The Sea Stratus Experiments, April 1976 (2 parts)

Källström, Claes

1976

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

Link to publication

Citation for published version (APA):
Källström, C. (1976). *The Sea Stratus Experiments, April 1976 (2 parts)*. (Technical Reports TFRT-7110). Department of Automatic Control, Lund Institute of Technology (LTH).

Total number of authors:
1

CODEN: LUTFD2/(TFRT-7110)/01-587/(1976)

THE SEA STRATUS EXPERIMENTS, APRIL 1976
PART I

CLAES KÄLLSTRÖM

Lund Institute of Technology
Department of Automatic Control
September 1976

Dokumentutgivare	Dokumentnamn	Dokumentbeteckning
Lund Institute of Technology	04T4 REPORT	04T6 LUTFD2/(TFRT-7110)/1-587/(1976)
Handläggare Dept of Automatic Control	**Utgivningsdatum**	**Ärendebeteckning**
06T0 Claes Källström	06T4 Sept 1976	06T6 STU 73 41 87 STU 74 41 27
Författare		
08T0 Claes Källström		

10T4

Dokumenttitel och undertitel

18T0

The Sea Stratus Experiments, April 1976

Referat (sammandrag)

26T0

Experiments of steady state course keeping and turning on a tanker in ballast condition are presented. An adaptive autopilot, consisting of a Kalman filter, a self-tuning regulator for straight course keeping and a turning regulator, was tested in different speed and weather conditions. Comparative experiments with a conventional autopilot based on a PID-regulator were also performed.

Referat skrivet av

Author

Förslag till ytterligare nyckelord

44T0

Ship control, Ship regulator, Ship manoeuvring

Klassifikationssystem och -klass(er)

50T0

Indextermer (ange källa)

52T0

Ship manoeuvring (Thesaurus of Engineering and Scientific Terms, Engineers Joint Council, N Y, USA)

Omfång	Övriga bibliografiska uppgifter
56T0 587 pages	56T2
Språk	
58T0 English	

Sekretessuppgifter	ISSN	ISBN
60T0	60T4	60T6

Dokumentet kan erhållas från

62T0

Department of Automatic Control
Lund Institute of Technology
P O Box 725, S-220 07 Lund 7, Sweden

Mottagarens uppgifter

62T4

Pris

66T0

THE SEA STRATUS EXPERIMENTS, APRIL 1976

PART I

CLAES KÄLLSTRÖM

ABSTRACT

Experiments of steady state course keeping and turning on a tanker in ballast condition are presented. An adaptive autopilot, consisting of a Kalman filter, a self-tuning regulator for straight course keeping and a turning regulator, was tested in different speed and weather conditions. Comparative experiments with a conventional autopilot based on a PID-regulator were also performed.

TABLE OF CONTENTS

	Page
PART I	
1. INTRODUCTION	6
2. MEASUREMENT EQUIPMENT	8
3. AUTOPILOT	10
3.1 Kalman Filter	12
3.2 Self-tuning Regulator	17
3.3 PID-regulator	21
3.4 Yaw Regulator	22
4. DISCUSSION OF THE EXPERIMENTS	27
4.1 Kalman Filter Testing	28
4.2 Straight Course Keeping	32
4.3 Yawing	37
4.4 Experiments for Identification	38
5. CONCLUSIONS	40
6. ACKNOWLEDGEMENTS	42
7. REFERENCES	43
APPENDIX A - NOTATIONS	44
APPENDIX B - STANDARD PARAMETER VALUES	50
APPENDIX C - PROGRAM LISTINGS	56
APPENDIX D - EXPERIMENTS	67
A1	79
A2	89
A3	99
A4	109
A5	119
A6	129
A7	139

	Page
A8	149
A9	159
A10	169
A11	179
A12	189
A13	199
A14	209
A15	219
A16	229
A17	239
A18	249
A19	259
A20	269
A21	278
PART II	
A22	288
A23	298
A24	308
A25	318
A26	328
A27	338
A28	348
A29	358
A30	368
A31	377
A32	386
A33	396

	Page
A34	406
A35	416
A36	425
B1	435
B2	441
B3	447
C1	453
C2	463
C3	473
C4	483
C5	493
C6	503
D1	513
D2	523
D3	533
E1	543
E2	552
E3	561
E4	571
F1	580
F2	581
F3	582
F4	583

1. INTRODUCTION

The purpose of the experiments was to test an adaptive autopilot, consisting of a Kalman filter, a self-tuning regulator and a yaw regulator, in different weather conditions and at different speeds. Comparative experiments performed with a PID-regulator were also recorded.

The ship, T/T Sea Stratus, is a 355 000 tdw oil tanker built for the Salén Shipping Co in Stockholm by Kockums in Malmö. The length between perpendiculars is 350 m and the beam is 60 m. The draught of the ship is 22.3 m in full load condition. The main engine power is 29.4 MW (40 000 shp), which implies that the speed obtained is 15.5 knots when the tanker is fully loaded. The adaptive autopilot was implemented by use of the programming language FORTRAN as a task of the Integrated Navigation System, Kockums Bridge System type 546, which is a standard software package designed for the process computer Kongsberg SM 406 S. A special paper tape punch was installed to record the experiments.

Extensive computer simulations had preceded the experiments. A mathematical model of a 255 000 tdw tanker was used in Aspernäs and Foisack (1975), Aspernäs and Källström (1975), and Källström (1976a). A model, which describes the steering dynamics of the actual tanker T/T Sea Stratus, was simulated in Källström (1976b) and (1976c). The latter report shows the performance of the same adaptive autopilot, which is used in the experiments described here, for different load and speed conditions.

Preliminary full scale experiments on 255 000 tdw tankers, T/T Sea Scout and T/T Sea Swift, are described in Källström (1974) and (1975), resp. Most of the Sea Swift experiments were performed in full load condition, while the Sea Scout was ballasted during the experiments.

The experiments on the Sea Stratus were performed during a voyage from Lisbon, Portugal, to Cape Town, South Africa, between 1976-04-18 and 1976-05-03. At the departure from Lisbon the ship had a ballast of 134 000 tdw, which implies a mean draught of 10.5 m. The ballast was changed to 160 000 tdw on 1976-04-26 and then the mean draught obtained was 11.9 m. The average speed of the ship varied between 12.1 knots and 15.9 knots. The largest wind velocity measured was 15 m/s, which means moderate gale, but complete calm was also prevailing during some of the experiments.

Thirty-six experiments, A1-A36, of straight course keeping were recorded. The PID-regulator was used during some of the experiments, but most of them were performed using the adaptive autopilot. Three experiments, B1-B3, were specially carried out to record the performance of the Kalman filter by punching data at a high sampling rate. Six turning experiments, C1-C6, and three normal operating experiments, D1-D3, were also recorded as well as four experiments, E1-E4, for off-line identification of the ship steering dynamics. Finally four straight course keeping experiments, F1-F4, were performed to compare the steering quality of the adaptive autopilot to that of the PID-regulator. Notice that no data were punched on paper tape during these experiments. The Kalman filter was running during all the experiments, but the estimates were not always used by the regulators. All the fifty-six experiments are described in Appendix D. The total experimental time was about 33 h, but the testing was going on during almost all the days and nights of the voyage, i.e. during about 2 weeks.

The notations used in this report are explained in Appendix A and the standard parameter values of the autopilot are summarized in Appendix B. The listings of the FORTRAN subroutines of the autopilot are given in Appendix C.

2. MEASUREMENT EQUIPMENT

Several measurement signals are usually available in the computer, and no special equipment, besides the paper tape punch, had to be installed to carry through the experiments. Following measurement signals were recorded:

- o Rudder servo position δ_s [deg], scan cycle 1 s.
- o Rudder angle δ [deg], scan cycle 1 s, accuracy about 0.2 deg.
- o Propeller effect P_s [MW] (mean value during 5 min), scan cycle 10 s.
- o Number of propeller revolutions n [rpm], scan cycle 2 s.
- o Forward velocity u [knots], scan cycle 1 s, measured by a doppler log, type Atlas, with an accuracy of 0.02 knots.
- o Transversal velocity of bow v_l [knots], scan cycle 1 s, measured by the same device and with the same accuracy as the forward velocity.
- o Yaw angular velocity or yaw rate r [deg/s], scan cycle 1 s, measured with an accuracy of about 0.005 deg/s by a rate gyro manufactured by ATEW AB.
- o Heading angle ψ [deg], scan cycle 0.25 s, measured by a Sperry gyro compass, and transformed by a synchro--digital converter with an accuracy of about 0.02 deg.

During two experiments, A1 and D1, the forward velocity u was measured by Sperrys log. Sometimes that signal had an incorrect value in the computer. No measurements of the transversal velocity of bow v_l were recorded during these two experiments. The sign of v_l was incorrect during experiment C1 and a defect rudder servo was used during experiment A1.

The relative wind direction and the relative wind velocity were manually recorded once at the beginning of each experiment. However, absolute values have been calculated and these are used in this report.

The distance from the origin, which is placed half-way between the perpendiculars, to the forward doppler log (ℓ_1) is 164.35 m. The centre of mass is situated 9.3 m in front of the origin in full load condition. The distance is 6.9 m when the ship is ballasted.

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

3. AUTOPILOT

The structure of the autopilot is shown in Fig. 3.1. To obtain a good performance of all speeds, the autopilot performs a speed scaling using the speed V_s [m/s]. V_s is computed with sampling interval T_k = 1 s according to

$$V_s = u \cdot CKM \quad \text{if} \quad IVVC = 1 \tag{3.1}$$

or

$$V_s = V_c \quad \text{if} \quad IVVC = 3 \tag{3.2}$$

where CKM = 0.514444 denotes the conversion factor from knots to m/s and V_c [m/s] is a constant user-defined speed. The standard value of IVVC is equal to 1.

The Kalman filtering as well as the computation of the transversal velocity of the origin v [knots] according to

$$v = v_1 - \ell_1 \cdot r \cdot CGR/CKM \tag{3.3}$$

is performed with sampling interval T_k. The lever arm ℓ_1 is equal to 164.35 m and the conversion factor from degrees to radians CGR is equal to 0.0174533. Either the estimates from the Kalman filter $\hat{v}$ [knots], $\hat{r}$ [deg/s], and $\hat{\psi}$ [deg] or the measurements v, r, and ψ are used by the self-tuning regulator, the PID-regulator, and the yaw regulator. The standard configuration is the one when Kalman filter estimates are fed into the different regulators.

The rudder command δ_c [deg] is computed with sampling interval T_s, where T_s mostly is equal to 10 s. The PID--regulator for straight course keeping is only used for comparison. The reference course ψ_{ref} [deg] and the reference yaw rate r_{ref} [deg/s] for turning as well as the rudder limit δ_ℓ [deg] are also used by the autopilot. The complete autopilot is implemented by the FORTRAN subroutines AUTP3 and STUR listed in Appendix C.

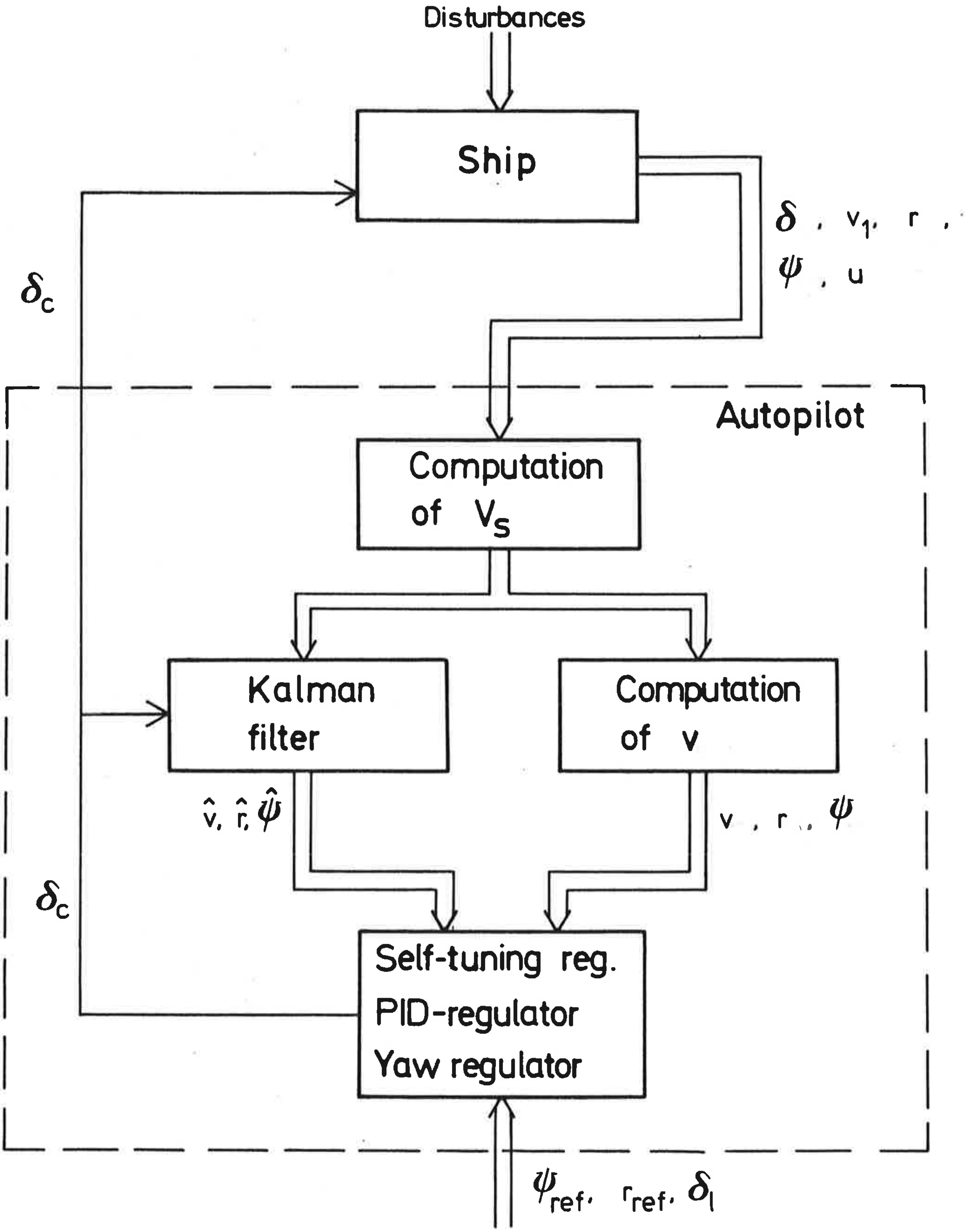


Fig. 3.1 - Structure of the autopilot.

