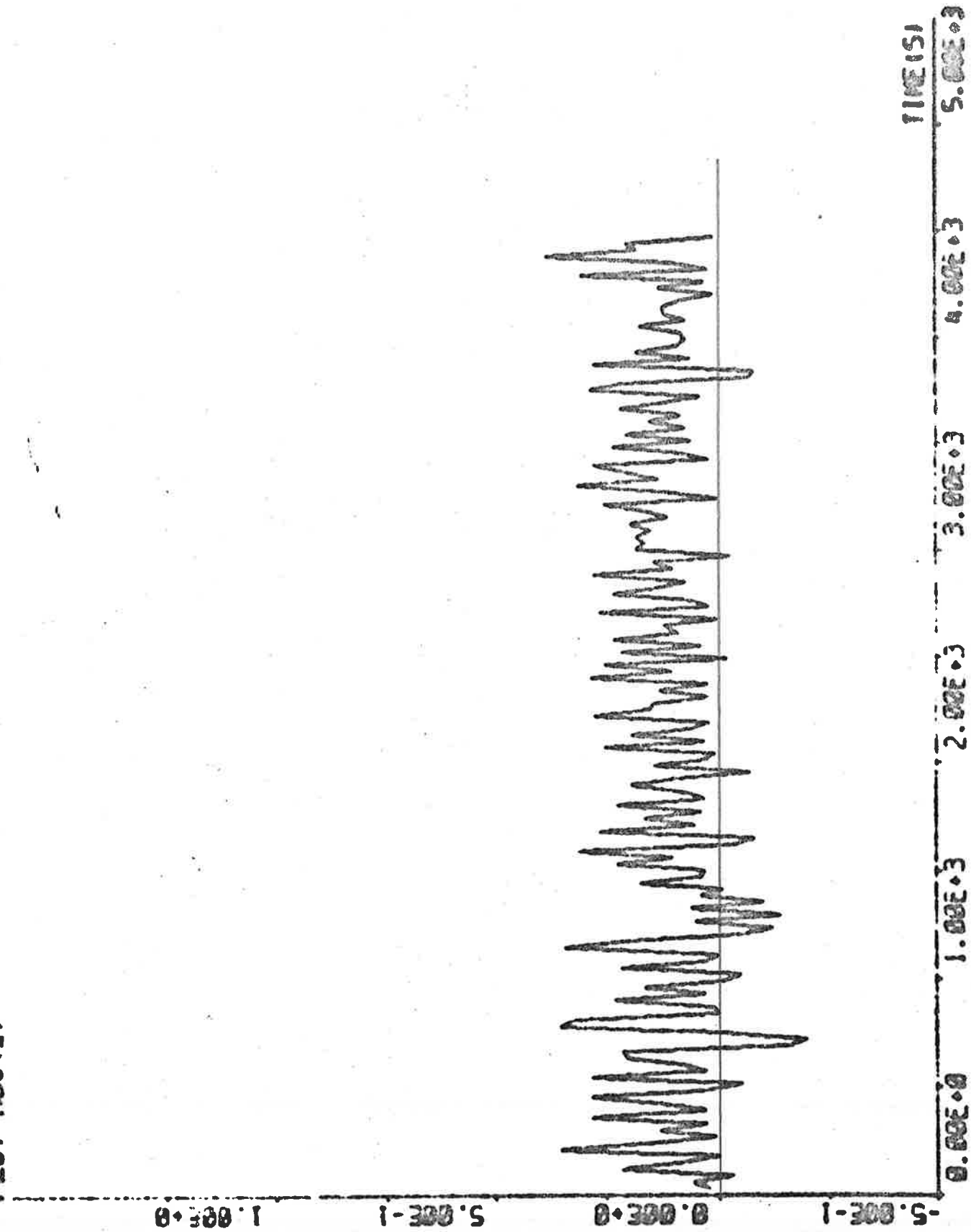

PLOT A38(4)
2.0E+0
1.0E+0
0.0E+0
-1.0E+0
TIME(S)
0.0E+0
1.0E+3
2.0E+3
3.0E+3
4.0E+3
5.0E+3

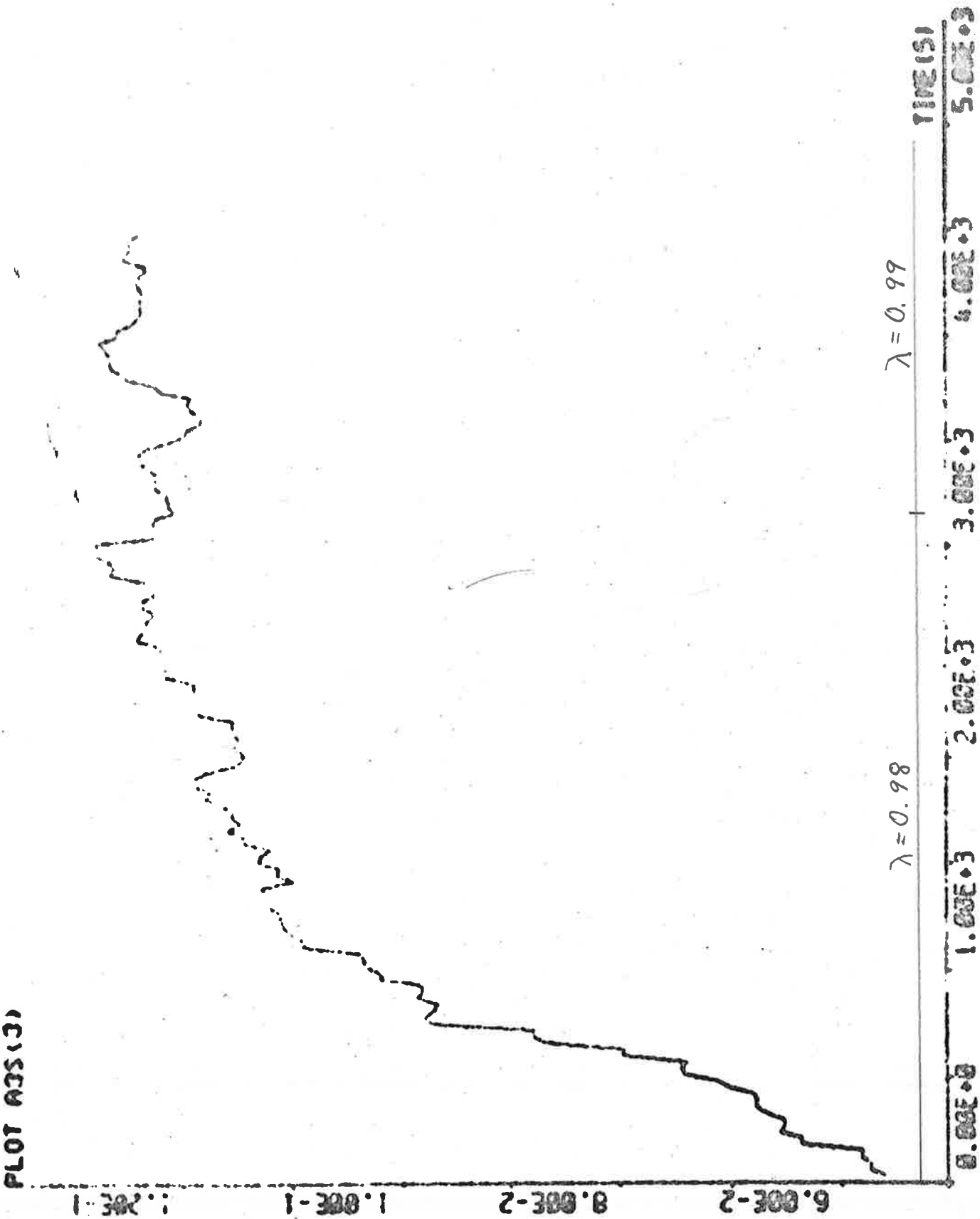

PLOT A3B(S)
r degr/s
-1.00E-1
-5.00E-2
0.00E+0
5.00E-2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)



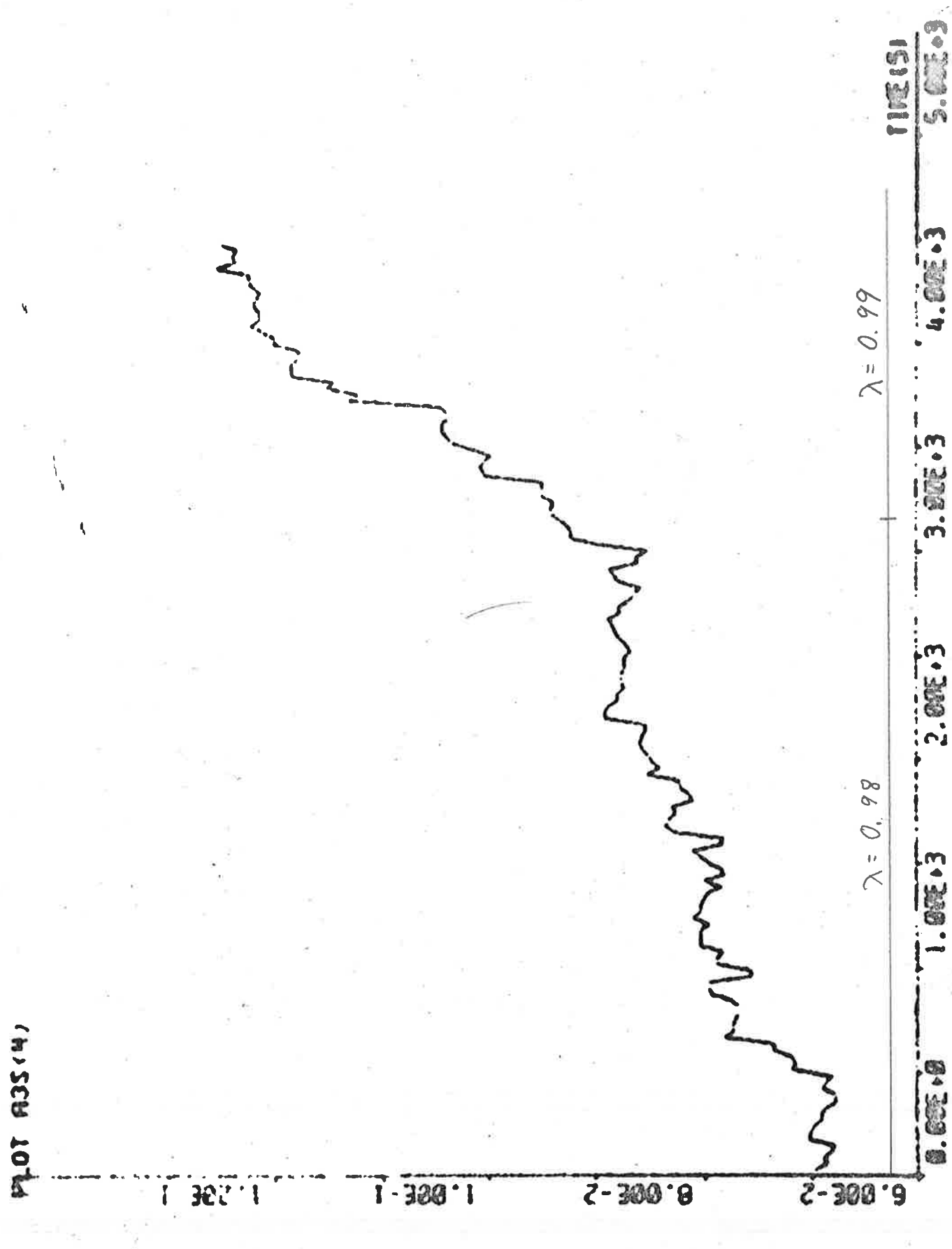
ψ degr
PLOT A3B(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
142.5°
142.0°
141.5°
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


u knots
PLOT A3B(7)
1.70E+1
1.65E+1
1.60E+1
1.55E+1
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

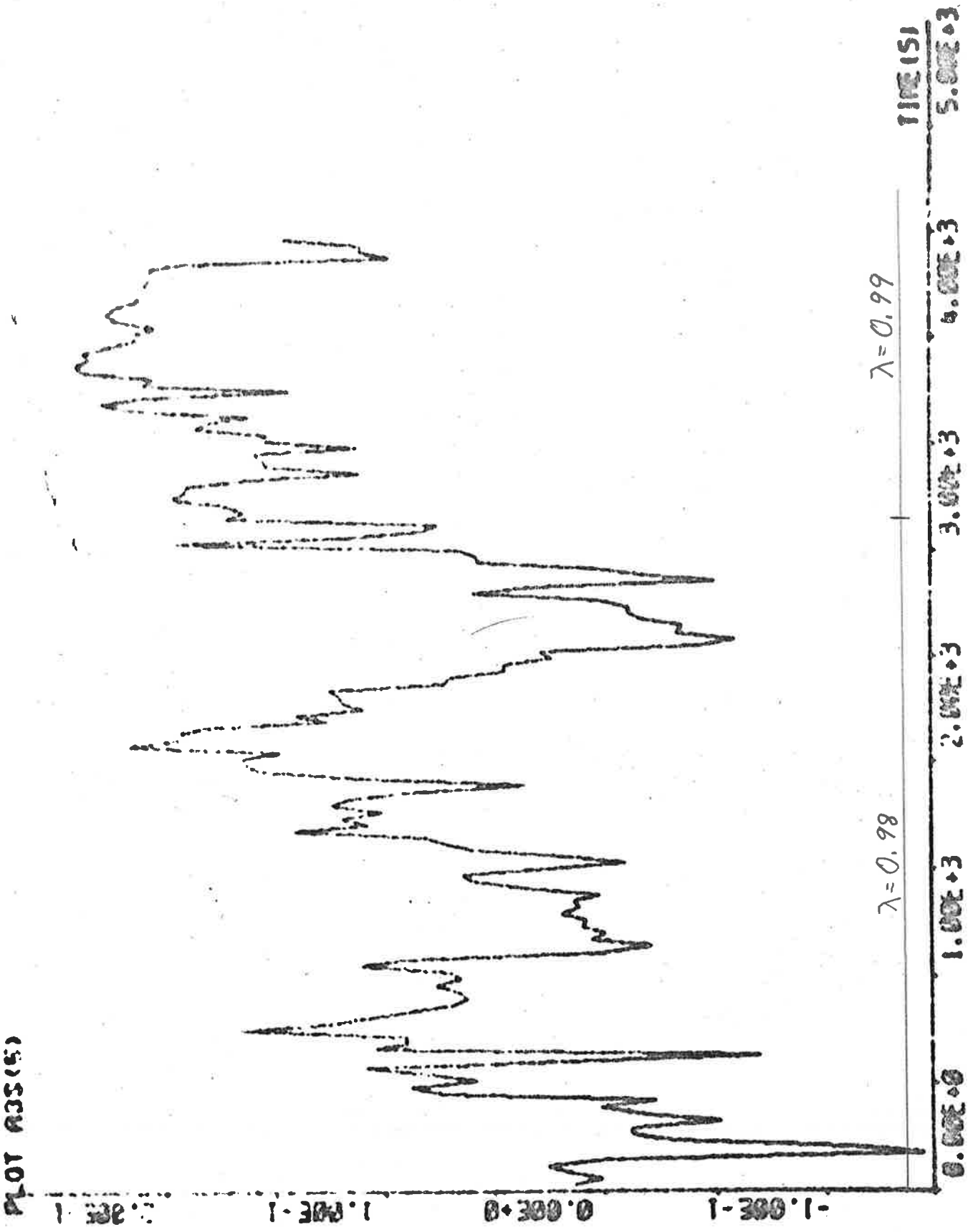

PLOT ACS(2)
V m/s
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)


PLOT AXIS(3)
1.38E-1
1.38E-1
8.38E-2
6.38E-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

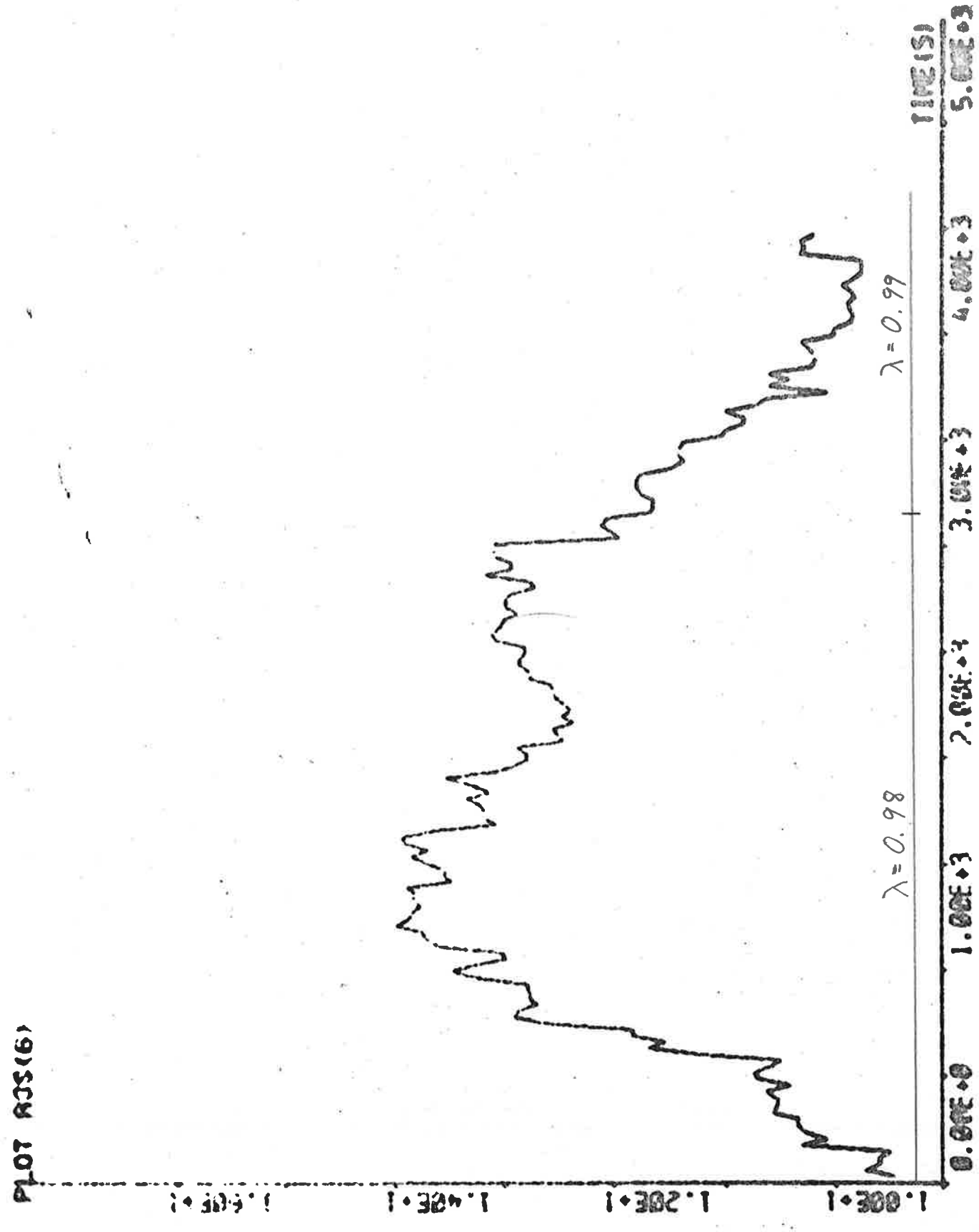
b_1


PLOT A3S(4)
1.30E-1
1.00E-1
8.00E-2
6.00E-2
0.00+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
λ = 0.98
λ = 0.99

b_2


PLOT ABS(S)
TIME(S)
λ=0.98
λ=0.99
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

d_1


PLOT RES(6)
1.300E-1
1.302E-1
1.304E-1
1.306E-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

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: $\pm 3^{\circ}$

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

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:

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

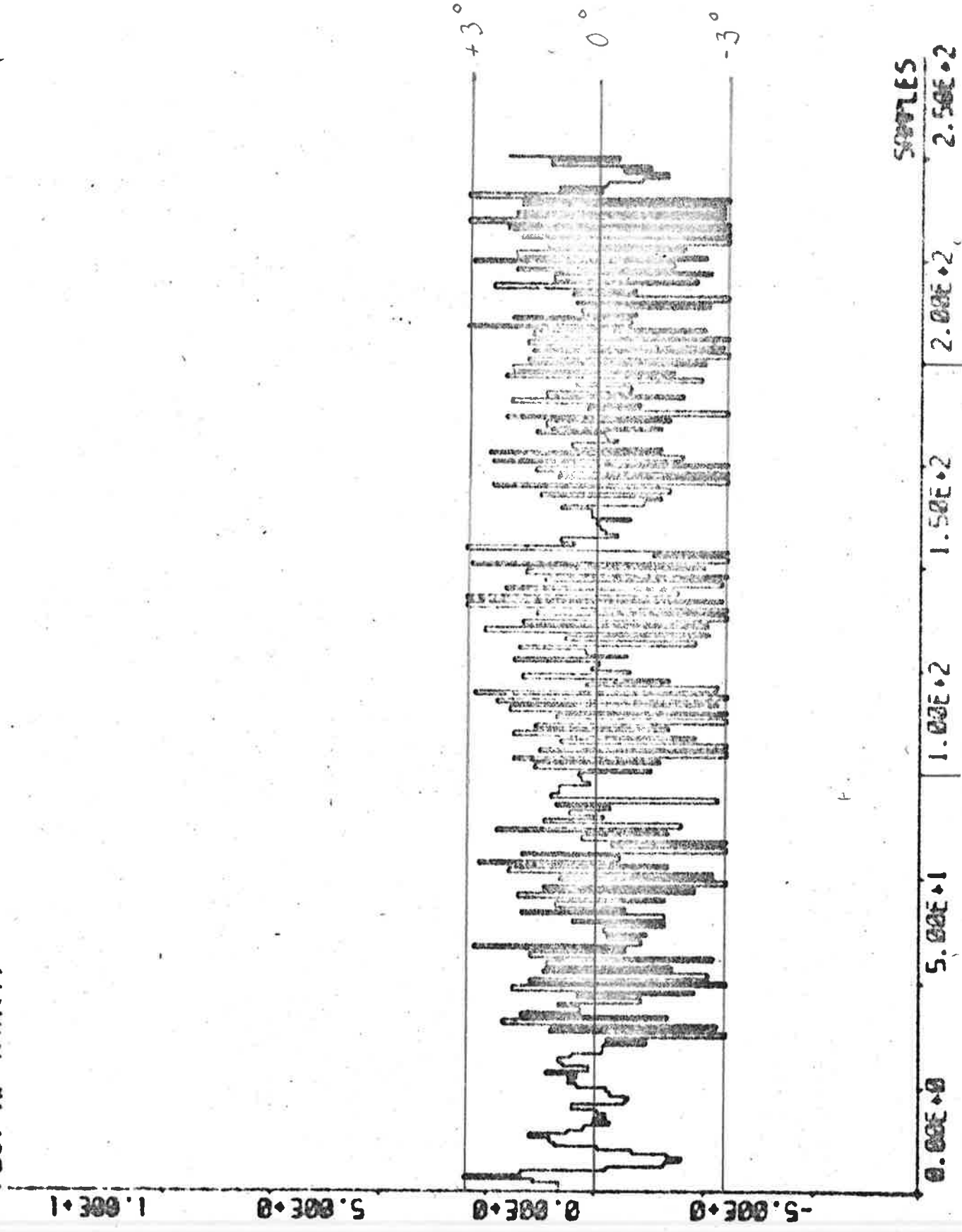
Regulator:

$$\delta(t) = -8.3403(\Psi(t) - \Psi_{ref}) - 1.3328\delta(t-1) - 16.3937\hat{v}(t) +$$

$$+ 14.2811\hat{r}(t) + 154.3019\hat{F}(t) - 19.8265\hat{M}(t)$$

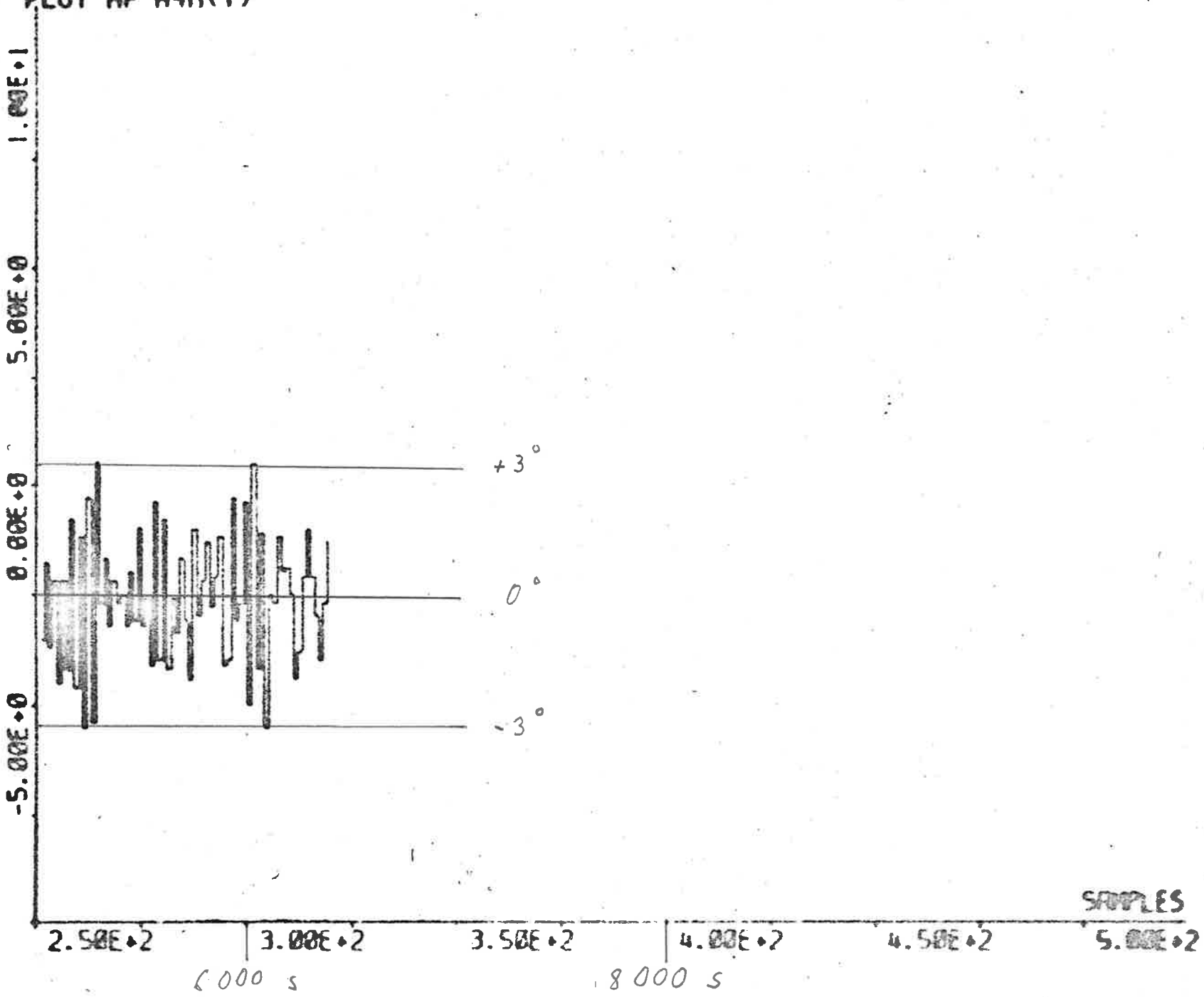
Statistics:

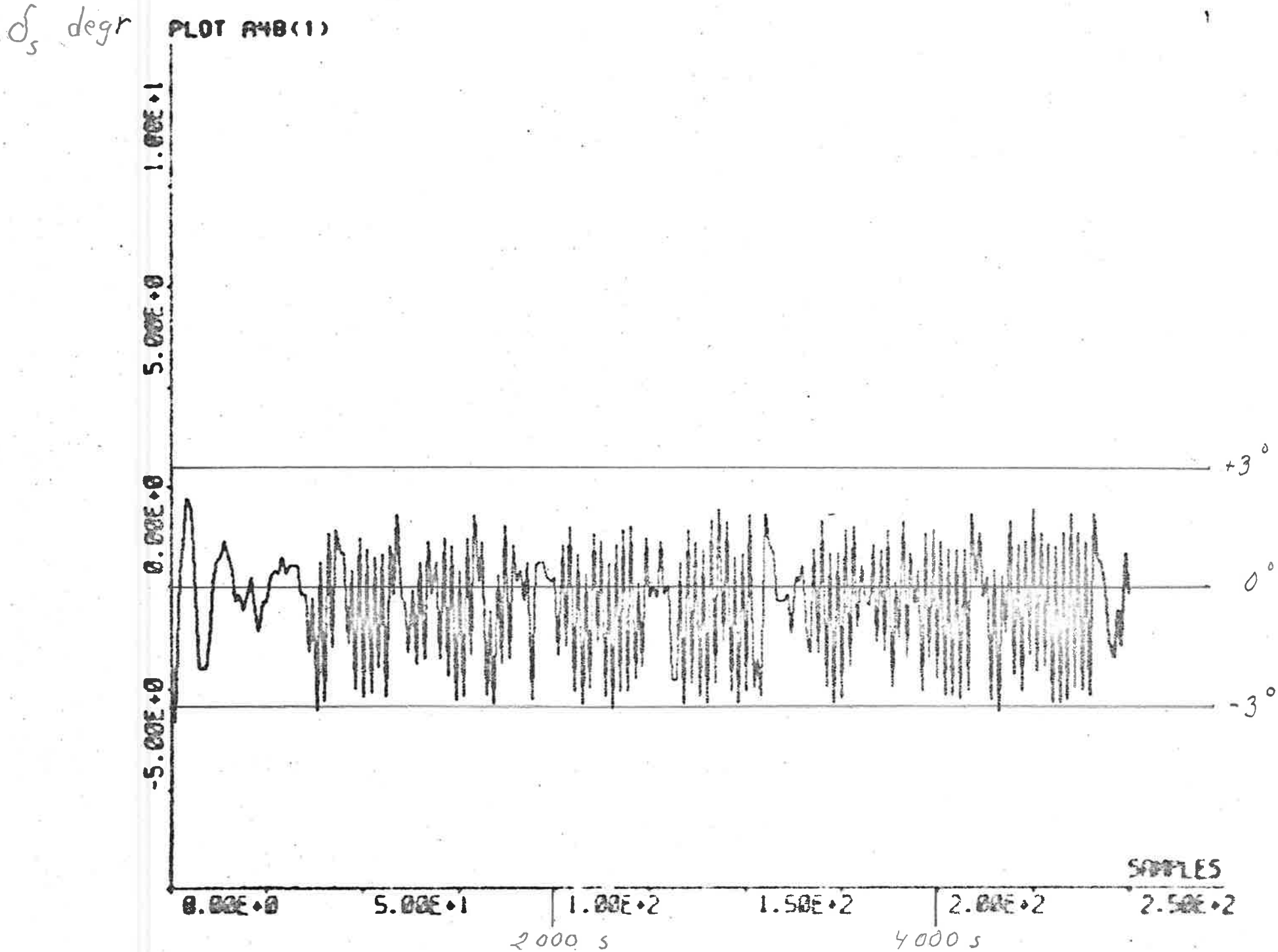
	0 - 6360 s (all data)				4000 - 6360 s			
	Mean value	Standard deviation	Minimum value	Maximum value	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.18	1.73	-3.0	3.0	-0.17	1.73	-3.0	3.0
δ_s degr	-0.38	1.47	-3.3	2.2	-0.33	1.45	-3.1	1.9
δ degr	-0.65	1.58	-4.1	2.6	-0.63	1.55	-3.7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



δ_{com} degr

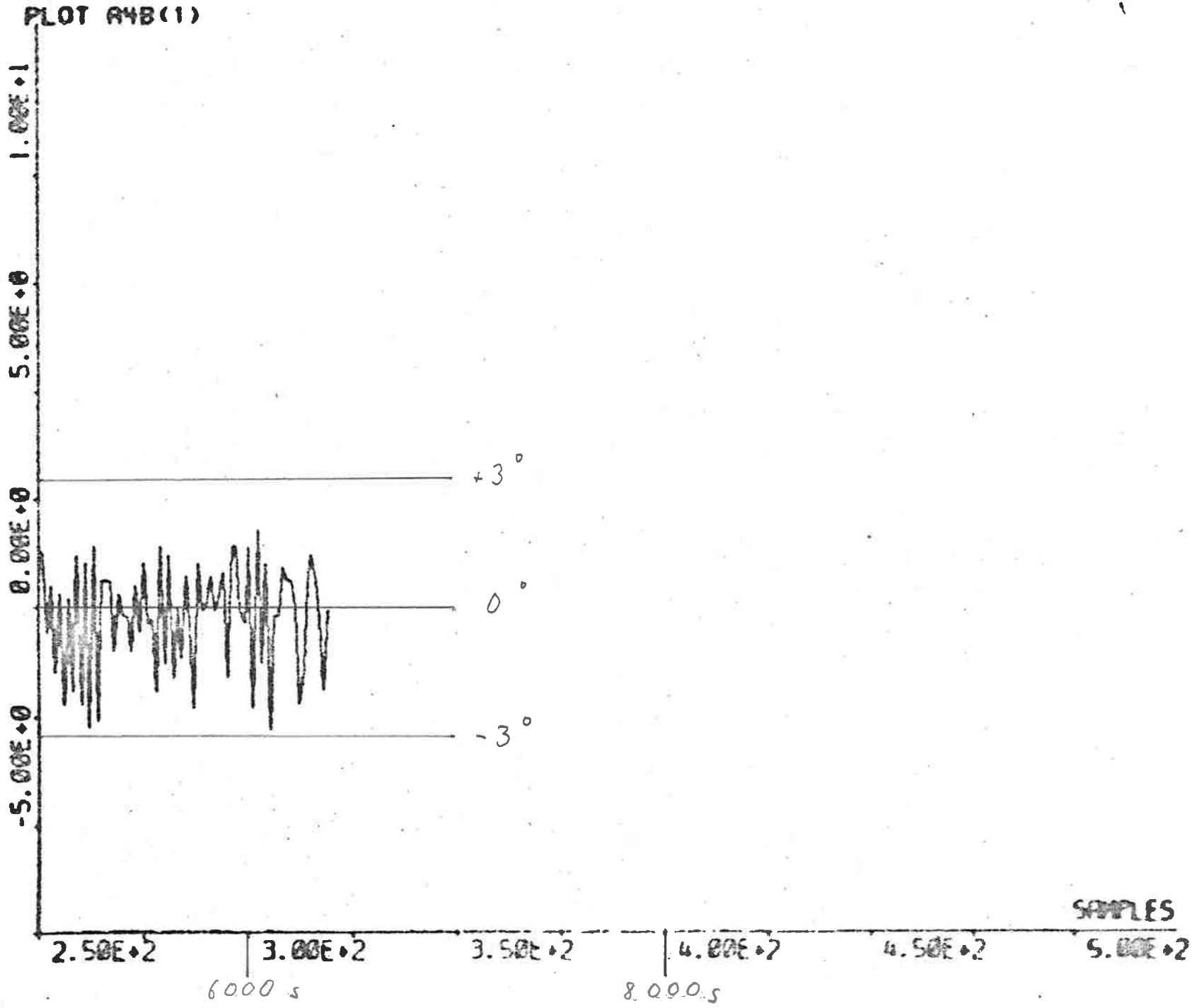
δ_{com} degr

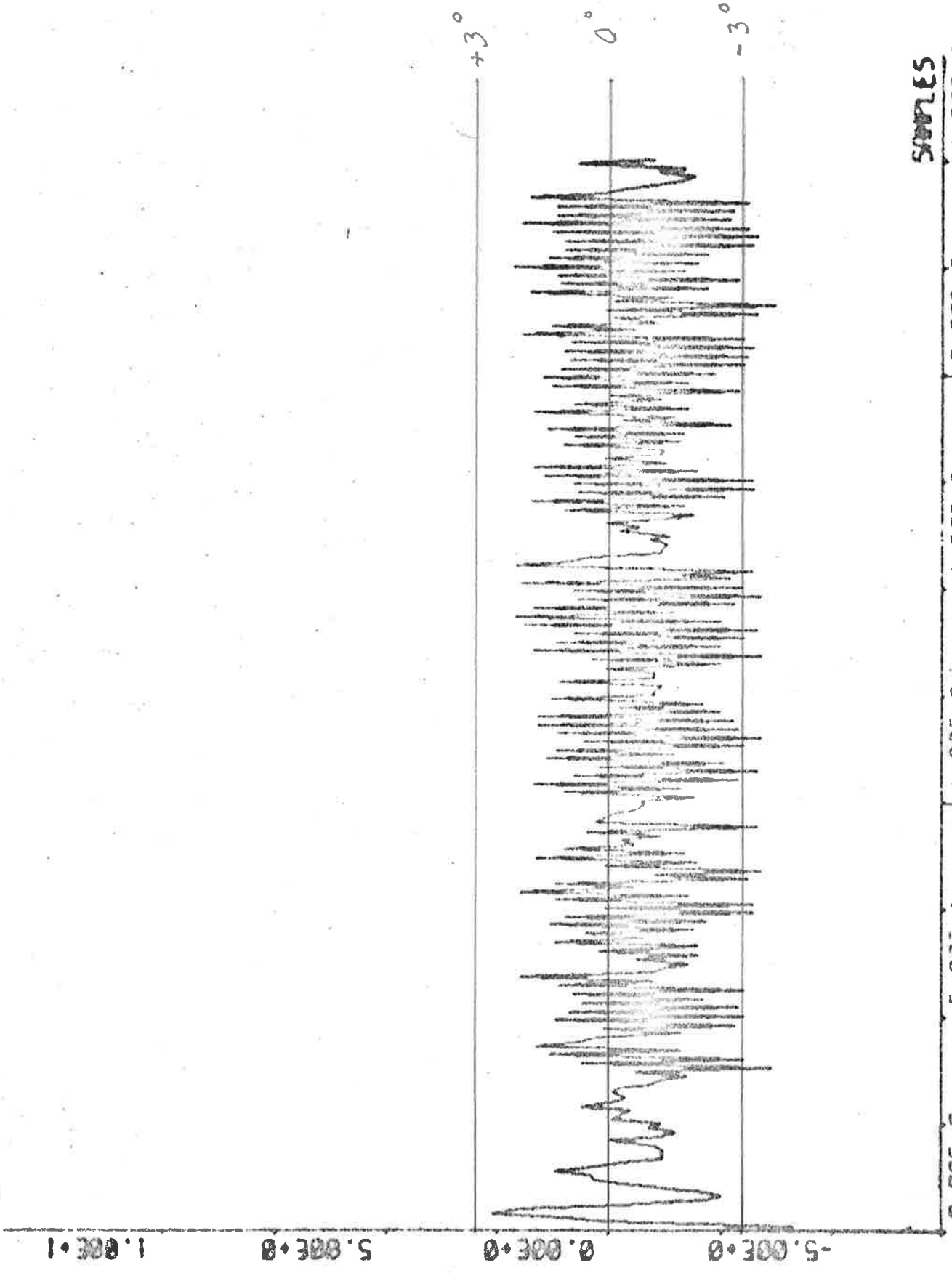


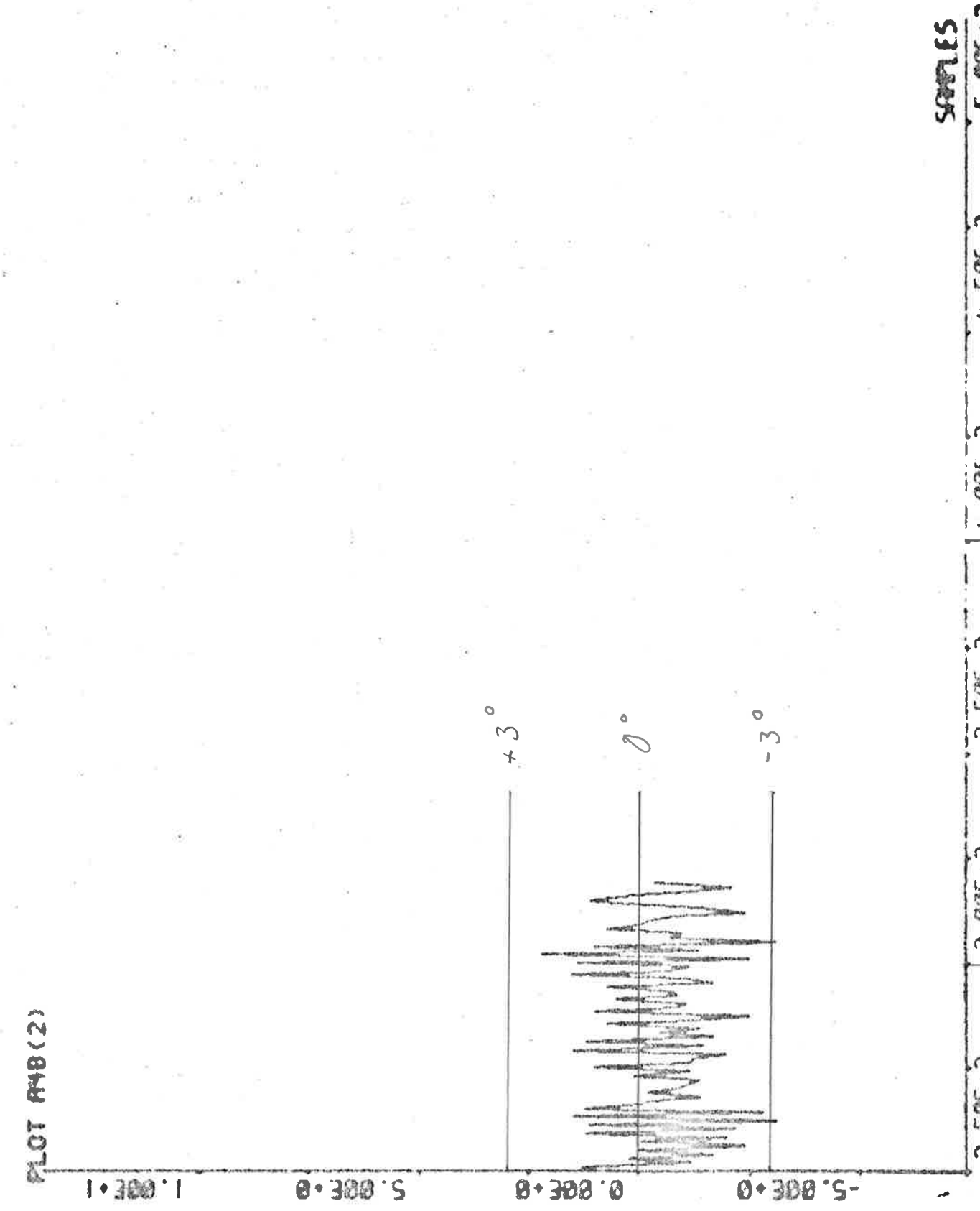


δ_s degr
PLOT A4B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
0°
-3°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

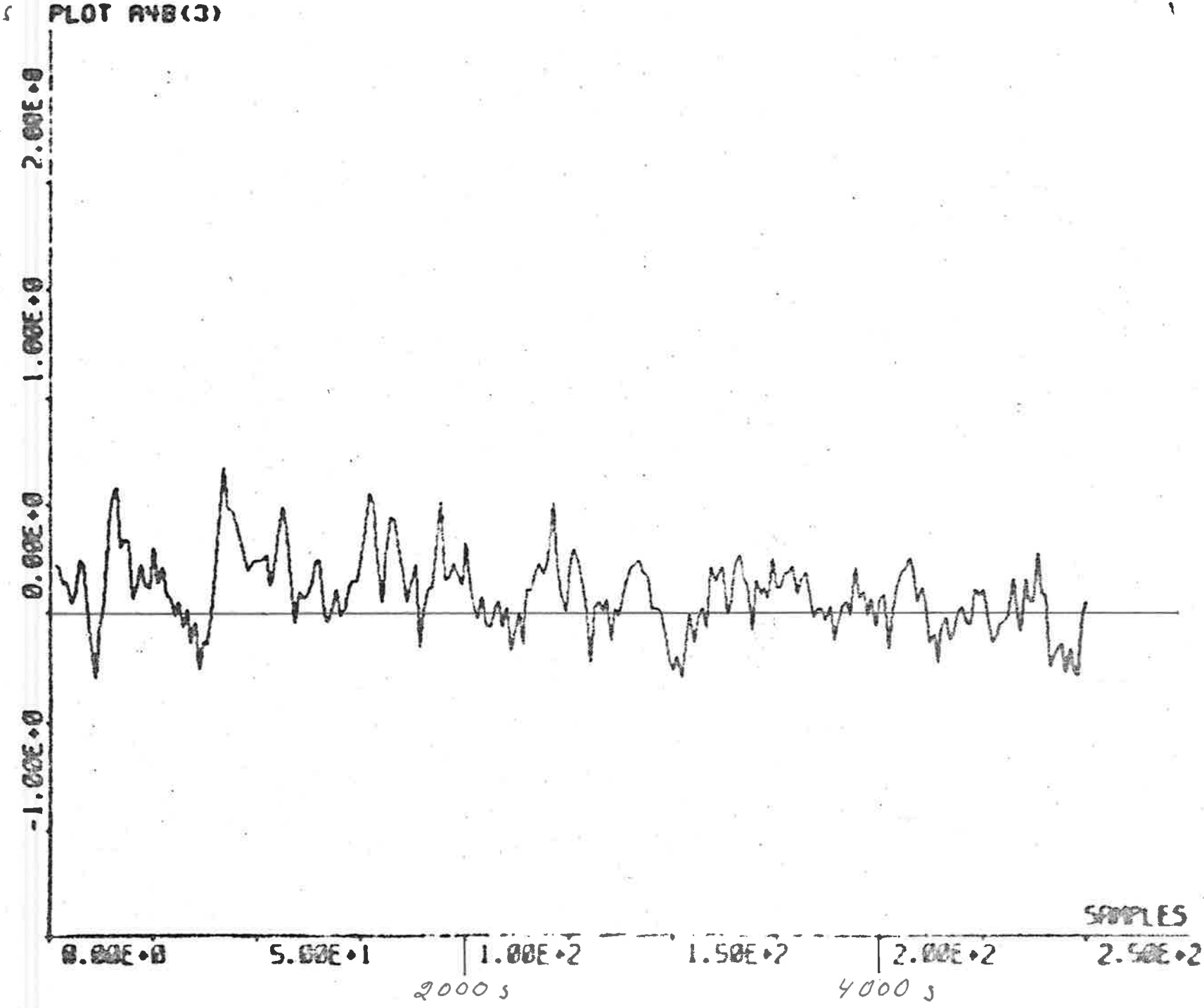
δ_s degr


PLOT A4B(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

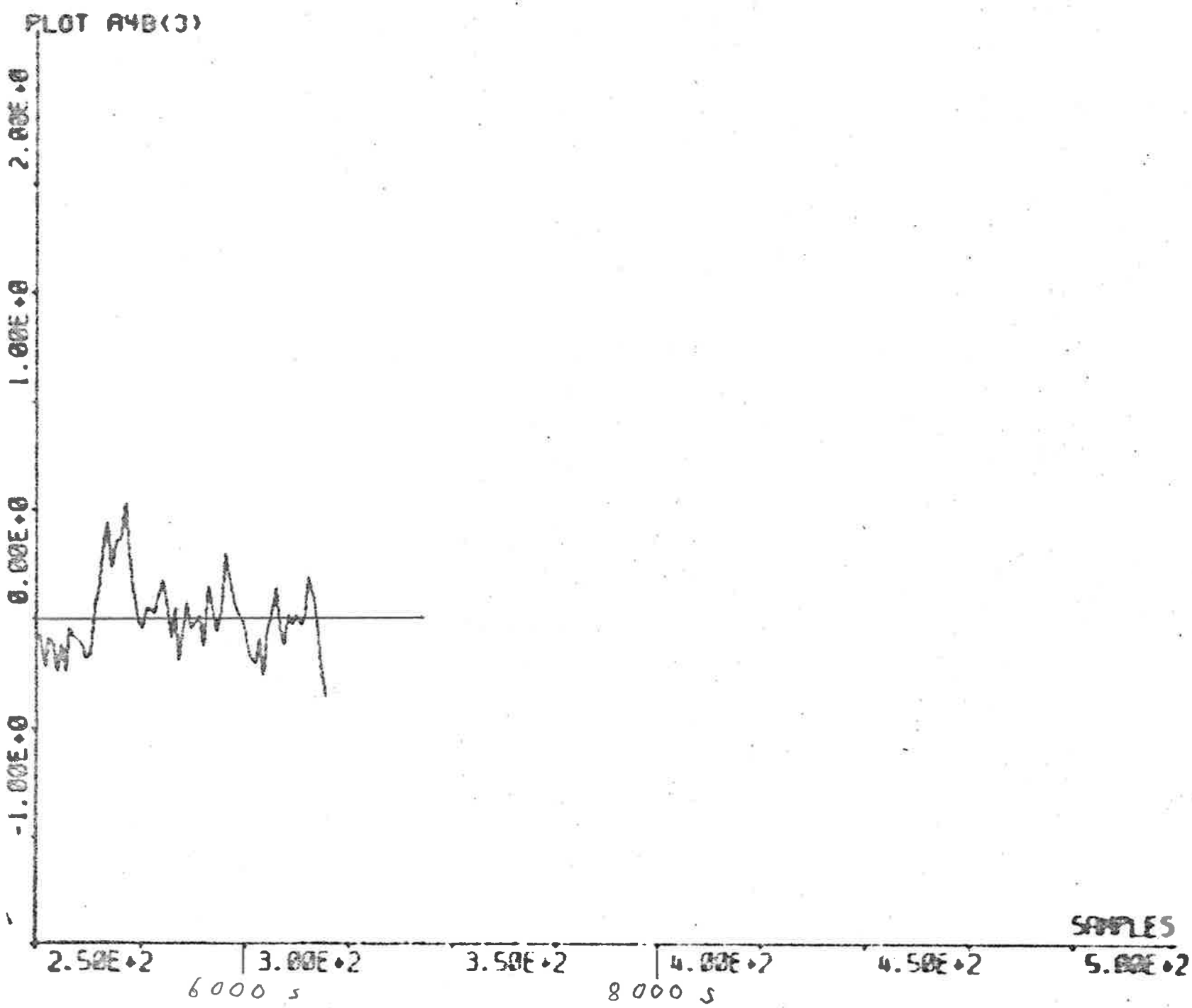

PLOT AYB(2)
1.000E-1
5.000E-0
0.000E-0
-5.000E-0
0.000E+0
5.000E+1
1.000E+2
1.500E+2
2.000E+2
2.500E+2
SAMPLES
2000 s
4000 s
+3°
0°
-3°
δ degr

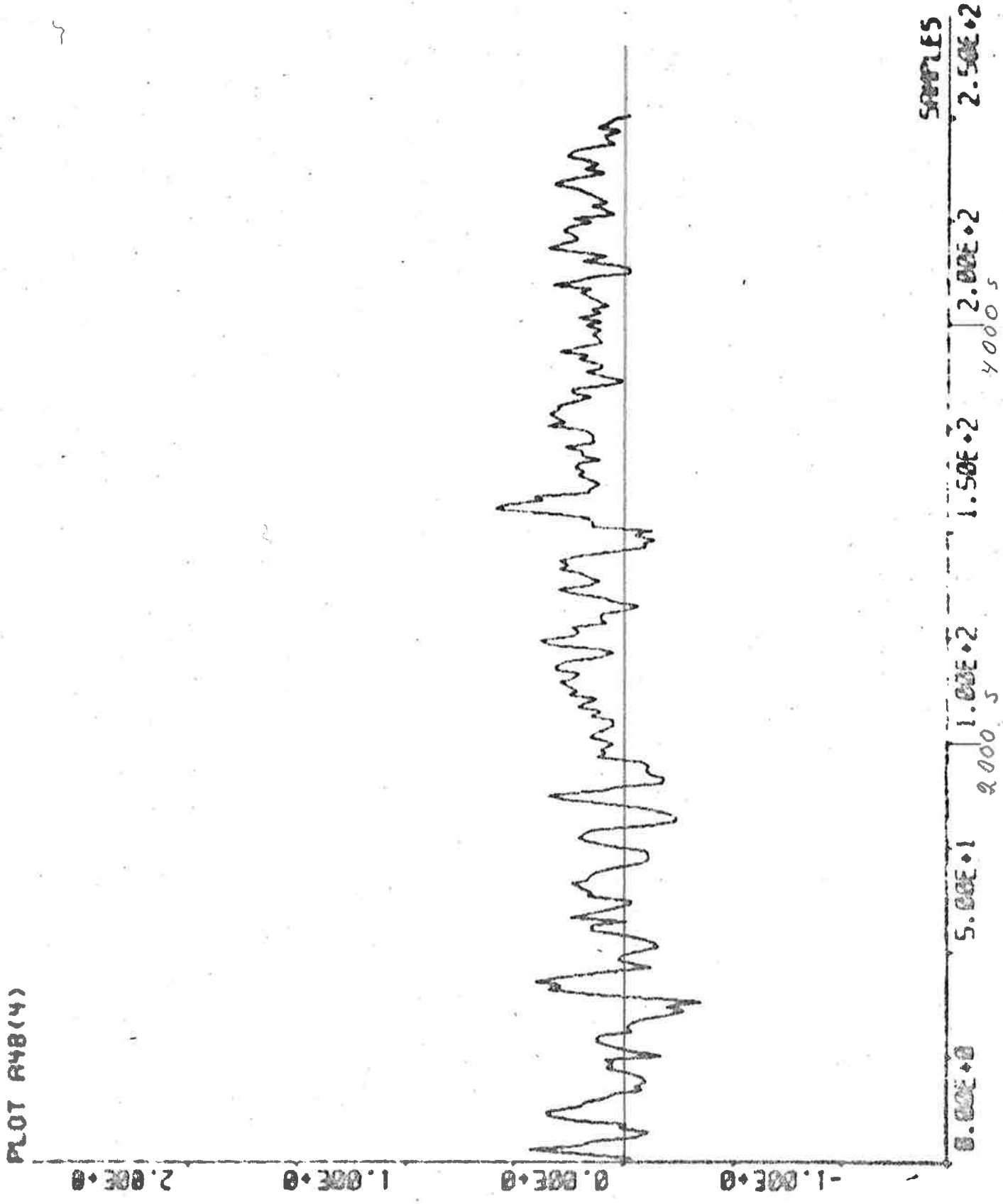

SCALES
5.00E+2
4.50E+2
4.00E+2
3.50E+2
3.00E+2
2.50E+2
8000 s
6000 s
+3°
0°
-3°
PLOT AMB(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
δ degr

V_1 knots


PLOT A+B(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

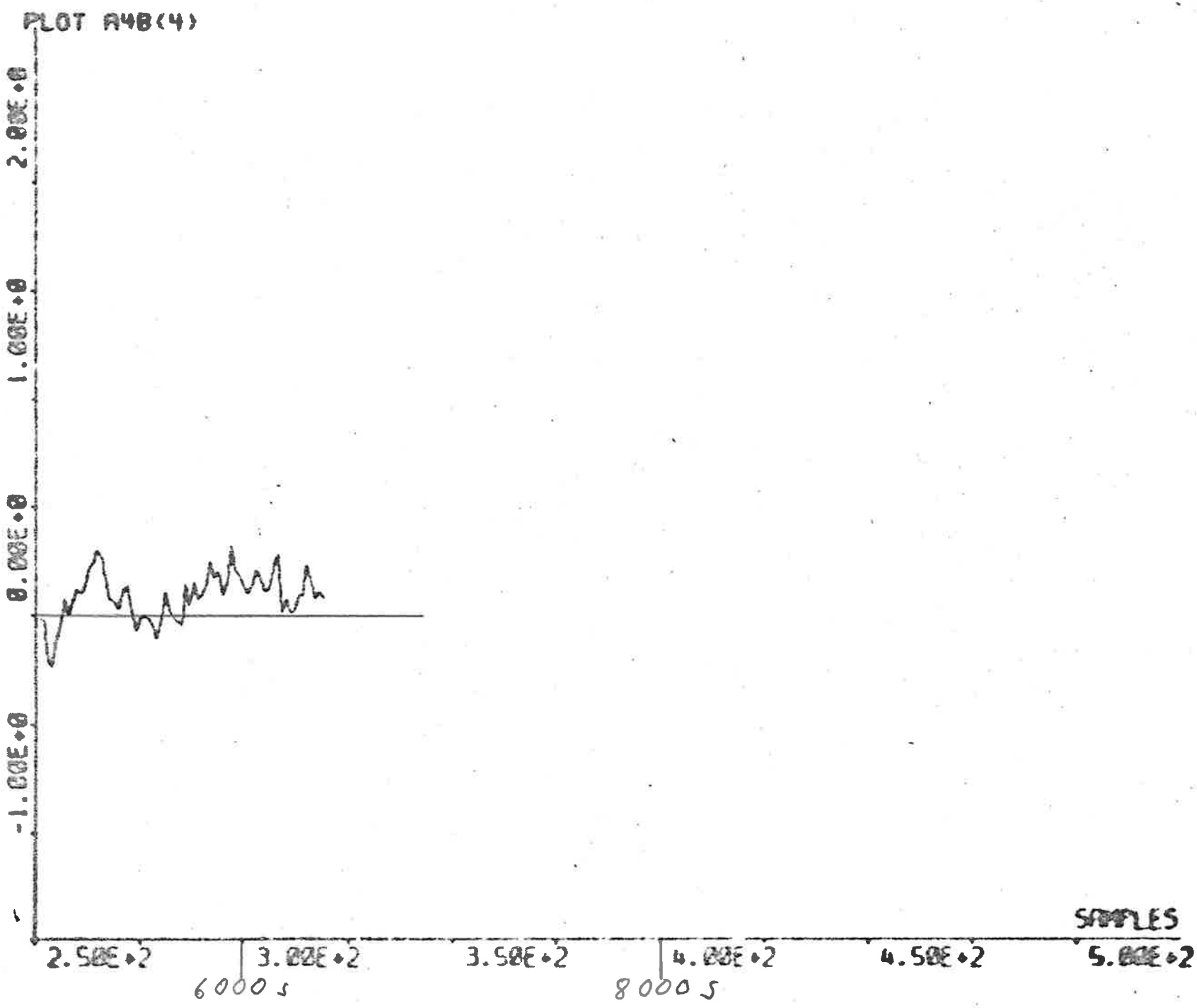
V_1 knots

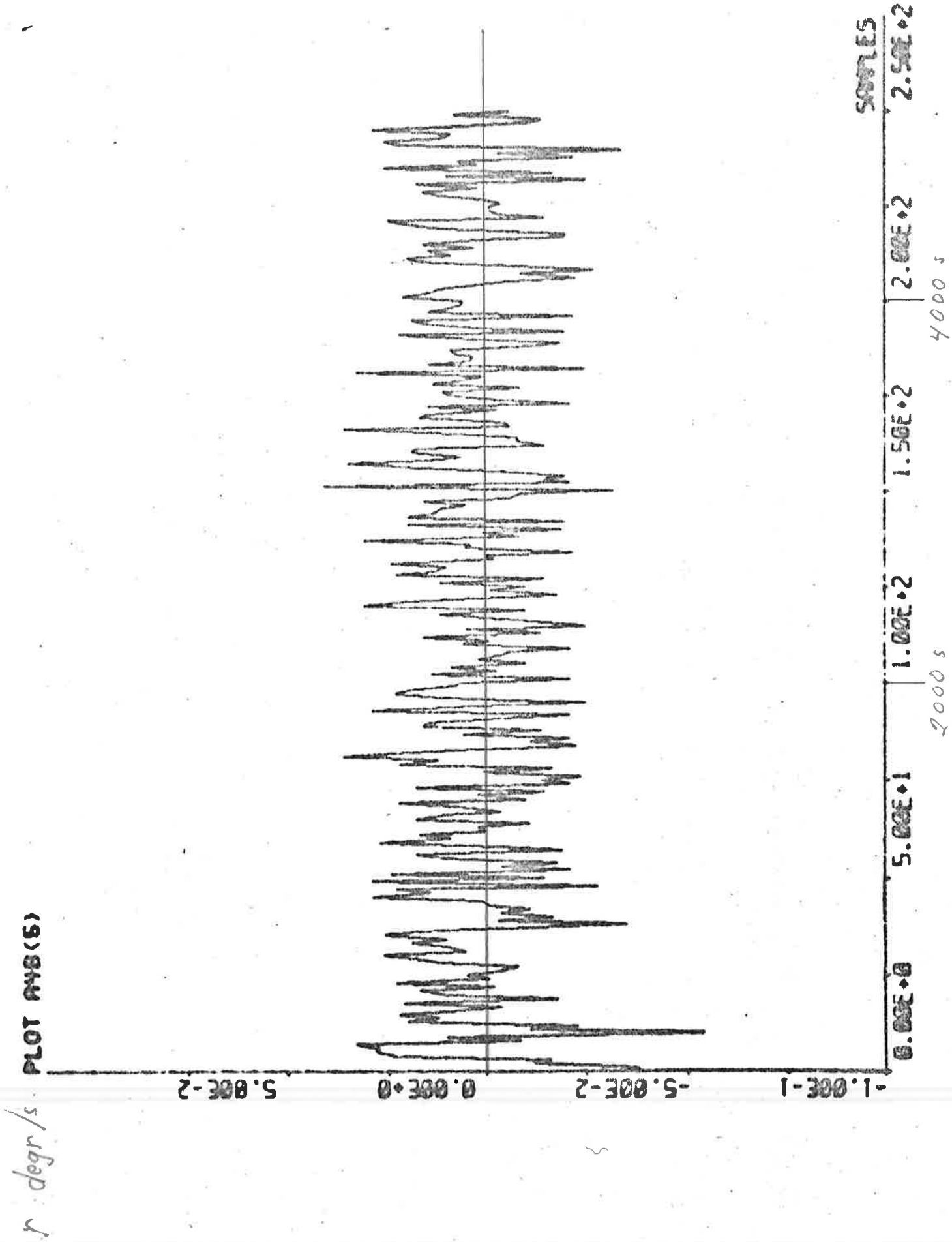

PLOT A4B(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

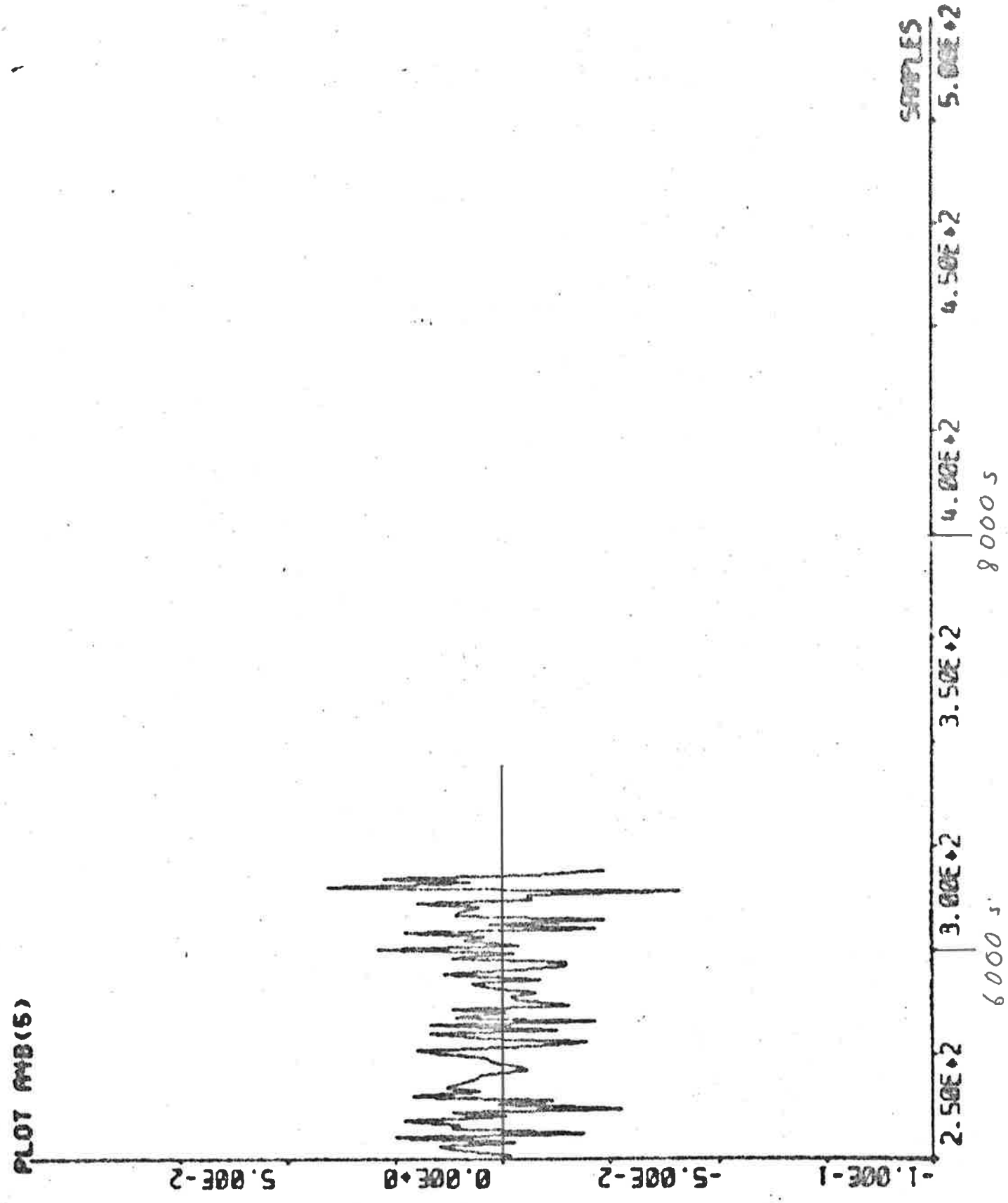

PLOT R48(4)
SAMPLES
0.000E+0
5.000E+1
1.000E+2
1.500E+2
2.000E+2
2.500E+2
2.000 s
4000 s
-1.000E+0
0.000E+0
1.000E+0
2.000E+0

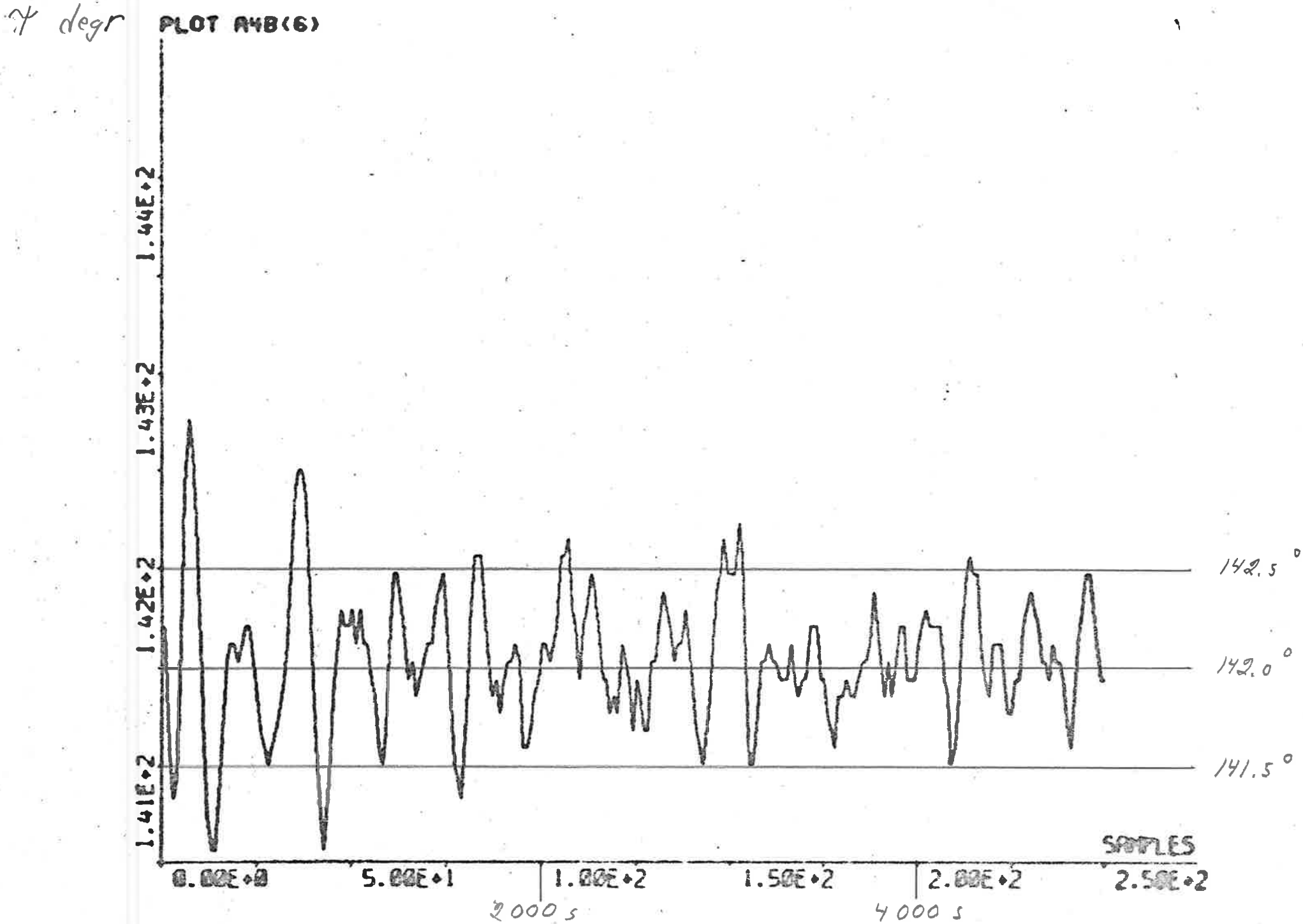
Vq knots

V_2 knots

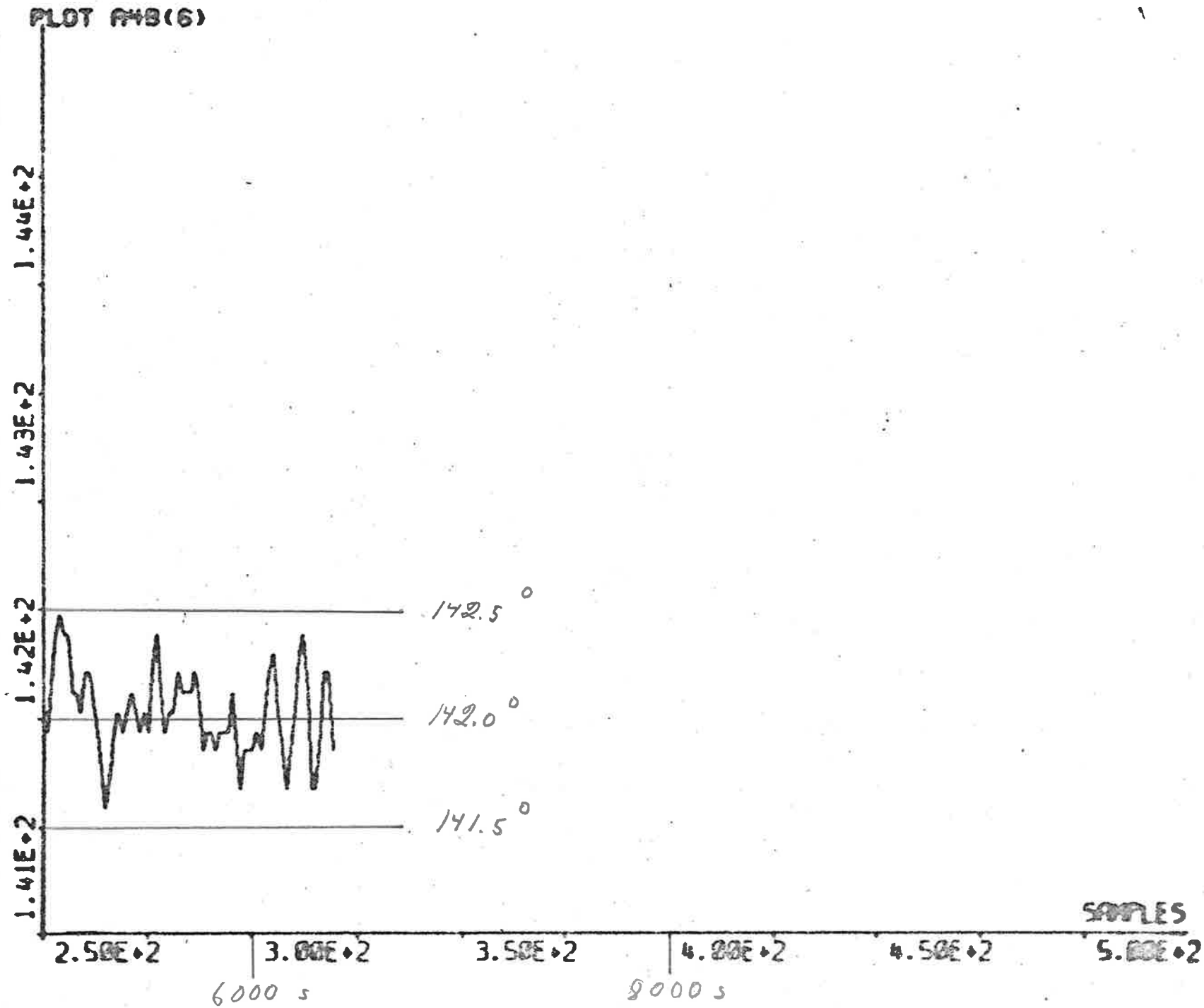

PLOT R4B(4)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s


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

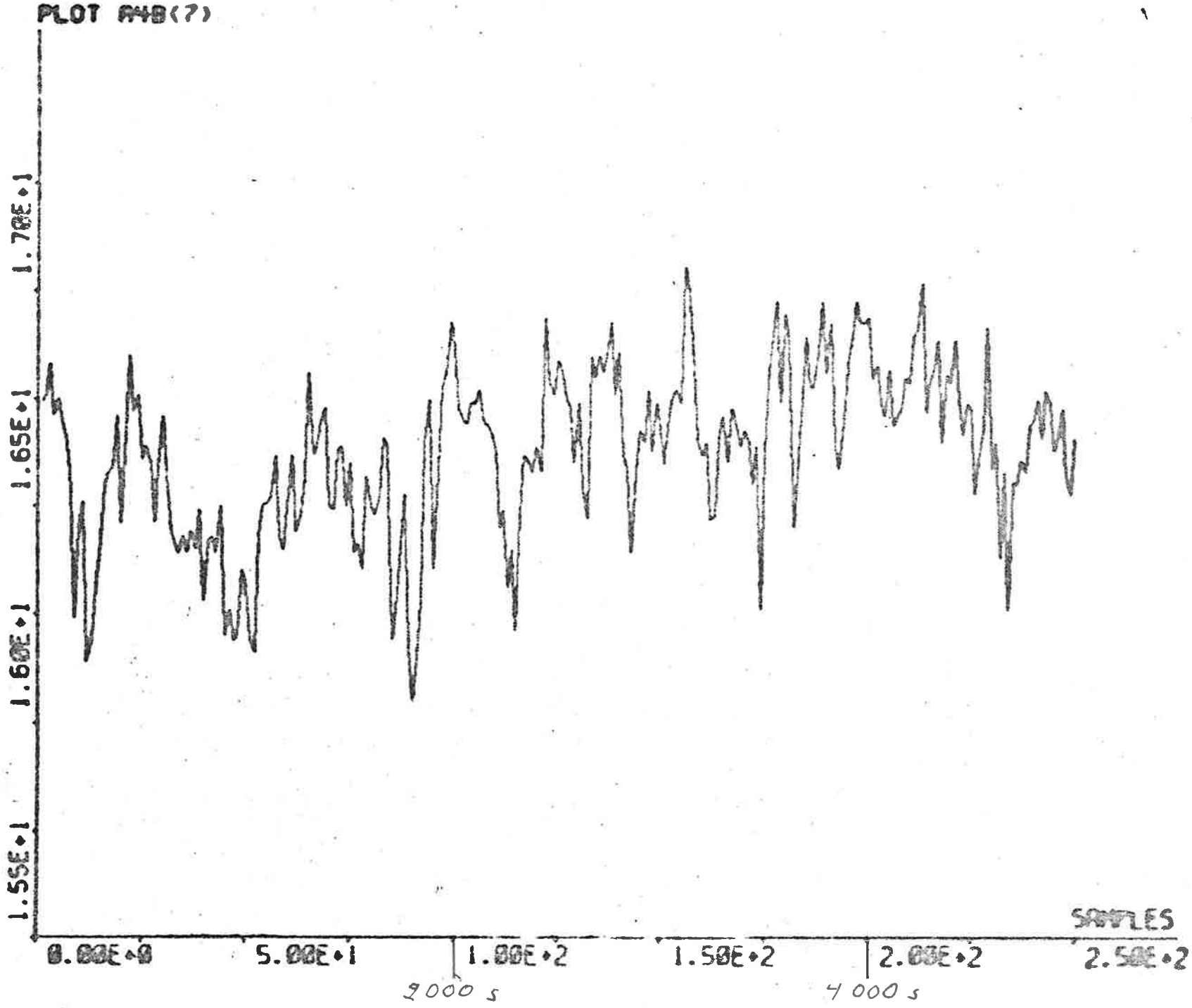

PLOT AMB(5)
-1.00E-1
-5.00E-2
0.00E+0
5.00E-2
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
SAMPLES
6000 s
8000 s
r degr/s