3.1 Kalman Filter

The design of the Kalman filter follows in detail the description given in Källström (1976c). A model of a fully loaded tanker is used. Notice, however, that the covariance matrix R_1 for the process noise is changed somewhat:

$$\text{diag}(R_1) = \tag{3.4}$$

$$= \left\{2.5\cdot 10^{-5} \quad 5\cdot 10^{-9} \quad 8\cdot 10^{-8} \quad 8\cdot 10^{-8} \quad 1.2\cdot 10^{-8} \quad 4\cdot 10^{-7} \quad 3\cdot 10^{-12} \quad 8\cdot 10^{-11}\right\}$$

The following Kalman filter equations are obtained:

$$\begin{cases} \hat{x}'(t|t-1) = A\,\hat{x}'(t-1|t-1) + B\,u'(t-1) \\ \hat{x}'(t|t) = \hat{x}'(t|t-1) + K\,\varepsilon'(t) \\ y'(t) = C\,\hat{x}'(t|t-1) + \varepsilon'(t) \end{cases} \tag{3.5}$$

where all variables are normalized using the length of the ship L (L = 350 m) as unit of length and the time to cover the length L, i.e. L/V_s, as unit of time. The notation x'(t|t-1) stands for the estimate of x' at the time t based on measurements up to and including time t-1. The vectors and matrices of (3.5) are explained by:

$$u' = \delta_c \cdot CGR$$

$$(\hat{x}')^T = \left[\hat{v}' \quad \hat{r}' \quad \hat{\psi}' \quad \hat{\delta}_d' \quad \hat{\delta}_o' \quad \hat{d}_v' \quad \hat{d}_r' \quad \hat{d}_\delta'\right]$$

$$(y')^T = \left[\delta\cdot CGR \quad v_1\cdot CKM/V_s \quad r\cdot CGR\cdot L/V_s \quad \psi\cdot CGR\right]$$

$$(\varepsilon')^T = \left[\varepsilon_\delta' \quad \varepsilon_v' \quad \varepsilon_r' \quad \varepsilon_\psi'\right]$$

$$A = \begin{pmatrix} a_{11} & a_{12} & 0 & a_{14} & a_{15} & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & a_{24} & a_{25} & 0 & 0 & 0 \\ a_{31} & a_{32} & 1 & a_{34} & a_{35} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{44} & a_{45} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$B^T = \begin{pmatrix} b_{11} & b_{21} & b_{31} & b_{41} & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$C = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & \ell_1/L & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$K = \begin{pmatrix} -9.27\cdot10^{-5} & 8.82\cdot10^{-2} & -2.40\cdot10^{-2} & -0.367 \\ 6.30\cdot10^{-4} & 0.481 & 9.65\cdot10^{-2} & 1.02 \\ 1.69\cdot10^{-5} & 7.86\cdot10^{-3} & 3.14\cdot10^{-3} & 0.326 \\ 1.66\cdot10^{-2} & -2.90\cdot10^{-3} & 5.65\cdot10^{-3} & 6.51\cdot10^{-2} \\ 1.03\cdot10^{-3} & 2.98\cdot10^{-3} & -5.63\cdot10^{-3} & -6.49\cdot10^{-2} \\ -1.26\cdot10^{-4} & 2.00\cdot10^{-2} & -6.69\cdot10^{-5} & -5.06\cdot10^{-3} \\ 1.63\cdot10^{-6} & -1.68\cdot10^{-3} & 3.02\cdot10^{-3} & -5.77\cdot10^{-2} \\ 2.54\cdot10^{-3} & 7.61\cdot10^{-6} & 1.24\cdot10^{-5} & 1.41\cdot10^{-4} \end{pmatrix}$$

where

a_{11}	$= 0.99163$	a_{32}	$= 0.0224515$
a_{12}	$= -0.0100810$	a_{34}	$= 0.000195418$
a_{14}	$= -0.00208207$	a_{35}	$= -0.0000132723$
a_{15}	$= 0.000212358$	a_{44}	$= 0.81873$
a_{21}	$= -0.0759537$	a_{45}	$= -0.18127$
a_{22}	$= 0.96485$	b_{11}	$= -0.000212358$
a_{24}	$= 0.0164706$	b_{21}	$= 0.00170991$
a_{25}	$= -0.00170991$	b_{31}	$= 0.0000132723$
a_{31}	$= -0.000874514$	b_{41}	$= 0.18127$

The elements of the state estimate vector $\hat{x}'$ are normalized estimates of the following variables: transversal velocity of the origin ($\hat{v}'$), yaw rate ($\hat{r}'$), heading ($\hat{\psi}'$), rudder angle minus rudder bias ($\hat{\delta}'_d = \hat{\delta}' - \hat{\delta}'_o$), rudder bias ($\hat{\delta}'_o$), measurement biases of v_1, r, δ, resp. ($\hat{d}'_v$, $\hat{d}'_r$, $\hat{d}'_\delta$). The initial state estimate vector is equal to

$$(\hat{x}'(t_o))^T = \left[v \cdot CKM / V_s \quad r \cdot CGR \cdot L / V_s \quad \psi \cdot CGR \quad \delta \cdot CGR \quad 0 \quad 0 \quad 0 \quad 0 \right]$$

where v i obtained from (3.3) and all the measurements are from the time t_o.

If

$$|\varepsilon'_\delta| > t'_\delta ,$$

$$|\varepsilon'_v| > t'_v ,$$

$$|\varepsilon'_r| > t'_r ,$$

or

$$|\varepsilon'_\psi| > t'_\psi ,$$

where

$$t'_\delta = 1$$
$$t'_v = 0.06$$
$$t'_r = 0.25 \qquad (3.6)$$
$$t'_\psi = 0.015$$

then the corresponding measurement or measurements are rejected, when the state estimate vector is updated. A measurement signal is definitively rejected when IMX (IMX = 10) consecutive measurements are rejected. However, during the first IKMX = 900 s after the Kalman filter is initialized, no measurements are rejected because the bias states of the Kalman filter must be fairly estimated to avoid incorrect rejectings. The rejecting of a measurement is performed by putting the corresponding column of K equal to zero. Notice that the values of (3.6) are chosen very large to avoid rejectings when the Kalman filter is tested.

The only measurement signal used by the Kalman filter in the experiments A26 and A27 is the heading angle. The first three columns of the filter gain K are cancelled in experiment A27, while the following filter gain, designed correctly for the case of heading measurements only, is used in experiment A26:

$$K^T = \begin{pmatrix} -0.481 & 2.40 & 0.390 & 0.0720 & -0.0716 & 0 & 0 & 0 \end{pmatrix} \qquad (3.7)$$

The bias estimates $\hat{\delta}'_o$, $\hat{d}'_v$, $\hat{d}'_r$, and $\hat{d}'_\delta$ were not updated during the turning experiments C3 and C4.

The non-normalized state estimate vector is obtained as:

$$(\hat{x})^T = \begin{pmatrix} \hat{v} & \hat{r} & \hat{\psi} & \hat{\delta}_d & \hat{\delta}_o & \hat{d}_v & \hat{d}_r & \hat{d}_\delta \end{pmatrix}$$

where

$$\hat{v} = \hat{v}' \cdot V_s/CKM \quad [knots]$$

$$\hat{r} = \hat{r}' \cdot V_s/(CGR \cdot L) \quad [deg/s]$$

$$\hat{\psi} = \hat{\psi}' / CGR \quad [deg]$$

$$\hat{\delta}_d = \hat{\delta}_d' / CGR \quad [deg]$$

$$\hat{\delta}_o = \hat{\delta}_o' / CGR \quad [deg]$$

$$\hat{d}_v = \hat{d}_v' \cdot V_s / CKM \quad [knots]$$

$$\hat{d}_r = \hat{d}_r' \cdot V_s / (CGR \cdot L) \quad [deg/s]$$

$$\hat{d}_\delta = \hat{d}_\delta' / CGR \quad [deg]$$

Notice the following expressions, too:

$$\hat{v}_1 = \hat{v} + \ell_1 \cdot \hat{r} \cdot CGR/CKM \quad [knots]$$

$$\hat{\delta} = \hat{\delta}_d + \hat{\delta}_o \quad [deg]$$

The non-normalized residual vector is obtained as:

$$\varepsilon^T = \left(\varepsilon_\delta \quad \varepsilon_v \quad \varepsilon_r \quad \varepsilon_\psi \right)$$

where

$$\varepsilon_\delta = \varepsilon_\delta' / CGR \quad [deg]$$

$$\varepsilon_v = \varepsilon_v' \cdot V_s / CKM \quad [knots]$$

$$\varepsilon_r = \varepsilon_r' \cdot V_s / (CGR \cdot L) \quad [deg/s]$$

$$\varepsilon_\psi = \varepsilon_\psi' / CGR \quad [deg]$$

3.2 Self-tuning Regulator

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

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

$$
\begin{aligned}
&(\hat{\psi}(t) - \psi_{ref}) + a_1(\hat{\psi}(t-k-1) - \psi_{ref}) + \dots + \\
&+ a_{NA}\ (\hat{\psi}(t-k-NA) - \psi_{ref}) = \\
&= (V_s(t-k-1)/V_o)^2\ b_o\ \nabla\delta_c(t-k-1)\ + \\
&+ (V_s(t-k-2)/V_o)^2\ b_o\ b_1\ \nabla\delta_c(t-k-2) + \dots + \\
&+ (V_s(t-k-NB-1)/V_o)^2\ b_o\ b_{NB}\ \nabla\delta_c(t-k-NB-1)\ + \\
&+ V_s(t-k-1)\ c_1\ \nabla\ \hat{v}(t-k-1)\ + \\
&+ c_2\ \nabla\ \hat{r}(t-k-1) + e(t)
\end{aligned}
\qquad (3.8)
$$

where the design speed is denoted V_o [m/s]. The minimum variance control is given by

$$
\begin{aligned}
\nabla\delta_c(t) \ = \ &\left(\frac{V_o}{V_s(t)}\right)^2 \frac{1}{b_o}\ \Big[a_1(\hat{\psi}(t) - \psi_{ref}) + \dots + \\
&+ a_{NA}(\hat{\psi}(t-NA+1) - \psi_{ref})\ - \\
&- (V_s(t-1)/V_o)^2\ b_o\ b_1\ \nabla\delta_c(t-1) - \dots - \\
&- (V_s(t-NB)/V_o)^2\ b_o\ b_{NB}\ \nabla\delta_c(t-NB)\ - \\
&- V_s(t)\ c_1\ \nabla\ \hat{v}(t) - c_2\ \nabla\ \hat{r}(t)\ \Big]
\end{aligned}
\qquad (3.9)
$$

where

$$\nabla\delta_c(t) = \delta_c(t) - \delta_c(t-1)$$
$$\nabla\hat{v}(t) = \hat{v}(t) - \hat{v}(t-1)$$
$$\nabla\hat{r}(t) = \hat{r}(t) - \hat{r}(t-1)$$

Notice that the speed scaling of (3.8) and (3.9) is introduced in such a way that the parameters $a_1,\ldots,a_{NA}$, $b_1,\ldots,b_{NB}$, c_1 and c_2 are approximately independent of the forward speed. This fact will, of course, simplify the mission of the self-tuning regulator.

The following standard values are used:

$NA = 4$

$NB = 2$

$k = 7$

$T_s = 10$ s

$\lambda_f = 0.99$

$b_o = 1$

$V_o = 6$ m/s

where T_s is the sampling interval and λ_f the exponential forgetting factor. Other values of k, T_s, and V_o are sometimes used. The following initial values of the parameters and of the covariance matrix P are used:

$$\begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} -6.91 \\ 5.95 \\ 3.88 \\ -3.57 \\ 0.48 \\ 0.11 \\ -2.10 \\ 34.73 \end{pmatrix} \qquad P = \begin{pmatrix} 1 & & & & & & & \\ & 1 & & & & & 0 & \\ & & 1 & & & & & \\ & & & 1 & & & & \\ & & & & 0.01 & & & \\ & & & & & 0.01 & & \\ & 0 & & & & & 1 & \\ & & & & & & & 100 \end{pmatrix} \tag{3.10}$$

Sometimes $c_1 = 0$ or $c_2 = 0$, which is indicated by assigning NC1 resp NC2 the value zero. The corresponding diagonal element of P is then also equal to zero. The standard values are NC1 = 1 and NC2 = 1.

By use of the minimum variance control (3.9) the following criterion is minimized:

$$J_1 = \sum_{n=0}^{\infty} (\hat{\psi}(n+k+1) - \psi_{ref})^2 \tag{3.11}$$

If the criterion

$$J_2 = \sum_{n=0}^{\infty} \left[(\hat{\psi}(n+k+1) - \psi_{ref})^2 + q_2(\nabla\delta_c(n))^2 \right] \tag{3.12}$$

is minimized instead, a penalty on the rudder motions is introduced by the parameter q_2. However, a proper solution of this problem requires the solving of a Riccati equation. A self-tuning regulator, which performs this, is used in Källström (1976a).

If the criterion (3.12) is modified to read

$$J_3(n) = (\hat{\psi}(n+k+1) - \psi_{ref})^2 + q_2(\nabla\delta_c(n))^2 \qquad n = 0, 1, 2, \ldots \tag{3.13}$$

and if (3.13) is minimized at every sample event, then a simpler regulator is obtained. By inserting (3.8) into (3.13) and then performing the minimization, the following control is obtained:

$$\overline{\nabla\delta_c(t)} = \frac{(V_s(t)/V_o)^4 \, b_o^2}{(V_s(t)/V_o)^4 \, b_o^2 + q_2} \nabla\delta_c(t) \tag{3.14}$$

where $\nabla\delta_c(t)$ is the minimum variance control given by (3.9). If $q_2 = 0$, then minimization of (3.13) gives the same result as minimization of (3.11) and consequently the controls (3.14) and (3.9) are equivalent. Notice that (3.14) only is a very small modification of (3.19) and that the identification part of the self-tuning regulator is unchanged. However, the control (3.14) has the serious disadvantage that no guarantee of closed loop stability is obtained in the general case.

The minimum variance control (3.9) is approximately scaled by $(V_o/V_s(t))^2$ when the speed changes, i.e. (3.14) may be rewritten

$$\overline{\nabla\delta_c(t)} = \frac{b_o^2}{b_o^2 + \left(\frac{V_o}{V_s(t)}\right)^4 q_2} \left(\frac{V_o}{V_s(t)}\right)^2 \left[\nabla\delta_c(t)\right]_{V_o} \tag{3.15}$$

where $[\nabla\delta_c(t)]_{V_o}$ denotes the minimum variance control when $V_s = V_o$. By introducing $q = (V_o/V_s(t))^4 q_2$ we obtain

$$\overline{\nabla\delta_c(t)} = \frac{b_o^2}{b_o^2 + q} \left(\frac{V_o}{V_s(t)}\right)^2 [\nabla\delta_c(t)]_{V_o} =$$

$$= \frac{b_o^2}{b_o^2 + q} \nabla\delta_c(t) \tag{3.16}$$

which is the actual control used in the autopilot. The standard value of q is equal to zero.

The estimates from the Kalman filter are used in all formulas of this section. Notice, however, that it is possible to use the non-filtered measurements instead.

3.3 PID-regulator

The following discrete PID-regulator for straight course keeping is also implemented for comparison:

$$\delta_c(nT_s) = -\left(\frac{V_o}{V_s(nT_s)}\right)^2 \left[k_P(\hat{\psi}(nT_s)-\psi_{ref}) + k_D\,\hat{r}(nT_s) + \right.$$

$$\left. + k_I\,T_s \sum_{i=0}^{n-1} (\hat{\psi}(iT_s)-\psi_{ref}) \right] \qquad (3.17)$$

$$n = 0,\ 1,\ 2,\ \ldots$$

The following standard values are used:

$$\begin{aligned} k_P &= 3 \\ k_D &= 75 \ \text{s} \\ k_I &= 0.02 \ \text{1/s} \\ T_s &= 10 \ \text{s} \\ V_o &= 6 \ \text{m/s} \end{aligned} \qquad (3.18)$$

Notice that it is possible to use the non-filtered measurements instead of the Kalman filter estimates in (3.17). The special speed scaling used in (3.17) will approximately give the same course keeping performance independent of the forward speed. The rudder deviations, however, are increased proportional to $(V_o/V_s)^2$ when the speed is decreased.

3.4 Yaw Regulator

A yaw performed by the yaw regulator consists of four different phases, viz. the initial phase (phase 1), the phase of constant yaw rate (phase 2), the checking rudder phase (phase 3), and the terminating phase (phase 4). However, if the requested heading change $\Delta\psi_{ref}$ is small, one or more of the phases may be skipped. The Kalman filter estimates used by the yaw regulator are the yaw rate $\hat{r}$ and the heading $\hat{\psi}$, and the reference values used are the requested yaw rate r_{ref} and the new requested heading ψ_{ref}. The phase of straight course keeping is denoted phase 0.

Modified discrete, fixed gain PID-regulators are used in the different phases (note that n = 0,1,2,...):

Phase 1:

$$\delta_c(nT_s) = -\left(\frac{V_o}{V_s(nT_s)}\right)^2 k_4(\hat{r}(nT_s) - r_o) + \bar{\delta}_c$$

$$| k_4(\hat{r}(nT_s)-r_o) | \leq | \bar{c}_1 r_o |$$

Phase 2:

$$\delta_c(nT_s) = -\left(\frac{V_o}{V_s(nT_s)}\right)^2 \left[k_5(\hat{r}(nT_s) - r_o) + \right.$$

$$\left. + k_6 T_s \sum_{i=0}^{n-1} (\hat{r}(iT_s)-r_o)\right] + \bar{\delta}_c$$

Phase 3:

$$\delta_c(nT_s) = -\left(\frac{V_o}{V_s(nT_s)}\right)^2 \left[k_7(\hat{\psi}(nT_s) - \psi_{ref}) + k_8 \hat{r}(nT_s)\right]$$

$$| k_7(\hat{\psi}(nT_s)-\psi_{ref}) + k_8 \hat{r}(nT_s) | \leq | \bar{c}_3 r_o |$$

Phase 4:

$$\delta_c(nT_s) = -\left(\frac{V_o}{V_s(nT_s)}\right)^2 \left[k_1(\hat{\psi}(nT_s) - \psi_{ref}) + k_2\,\hat{r}(nT_s) + \right.$$

$$\left. + k_3\,T_s \sum_{i=0}^{n-1} (\hat{\psi}(iT_s) - \psi_{ref})\right]$$

The moving average $\bar{\delta}_c$ of the rudder commands δ_c is only updated during phase 0 and phase 4:

$$\bar{\delta}_c((k+1)T_s) = \bar{\delta}_c(kT_s) + \left(\frac{1-\gamma}{k+1} + \gamma\right)(\delta_c(kT_s) - \bar{\delta}_c(kT_s))$$

$$k = 0,1,2,...$$

$$\bar{\delta}_c(0) = 0$$

The reference yaw rate r_o including sign is computed once, when the yaw is initiated, as

$$r_o = r_{ref} \quad \text{if} \quad \hat{\psi} - \psi_{ref} \leq 0$$

or as

$$r_o = -r_{ref} \quad \text{if} \quad \hat{\psi} - \psi_{ref} > 0$$

Notice that the value of r_{ref} always is positive.

The conditions to jump from one phase to another read:

Phase 0 → phase 4:

$$\psi_1 < \Delta\psi_{ref} \leq \psi_2$$

Phase 0 → phase 1:

$$\Delta\psi_{ref} > \psi_2$$

<u>Phase 1 → phase 2:</u>

$r_o \geq 0$ and $\hat{r} - r_o > -\varepsilon_1$

or

$r_o < 0$ and $\hat{r} - r_o < \varepsilon_1$

or

(time in phase 1) $> T_1$

<u>Phase 1 or 2 → phase 3:</u>

$r_o \geq 0$ and $-\bar{c}_2 \hat{r} < \hat{\psi} - \psi_{ref}$

or

$r_o < 0$ and $-\bar{c}_2 \hat{r} > \hat{\psi} - \psi_{ref}$

<u>Phase 3 → phase 4:</u>

$|\hat{r}| < \varepsilon_2$

or

$r_o \geq 0$ and $\hat{\psi} - \psi_{ref} > -\varepsilon_3$

or

$r_o < 0$ and $\hat{\psi} - \psi_{ref} < \varepsilon_3$

or

(time in phase 3) $> T_3$

<u>Phase 4 → phase 0:</u>

(time in phase 4) $> T_4$

The condition to remain in phase 0 is:

$\Delta\psi_{ref} \leq \psi_1$

If the reference yaw rate r_{ref} is changed during a yaw, the new value is immediately used, but no other changes. It is also possible to change the reference course ψ_{ref} during a yaw, and then a new yaw is initiated by entering phase 1, if

$$|\Delta\psi_{ref}| > \psi_3$$

and (3.19)

the actual phase is 3 or 4

or if

$$|\Delta\psi_{ref}| > \psi_3,$$

the actual phase is 1 or 2,

and one of the two conditions (3.20)

$$r_o > 0, \quad \hat{\psi} - \psi_{ref} > 0$$

and

$$r_o \leq 0, \quad \hat{\psi} - \psi_{ref} < 0$$

is satisfied.

If neither condition (3.19) nor condition (3.20) is fulfilled, the new value of ψ_{ref} is used, but no other changes.

The following parameter values of the yaw regulator are used:

$k_1 = 5$	$k_7 = 2$
$k_2 = 200$ s	$k_8 = 200$ s
$k_3 = 0.005$ 1/s	$\varepsilon_1 = 0$ deg/s
$k_4 = 200$ s	$\varepsilon_2 = 0.02$ deg/s
$k_5 = 200$ s	$\varepsilon_3 = 1$ deg
$k_6 = 8$	

$\bar{c}_1$ = 60 s	ψ_1 = 0.35 deg
$\bar{c}_2$ = 50 s	ψ_2 = 2.5 deg
$\bar{c}_3$ = 60 s	ψ_3 = 2.5 deg
T_1 = 30 s	V_o = 6 m/s
T_3 = 100 s	T_s = 10 s
T_4 = 300 s	γ = 0.05

A special indicator M_y is used to describe the actual yaw phase, i.e. M_y = 0, 1, 2, 3, 4 corresponds to phase 0, 1, 2, 3, 4, resp. Notice that it is possible to use the non-filtered measurements instead of the Kalman filter estimates in the yaw regulator. The special speed scaling used in the yaw regulator will approximately give the same performance of the yaw rate and the heading independent of the forward speed. The rudder deviations, however, are increased proportional to $(V_o/V_s)^2$ when the speed is decreased.

4. DISCUSSION OF THE EXPERIMENTS

All the experiments are described in Appendix D, where also plots of the recorded variables are shown. A complete summary of the experiments is given in the Tables D.1 - D.6 at the beginning of Appendix D.

To make it possible to compare the steering quality of different autopilot structures, two loss functions are now introduced:

$$V_1 = \frac{1}{\tau} \int_0^\tau \left[(\psi(t) - \psi_{ref})^2 + \lambda(\delta_c(t) - m_{\delta_c})^2 \right] dt \tag{4.1}$$

and

$$V_2 = \frac{1}{\tau} \int_0^\tau \left[(\psi(t) - \psi_{ref})^2 + \lambda(\delta(t) - m_\delta(t))^2 \right] dt \tag{4.2}$$

where the mean values of δ_c and δ are denoted m_{δ_c} and m_δ, resp., and the weighting factor λ is equal to 1/12. The duration of the experiment is denoted τ. The loss functions are approximated by:

$$V_1 = \frac{1}{N_1} \sum_{n=0}^{N_1-1} \left[(\psi(nT_s) - \psi_{ref})^2 + \lambda(\delta_c(nT_s) - m_{\delta_c})^2 \right] \tag{4.3}$$

and

$$V_2 = \frac{1}{N_2} \sum_{n=0}^{N_2-1} \left[(\psi(nh) - \psi_{ref})^2 + \lambda(\delta(nh) - m_\delta(nh))^2 \right] \tag{4.4}$$

where $N_1 T_s = \tau$ and $N_2 h = \tau$, resp. Notice that T_s is the sampling interval of the regulator, usually equal to 10 s, while h always is equal to 1 s. The loss function V_1 is used to compare the experiments A1 - A36, while the loss function V_2 is computed during experiments F1 - F4.

4.1 Kalman Filter Testing

The Kalman filter was running during all the experiments. Discussions and comparisons of some of the experiments are given in this section.

Three experiments, B1 - B3, were performed to test the Kalman filter by recording some of the estimates at the same sampling rate as the filter was running at, i.e. with sampling interval 1 s. The wind velocity during the experiments was 6, 8, and 15 m/s, resp., and the forward speed was 13.7, 13.3, and 15.9 knots, resp. The experiments are summarized in Table D.2 of Appendix D. It can be concluded from the plots that the performance of the Kalman filter seems to be very good in the different wind and speed conditions. Notice, however, that the yaw rate measurements are filtered in a rather hard way, although the filtering is not at all unreasonable. Another yaw rate estimate $\hat{r}_d$ is also computed every second:

$$\hat{r}_d(t) = \frac{\psi(t) - \psi(t-5)}{5} \tag{4.5}$$

It can be concluded that these estimates are not at all as smooth as the Kalman filter estimates, but that they are preferable compared to the measurements. By use of the measurement devices of the heading and the yaw rate, which are installed on the Sea Stratus, it thus can be concluded that a yaw rate estimate computed by the difference approximation formula (4.5) seems to be preferable in front of the noisy measurement signal r.

A summary of 8 experiments of straight course keeping by the self-tuning regulator using Kalman filter estimates, when the measurement signals used by the filter are varied, is given in Table 4.1. The Kalman filter estimates obtained when δ, v_1 or r is not used by the filter, experiments A22, A23, and A24, resp., are approximately of the same

Experiment	Rel. wind direction	Wind velocity [m/s]	δ_c		$\psi-\psi_{ref}$		Mean value of u [knots]	V_1	Remarks
			Mean value [deg]	Std. dev. [deg]	Mean value [deg]	Std. dev. [deg]			
A 19	1	9	0.45	1.11	-0.005	0.176	13.0	0.134	
A 22	1	13	2.32	0.95	-0.006	0.204	12.8	0.117	δ not used by filter
A 23	1	13	1.71	0.94	0.015	0.217	12.6	0.121	v_1 not used by filter
A 24	1	14	1.34	1.25	0.130	0.317	12.5	0.248	r not used by filter
A 25	1	14	1.25	0.90	-0.034	0.240	12.5	0.126	After 9.5 min, ψ was not used by filter
A 26	1	6	0.24	0.89	0.030	0.230	13.4	0.120	v_1, r and δ not used by filter. Correct K.
A 27	1	7	0.30	0.92	0.043	0.197	13.2	0.111	v_1, r and δ not used by filter
A 28	1	4	0.16	0.95	0.006	0.239	13.5	0.132	

Table 4.1 - Experiments of straight course keeping by the self-tuning regulator using Kalman filter estimates, when the measurement signals used by the filter are varied. If nothing else is remarked, all measurement signals v_1, r, ψ, and δ are used by the Kalman filter. An explanation of the relative wind direction is given in Appendix A. The tuning time before the experiment started was equal to 30 min. The following standard values are used: $T_s = 10$ s, $V_0 = 6$ m/s, IVVC = 1, NC1 = 1, NC2 = 1, k = 7, and q = 0. The experiments were performed during a period of 3 days.

quality as the estimates obtained in experiments A19 and A28, where all the measurement signals are used. The steering performances obtained are also approximately of the same quality, with one exception; extraordinary disturbances seem to have affected experiment A24, where r is not used by the filter. Experiment A25 shows that it is possible to obtain an acceptable course keeping during at least 15 min after the heading measurement signal ψ is rejected by the filter.

The Kalman filter estimates obtained, when the only measurement signal used is the heading ψ, are quite acceptable, which can be concluded from experiments A26 and A27. It is also concluded that the difference between using a correctly designed filter gain K (cf. (3.7)) and cancelling the corresponding columns of the original filter gain is very insignificant. The steering performance obtained is approximately of the same quality, when the only measurement signal used by the Kalman filter is the heading ψ (experiments A26 and A27), compared to the performance obtained when all measurement signals are used (experiments A19 and A28). From the experiments of Table 4.1 it thus can be concluded that it is not necessary to use all the measurement signals to obtain a good performance of the Kalman filter. In fact, acceptable filter estimates are obtained when the only measurement signal used is the heading ψ.

By comparing experiment A14, where complete calm was prevailing, with experiment A22, where the wind velocity was 13 m/s, it can be concluded that the quality of the Kalman filter estimates is rather insensitive to wind changes. Experiments A34 and A35 show that the performance of the Kalman filter is approximately of the same quality at the forward speed 15.8 knots compared to the forward speed 12.1 knots.

Experiments A1, D2 and D3 show the initial performance of the Kalman filter. The bias estimates of the filter are approximately tuned after about 30 min.