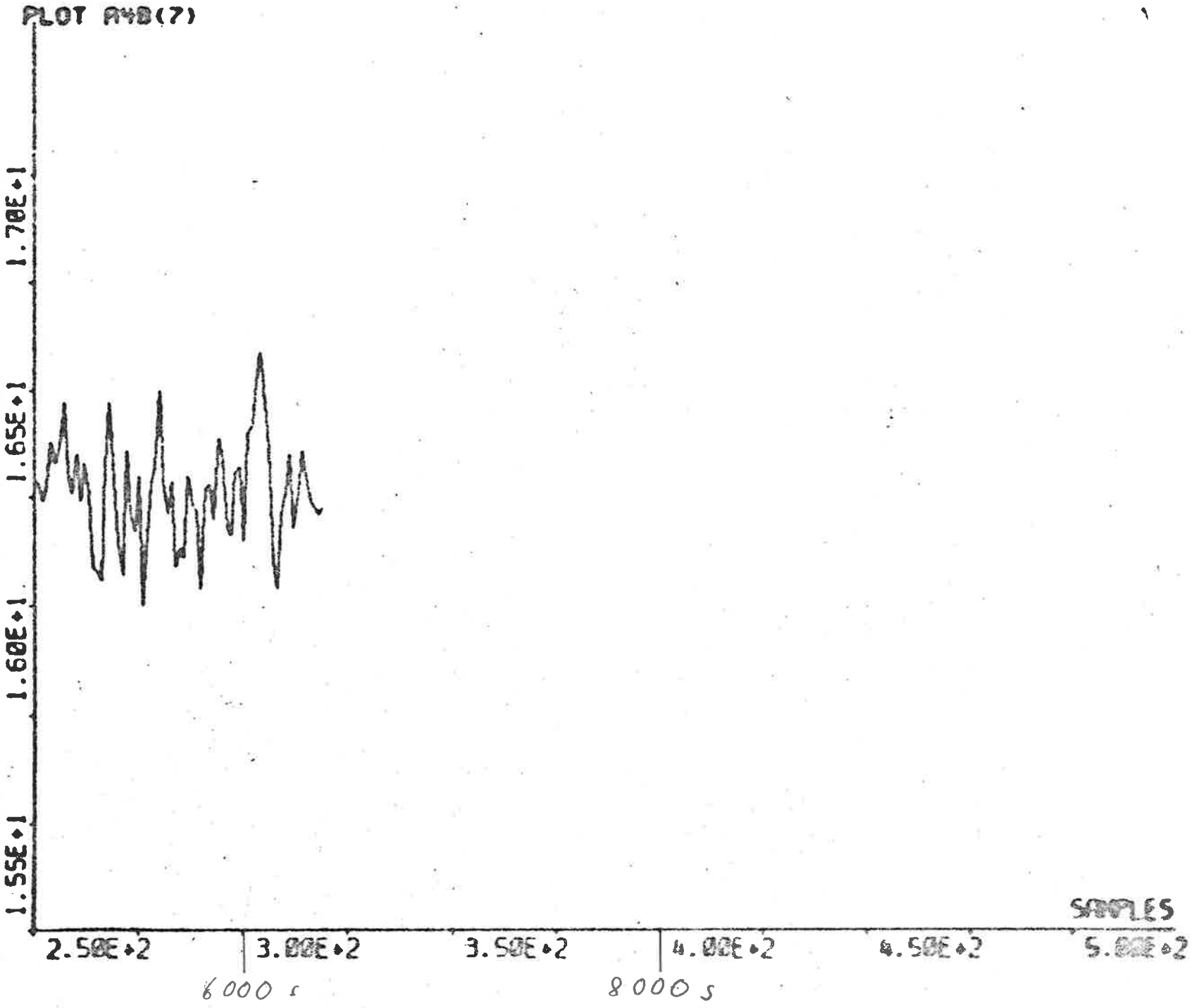
ψ degr
PLOT A4B(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
142.5°
142.0°
141.5°
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

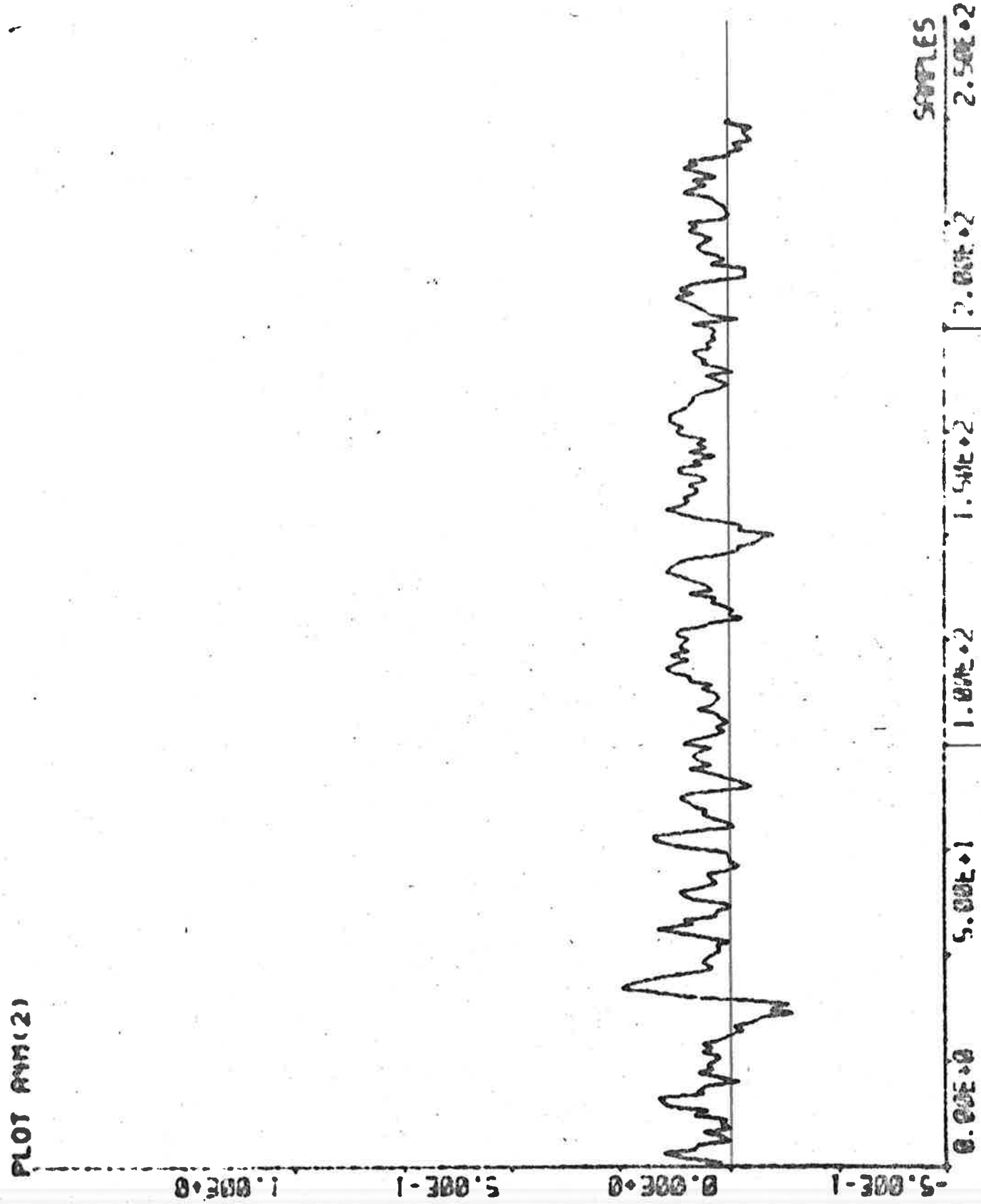

γ degr
PLOT AMB(6)
1.44E+2
1.43E+2
1.42E+2
1.41E+2
142.5 °
142.0 °
141.5 °
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

u knots


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

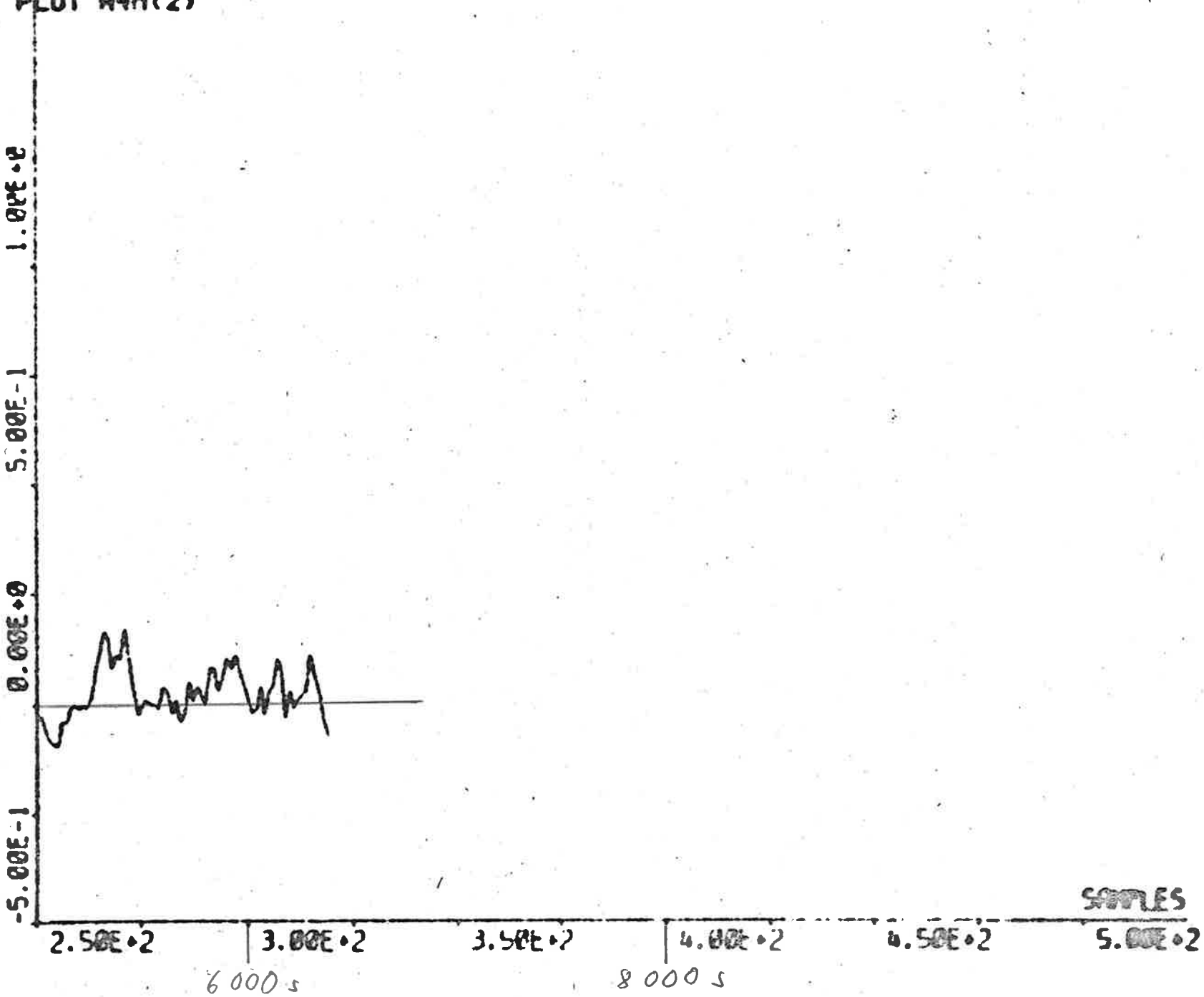
u knots

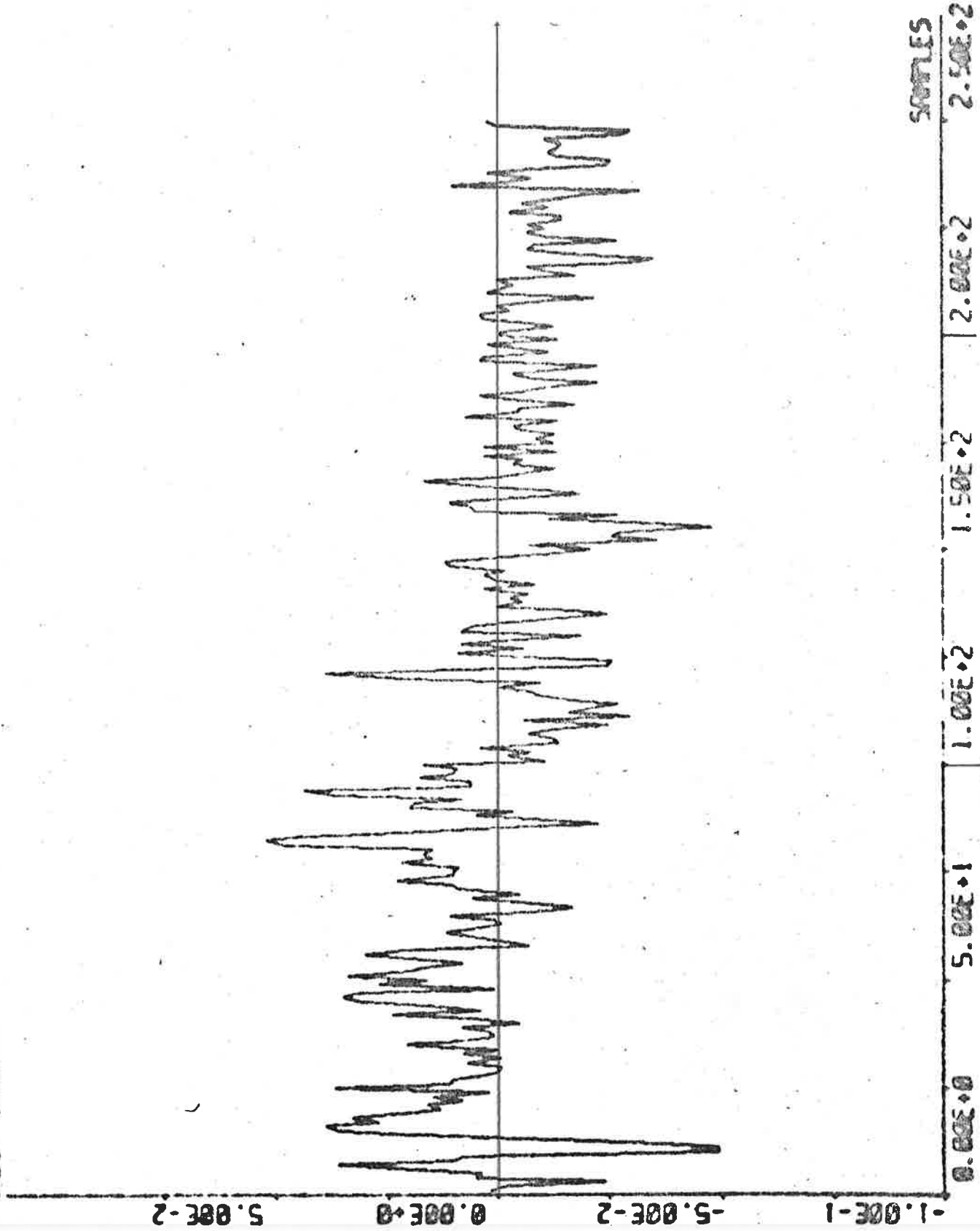

PLOT A4B(7)
1.70E+1
1.65E+1
1.60E+1
1.55E+1
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s



$\langle v \rangle$ m/s

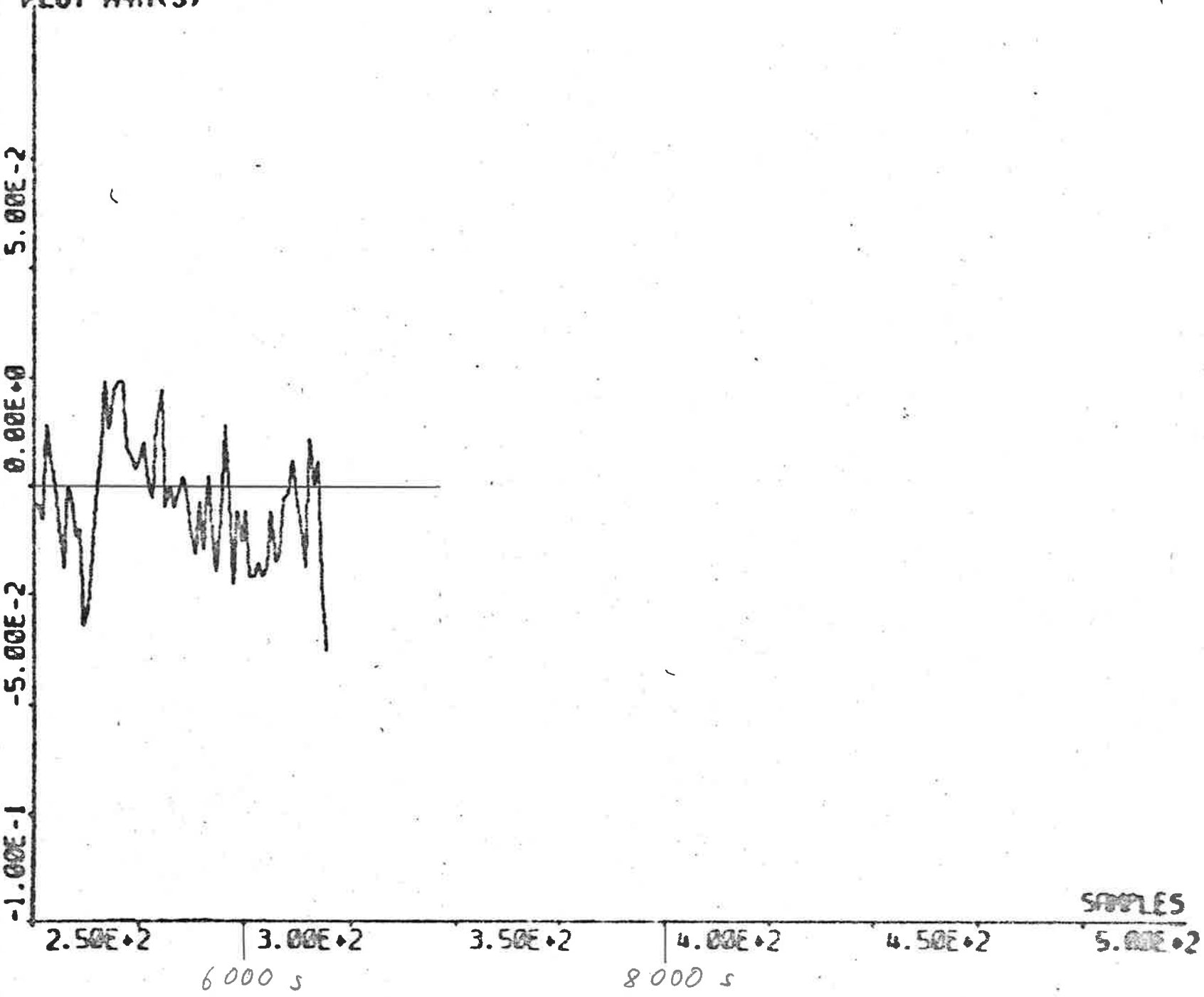
$\hat{v}$ m/s

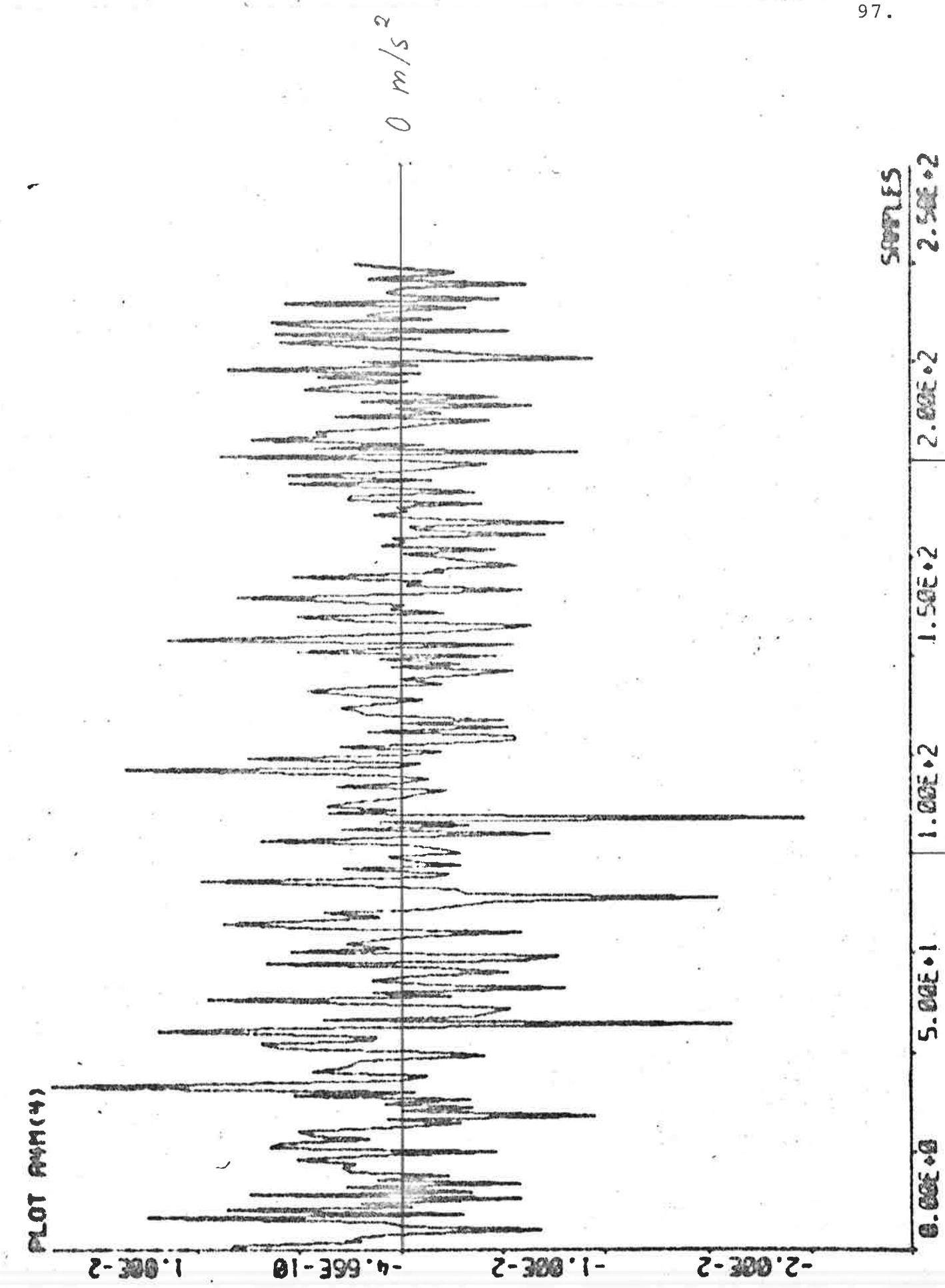

PLOT A4M(2)
1.00E+0
5.00E-1
0.00E+0
-5.00E-1
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

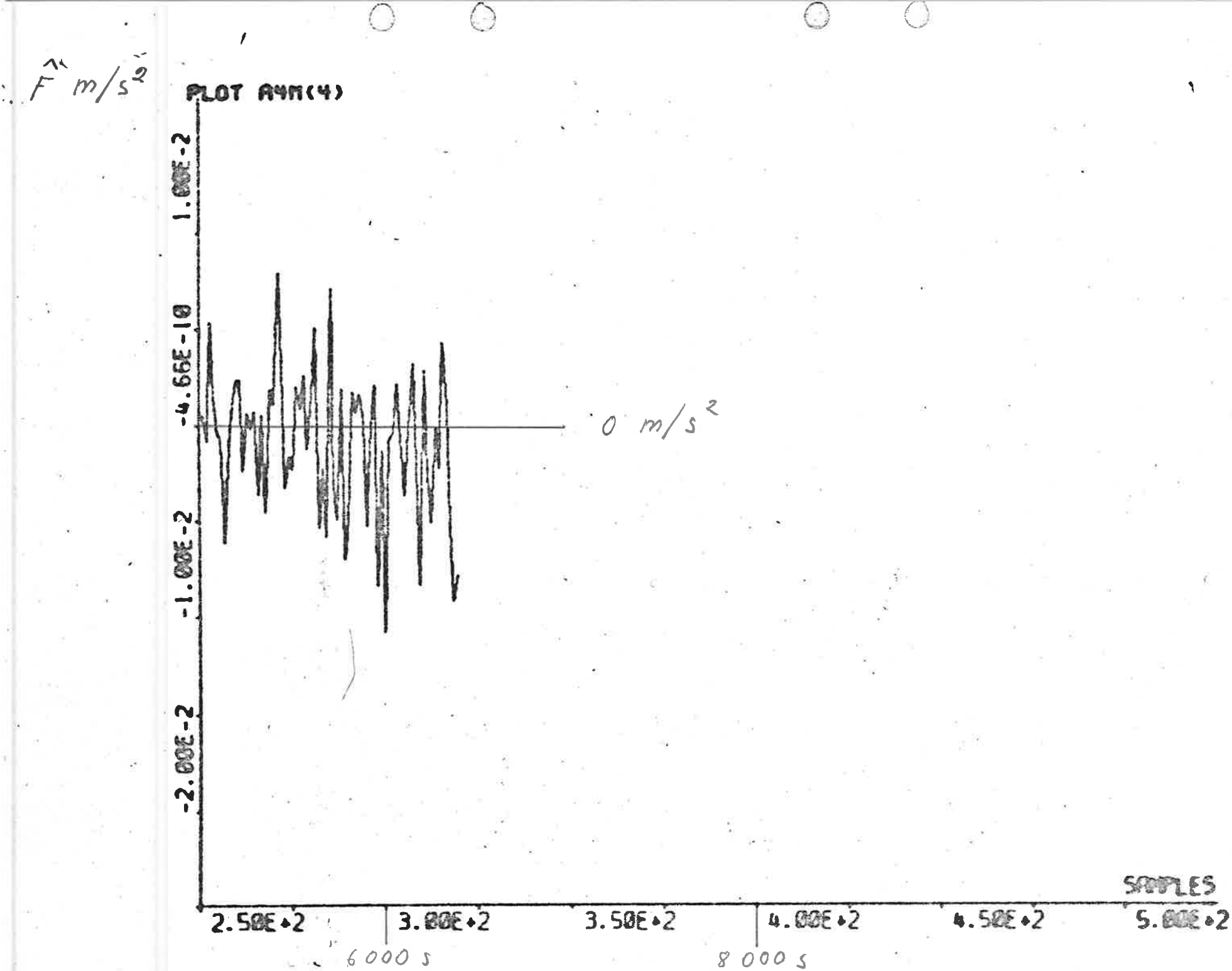

PLOT AHM(3)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
8000s
4000s

$\hat{r}$ degr/s

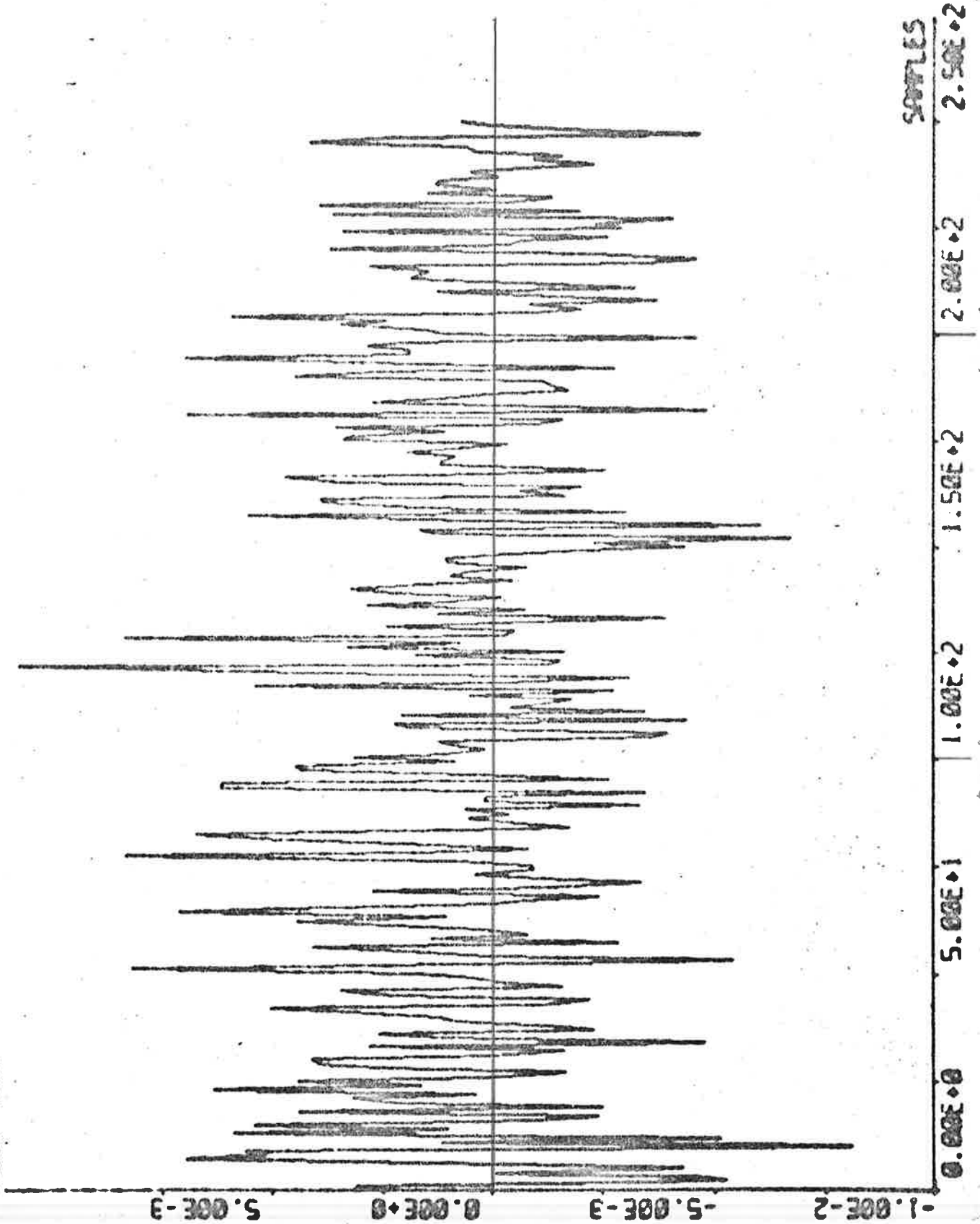
$\hat{r}$ degr/s


PLOT AMM(3)
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

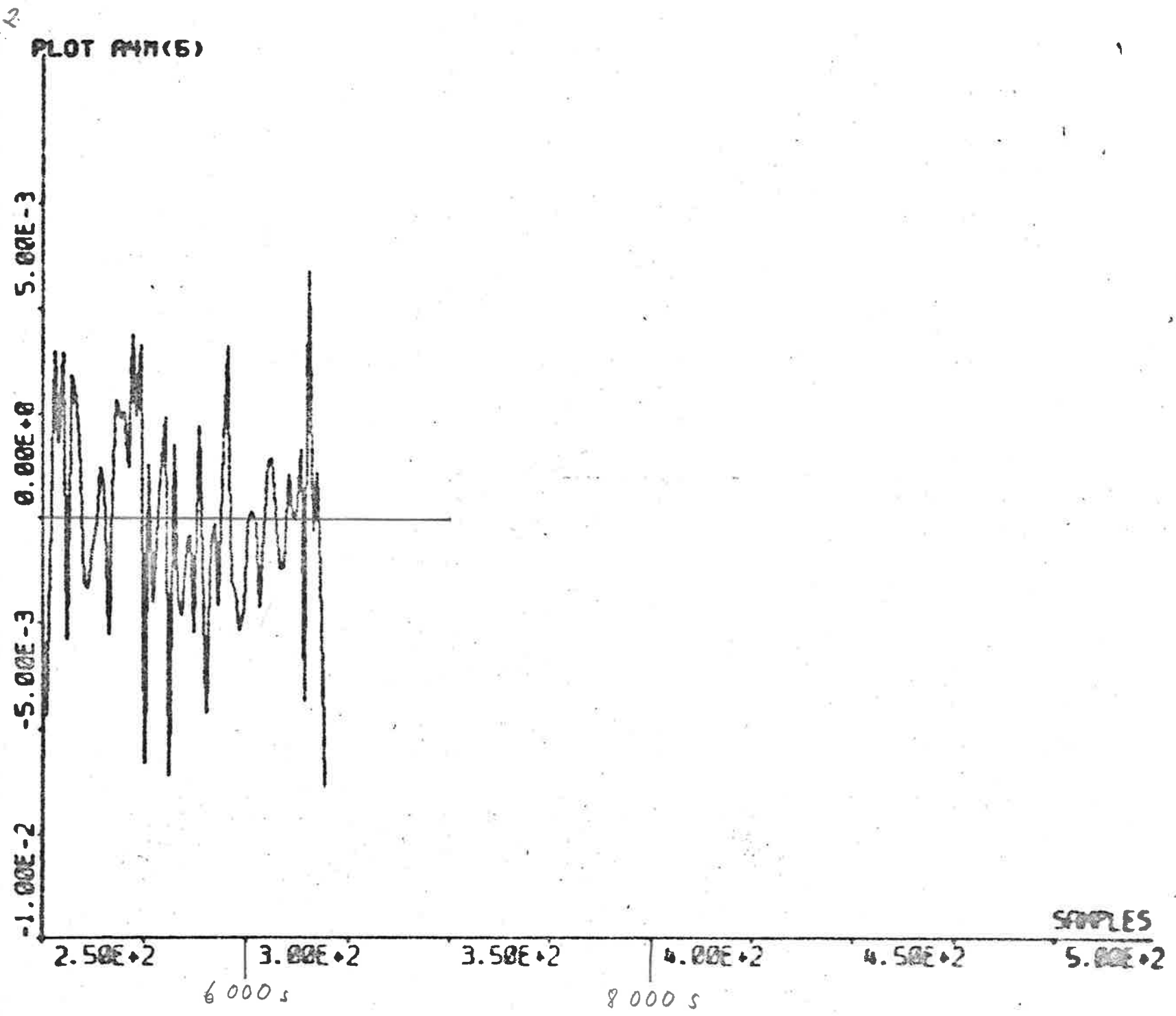

PLOT AAM(4)
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s
0 m/s²
-2.00E-2
-1.00E-2
-4.66E-10
1.00E-2
F m/s²

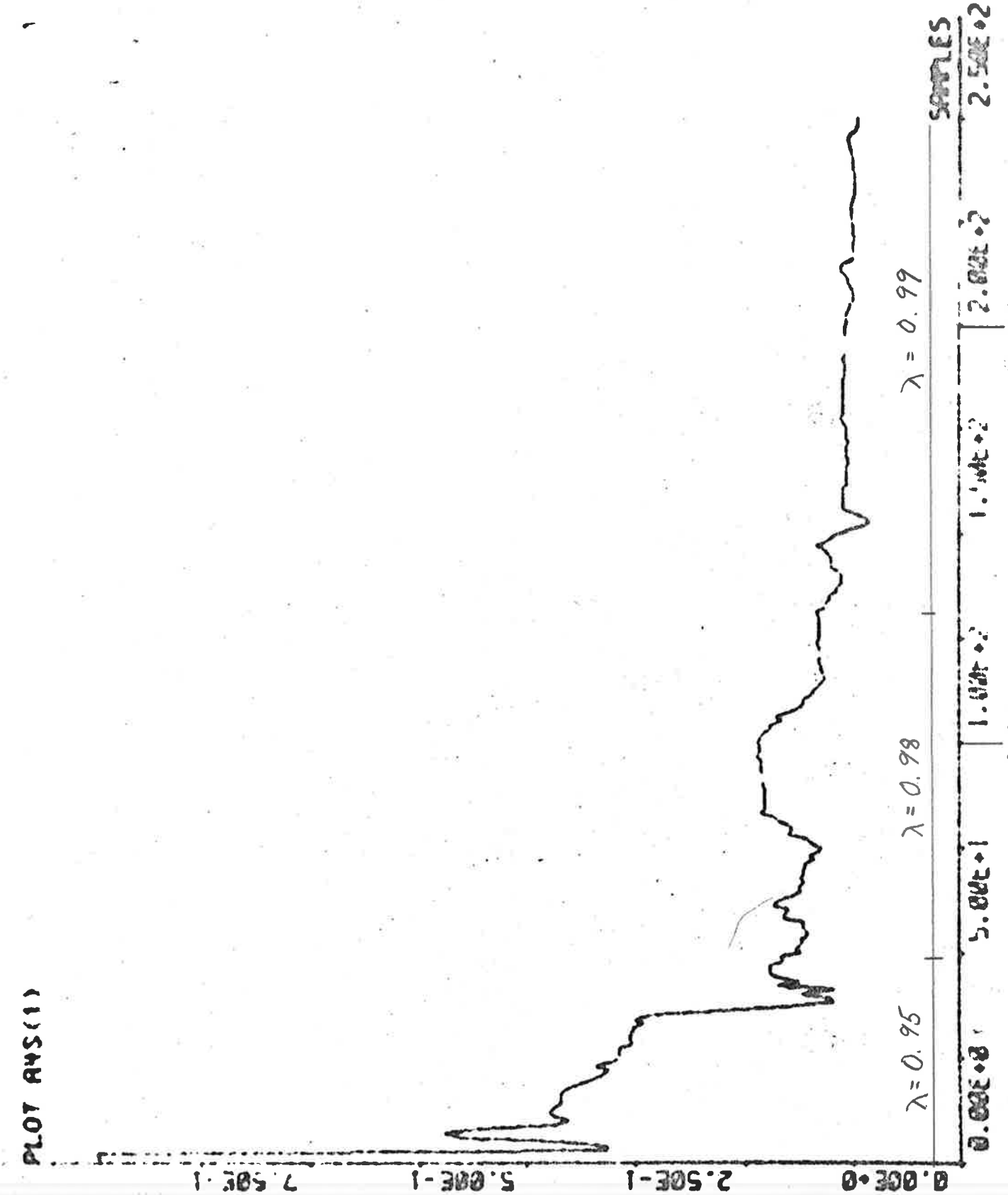


$\hat{F}$ m/s²
PLOT A4M(4)
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
0 m/s²
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s


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

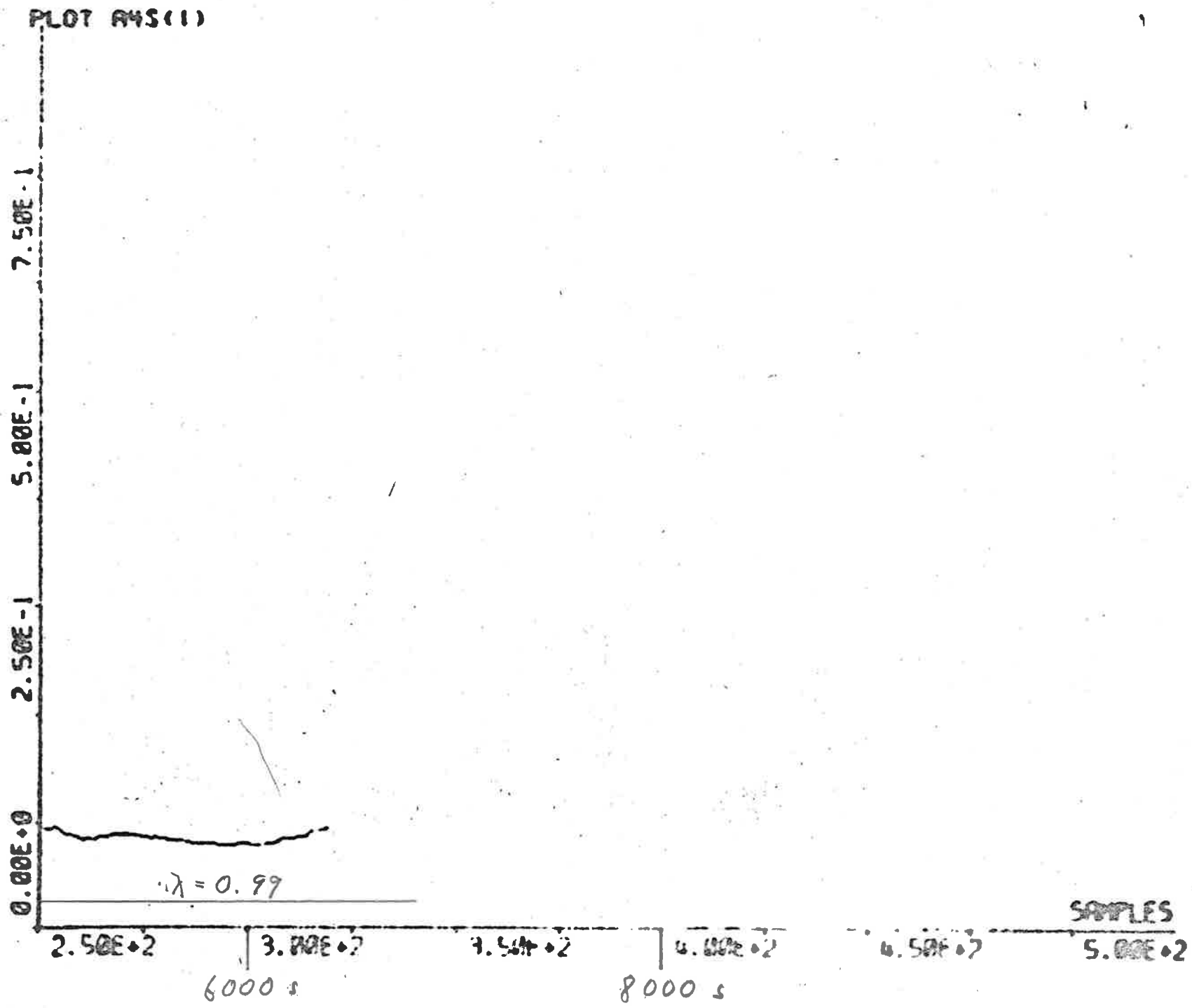
$\hat{M}$ degr/s^2


$\hat{M}$ degr/s^2
PLOT AHM(6)
5.00E-3
0.00E+0
-5.00E-3
-1.00E-2
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

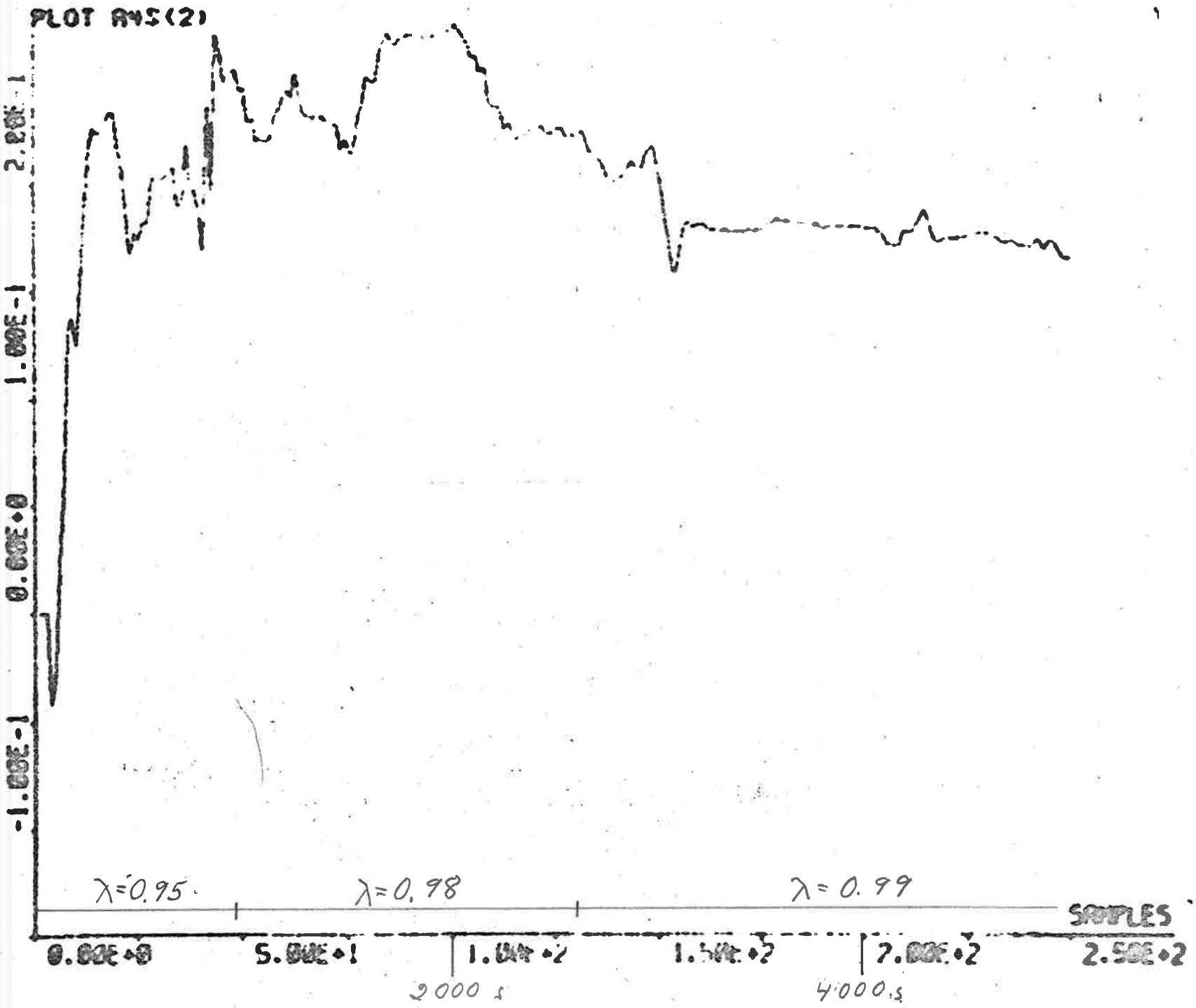

PLOT AVS(1)
7.50E-1
5.00E-1
2.50E-1
0.00E+0
SAMPLES
λ = 0.95
λ = 0.98
λ = 0.99
2000 s
4000 s

b_1

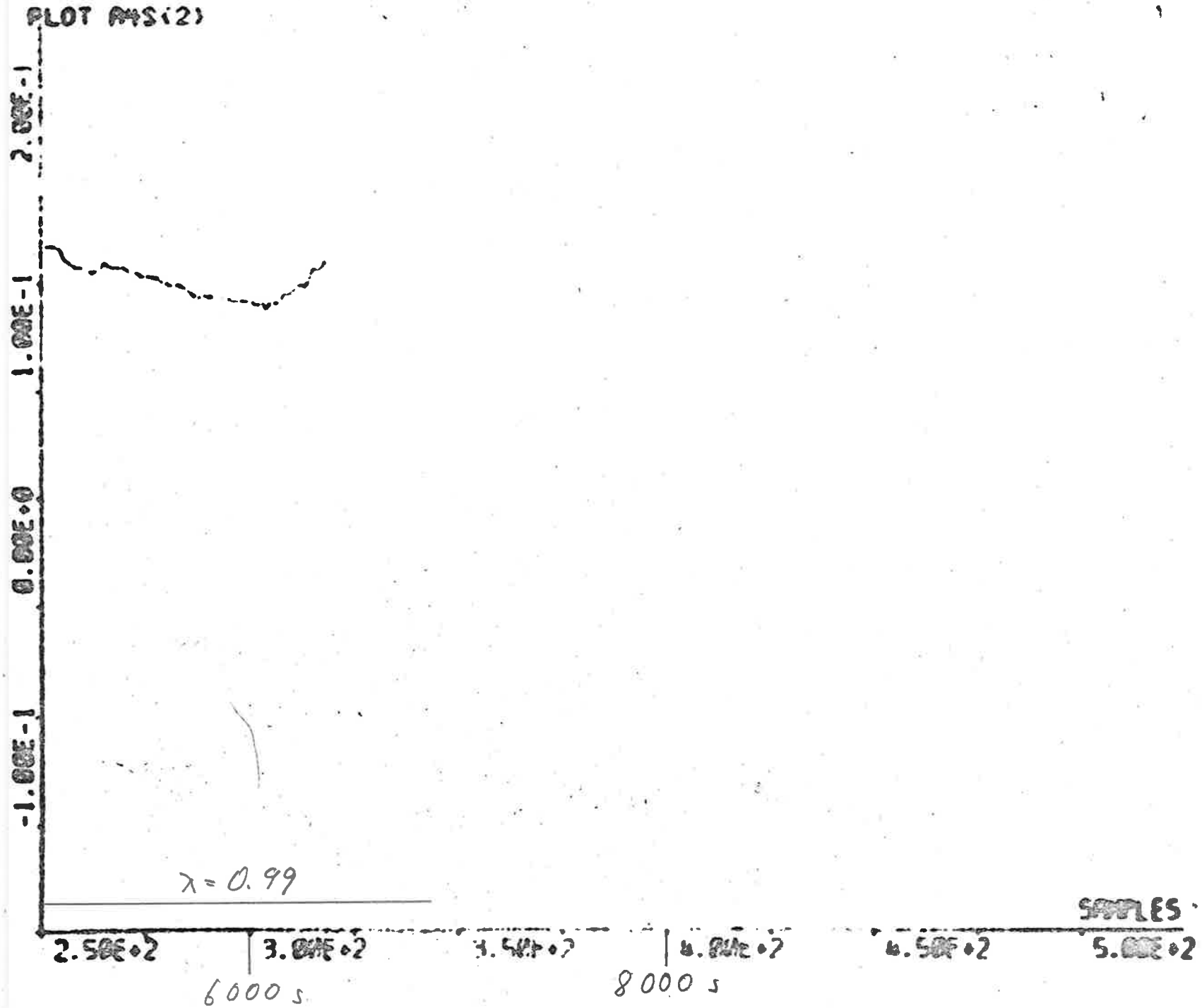
b_1

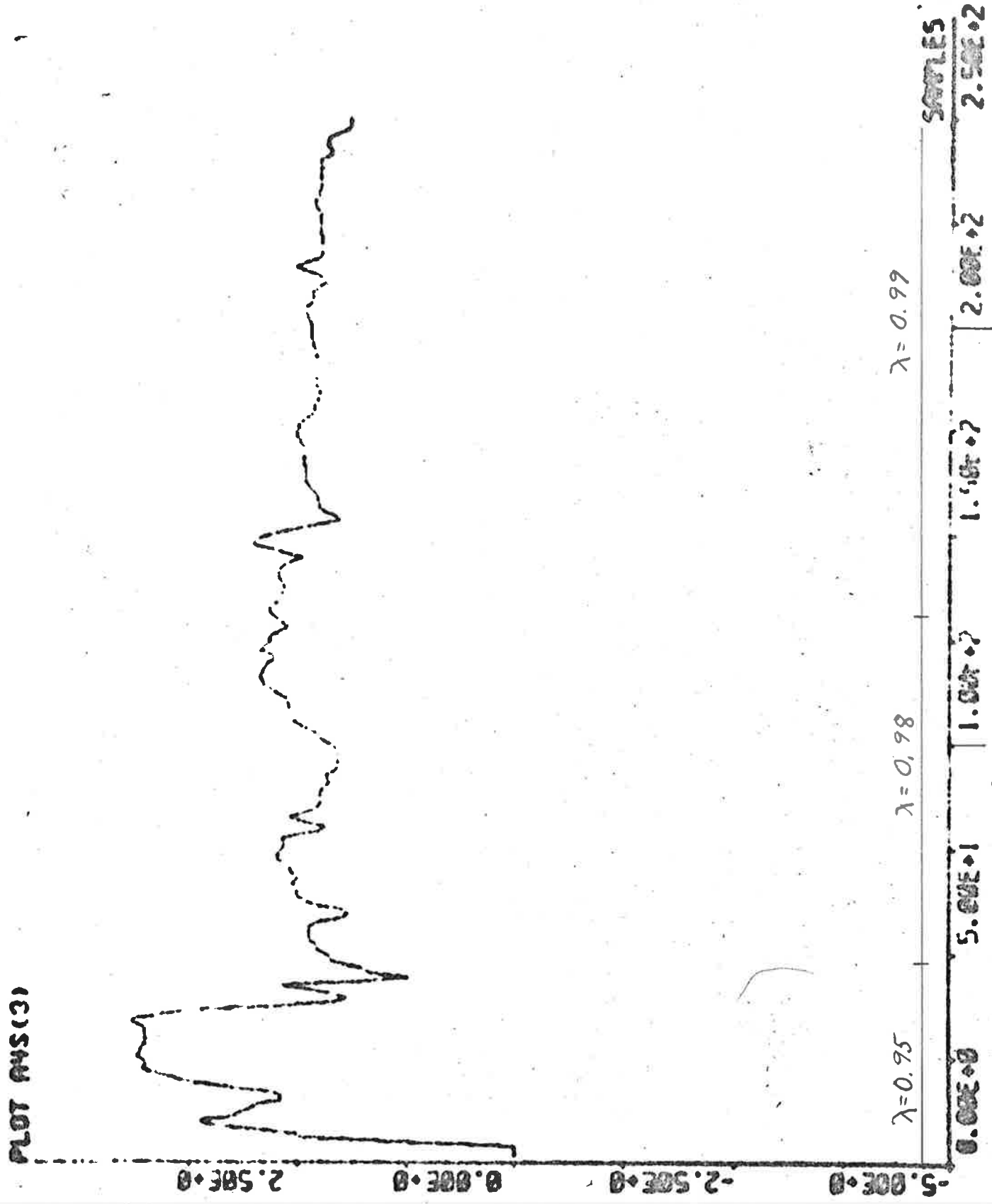

PLOT RMS(1)
7.50E-1
5.00E-1
2.50E-1
0.00E+0
λ = 0.99
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s

b_2

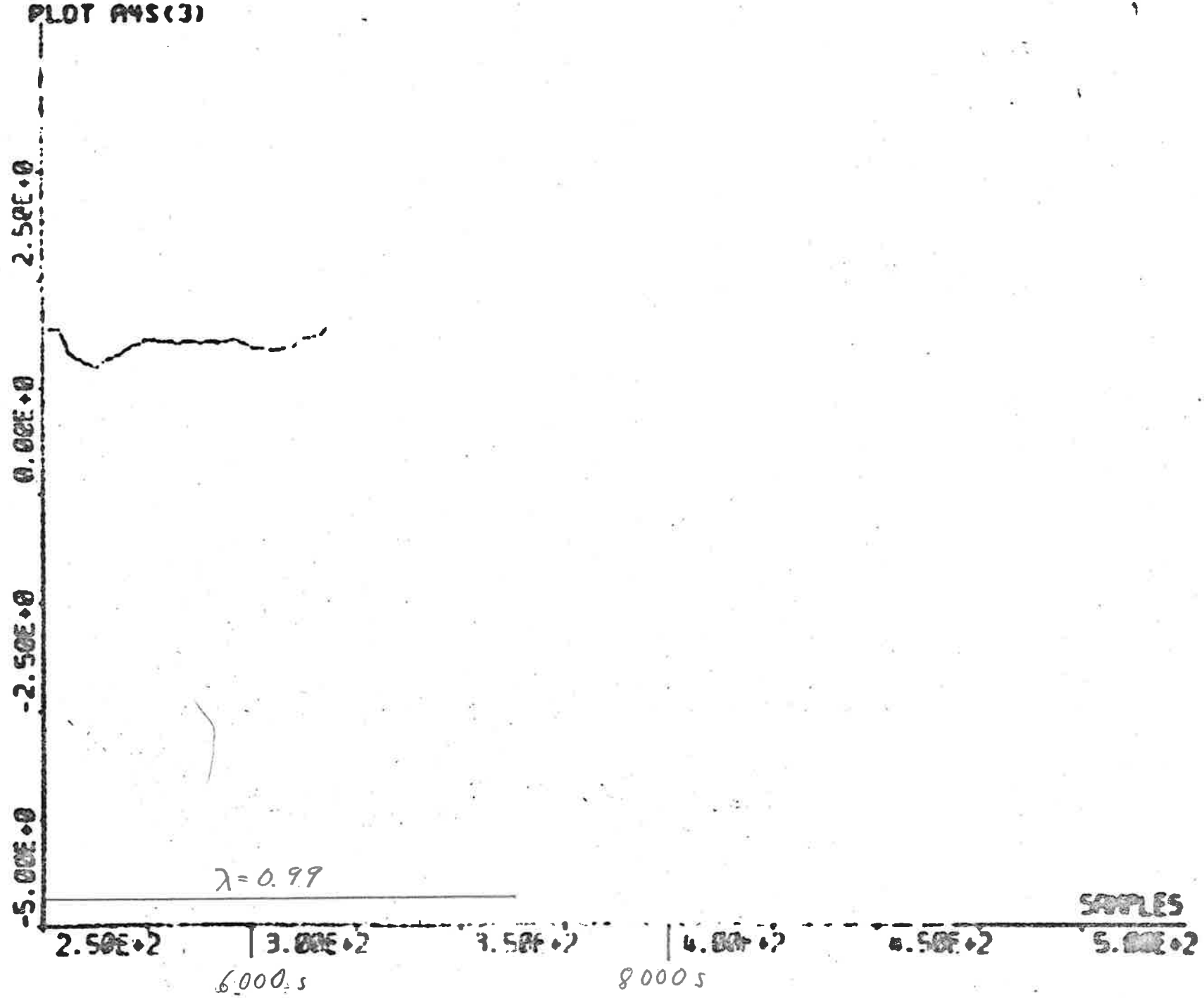

PLOT RMS(2)
2.00E-1
1.00E-1
0.00E+0
-1.00E-1
λ=0.95
λ=0.98
λ=0.99
SAMPLES
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
2000 s
4000 s

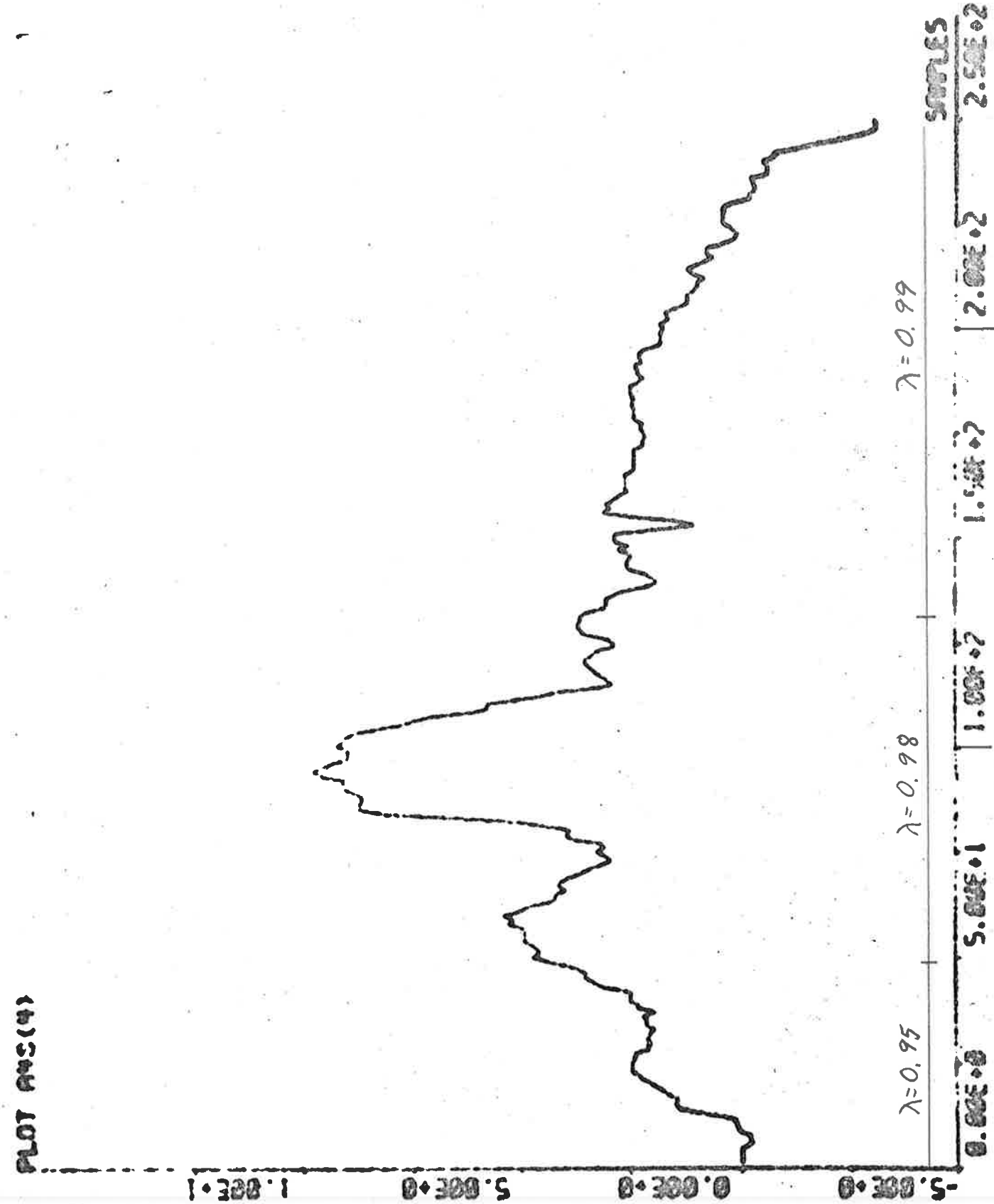
b_2


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

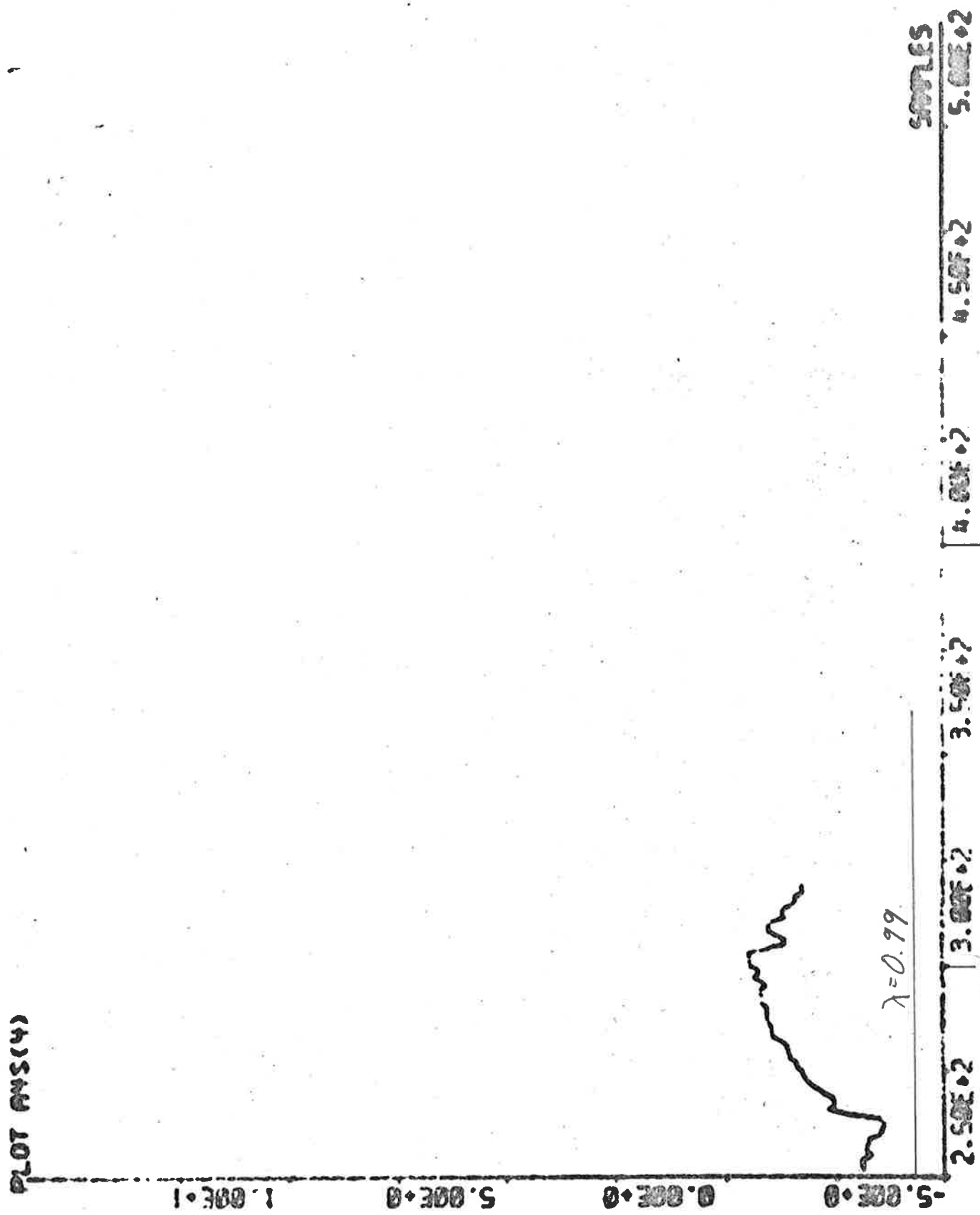

PLOT AMS(3)
2.50E+0
0.00E+0
-2.50E+0
-5.00E+0
0.00E+0
5.00E+1
1.00E+2
1.50E+2
2.00E+2
2.50E+2
SAMPLES
λ=0.95
λ=0.98
λ=0.99
2000 s
2000 s
4000 s

d_1

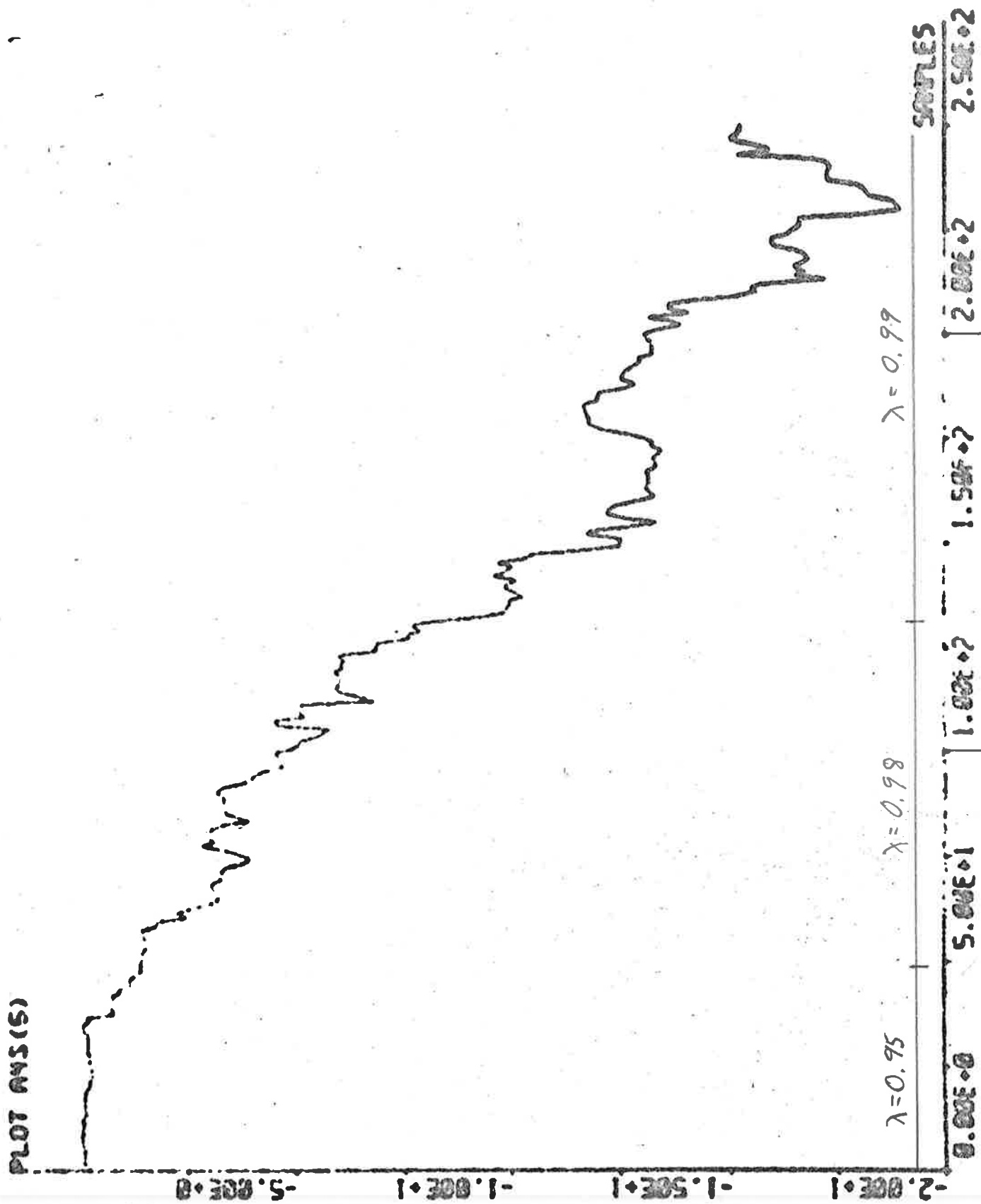

PLOT AMS(3)
2.50E+0
0.00E+0
-2.50E+0
-5.00E+0
λ=0.99
SAMPLES
2.50E+2
3.00E+2
3.50E+2
4.00E+2
4.50E+2
5.00E+2
6000 s
8000 s


PLOT AMS(4)
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
λ=0.95
λ=0.98
λ=0.99
2000 s
2000 s
4000 s

d2

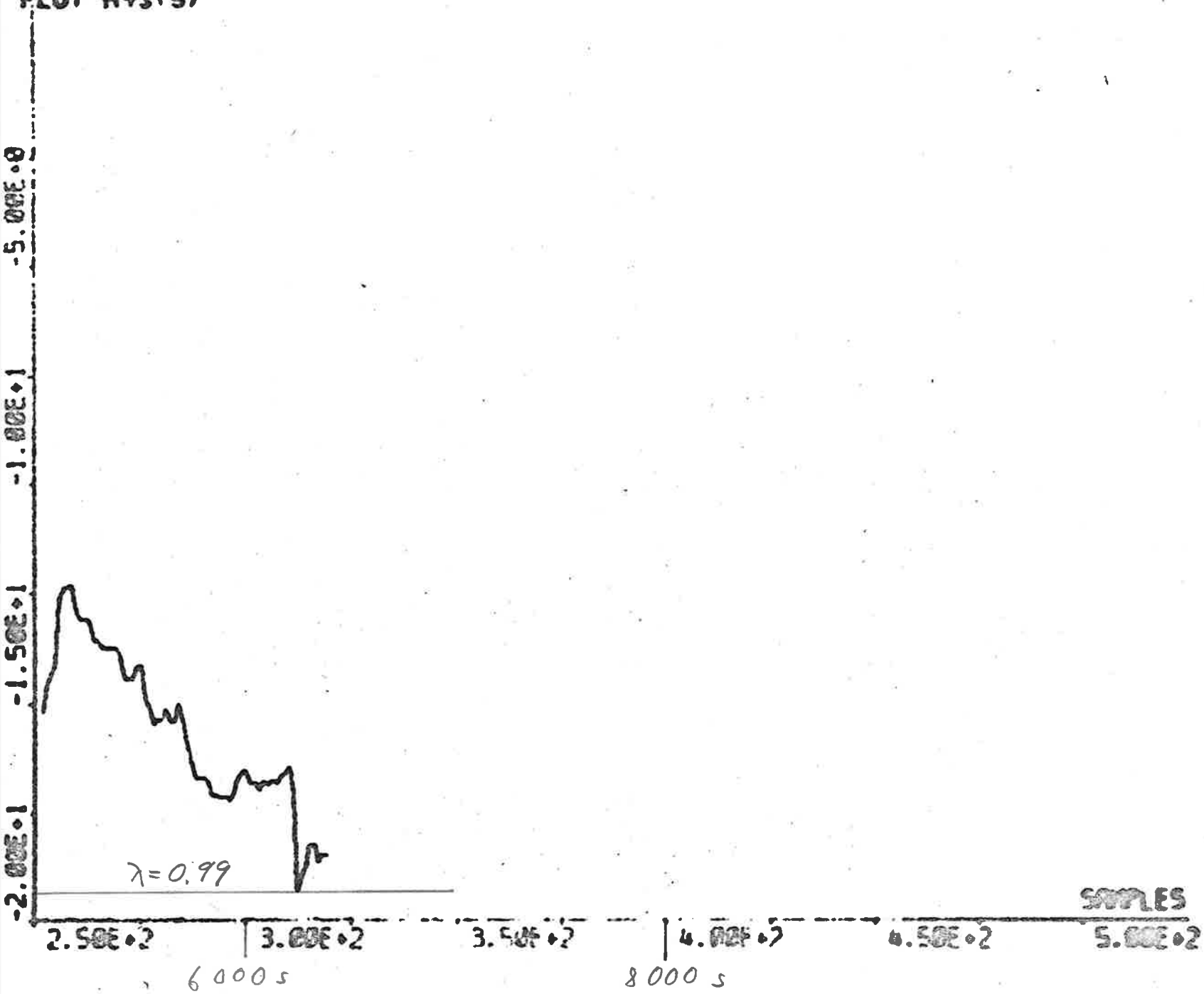

PLOT ANS(4)
1.000·1
5.000·0
0.000·0
-5.000·0
2.500·2
3.000·2
3.500·2
4.000·2
4.500·2
5.000·2
SECS
λ=0.99
8000 s
6000 s