The performance of the Kalman filter during turns is shown in experiments C1-C6 and D1. From experiments C1, C2, and D1 it is immediately concluded that it is very important to skip the updating of the bias estimates $\hat{\delta}_o'$, $\hat{d}_v'$, $\hat{d}_r'$, and $\hat{d}_\delta'$ when turning, because otherwise the bias estimates are disturbed significantly. The updating is skipped during experiments C3 and C4. From experiments C3-C6 it is concluded that the performance of the Kalman filter is approximately of the same good quality during turning as during straight course keeping. Experiments E1-E4 also illustrate the good performance of the Kalman filter.

Considering all the experiments it is obvious that the test values (3.6) of the Kalman filter are chosen too large, at least when the speed of the ship is larger than about 10 knots. The following non-normalized values seem to be suitable when the speed is about 13 knots:

$$\begin{aligned} t_\delta &= 10 \text{ deg} \\ t_v &= 0.15 \text{ knots} \\ t_r &= 0.15 \text{ deg/s} \\ t_\psi &= 0.3 \text{ deg} \end{aligned} \tag{4.6}$$

Then the normalized test values are (cf. (3.6)):

$$\begin{aligned} t_\delta' &= 0.17 \\ t_v' &= 0.012 \\ t_r' &= 0.14 \\ t_\psi' &= 0.0052 \end{aligned} \tag{4.7}$$

The test values (4.7) seem to be reasonable when the speed is larger than about 10 knots, while the values (3.6), obtained from simulations in Källström (1976c), are suitable at lower speeds.

4.2 Straight Course Keeping

Experiments of straight course keeping by the self-tuning regulator using Kalman filter estimates, when the parameters T_s, V_o, NC1, NC2, k and q are varied, are summarized in Table 4.2.

The straight course keeping is mainly affected by the value of the design speed V_o during the initial phase, when the parameters of the self-tuning regulator not yet are tuned. However, from experiments A2, A5, A6, and A10 it can be concluded that V_o = 7 m/s is to prefer in front of V_o = 6 m/s. Since the parameter V_o also is used in the yaw regulator, the value 6 m/s is nevertheless used during most of the experiments by reasons explained in Section 4.3.

By comparing experiments A2-A9 it is concluded that T_s = 10 s, k = 7 (experiments A2, A5, A6) in average is the best choice. An acceptable alternative is T_s = 15 s, k = 5 (experiment A9). Experiments A10-A13 show clearly that the best steering performance is obtained when q = 0.

The importance of the feedforward signals is illustrated by experiments A15-A17. It is concluded that the quality of the steering performance is significantly decreased when both feedforward signals are omitted. The comparative experiment A14 was unfortunately disturbed by a temporarily reduction of the number of propeller revolutions immediately before the experiment started. No comparisons with experiment A14 are thus performed.

Experiment	Rel. wind dir.	Wind velocity [m/s]	T_s [s]	V_0 [m/s]	Structure of self-tuning regulator				δ_c		$\psi - \psi_{ref}$		Mean value of u [knots]	V_1	Remarks
					NC1	NC2	k	q	Mean value [deg]	Std. dev. [deg]	Mean value [deg]	Std. dev. [deg]			
A 2	5	5	10	7	1	1	7	0	0.41	1.14	0.017	0.182	13.9	0.142	Tuning time: > 120 min.
A 3	5	10	10	7	1	1	5	0	0.74	1.20	0.009	0.239	14.2	0.177	
A 4	5	5	10	7	1	1	6	0	1.39	1.41	-0.009	0.246	14.0	0.226	
A 5	5	4	10	7	1	1	7	0	0.66	1.17	0.014	0.219	14.0	0.162	
A 6	4	4	10	7	1	1	7	0	-0.73	1.32	-0.051	0.290	13.5	0.232	
A 7	3	4	10	7	1	1	8	0	-0.17	1.19	0.034	0.260	14.1	0.187	
A 8	5	4	15	6	1	1	4	0	0.17	1.46	-0.027	0.309	13.9	0.274	
A 9	5	4	15	6	1	1	5	0	0.05	1.24	-0.022	0.301	13.8	0.219	
A 10	5	3	10	6	1	1	7	0	0.08	1.62	0.013	0.344	13.7	0.337	
A 11	5	3	10	6	1	1	6	0.05	-0.06	1.79	-0.033	0.400	13.9	0.428	
A 12	5	3	10	6	1	1	6	0.1	0.05	1.69	0.013	0.444	13.7	0.435	
A 13	6	3	10	6	1	1	6	0.2	0.24	1.84	0.016	0.420	13.6	0.459	The speed was reduced.
A 14	-	0	10	6	1	1	7	0	-0.61	1.66	-0.017	0.111	13.5	0.242	Tuning time: > 120 min.
A 15	-	0	10	6	1	0	7	0	-0.68	0.82	0.015	0.158	13.3	0.081	
A 16	1	5	10	6	0	1	7	0	-0.43	0.62	-0.066	0.169	12.9	0.065	
A 17	1	5	10	6	0	0	7	0	0.01	0.89	-0.188	0.247	12.9	0.162	

Table 4.2 - Experiments of straight course keeping by the self-tuning regulator using Kalman filter estimates, when the parameters T_s, V_0, NC1, NC2, k and q are varied. All measurement signals v_1, r, ψ and δ are used by the Kalman filter. An explanation of the relative wind direction is given in Appendix A. The tuning time before the experiment started was equal to 30 min, if nothing else is remarked. The value of IVVC is equal to 1. The experiments were performed during a period of 3 days.

The following standard parameter values are used during most of the remaining experiments:

$$
\begin{aligned}
T_s &= 10 \text{ s} \\
V_0 &= 6 \text{ m/s} \\
\text{IVVC} &= 1 \\
\text{NC1} &= 1 \\
\text{NC2} &= 1 \\
k &= 7 \\
q &= 0
\end{aligned}
\tag{4.8}
$$

The good performance of the self-tuning regulator in different weather conditions is illustrated by e.g. experiments A15 and A22, where the wind velocity was 0 resp. 13 m/s. Experiments A34 and A36 show the good performance of the self-tuning regulator when the forward speed was 15.8 resp. 12.1 knots.

Experiments A1, D2 and D3 show the initial performance of the self-tuning regulator when the autopilot is switched on. It is concluded that the steering quality is quite acceptable from the beginning. Experiment D3 also illustrates the performance of the self-tuning regulator in connection with the Sailmaster and the Course Correction. From experiments C1-C6 and D1 it is concluded that the self-tuning regulator has no initial problems after the yaw regulator has terminated a turn.

Straight course keeping experiments to compare the performance of the self-tuning regulator and the PID-regulator are summarized in Table 4.3. The performance of both the self-tuning regulator and the PID-regulator is improved when Kalman filter estimates are used instead of non--filtered measurements. When Kalman filter estimates are used, the performance of the self-tuning regulator is

Ex-peri-ment	Rel. wind dir.	Wind velo-city [m/s]	NC1	NC2	δ_c		$\psi-\psi_{ref}$		Mean value of u [knots]	V_1	V_2
					Mean value [deg]	Std. dev. [deg]	Mean value [deg]	Std. dev. [deg]			
A 16	1	5	0	1	-0.43	0.62	-0.066	0.169	12.9	0.065	-
A 17	1	5	0	0	0.01	0.89	-0.188	0.247	12.9	0.162	-
A 18	1	5	0	0	0.24	1.01	-0.052	0.245	12.8	0.148	-
A 19	1	9	1	1	0.45	1.11	-0.005	0.176	13.0	0.134	-
A 20	1	9	-	-	0.53	2.48	0.026	0.556	13.1	0.822	-
A 21	1	4	-	-	0.53	0.91	-0.018	0.293	12.9	0.155	-
A 27	1	7	1	1	0.30	0.92	0.043	0.197	13.2	0.111	-
A 28	1	4	1	1	0.16	0.95	0.006	0.239	13.5	0.132	-
A 29	1	3	0	0	-0.01	1.51	0.001	0.324	13.4	0.295	-
A 30	1	5	-	-	-0.10	0.89	-0.026	0.256	13.5	0.132	-
A 31	1	3	-	-	0.22	2.41	-0.103	1.085	13.4	1.672	-
A 35	1	11	-	-	0.01	1.66	0.008	0.295	12.1	0.317	-
A 36	1	11	1	1	-0.05	1.08	-0.058	0.206	12.1	0.143	-
F 1	6	3	1	1	-	-	-0.002	-	14.4	-	0.038
F 2	7	3	-	-	-	-	-0.016	-	14.4	-	0.259
F 3	1	11	1	1	-	-	-0.073	-	12.1	-	0.160
F 4	1	11	-	-	-	-	-0.009	-	12.2	-	0.304

Table 4.3 - Comparable straight course keeping experiments. An explanation of the relative wind direction is given in Appendix A. All measurement signals v_1, r, ψ and δ are used by the Kalman filter, if nothing else is remarked. The following standard values are used, if nothing else is remarked: T_s = 10 s, V_0 = 6 m/s, IVVC = 1, k = 7, q = 0, k_P = 3, k_D = 75 s, k_I = 0.02 1/s. The standard values of the PID-regulator are obtained by simulations, see Källström (1976c). The standard values are used in the experiments A20, A21, and F2, while the values of k_P, k_D, and k_I were manually tuned before the experiments A30, A31, A35, and F4 started. The groups of experiments A16-A21 and A27-A31 were both performed during a period of 6 h, while the groups A35-A36, F1-F2, and F3-F4 were performed during a period of 2 h each. The experiments within each group are fairly comparable.

Experiment	Kalman filter estimates used		Non-filtered measurements used		Remarks
	Self-tuning regulator	PID-regulator	Self-tuning regulator	PID-regulator	
A 16	x				
A 17	x				
A 18			x		
A 19	x				
A 20				x	
A 21		x			
A 27	x				v_1, r and δ not used by filter.
A 28	x				
A 29			x		
A 30		x			k_D = 120 s.
A 31				x	k_P = 2, k_D = 100 s.
A 35		x			k_D = 140 s.
A 36	x				
F 1	x				V_0 = 8 m/s, IVVC = 3, V_c = 7 m/s. v_1 not used by filter. Sailmaster.
F 2				x	V_0 = 8 m/s, IVVC = 3, V_c = 7 m/s. Sailmaster.
F 3	x				
F 4		x			k_D = 140 s.

Table 4.3 - Continued.

significantly better than the performance of the PID-regulator, particularly when the wind speed is increased. The good steering quality of the self-tuning regulator compared to the PID-regulator is still more emphasized, when non-filtered measurements are used in both regulators. Of course, the self-tuning regulator using Kalman filter estimates is consequently also to prefer in front of the PID-regulator using non-filtered measurements. Finally, it is not possible to conclude anything definitively when the self-tuning regulator using non-filtered measurements is compared to the PID-regulator using Kalman filter estimates.

It is now possible to sum up that, even if the heading is the only measurement signal available, a self-tuning regulator with the standard values (4.8) combined with a Kalman filter is very much advantageous to a well tuned PID-regulator.

4.3 Yawing

Experiments C1-C6 and D1 show turns performed by the yaw regulator. The Kalman filter estimates were fed into both the self-tuning regulator and the yaw regulator during all the experiments, which are summarized in Tables D.3 and D.4 of Appendix D.

It is concluded from experimen D1, where V_0 = 8 m/s, that the rudder deviations are too large during phase 4. A simple way to improve the performance of the yaw regulator in this respect is to decrease the value of V_0. Thus V_0 = 7 m/s during experiment C1 and V_0 = 6 m/s during experiments C2-C6. Experiments C1, C2 and D1 show the importance of skipping the updating of the bias estimates

$\hat{\delta}_0'$, $\hat{d}_v'$, $\hat{d}_r'$, and $\hat{d}_\delta'$ during large course changes. This is performed during experiments C3 and C4, where the very good performance of the yaw regulator for large turns is illustrated. The same good performance for small course changes is shown in experiments C5 and C6.

4.4 Experiments for Identification

Two different kinds of identification experiments were performed, viz. open loop experiments (E1, E2, E4) and closed loop experiment using additive rudder disturbances (E3). The experiments are summarized in Table D.5 of Appendix D. The sampling interval was equal to 10 s. Notice that experiment E2 is a $5^o/5^o$ zig-zag test. The rudder commands δ_c during experiments E1 and E4 and the additive rudder disturbances δ_{add} during experiment E3 were approximately chosen as a PRBS containing the values $+\delta_{amp}$, $-\delta_{amp}$, and zero.

The feedback is explained by Fig. 4.1. The rudder command δ_c is obtained as

$$\delta_c = -k_{id}(\psi-\psi_{ref}) + \delta_{add}$$

Obviously an open loop experiment is performed by assigning k_{id} the value zero.

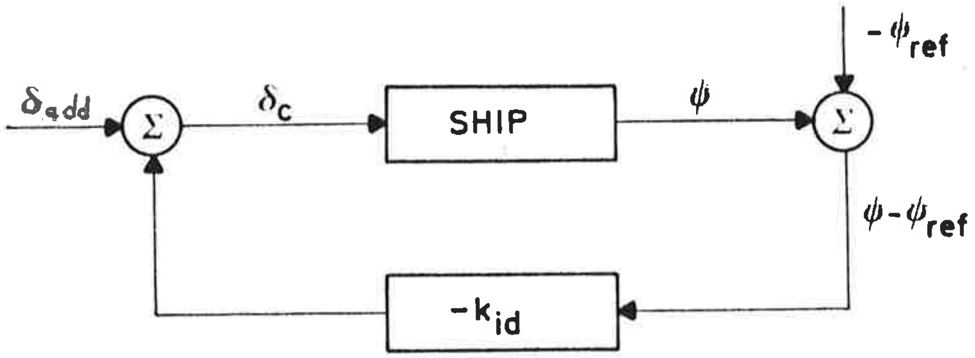


Fig. 4.1 - Proportional feedback from the course error used for identification experiments.

5. CONCLUSIONS

An adaptive autopilot, consisting of a Kalman filter, a self-tuning regulator and a yaw regulator, was tested on a ballasted 355 000 tdw oil tanker. Comparative straight course keeping experiments with a well tuned PID-regulator were also performed. The average speed of the ship varied between 12.1 knots and 15.9 knots during the experiments. The range of the wind velocity measured was 0-15 m/s, which corresponds to complete calm and moderate gale. Fifty-six experiments were performed during a total time of 33 h. The testing, however, was in fact going on during almost all the days and nights of the voyage , i.e. during about 2 weeks.