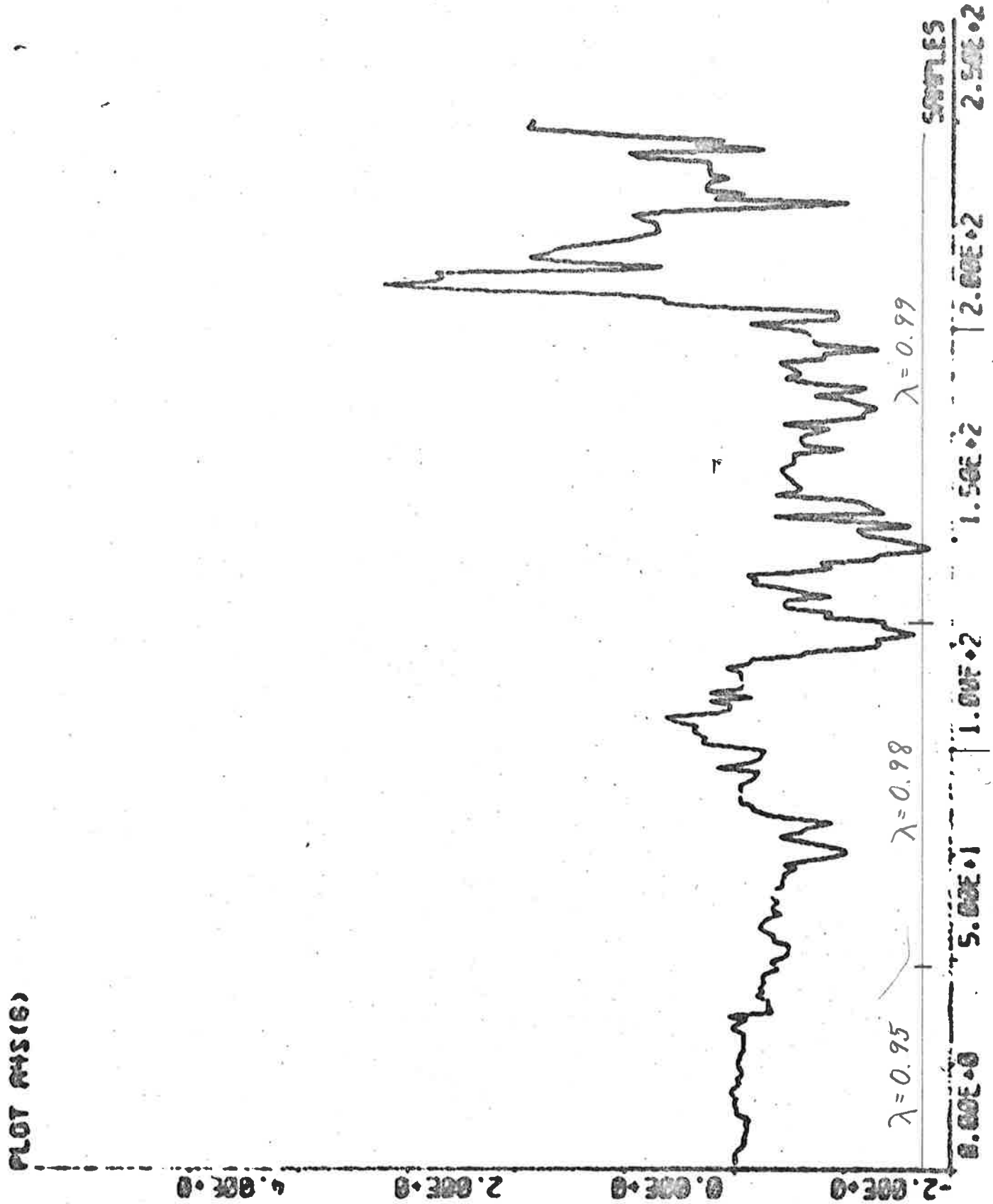
d_2

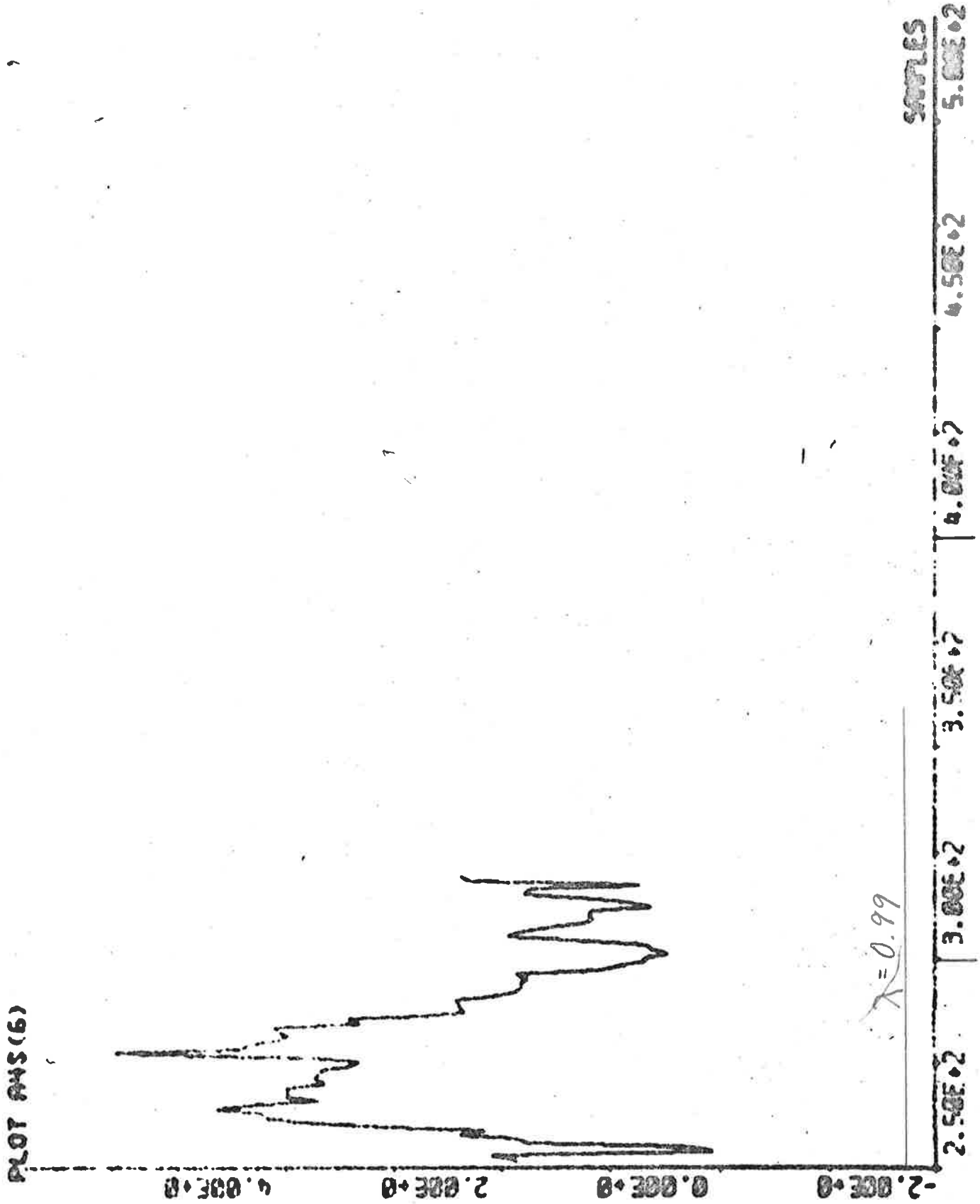

PLOT ANS(S)
-5.000E-0
-1.000E-1
-1.500E-1
-2.000E-1
0.000E+0
5.000E-1
1.000E+0
1.500E+0
2.000E+0
2.500E+0
SAMPLES
λ=0.95
λ=0.98
λ=0.99
2000 s
4000 s

d_3

d_3


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)
-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=0.95
λ=0.98
λ=0.99


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

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:

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

Regulator:

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

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

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

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:

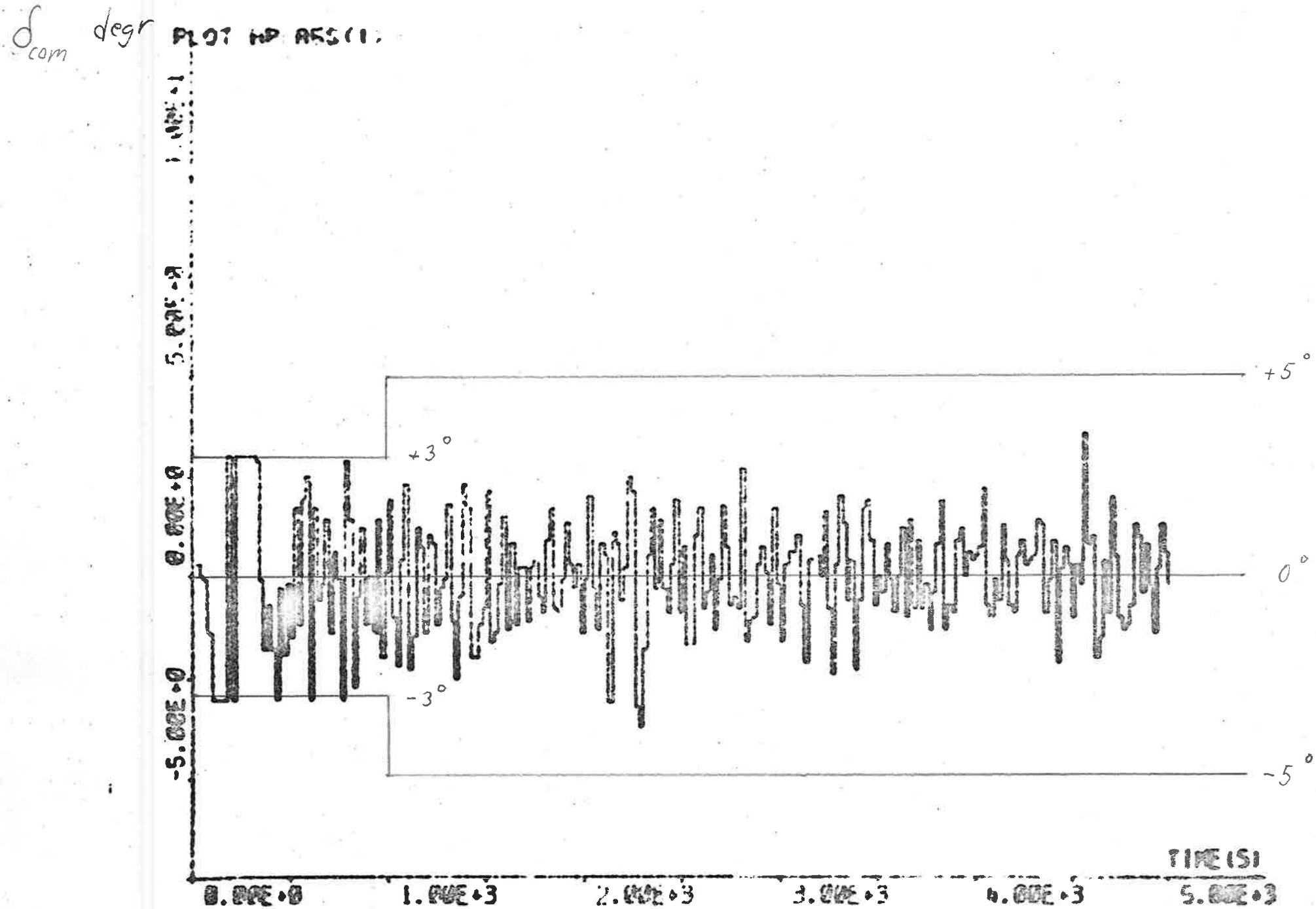
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.3544 \\ 0.0249 \\ 14.1280 \end{bmatrix} \qquad P = \begin{bmatrix} 0.02550 & & \\ -0.01440 & 0.01420 & \\ 1.413 & -0.9150 & 102.4 \end{bmatrix}$$

Regulator:

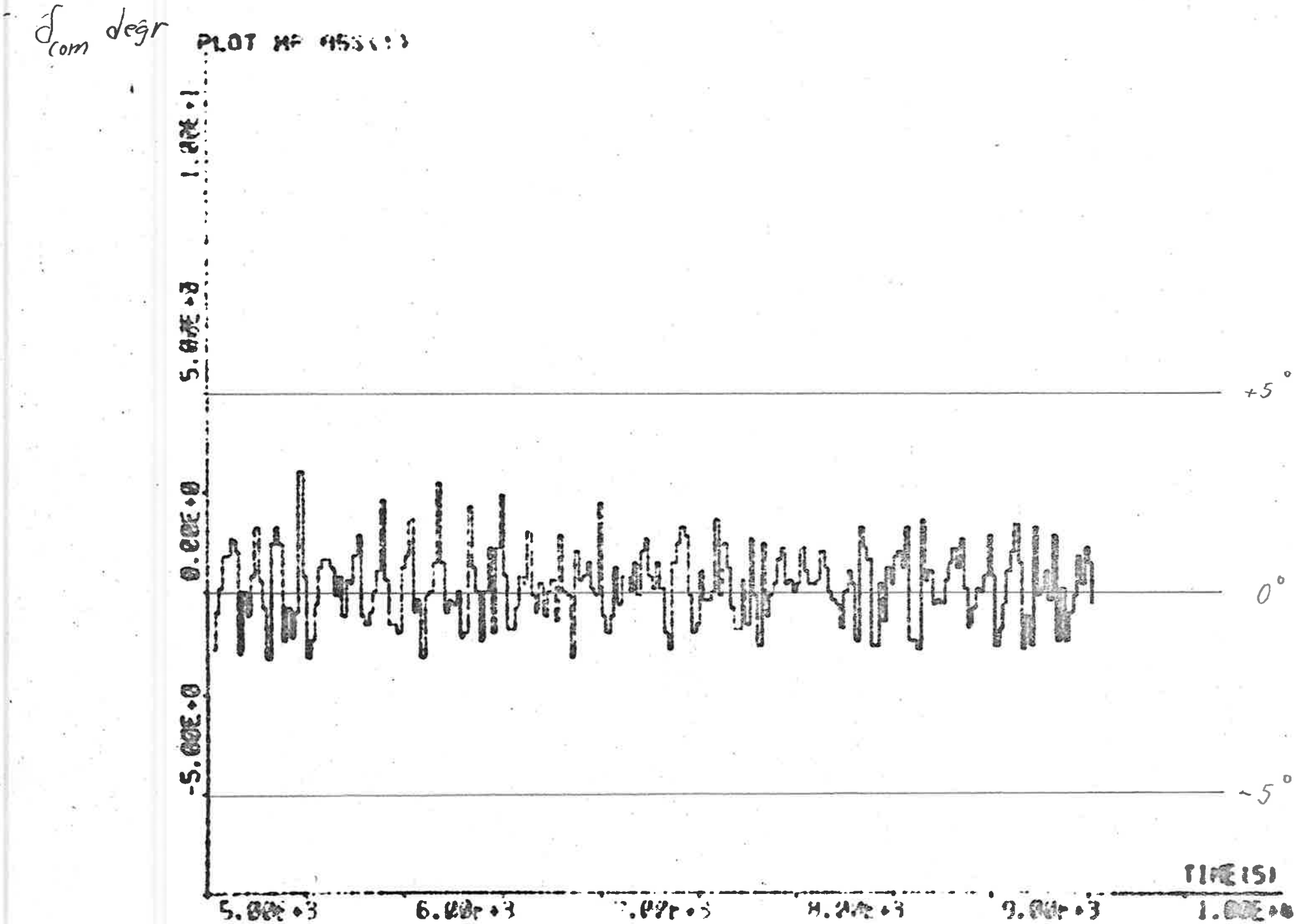
$$\delta(t) = -2.8217(\Psi(t) - \Psi_{ref}) - 0.0703\delta(t-1) - 39.8646r(t)$$

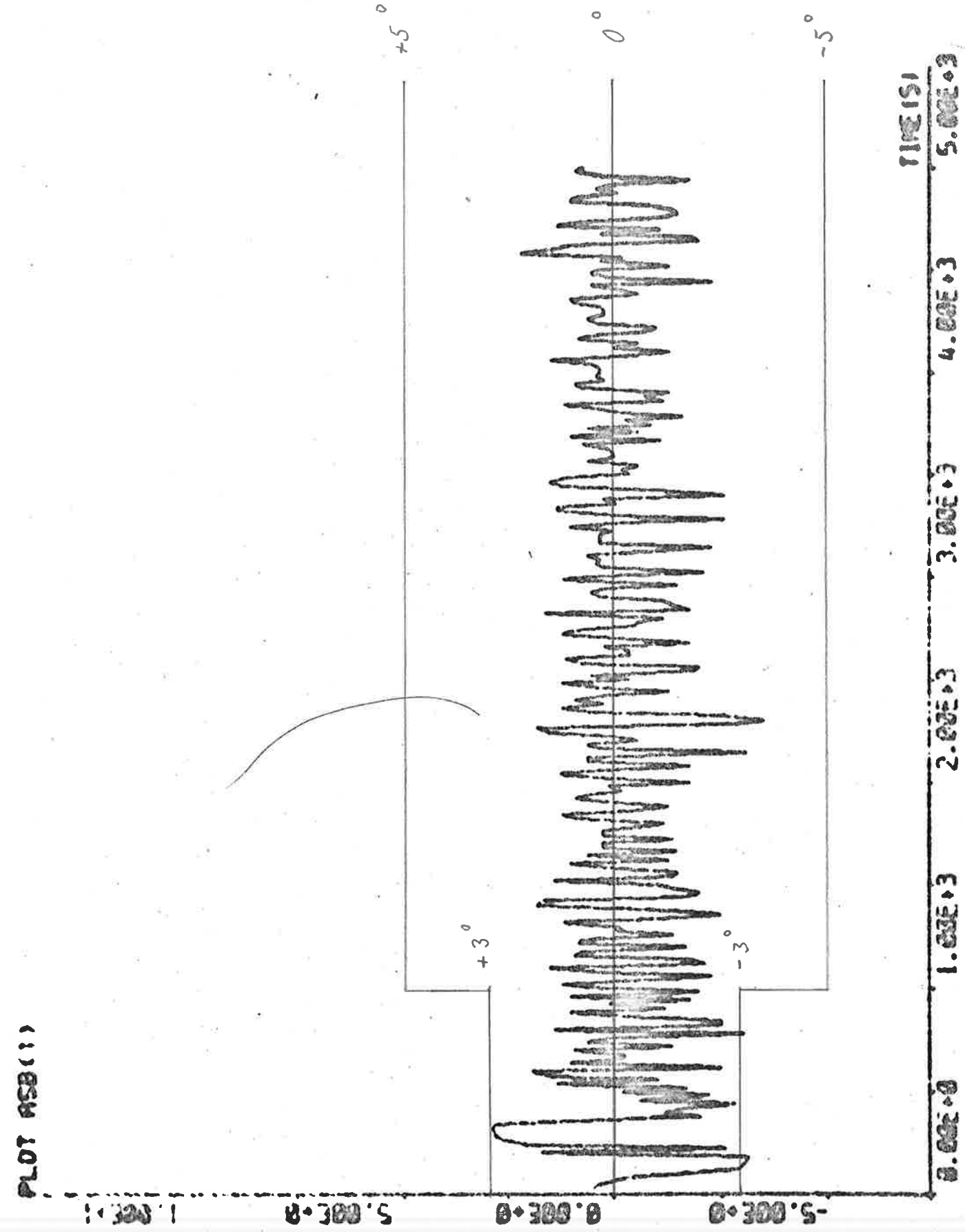
Statistics:

	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

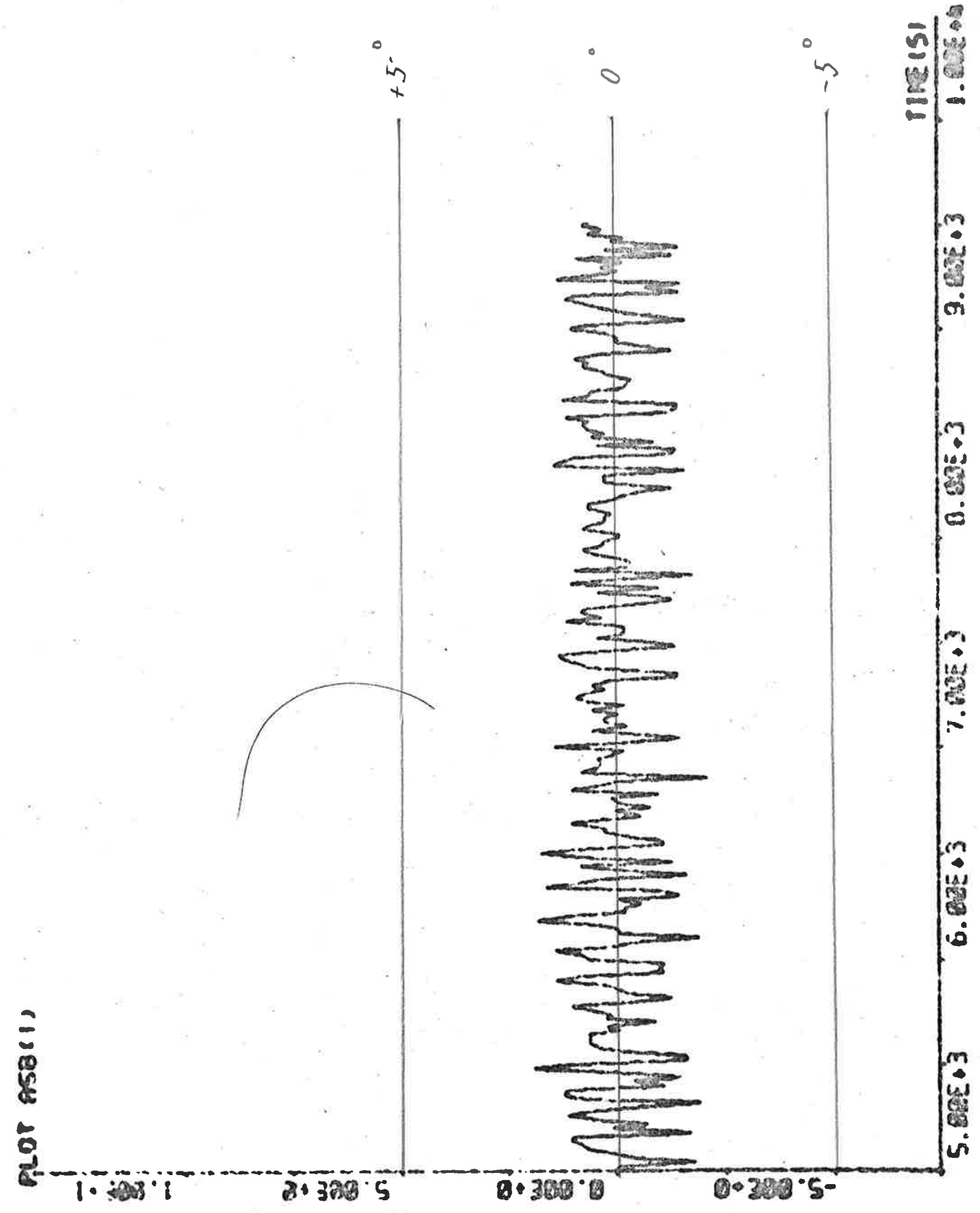


δ_{com} degr
PLOT HP ASS(1)
+5°
+3°
0°
-3°
-5°
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


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

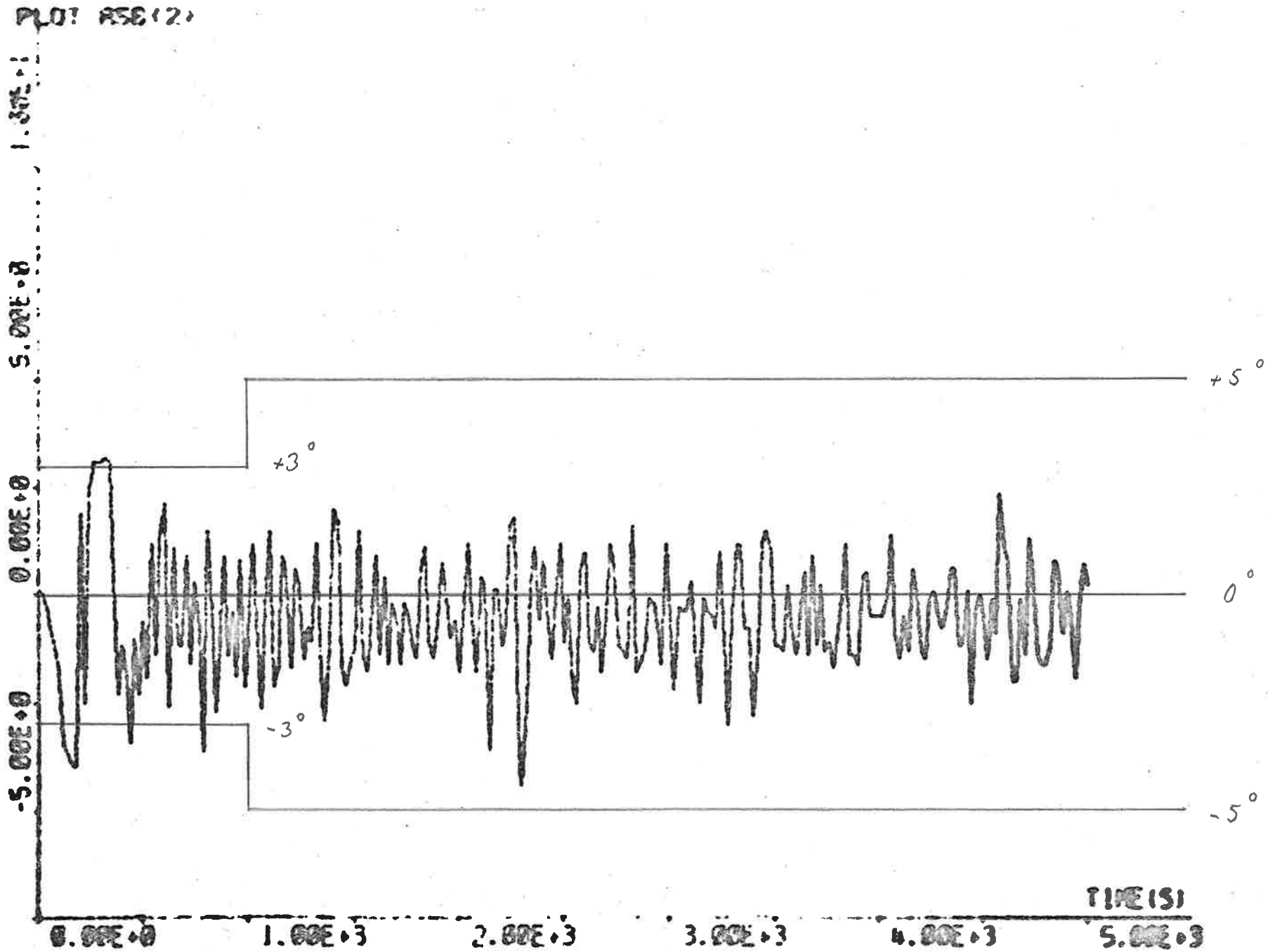

PLOT ASB(1)
TIME(S)
+5°
0°
-5°
+3°
-3°
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.00E+1
5.00E+0
0.00E+0
-5.00E+0

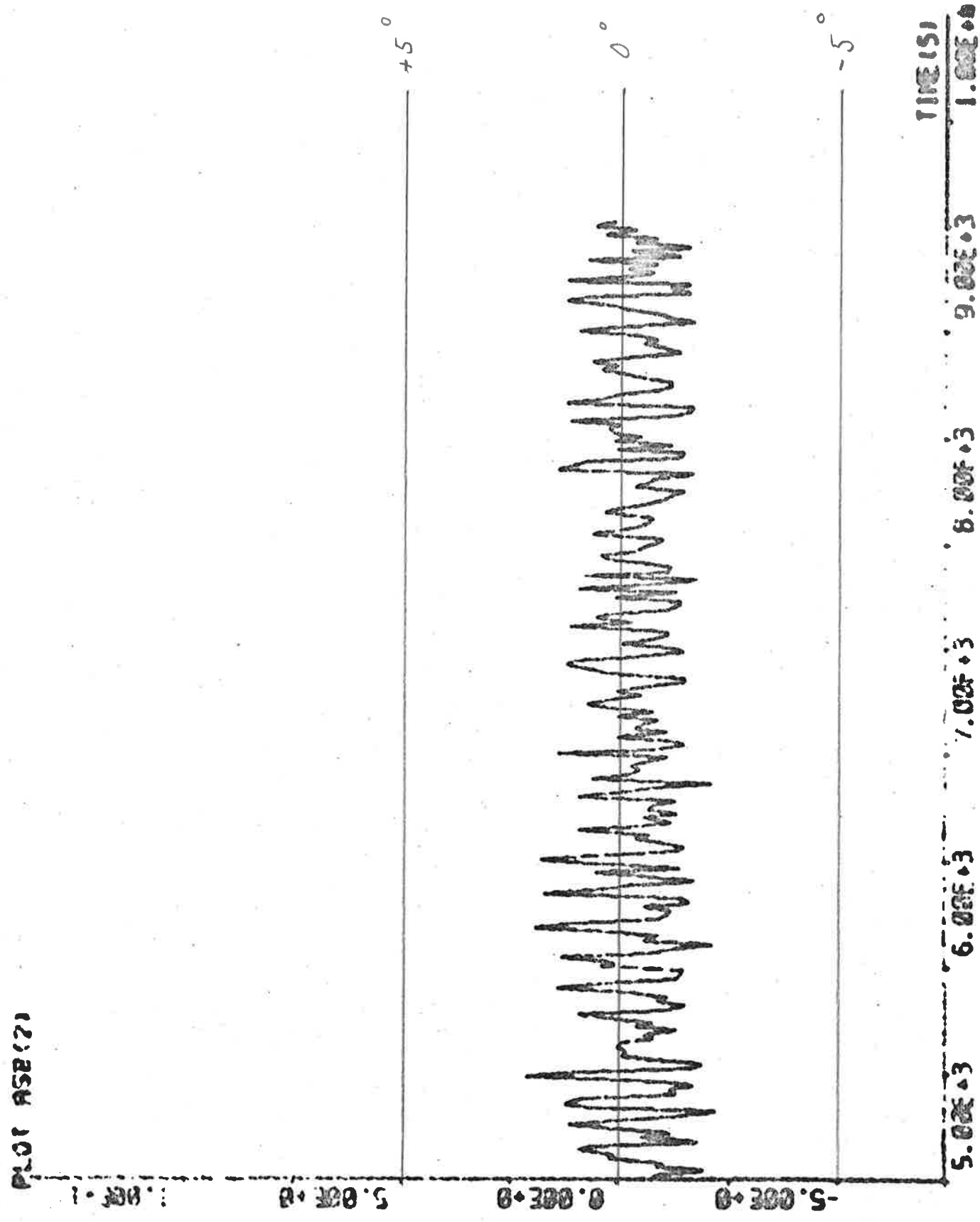
δ_s degr

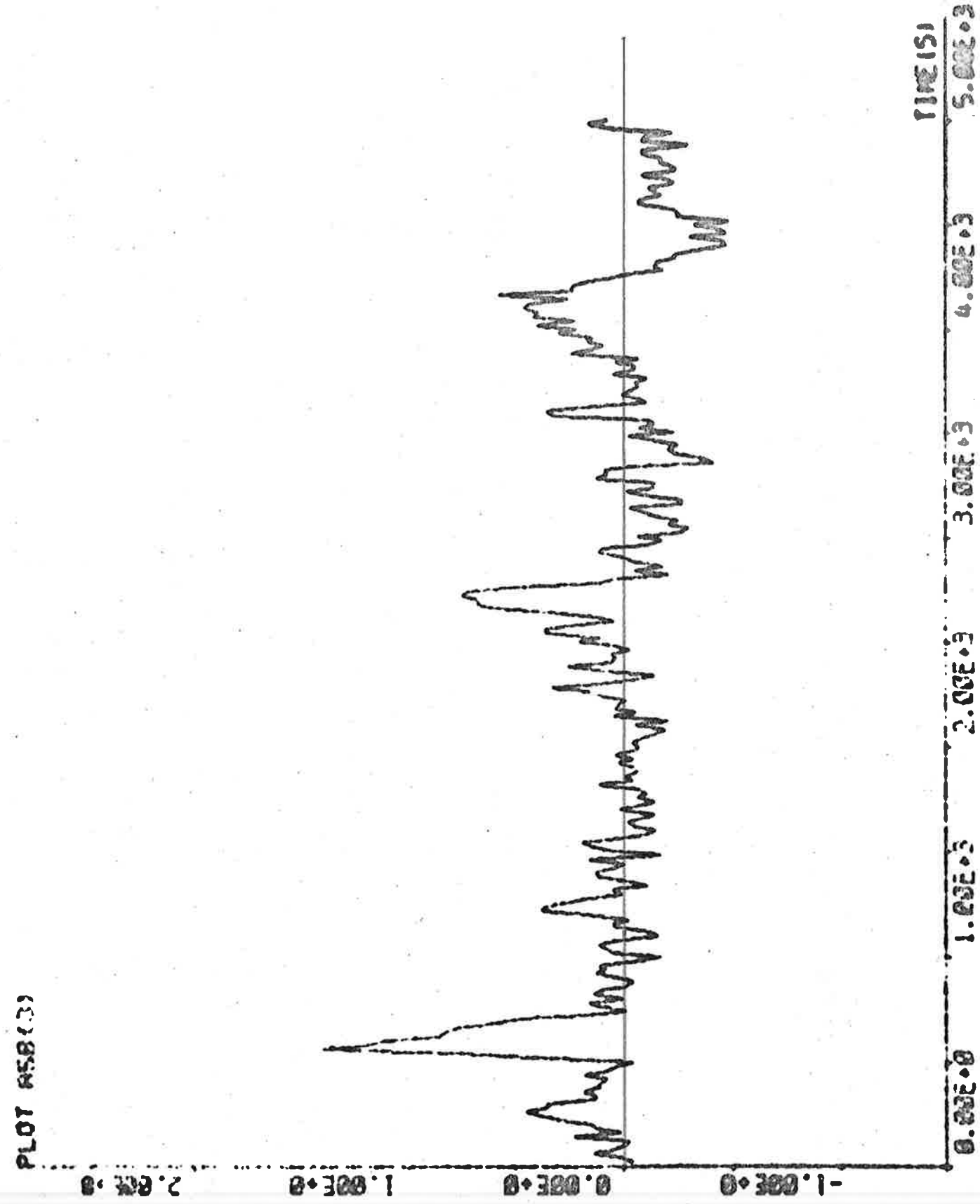

+5°
0°
-5°
TIME (S)
5.000E+3
6.000E+3
7.000E+3
8.000E+3
9.000E+3
1.000E+4
-5.000E-0
0.000E+0
5.000E+0
1.000E+1
PLOT ASB(1)

δ_s degr

δ degr

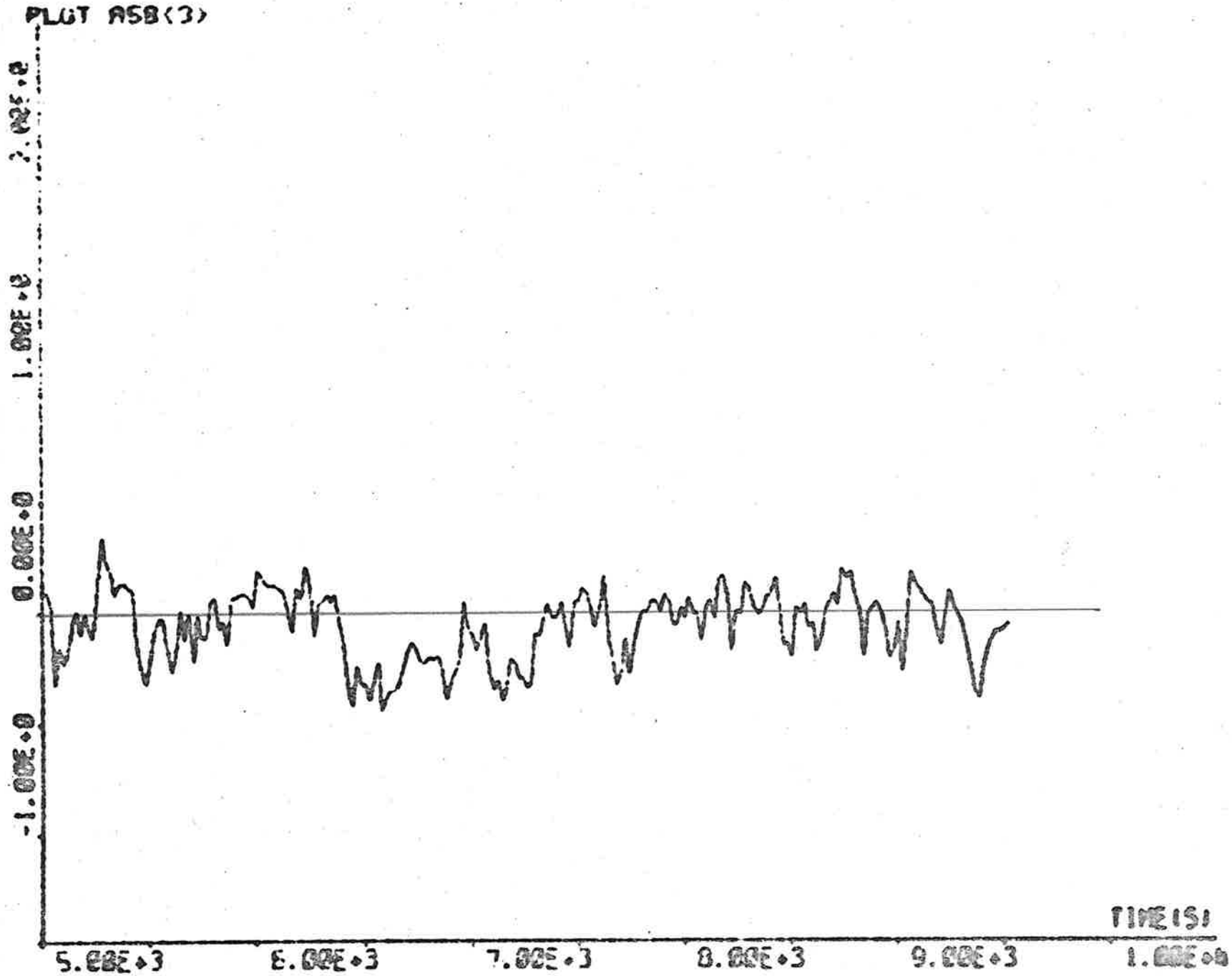

PLOT RSE(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
+3°
-3°
+5°
0°
-5°
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

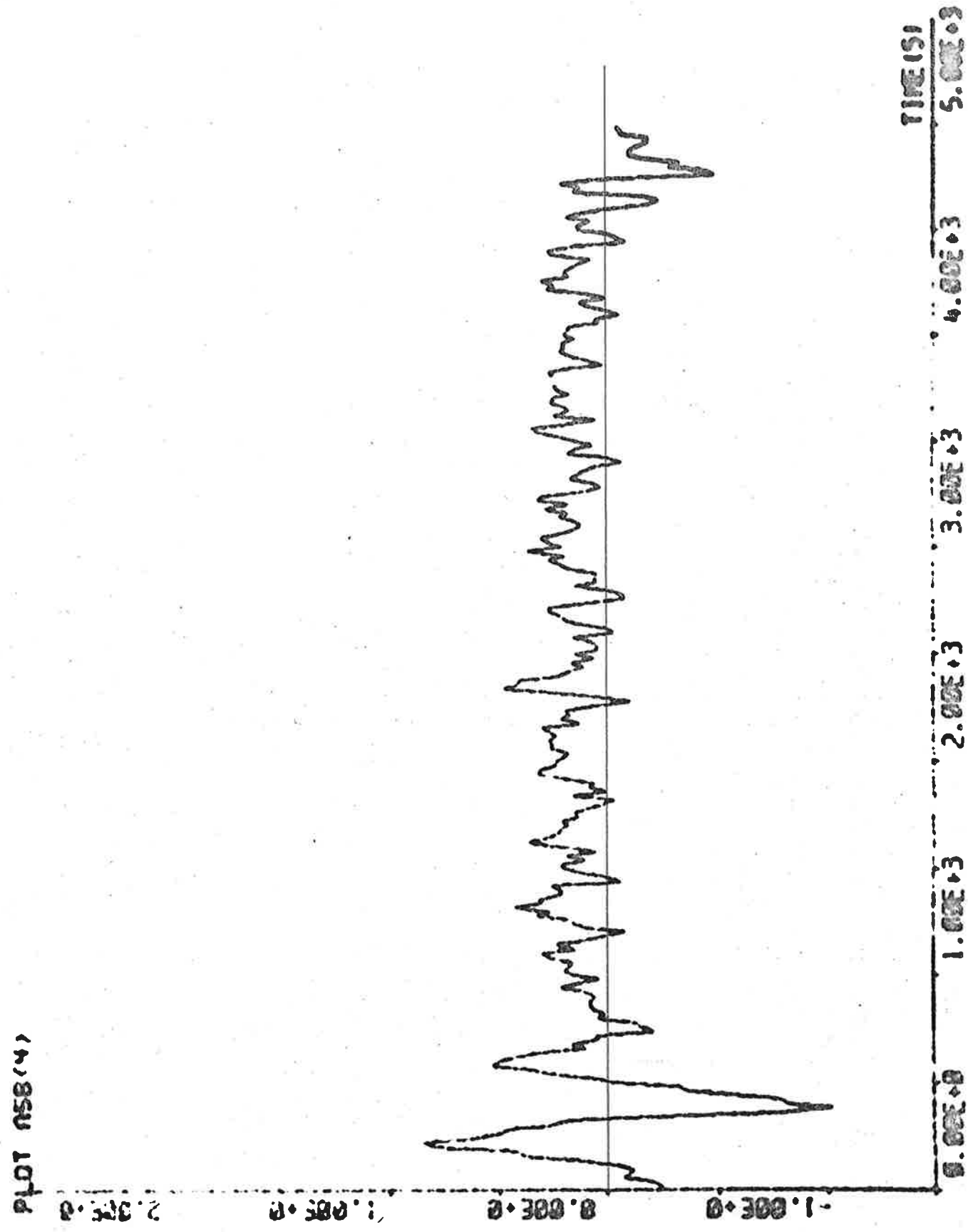

+5°
0°
-5°
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
PLOT ASE(2)


PLOT A58(3)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-1.00E+0
0.00E+0
1.00E+0
2.00E+0

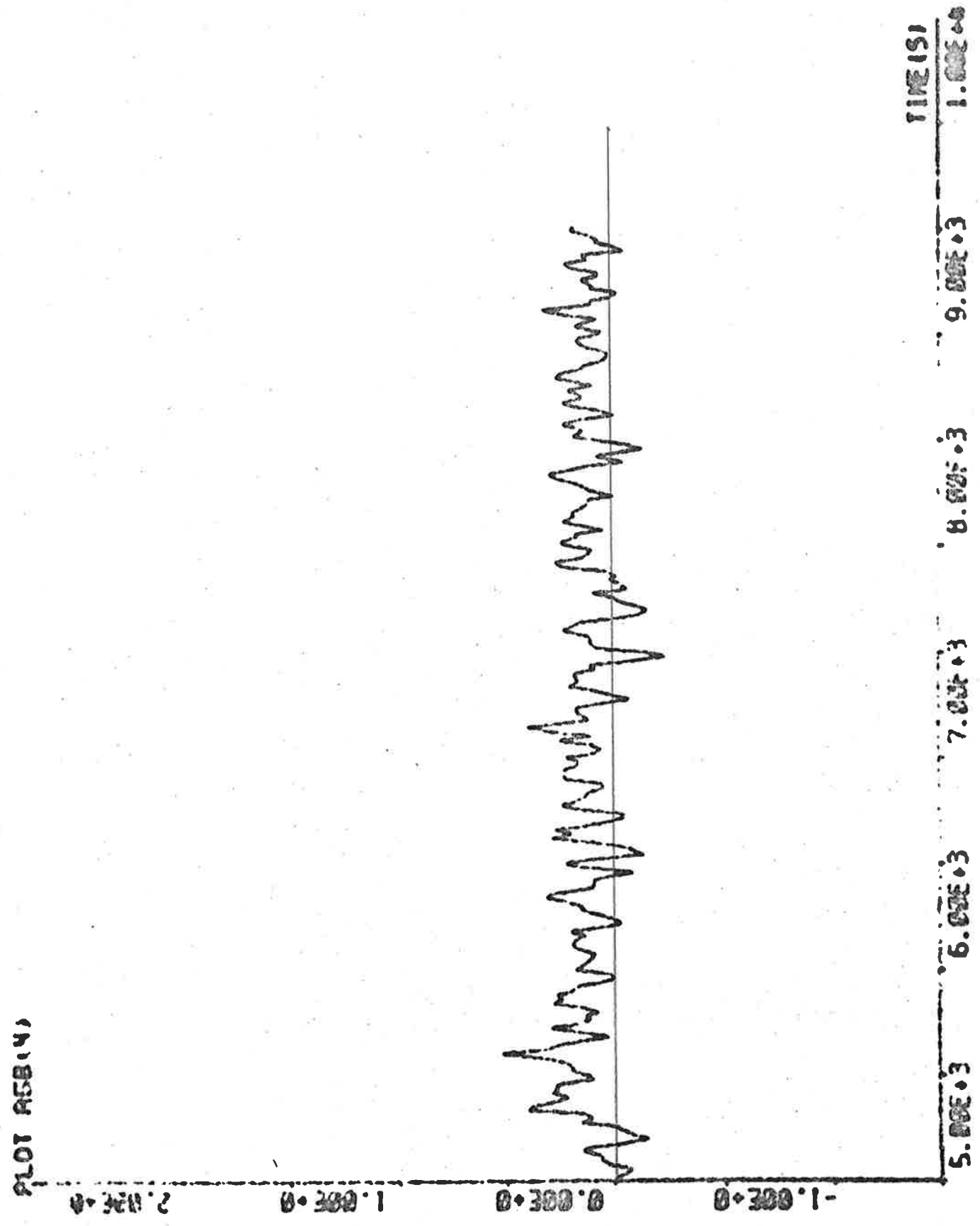
V_1 knots

V_1 knots

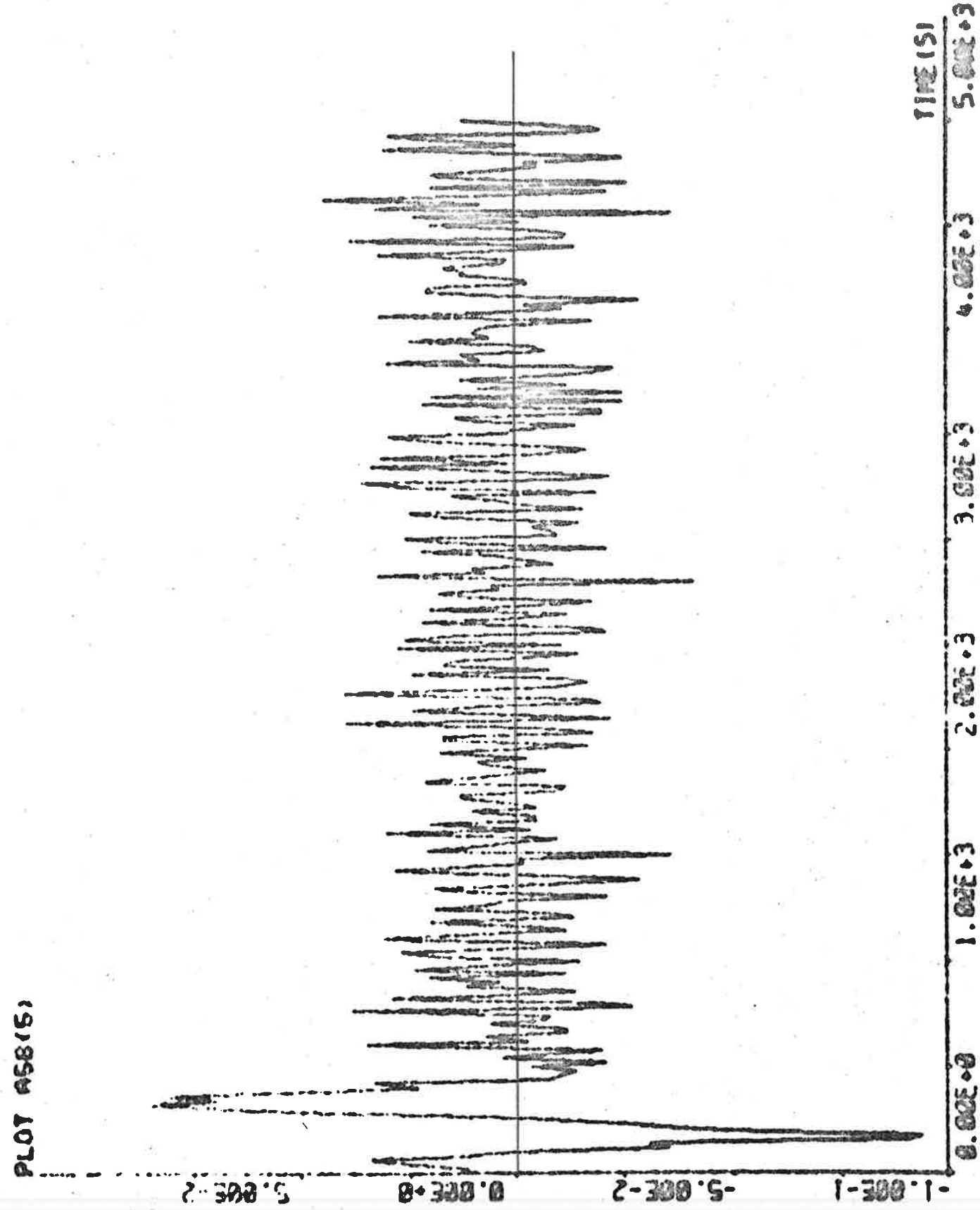

PLOT A58(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4


PLOT ASB(4)
-1.000E+0
0.000E+0
1.000E+0
2.000E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

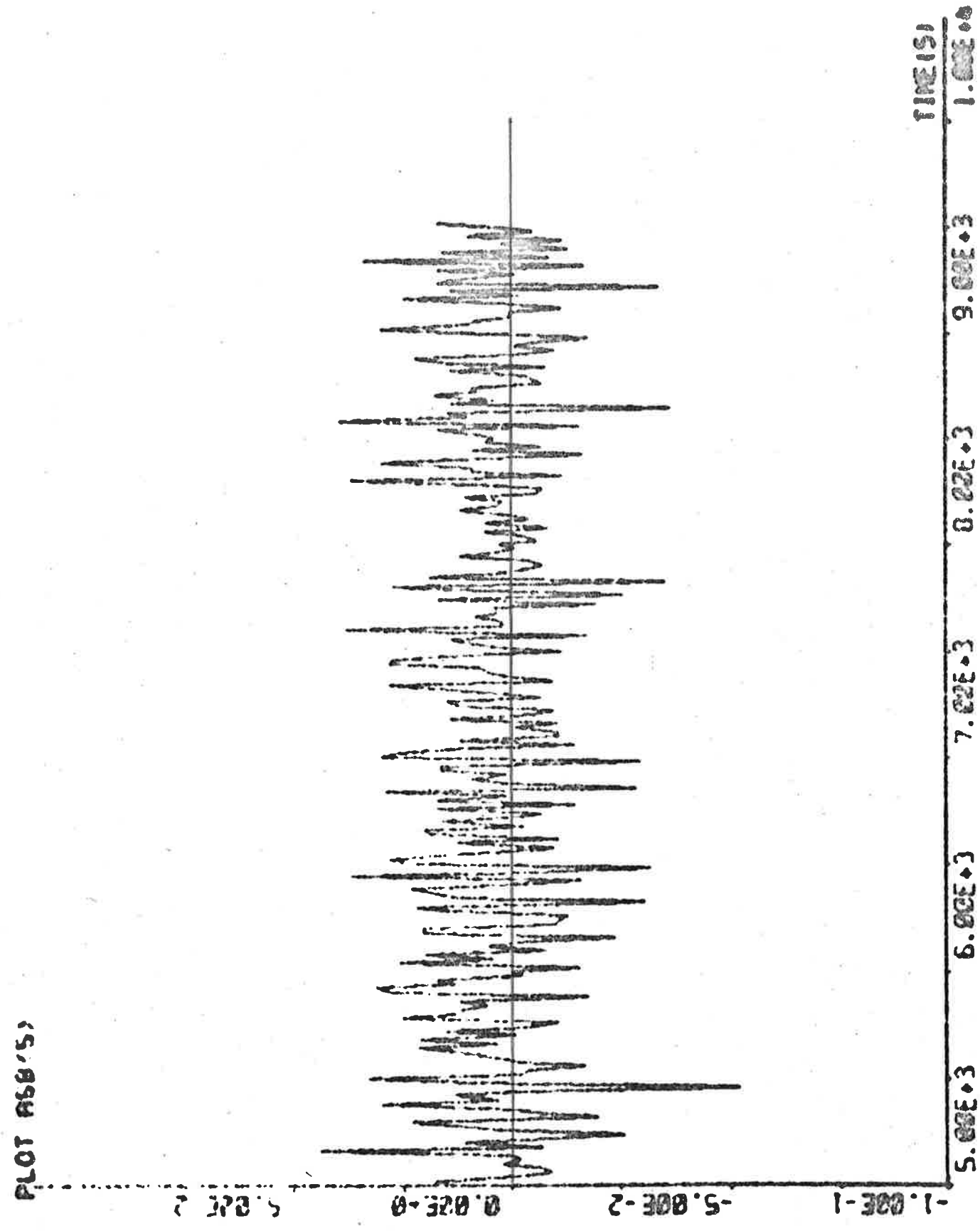
4 knots


PLOT ASB(4)
TIME(S)
5.000+3
6.000+3
7.000+3
8.000+3
9.000+3
1.000+4
0.300+0
0.300+1
-1.000+0

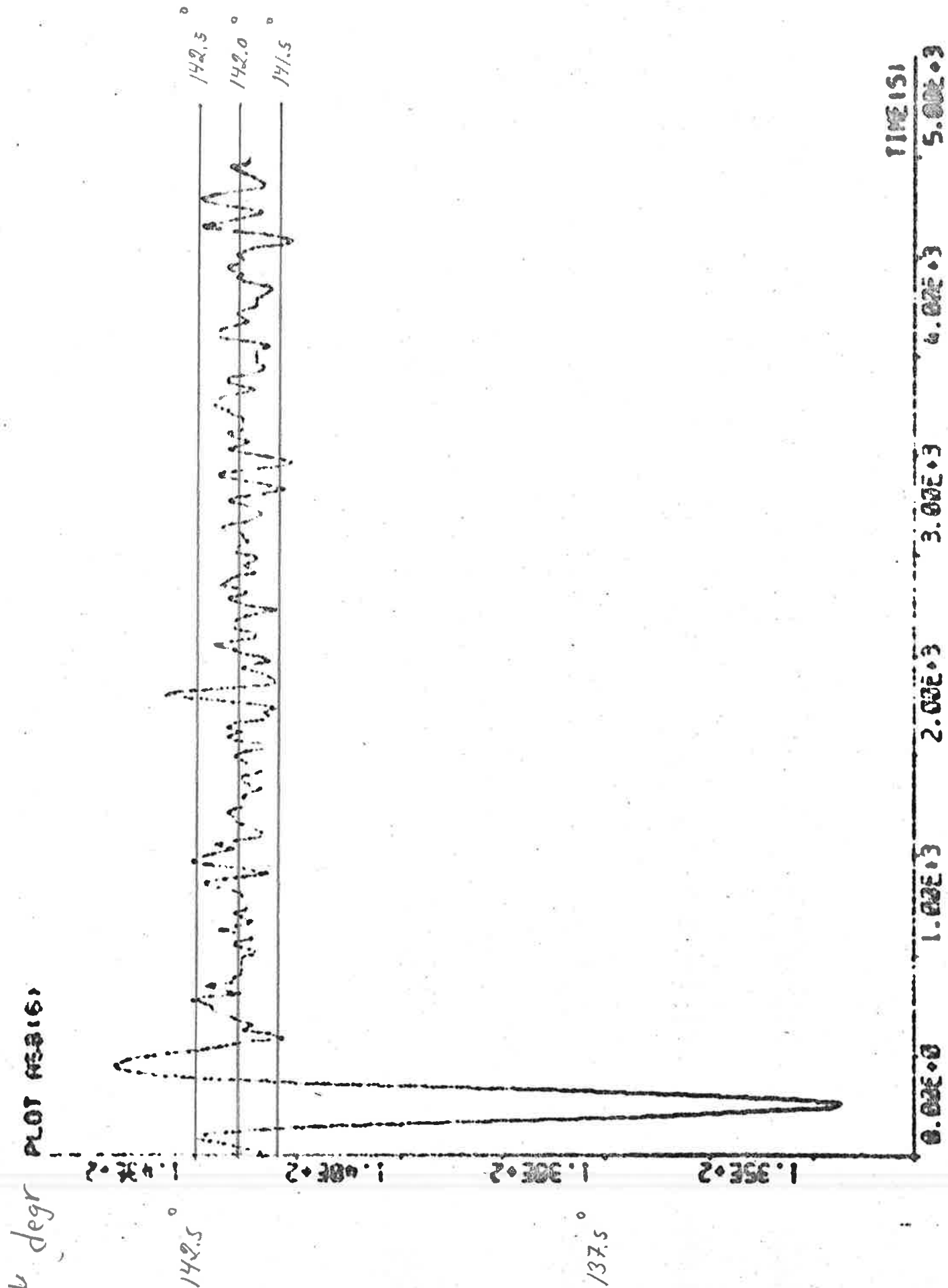
½ knots

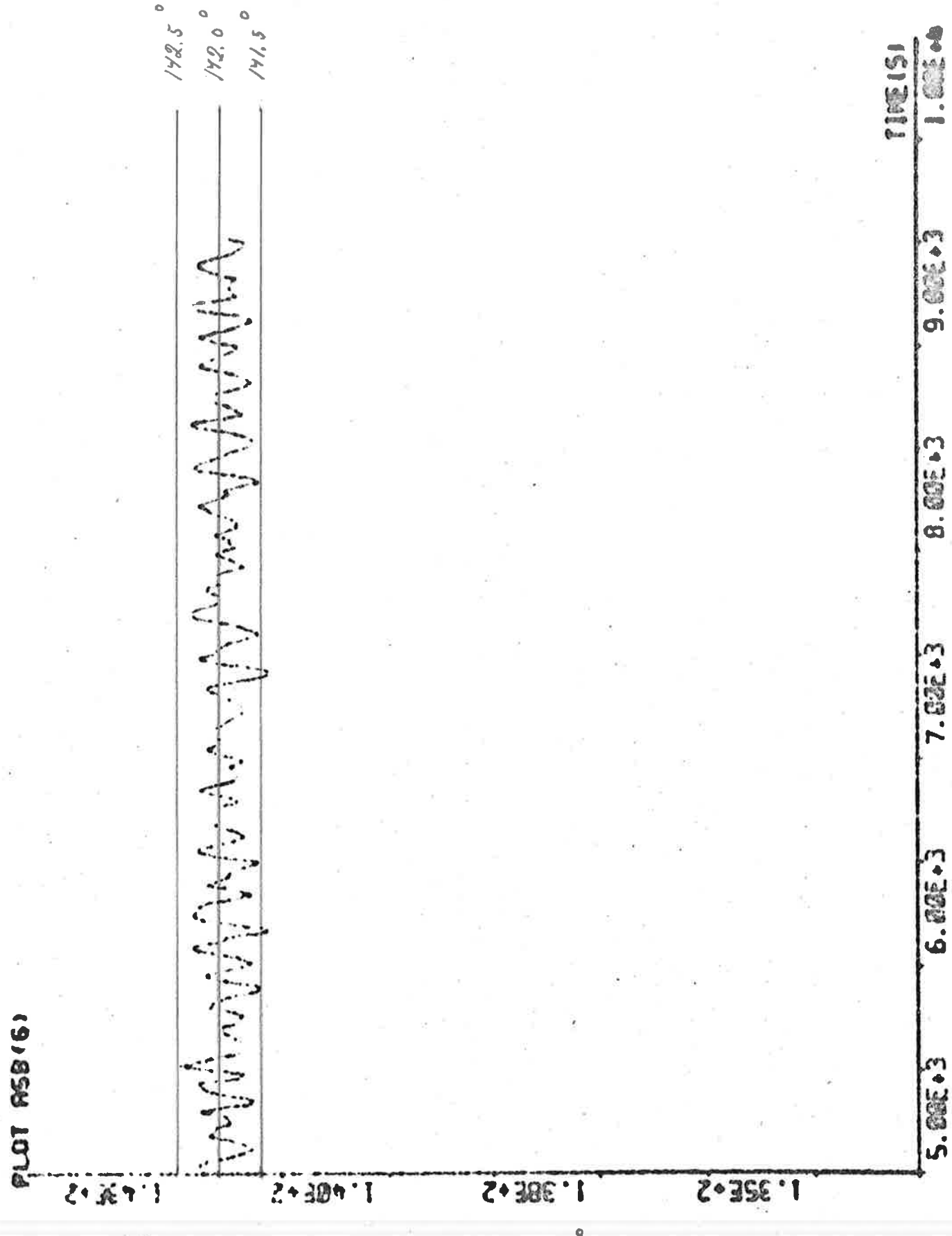

PLOT AS8(5)
TIME(S)
0.000E+0
1.025E+3
2.050E+3
3.075E+3
4.100E+3
5.125E+3
-1.000E-1
-5.000E-2
0.000E+0
5.000E-2

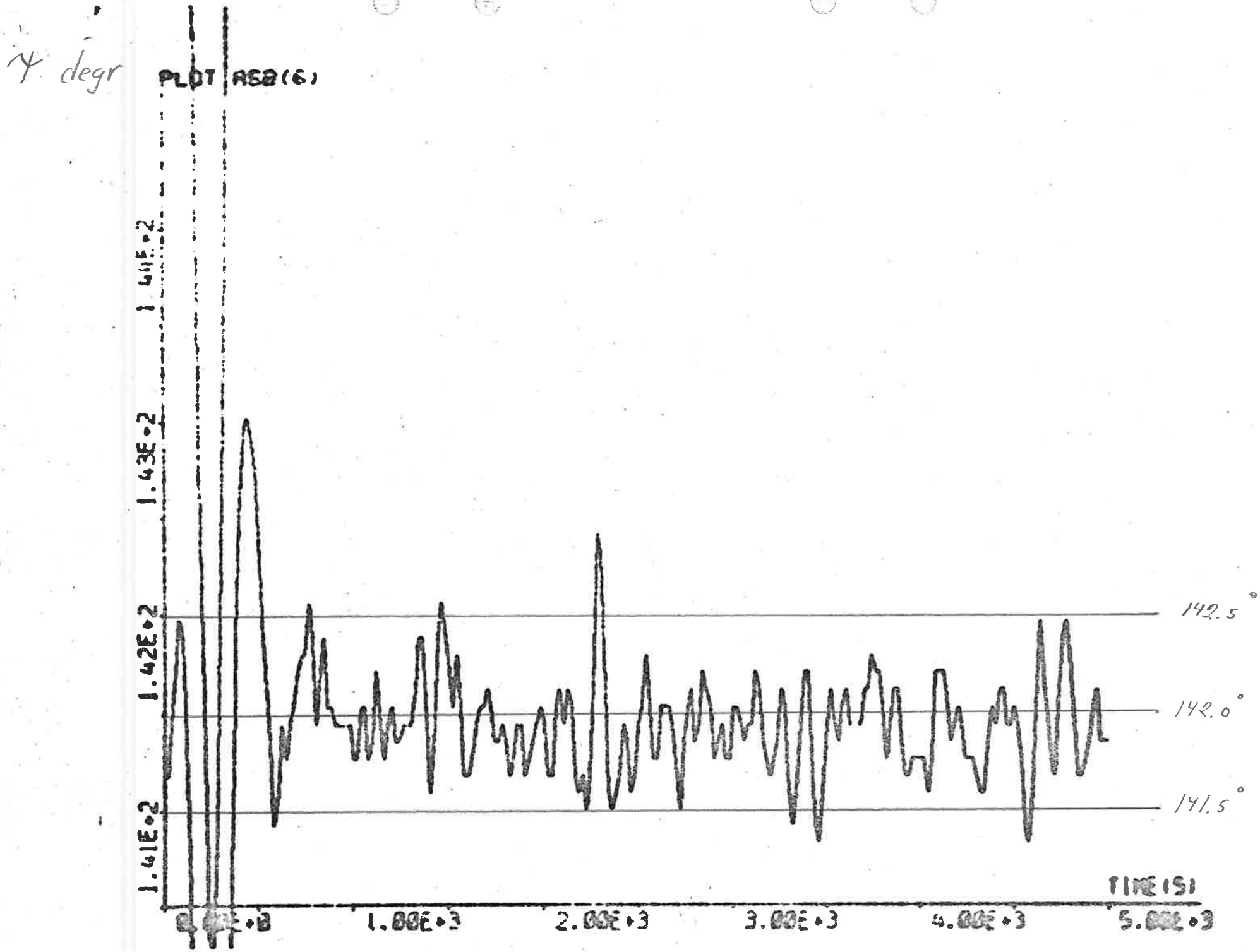
r degr/s


PLOT ASB('S)
-1.000E-1
-5.000E-2
0.000E+0
5.000E+3
6.000E+3
7.000E+3
8.000E+3
9.000E+3
TIME(S)

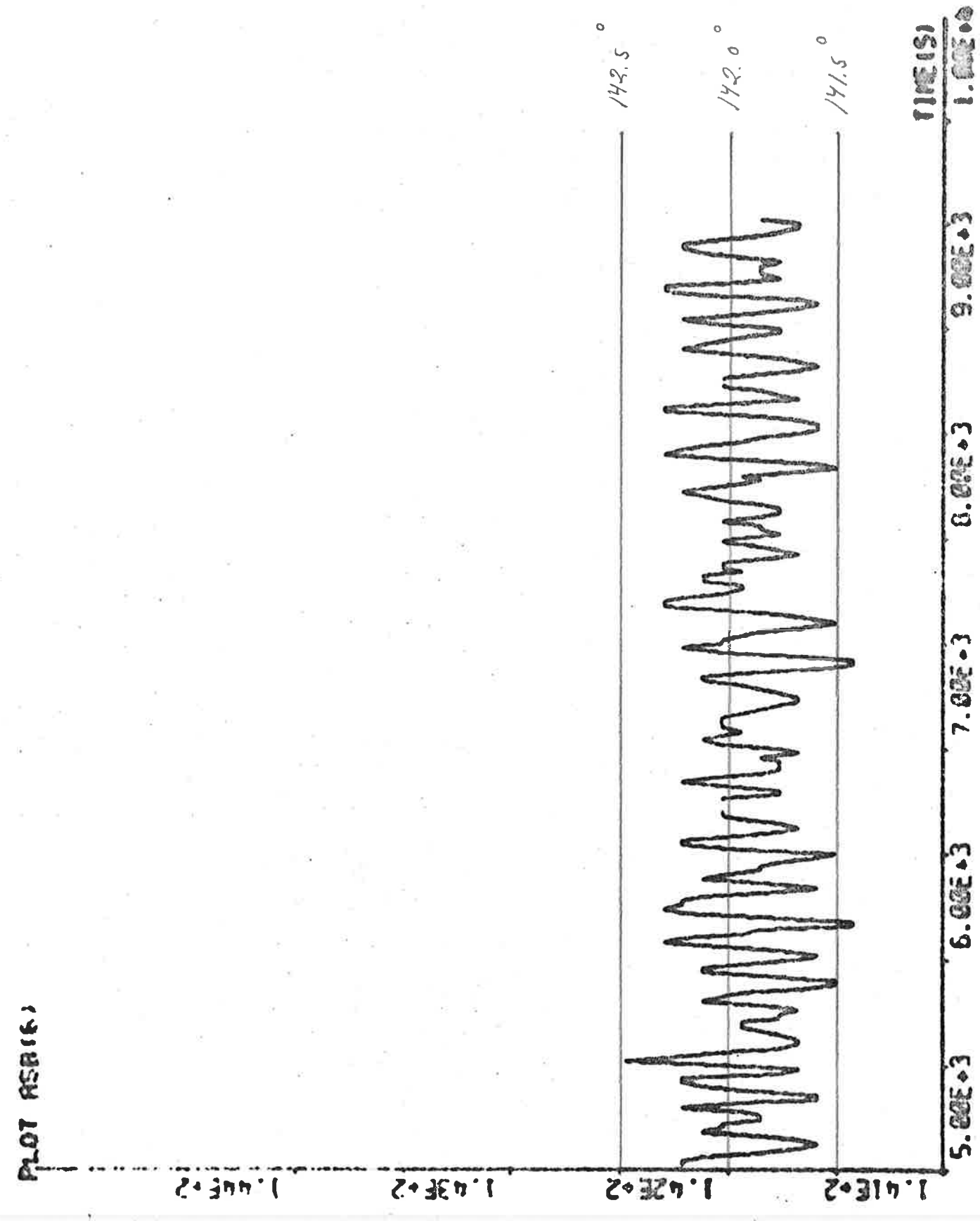
r degr/s


PLOT #3161
TIME(S)
0.0E+0
1.0E+3
2.0E+3
3.0E+3
4.0E+3
5.0E+3
1.4E+2
1.3E+2
1.2E+2
1.1E+2
142.5°
137.5°
142.5°
142.0°
141.5°
ψ degr

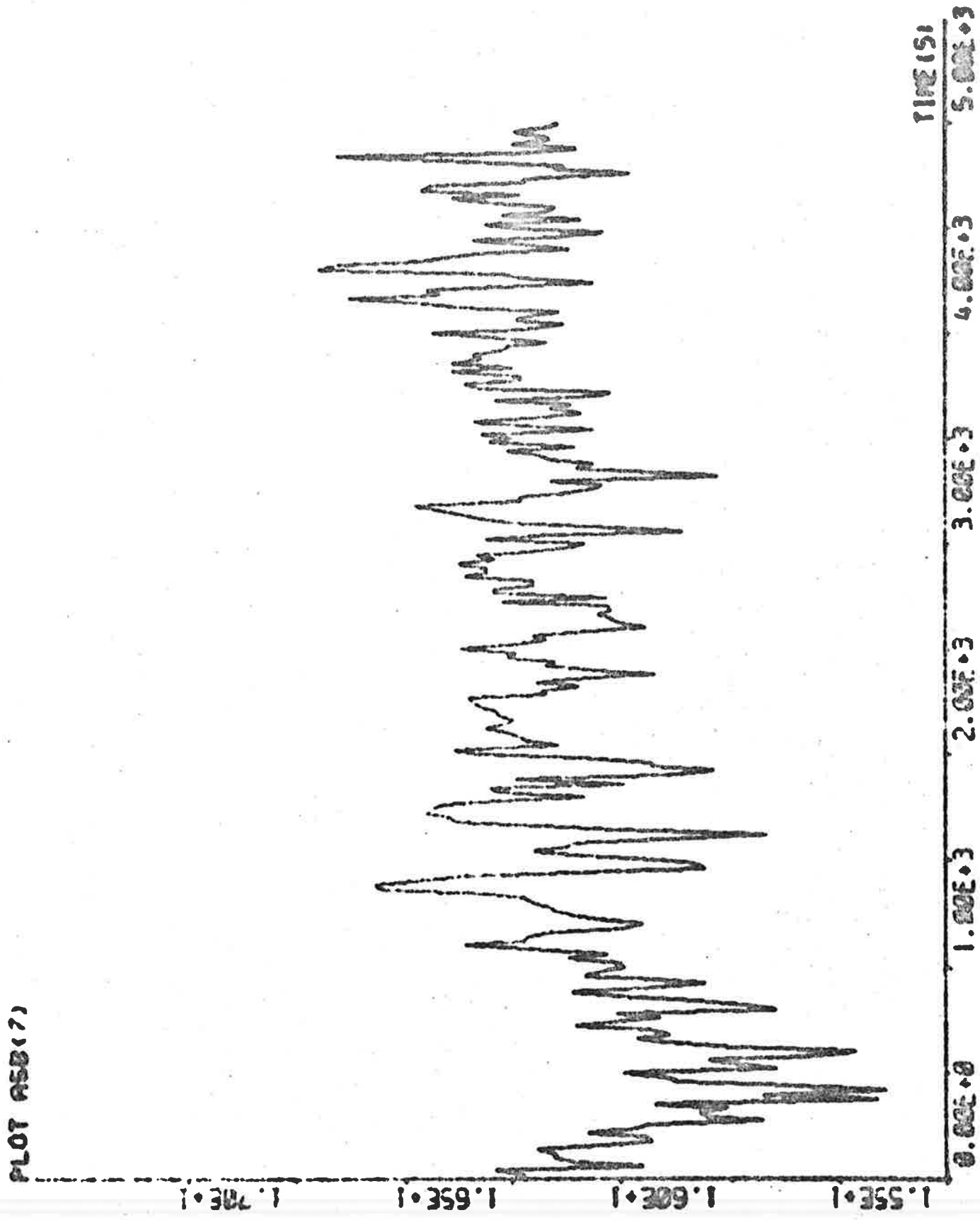

PLOT ASB(6)
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
1.35E+2
1.38E+2
1.40E+2
1.42E+2
142.5°
142.0°
141.5°
γ degr
142.5°
137.5°



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

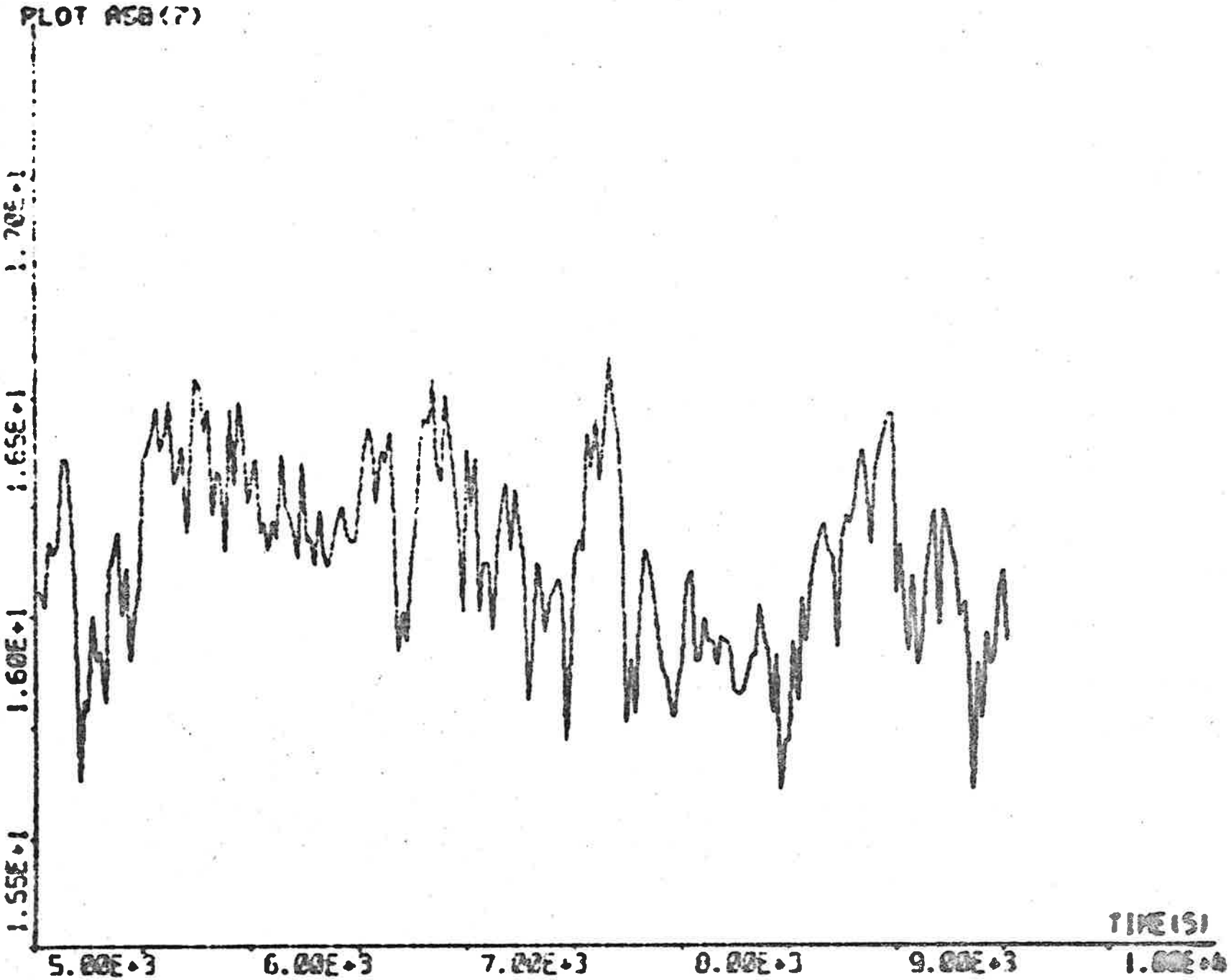

PLOT ASB(6)
1.4E+2
1.4E+2
1.4E+2
1.4E+2
5.0E+3
6.0E+3
7.0E+3
8.0E+3
9.0E+3
1.0E+4
TIME(S)
142.5°
142.0°
141.5°

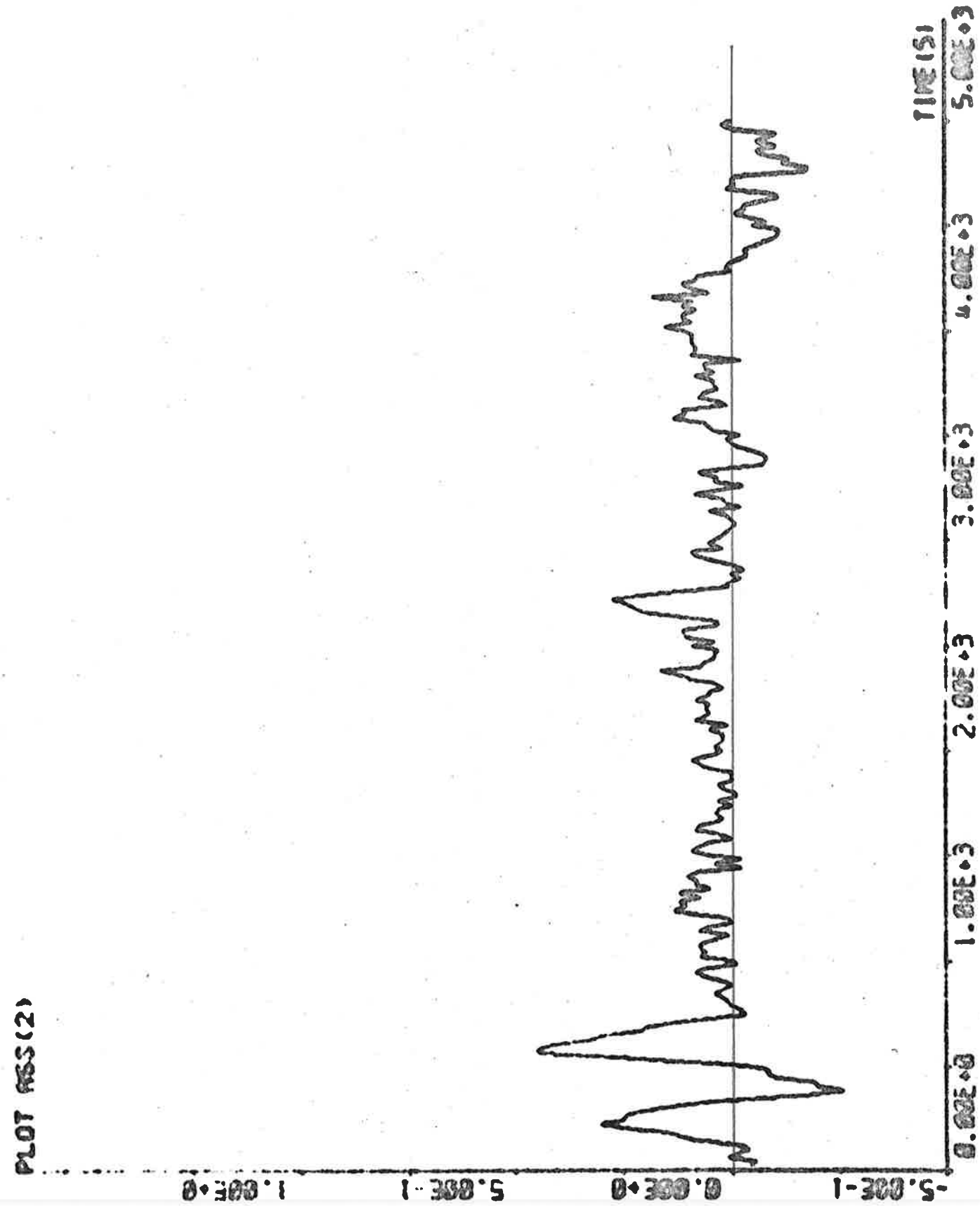
γ deg


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

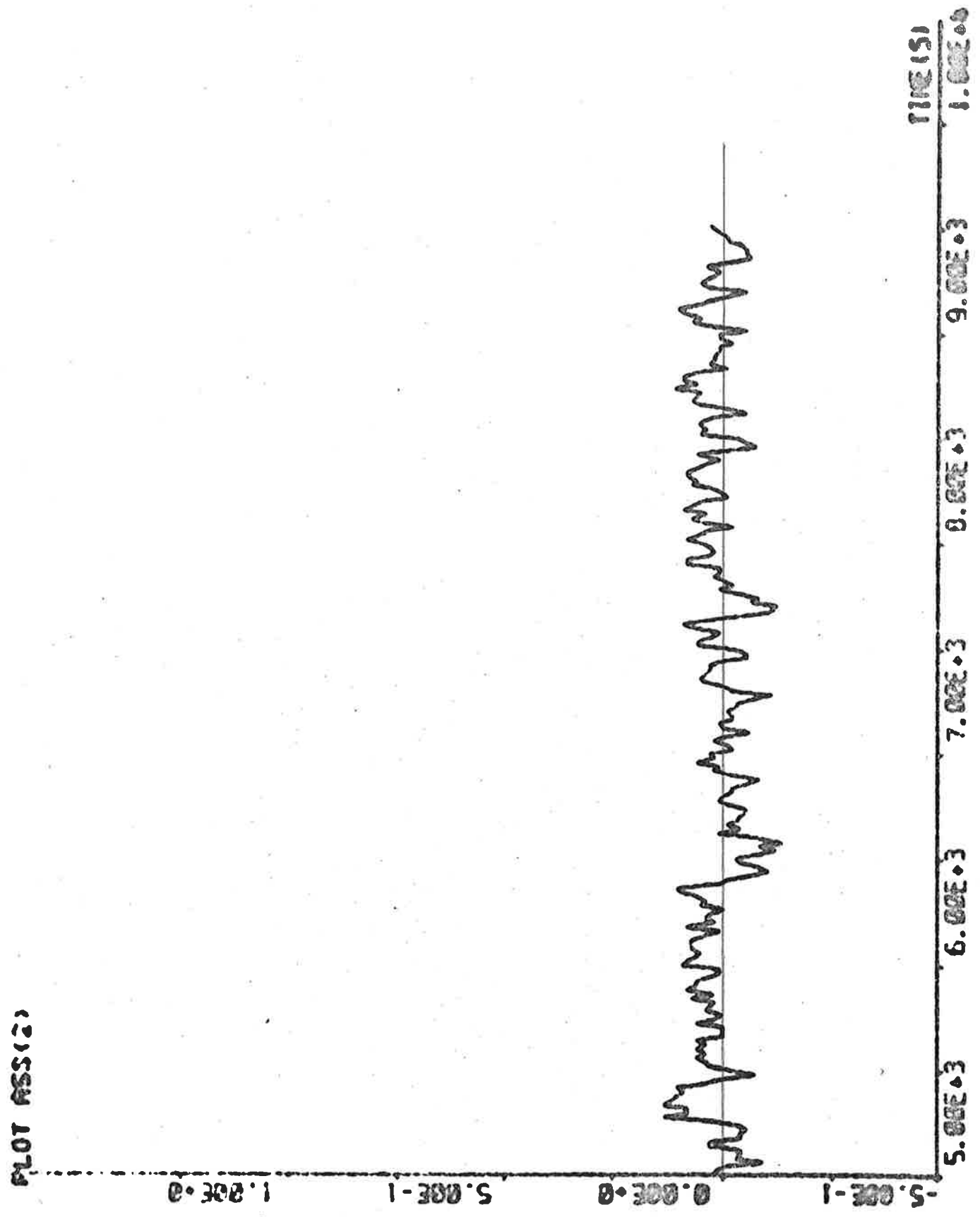
U knots

u knots

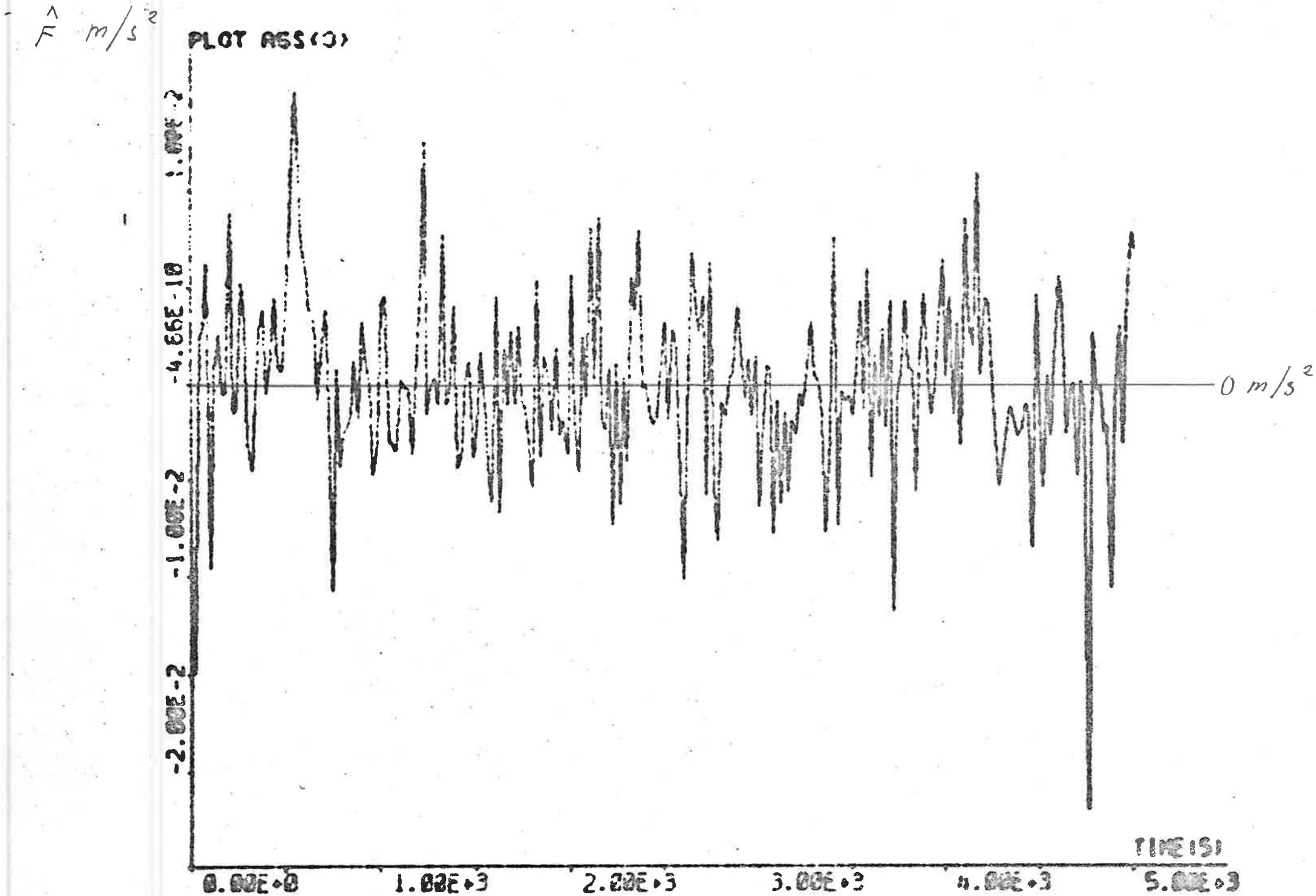

PLOT ASB(7)
1.70E+1
1.65E+1
1.60E+1
1.55E+1
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4


PLOT ABS(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)

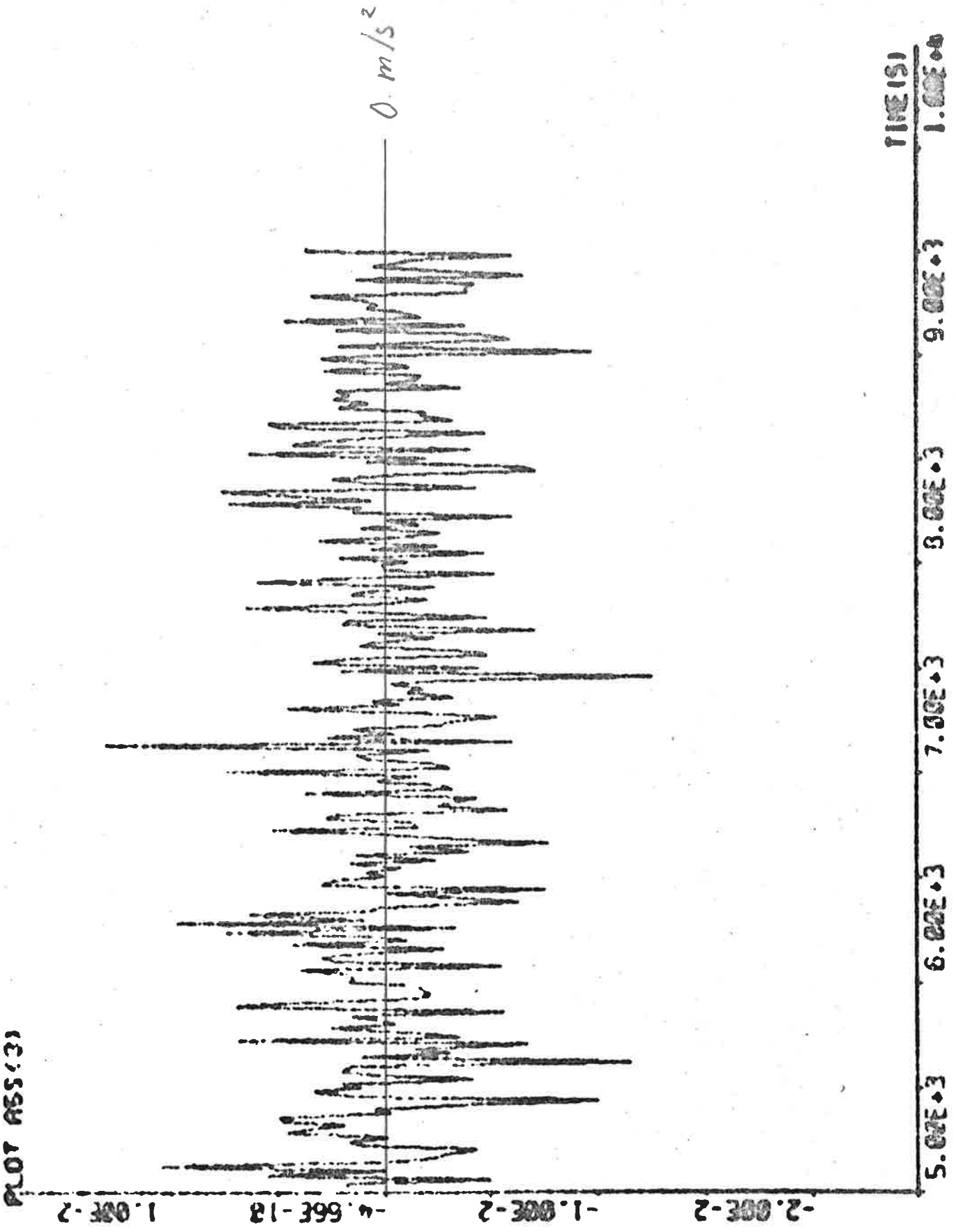
V m/s

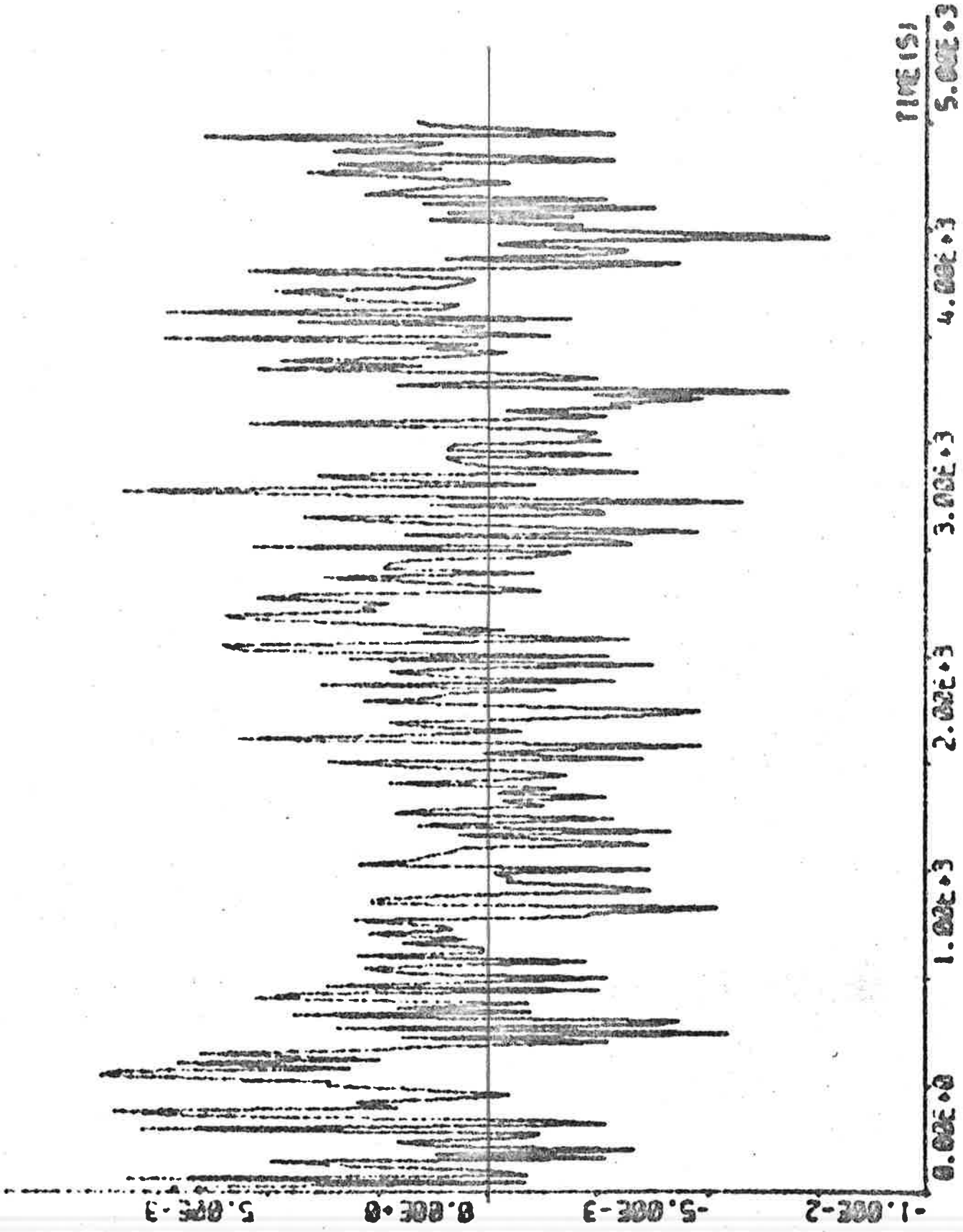

PLOT ASS(2)
-5.00E-1
0.00E+0
5.00E-1
1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

< m/s

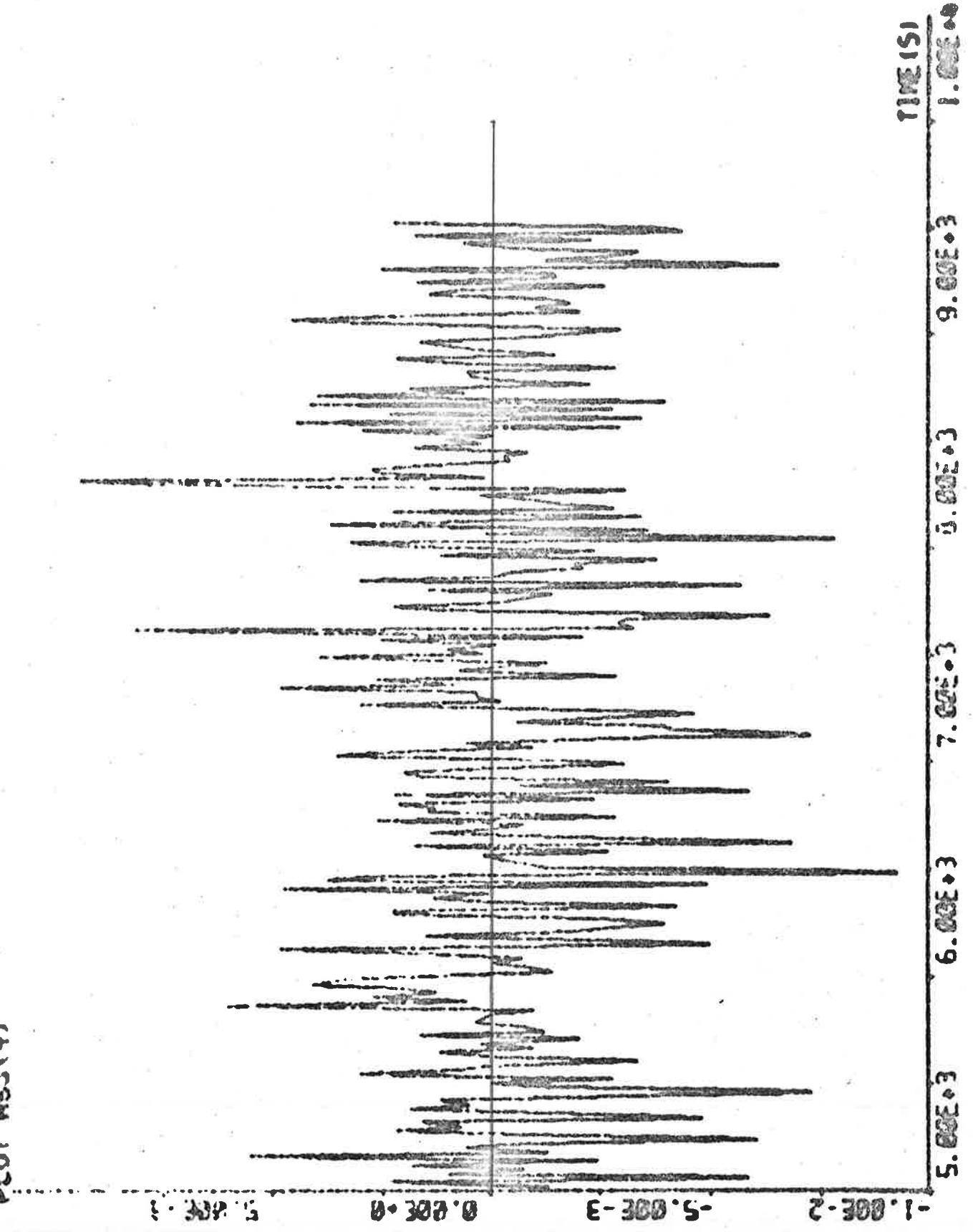


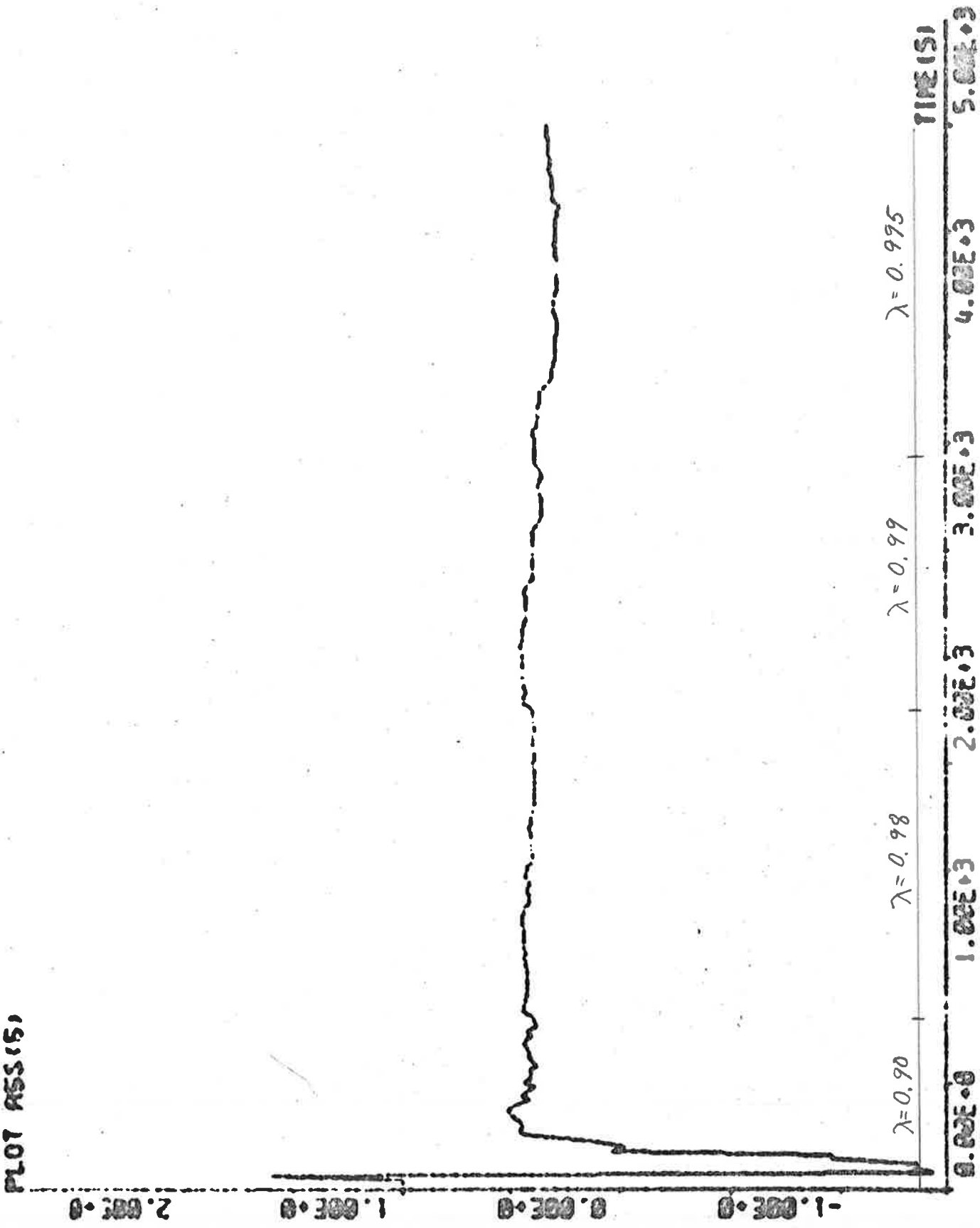
$\hat{F}$ m/s²
PLOT ASS(3)
1.00E-2
-4.66E-10
-1.00E-2
-2.00E-2
0 m/s²
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


0 m/s²
TIME (S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
PLOT ABS(3)
-2.00E-2
-1.00E-2
-4.66E-13
1.00E-2

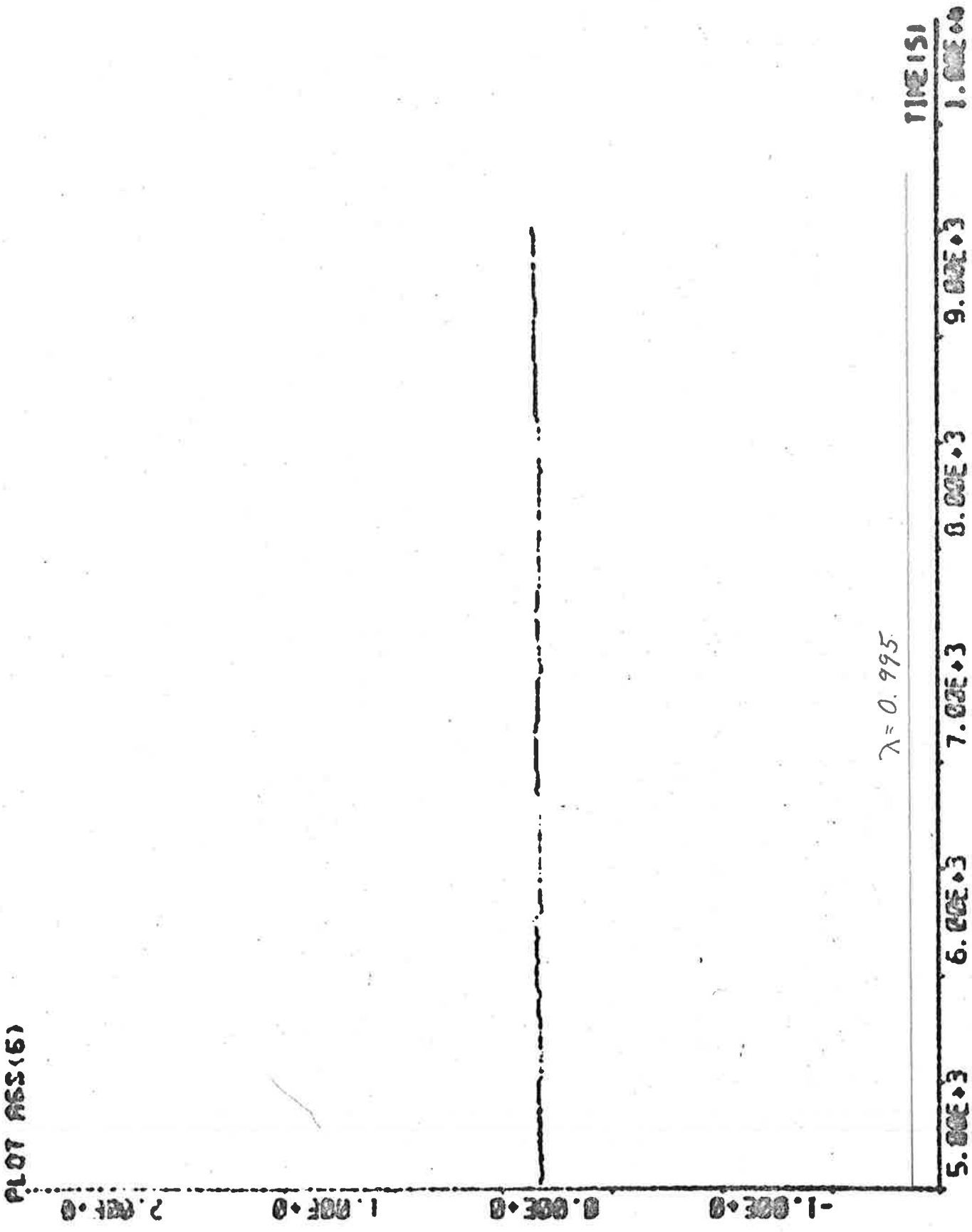

PLOT AGS(4)
TIME (S)
-1.00E-2
-5.00E-3
0.00E+0
5.00E-3
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

$\hat{M}$ degr/s^2


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
PLOT ASS(4)
$\hat{M}$ degr/s^2

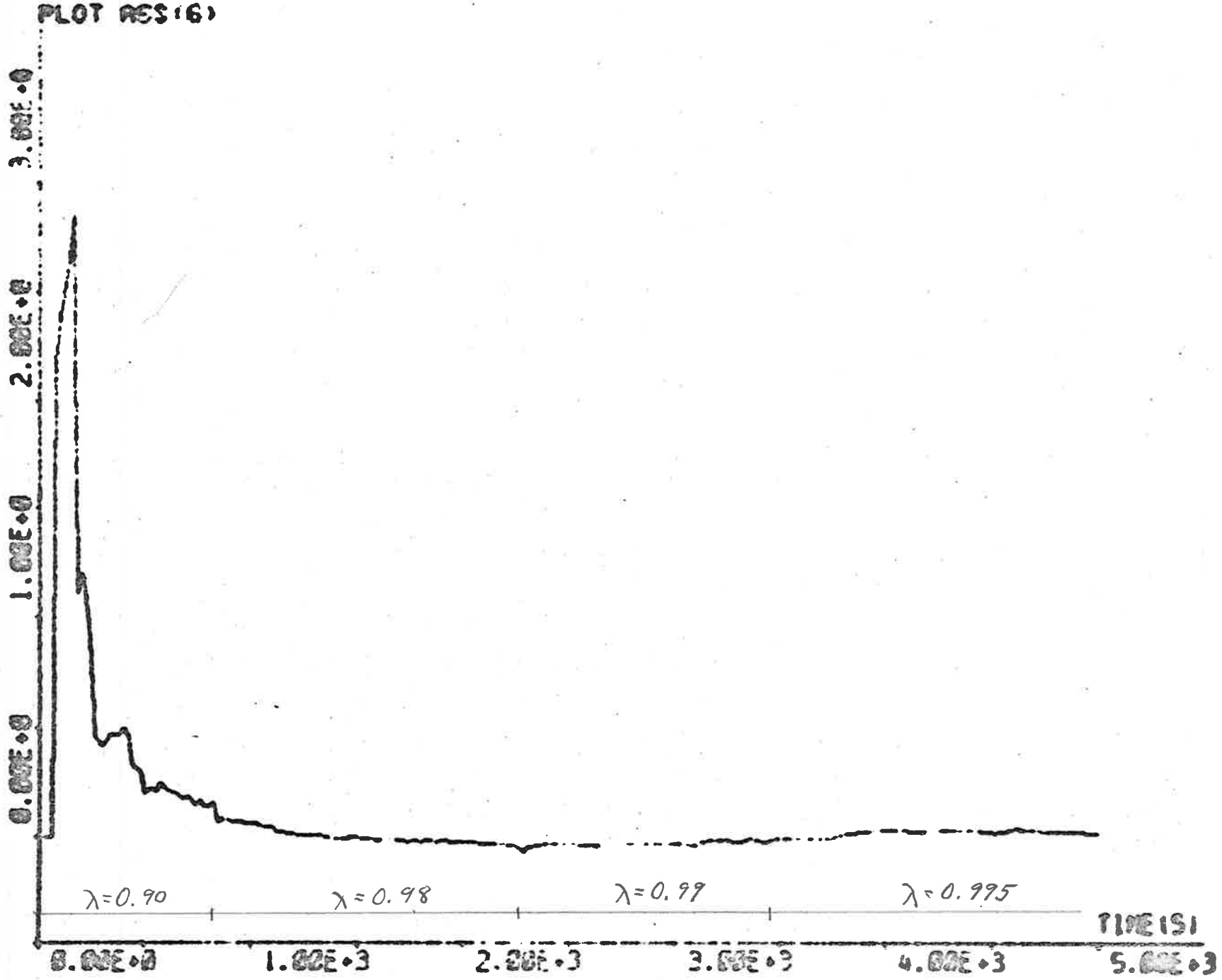

PLOT ASS(S)
2.000·0
1.000·0
0.000·0
-1.000·0
0.00E·0
1.00E·3
2.00E·3
3.00E·3
4.00E·3
5.00E·3
TIME(S)
λ=0.90
λ=0.98
λ=0.99
λ=0.995

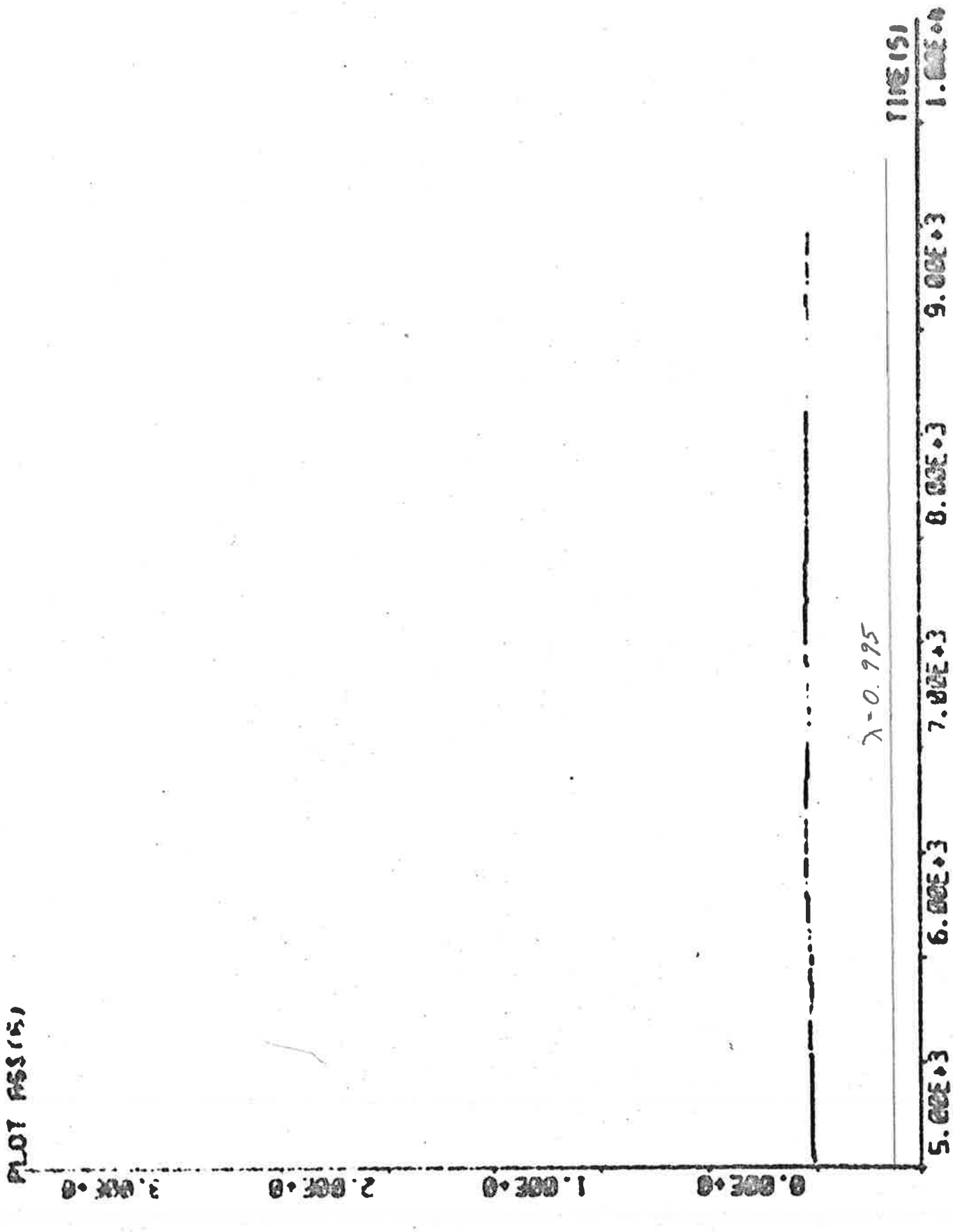
b_1



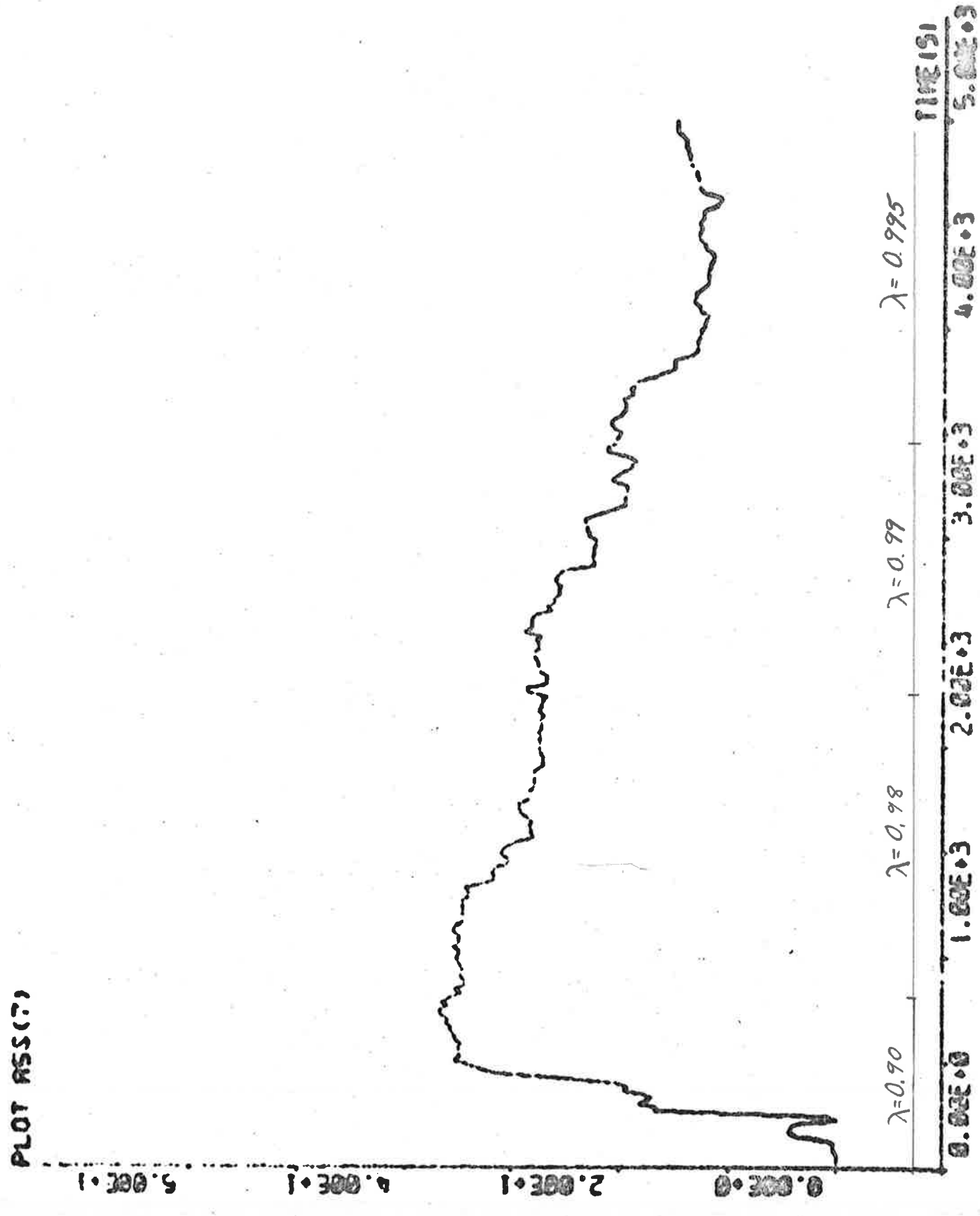
b_1

b_2


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

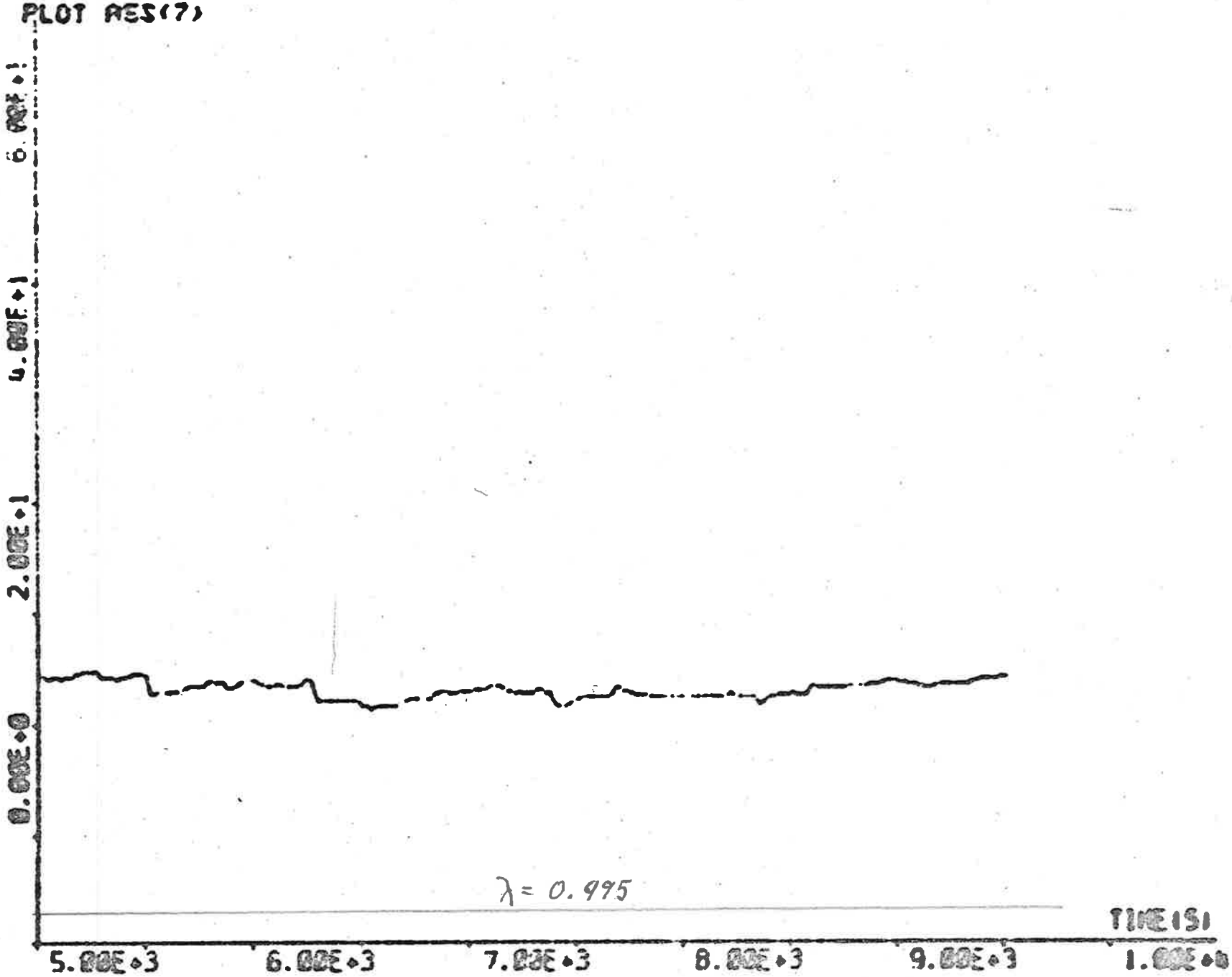

PLOT ASS(5)
0.000E+0
1.000E+0
2.000E+0
3.000E+0
TIME(S)
5.000E+3
6.000E+3
7.000E+3
8.000E+3
9.000E+3
1.000E+4
λ-0.995

b_2


PLOT RSS(?)
1.300.5
1.300.4
1.300.2
0.300.0
λ=0.90
λ=0.98
λ=0.99
λ=0.995
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
TIME(S)

d2

d_2


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

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: $\pm 10^{\circ}$ (0 - 3220 s)
$\pm 10^{\circ}, \pm 5^{\circ}, \pm 3^{\circ}$ (3220 - 5360 s)
Ψ_{ref}: 142°, 144°, 136°, 150°, 142°, 144°, 142°

Initial values:

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

Regulator:

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

Values after 3220 s:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.7227 \\ -0.2554 \\ 38.2554 \end{bmatrix}$$

P unknown

Regulator:

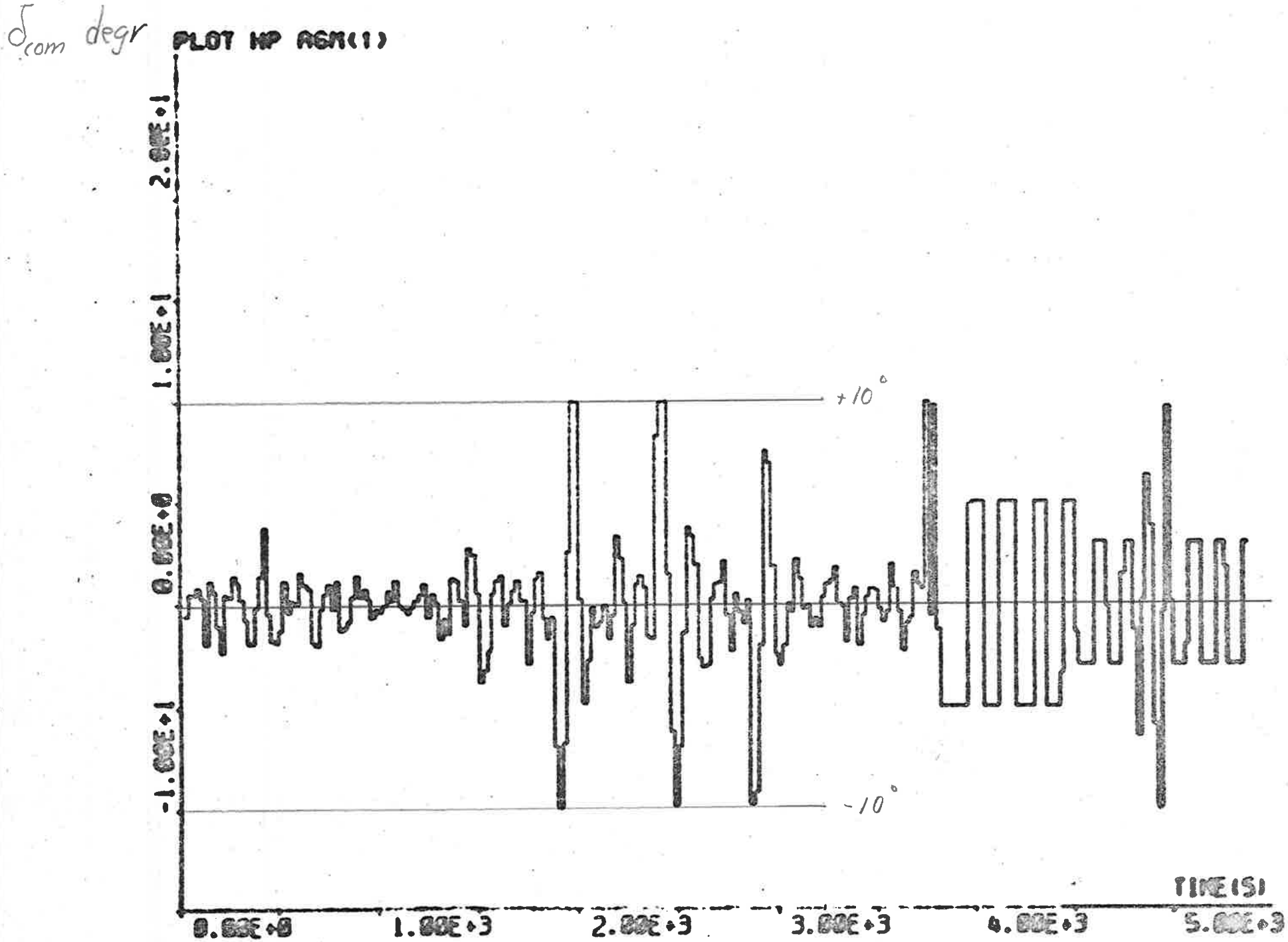
$$\delta(t) = -1.3837(\Psi(t) - \Psi_{ref}) + 0.3534\delta(t-1) - 52.9340r(t)$$

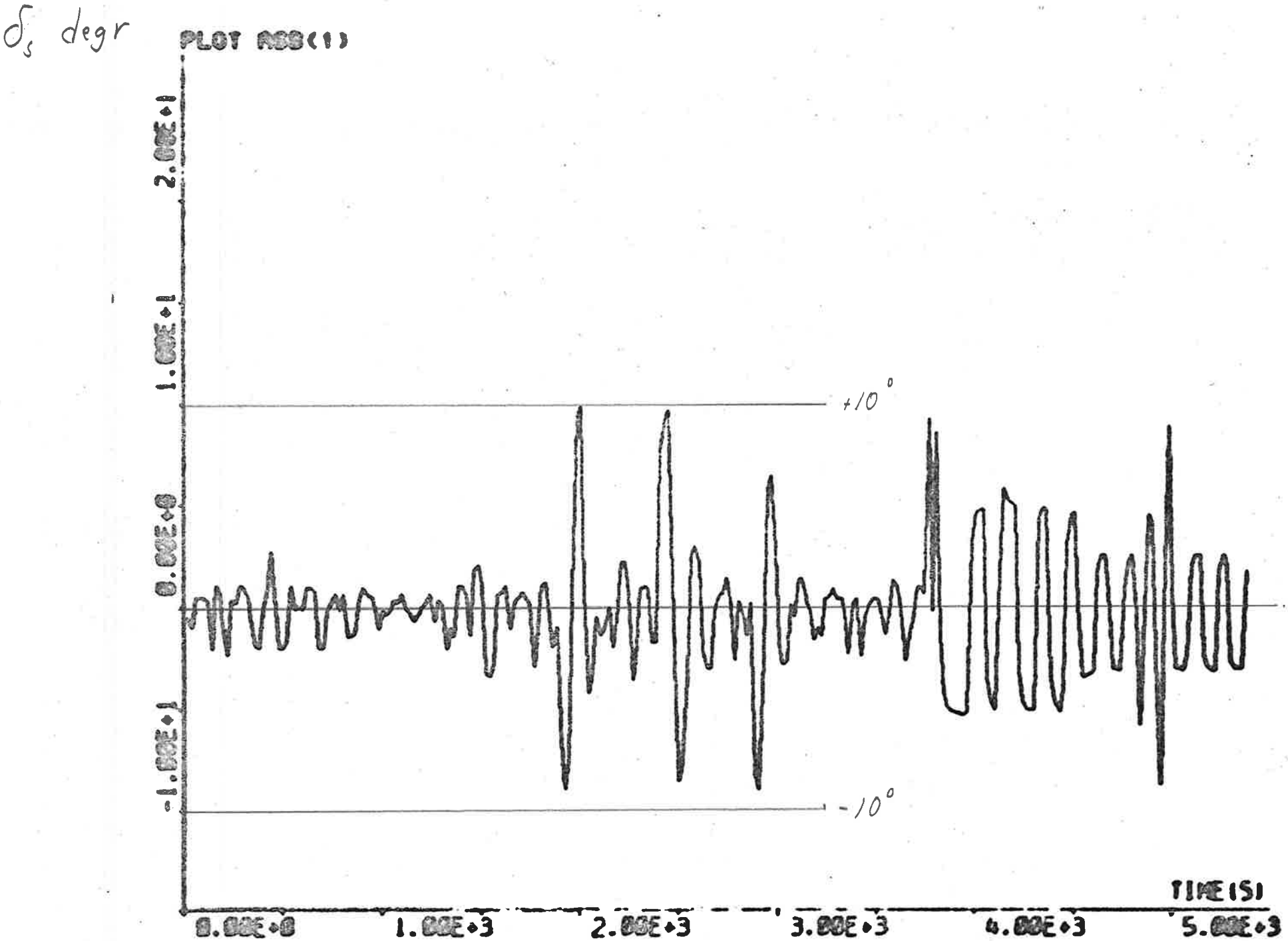
Final values:

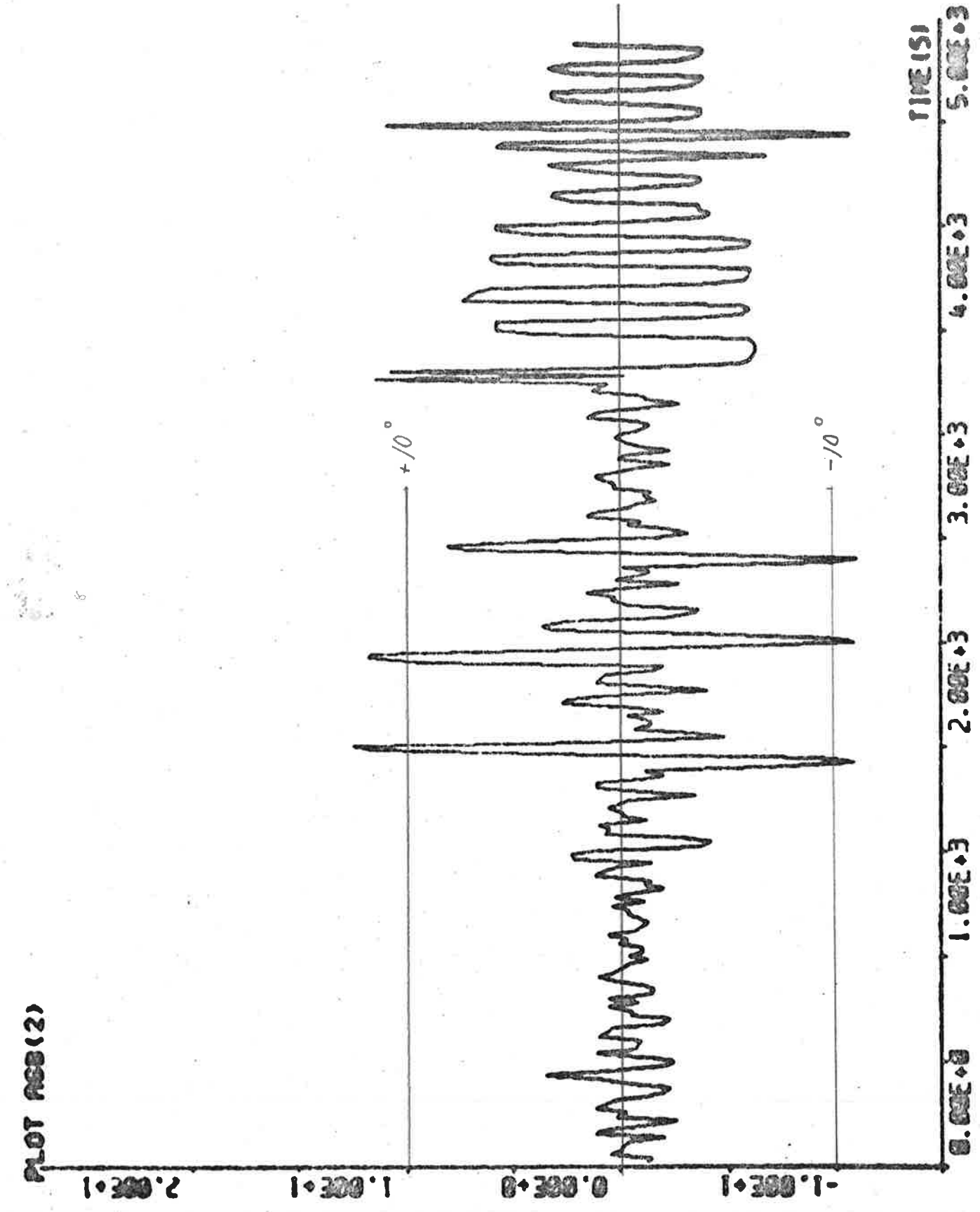
$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.0925 \\ 0.0631 \\ 1.7870 \end{bmatrix} \qquad P = \begin{bmatrix} 0.0000154 & & \\ -0.0000017 & 0.0000511 & \\ 0.001778 & -0.006988 & 1.277 \end{bmatrix}$$

Regulator:

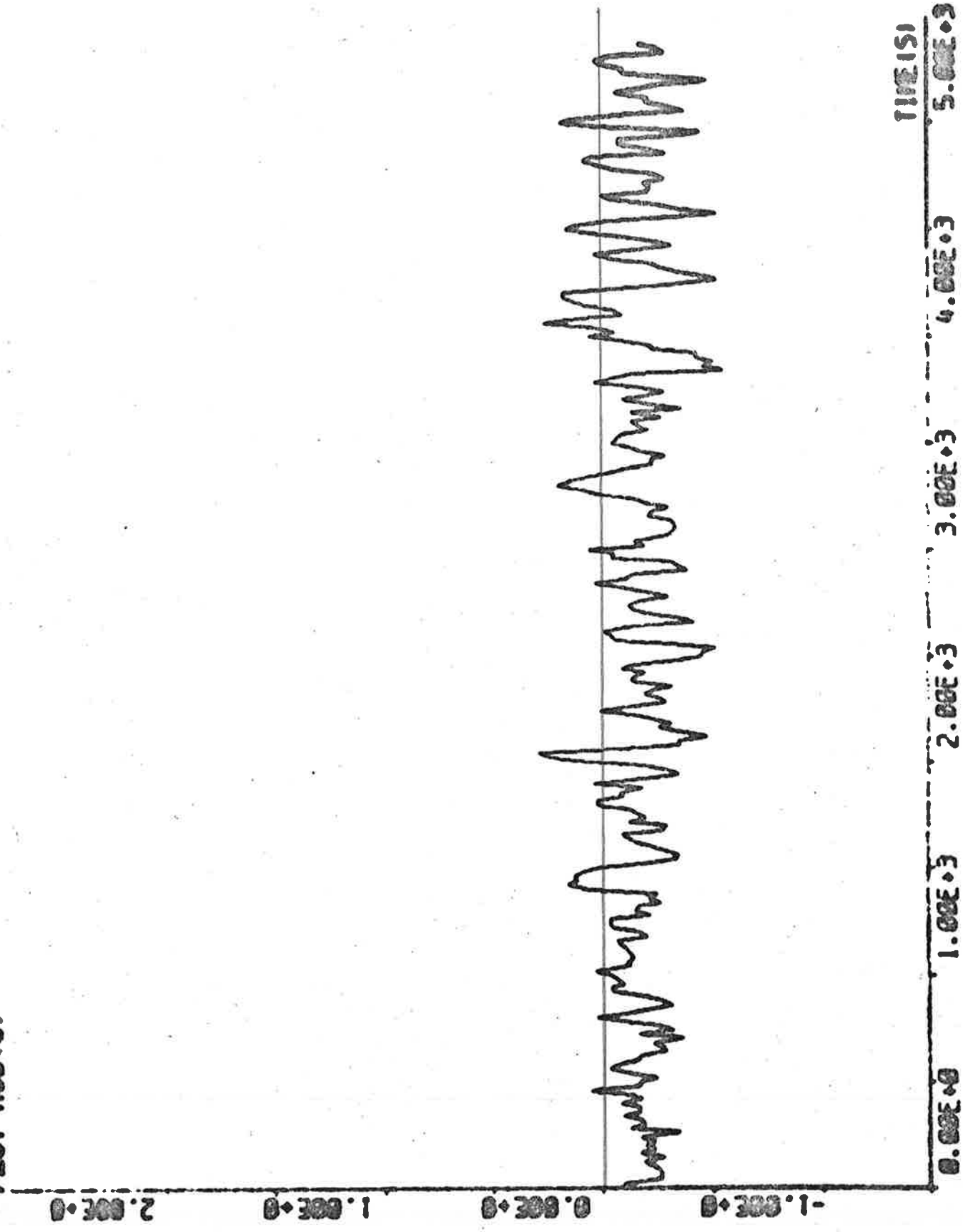
$$\delta(t) = -10.8108(\Psi(t) - \Psi_{ref}) - 0.6822\delta(t-1) - 19.3189r(t)$$


δ_{com} degr
PLOT HP AGM(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

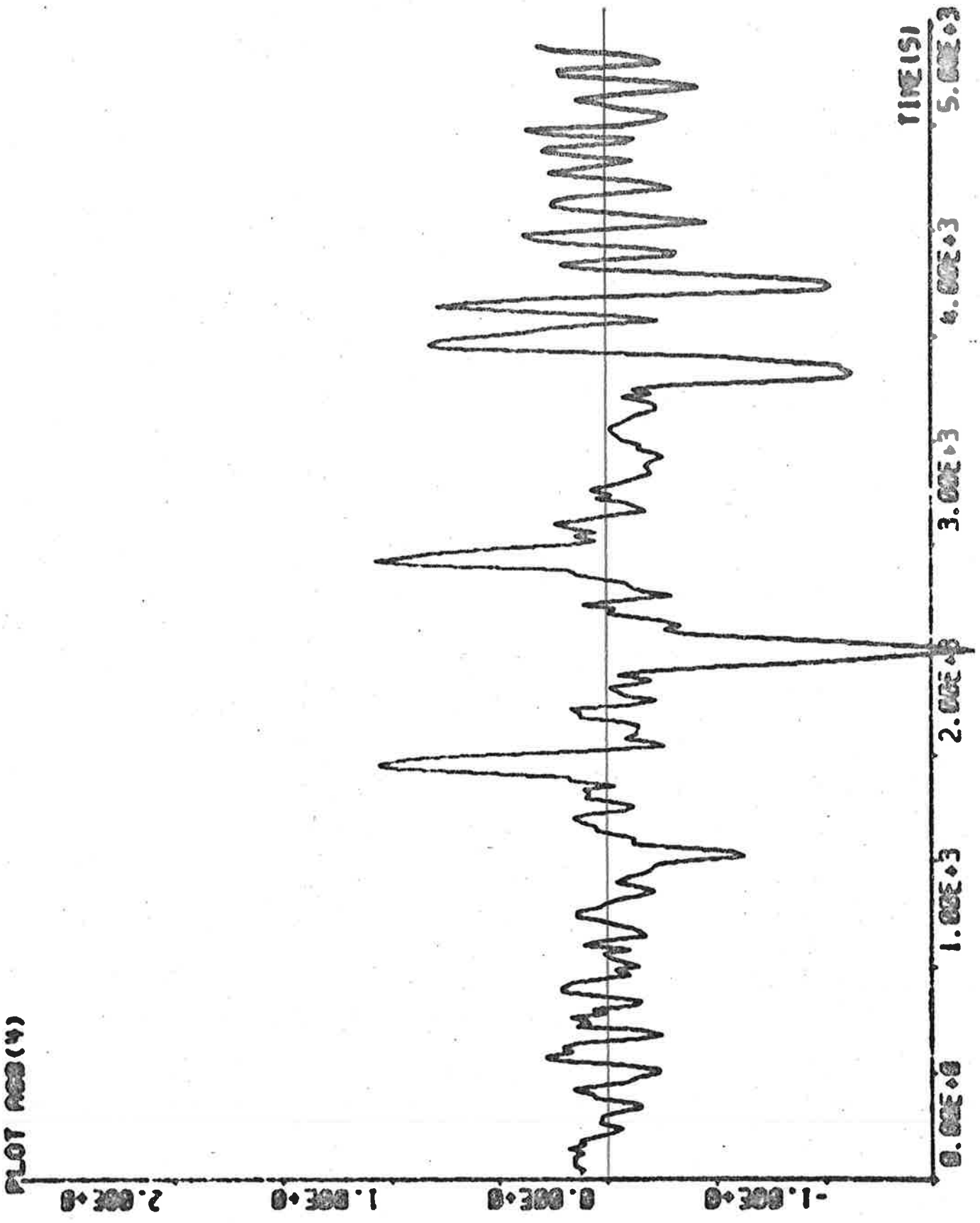

δ_s degr
PLOT ASB(1)
2.00E+1
1.00E+1
0.00E+0
-1.00E+1
+10°
-10°
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3


PLOT ACB(2)
1.000E+2
1.000E+1
0.000E+0
-1.000E+1
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
+10°
-10°