The performance of the Kalman filter was very good in the different speed and wind conditions during straight course keeping as well as during turning. Notice, however, that it is important to skip the updating of the bias estimates during turns. Usually all measurement signals, i.e. the transversal velocity of bow, the yaw rate, the heading and the rudder angle were used by the Kalman filter. However, the performance, when the only measurement signal used was the heading angle, was approximately of the same quality as the performance when all measurement signals were used. One experiment showed that it was possible to obtain an acceptable course keeping during at least 15 min. after the heading measurement signal was rejected by the Kalman filter, when the three other measurement signals were used. The initial performance of the Kalman filter, when the autopilot was switched on, was quite acceptable and the bias estimates were approximately tuned after about 30 min.

The straight course keeping performance of the self-tuning regulator using Kalman filter estimates was very good in the different speed and wind conditions. The use of the estimates of transversal velocity and yaw rate as feedforward signals was improving the steering quality significantly, even if the only measurement signal used by the Kalman filter was the heading angle. The initial performance of the self-tuning regulator when the auto-pilot was switched on as well as the performance after the termination of a turn was quite satisfactory.

The performance of both the self-tuning regulator and the PID-regulator was improved when Kalman filter estimates were used instead of non-filtered measurements. When Kalman filter estimates were used, the performance of the self-tuning regulator was significantly better than the performance of the PID-regulator, particularly when the wind speed was increased. The good steering quality of the self-tuning regulator compared to the PID-regulator was still more emphasized when non-filtered measurements were used in both regulators. The self-tuning regulator using Kalman filter estimates was consequently also to prefer in front of the PID-regulator using non-filtered measurements. It was not possible to conclude anything definitively when the self-tuning regulator using non-filtered measurements was compared to the PID-regulator using Kalman filter estimates.

The yaw regulator was tested by performing small course changes as well as large turns. The performance was very good in both cases.

It is now possible to confirm a rather good consistency between the experiments on the Sea Stratus and the simulations reported in Källström (1976c). However, the performance of a well tuned PID-regulator seems to be over-estimated in simulations compared to full-scale experiments.

6. ACKNOWLEDGEMENTS

I would like to express my gratitude to the Salén Shipping Co for their willingness to allow experiments to be performed with their ship. I am particularly grateful to the captain of the Sea Stratus, Mr B Svensson.

This work has been supported by the Swedish Board for Technical Development under contracts 734187 and 744127.

7. REFERENCES

Aspernäs B and Foisack P (1975), "Simulering av styrsystem för tankfartyg", TFRT-5154, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Aspernäs B and Källström C (1975), "Simulering av adaptiv fartygsstyrning med Kalmanfilter", TFRT-3123, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Källström C (1974), "The Sea Scout Experiments, October 1973", TFRT-7063, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Källström C (1975), "The Sea Swift Experiments, October 1974", TFRT-7078, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Källström C (1976a), "Simulation of Adaptive Ship Steering with Penalty on the Rudder Motion", TFRT-3133, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Källström C (1976b), "Simulation of Ship Yawing", Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, CODEN: LUTFD2/(TFRT-7108)/1-092/(1976).

Källström C (1976c), "Simulation of Ship Steering", Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, CODEN: LUTFD2/(TFRT-7109)/1-353/(1976).

Wittenmark B (1973), "A Self-tuning Regulator", TFRT-3054, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

APPENDIX A - NOTATIONS

A	system matrix of Kalman filter
a_i, $i = 1,2,...$	parameters of self-tuning regulator
a_{ij}, $i=1,2,...,$ $j=1,2,...$	elements of system matrix A
B	system matrix of Kalman filter
BV	weighting factor
b_0	parameter of self-tuning regulator
b_i, $i = 1,2,...$	parameters of self-tuning regulator
b_{i1}, $i = 1,2,3,4$	elements of system matrix B
C	system matrix of Kalman filter
CGR	conversion factor from degrees to radians
CKM	conversion factor from knots to m/s
c_1, c_2	parameters of self-tuning regulator
$\bar{c}_1$, $\bar{c}_2$, $\bar{c}_3$	parameters of yaw regulator
$\hat{d}_v$, $\hat{d}_r$, $\hat{d}_\delta$	estimated measurement biases of v_1, r, and δ, resp.
$\hat{d}'_v$, $\hat{d}'_r$, $\hat{d}'_\delta$	normalized estimates corresponding to $\hat{d}_v$, $\hat{d}_r$, and $\hat{d}_\delta$, resp.
e	disturbances of the self-tuning regulator model
h	sampling interval of V_2
IDEXP	control parameter of AUTP3
IFLAG	control parameter of printing and punching
IKAL	control parameter of AUTP3
IKMX	number of times the measurement testing is skipped when the Kalman filter is initialized
ILOS	control parameter of AUTP3

IMX	number of consecutive times a measurement signal must be rejected to definitively reject the signal
IPC	control parameter of punching
IPID	control parameter of AUTP3
IPK	control parameter of punching
IPR	sampling interval of punching
IREGY	sampling interval of yaw regulator
IREGYT	sampling interval of yaw testing
IST	control parameter of AUTP3
IVVC	control parameter of computation of V_s
IYAW	control parameter of AUTP3
J_1, J_2, J_3	criteria of self-tuning regulator
K	gain matrix of Kalman filter
k	number of pure time-delays of self-tuning regulator
k_P, k_D, k_I	parameters of PID-regulator
k_{id}	parameter of P-regulator used for identification experiments
k_i, $i = 1,2,\ldots,8$	parameters of yaw regulator
L	length of ship
ℓ_1	distance from origin to forward doppler log
MEAS	control parameter vector of AUTP3
M_Y	yaw phase indicator
m_δ	mean value of δ
m_{δ_c}	mean value of δ_c
NA	number of a-parameters of self-tuning regulator
NB	number of b-parameters of self-tuning regulator

NC1	indicator of parameter c_1 of self-tuning regulator
NC2	indicator of parameter c_2 of self-tuning regulator
N_1, N_2	number of sampling events to compute V_1 and V_2, resp.
n	number of propeller revolutions
P	covariance matrix of self-tuning regulator
PI	parameter of AUTP3 containing π
PI2	parameter of AUTP3 containing $2 \times \pi$
PP0	vector containing initial diagonal values of P
PSI0	reference course used for identification experiments
P_s	propeller effect
q	penalty on rudder deviation when self-tuning regulator is used
q_2	weighting factor of J_2 and J_3
R_1	covariance matrix of process noise
r	yaw rate
$\hat{r}$	estimated yaw rate
$\hat{r}'$	normalized estimate corresponding to $\hat{r}$
$\hat{r}_d$	estimated yaw rate computed by difference approximation
r_{ref}	reference value of yaw rate
r_0	reference value of yaw rate including sign
TH0	vector containing initial parameter values of self-tuning regulator
T_k	sampling interval of Kalman filter
T_s	sampling interval
T_1, T_3, T_4	parameters of yaw regulator

t	time
t_0	initial time
t_δ, t_v, t_r, t_ψ	test values of Kalman filter for δ, v_1, r, and ψ, resp.
t'_δ, t'_v, t'_r, t'_ψ	normalized test values corresponding to t_δ, t_v, t_r, and t_ψ, resp.
u	forward velocity
u'	normalized input signal of Kalman filter
VMAX	parameter of AUTP3
VMIN	parameter of AUTP3
V_c	parameter containing a constant forward velocity
V_s	scaling speed
V_0	design speed
V_1, V_2	loss functions
v	transversal velocity of origin
$\hat{v}$	estimated transversal velocity of origin
$\hat{v}'$	normalized estimate corresponding to $\hat{v}$
v_1	transversal velocity of bow
$\hat{v}_1$	estimated transversal velocity of bow
$\hat{x}$	state estimate vector of Kalman filter
$\hat{x}'$	normalized state estimate vector of Kalman filter
y'	Normalized measurement vector of Kalman filter
γ	parameter of yaw regulator
$\Delta\psi_{ref}$	change of reference value of course
δ	rudder angle
$\hat{\delta}$	estimated rudder angle

$\hat{\delta}'$	normalized estimate corresponding to $\hat{\delta}$
δ_{add}	additive rudder disturbance signal used for identification experiments
δ_{amp}	rudder amplitude used for identification experiments
δ_c	rudder command
$\bar{\delta}_c$	moving average value of δ_c
$\hat{\delta}_d$	estimated value equal to $\hat{\delta}-\hat{\delta}_0$
$\hat{\delta}'_d$	normalized estimate corresponding to $\hat{\delta}_d$
δ_ℓ	rudder limit
δ_s	rudder servo position
$\hat{\delta}_0$	estimated rudder bias
$\hat{\delta}'_0$	normalized estimate corresponding to $\hat{\delta}_0$
ε	residual vector of Kalman filter
ε'	normalized residual vector of Kalman filter
ε_δ, ε_v, ε_r, ε_ψ	elements of residual vector ε
ε'_δ, ε'_v, ε'_r, ε_ψ	normalized values corresponding to ε_δ, ε_v, ε_r, and ε_ψ, resp., i.e. elements of normalized residual vector ε'
ε_1, ε_2, ε_3,	parameters of yaw regulator
λ	weighting factor of V_1 and V_2
λ_f	exponential forgetting factor of self-tuning regulator
τ	duration of experiment
ψ	heading angle
$\hat{\psi}$	estimated heading angle
$\hat{\psi}'$	normalized estimate corresponding to $\hat{\psi}$
ψ_{ref}	reference value of course
ψ_1, ψ_2, ψ_3	parameters of yaw regulator
∇	change of value (e.g. $\nabla\delta_c(t) = \delta_c(t) - \delta_c(t-1)$)

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

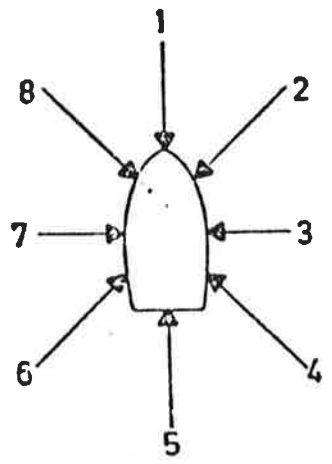


Fig. A.1 - Explanation of the relative wind direction. Notice that the absolute wind is used.

APPENDIX B - STANDARD PARAMETER VALUES

The standard parameter values of the autopilot used during the experiments are summarized in this appendix. When the notation used in this report differs from the variable name used in the computer programs, the latter name is given in brackets.

IDEXP	0
IFLAG	30
MEAS(1)	0
MEAS(2)	0
MEAS(3)	0
MEAS(4)	0
CGR	0.0174533
CKM	0.514444
PI	3.141593
PI2	6.283185
L (AL)	350
ℓ_1 (AL1)	164.35
a_{11} (A(1))	0.99163
a_{12} (A(2))	-0.0100810
a_{14} (A(3))	-0.00208207
a_{15} (A(4))	0.000212358
a_{21} (A(5))	-0.0759537
a_{22} (A(6))	0.96485
a_{24} (A(7))	0.0164706
a_{25} (A(8))	-0.00170991
a_{31} (A(9))	-0.000874514

a_{32}	(A(10))	0.0224515
a_{34}	(A(11))	0.000195418
a_{35}	(A(12))	-0.0000132723
a_{44}	(A(13))	0.81873
a_{45}	(A(14))	-0.18127
b_{11}	(A(15))	-0.000212358
b_{21}	(A(16))	0.00170991
b_{31}	(A(17))	0.0000132723
b_{41}	(A(18))	0.18127
K(1,1)	(AK(1,1))	$-9.27\cdot10^{-5}$
K(2,1)	(AK(2,1))	$6.30\cdot10^{-4}$
K(3,1)	(AK(3,1))	$1.69\cdot10^{-5}$
K(4,1)	(AK(4,1))	$1.66\cdot10^{-2}$
K(5,1)	(AK(5,1))	$1.03\cdot10^{-3}$
K(6,1)	(AK(6,1))	$-1.26\cdot10^{-4}$
K(7,1)	(AK(7,1))	$1.63\cdot10^{-6}$
K(8,1)	(AK(8,1))	$2.54\cdot10^{-3}$
K(1,2)	(AK(1,2))	$8.82\cdot10^{-2}$
K(2,2)	(AK(2,2))	0.481
K(3,2)	(AK(3,2))	$7.86\cdot10^{-3}$
K(4,2)	(AK(4,2))	$-2.90\cdot10^{-3}$
K(5,2)	(AK(5,2))	$2.98\cdot10^{-3}$
K(6,2)	(AK(6,2))	$2.00\cdot10^{-2}$
K(7,2)	(AK(7,2))	$-1.68\cdot10^{-3}$
K(8,2)	(AK(8,2))	$7.61\cdot10^{-6}$
K(1,3)	(AK(1,3))	$-2.40\cdot10^{-2}$
K(2,3)	(AK(2,3))	$9.65\cdot10^{-2}$
K(3,3)	(AK(3,3))	$3.14\cdot10^{-3}$

K(4,3)	(AK(4,3))	$5.65 \cdot 10^{-3}$
K(5,3)	(AK(5,3))	$-5.63 \cdot 10^{-3}$
K(6,3)	(AK(6,3))	$-6.69 \cdot 10^{-5}$
K(7,3)	(AK(7,3))	$3.02 \cdot 10^{-3}$
K(8,3)	(AK(8,3))	$1.24 \cdot 10^{-5}$
K(1,4)	(AK(1,4))	-0.367
K(2,4)	(AK(2,4))	1.02
K(3,4)	(AK(3,4))	0.326
K(4,4)	(AK(4,4))	$6.51 \cdot 10^{-2}$
K(5,4)	(AK(5,4))	$-6.49 \cdot 10^{-2}$
K(6,4)	(AK(6,4))	$-5.06 \cdot 10^{-3}$
K(7,4)	(AK(7,4))	$-5.77 \cdot 10^{-2}$
K(8,4)	(AK(8,4))	$1.41 \cdot 10^{-4}$
t'_δ	(TEST(1))	1
t'_v	(TEST(2))	0.06
t'_r	(TEST(3))	0.25
t'_ψ	(TEST(4))	0.015
V_c	(VCONST)	8
VMIN		0.2
VMAX		12
V_0	(V0)	6
THO(1)	(initial value of $-a_1$)	6.91
THO(2)	(" - $-a_2$)	-5.95
THO(3)	(" - $-a_3$)	-3.88
THO(4)	(" - $-a_4$)	3.57
THO(5)	(" - b_1)	0.48
THO(6)	(" - b_2)	0.11
THO(7)	(" - c_1)	-2.10
THO(8)	(" - c_2)	34.73