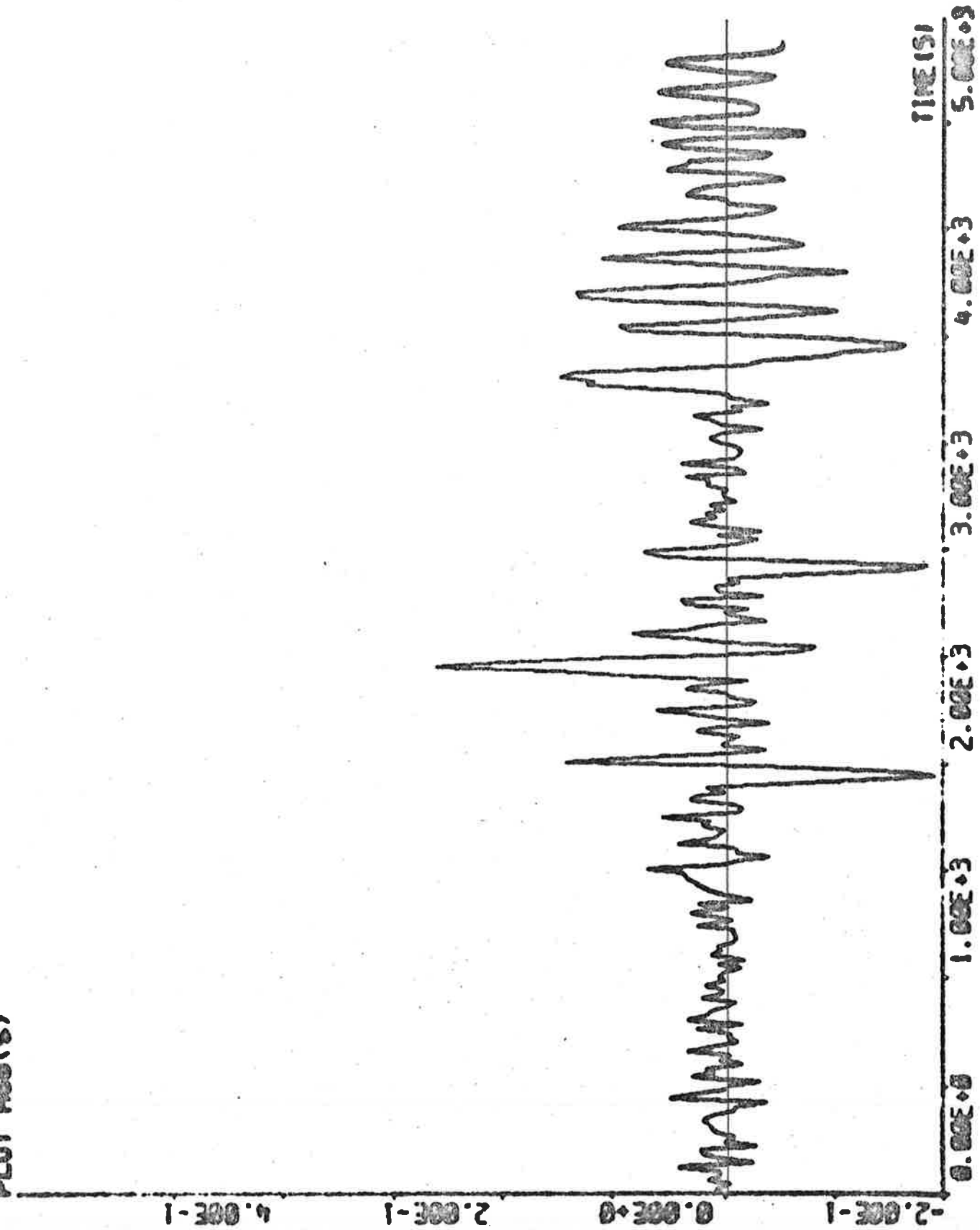
ρ deg r


PLOT NO3(3)
TIME(S)
0.000E+0
1.000E-3
2.000E-3
3.000E-3
4.000E-3
5.000E-3
2.000E-1
1.000E-1
0.000E+0
-1.000E-1

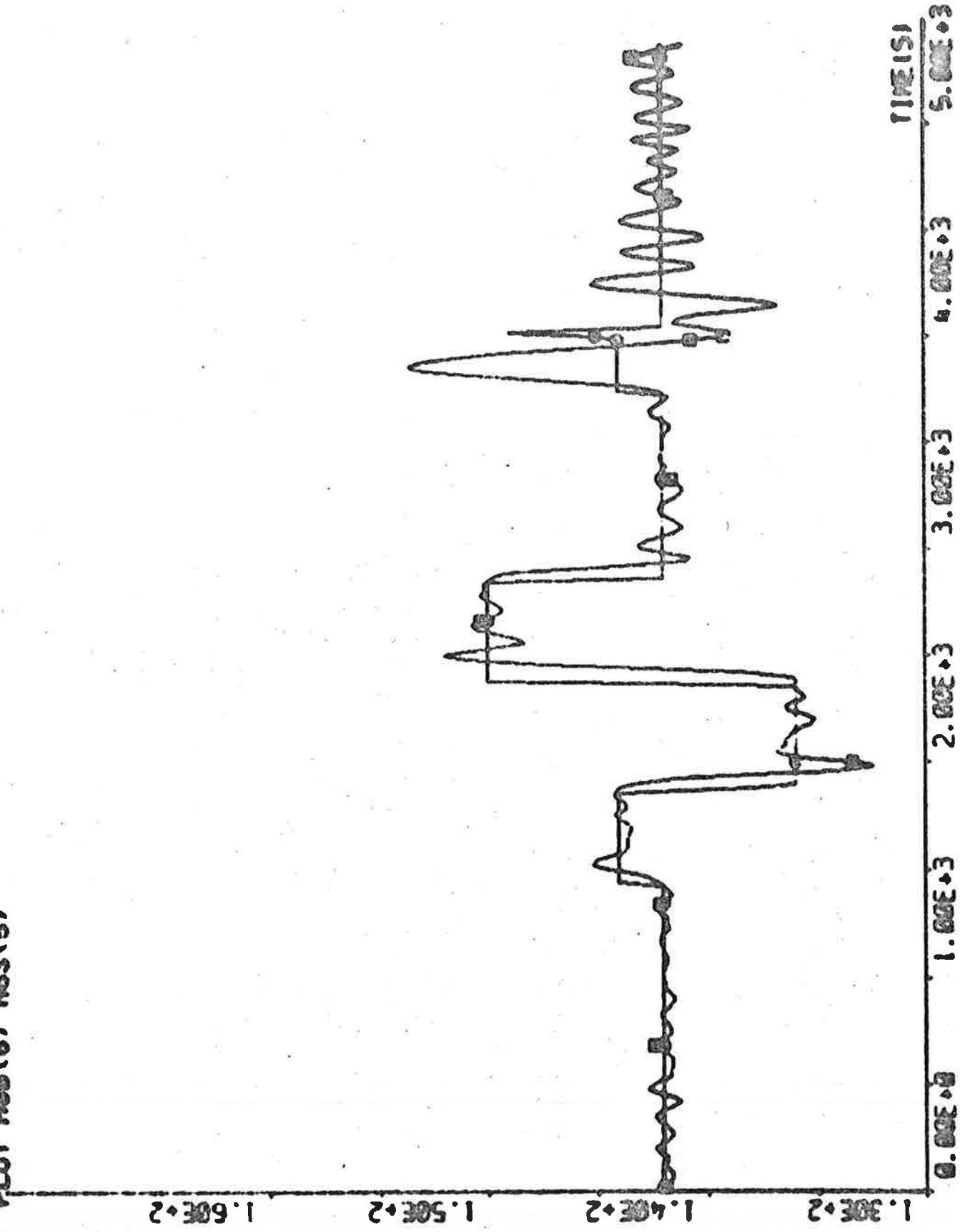
V1 knots


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

V_2 knots

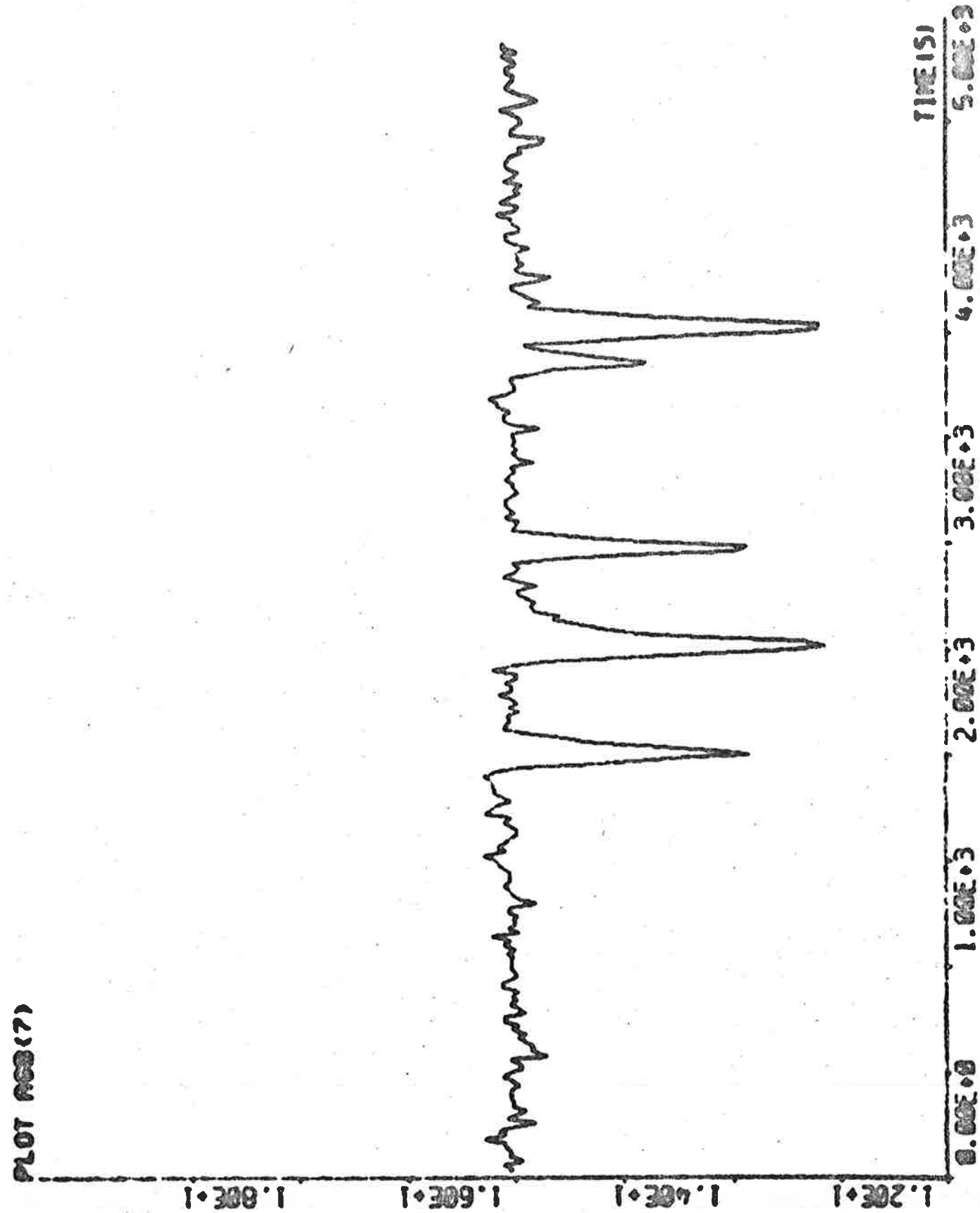

PLOT AB(5)
-2.00E-1
0.00E+0
2.00E-1
4.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

r degr/s

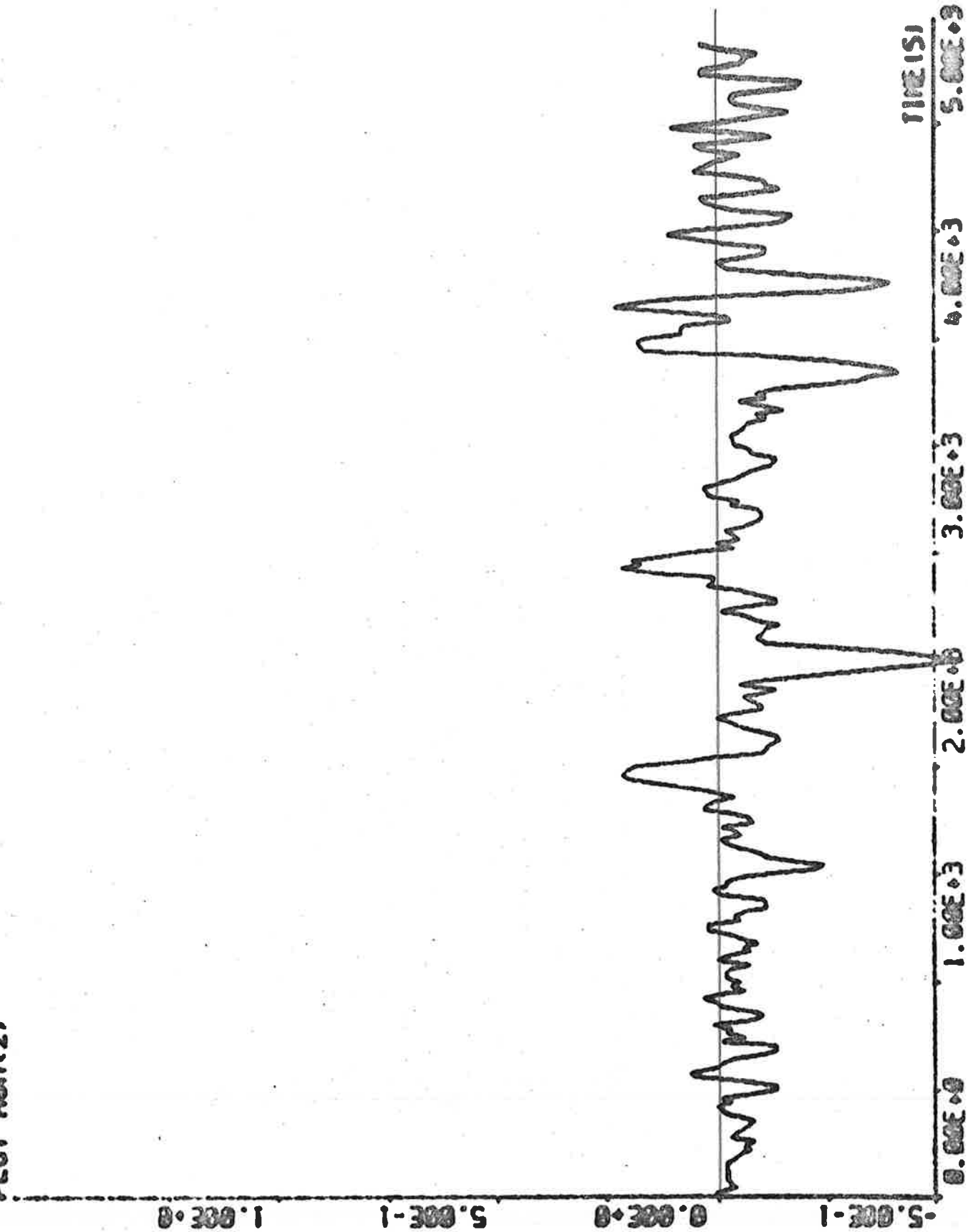


ψ degr

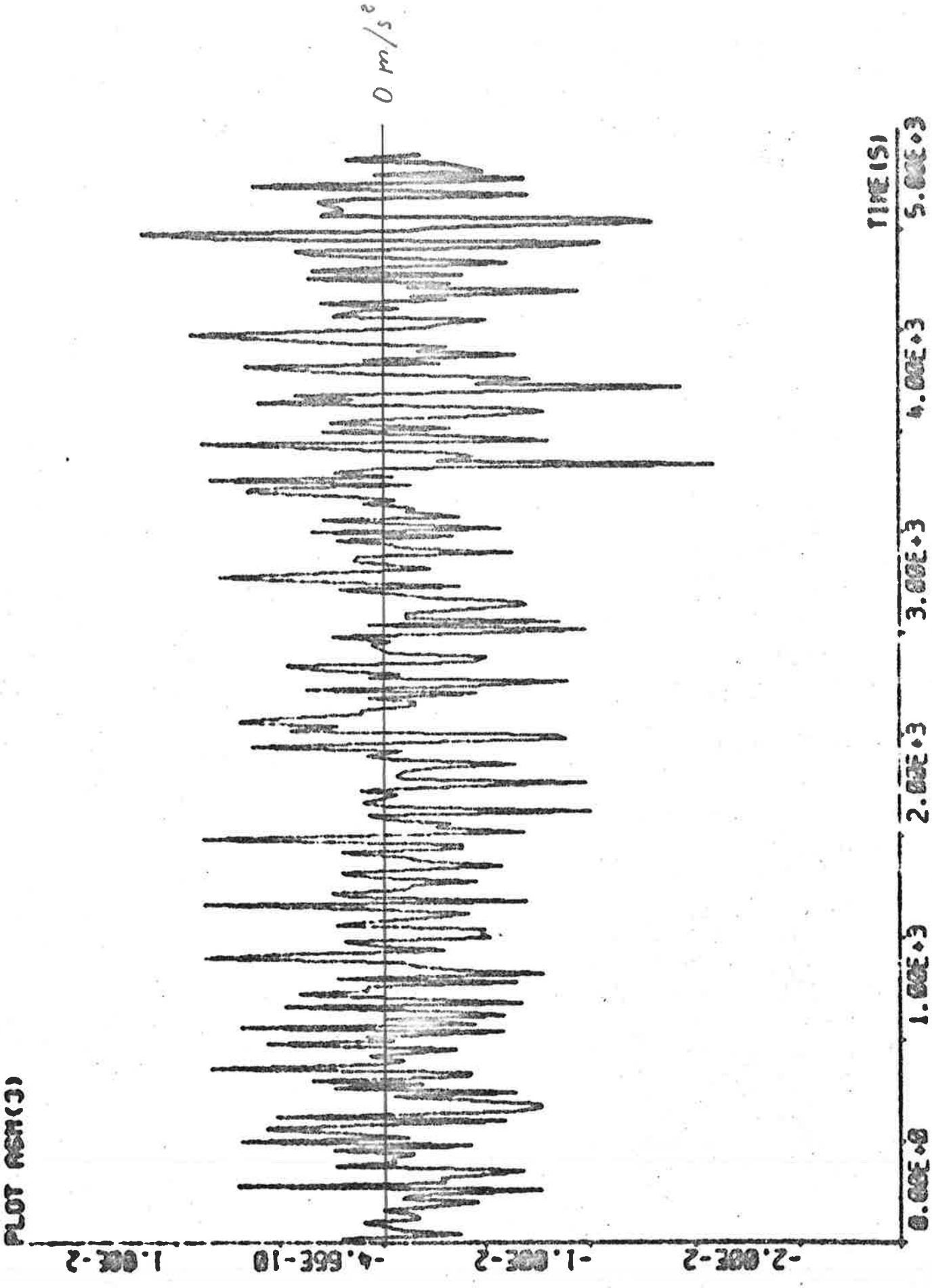
ψ_{ref} degr


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

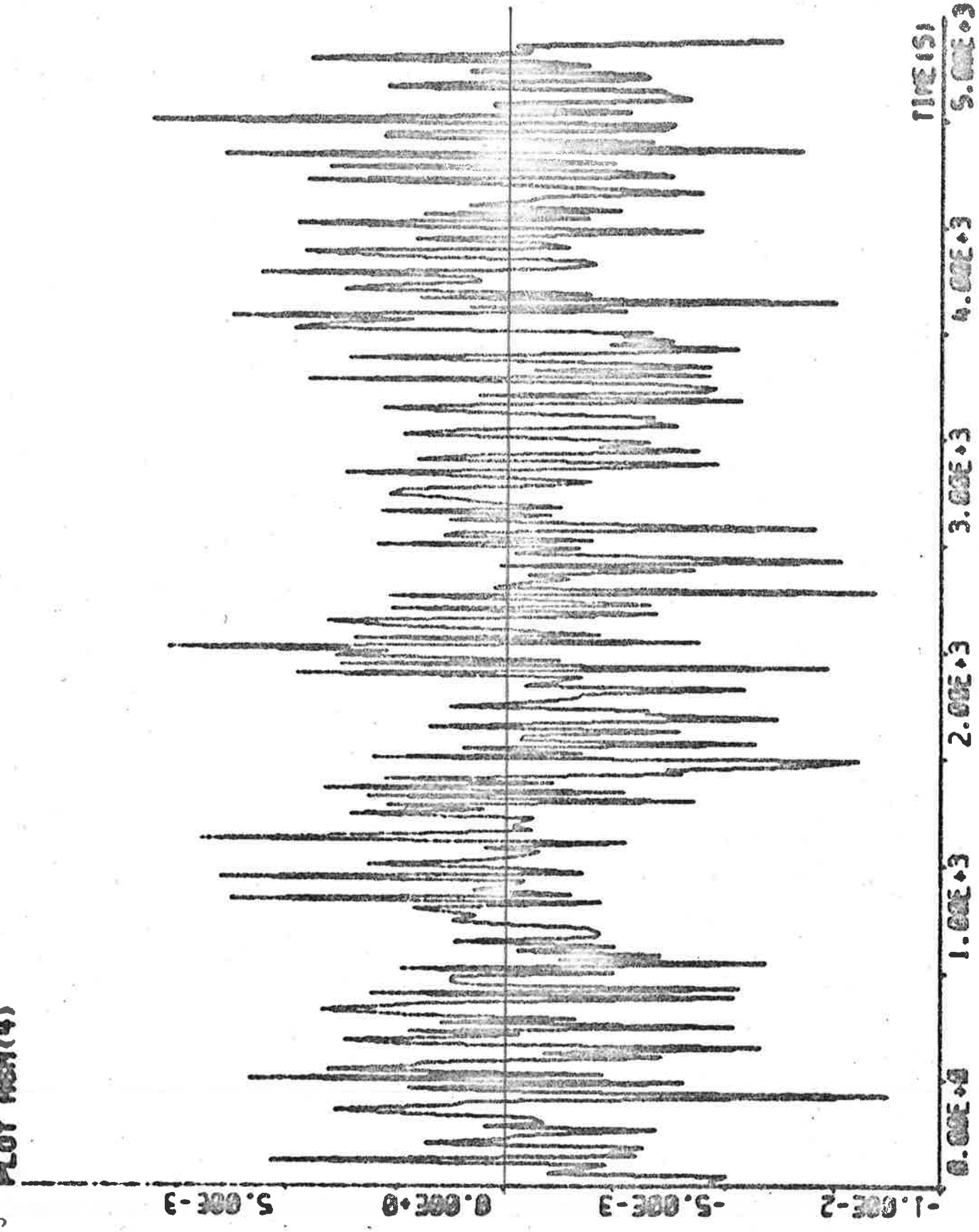
u knots


PLOT AGM(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)

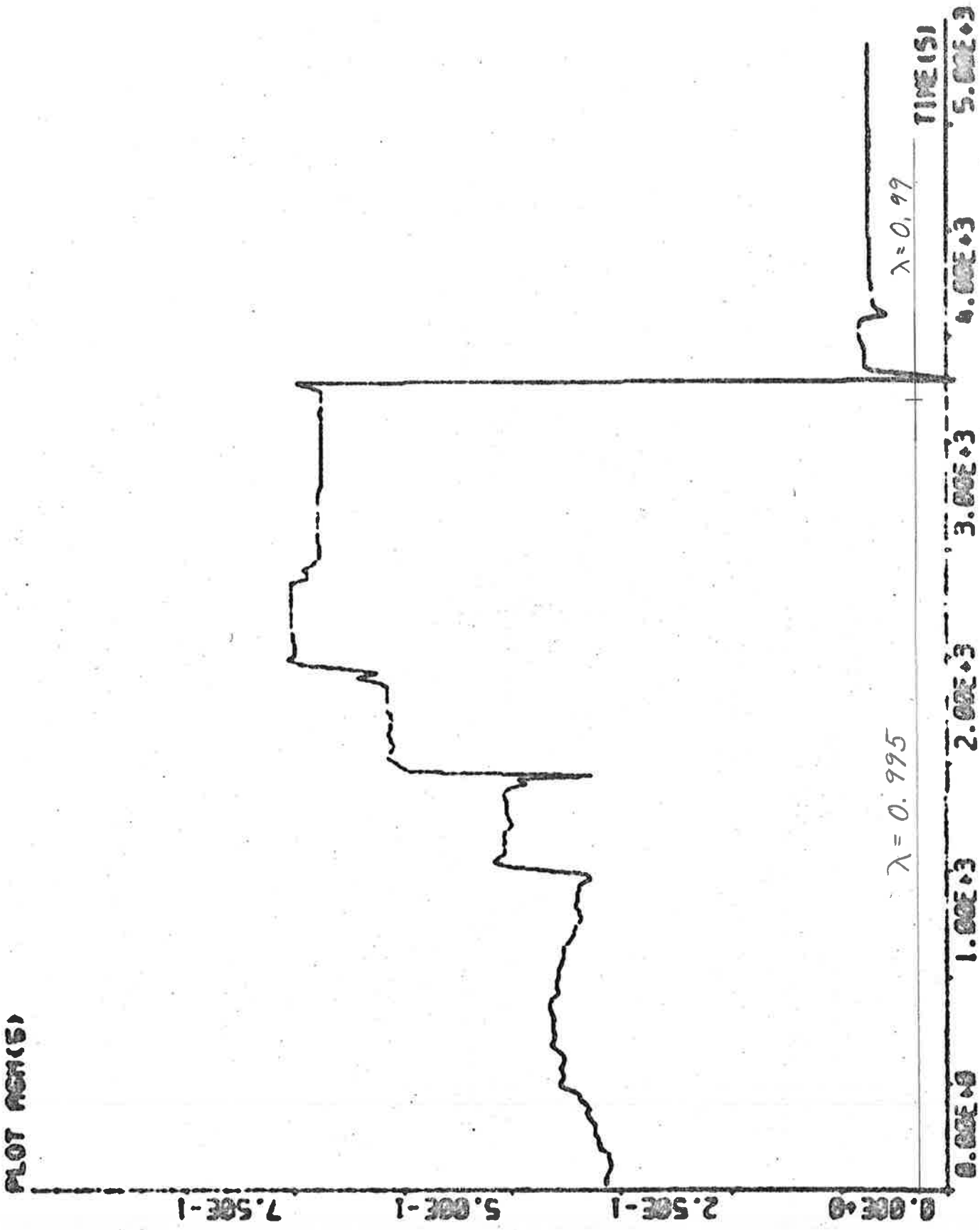
v m/s


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

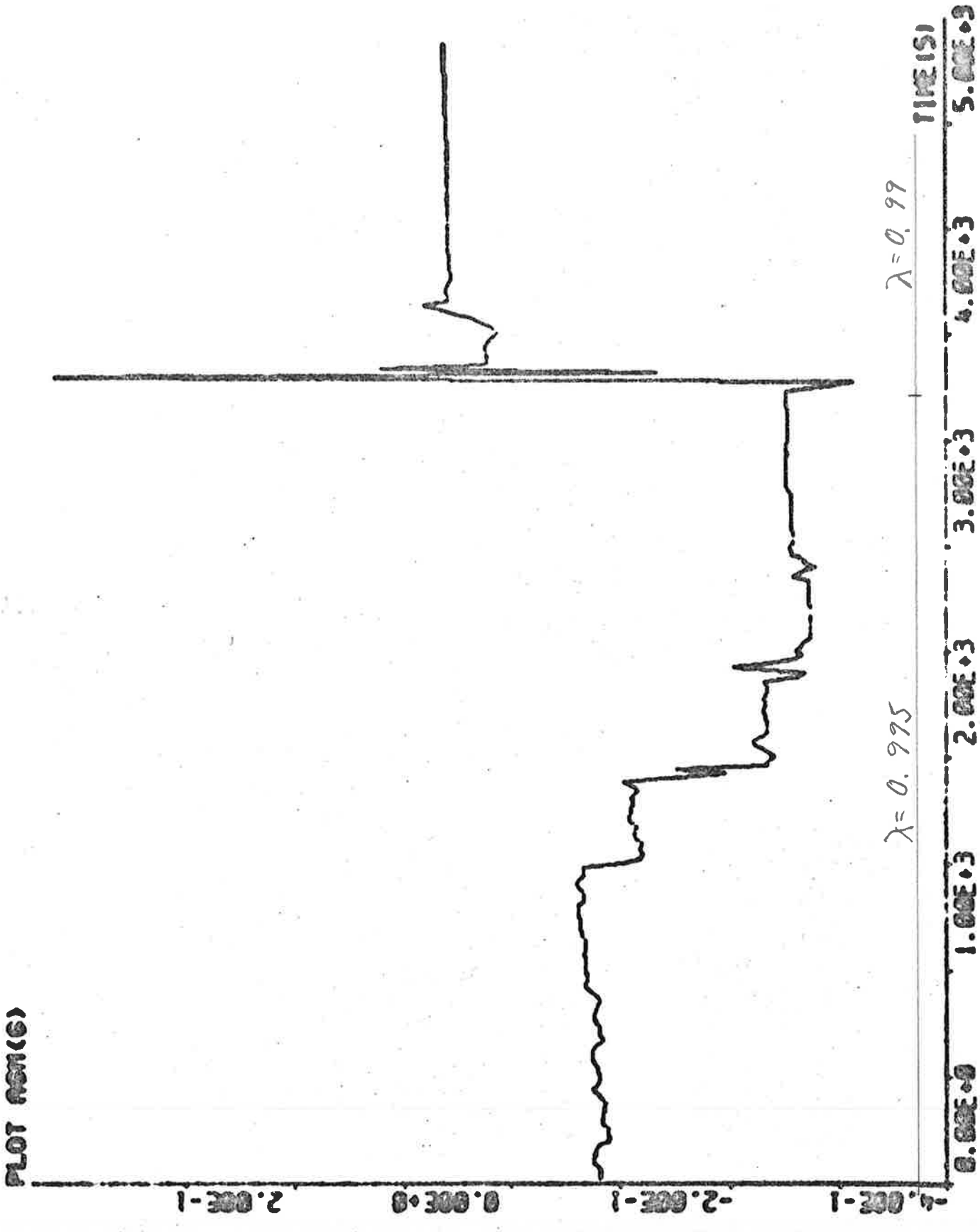
$\hat{F}$ m/s²



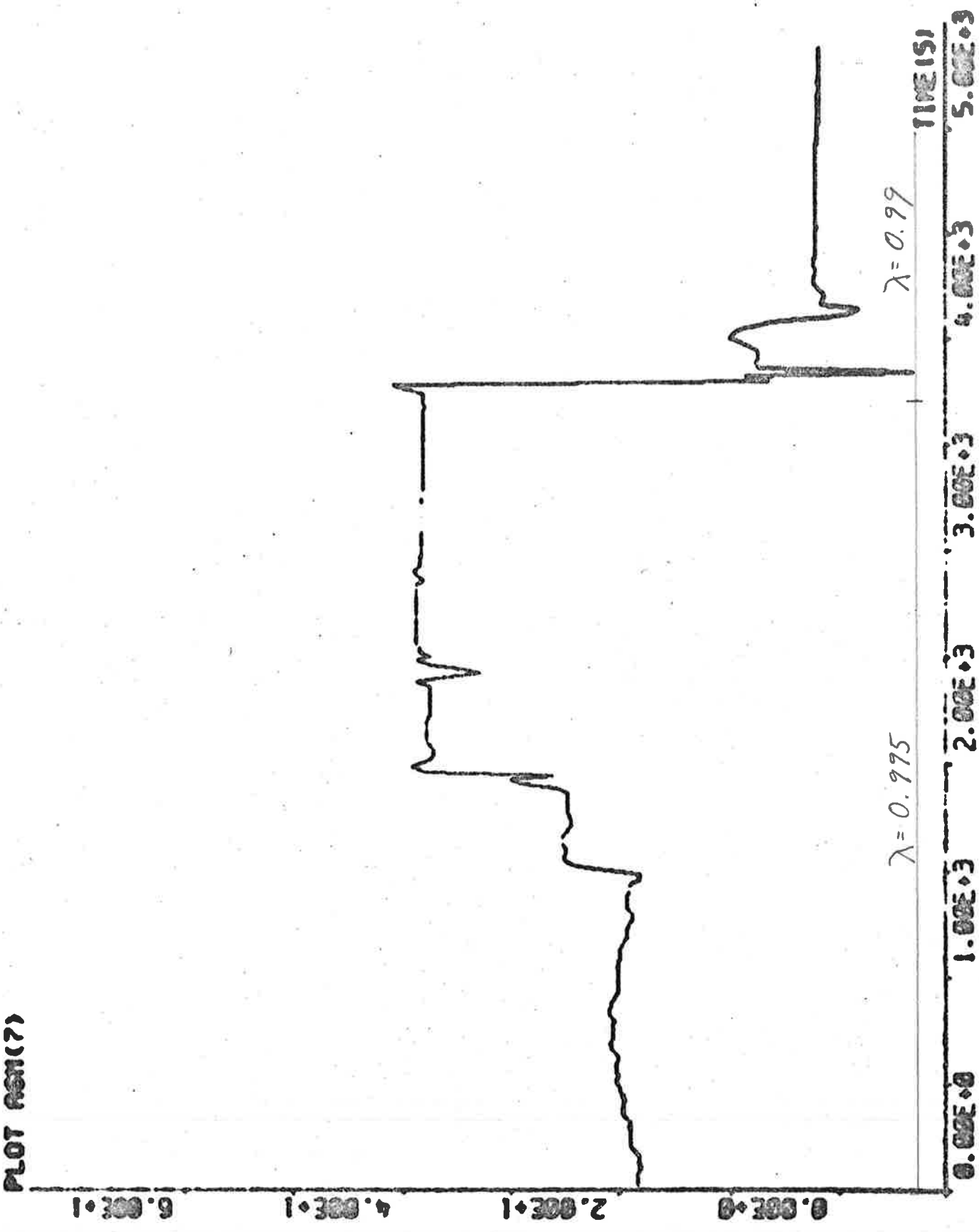
$\ddot{\psi}$ degr/s^2


PLOT AGAIN(S)
0.000+0
2.50E-1
5.00E-1
7.50E-1
0.00E+3
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)
λ = 0.995
λ = 0.99

b_1


PLOT NUM(6)
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)
λ=0.99
λ=0.995

b2



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:

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

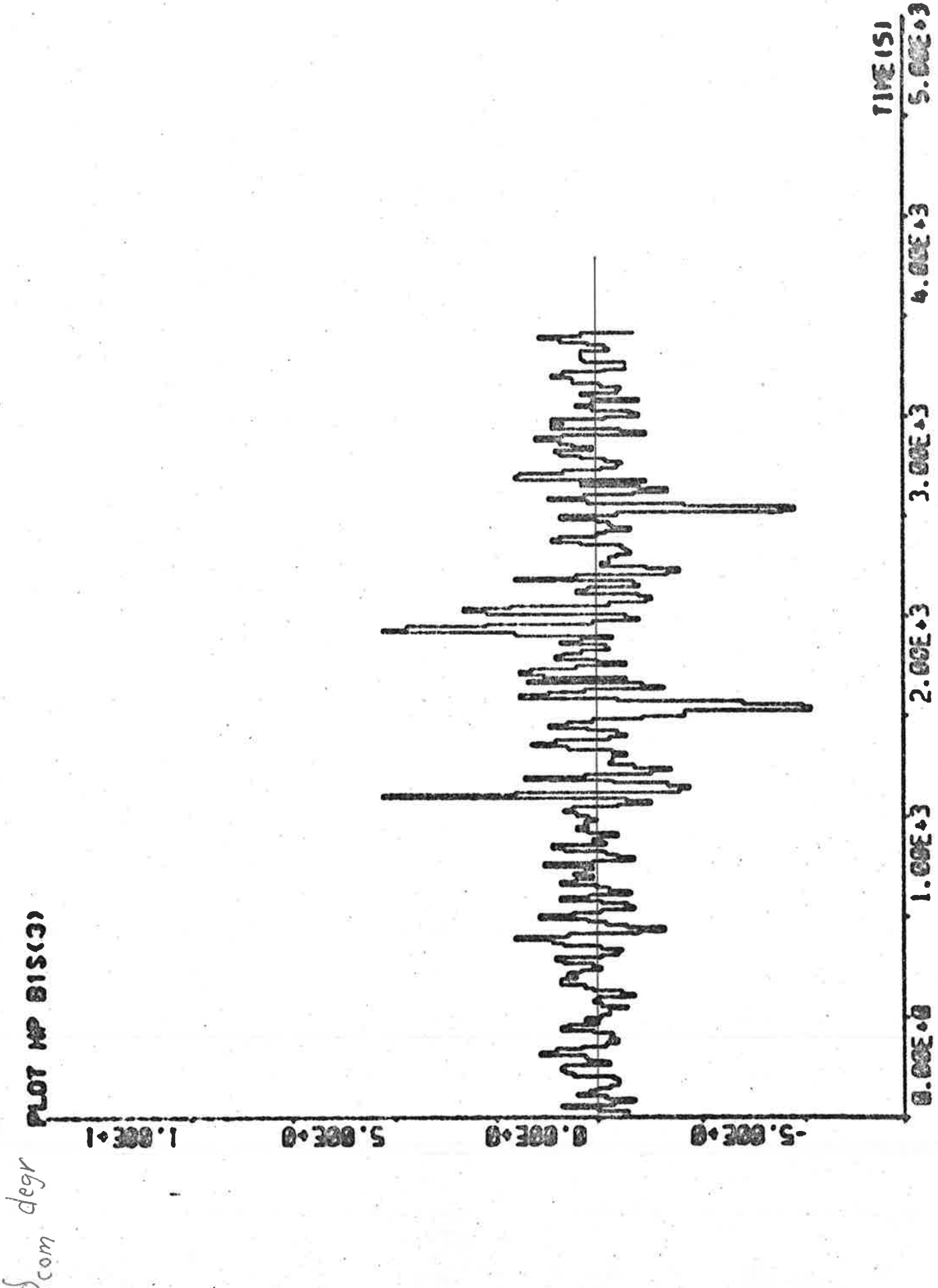
The parameters k_1 and k_2 were manually tuned for the actual weather disturbances:

$k_1 = 1.5$
$k_2 = 80.0$

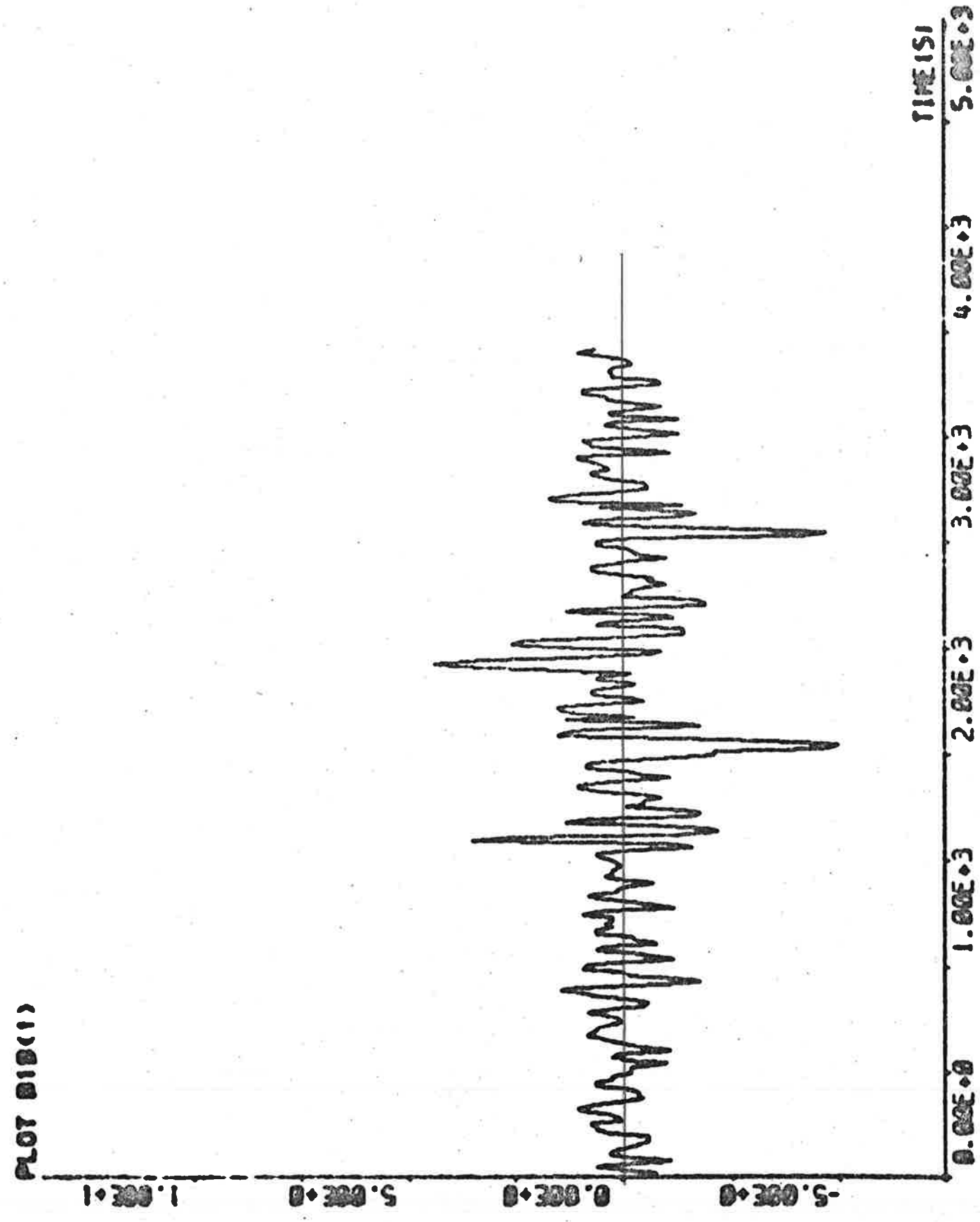
Sampling interval: 15 s
Rudder limits: $\pm 15^{\circ}$
Maximum yaw rate r during yaws: 0.1 degr/s
Ψ_{ref}: 142°, 144°, 136°, 150°, 142°

Statistics:

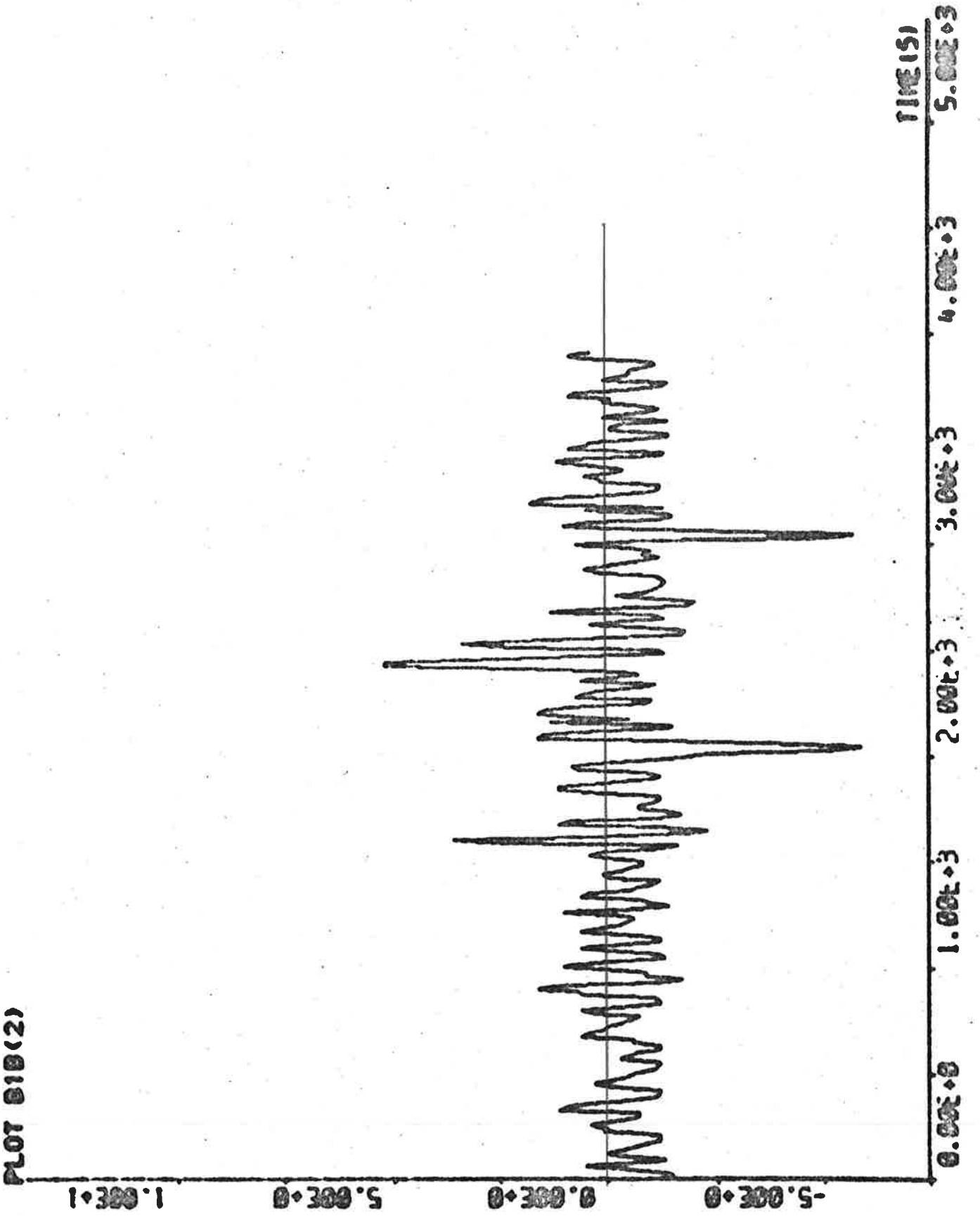
	0 - 1500 s			
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	0.13	0.63	-1.6	2.0
δ_s degr	0.05	0.58	-1.8	1.4
δ degr	-0.40	0.70	-1.7	1.6
v_1 knots	-0.102	0.135	-0.50	0.19
v_2 knots	0.014	0.128	-0.21	0.37
r degr/s	0.0030	0.0099	-0.021	0.030
Ψ degr	142.001	0.171	141.59	142.38
v knots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



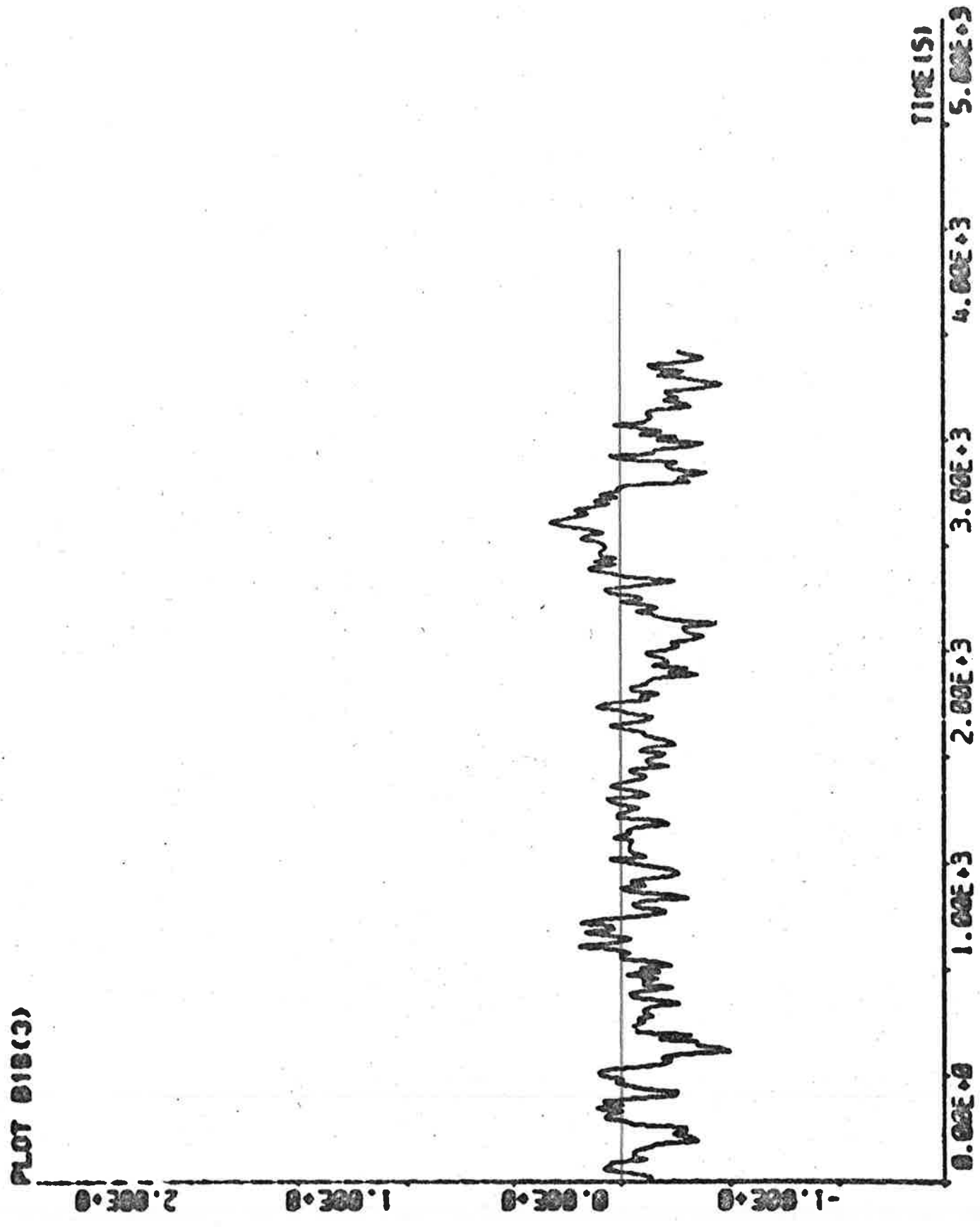
δ_{com} degr


PLOT DIB(I)
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

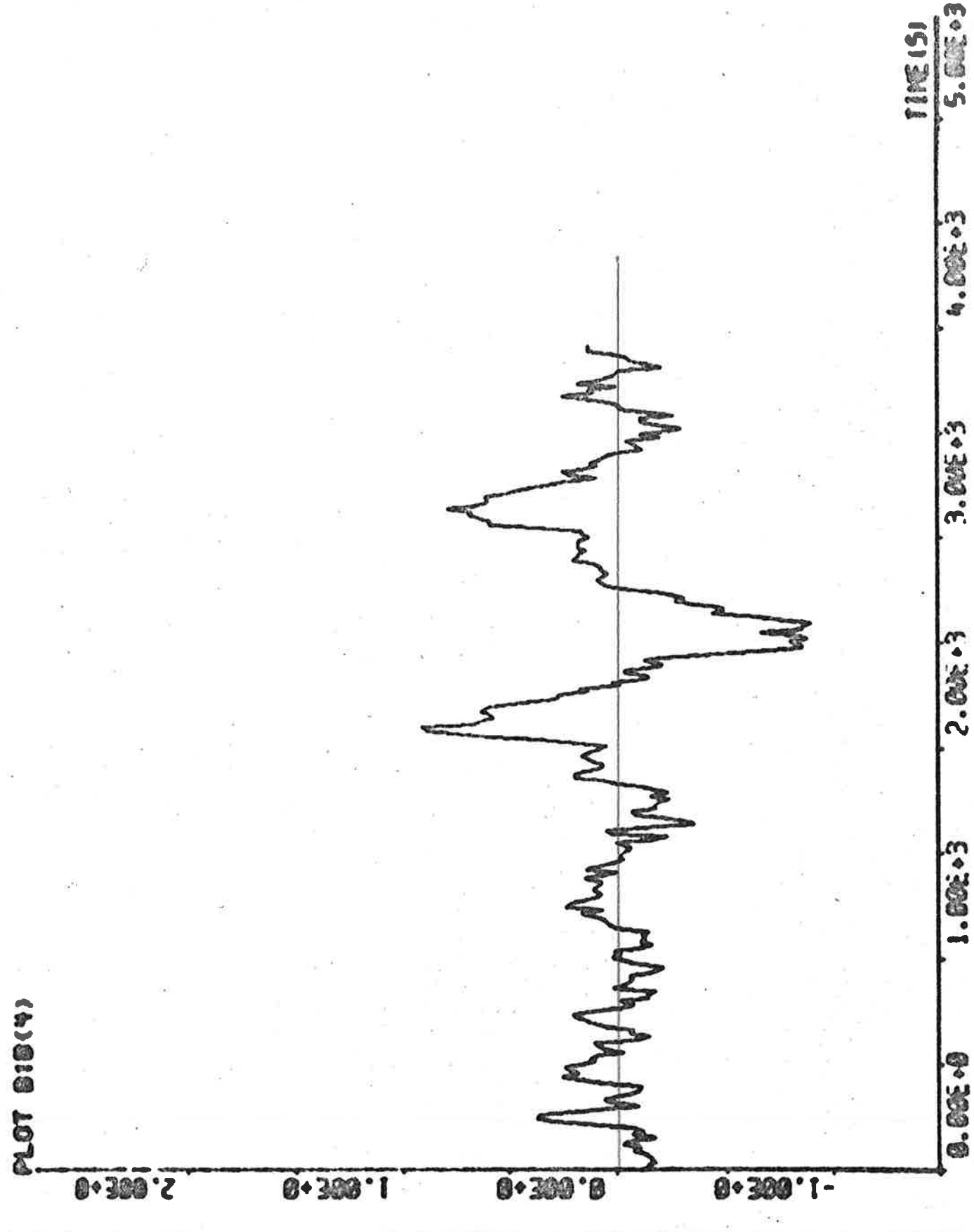
δ_s degr


PLOT B1B(2)
1.00E+0
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)

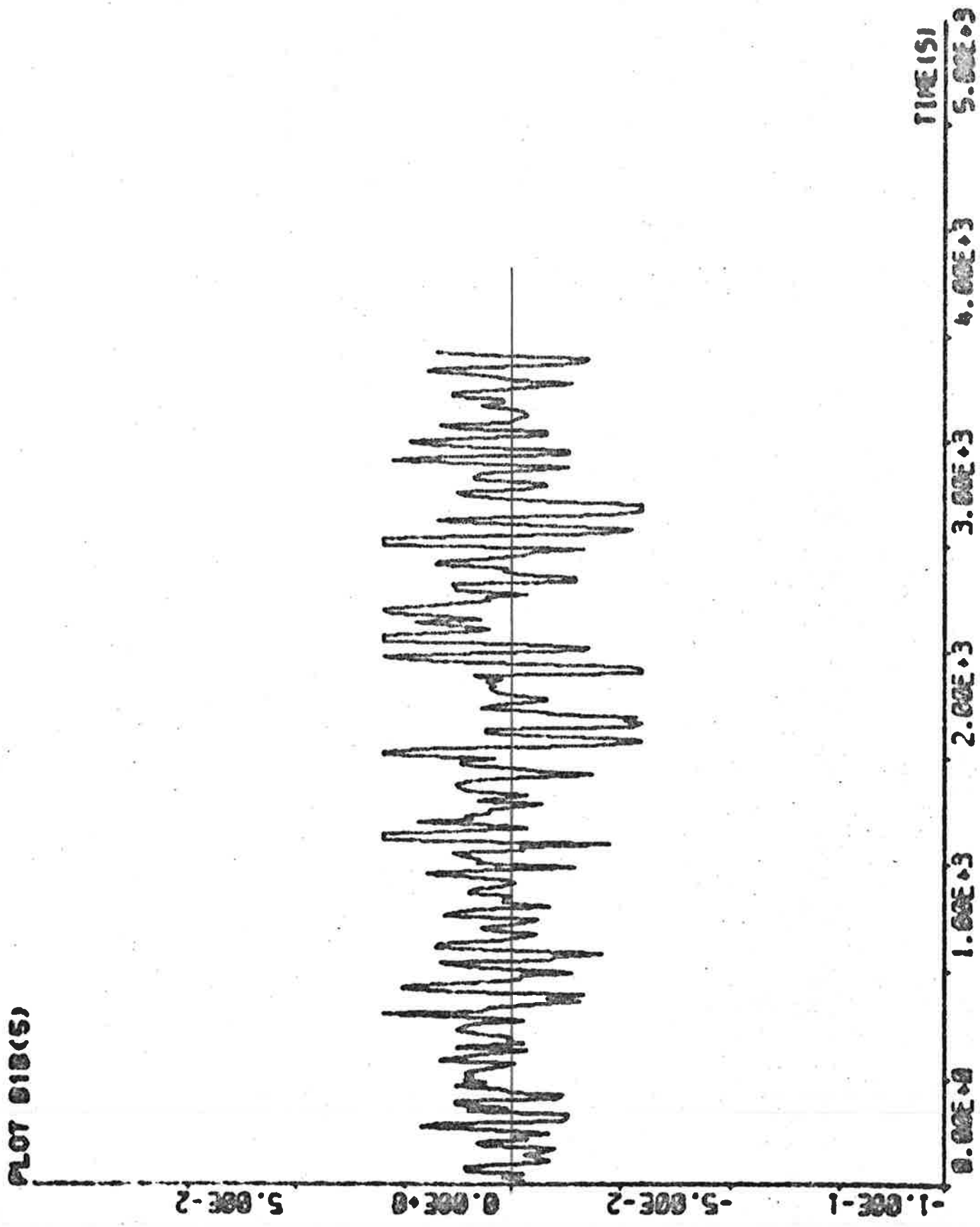
δ degr


PLOT BIB(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)

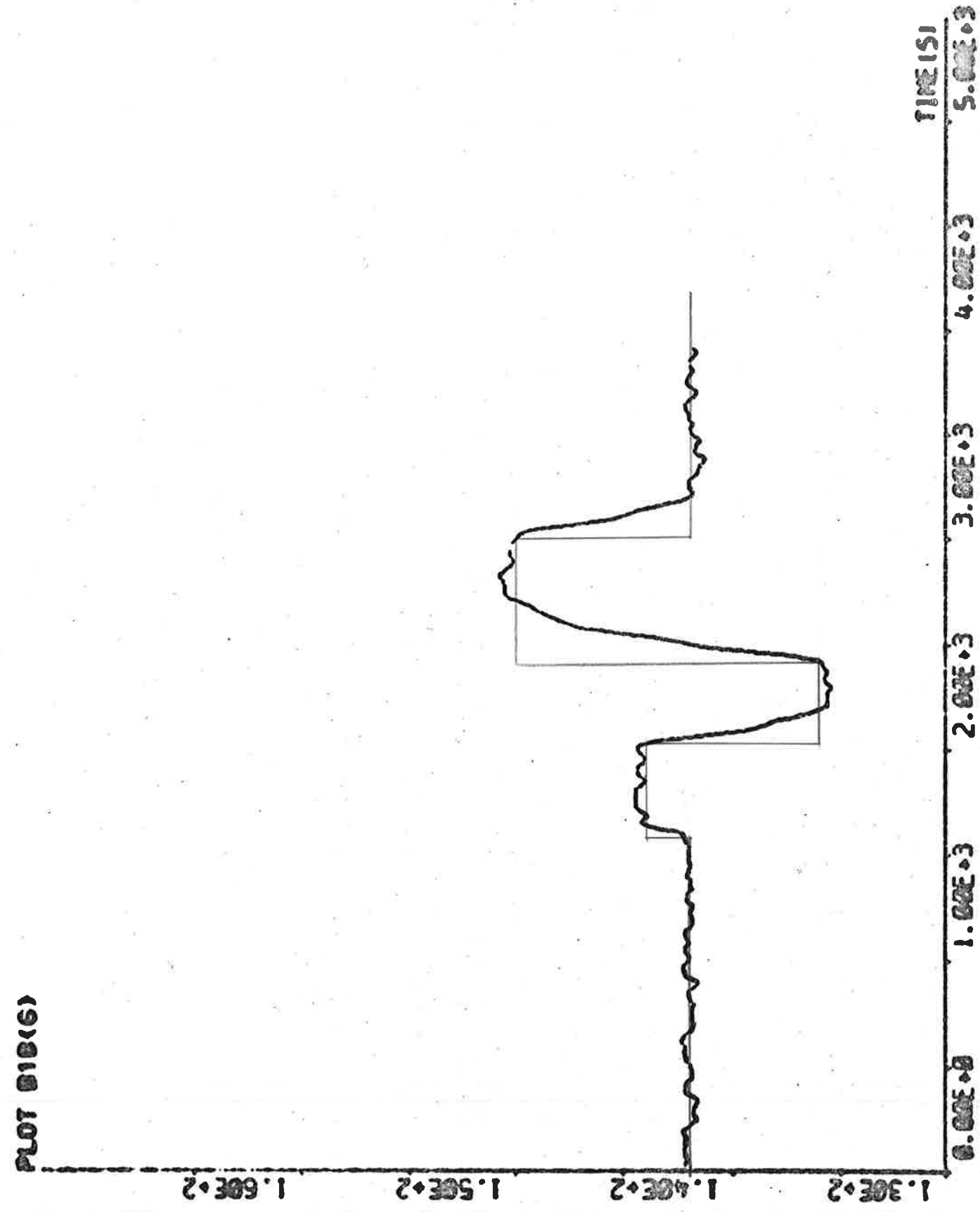
$\dot{V}_1$ knots


PLOT BIB(4)
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

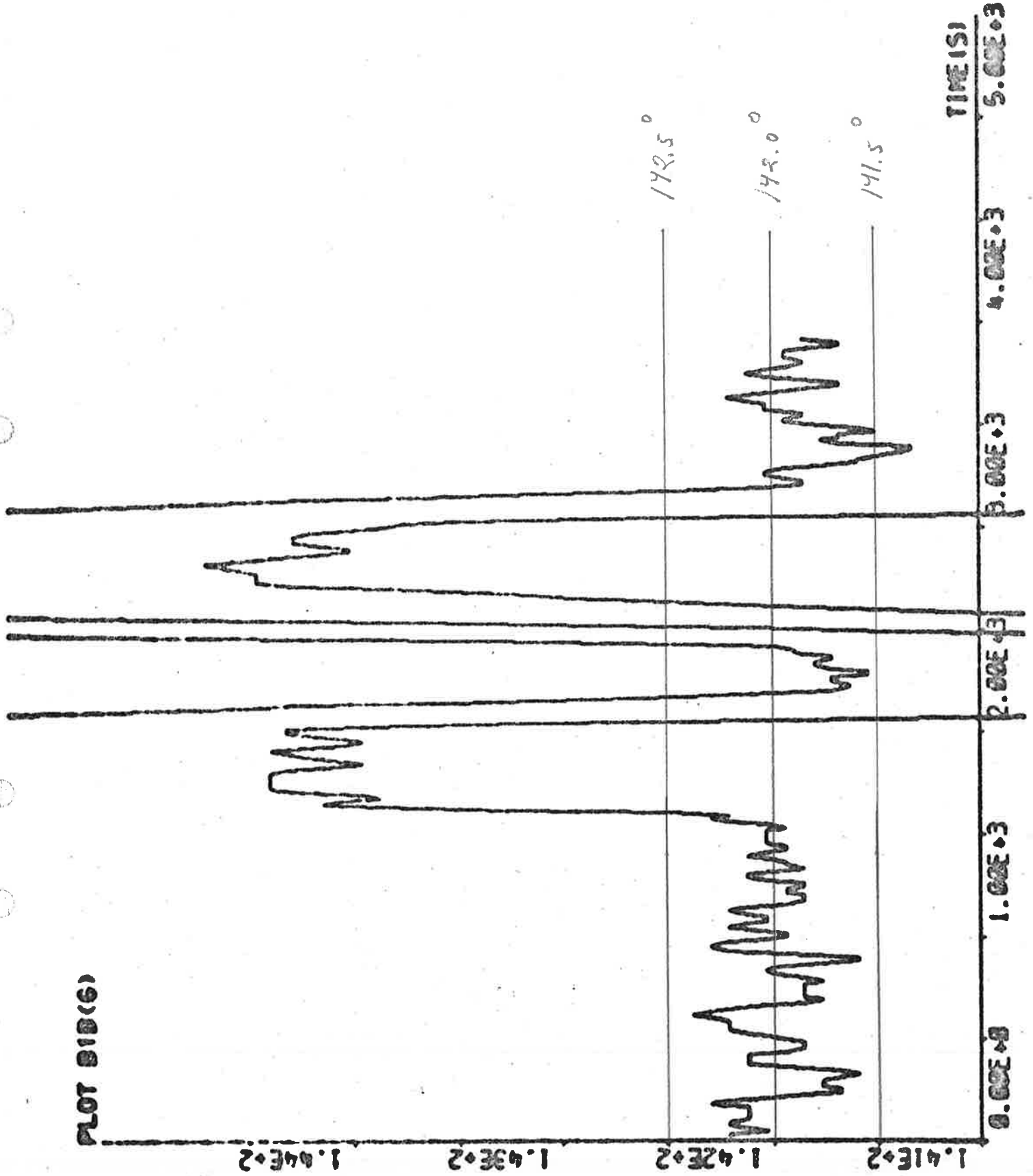
½ knots


PLOT DIB(5)
TIME(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

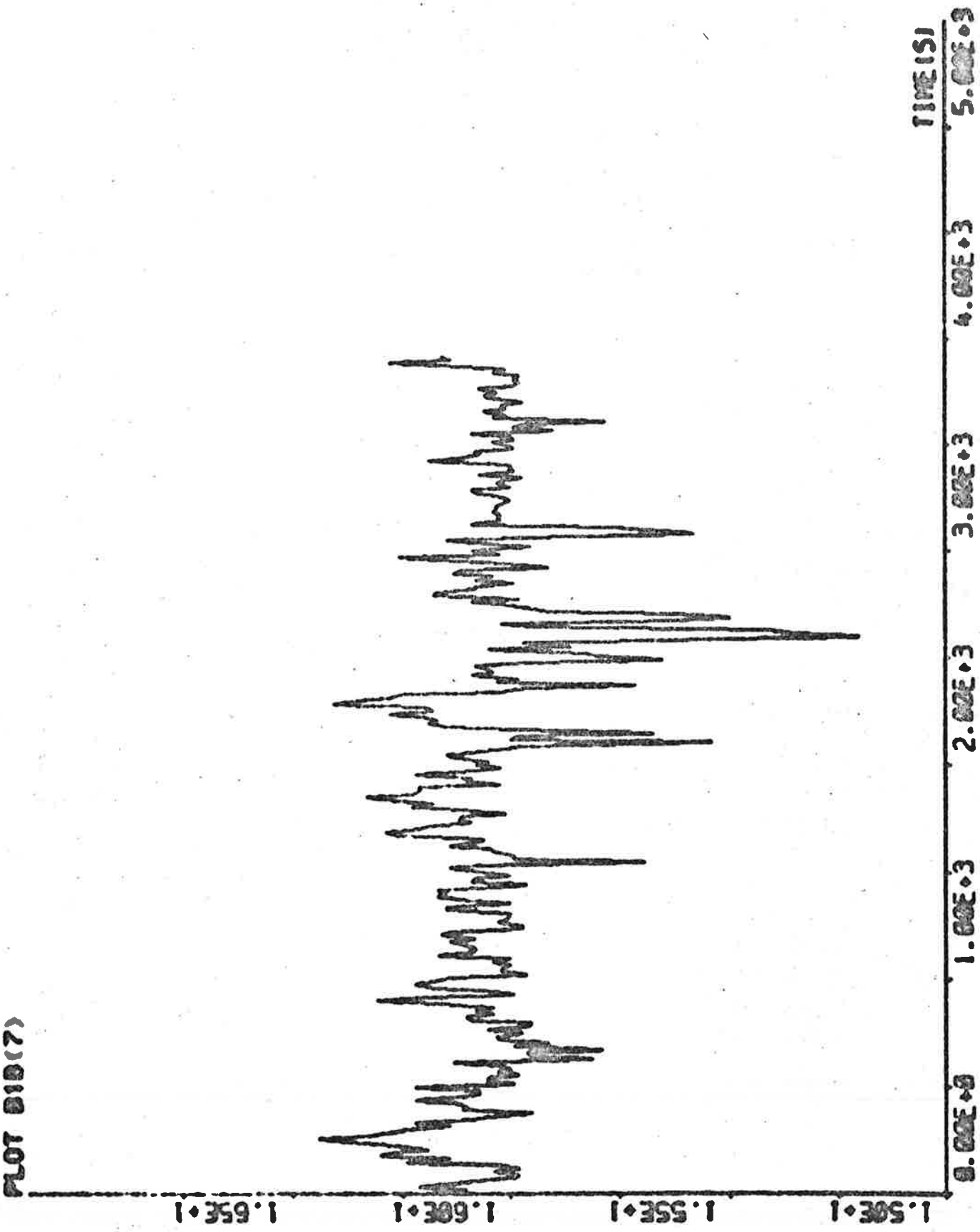
r degr/s



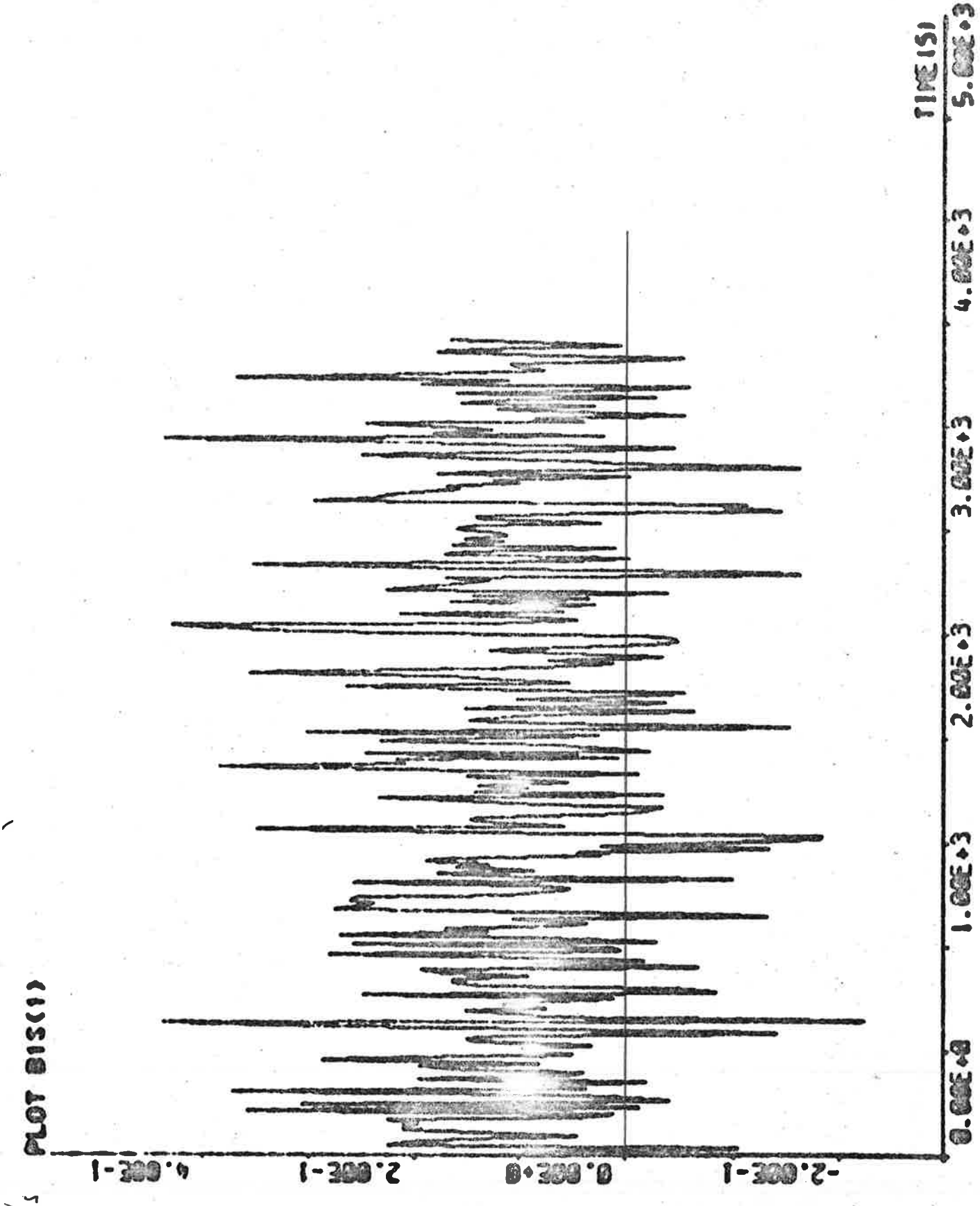
γ degr
γ_{ref} degr


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

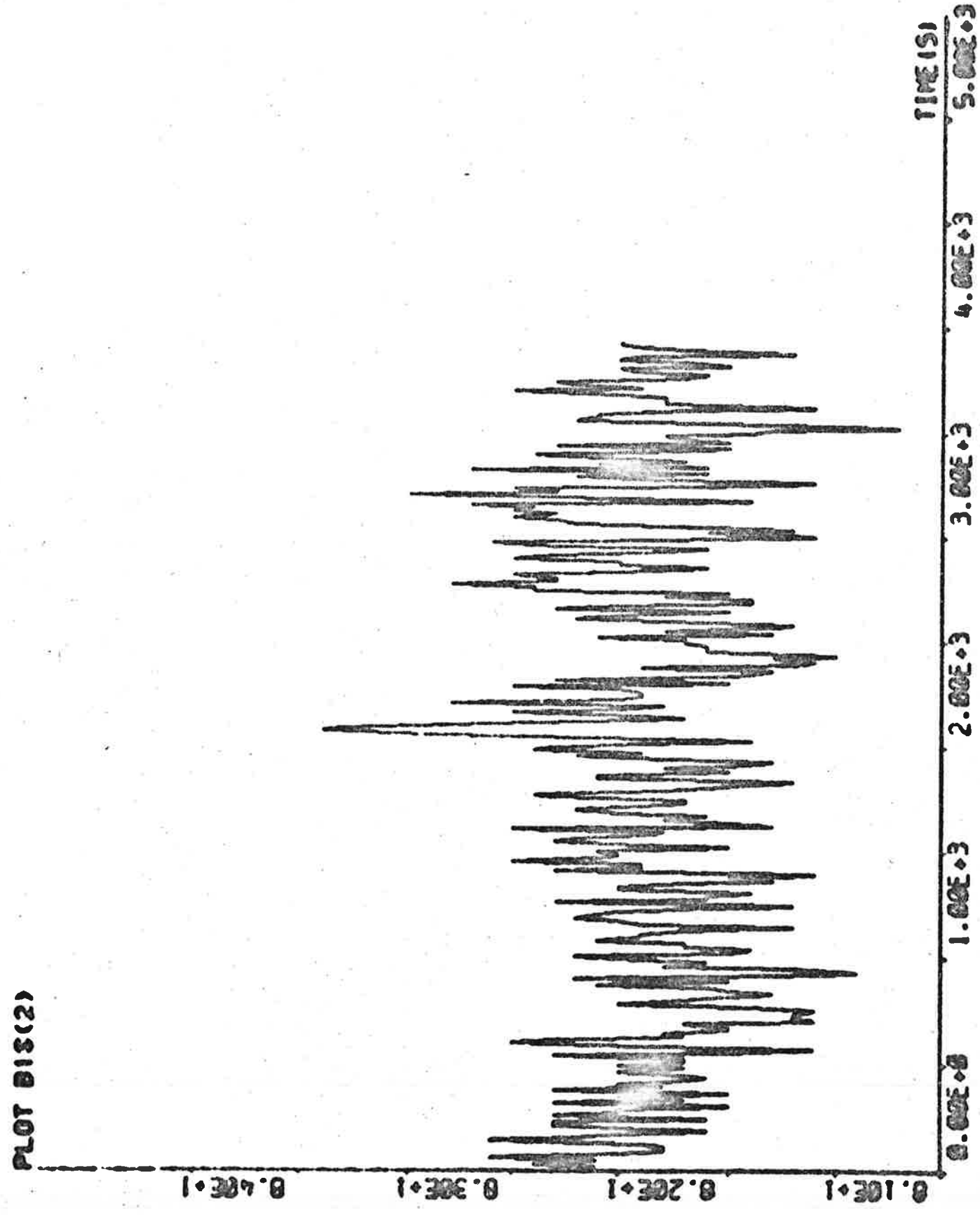
γ degr


PLOT DID(7)
1.359+1
1.309+1
1.259+1
1.209+1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+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
-2.00E-1
0.00E+0
2.00E-1
4.00E-1

7 degr/s


PLOT BIS(2)
8.1E+1
8.2E+1
8.3E+1
8.4E+1
0.0E+0
1.0E+3
2.0E+3
3.0E+3
4.0E+3
5.0E+3
TIME(S)

n rpm

Experiment C1

Date: 73 - 10 -17
Time: 22^{40} - 23^{40}
Position: S 19° E 05°

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

Regulator 2

No Kalman filter
No yaw
Data is punched every second during the experiment

Calibration of the rudder servo:

10 volts = 36.9°
-10 volts = -43.1°

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

Model in the regulator:

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

Regulator:

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

Sampling interval for punching: 1 s
Sampling interval for control: 20 s
Forgetting factor λ: 0.98
Rudder limits: Unknown
$\Psi_{ref} = 142^{\circ}$

Initial values:

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

Regulator:

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

Final values:

$$\begin{bmatrix} b_1 \\ b_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} 0.353 \\ 0.003 \\ 13.729 \end{bmatrix}$$

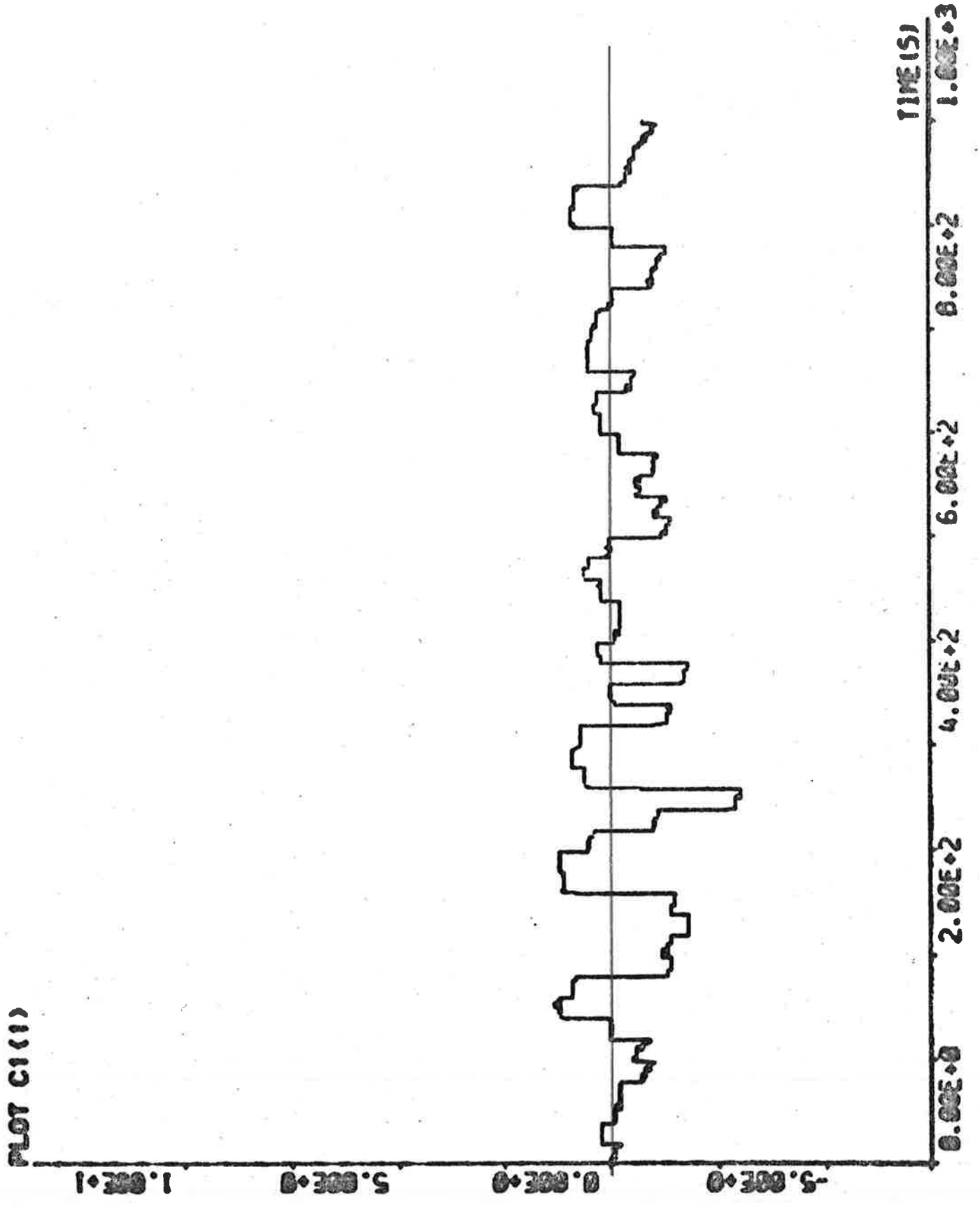
P unknown

Regulator:

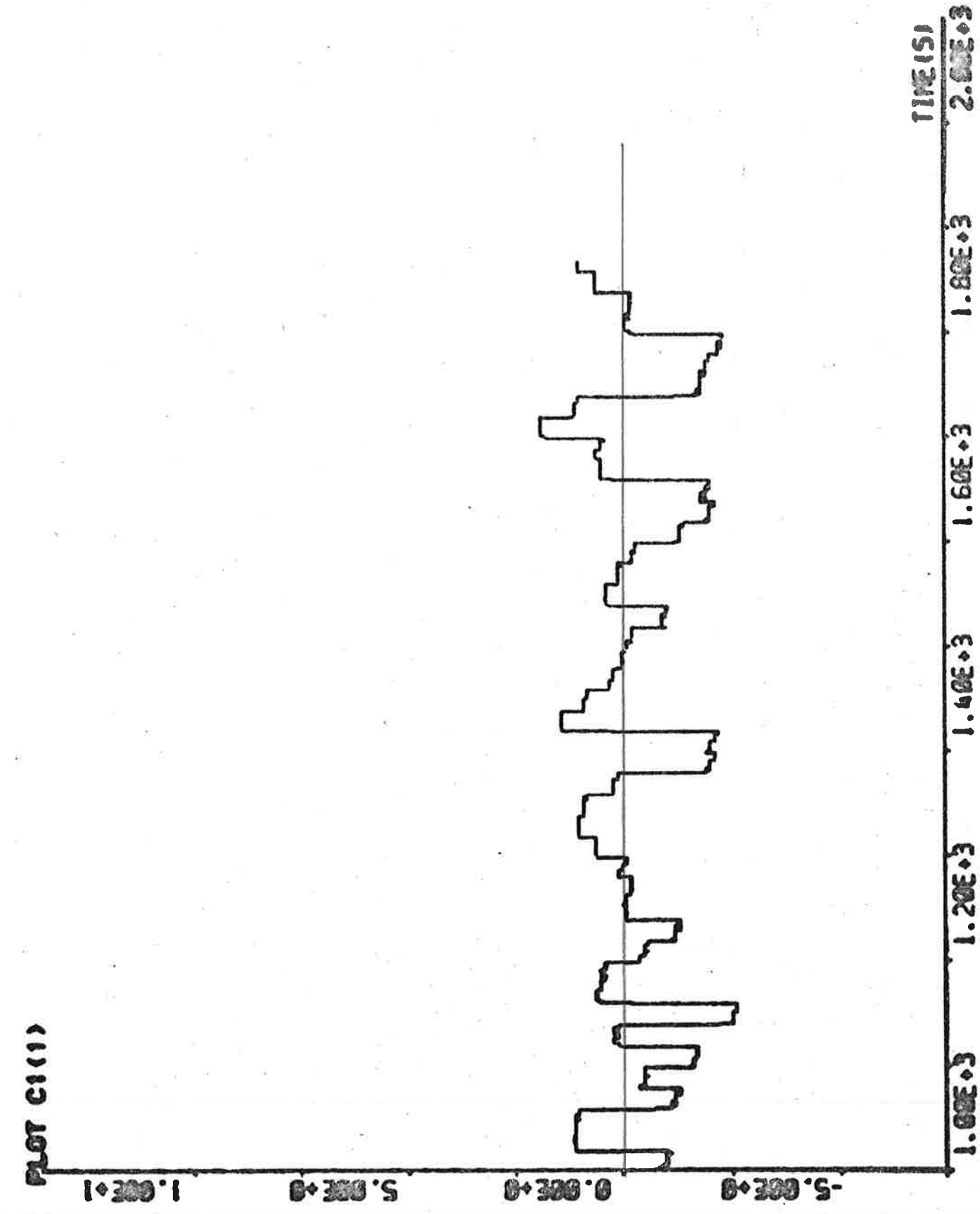
$$\delta(t) = -2.83(\Psi(t) - \Psi_{ref}) - 0.008\delta(t-1) - 38.892r(t)$$

Statistics:

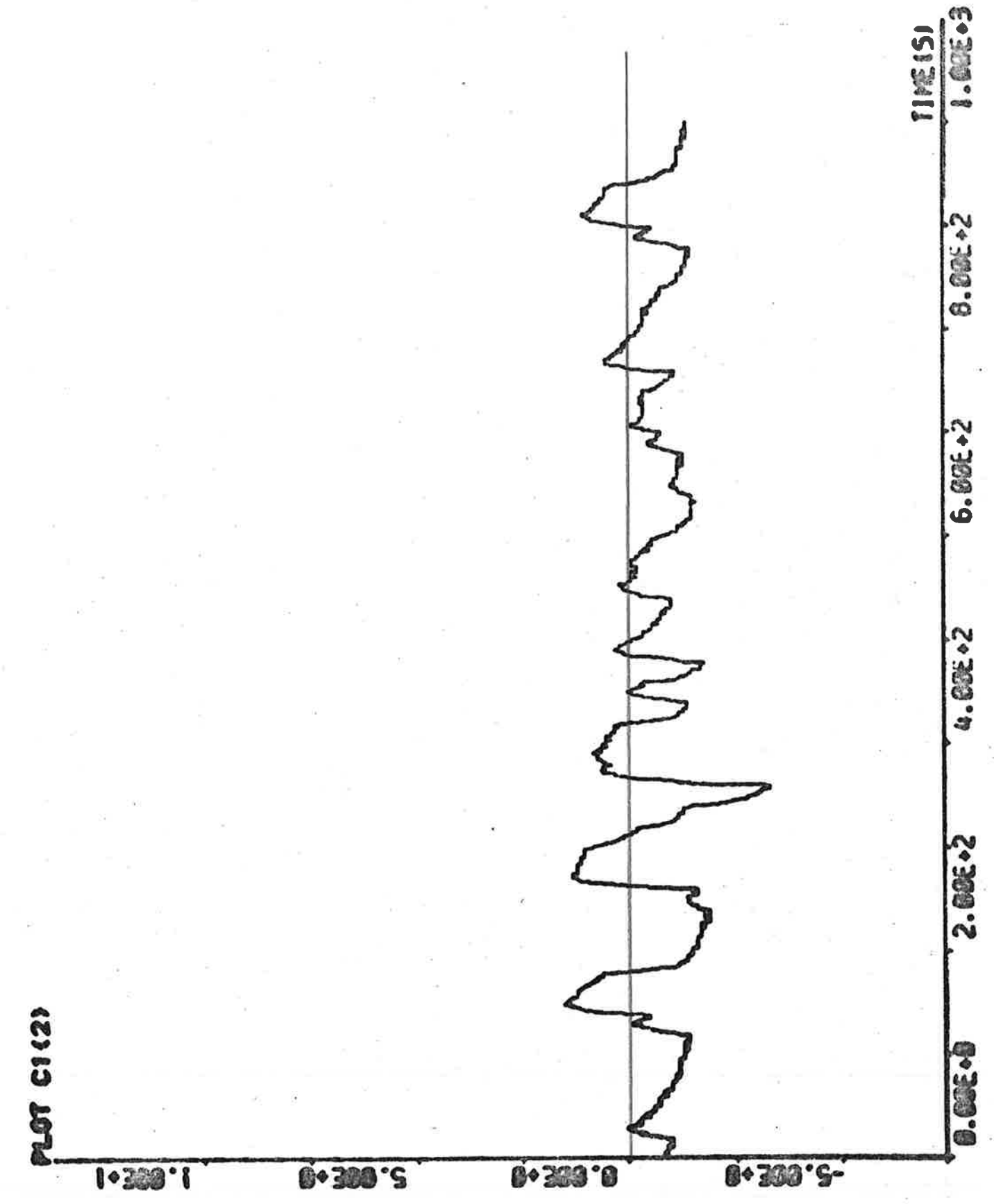
		Mean value	Standard deviation	Minimum value	Maximum value
δ_s	degr	-0.26	1.00	-3.0	1.9
δ	degr	-0.57	0.96	-3.3	2.2
v_1	knots	-0.129	0.145	-0.47	0.19
v_2	knots	0.036	0.119	-0.26	0.29
r	degr/s	0.0031	0.0171	-0.058	0.055
Ψ	degr	142.018	0.232	141.50	142.65
u	knots	16.036	0.136	15.47	16.30


PLOT C1(1)
1.000E-1
5.000E-0
0.000E-0
-5.000E-0
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
TIME(S)

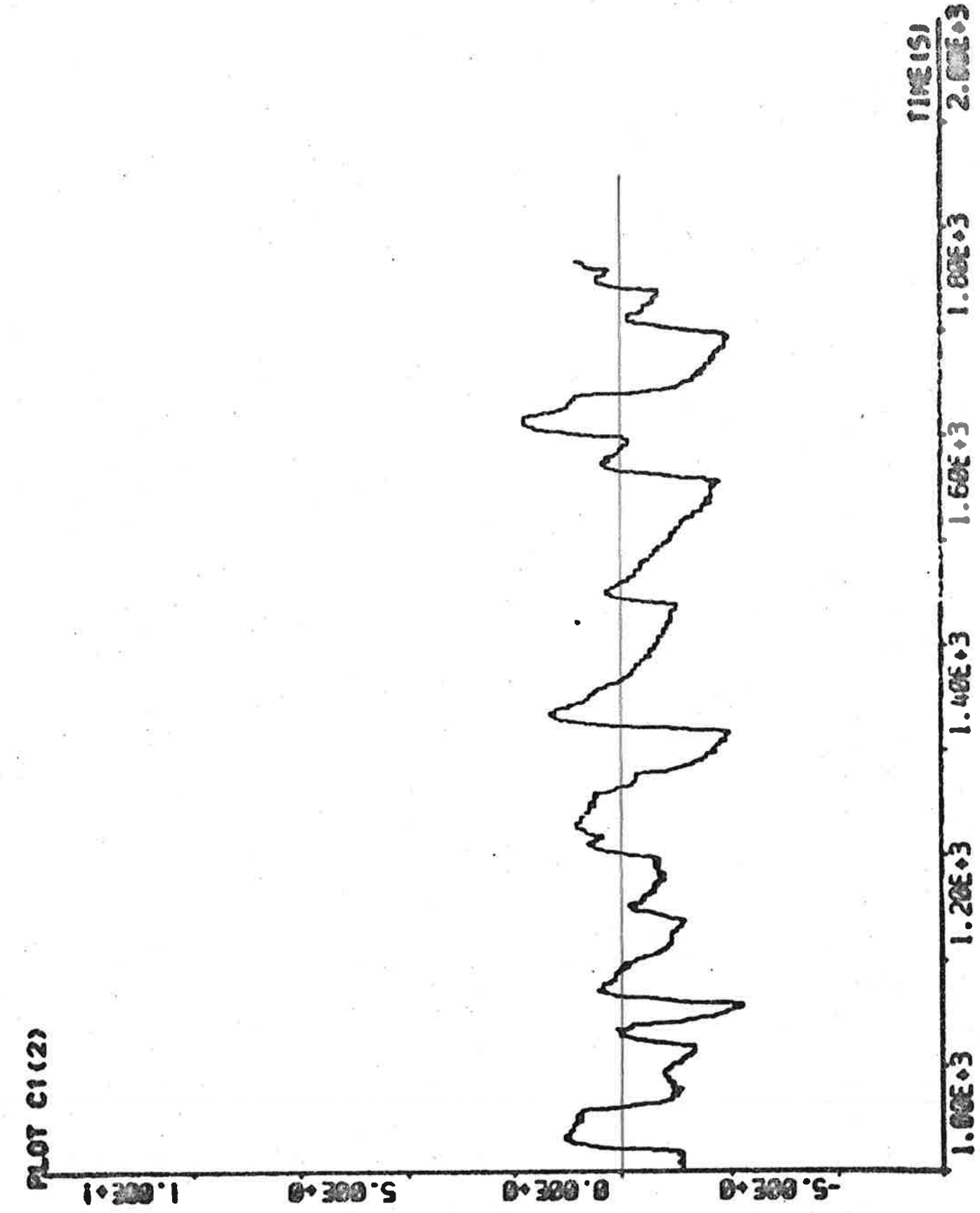
δ_s degr


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)

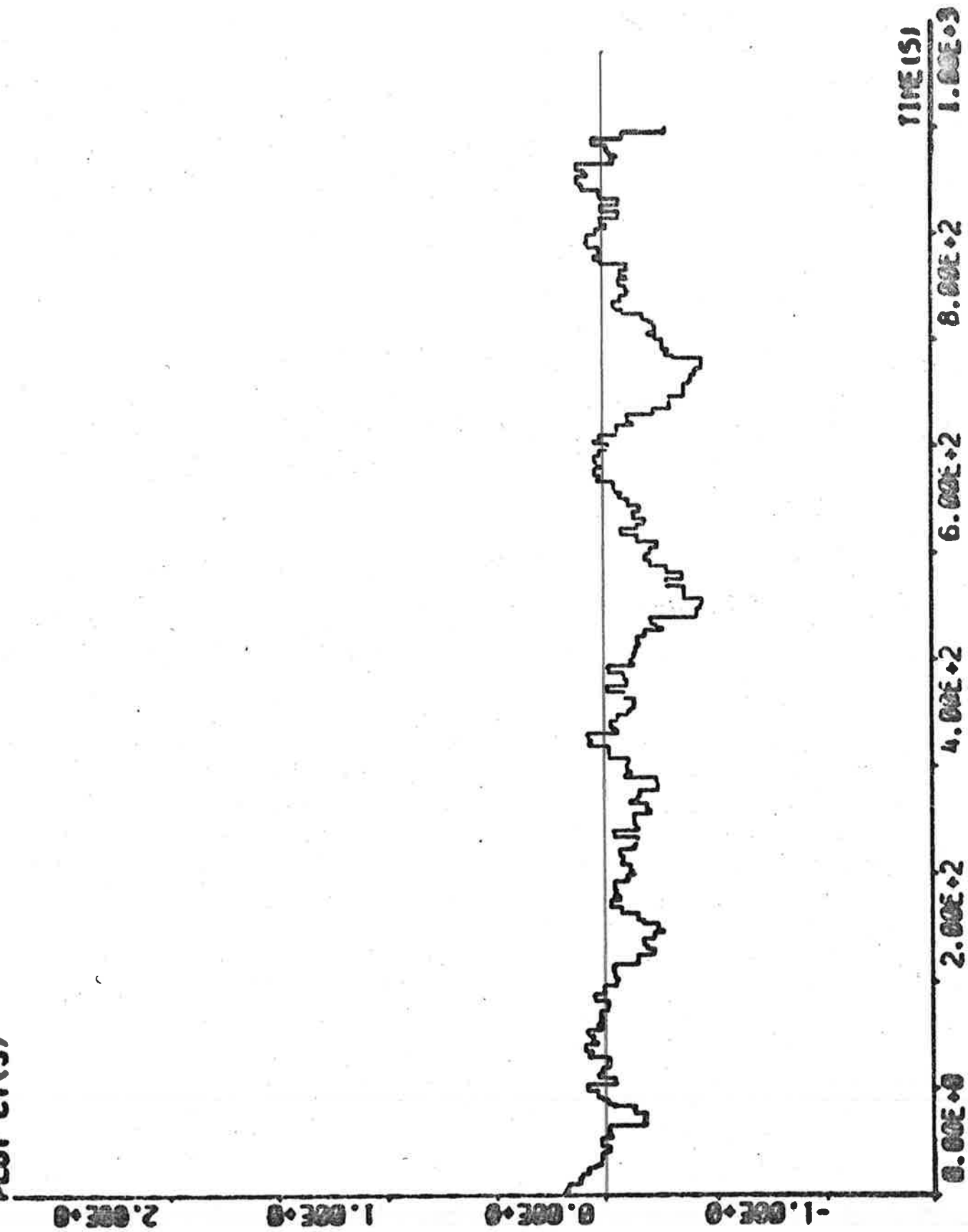
δ_s degr


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

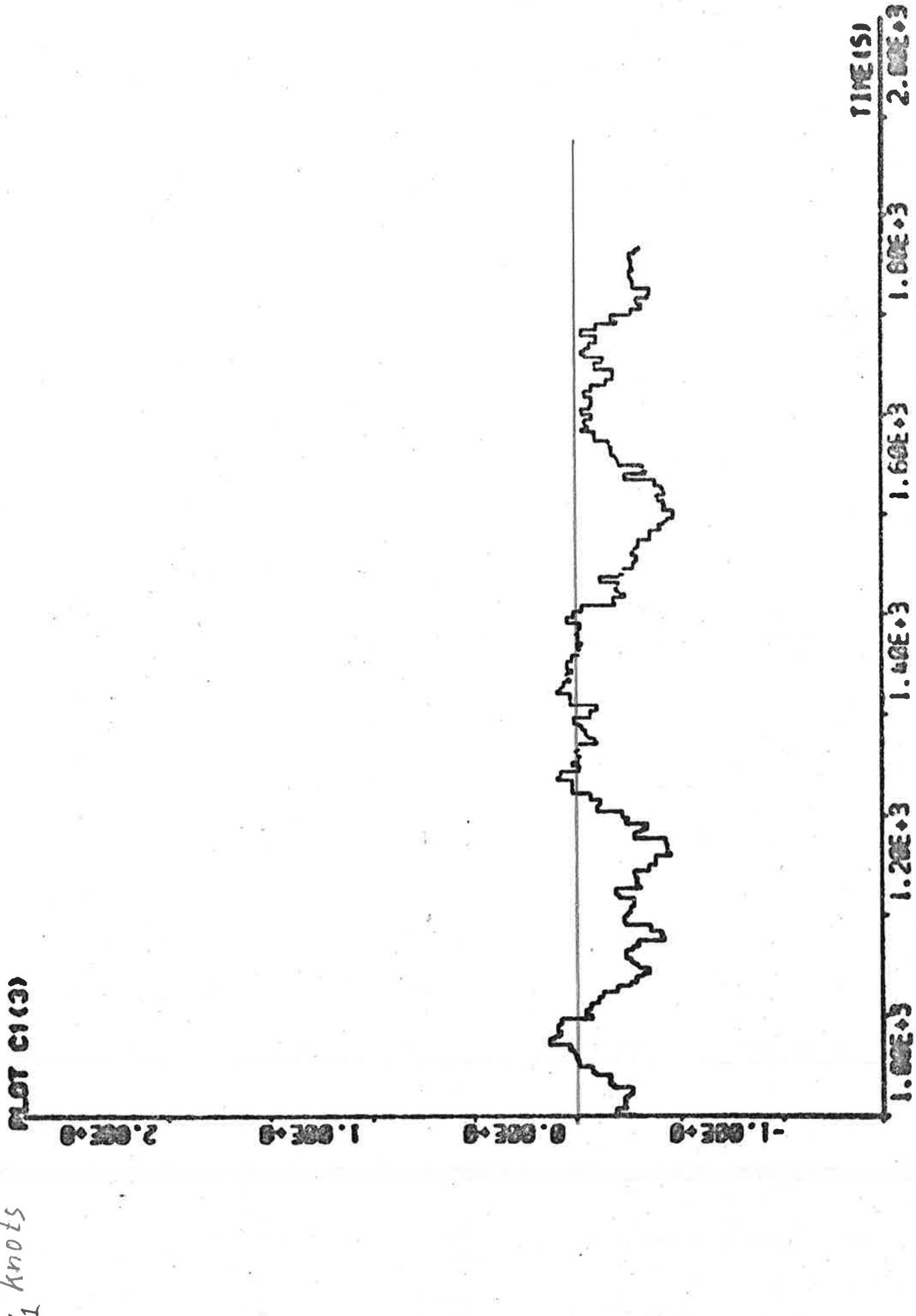
δ degr


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

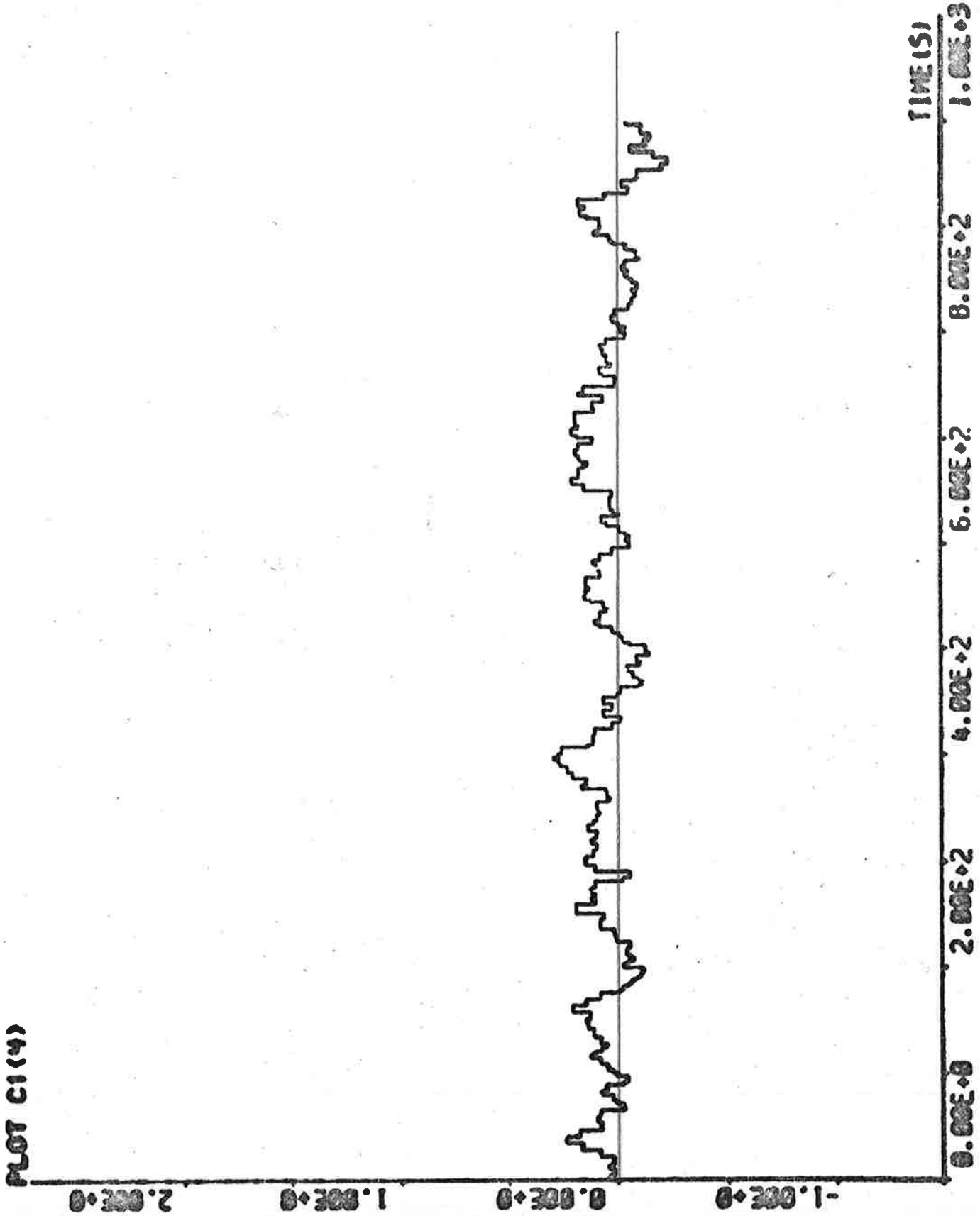
δ degr


PLOT C1(3)
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)

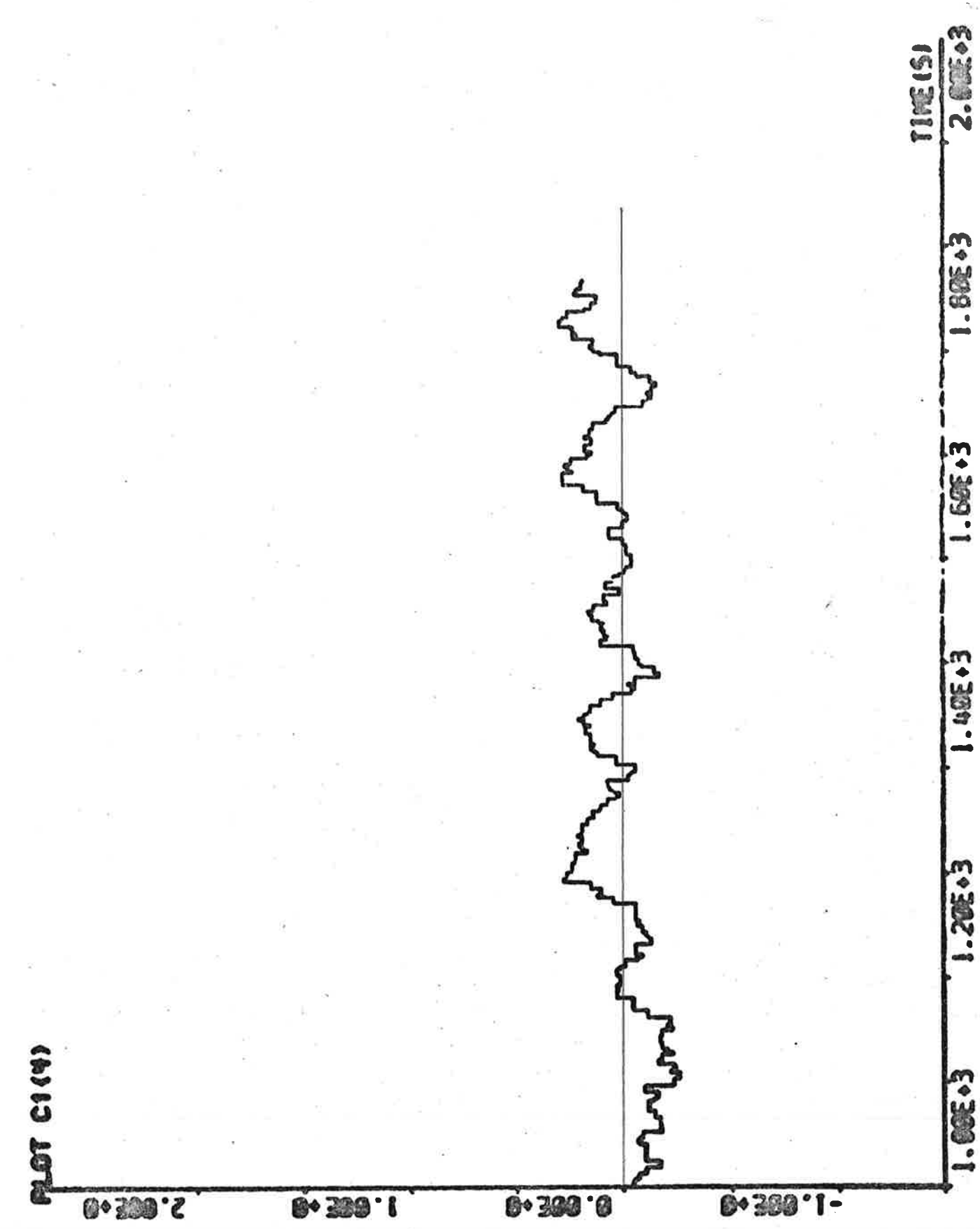
V_1 knots


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

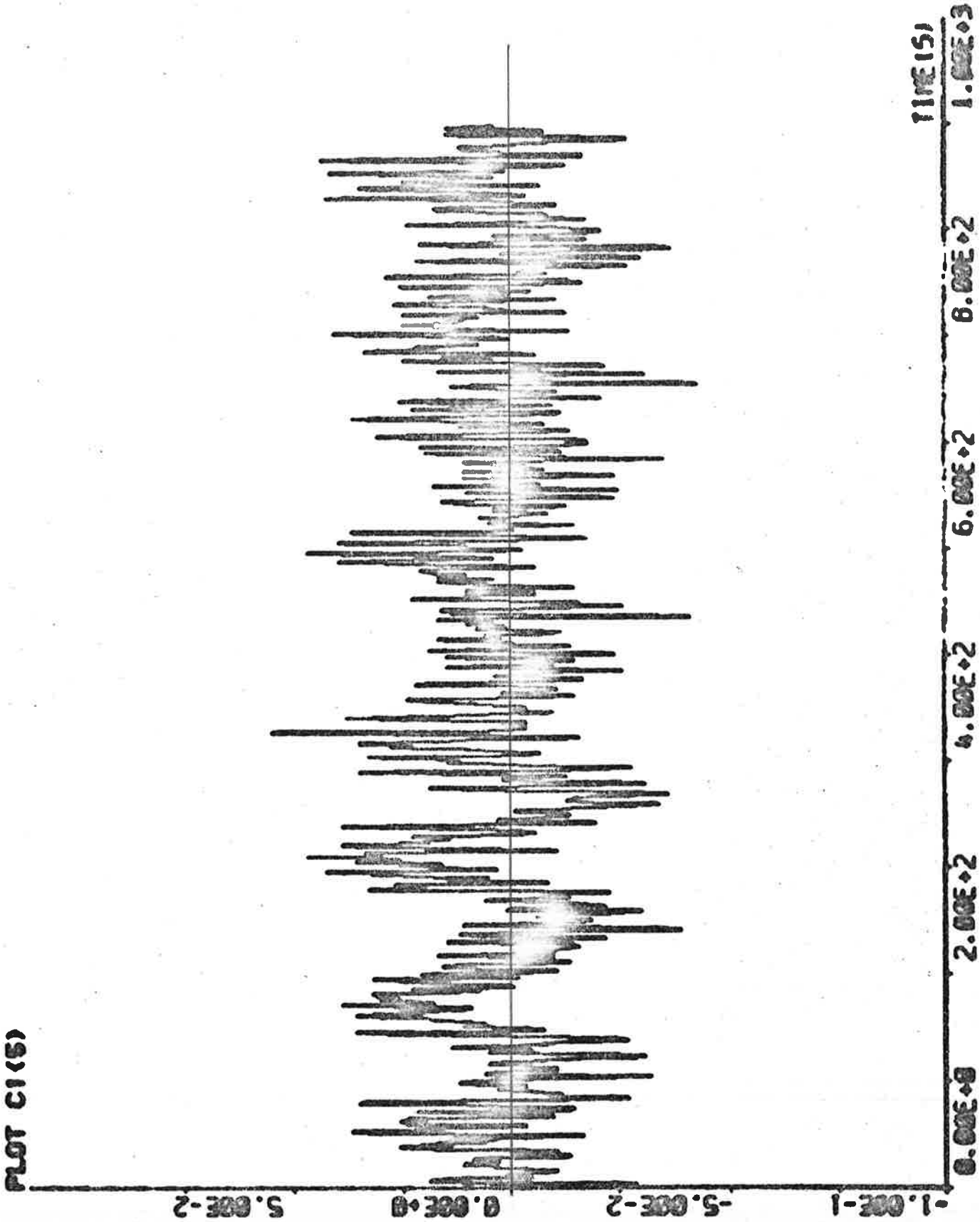
V_1 knots


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)

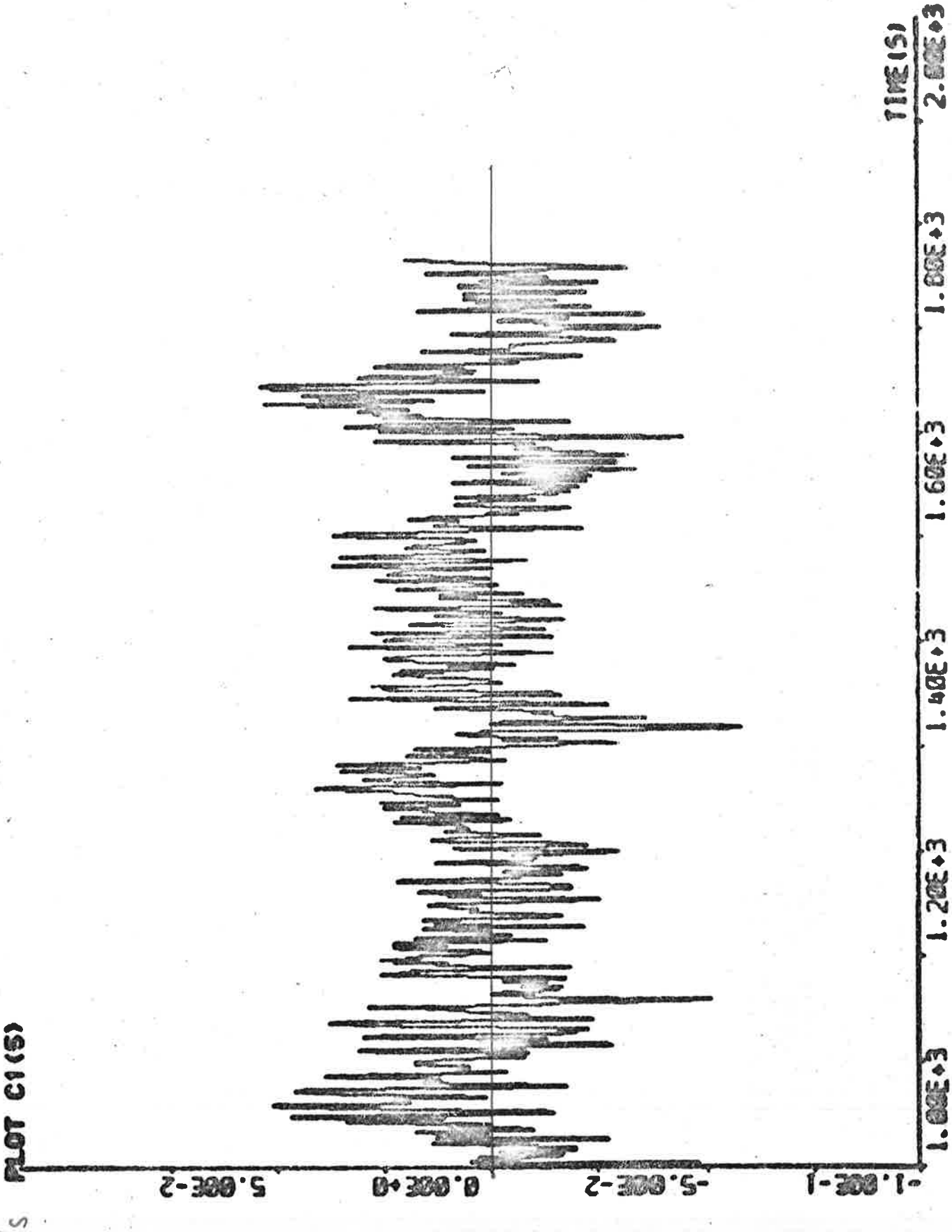
V_2. knots


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

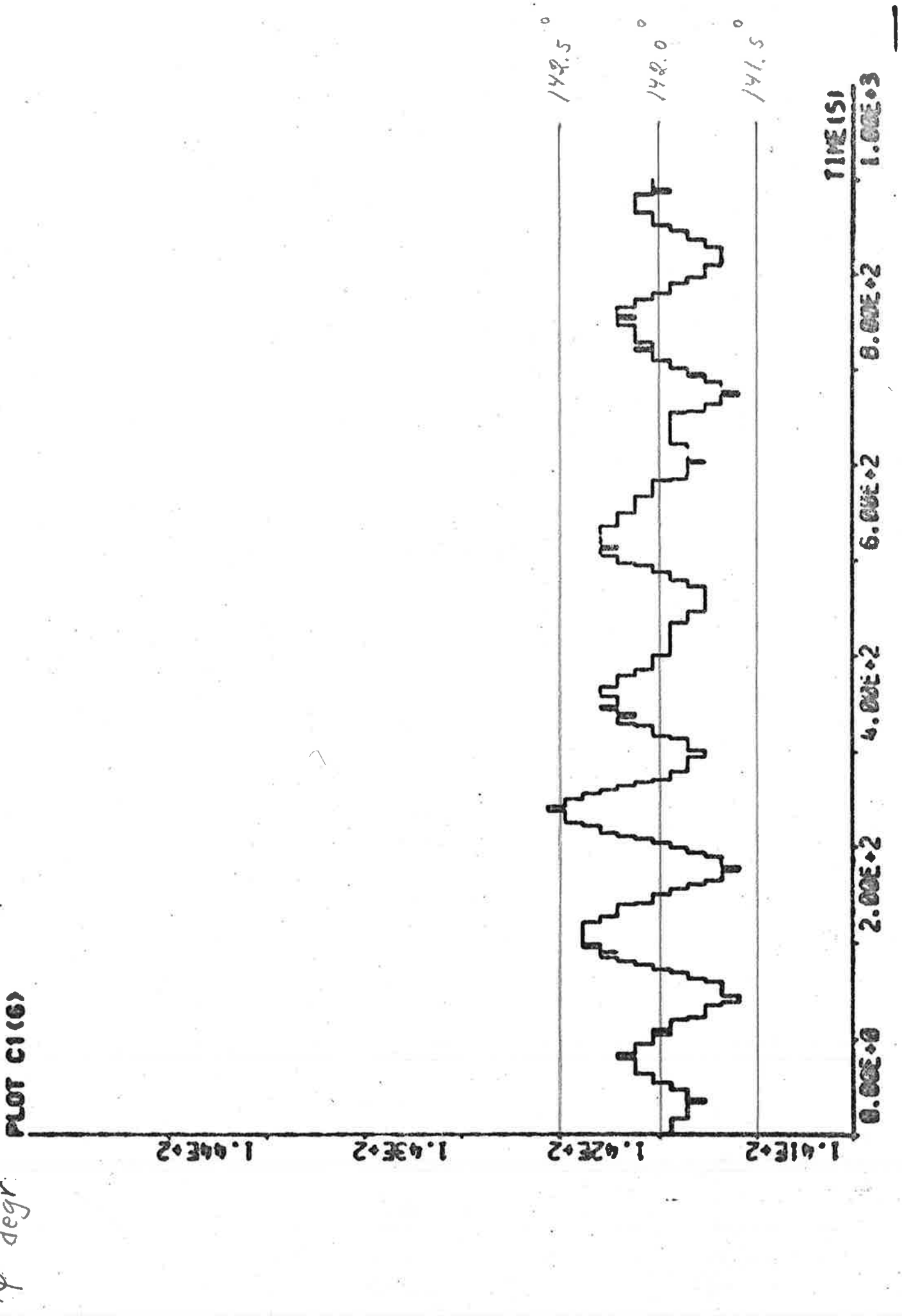
V_i knots


PLOT C1(5)
5.00E-2
0.00E+0
-5.00E-2
-1.00E-1
TIME(5)
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3

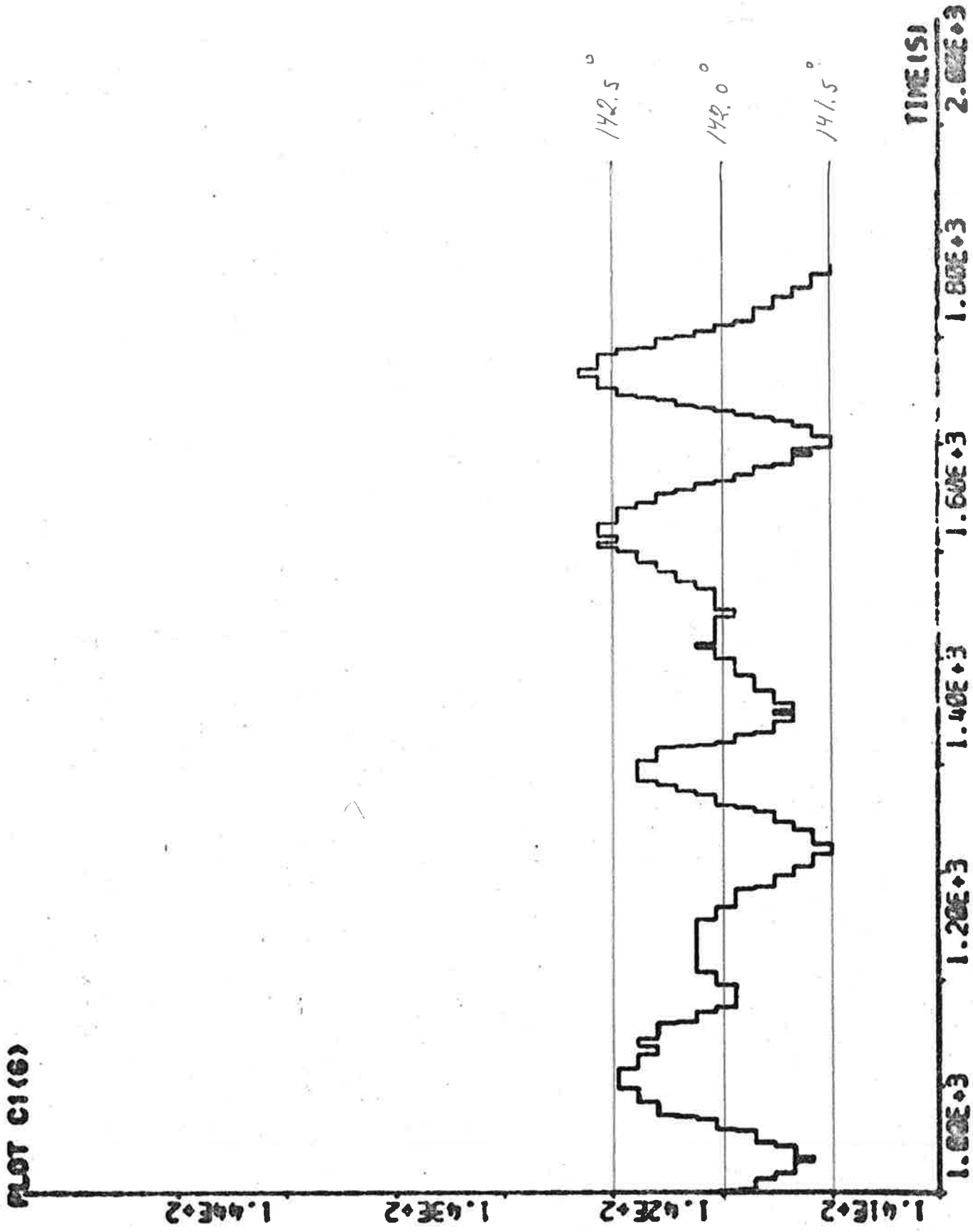
r deg/s


PLOT C1(5)
-1.00E-1
-5.00E-2
0.00E+0
5.00E-2
1.00E+3
1.20E+3
1.40E+3
1.60E+3
1.80E+3
2.00E+3
TIME(S)

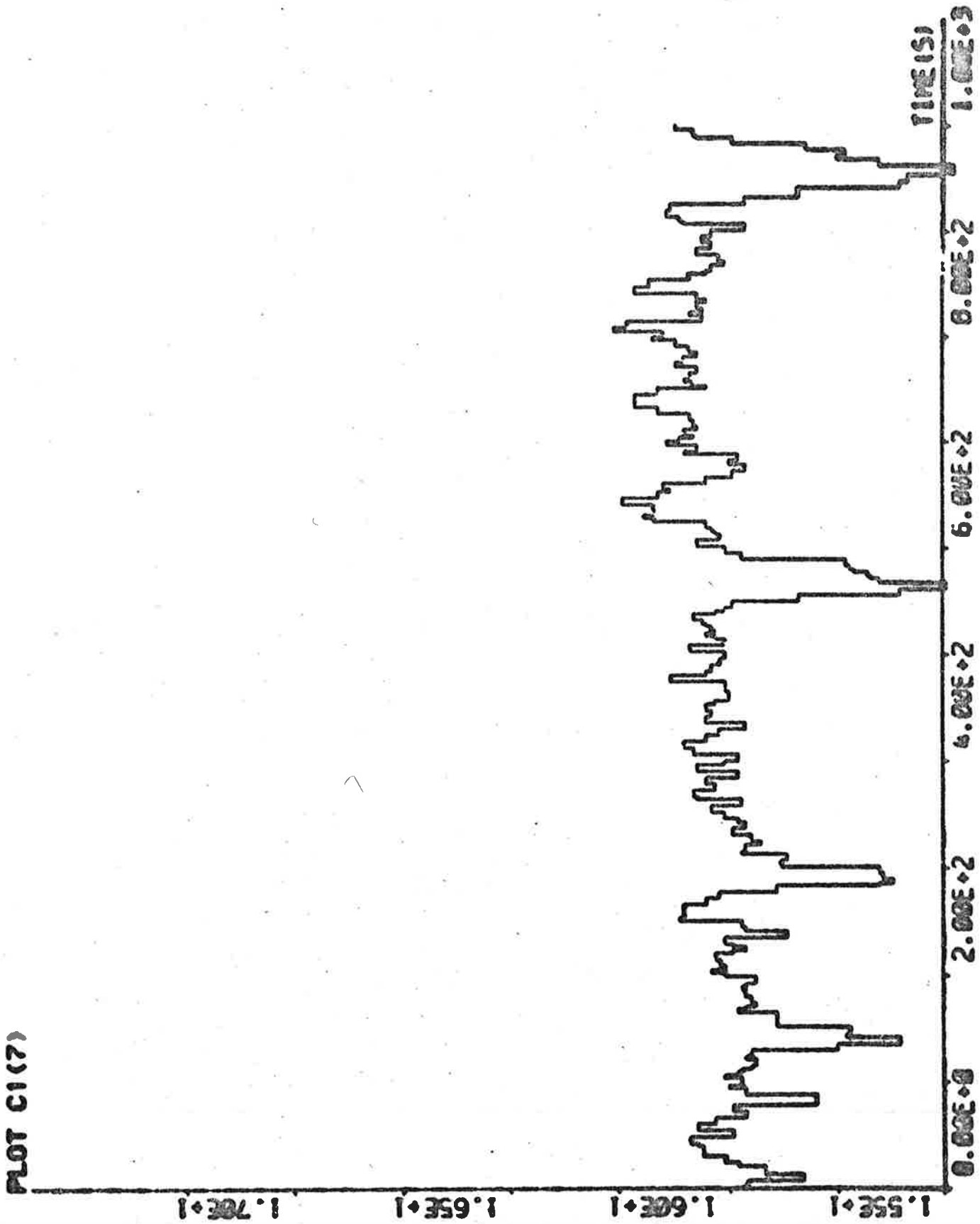
r degr/s


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

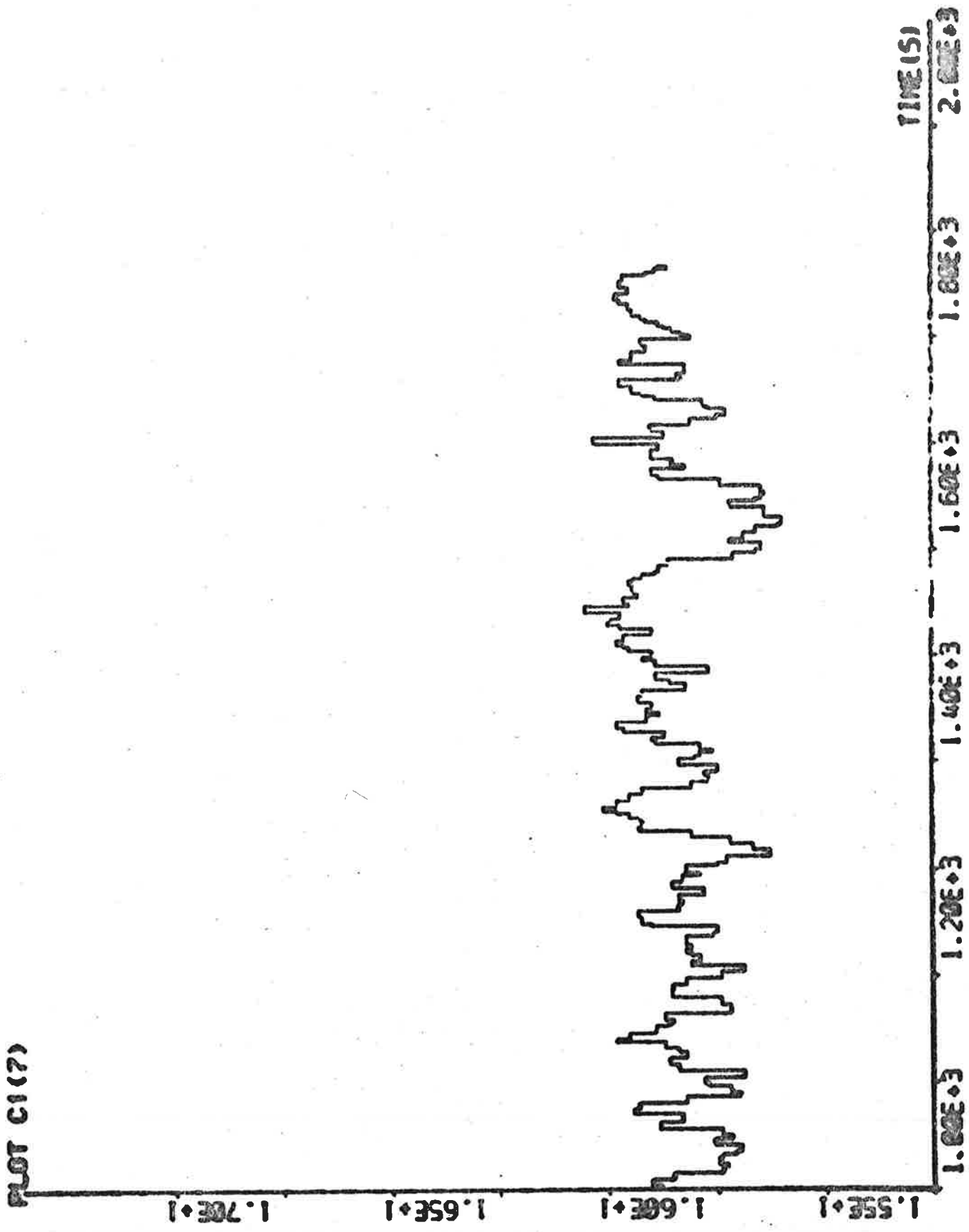
ψ degr


PLOT C1(6)
1.4E+2
1.3E+2
1.2E+2
1.1E+2
142.5°
142.0°
141.5°
1.6E+3
1.2E+3
1.4E+3
1.6E+3
1.8E+3
2.0E+3
TIME(S)

ψ degr


PLOT C1(7)
1.555+1
1.605+1
1.655+1
1.705+1
0.00E+0
2.00E+2
4.00E+2
6.00E+2
8.00E+2
1.00E+3
TIME(S)

y knots


PLOT C1(2)
1.755+1
1.655+1
1.555+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.

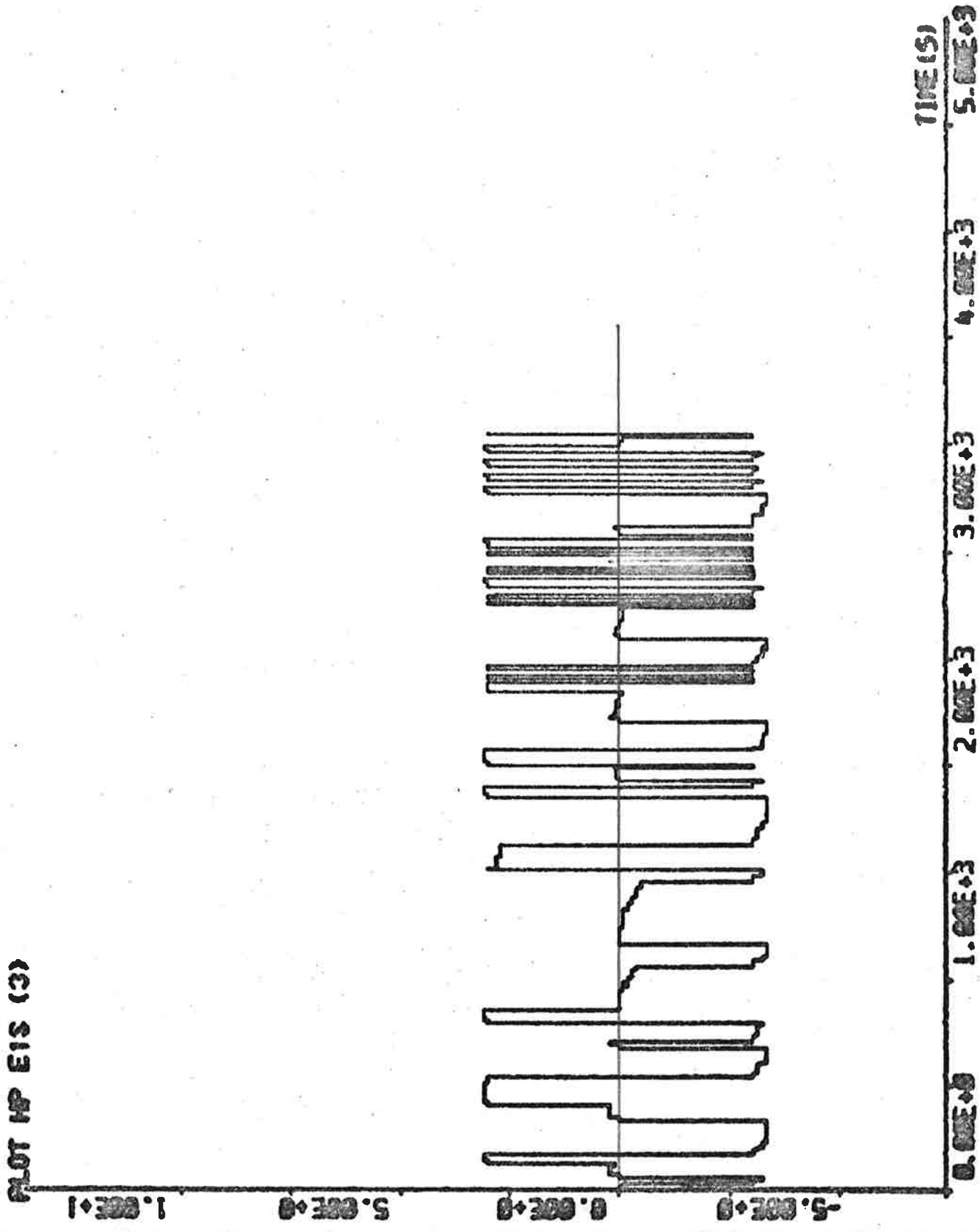
Calibration of the rudder servo:

10 volts = 36.5°
-10 volts = -43.5°

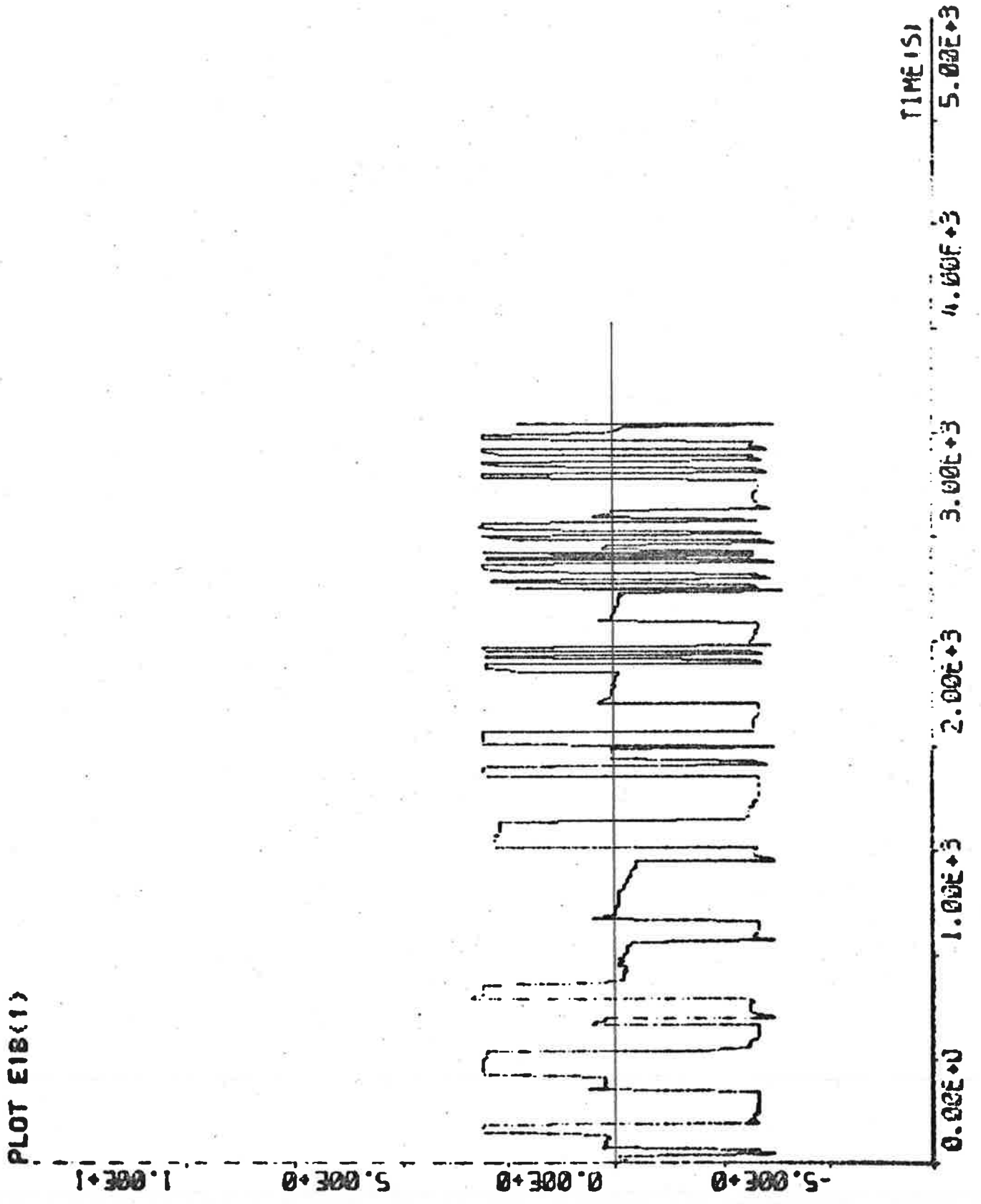
Sampling interval: 10 s
Rudder angles: $+3^{\circ}$, 0°, -3°

Statistics:

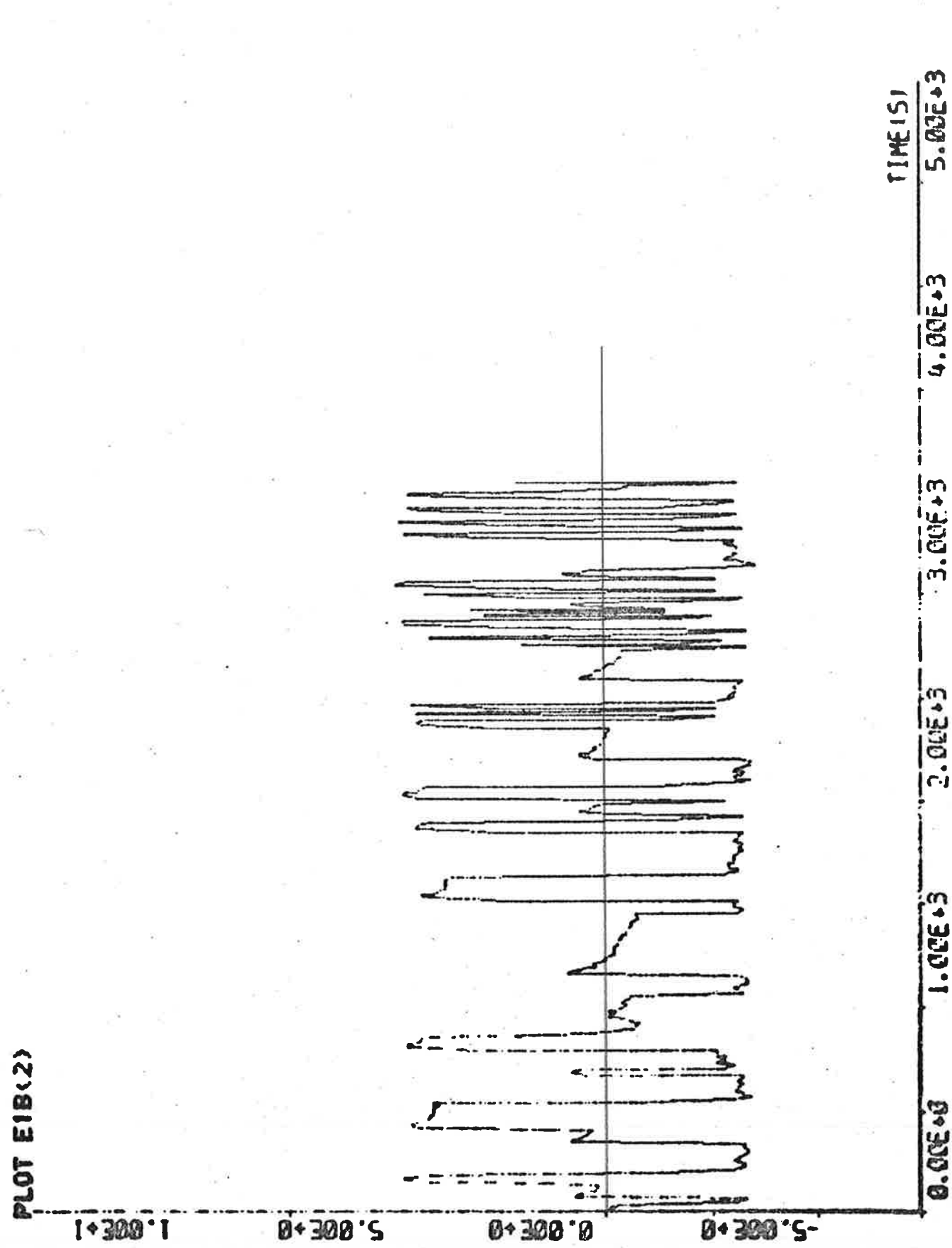
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.65	2.47	-3.3	3.1
δ_s degr	-0.72	2.50	-3.9	3.4
δ degr	-0.28	2.75	-3.5	5.0
v_1 knots	-0.506	0.164	-1.01	-0.14
v_2 knots	0.206	0.497	-1.15	1.13
r degr/s	0.0087	0.0549	-0.110	0.160
Ψ degr	182.754	3.722	176.60	192.10
u knots	16.896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



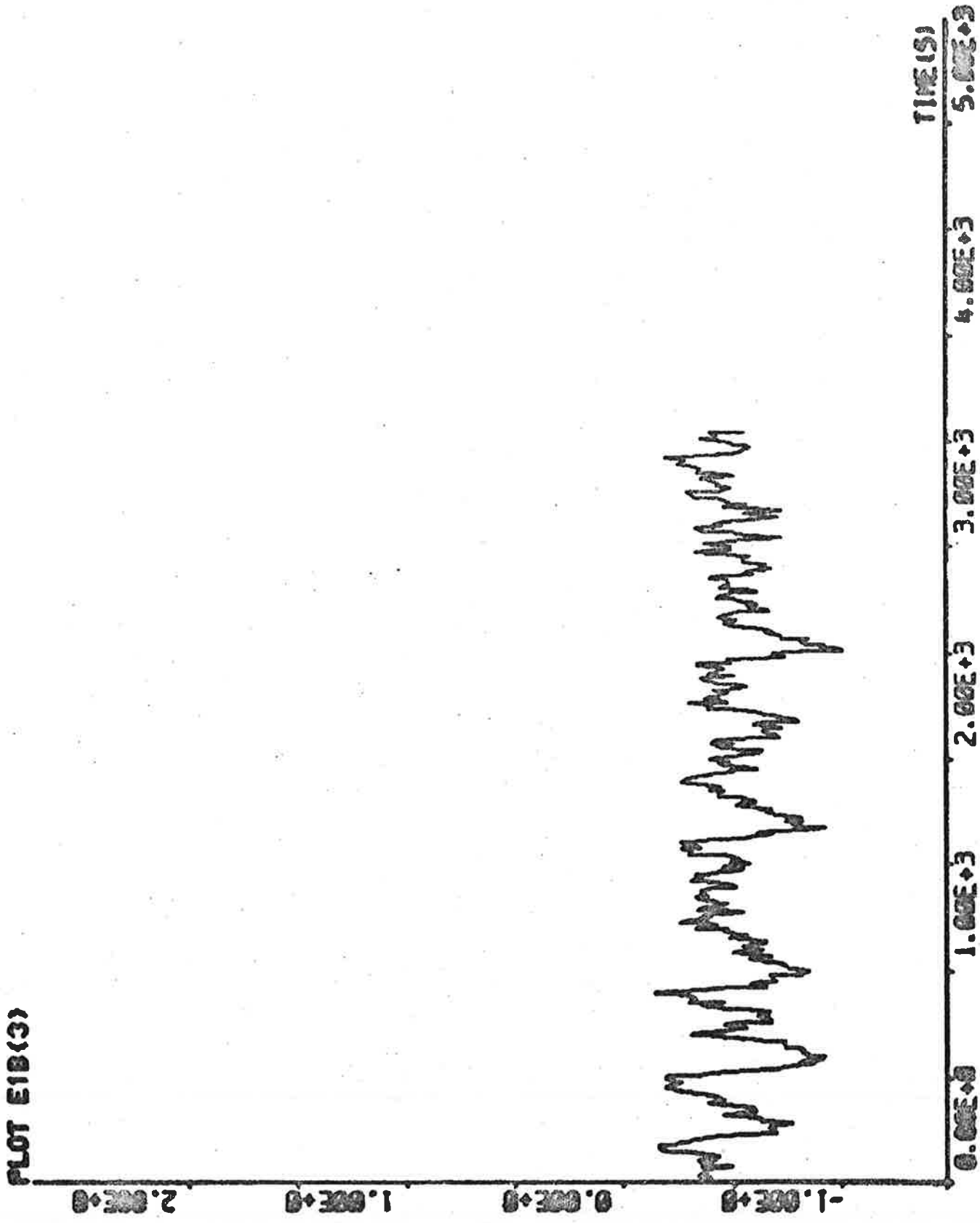
δ_{com} degr


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

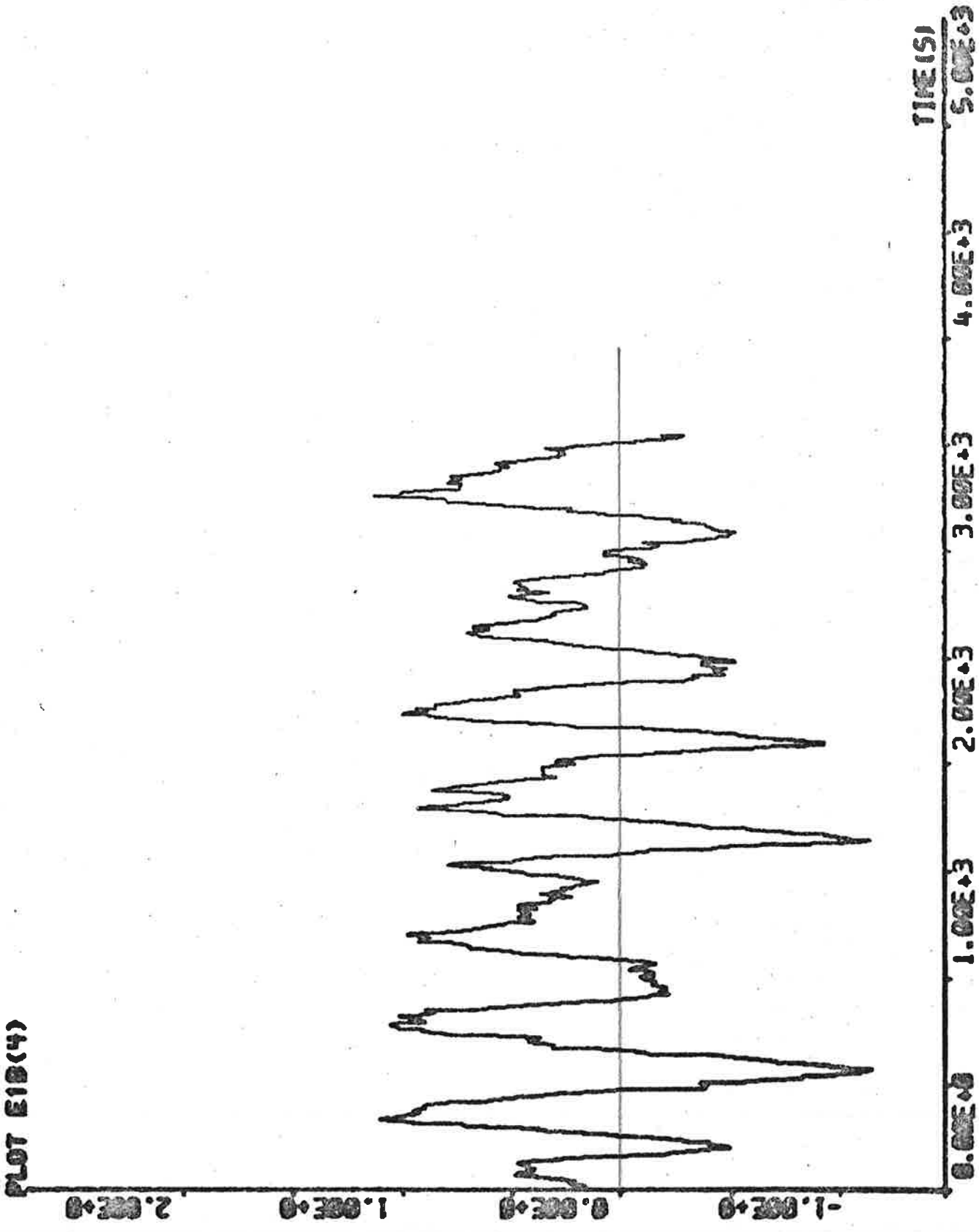
δ_s degr


PLOT E1B(2)
1.300+1
5.300+0
0.300+0
-5.300+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

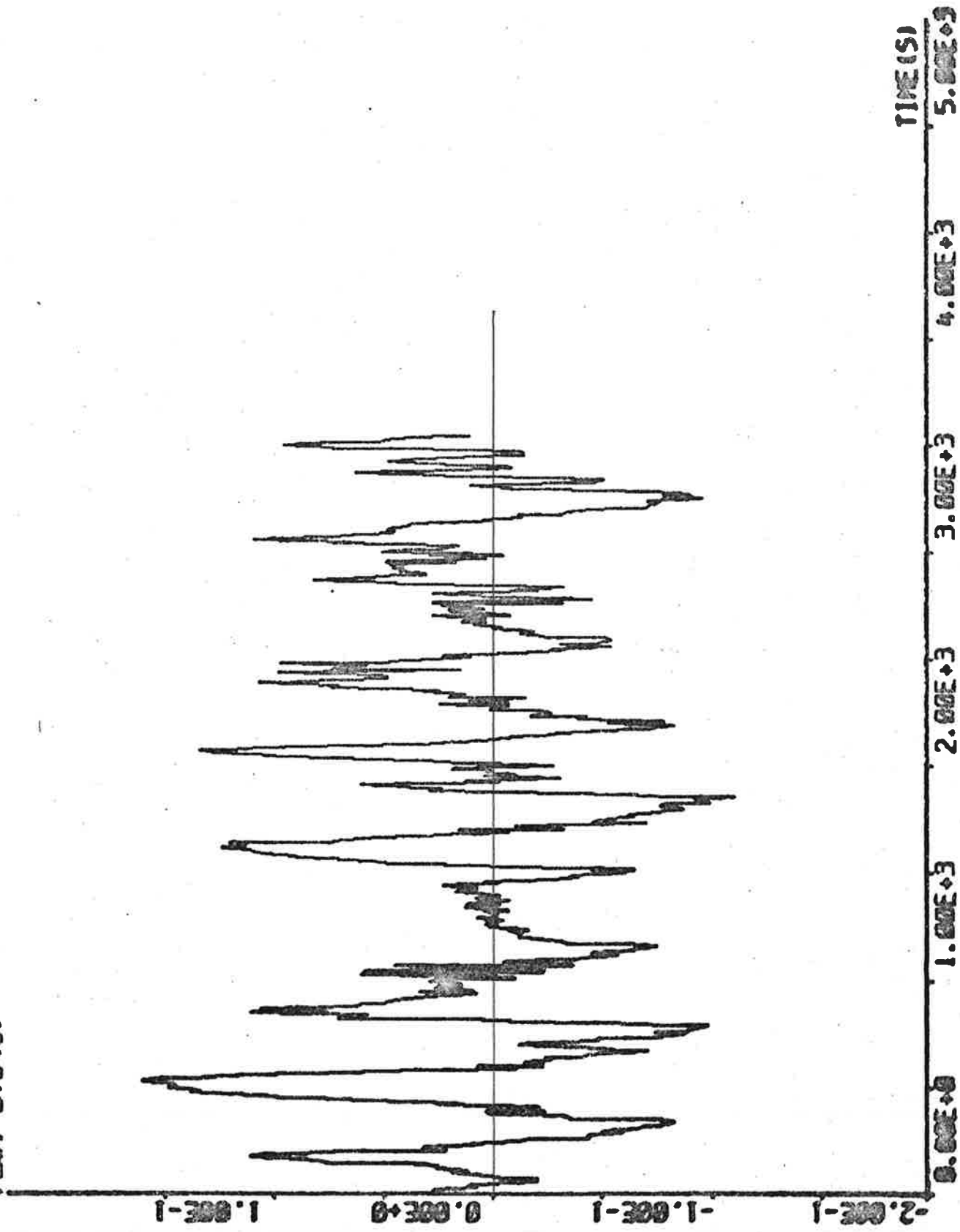
d degr


PLOT E1B(3)
TIME(S)
0.0E+0
1.0E+3
2.0E+3
3.0E+3
4.0E+3
5.0E+3
-1.0E+0
0.0E+0
1.0E+0
2.0E+0

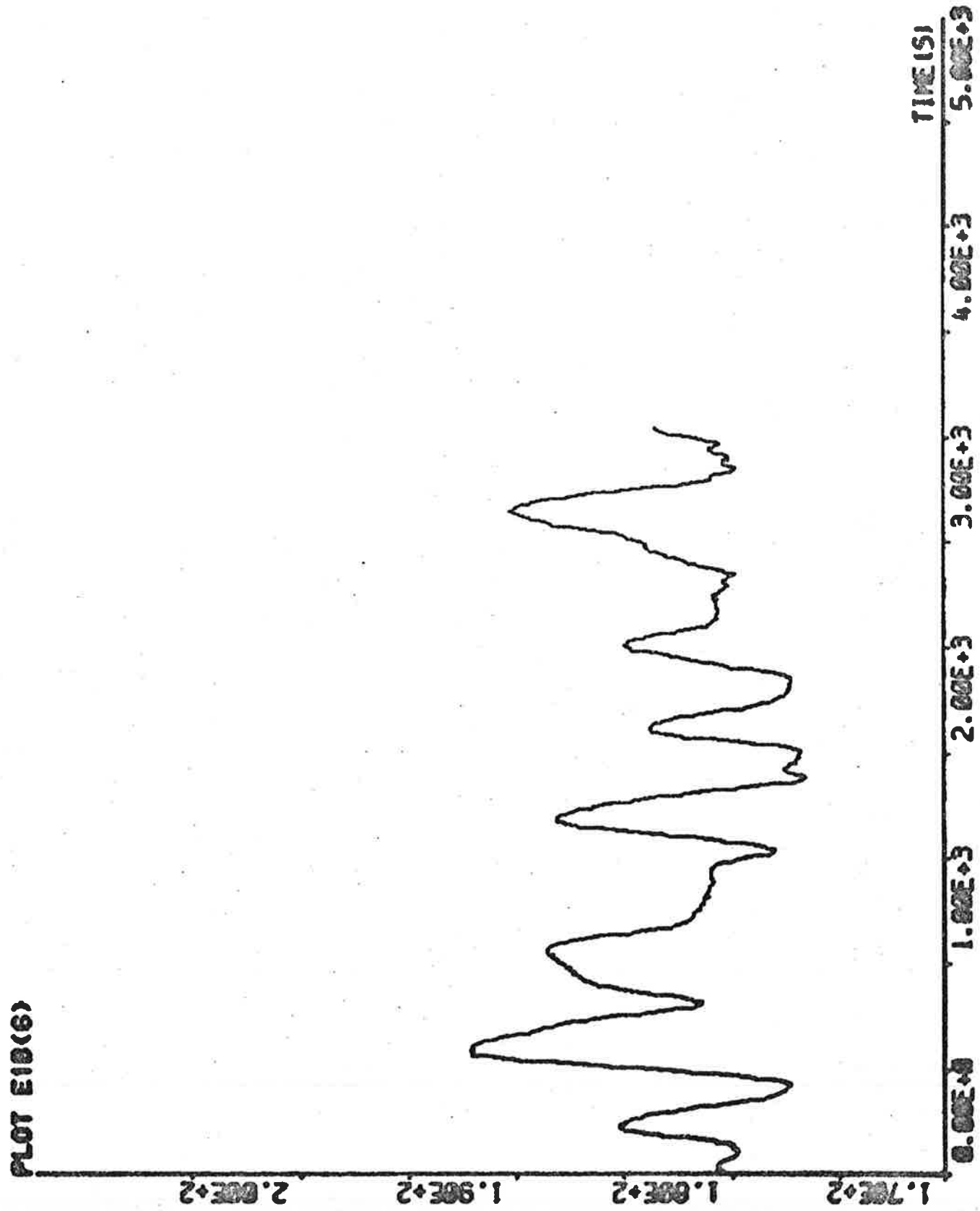
V_1 knots


PLOT E1B(4)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
-1.00E+0
0.00E+0
1.00E+0
2.00E+0