THO(9)		0
THO(10)		0
PPO(1)	(initial value of P(1,1))	1
PPO(2)	(" - P(2,2))	1
PPO(3)	(" - P(3,3))	1
PPO(4)	(" - P(4,4))	1
PPO(5)	(" - P(5,5))	0.01
PPO(6)	(" - P(6,6))	0.01
PPO(7)	(" - P(7,7))	1
PPO(8)	(" - P(8,8))	100
PPO(9)		0
PPO(10)		0
λ_f	(RL)	0.99
b_0	(B0)	1
q	(Q2)	0
k_P	(AK1)	3
k_D	(AK2)	75
k_I	(AK3)	0.02
ψ_1	(Y(1))	0.35
ψ_2	(Y(2))	2.5
ψ_3	(Y(3))	2.5
ε_1	(Y(4))	0
ε_2	(Y(5))	0.02
ε_3	(Y(6))	1
$\bar{c}_1$	(Y(7))	60
$\bar{c}_2$	(Y(8))	50
$\bar{c}_3$	(Y(9))	60
k_1	(Y(10))	5
k_2	(Y(11))	200

k_3 (Y(12))	0.005
k_4 (Y(13))	200
k_5 (Y(14))	200
k_6 (Y(15))	8
k_7 (Y(16))	2
k_8 (Y(17))	200
γ (BD)	0.05
BV	0.05
λ (ALAM)	0.0833333
δ_{amp} (DELAMP)	3
PSI0	0
k_{id} (AKID)	0
T_k (IREGK)	1
IKAL	1
IKMX	900
IMX	10
IVVC	1
ILOS	1
IREGYT	5
T_s (IREG)	10
IPID	0
IST	2
NA	4
NB	2
NC1	1
NC2	1
k (K)	7
IREGY	10

IYAW	2
T_1 (IT1Y)	30
T_3 (IT3Y)	100
T_4 (IT4Y)	300
IPK	0
IPC	0
IPR	0

```
      SUBROUTINE AUTP3
C
C     AUTOPILOT FOR SHIP, INCLUDING KALMAN FILTER,
C     SELF-TUNING REGULATOR AND PID-REGULATOR FOR
C     STRAIGHT COURSE KEEPING, AND YAW REGULATOR.
C
C     AUTHOR, C.KALLSTROM 1976-02-22.
C     REVISED, C.KALLSTROM 1976-04-04.
C
C     SUBROUTINE REQUIRED
C          STUR
C          COSC
C
      COMMON /DATA/ ITIME,IDELC,MODYAW,IDEXP,ISTBD,IPORT,
     *   IFLAG,IPRINT,INAUT,IKX,MEAS(4),
     *   DELCO,DELTA(2),V1(2),R(2),PSI(2),DELO,DELCOM,DELTAS,U,AN,
     *   P,VEST,PSIREF,RREF,DLIM,V(2),DELTA0,D1,D2,D3,TH(10),
     *   CGR,CKM,PI,PI2,AL,AL1,A(18),
     *   AK(8,4),TEST(4),VCONST,VMIN,VMAX,V0,TH0(10),
     *   PP0(10),RL,B0,Q2,AK1,AK2,AK3,Y(17),
     *   BD,BV,ALAM,DELAMP,PSI0,AKID,
     *   IREGK,IKAL,IKMX,IMX,IVVC,ILOS,IREGYT,IREG,IPID,
     *   IST,NA,NB,NC1,NC2,K,IREGY,IYAW,IT1Y,IT3Y,IT4Y,IPK,IPC,IPR,
     *   EPS(4),VV,PP(55),VLOS(8),
     *   CN,EDELTA,EPSI2,VLOS2,ENM2,
     *   MEASUM(4),IVV1,
     *   X(8),VVV(3),V0V,V0V2,
     *   PF01,PF02,DELOLD,VOLD,ROLD,DAT(46),SINT,RRF,AINT2,
     *   AINT4,STD,STV,SL1,SL2,SL3,SL4,SL5,DUM(10),
     *   IRK,IMEAS(4),IRYT,IR,NC,NAB,NP,K1,NDAT,NDAT1,
     *   NU1,N1,IRY,ITIM1,ITIM3,ITIM4,IP,I,J,L
C
C     COMPUTE THE SWAY VELOCITY V(1).
C
      V(1)=V1(1)-AL1*R(1)*CGR/CKM
C
      IF(INAUT) 80,80,10
C
C     INITIALIZE IF INAUT=1.
C
10    IVV1=IVVC
      VVV(1)=U*CKM
      VVV(2)=AN*0.18*CKM
      VVV(3)=VCONST
12    IF(VVV(IVV1)-VMIN) 16,14,14
14    IF(VVV(IVV1)-VMAX) 18,18,16
16    IVV1=IVV1+1
      GO TO 12
18    VV=VVV(IVV1)
      V0V=V0/VV
      V0V2=V0V*V0V
      VEST=VV/CKM
C
      IRK=IREGK
      IKX=0
      DELCOM=0.
      DELCO=0.
      IF(IKAL) 50,50,20
C
20    IF(MEAS(1)) 22,22,24
22    X(4)=DELTA(1)*CGR
      GO TO 26
24    X(4)=0.
```

```
26      IF(MEAS(3)) 28,28,30
28      X(2)=R(1)*AL*CGR/VV
        GO TO 32
30      X(2)=0.
        GO TO 36
32      IF(MEAS(2)) 34,34,36
34      X(1)=V(1)*CKM/VV
        GO TO 38
36      X(1)=0.
38      IF(MEAS(4)) 40,40,999
40      X(3)=PSI(1)*CGR
        X(5)=0.
        X(6)=0.
        X(7)=0.
        X(8)=0.
        DO 42 I=1,4
        IMEAS(I)=0
42      MEASUM(I)=0
C
50      IRYT=IREGYT
        PFO1=PSI(1)
        MODYAW=0
        IR=IREG
        NC=NC1+NC2
        NAB=NA+NB
        NP=NAB+NC
        K1=K+1
        NDAT=NAB+(K1+1)*(NC+2)-2
        NDAT1=NDAT+1
        NU1=NA+K+2
        N1=NU1+K
        J=NU1-1
        SL1=PSI(1)-PSIREF
        IF(SL1 .LE. -180.) SL1=SL1+360.
        IF(SL1 .GT. 180.) SL1=SL1-360.
        DO 52 I=1,J
52      DAT(I)=SL1
        J=J+1
        DO 54 I=J,46
54      DAT(I)=0.
        DELOLD=0.
        VOLD=0.
        ROLD=0.
        SINT=0.
        DO 60 I=1,10
        DO 60 J=1,I
        L=I*(I-1)/2+J
        IF(I-J) 58,56,58
56      PP(L)=PP0(I)
        GO TO 60
58      PP(L)=0.
60      CONTINUE
        DO 62 I=1,10
62      TH(I)=TH0(I)
        EDELTA=0.
        STD=1.-BD
        EPSI2=0.
        VLOS2=0.
        ENM2=0.
        STV=1.-BV
        ISTBD=0
        IPORT=0
        IP=IPR
        INAUT=0
```

```
80      IF(IREGK) 200,200,90
90      IF(IRK-IREGK) 180,100,200
C
C       LOOP WITH SAMPLING INTERVAL IREGK.
C
100     IRK=1
        IF(IKAL) 140,140,102
C
C       KALMAN FILTER.
C
102     SL5=CGR*DELCOM
        SL1=A(1)*X(1)+A(2)*X(2)+A(3)*X(4)+A(4)*X(5)+A(15)*SL5
        SL2=A(5)*X(1)+A(6)*X(2)+A(7)*X(4)+A(8)*X(5)+A(16)*SL5
        SL3=A(9)*X(1)+A(10)*X(2)+X(3)+A(11)*X(4)+A(12)*X(5)+A(17)*SL5
        SL4=A(13)*X(4)+A(14)*X(5)+A(18)*SL5
        X(1)=SL1
        X(2)=SL2
        X(3)=SL3
        X(4)=SL4
C
        EPS(1)=DELTA(1)*CGR-X(4)-X(5)-X(8)
        EPS(2)=V1(1)*CKM/VV-X(1)-X(2)*AL1/AL-X(6)
        EPS(3)=R(1)*CGR*AL/VV-X(2)-X(7)
        EPS(4)=PSI(1)*CGR-X(3)
        IF(EPS(4) .LE. -PI) EPS(4)=EPS(4)+PI2
        IF(EPS(4) .GT. PI) EPS(4)=EPS(4)-PI2
C
        IF(IKX-IKMX) 104,108,108
104     IKX=IKX+1
        DO 106 I=1,4
106     IMEAS(I)=0
        GO TO 122
C
108     DO 120 I=1,4
        IF(MEAS(I)) 112,112,118
112     IF(ABS(EPS(I))-TEST(I)) 118,118,114
114     IMEAS(I)=IMEAS(I)+1
        MEASUM(I)=MEASUM(I)+1
        IF(IMEAS(I)-IMX) 120,116,116
116     MEAS(I)=1
118     IMEAS(I)=0
120     CONTINUE
C
122     DO 134 I=1,4
        IF(MEAS(I)+IMEAS(I)) 130,130,134
130     DO 132 J=1,8
        IF((J .EQ. 8) .AND. (MEAS(1) .GT. 0)) GO TO 132
        IF((J .EQ. 6) .AND. (MEAS(2) .GT. 0)) GO TO 132
        IF((J .EQ. 7) .AND. (MEAS(3) .GT. 0)) GO TO 132
        X(J)=X(J)+AK(J,I)*EPS(I)
132     CONTINUE
134     CONTINUE
C
        IF(X(3) .LT. 0.) X(3)=X(3)+PI2
        IF(X(3) .GE. PI2) X(3)=X(3)-PI2
C
        V(2)=VV*X(1)/CKM
        R(2)=VV*X(2)/(AL*CGR)
        PSI(2)=X(3)/CGR
        DELTA(2)=(X(4)+X(5))/CGR
        V1(2)=VV*(X(1)+X(2)*AL1/AL)/CKM
        DELTA0=X(5)/CGR
        D1=VV*X(6)/CKM
        D2=VV*X(7)/(AL*CGR)
```

```
      D3=X(8)/CGR
C
C     COMPUTE THE FORWARD SPEED VV.
C
140   VVV(1)=U*CKM
      VVV(2)=AN*0.18*CKM
      VVV(3)=VCONST
C
148   IF(VVV(IVV1)-VMIN) 152,150,150
150   IF(VVV(IVV1)-VMAX) 154,154,152
152   IVV1=IVV1+1
      GO TO 148
154   VV=VVV(IVV1)
      VOV=V0/VV
      VOV2=VOV*VOV
      VEST=VV/CKM
C
C     COMPUTE THE LOSS FUNCTIONS.
C
160   IF(ILOS) 170,166,162
162   ILOS=0
      CN=0.
      DO 164 I=1,8
164   VLOS(I)=0.
166   CN=CN+1.
      SL1=(CN-1.)/CN
      DO 168 I=1,2
      SL2=PSI(I)-PSIREF
      IF(SL2 .LE. -180.) SL2=SL2+360.
      IF(SL2 .GT. 180.) SL2=SL2-360.
      VLOS(I)=SL1*VLOS(I)+SL2/CN
      L=I+2
      VLOS(L)=SL1*VLOS(L)+DELTA(I)/CN
      L=L+2
      J=L-2
      VLOS(L)=SL1*VLOS(L)+(SL2*SL2+ALAM*(DELTA(I)-VLOS(J))*
     *    (DELTA(I)-VLOS(J)))/CN
      L=L+2
168   VLOS(L)=SL1*VLOS(L)+P/(CKM*U*COSC(SL2*CGR)*CN)
C
170   IF(IPK .GT. 0) IPRINT=1
      GO TO 200
C
180   IRK=IRK+1
C
200   IF(IDEXP) 201,201,700
C
C     LOOP WITH SAMPLING INTERVAL IREGYT FOR YAW TEST.
C
201   IF(IRYT-IREGYT) 206,202,208
C
202   IRYT=1
      SL1=PSIREF-PF01
      PF01=PSIREF
      IF(MODYAW) 204,204,300
204   PF02=PSIREF-SL1
      IF(SL1 .LE. -180.) SL1=SL1+360.
      IF(SL1 .GT. 180.) SL1=SL1-360.
      IF(ABS(SL1)-Y(1)) 500,500,302
C
206   IRYT=IRYT+1
C
208   IF(MODYAW) 500,500,300
C
```

```
C       LOOP WITH SAMPLING INTERVAL IREGY FOR YAWING.
C
300     IF(IRY-IREGY) 390,302,392
C
302     IRY=1
        SL1=PSIREF-PF02
        PF02=PSIREF
        IF(SL1 .LE. -180.) SL1=SL1+360.
        IF(SL1 .GT. 180.) SL1=SL1-360.
        SL2=PSI(IYAW) - PSIREF
        IF(SL2 .LE. -180.) SL2=SL2+360.
        IF(SL2 .GT. 180.) SL2=SL2-360.
        IF(MODYAW) 309,309,304
304     IF(ABS(SL1)-Y(3)) 320,320,306
306     IF(MODYAW-2) 314,314,308
308     MODYAW=1
        ITIM1=-IREGY
309     IF(SL2) 310,310,312
310     RRF=RREF
        GO TO 320
312     RRF=-RREF
        GO TO 320
314     IF(RRF) 316,316,318
316     IF(SL2) 308,320,320
318     IF(SL2) 320,320,308
C
320     RRF=RREF*ABS(RRF)/RRF
        SL3=R(IYAW)-RRF
C
        IF(MODYAW) 322,322,324
322     IF(ABS(SL1)-Y(2)) 338,338,326
324     IF(MODYAW-2) 328,332,325
325     IF(MODYAW-4) 336,339,339
C
326     MODYAW=1
        ITIM1=-IREGY
328     ITIM1=ITIM1+IREGY
        IF(RRF .GE. 0. .AND. SL3 .GT. -Y(4)) GO TO 330
        IF(RRF .LT. 0. .AND. SL3 .LT. Y(4)) GO TO 330
        IF(ITIM1-IT1Y) 332,332,330
C
330     MODYAW=2
        AINT2=0.
332     IF(RRF .GE. 0. .AND. -Y(8)*R(IYAW) .LT. SL2) GO TO 334
        IF(RRF .LT. 0. .AND. -Y(8)*R(IYAW) .GT. SL2) GO TO 334
        IF(MODYAW-1) 340,340,350
C
334     MODYAW=3
        ITIM3=-IREGY
336     ITIM3=ITIM3+IREGY
        IF(ABS(R(IYAW)) .LT. Y(5)) GO TO 338
        IF(RRF .GE. 0. .AND. SL2 .GT. -Y(6)) GO TO 338
        IF(RRF .LT. 0. .AND. SL2 .LT. Y(6)) GO TO 338
        IF(ITIM3-IT3Y) 360,360,338
C
338     MODYAW=4
        ITIM4=-IREGY
        AINT4=0.
339     ITIM4=ITIM4+IREGY
        IF(ITIM4-IT4Y) 370,370,400
C
C       YAW PHASE 1.
C
340     SL4=Y(13)*SL3
```

```
      SL5=ABS(Y(7)*RRF)
      IF(SL4 .GT. SL5) SL4=SL5
      IF(SL4 .LT. -SL5) SL4=-SL5
      DELCOM=-VOV2*SL4+EDELTA
      GO TO 380
C
C     YAW PHASE 2.
C
350   DELCOM=-VOV2*(Y(14)*SL3+Y(15)*AINT2)+EDELTA
      AINT2=AINT2+SL3*FLOAT(IREGY)
      GO TO 380
C
C     YAW PHASE 3.
C
360   SL4=Y(16)*SL2+Y(17)*R(IYAW)
      SL5=ABS(Y(9)*RRF)
      IF(SL4 .GT. SL5) SL4=SL5
      IF(SL4 .LT. -SL5) SL4=-SL5
      DELCOM=-VOV2*SL4
      GO TO 380
C
C     YAW PHASE 4.
C
370   DELCOM=-VOV2*(Y(10)*SL2+Y(11)*R(IYAW)+Y(12)*AINT4)
      AINT4=AINT4+SL2*FLOAT(IREGY)
C
C
380   IF(DELCOM .GT. DLIM) DELCOM=DLIM
      IF(DELCOM .LT. -DLIM) DELCOM=-DLIM
      GO TO 600
C
390   IRY=IRY+1
C
392   GO TO 900
C
C     INITIALIZING OF STRAIGHT COURSE KEEPING.
C
400   J=NU1-1
      SL1=PSI(IST)-PSIREF
      IF(SL1 .LE. -180.) SL1=SL1+360.
      IF(SL1 .GT. 180.) SL1=SL1-360.
      DO 402 I=1,J
402   DAT(I)=SL1
      J=J+1
      DO 404 I=J,46
404   DAT(I)=0.
      DELOLD=EDELTA
      VOLD=V(IST)
      ROLD=R(IST)
      MODYAW=0
      SINT=0.
      GO TO 502
C
C     LOOP WITH SAMPLING INTERVAL IREG FOR STRAIGHT COURSE KEEPING.
C
500   IF(IR-IREG) 540,502,542
C
502   IR=1
      SL1=PSI(IST)-PSIREF
      IF(SL1 .LE. -180.) SL1=SL1+360.
      IF(SL1 .GT. 180.) SL1=SL1-360.
      IF(IPID) 504,504,520
C
504   SL2=V(IST)-VOLD
```

```
      SL3=R(IST)-ROLD
      VOLD=V(IST)
      ROLD=R(IST)
      DAT(1)=SL1
      IF(NC-1) 514,506,508
506   IF(NC1) 512,512,508
508   J=NAB+2*K+3
      DAT(J)=SL2*VV
      IF(NC-1) 514,514,510
510   J=NAB+3*K+5
      DAT(J)=SL3
      GO TO 514
512   J=NAB+2*K+3
      DAT(J)=SL3
C
514   CALL STUR(DAT,TH,PP,DUM,RL,NA,NAB,NP,K1,NDAT,NDAT1,NU1,N1)
C
      SL2=VOV2*B0/(B0*B0+Q2)
      DELCOM=SL2*DAT(NU1)+DELOLD
      GO TO 530
C
520   DELCOM=-VOV2*(AK1*SL1+AK2*R(IST)+AK3*SINT)
      SINT=SINT+SL1*FLOAT(IREG)
C
530   IF(DELCOM .GT. DLIM) DELCOM=DLIM
      IF(DELCOM .LT. -DLIM) DELCOM=-DLIM
      IF(IDEXP) 531,531,800
531   IF(IPID) 532,532,534
532   DAT(NU1)=B0*(DELCOM-DELOLD)/VOV2
      DELOLD=DELCOM
534   GO TO 600
C
540   IR=IR+1
C
542   GO TO 900
C
C     COMPUTE THE MEAN RUDDER COMMAND EDELTA AND THE LOSS FUNCTIONS.
C
600   IF(MODYAW) 604,604,602
602   IF(MODYAW-4) 800,604,604
604   EDELTA=EDELTA+(STD+BD)*(DELCOM-EDELTA)
      STD=(1.-BD)*STD/(1.-BD+STD)
      IF(MODYAW) 606,606,800
606   EPSI2=EPSI2+(STV+BV)*(SL1-EPSI2)
      SL2=DELCOM-EDELTA
      SL3=SL1*SL1+ALAM*SL2*SL2
      VLOS2=VLOS2+(STV+BV)*(SL3-VLOS2)
      SL2=P/(CKM*U*COSC(SL1*CGR))
      ENM2=ENM2+(STV+BV)*(SL2-ENM2)
      STV=(1.-BV)*STV/(1.-BV+STV)
      GO TO 800
C
C     IDENTIFICATION EXPERIMENT.
C
700   IF(IR-IREG) 720,702,900
C
702   IR=1
      IF(ISTBD+IPORT-1) 712,704,710
704   IF(ISTBD) 708,708,706
706   DELO=DELAMP
      GO TO 712
708   DELO=-DELAMP
      GO TO 712
710   DELO=0.
```

```
712     ISTBD=0
        IPORT=0
        SL1=PSI(1)-PSI0
        IF(SL1 .LE. -180.) SL1=SL1+360.
        IF(SL1 .GT. 180.) SL1=SL1-360.
        DELCOM=DELO-AKID*SL1
        GO TO 530
C
720     IR=IR+1
        GO TO 900
C
C       INDICATE RUDDER CHANGE.
C
800     DELCO=DELCOM
        IDELC=1
C
        IF(IPC .GT. 0) IPRINT=1
C
900     IF(IPR) 999,999,902
C
902     IF(IP-IPR) 906,904,999
C
904     IP=1
        IPRINT=1
        GO TO 999
C
906     IP=IP+1
C
999     RETURN
        END
```

```
      SUBROUTINE STUR(DAT,TH,P,DUM,RL,NA,NAB,NP,K1,NDAT,NDAT1,NU1,N1)
C
C     SELFTUNING REGULATOR BASED ON LEAST SQUARES IDENTIFICATION
C     AND MINIMUM VARIANCE CONTROL, ADMITS FEEDFORWARD AND
C     EXPLOITS SYMMETRY OF P.
C
C     AUTHOR, C.KALLSTROM 1976-02-18.
C
C     THE ALGORITHM IS BASED ON THE MODEL
C
C     Y(T)+A(1)*Y(T-K-1)+...+A(NA)*Y(T-K-NA)=
C          B0*(U(T-K-1)+B(1)*U(T-K-2)+...+B(NB)*U(T-K-NB-1))+
C          C(1)*V1(T-K-1)+C(2)*V2(T-K-1)+...+C(NC)*VNC(T-K-1)+EPS(T)
C
C     AT EACH STEP THE LEAST SQUARES ESTIMATES OF THE PARAMETERS
C     OF THE MODEL ARE COMPUTED. THE CONTROL VARIABLE U(T) TO
C     BE APPLIED AT TIME T IS THEN COMPUTED FROM
C
C     US(T)= AE(1)*Y(T)+...+AE(NA)*Y(T-NA+1)
C             -BE(1)*US(T-1)-...-BE(NB)*US(T-NB)
C             -CE(1)*V1(T)-...-CE(NC)*VNC(T)
C
C     WHERE AE,BE AND CE ARE THE PARAMETER ESTIMATES
C     AND US THE SCALED CONTROL SIGNAL I.E. US=B0*U
C
C     WHEN USING THE ALGORITHM THE PROCESS OUTPUT Y(T) AND THE
C     FEEDFORWARD SIGNALS V(T) ARE READ AT TIME T AND THE CONTROL
C     SIGNAL U(T) TO BE APPLIED AT TIME T IS THEN COMPUTED
C
C     DAT- VECTOR OF DIMENSION NA+NB+(K+2)*(NC+2)-2 CONTAINING
C         PROCESS OUTPUTS Y, SCALED CONTROL VARIABLES U
C         AND FEED FORWARD SIGNALS V ORGANIZED AS FOLLOWS
C     DAT(1)=Y(T)                             RETURNED AS Y(T)
C     DAT(2)=Y(T-1)                           RETURNED AS Y(T)
C     DAT(3)=Y(T-2)                           RETURNED AS Y(T-1)
C     .
C     DAT(NA+K+1)=Y(T-K-NA)                   RETURNED AS Y(T-K-NA+1)
C     DAT(NA+K+2)=US(T-1)                     RETURNED AS US(T)
C     DAT(NA+K+3)=US(T-2)                     RETURNED AS US(T-1)
C     .
C     DAT(NA+NB+2*K+2)=US(T-K-NB-1)           RETURNED AS US(T-K-NB)
C     DAT(NA+NB+2*K+3)=V1(T)                  RETURNED AS US(T-K-NB-1)
C     DAT(NA+NB+2*K+4)=V1(T-1)                RETURNED AS V1(T)
C     .
C     DAT(NA+NB+3*K+4)=V1(T-K-1)              RETURNED AS V1(T-K)
C     .
C     DAT(NA+NB+(K+2)*(NC+1)-1)=VNC(T)        RETURNED AS V(NC-1)(T-K-1)
C     .
C     DAT(NA+NB+(K+2)*(NC+2)-2)=VNC(T-K-1)    RETURNED AS VNC(T-K)
C
C
C     TH- VECTOR OF DIMENSION NP=NA+NB+NC CONTAINING THE PARAMETER
C        ESTIMATES ORGANIZED AS FOLLOWS
C     TH(1)=-AE(1)
C     TH(2)=-AE(2)
C     .
C     TH(NA)=-AE(NA)
C     TH(NA+1)=BE(1)
C     TH(NA+2)=BE(2)
C     .
C     TH(NA+NB)=BE(NB)
C     TH(NA+NB+1)=CE(1)
C     TH(NA+NB+2)=CE(2)
```

```
C
C       .
C       TH(NA+NB+NC)=CE(NC)
C
C
C       P- COVARIANCE MATRIX STORED AS FOLLOWS
C       P(1)=P(1,1)
C       P(2)=P(2,1)
C       P(3)=P(2,2)
C       .
C       P(I*(I-1)/2+J)=P(I,J)
C       .
C       P(NP*(NP+1)/2)=P(NP,NP)
C
C
C       DUM- DUMMY VECTOR OF DIMENSION NP
C       RL- BASE OF EXPONENTIAL WEIGHTING FACTOR
C       NA- NUMBER OF A-PARAMETERS  (MAX 10, MIN 0)
C          NB- NUMBER OF B-PARAMETERS  (MAX 10, MIN 0)
C          NC- NUMBER OF C-PARAMETERS  (MAX 10, MIN 0)
C          K -NUMBER OF TIME DELAYS IN THE MODEL
C             (MAX ((46-NA-NB+2)/(NC+2))-2 , MIN 0)
C       NAB- NA+NB
C       NP- NA+NB+NC (MAX 10, MIN 1)
C       K1- K+1
C       NDAT- NAB+(K1+1)*(NC+2)-2
C       NDAT1- NDAT+1
C       NU1- NA+K+2
C       N1- NU1+K
C
C       SUBROUTINE REQUIRED
C            NONE
C
        DIMENSION DAT(46),TH(10),P(55),DUM(10)
C
        RES=DAT(1)-DAT(N1)
        DENOM=1.
        DO 12 I=1,NP
        R=0.
        DO 10 J=1,NP
        L=I*(I-1)/2+J
        IF (J.GT.I) L=J*(J-1)/2+I
        M=K1+J
        IF (J.GT.NA) M=M+K1
        IF (J.GT.NAB) M=2*K1+(J-NAB)*(K1+1)+NAB
10      R=R+P(L)*DAT(M)
        DUM(I)=R
        M=K1+I
        IF (I.GT.NA) M=M+K1
        IF (I.GT.NAB) M=2*K1+(I-NAB)*(K1+1)+NAB
        DENOM=DENOM+R*DAT(M)
12      RES=RES-DAT(M)*TH(I)
C
        DO 20 I=1,NP
        R=DUM(I)/DENOM
        TH(I)=TH(I)+R*RES
        DO 20 J=1,I
        L=I*(I-1)/2+J
20      P(L)=(P(L)-R*DUM(J))/RL
C
        R=0.
        DO 30 I=1,NP
        L=I
        IF (I.GT.NA) L=L+K1
        IF (I.GT.NAB) L=NAB+K1+(K1+1)*(I-NAB)
```

```
30        R=R-TH(I)*DAT(L)
C
          DO 32 I=2,NDAT
          L=NDAT1-I
32        DAT(L+1)=DAT(L)
          DAT(NU1)=R
C
          RETURN
          END
```