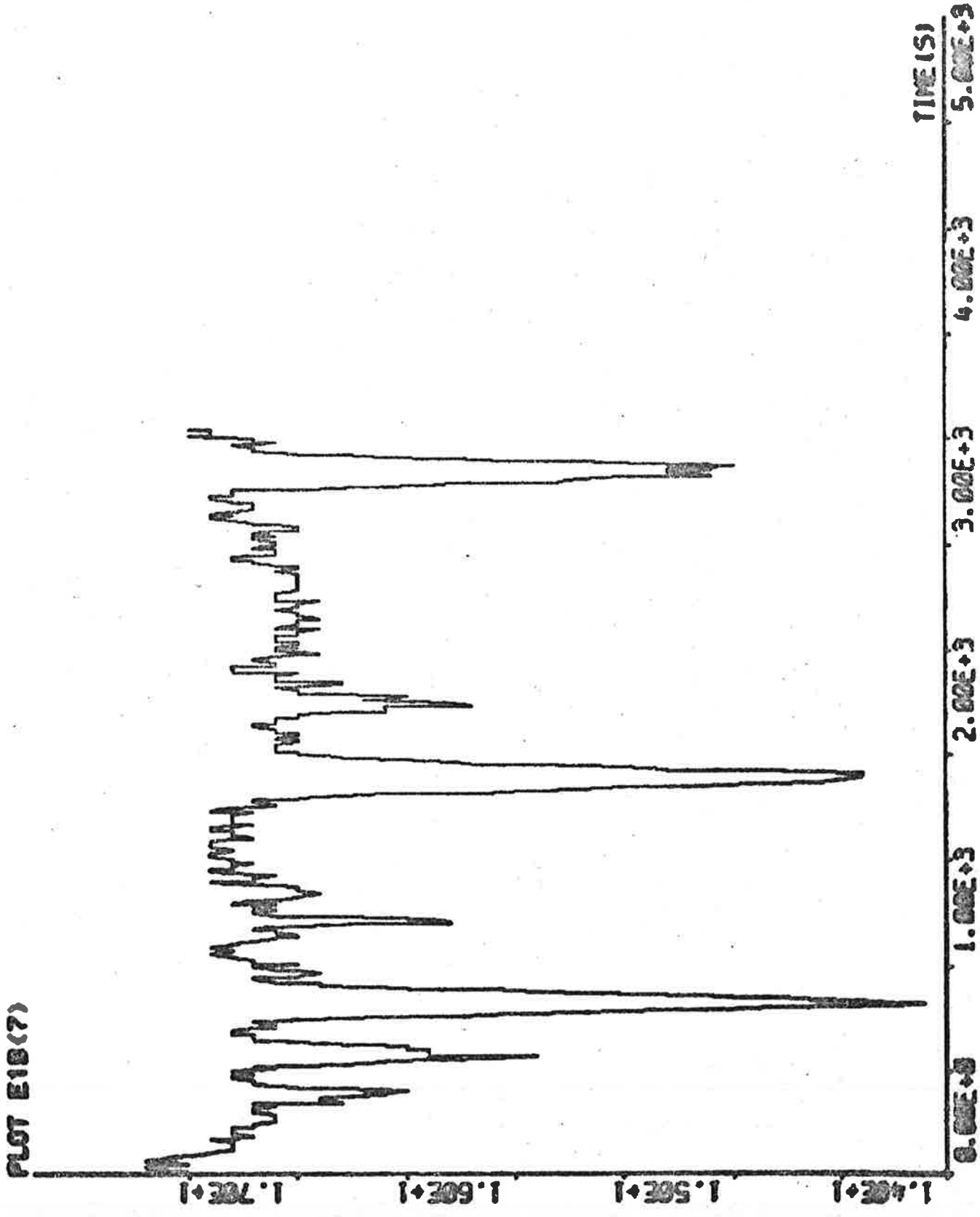
V_2 knots


PLOT E18(S)
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

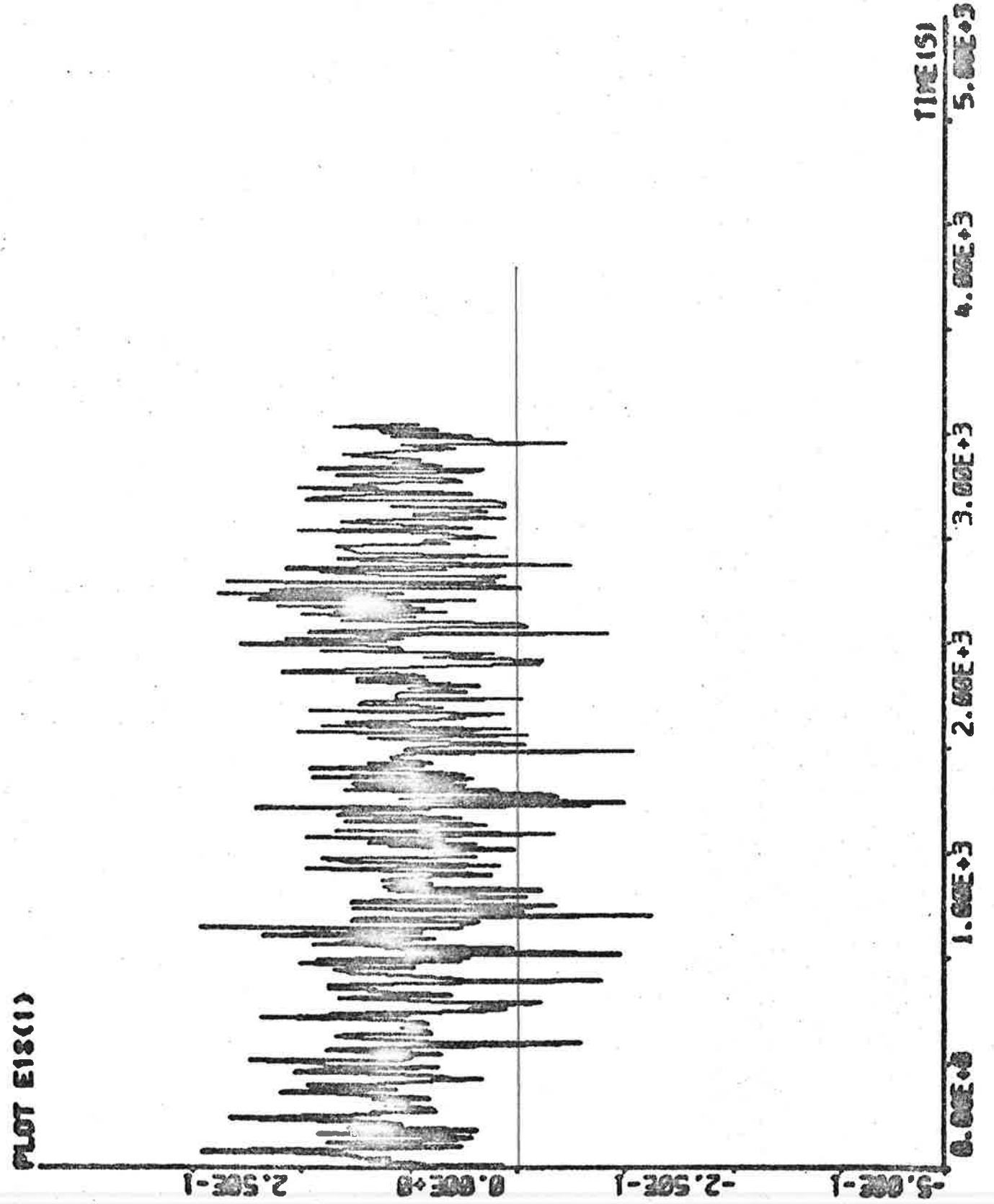
r degr/s


PLOT E1B(6)
1.70E+2
1.80E+2
1.90E+2
2.00E+2
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

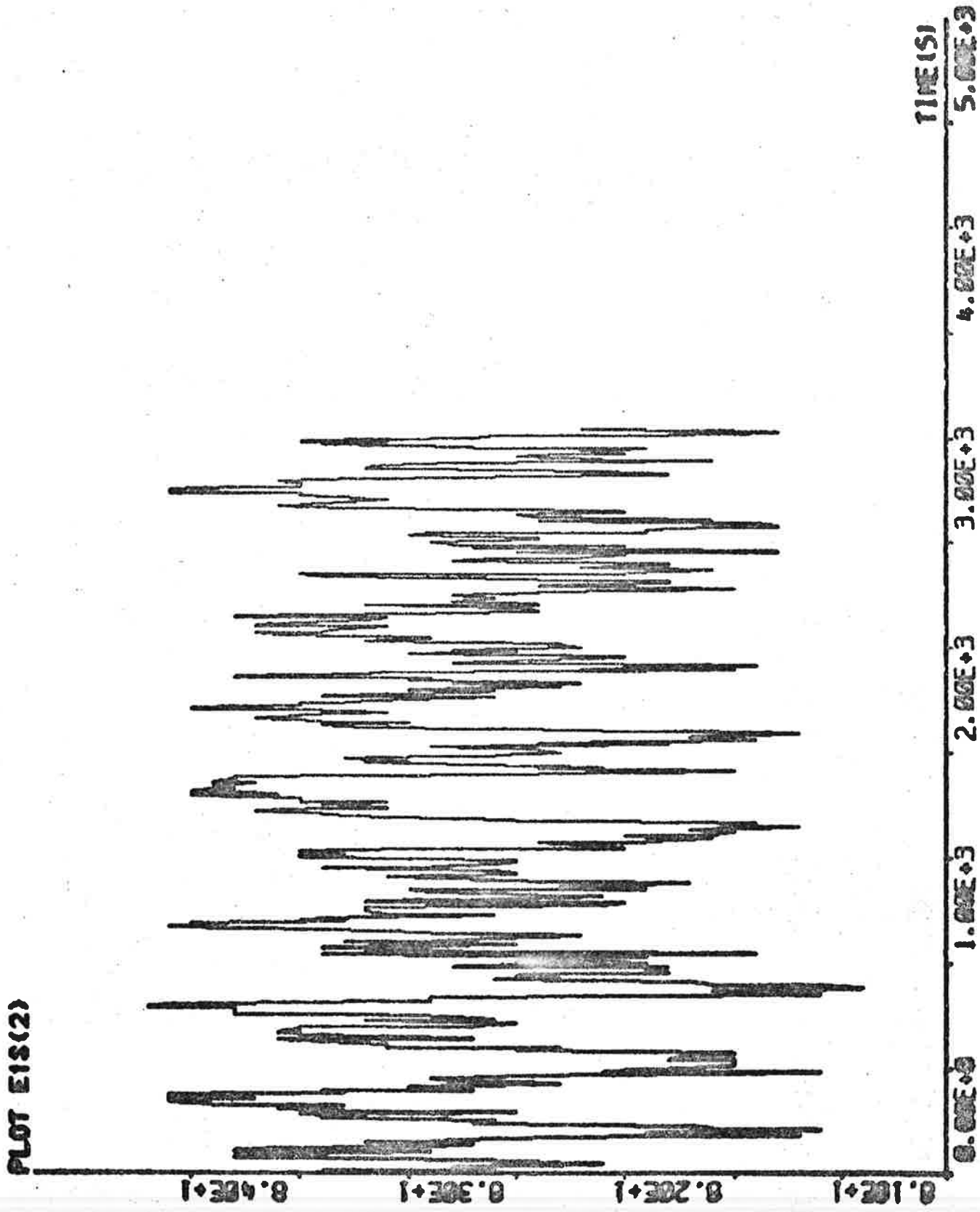
γ degr


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

v knots


PLOT E18(1)
2.50E-1
0.00E+0
-2.50E-1
-5.00E-1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

9 degr/s


PLOT EIS(2)
8.184+1
8.202+1
8.220+1
8.238+1
8.256+1
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

n rpm

Experiment E2

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

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

Experiment for system identification.

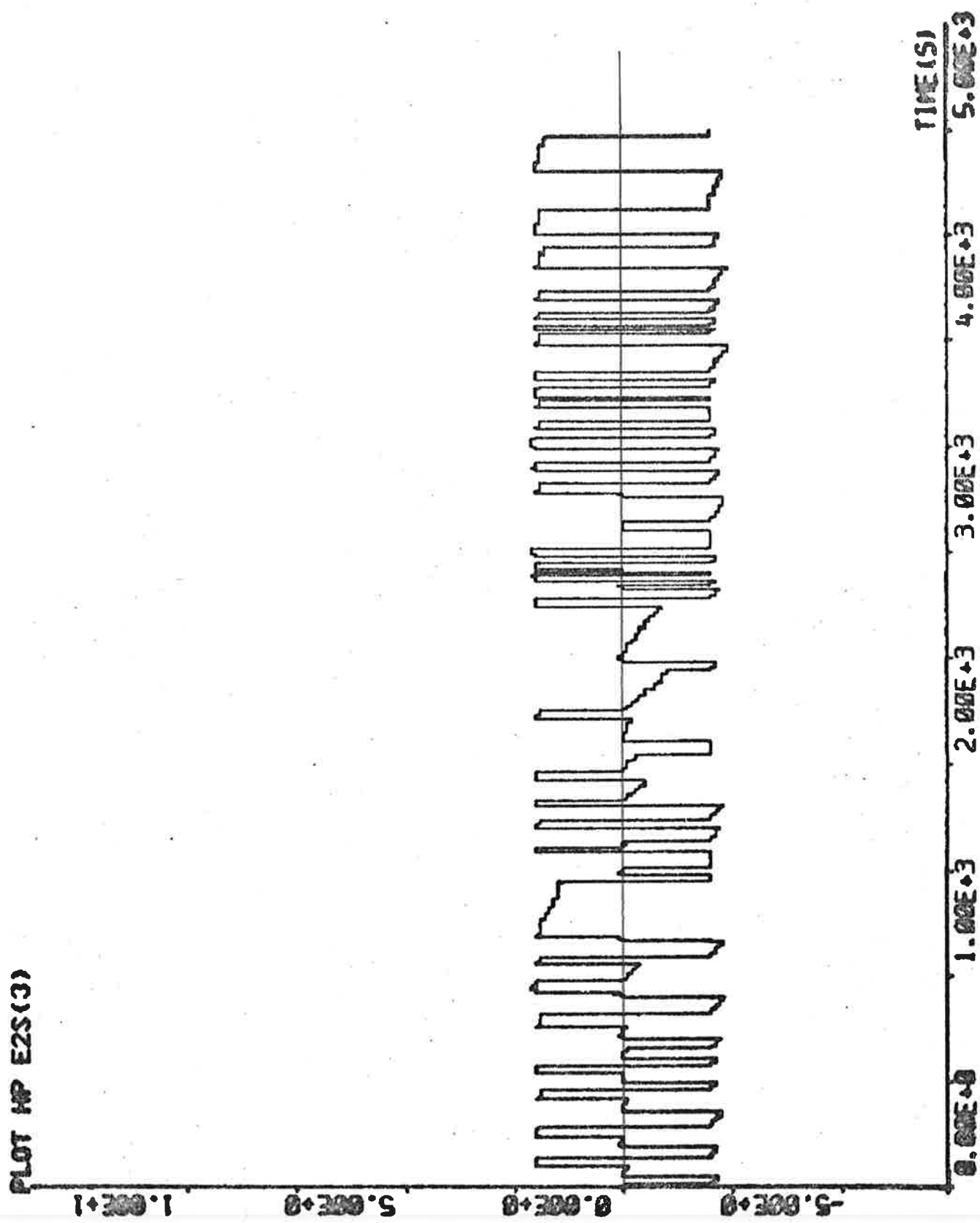
Calibration of the rudder servo:

10 volts = 36.9°
-10 volts = -43.1°

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

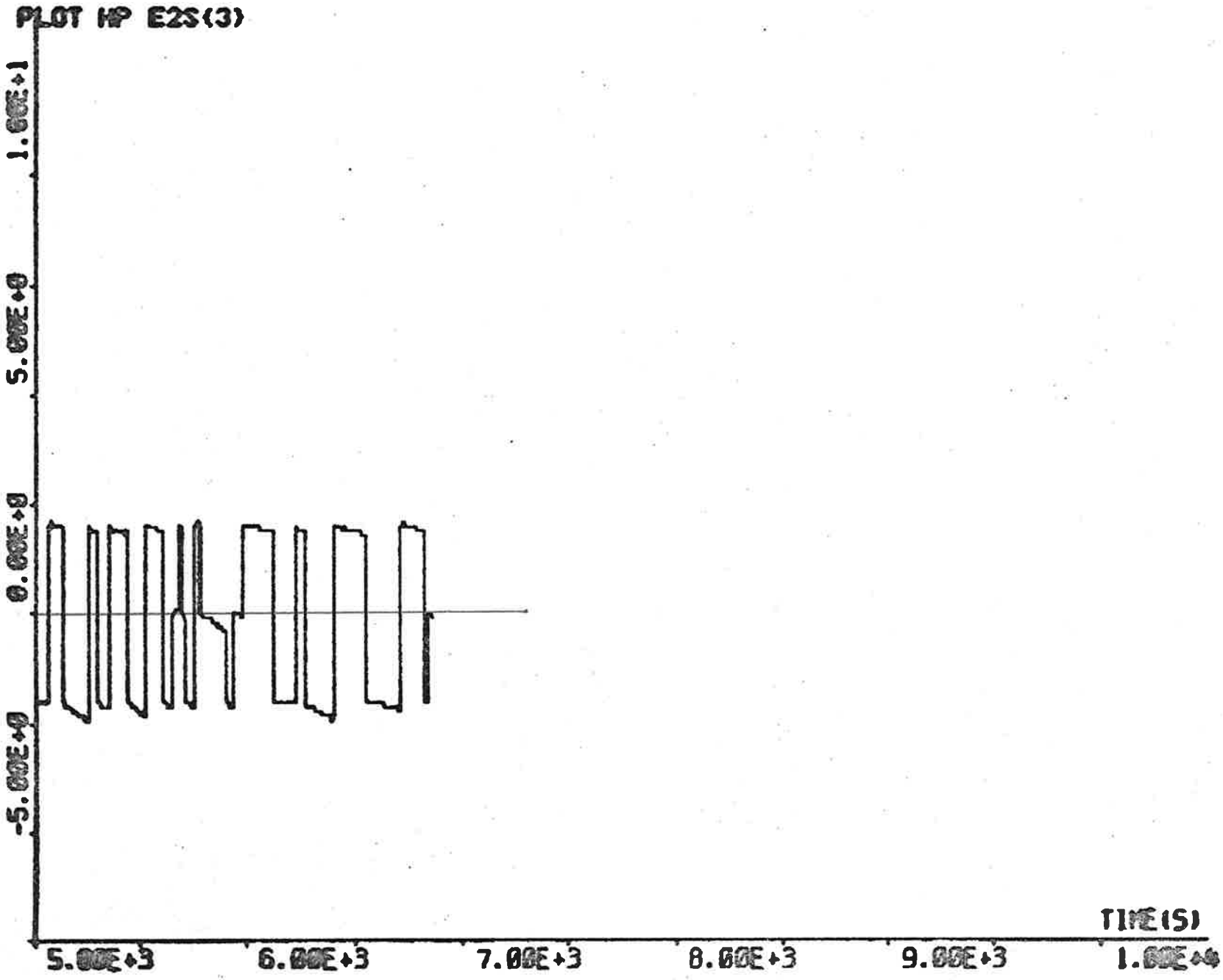
Statistics:

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

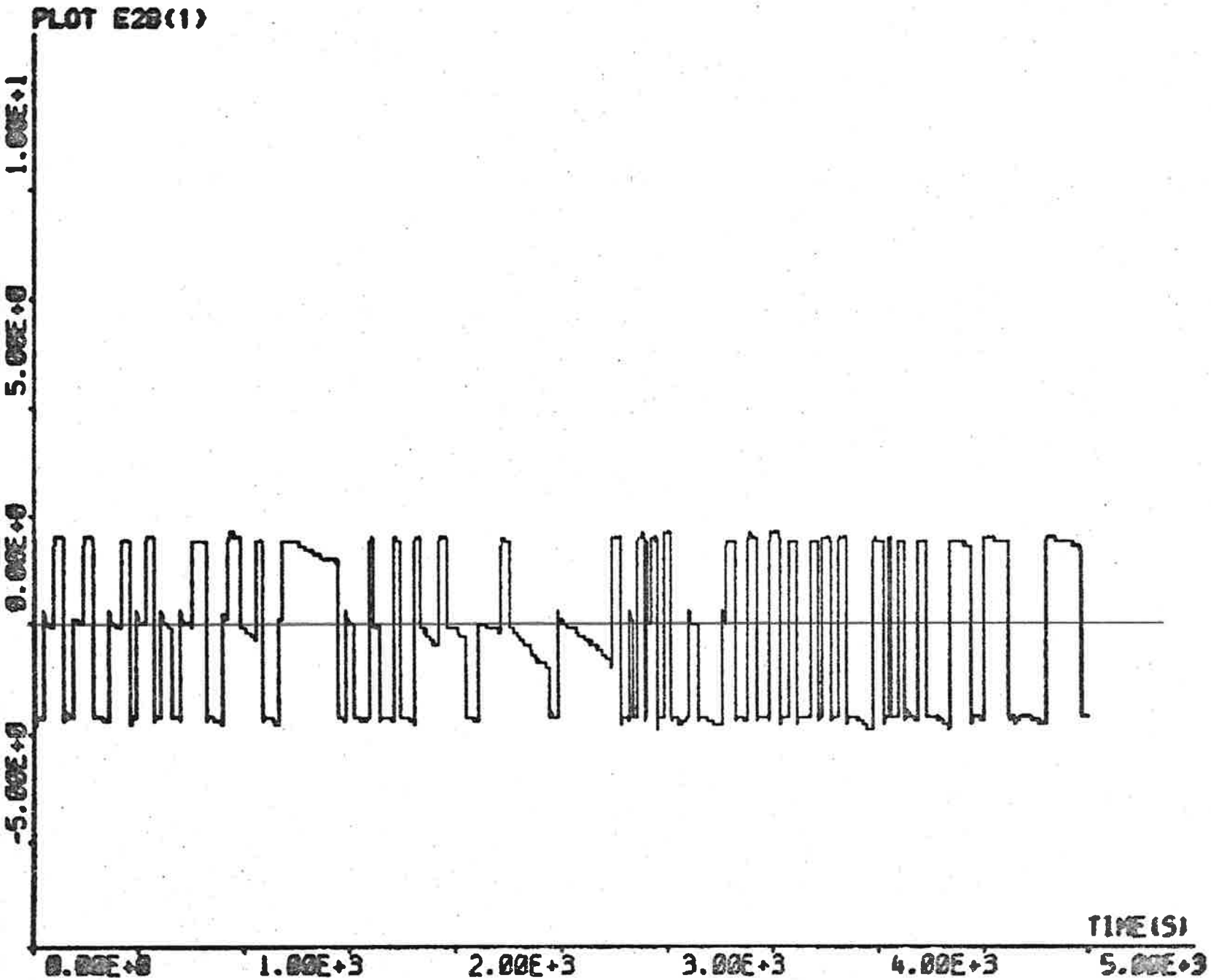


δ_{com} degr

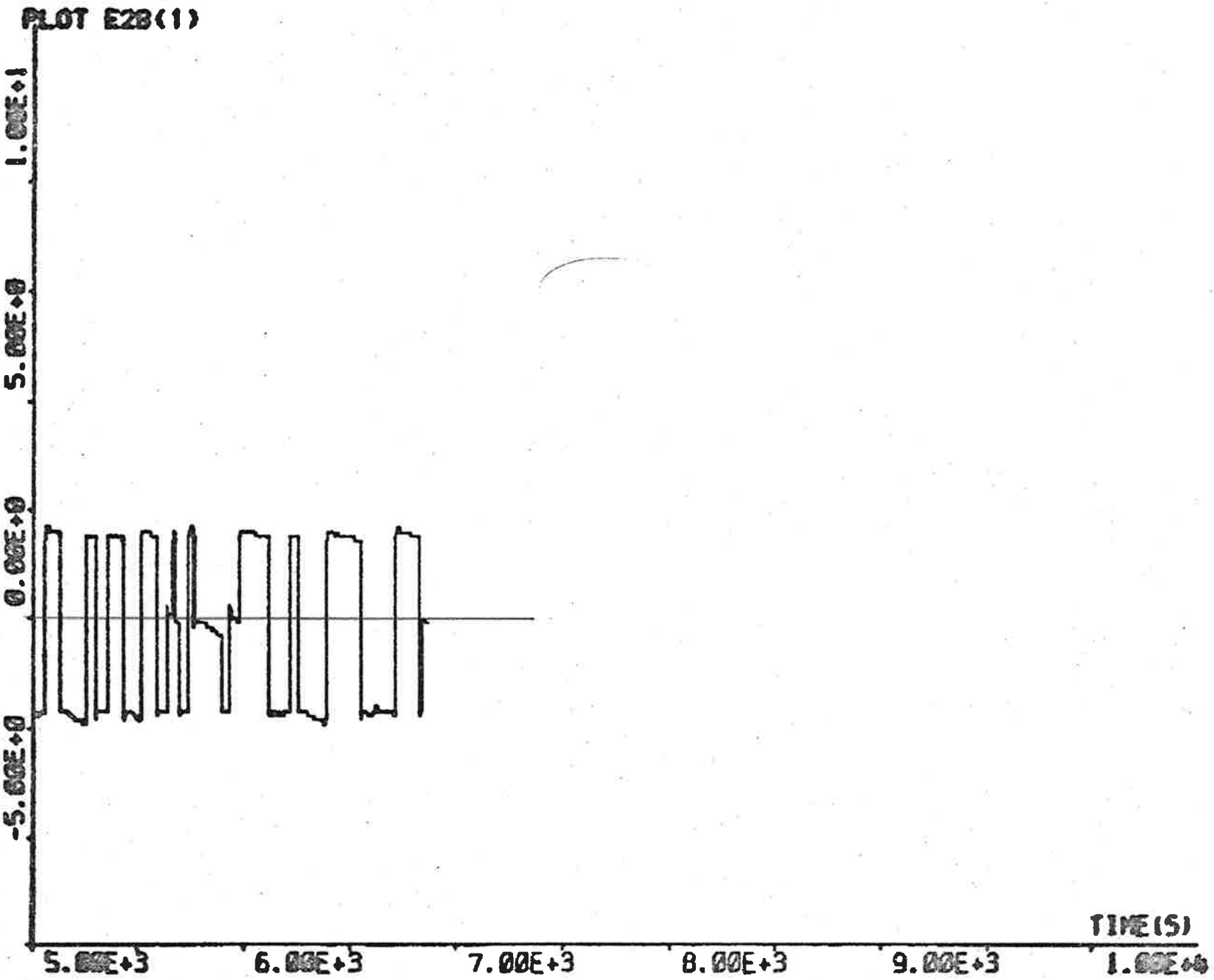
δ_{com} degr

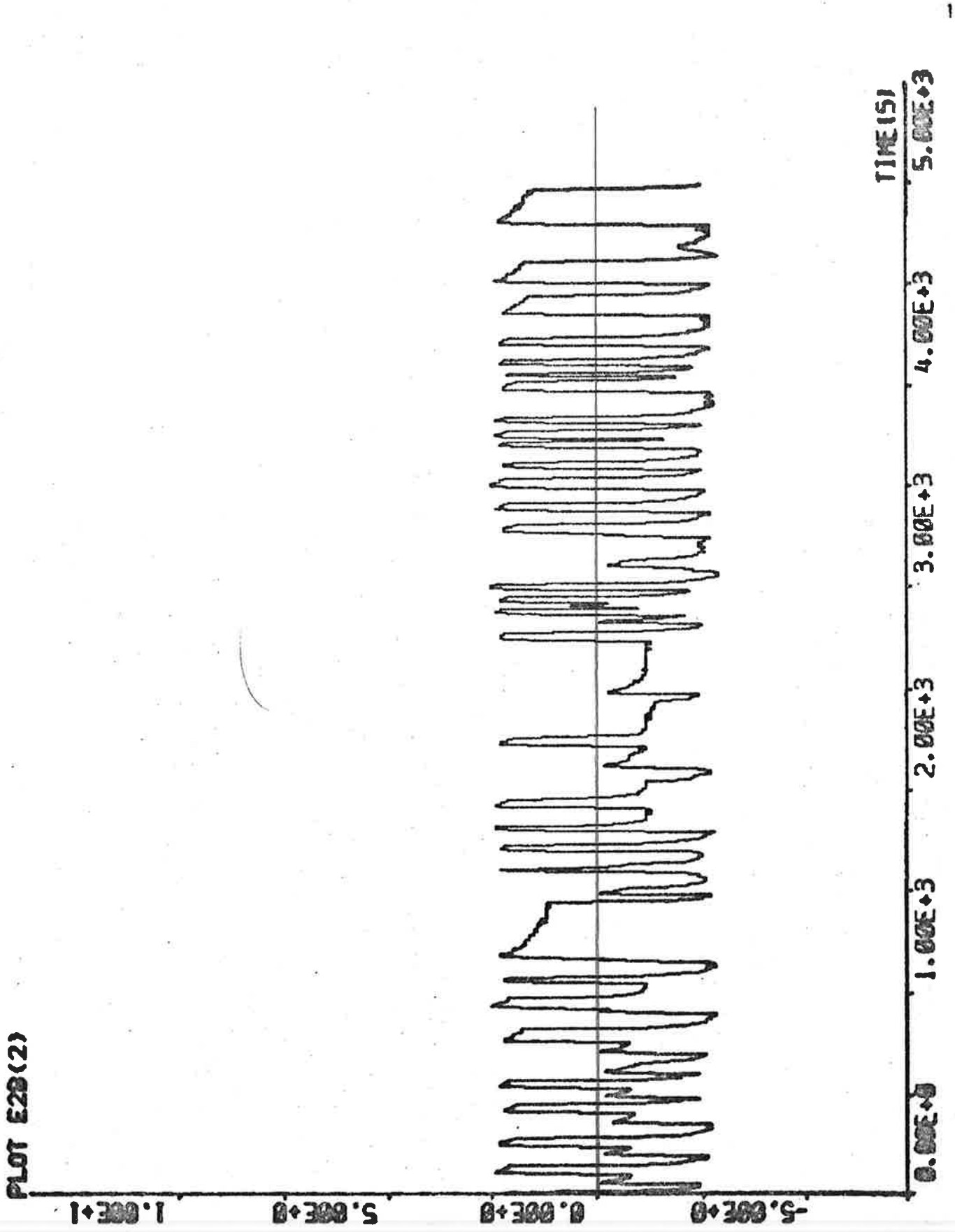


δ_s degr


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

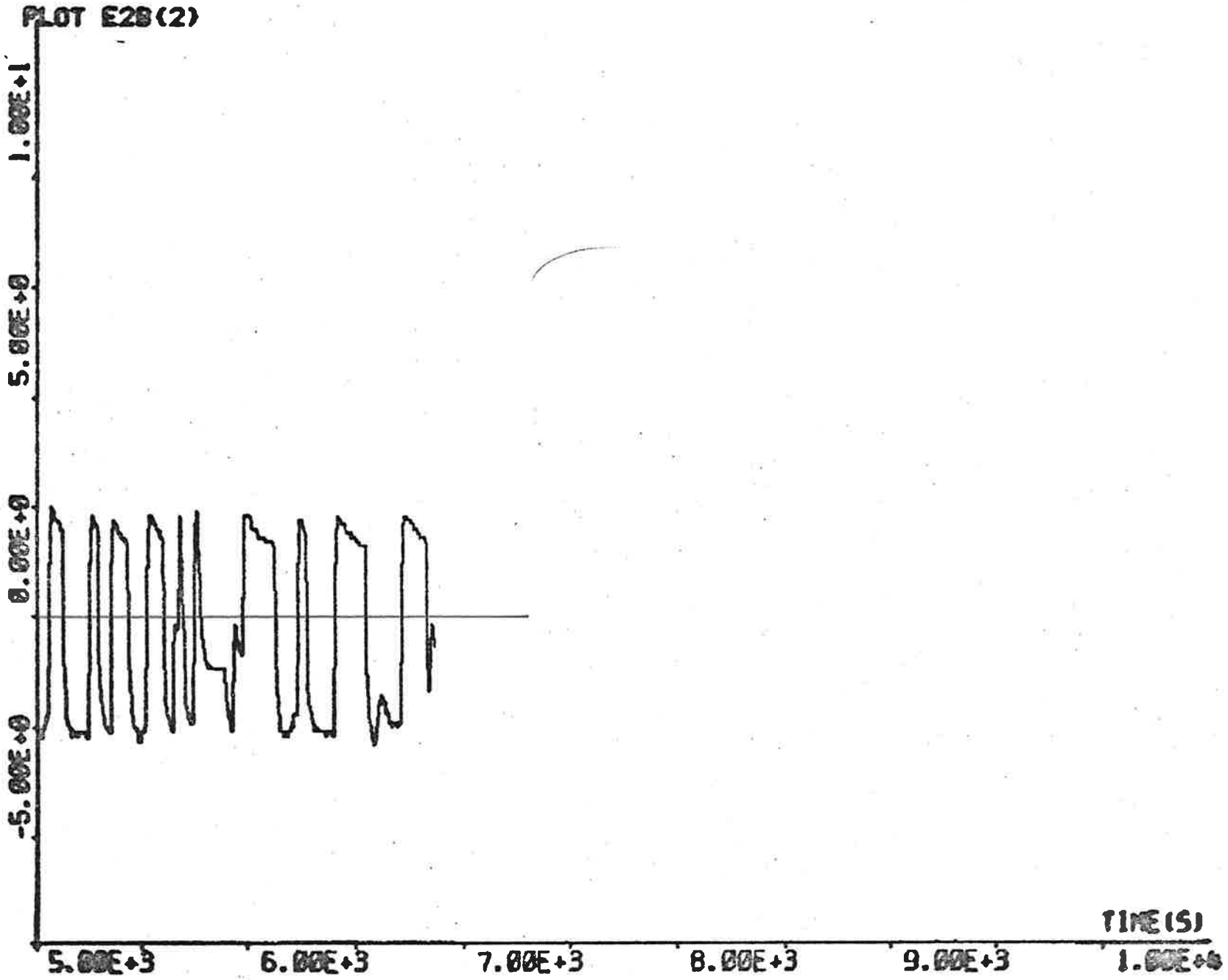
δ_s degr

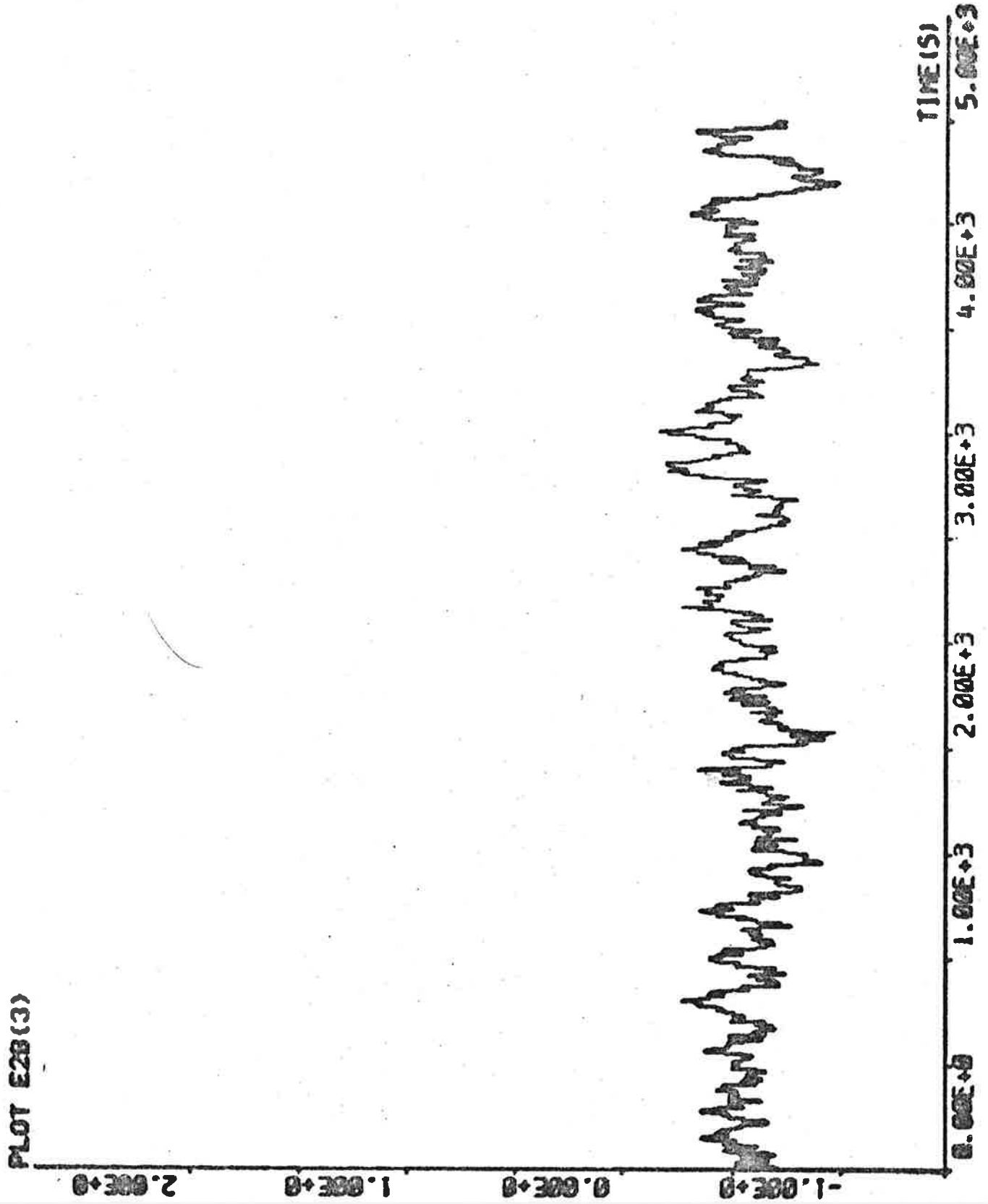

PLOT E2B(1)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4


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

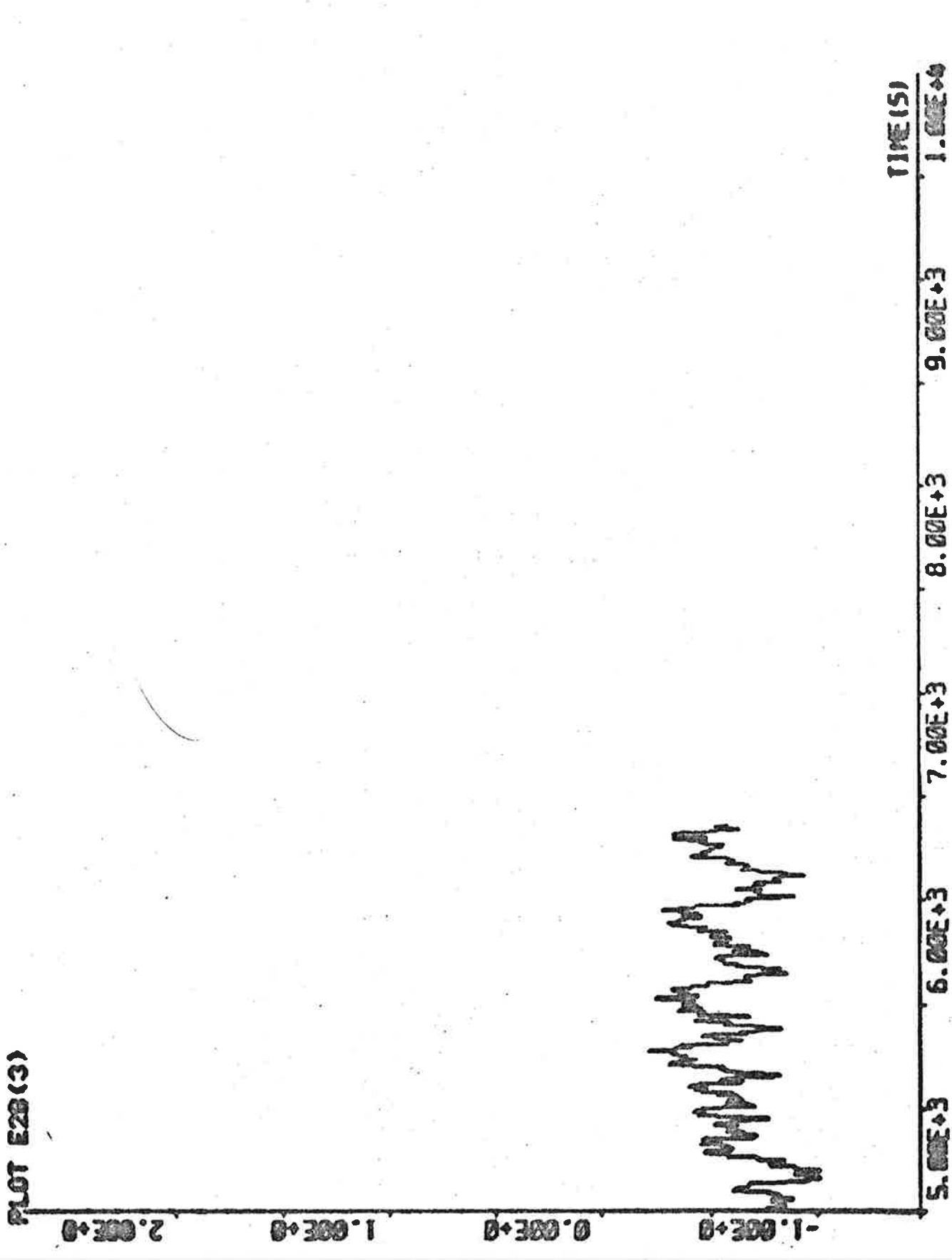
δ degr

δ degr

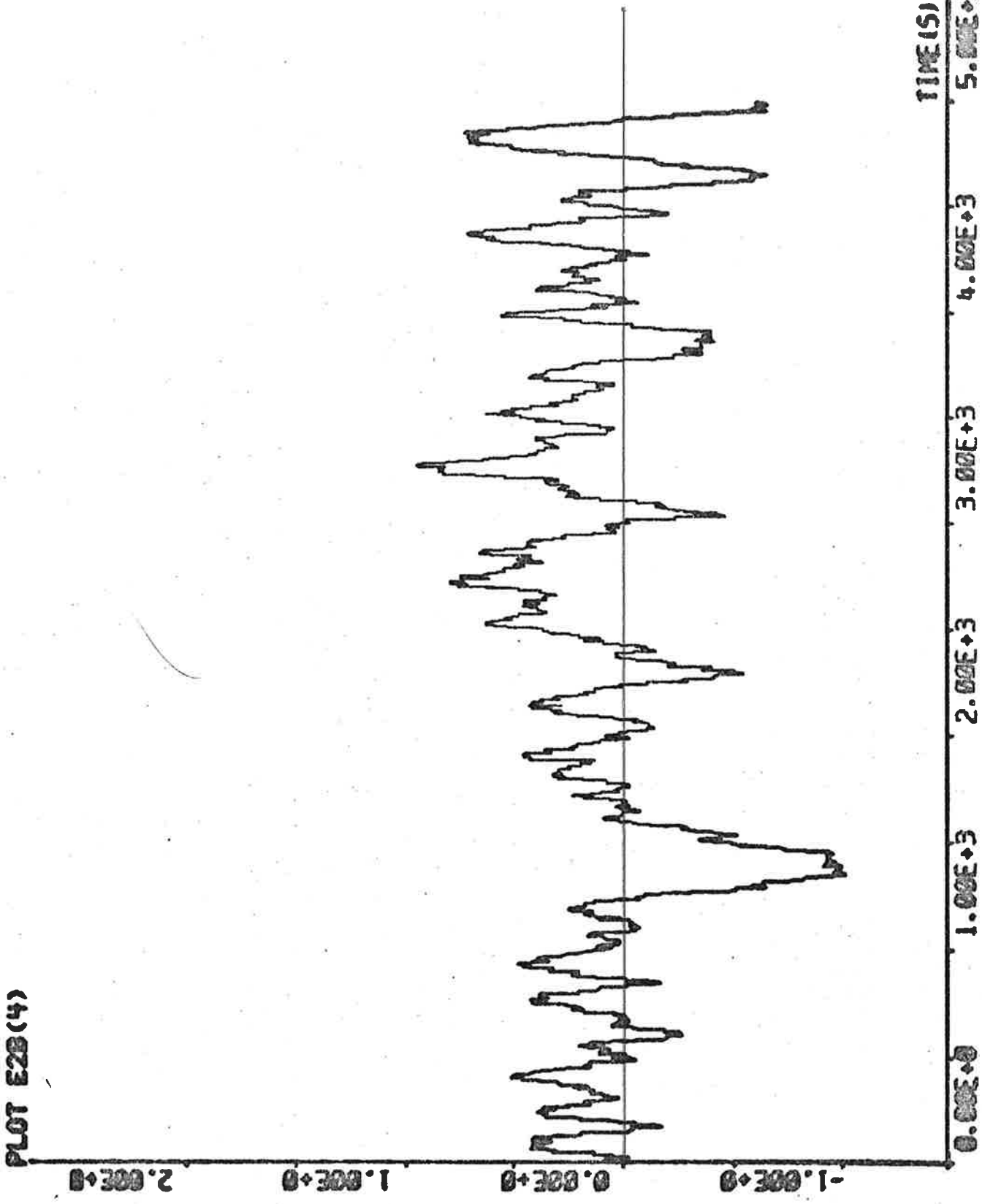

PLOT E28(2)
1.00E+1
5.00E+0
0.00E+0
-5.00E+0
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4


PLOT E2B(3)
2.000+0
1.000+0
0.000+0
-1.000+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

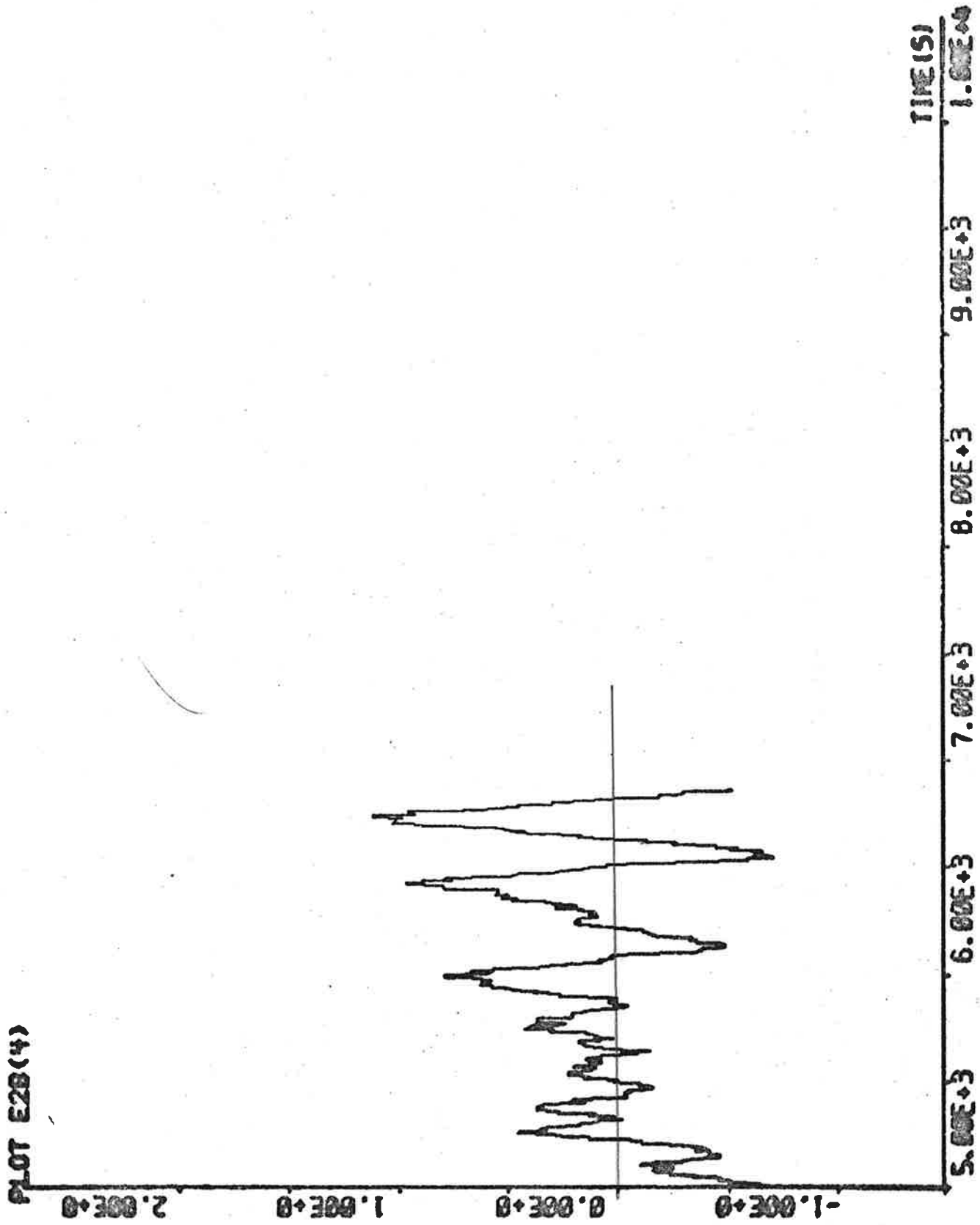
V_1 knots


PLOT E2B(3)
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)

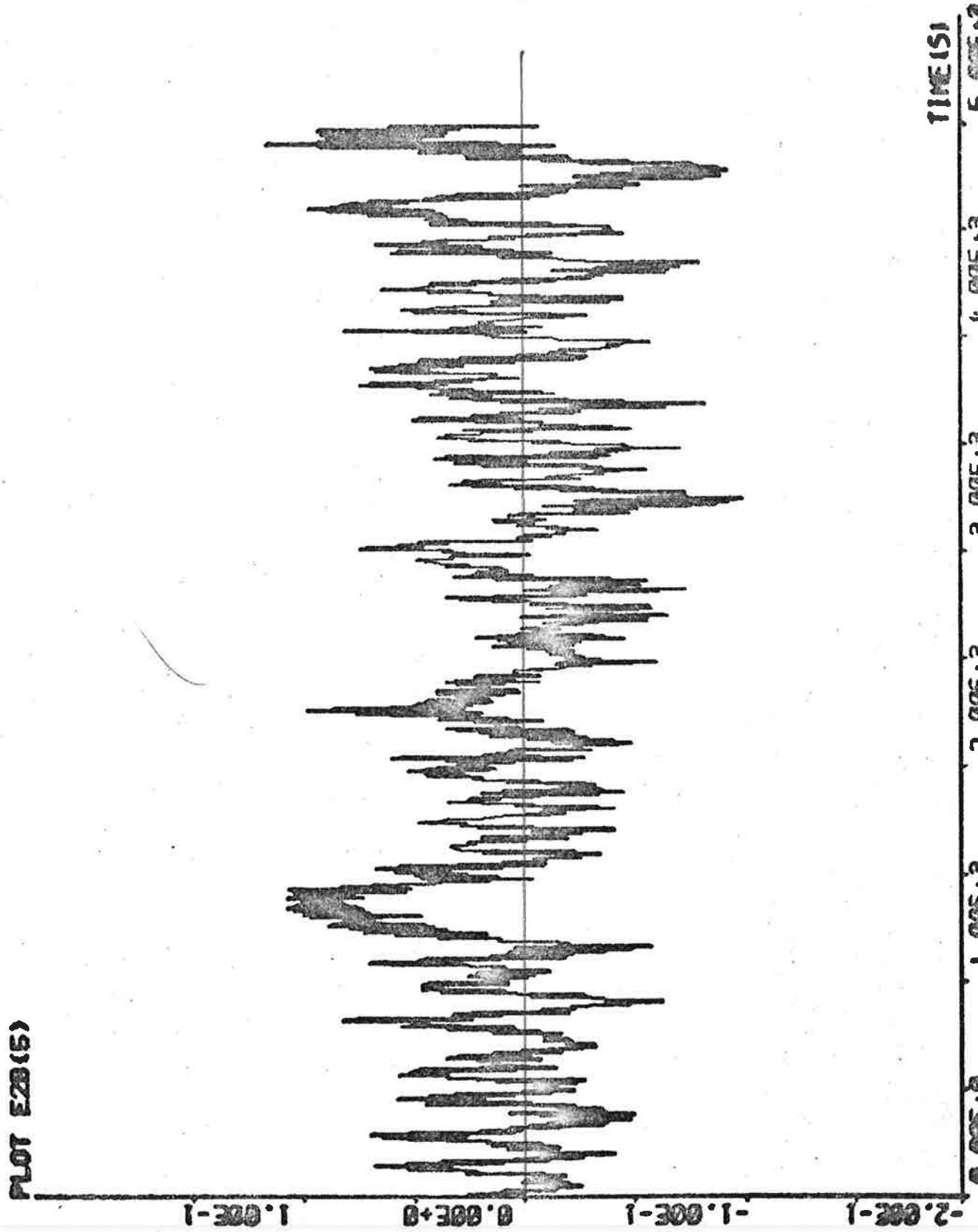
V_1 knots


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)

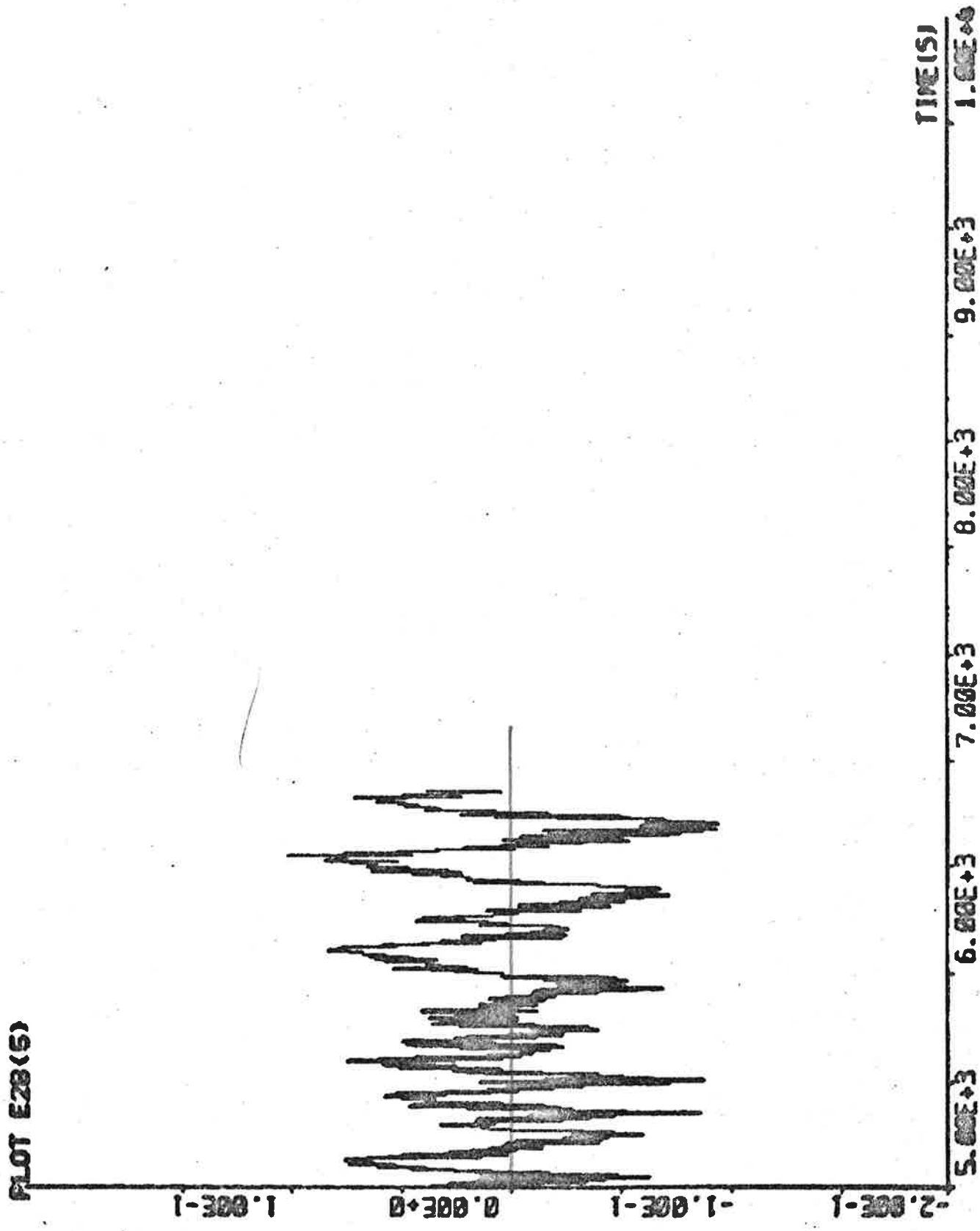
½ knots


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)

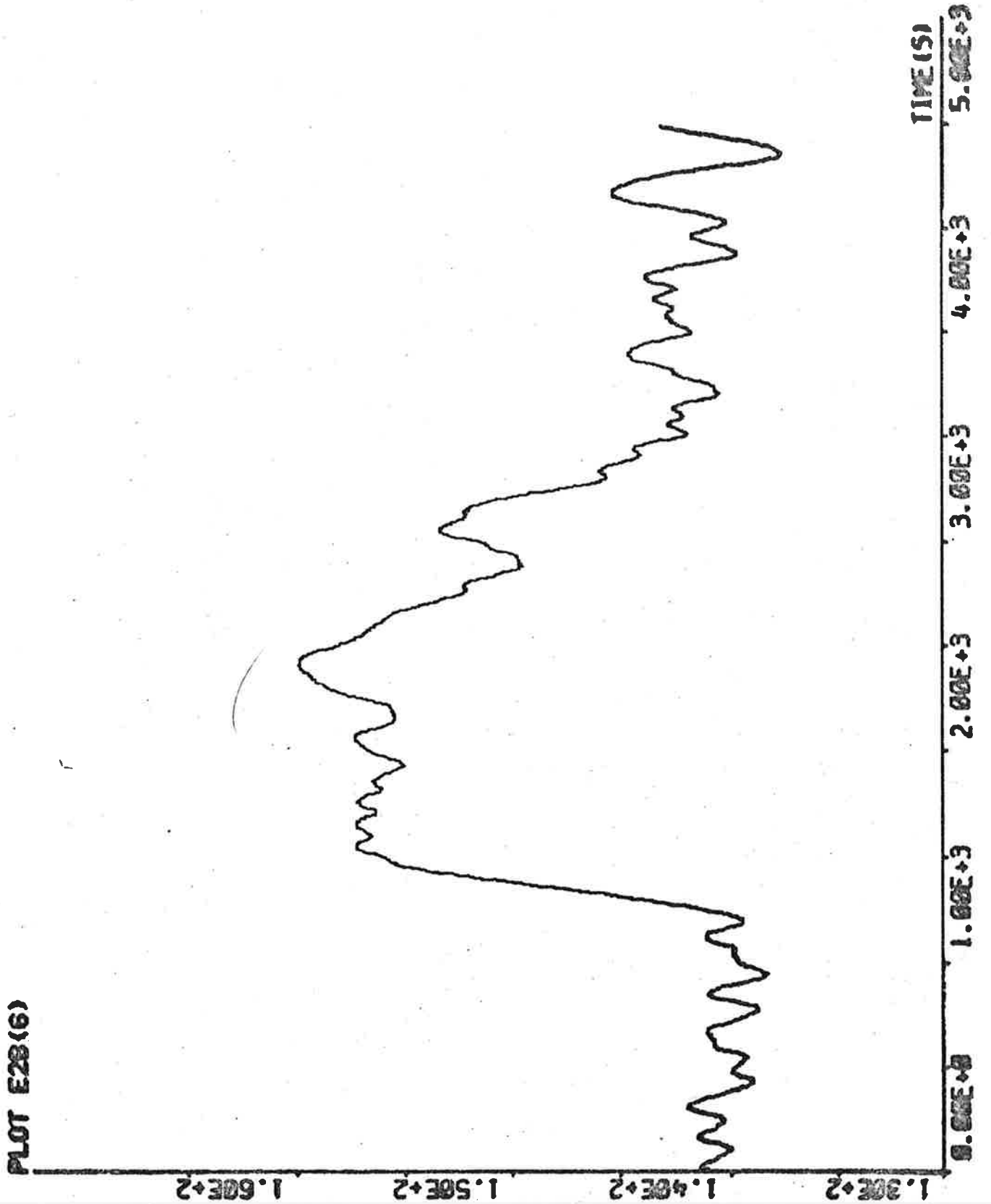
V_2 knots


PLOT E2B(5)
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.300'1
0.300+0
-1.300'1
-2.300'1

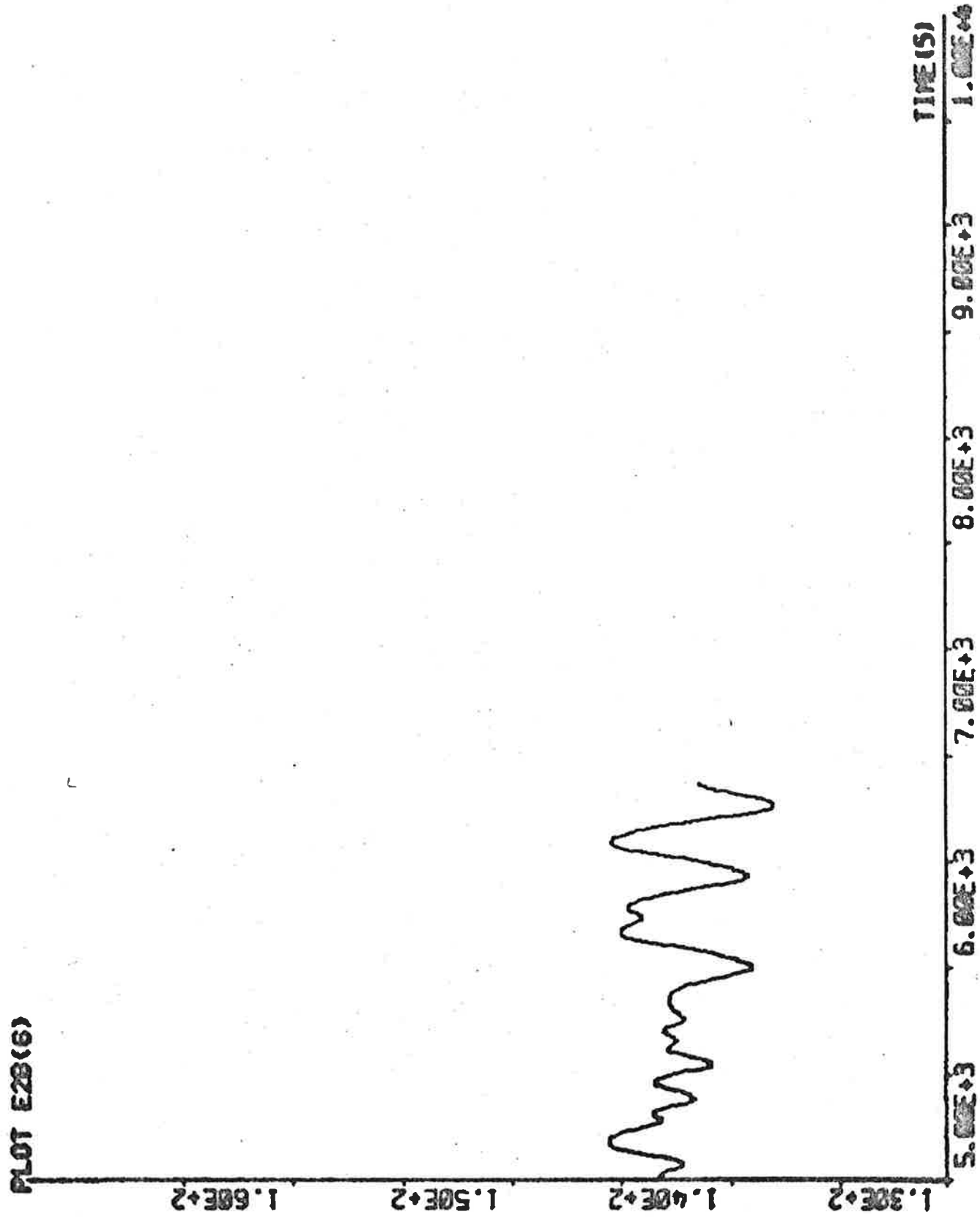
r degr/s


PLOT E28(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

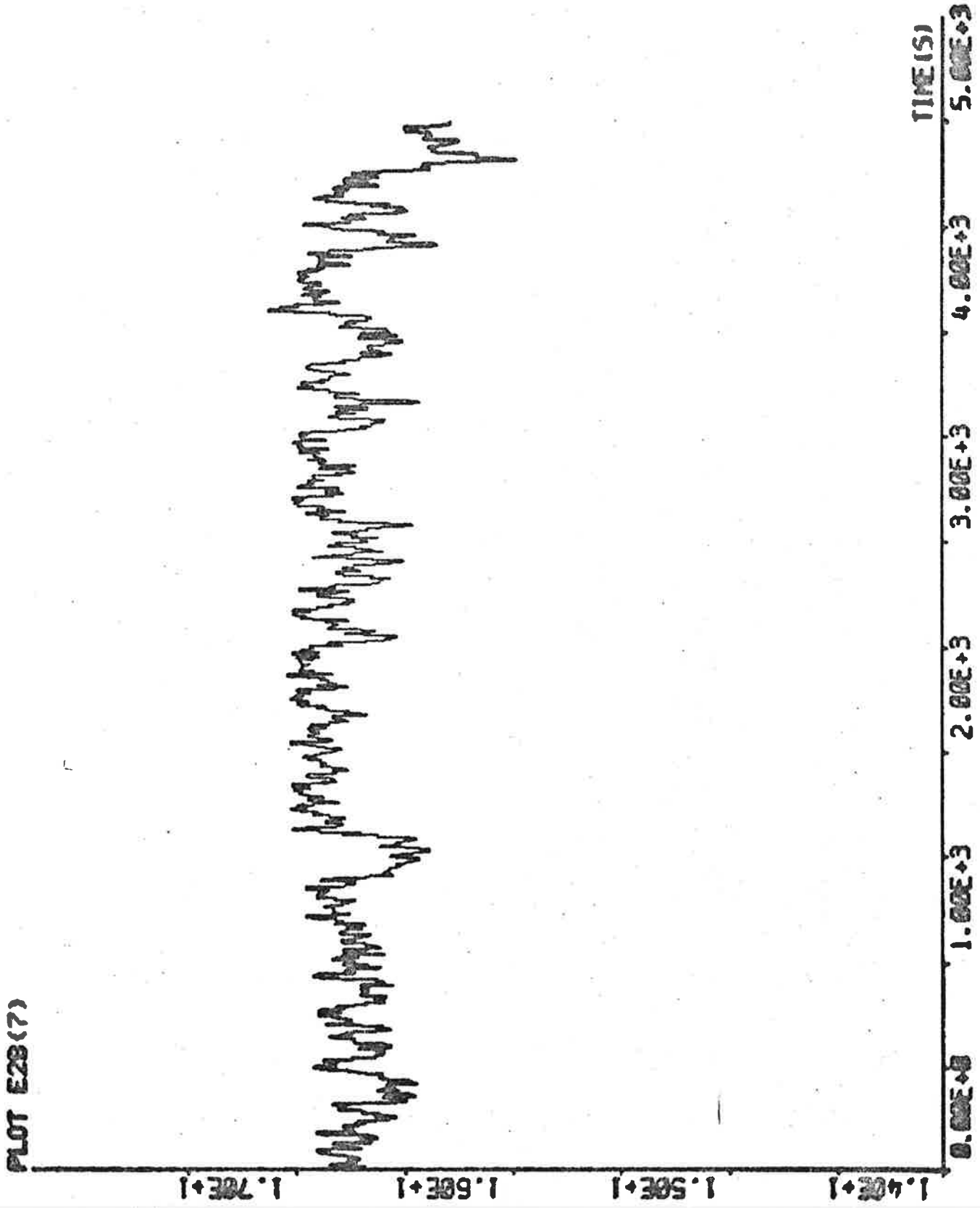
r degr/s


PLOT E23(6)
1.300E+2
1.400E+2
1.500E+2
1.600E+2
0.000E+0
1.000E+3
2.000E+3
3.000E+3
4.000E+3
5.000E+3
TIME(S)

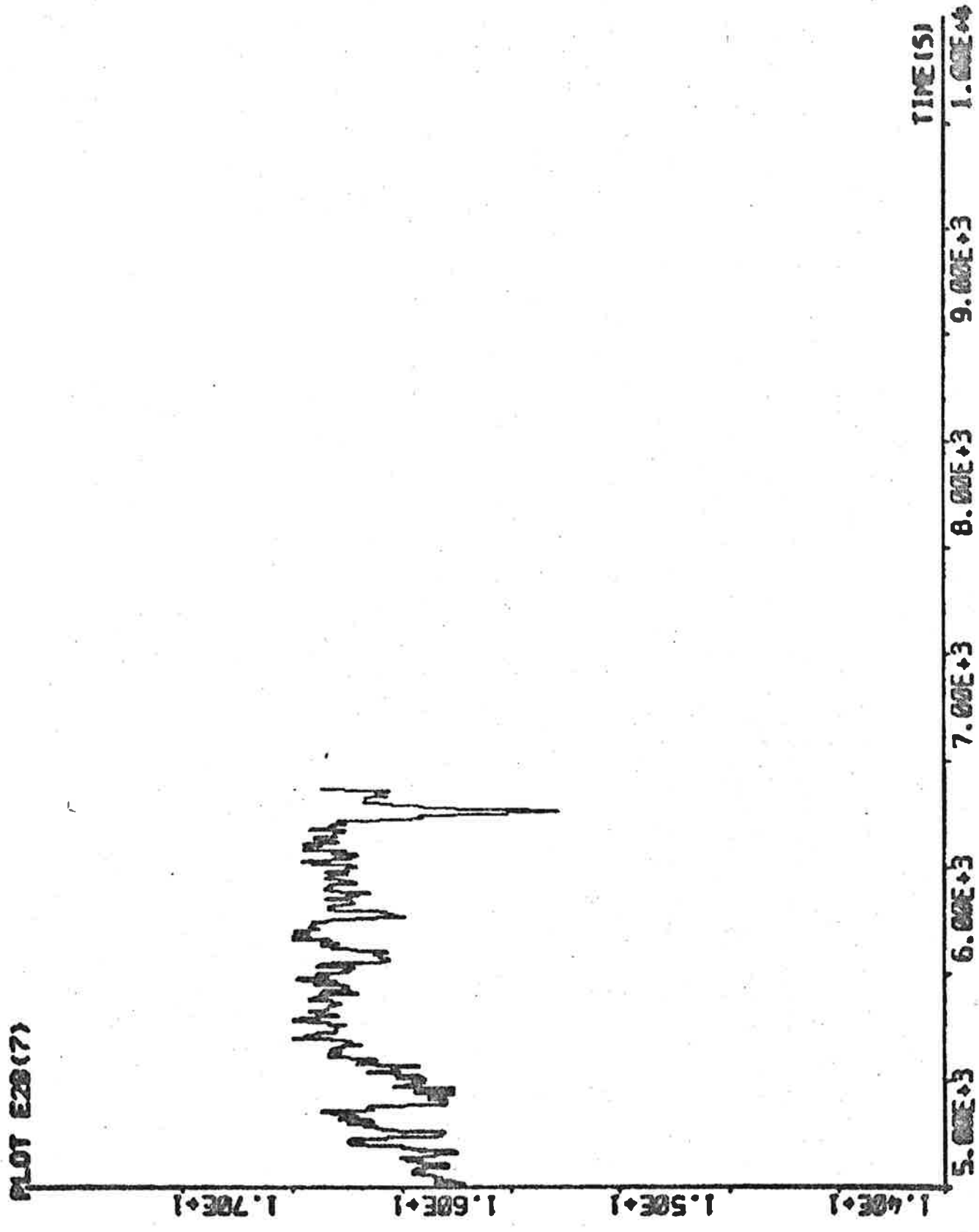
ψ degr


PLOT E2B(6)
1.300E+2
1.400E+2
1.500E+2
1.600E+2
5.000E+3
6.000E+3
7.000E+3
8.000E+3
9.000E+3
1.000E+4
TIME(S)

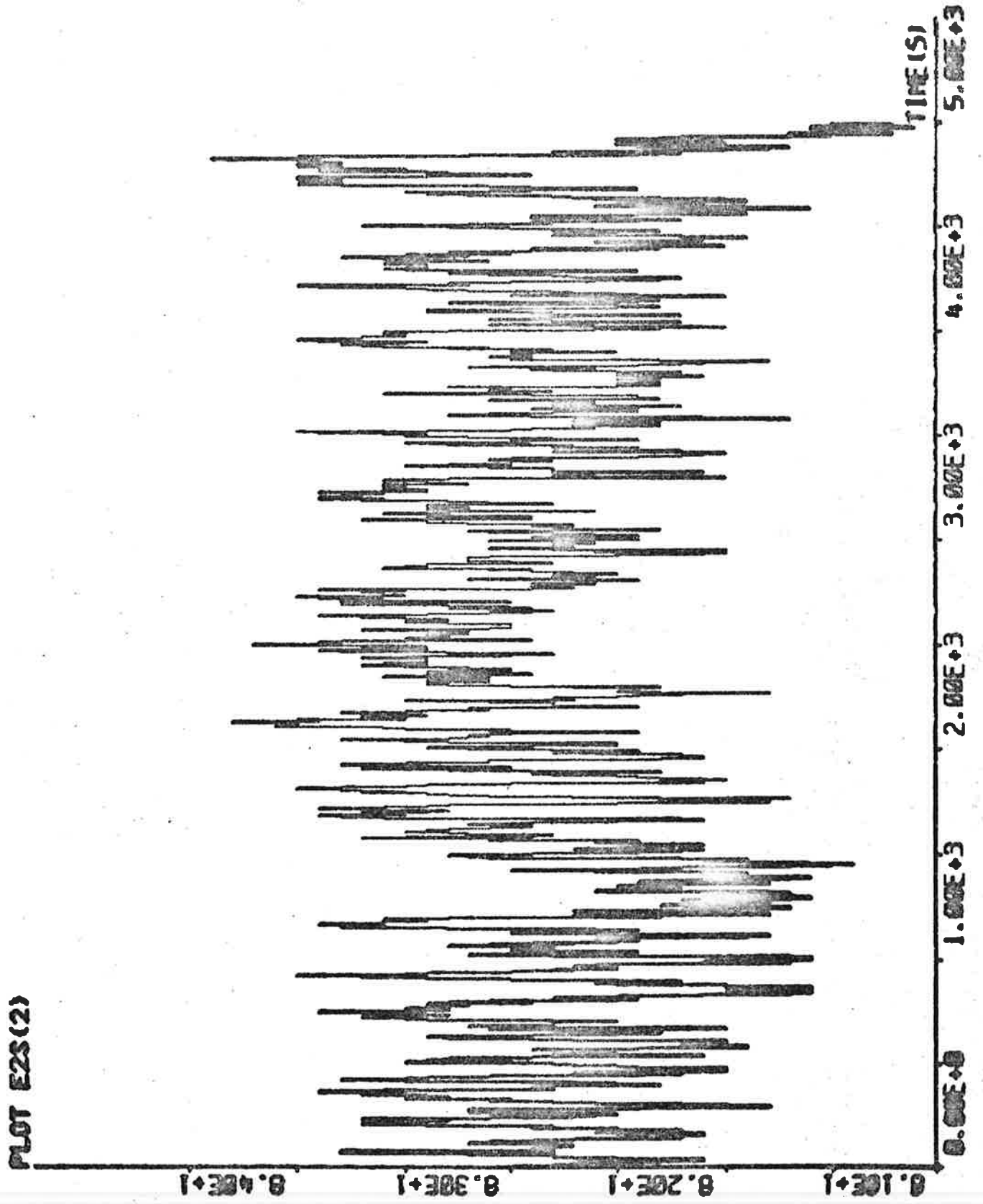
ψ degr


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

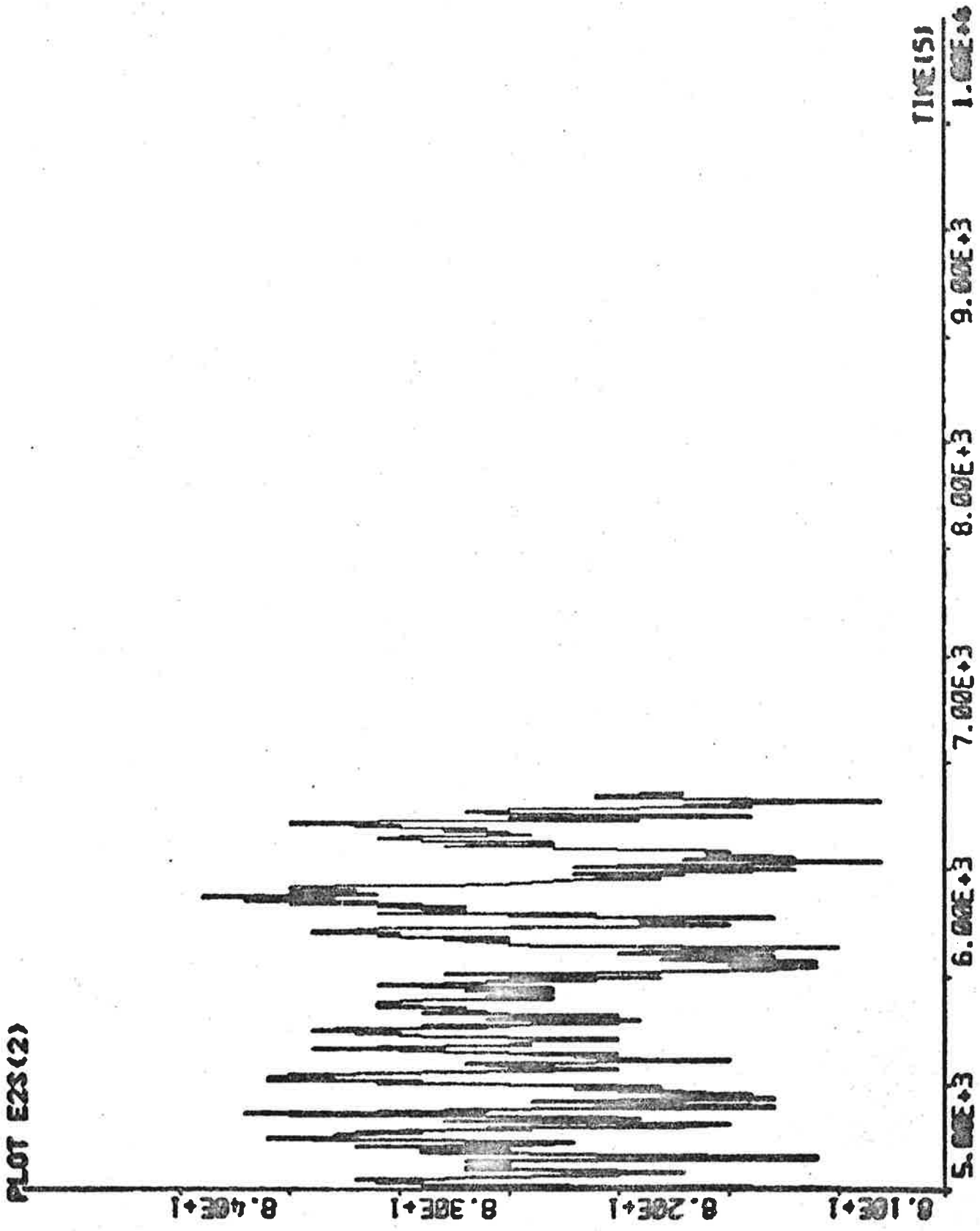
u knots


PLOT E2B(7)
1.4E+1
1.5E+1
1.6E+1
1.7E+1
5.0E+3
6.0E+3
7.0E+3
8.0E+3
9.0E+3
1.0E+4
TIME(S)

v knots


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

n rpm


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

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.