APPENDIX D - EXPERIMENTS

Plots from all the experiments, excluding F1 - F3 where no recording of data was performed, are shown in this appendix. Several plots are often shown in the same figure, and the plots are then slided in relation to each other. The corresponding straight line is the level zero. Usually the data were punched on paper tape every time a new rudder command δ_c was computed, i.e. with sampling interval T_s. However, during experiments B1 - - B3 the data were punched every second. In experiments B1 - B3 a yaw rate estimate $\hat{r}_d$ is computed from the heading ψ and plotted.

The Kalman filter was running during all the experiments, including E1 - E4, but the estimates were not always used by the regulators. If nothing else is remarked, all measurement signals v_1, r, ψ and δ were used by the Kalman filter. If the value of the rudder limit is not given, the rudder limit has not been active during the experiment. The water below the keel was deep, except during the last 15 min of experiment D1 when the water depth was about 100 m.

Experiments of straight course keeping are shown in Table D.1. A summary of experiments of Kalman filter testing is given in Table D.2, and the yawing experiments are summarized in Table D.3. Normal operating experiments are shown in Table D.4. Note that yaws were performed during experiment D1, while D2 and D3 are straight course keeping experiments. Table D.5 shows the experiments for identification and Table D.6 the experiments of straight course keeping, where no recording of data was performed. A summary of the final parameter values of the self-tuning regulator is given in Table D.7.