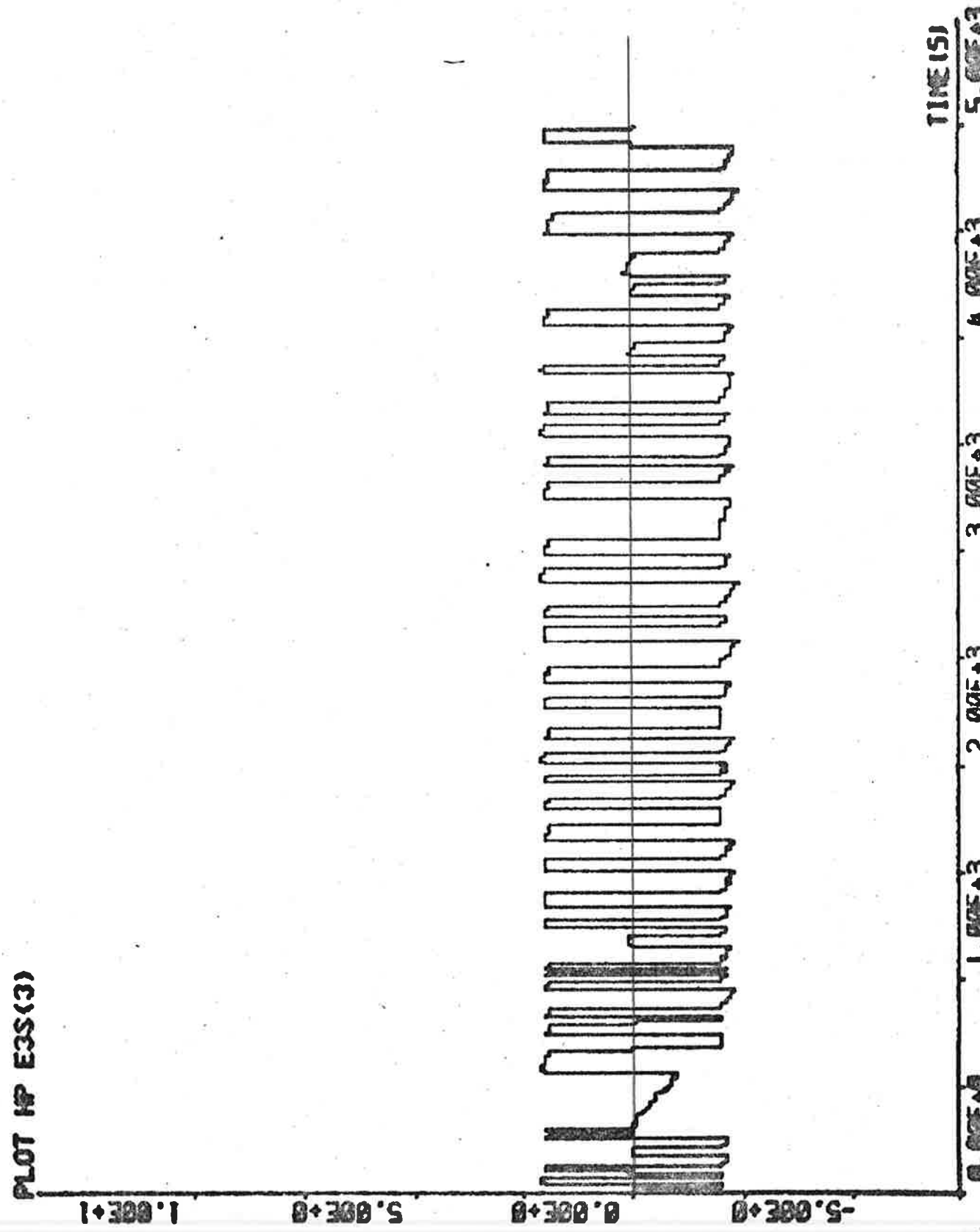
Calibration of the rudder servo:

10 volts = 36.9°
-10 volts = -43.1°

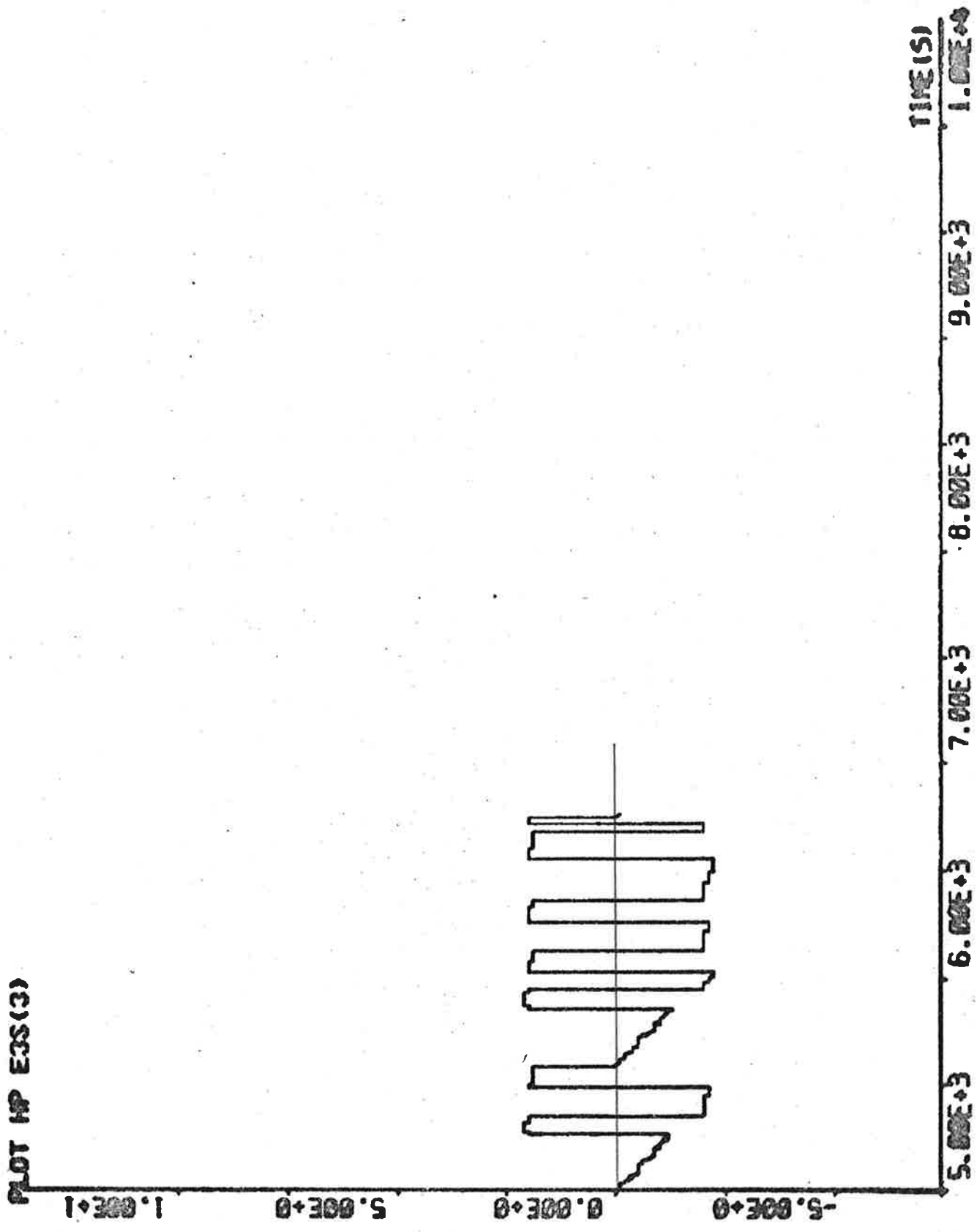
Sampling interval: 5 s
Rudder angles: $+2^{\circ}$, 0°, -2°

Statistics:

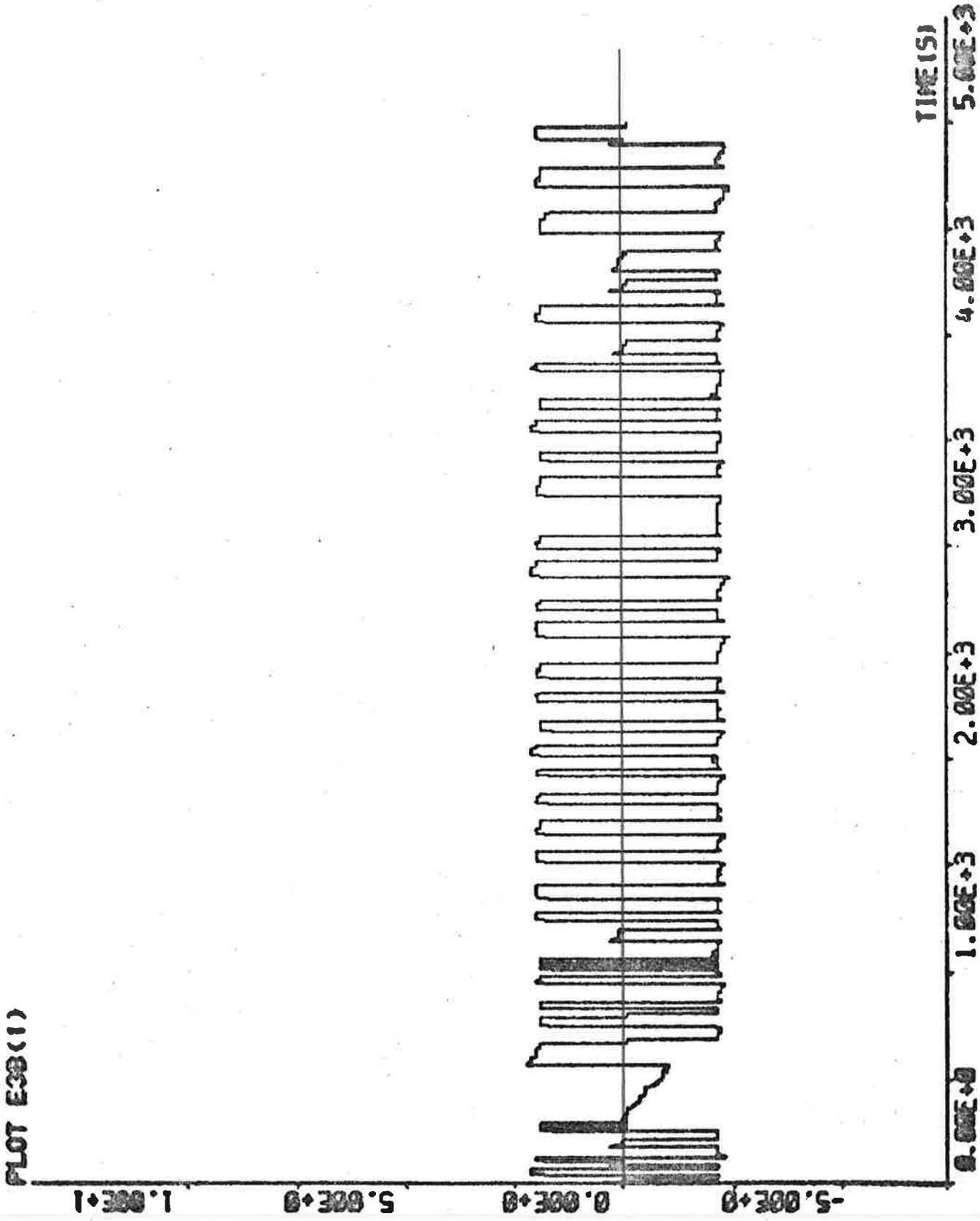
	Mean value	Standard deviation	Minimum value	Maximum value
δ_{com} degr	-0.38	1.82	-2.4	2.1
δ_s degr	-0.40	1.84	-2.4	2.2
δ degr	-0.58	1.91	-2.8	2.6
v_1 knots	-0.677	0.156	-1.05	-0.25
v_2 knots	0.015	0.300	-0.99	0.77
r degr/s	0.0063	0.0372	-0.084	0.112
Ψ degr	142.136	1.838	137.20	147.57
u knots	16.816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



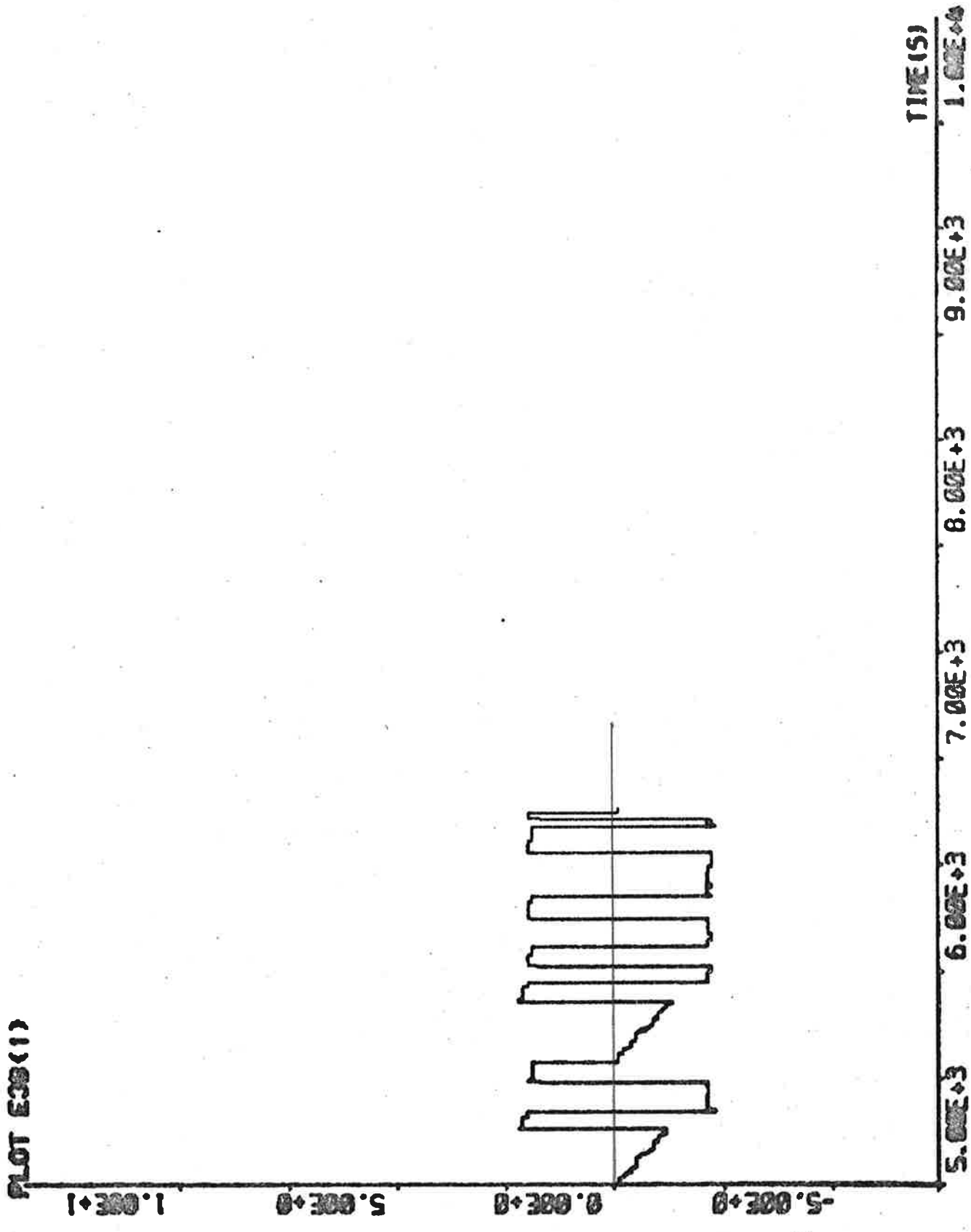
δ_{com} degr


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

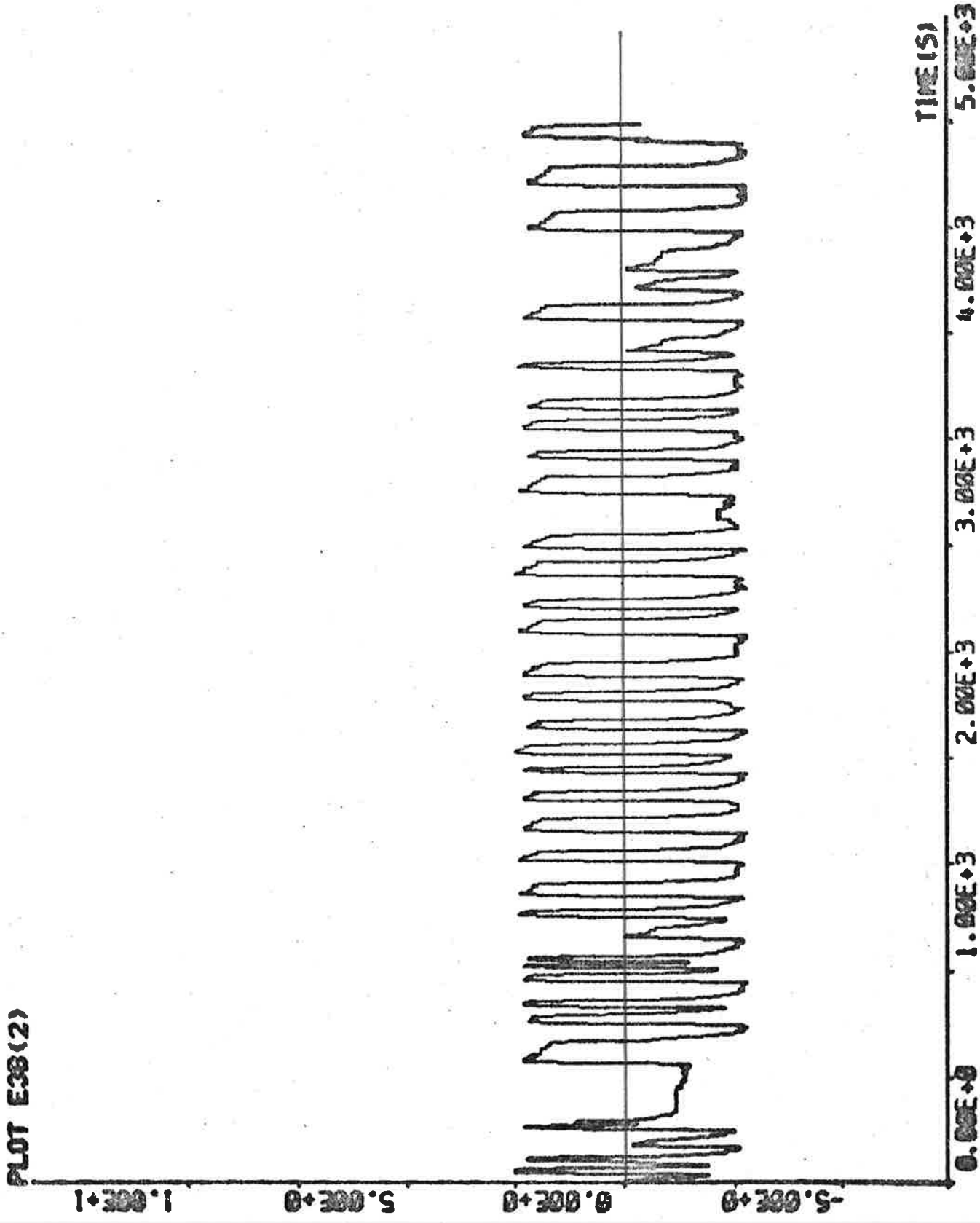
f_{com} degr


PLOT E3B(1)
1.000E+1
5.000E+0
0.000E+0
-5.000E+0
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
TIME(S)

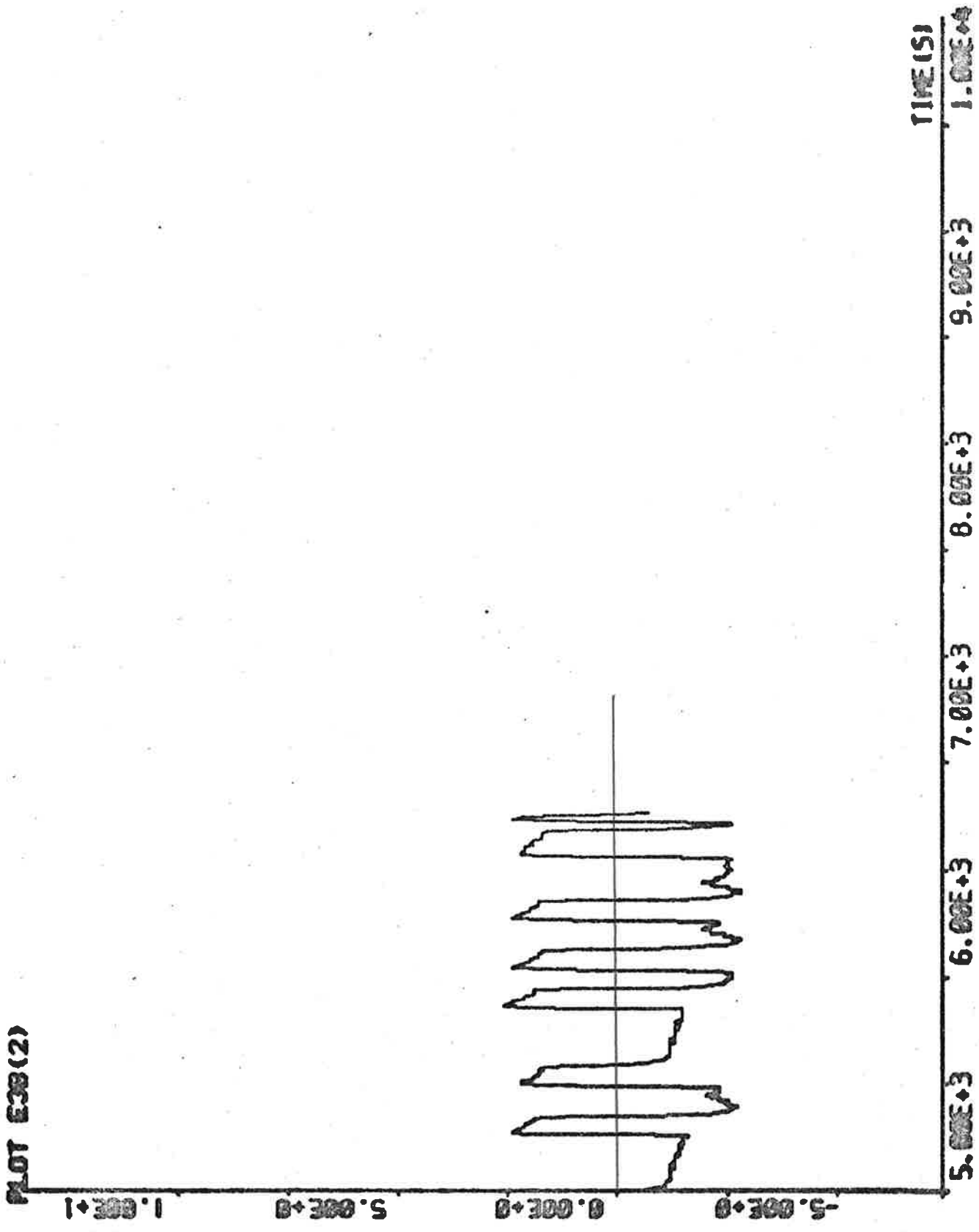
δ_s degr


PLOT E38(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)

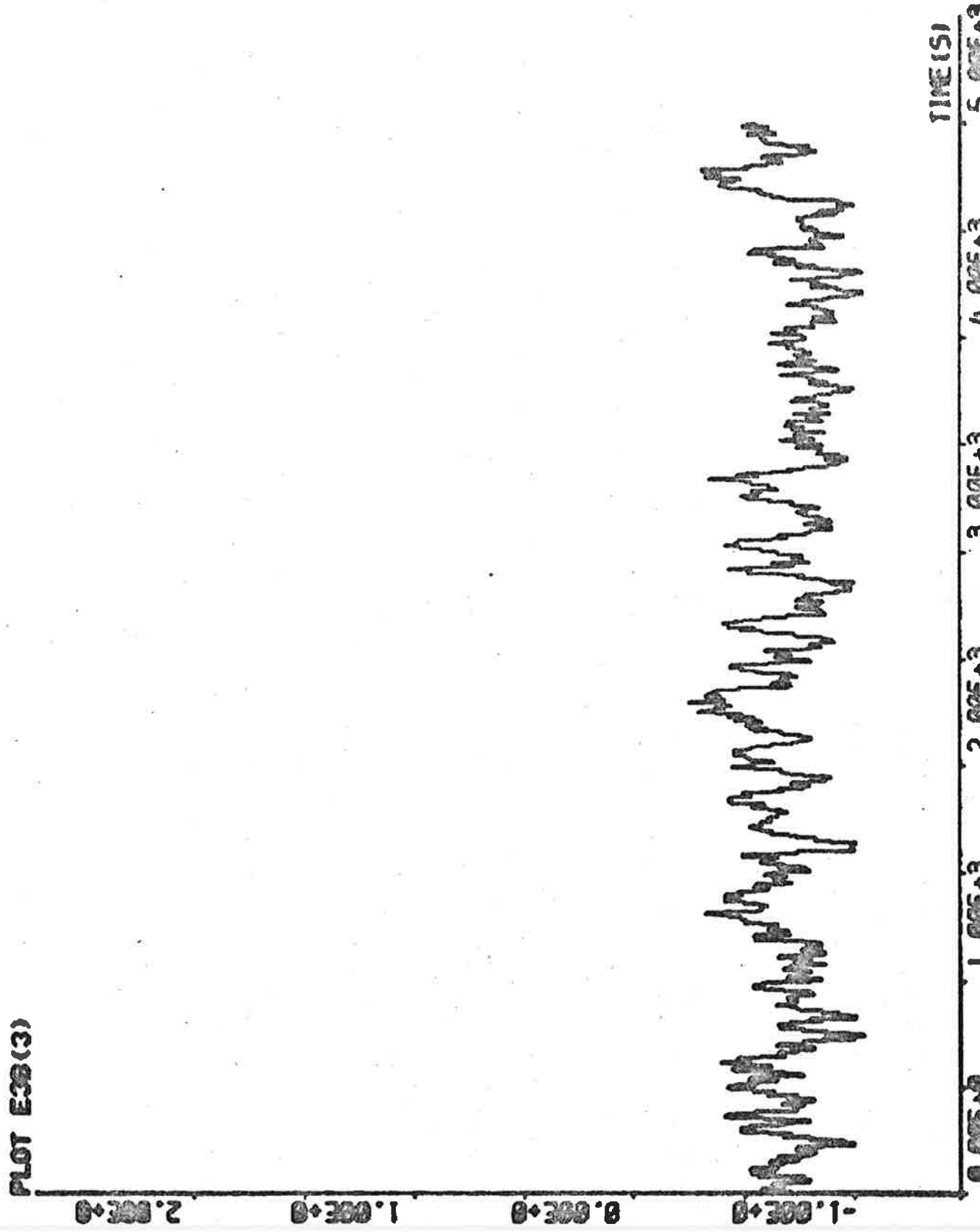
δ_s degr


PLOT E38(2)
1.000E+1
5.000E+0
0.000E+0
-5.000E+0
0.000E+0
1.000E+3
2.000E+3
3.000E+3
4.000E+3
5.000E+3
TIME(S)

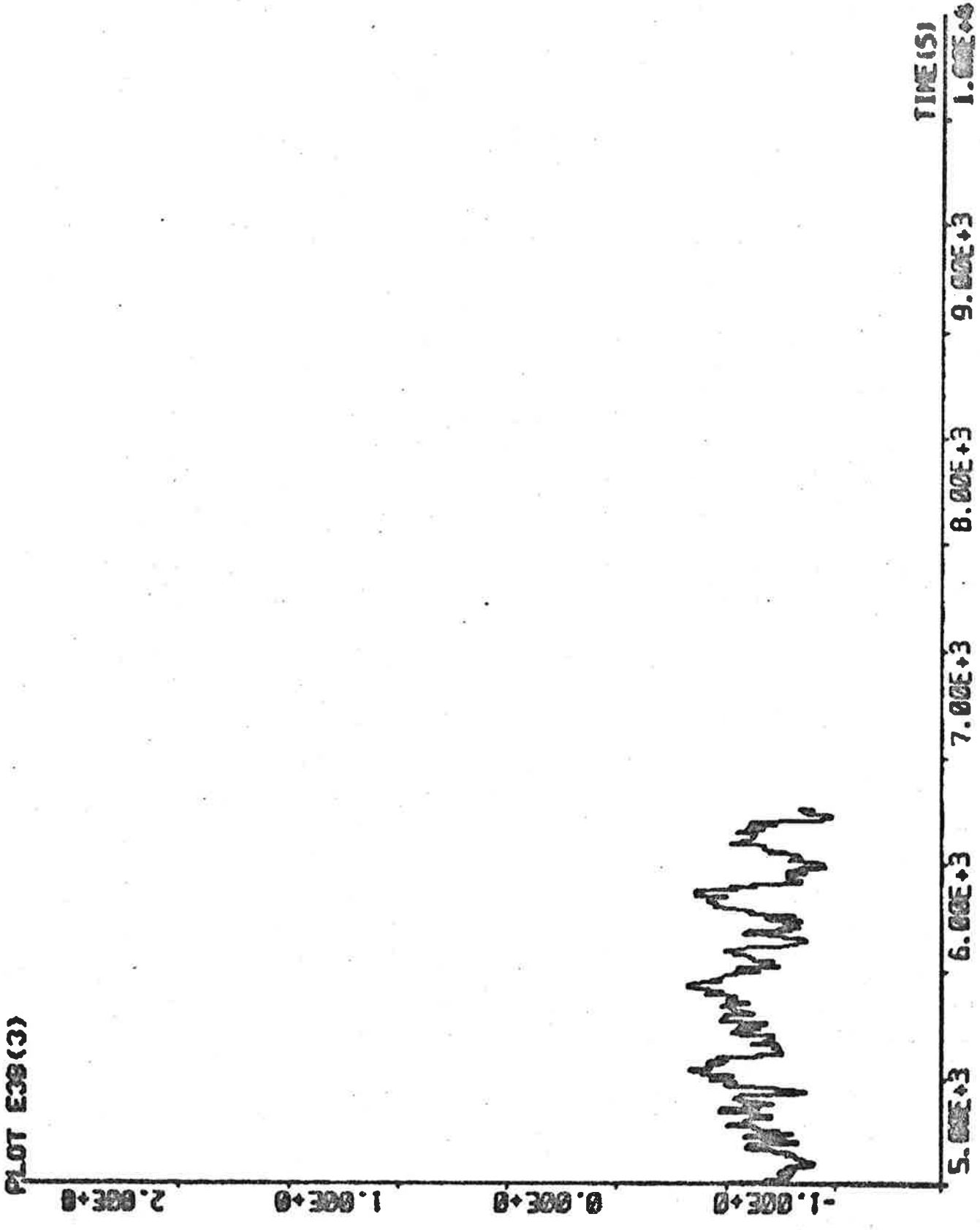
δ degr


PLOT E33(2)
-5.00E+0
0.00E+0
5.00E+0
1.00E+1
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

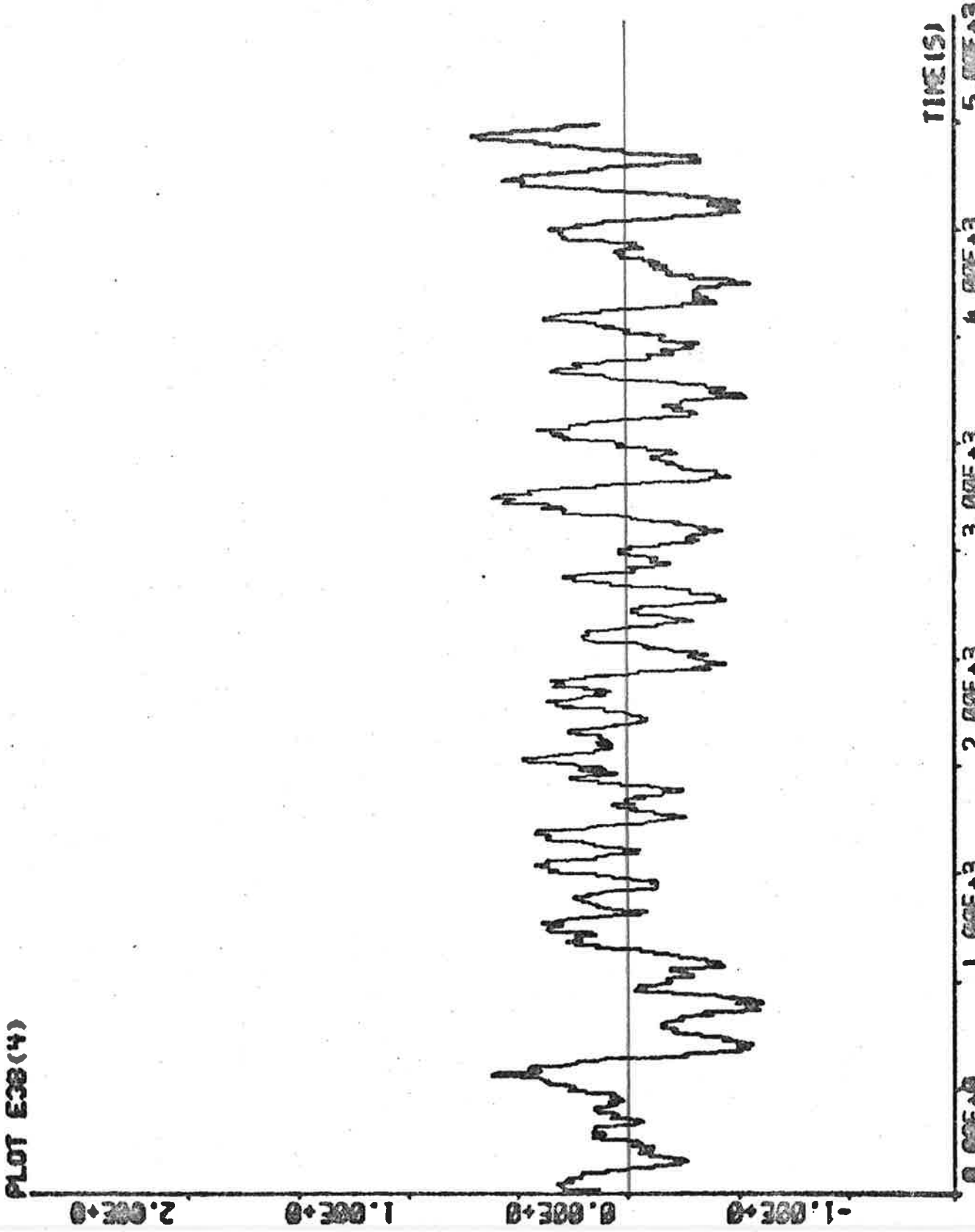
f: degr


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

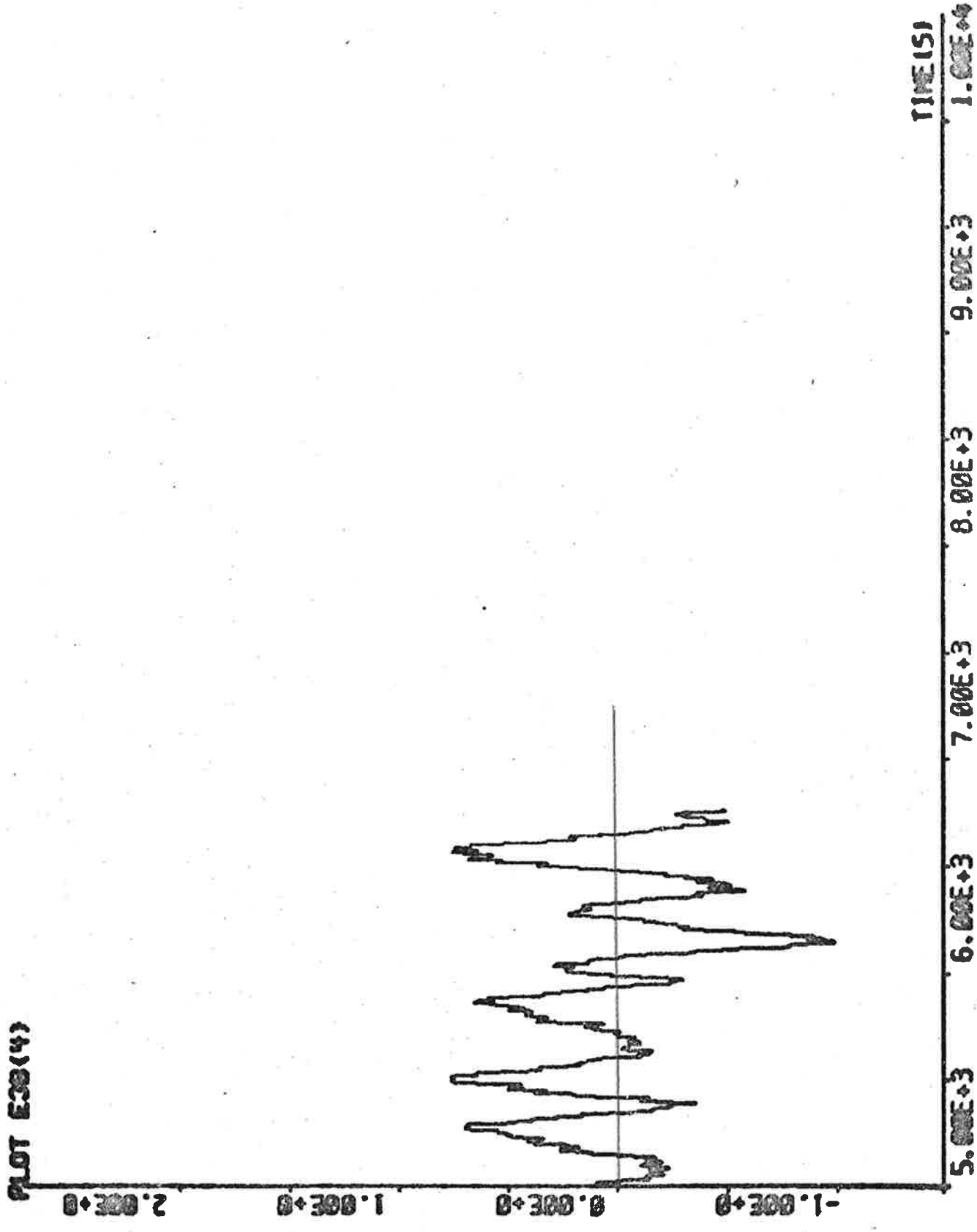
v_1 knots


PLOT E39(3)
2.00E+0
1.00E+0
0.00E+0
-1.00E+0
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

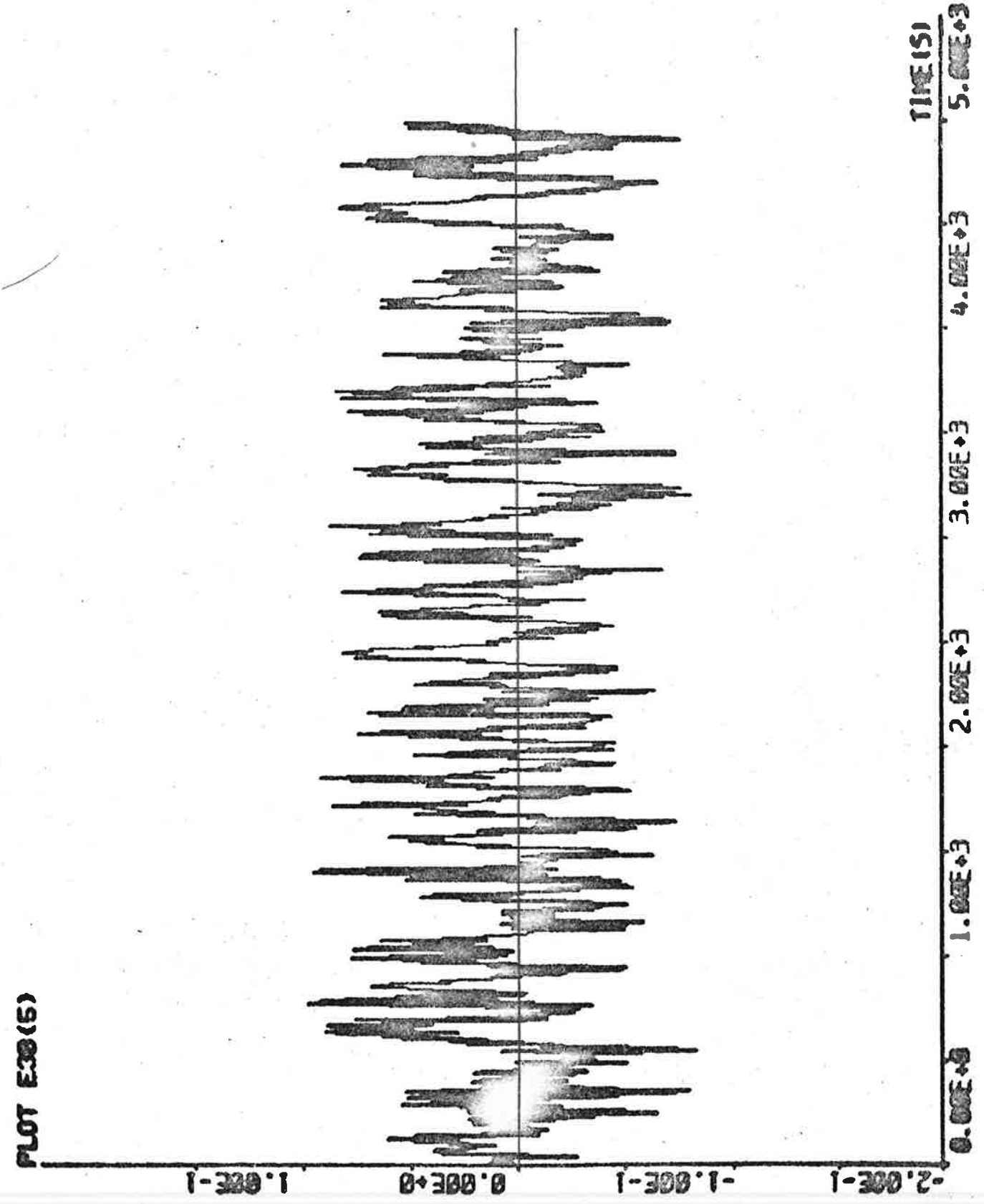
V_1 knots


PLOT E38(4)
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

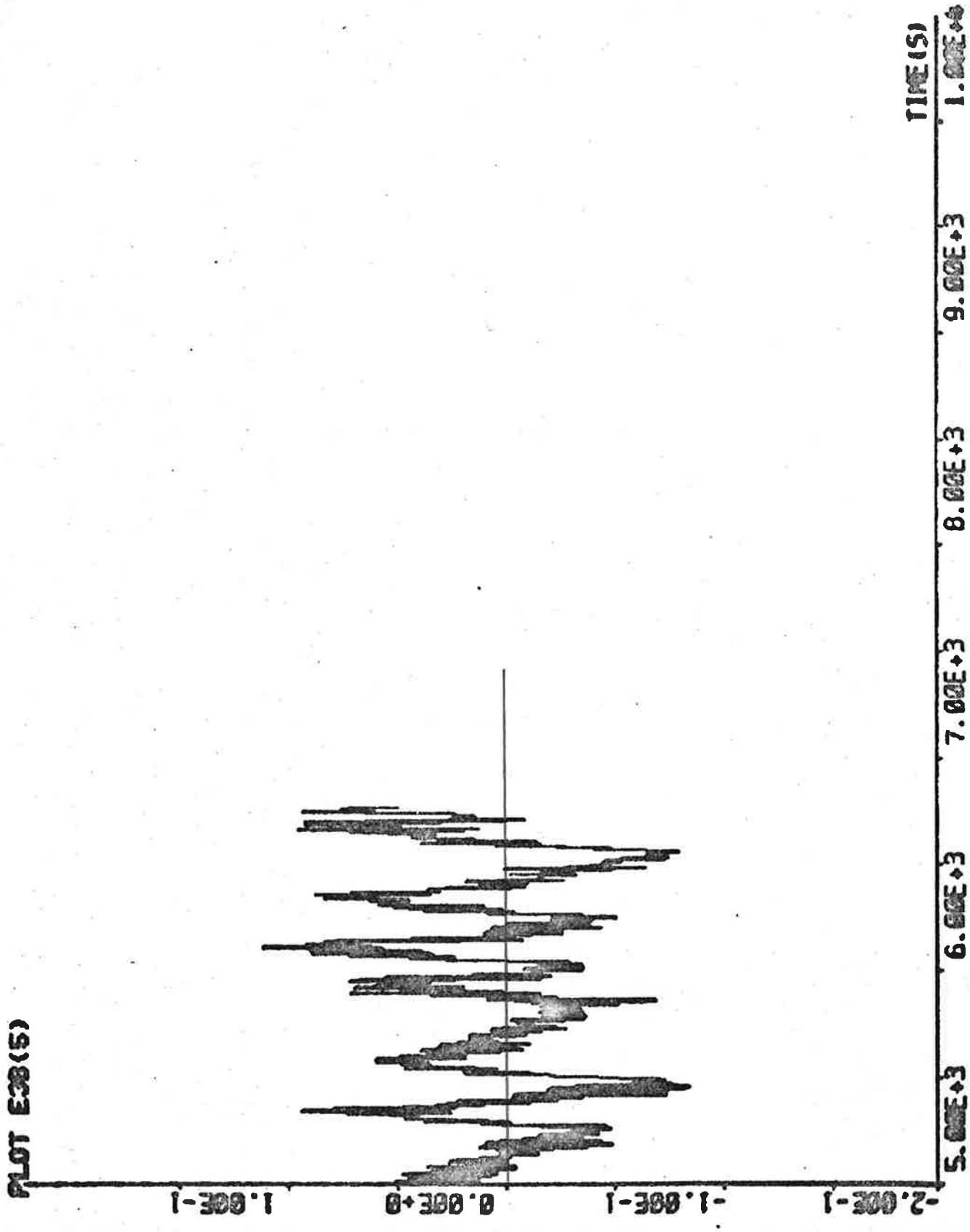
½ knots


PLOT E38(4)
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

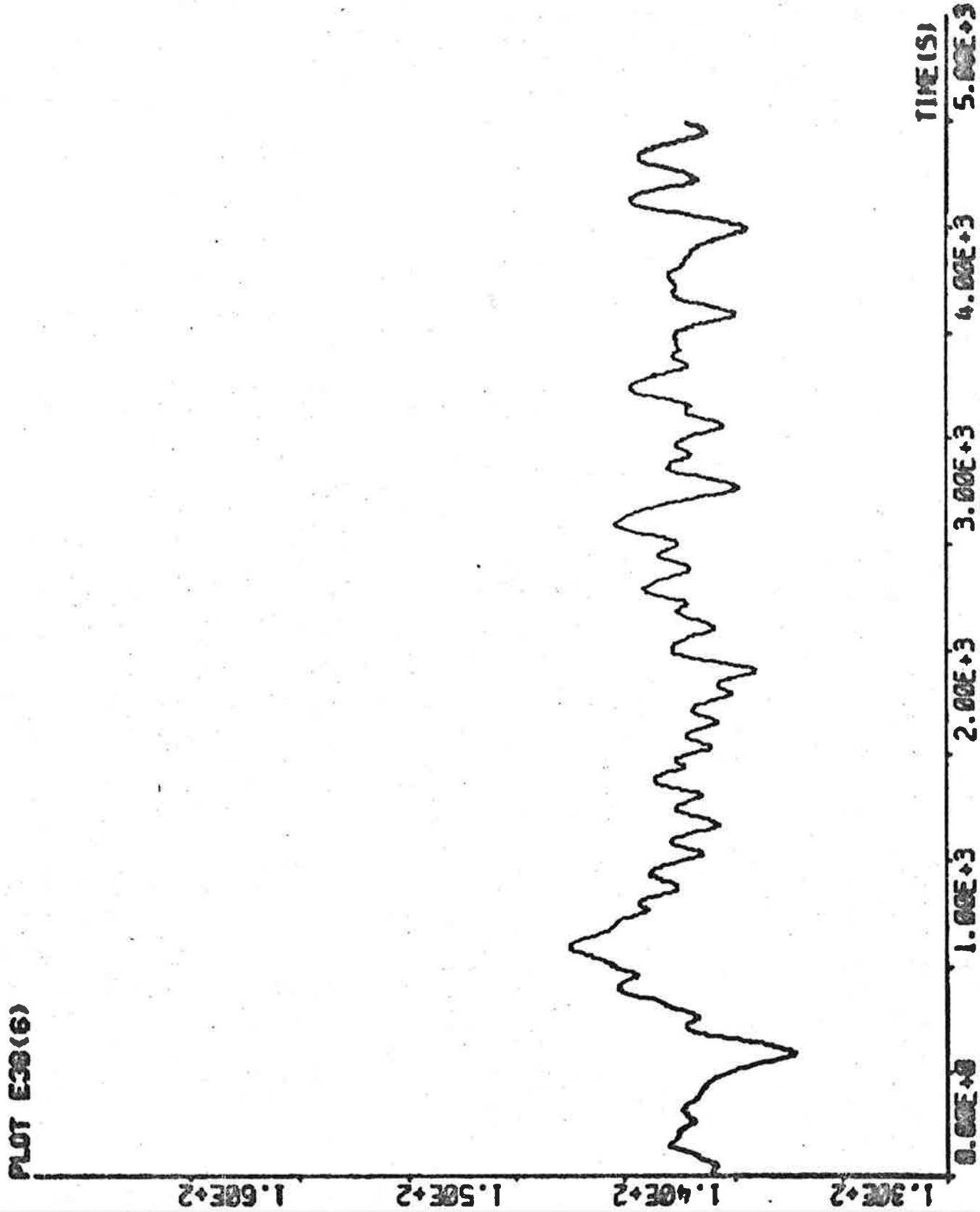
V_2 knots


PLOT E30(6)
TIME (S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3
1.300E-1
0.300E+0
-1.300E-1
-2.300E-1

r degr/s

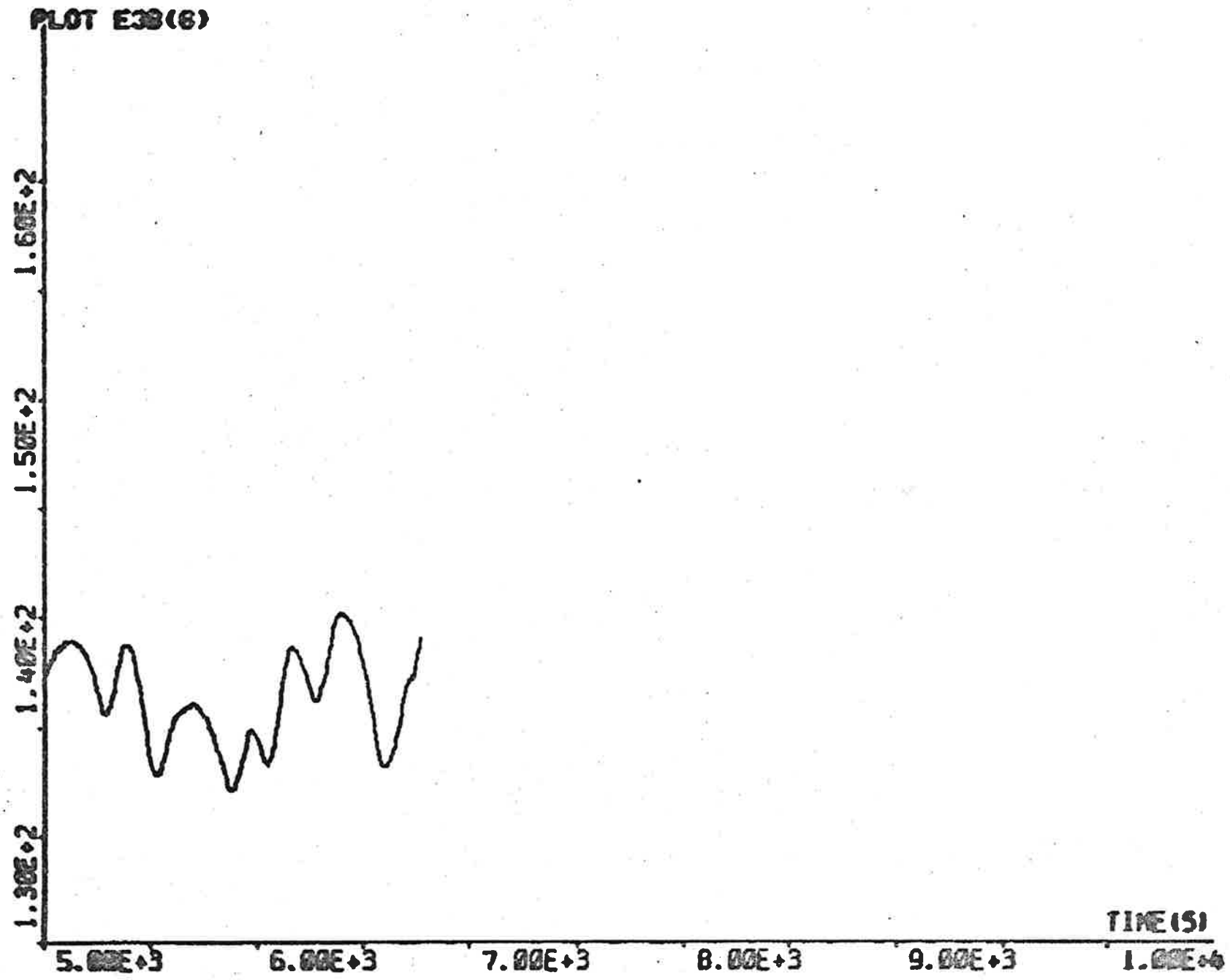

PLOT E38(5)
1.00E-1
0.00E+0
-1.00E-1
-2.00E-1
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

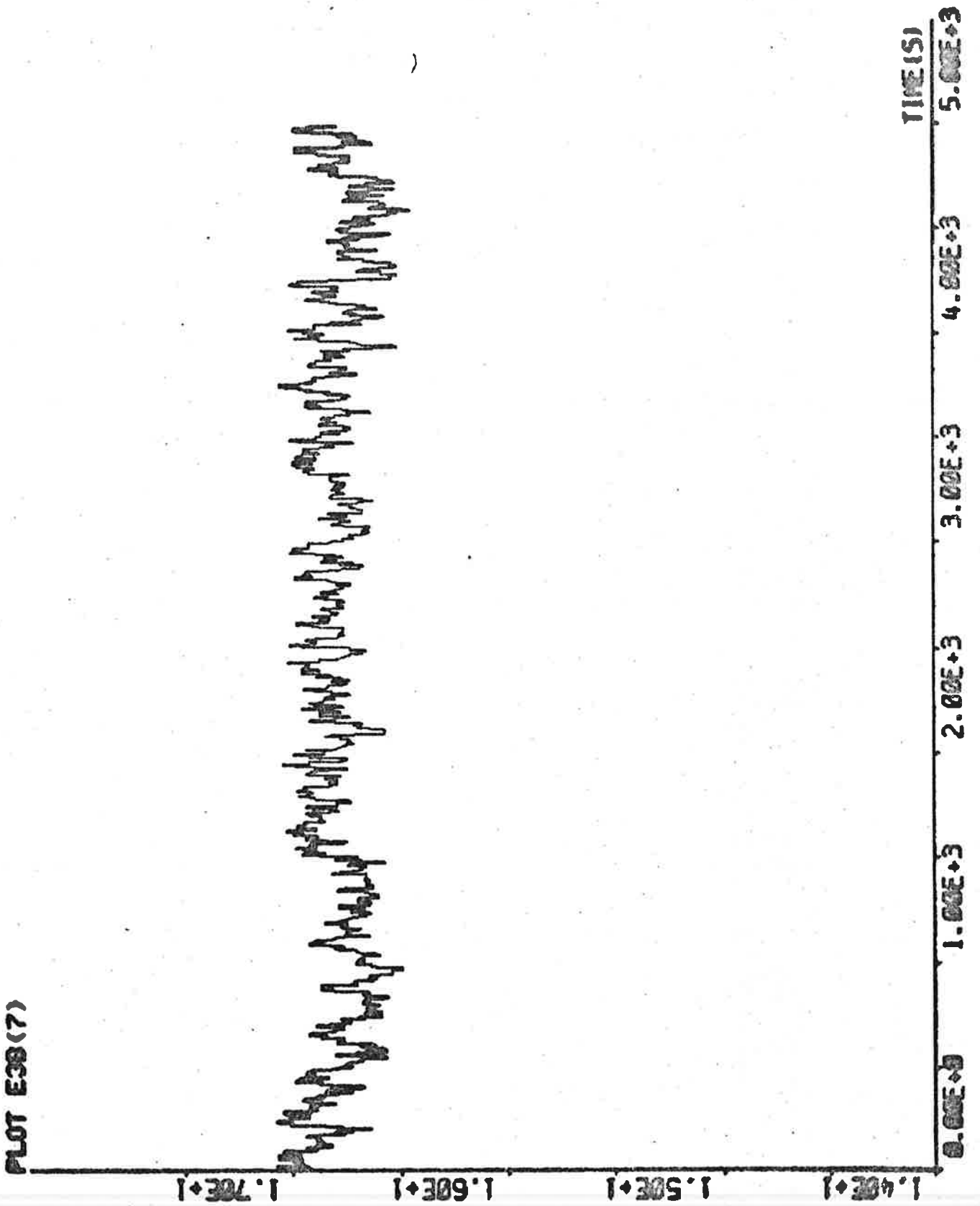
r degr/s


PLOT E3B(6)
1.300E+2
1.400E+2
1.500E+2
1.600E+2
0.000E+0
1.000E+3
2.000E+3
3.000E+3
4.000E+3
5.000E+3
TIME(S)

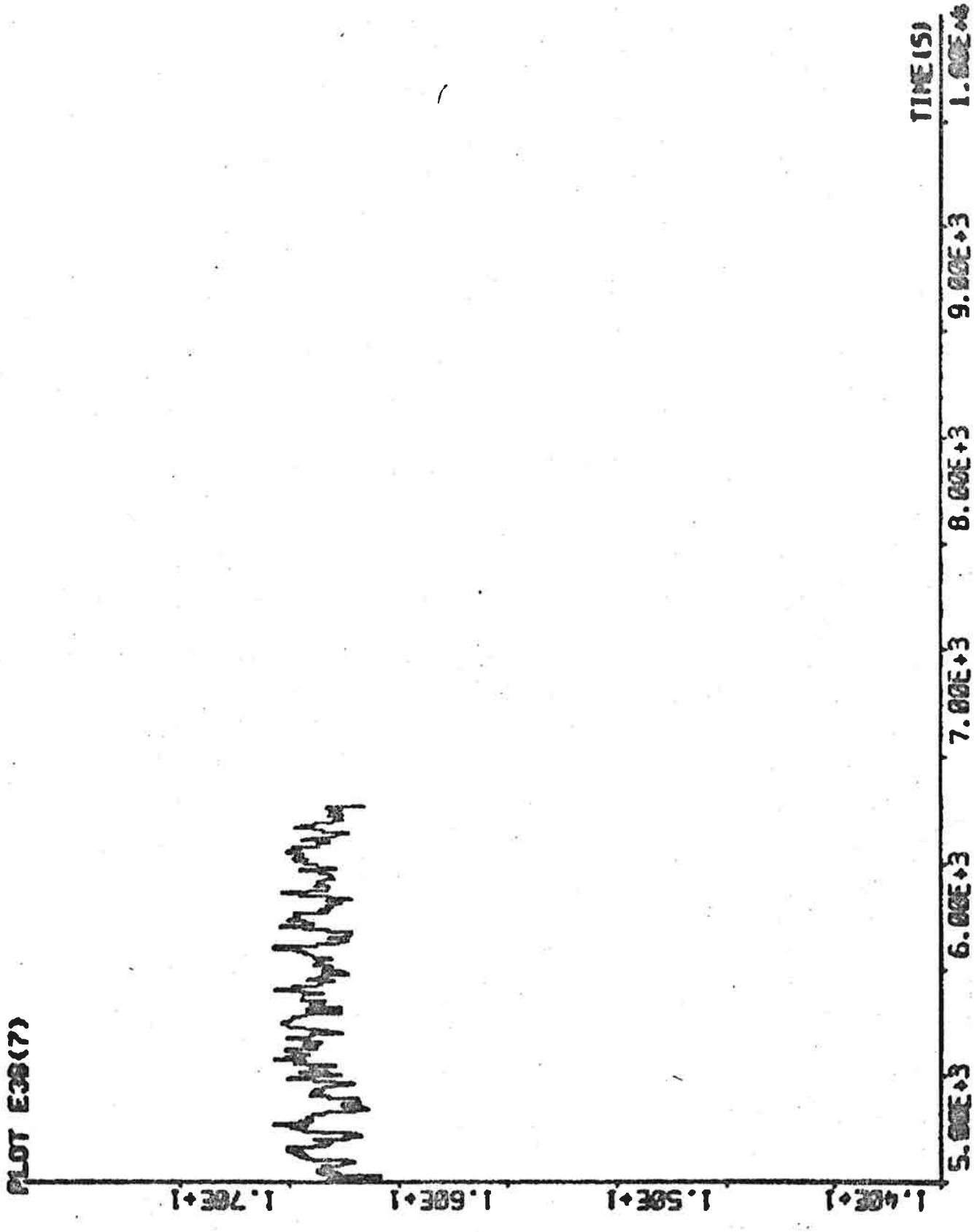
ψ degr

ψ degr

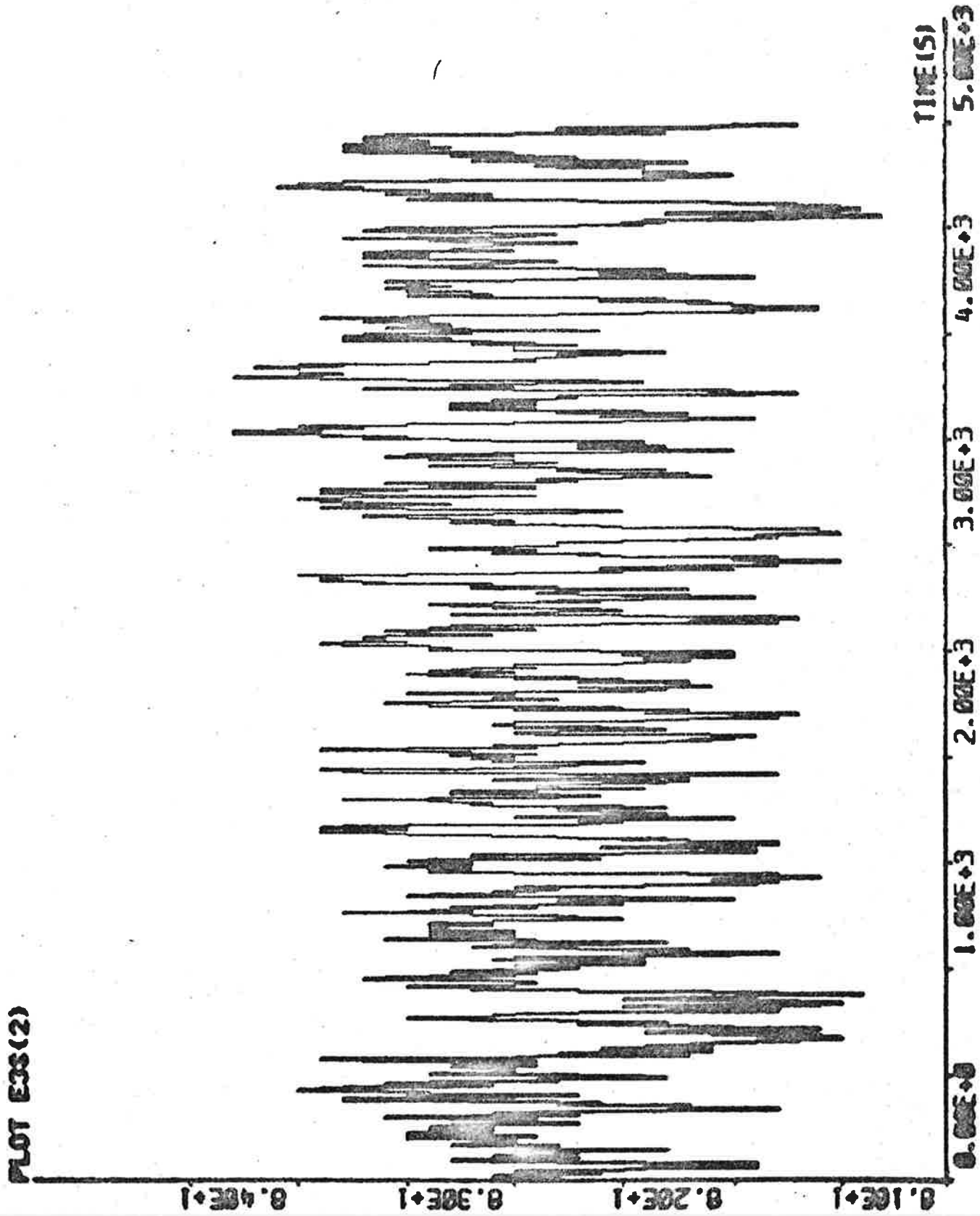

PLOT E38(6)
1.60E+2
1.50E+2
1.40E+2
1.30E+2
TIME(S)
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4


PLOT E38(7)
1.4E+1
1.5E+1
1.6E+1
1.7E+1
0.0E+0
1.0E+3
2.0E+3
3.0E+3
4.0E+3
5.0E+3
TIME(S)

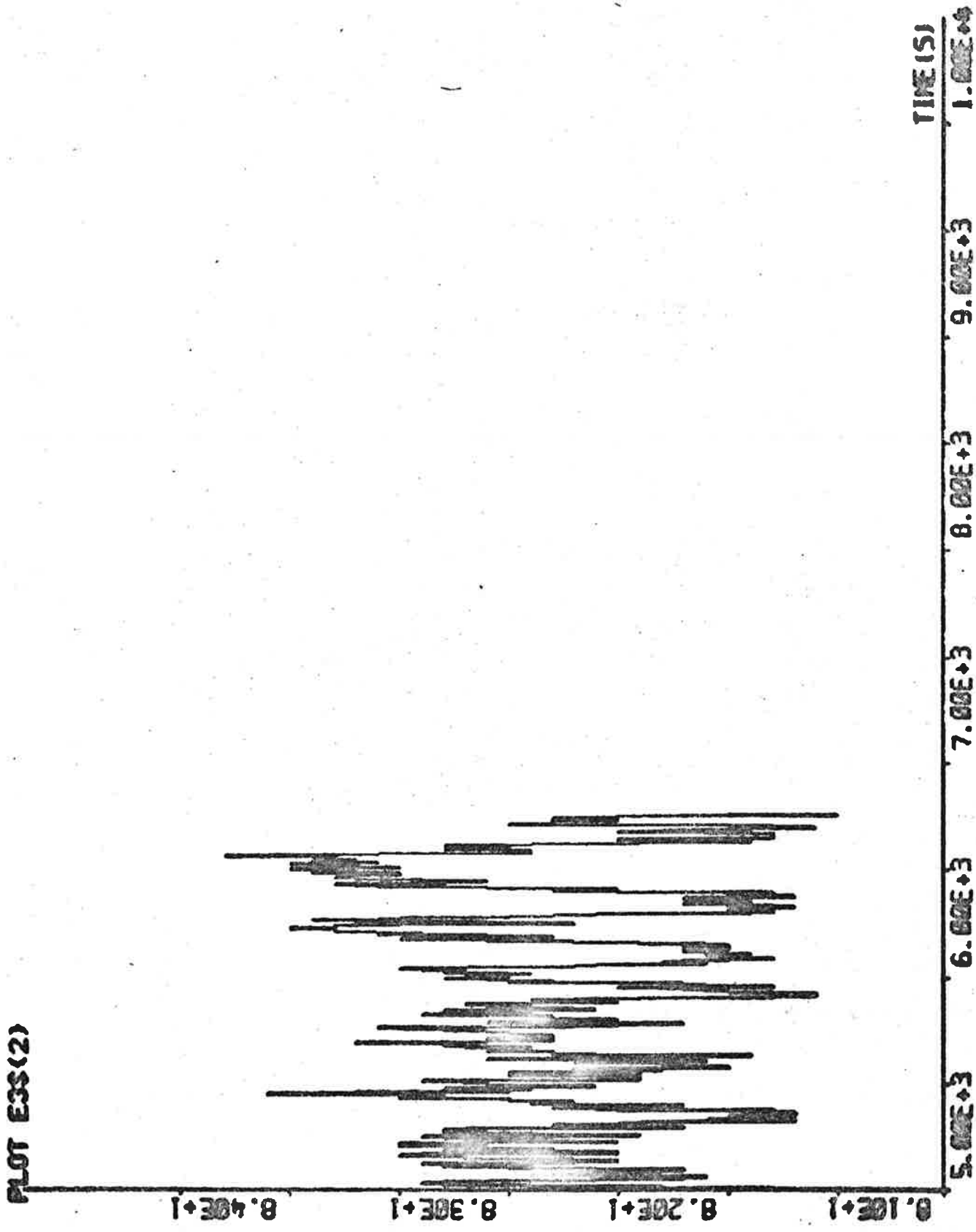
u knots


PLOT E3B(7)
1.706+1
1.686+1
1.586+1
1.466+1
5.00E+3
6.00E+3
7.00E+3
8.00E+3
9.00E+3
1.00E+4
TIME(S)

v knots


PLOT E33(2)
8.106+1
8.206+1
8.306+1
8.406+1
TIME(S)
0.00E+0
1.00E+3
2.00E+3
3.00E+3
4.00E+3
5.00E+3

n rpm


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