Experiment	Duration [min]	Draught Forward [m]	Draught Aft [m]	Rel. wind dir.	Wind velocity [m/s]	T_s [s]	V_0 [m/s]	IVVC	Structure of self-tuning reg. NC1	NC2	k	q	Parameters of PID-reg. k_P	k_D [s]	k_I [1/s]
A1	51	8.5	12.5	3	9	10	8	3	1	1	7	0	-	-	-
A2	26	8.5	12.5	5	5	10	7	1	1	1	7	0	-	-	-
A3	24	8.5	12.5	5	10	10	7	1	1	1	5	0	-	-	-
A4	24	8.5	12.5	5	5	10	7	1	1	1	6	0	-	-	-
A5	24	8.5	12.5	5	4	10	7	1	1	1	7	0	-	-	-
A6	24	8.5	12.5	4	4	10	7	1	1	1	7	0	-	-	-
A7	25	8.5	12.5	3	4	10	7	1	1	1	8	0	-	-	-
A8	24	8.5	12.5	5	4	15	6	1	1	1	4	0	-	-	-
A9	25	8.5	12.5	5	4	15	6	1	1	1	5	0	-	-	-
A10	33	8.5	12.5	5	3	10	6	1	1	1	7	0	-	-	-
A11	24	8.5	12.5	5	3	10	6	1	1	1	6	0.05	-	-	-
A12	26	8.5	12.5	5	3	10	6	1	1	1	6	0.1	-	-	-
A13	24	8.5	12.5	6	3	10	6	1	1	1	6	0.2	-	-	-
A14	24	8.5	12.5	-	0	10	6	1	1	1	7	0	-	-	-
A15	25	8.5	12.5	-	0	10	6	1	1	0	7	0	-	-	-
A16	24	8.5	12.5	1	5	10	6	1	0	1	7	0	-	-	-
A17	25	8.5	12.5	1	5	10	6	1	0	0	7	0	-	-	-
A18	24	8.5	12.5	1	5	10	6	1	0	0	7	0	-	-	-
A19	25	8.5	12.5	1	9	10	6	1	1	1	7	0	-	-	-
A20	25	8.5	12.5	1	9	10	6	1	-	-	-	-	3	75	0.02

Table D.1a - Summary of experiments of straight course keeping. An explanation of the relative wind direction is given in Appendix A. If nothing else is remarked, all measurement signals v_1, r, ψ and δ were used by the Kalman filter and the tuning time before the experiment started was equal to 30 min. The estimates from the Kalman filter were used by the regulator, if it is not remarked that non-filtered measurements were used.

Experiment	δ_c Mean value [deg]	δ_c Std. dev. [deg]	$\psi - \psi_{ref}$ Mean value [deg]	$\psi - \psi_{ref}$ Std. dev. [deg]	Mean value n [rpm]	Mean value u [knots]	Mean value P_s [MW]	V_1	Remarks
A1	-0.83	2.24	-0.004	0.161	72.3	14.2	16.4	0.444	Defect rudder servo. v_1 not used by filter. Tuning time: 0 min. V_c = 7 m/s.
A2	0.41	1.14	0.017	0.182	69.6	13.9	14.5	0.142	Tuning time: > 120 min
A3	0.74	1.20	0.009	0.239	69.4	14.2	14.5	0.177	
A4	1.39	1.41	-0.009	0.246	68.5	14.0	14.0	0.226	
A5	0.66	1.17	0.014	0.219	69.7	14.0	14.4	0.162	
A6	-0.73	1.32	-0.051	0.290	69.1	13.5	13.9	0.232	
A7	-0.17	1.19	0.034	0.260	69.5	14.1	14.2	0.187	
A8	0.17	1.46	-0.027	0.309	69.2	13.9	14.1	0.274	
A9	0.05	1.24	-0.022	0.301	69.0	13.8	14.0	0.219	
A10	0.08	1.62	0.013	0.344	69.0	13.7	14.1	0.337	
A11	-0.06	1.79	-0.033	0.400	69.2	13.9	14.2	0.428	
A12	0.05	1.69	0.013	0.444	69.2	13.7	14.2	0.435	
A13	0.24	1.84	0.016	0.420	66.7	13.6	13.1	0.459	The speed was reduced.
A14	-0.61	1.66	-0.017	0.111	69.7	13.5	14.6	0.242	Tuning time: > 120 min
A15	-0.68	0.82	0.015	0.158	69.4	13.3	14.4	0.081	
A16	-0.43	0.62	-0.066	0.169	69.3	12.9	14.4	0.065	
A17	0.01	0.89	-0.188	0.247	69.2	12.9	14.4	0.162	
A18	0.24	1.01	-0.052	0.245	69.2	12.8	14.3	0.148	Non-filt. meas. used.
A19	0.45	1.11	-0.005	0.176	69.3	13.0	14.4	0.134	
A20	0.53	2.48	0.026	0.556	69.5	13.1	14.5	0.822	Non-filt. meas. used. Stand. param. values

Table D.1a - Contd.

Experiment	Duration [min]	Draught Forward [m]	Draught Aft [m]	Rel. wind dir.	Wind velocity [m/s]	T_s [s]	V_0 [m/s]	IVVC	Structure of self-tuning reg. NC1	NC2	k	q	Parameters of PID-reg. k_P	k_D [s]	k_I [1/s]
A21	25	8.5	12.5	1	4	10	6	1	–	–	–	–	3	75	0.02
A22	24	8.5	12.5	1	13	10	6	1	1	1	7	0	–	–	–
A23	25	8.5	12.5	1	13	10	6	1	1	1	7	0	–	–	–
A24	25	8.5	12.5	1	14	10	6	1	1	1	7	0	–	–	–
A25	25	8.5	12.5	1	14	10	6	1	1	1	7	0	–	–	–
A26	27	8.5	12.5	1	6	10	6	1	1	1	7	0	–	–	–
A27	22	8.5	12.5	1	7	10	6	1	1	1	7	0	–	–	–
A28	24	10.9	12.9	1	4	10	6	1	1	1	7	0	–	–	–
A29	24	10.9	12.9	1	3	10	6	1	0	0	7	0	–	–	–
A30	25	10.9	12.9	1	5	10	6	1	–	–	–	–	3	120	0.02
A31	24	10.9	12.9	1	3	10	6	1	–	–	–	–	2	100	0.02
A32	25	10.9	12.9	1	9	10	6	1	1	1	7	0	–	–	–
A33	51	10.9	12.9	1	10	10	6	1	1	1	7	0	–	–	–
A34	48	10.9	12.9	1	10	10	6	1	1	1	7	0	–	–	–
A35	45	10.9	12.9	1	11	10	6	1	–	–	–	–	3	140	0.02
A36	47	10.9	12.9	1	11	10	6	1	1	1	7	0	–	–	–

Table D.1b

Experiment	δ_c Mean value [deg]	δ_c Std. dev. [deg]	$\psi - \psi_{ref}$ Mean value [deg]	$\psi - \psi_{ref}$ Std. dev. [deg]	Mean value n [rpm]	Mean value u [knots]	Mean value P_s [MW]	V_1	Remarks
A21	0.53	0.91	-0.018	0.293	69.3	12.9	14.4	0.155	Stand. parameter values.
A22	2.32	0.95	-0.006	0.204	68.9	12.8	14.5	0.117	δ not used by filter.
A23	1.71	0.94	0.015	0.217	69.0	12.6	14.5	0.121	v_1 not used by filter.
A24	1.34	1.25	0.130	0.317	68.9	12.5	14.5	0.248	r not used by filter.
A25	1.25	0.90	-0.034	0.240	69.6	12.5	14.9	0.126	After 9.5 min, ψ was not used by filter.
A26	0.24	0.89	0.030	0.230	69.7	13.4	14.9	0.120	v_1, r and δ not used by filter. Correct K.
A27	0.30	0.92	0.043	0.197	68.9	13.2	14.4	0.111	v_1, r and δ not used by filter.
A28	0.16	0.95	0.006	0.239	69.9	13.5	15.0	0.132	
A29	-0.01	1.51	0.001	0.324	69.5	13.4	14.6	0.295	Non-filt. meas. used.
A30	-0.10	0.89	-0.026	0.256	69.6	13.5	14.6	0.132	Tuned param. values.
A31	0.22	2.41	-0.103	1.085	69.4	13.4	14.5	1.672	Non-filt. meas. used. Tuned param. values.
A32	-0.01	0.98	-0.082	0.223	69.9	13.6	14.9	0.136	Tuning time: 120 min.
A33	-0.24	1.18	0.016	0.181	69.0	13.2	14.4	0.149	Tuning time: > 120 min.
A34	-0.33	0.95	0.001	0.251	87.6	15.8	29.6	0.138	Tuning time: > 120 min.
A35	0.01	1.66	0.008	0.295	68.6	12.1	14.7	0.317	Tuned param. values.
A36	-0.05	1.08	-0.058	0.206	68.5	12.1	14.7	0.143	Tuning time: > 120 min.

Table D.1b - Contd.

Experiment	Duration	Draught		Rel. wind dir.	Wind velocity	Standard dev.			Mean value		
		Forward	Aft			r	$\hat{r}$	$\hat{r}_d$	n	u	P_s
	[min]	[m]	[m]		[m/s]	[deg/s]	[deg/s]	[deg/s]	[rpm]	[knots]	[MW]
B1	26	10.9	12.9	1	6	0.022	0.009	0.014	69.2	13.7	14.9
B2	25	10.9	12.9	1	8	0.023	0.007	0.014	70.1	13.3	15.2
B3	26	10.9	12.9	1	15	0.034	0.011	0.021	87.4	15.9	29.5

Table D.2 - Summary of experiments of Kalman filter testing, where the data were punched on paper tape every second. An explanation of the relative wind direction is given in Appendix A. All measurement signals v_1, r, ψ and δ were used by the Kalman filter.

Experiment	Duration	Draught		Rel. wind dir.	Wind velocity	T_s	V_0	IVVC	Structure of self-tuning reg.				ψ_{ref}	r_{ref}	Mean value			Remarks
		Forward	Aft						NC1	NC2	k	q			n	u	P_s	
	[min]	[m]	[m]		[m/s]	[s]	[m/s]						[deg]	[deg/s]	[rpm]	[knots]	[MW]	
C1	41	9.0	12.0	5	9	10	7	1	1	1	7	0	175-195	0.05,0.1	69.5	14.2	14.4	The sign of v_1 was incorrect.
C2	33	8.5	12.5	4,5	6	10	6	1	1	1	8	0	143-180	0.1	69.3	13.7	14.0	
C3	63	10.9	12.9	1	7	10	6	1	1	1	7	0	122-162	0.05,0.1	69.8	13.4	14.9	$\hat{\delta}_0'$, $\hat{d}_v'$, $\hat{d}_r'$ and $\hat{d}_\delta'$ were not updated.
C4	49	10.9	12.9	1	11	10	6	1	1	1	7	0	125-165	0.1,0.2	69.1	12.5	14.5	$\hat{\delta}_0'$, $\hat{d}_v'$, $\hat{d}_r'$ and $\hat{d}_\delta'$ were not updated
C5	27	10.9	12.9	1	8	10	6	1	1	1	7	0	139-149	0.1	69.7	13.2	14.7	
C6	72	10.9	12.9	1	12	10	6	1	1	1	7	0	142-146	0.1	69.0	13.0	14.4	

Table D.3 - Summary of experiments of yawing. An explanation of the relative wind direction is given in Appendix A. All measurement signals v_1, r, ψ and δ were used by the Kalman filter. The estimates from the Kalman filter were used by the self-tuning regulator and the yaw regulator.

Experiment	Duration [min]	Draught Forward [m]	Draught Aft [m]	Rel. wind dir.	Wind velocity [m/s]	T_s [s]	V_0 [m/s]	IVVC	Structure of self-tuning reg. NC1	NC2	k	q	ψ_{ref} [deg]	r_{ref} [deg/s]	Mean value n [rpm]	u [knots]	P_s [MW]	Remarks
D1	83	8.5	12.5	7	5	10	8	3	1	1	7	0	180-205	0.1	69.6	14.2	14.7	Water depth was abt 100 m during the last 15 min. Rudder limit: 15 deg. v_1 not used by filter V_c = 7 m/s Tuning time: > 120 min.
D2	40	8.5	12.5	5	10	10	7	1	1	1	7	0	180	0.1	69.7	14.2	14.7	Tuning time: 0 min.
D3	68	10.9	12.9	1	9	10	6	1	1	1	7	0	144.3- -147.0	0.1	69.9	13.4	15.4	Sailmaster, Course Correction. Tuning time: 0 min.

Table D.4 - Summary of normal operating experiments. An explanation of the relative wind direction is given in Appendix A. If nothing else is remarked, all measurement signals v_1, r, ψ and δ were used by the Kalman filter. The estimates from the Kalman filter were used by the self-tuning regulator and the yaw regulator.

Experiment	Duration [min]	Draught		Rel. wind dir.	Wind velocity [m/s]	T_s [s]	IVVC	δ_{amp} [deg]	k_{id}	Mean value			Remarks
		Forward [m]	Aft [m]							n [rpm]	u [knots]	P_s [MW]	
E1	89	10.9	12.9	1	11	10	1	3,5	0	69.7	12.5	15.4	
E2	19	10.9	12.9	1	14	10	1	5	0	70.5	12.5	15.7	$5^{\circ}/5^{\circ}$ zig-zag test
E3	90	10.9	12.9	2	9	10	1	5	2	70.0	12.9	15.4	Rudder limit: 15 deg
E4	26	10.9	12.9	1	11	10	1	10	0	69.8	12.7	15.3	

Table D.5 - Summary of experiments for identification. An explanation of the relative wind direction is given in Appendix A.

Ex-periment	Duration [min]	Draught		Rel. wind dir.	Wind velocity [m/s]	T_s [s]	V_0 [m/s]	IVVC	Structure of self-tuning reg.				Parameters of PID-reg.		
		Forward [m]	Aft [m]						NC1	NC2	k	q	k_P	k_D [s]	k_I [1/s]
F1	60	8.5	12.5	6	3	10	8	3	1	1	7	0	-	-	-
F2	49	8.5	12.5	7	3	10	8	3	-	-	-	-	3	75	0.02
F3	57	10.9	12.9	1	11	10	6	1	1	1	7	0	-	-	-
F4	54	10.9	12.9	1	11	10	6	1	-	-	-	-	3	140	0.02

Table D.6 - Summary of experiments of straight course keeping, where no data were punched on paper tape. An explanation of the relative wind direction is given in Appendix A. If nothing else is remarked, all measurement signals v_1, r, ψ and δ were used by the Kalman filter. The estimates from the Kalman filter were used by the regulator, if it is not remarked that non-filtered measurements were used. The rudder limit was 15 deg during the experiments.

Experiment	Mean value					V_2	Remarks
	δ [deg]	$\psi-\psi_{ref}$ [deg]	n [rpm]	u [knots]	P_s [MW]		
F1	1.71	-0.002	69.8	14.4	14.7	0.038	v_1 not used by filter. V_c = 7 m/s. Sailmaster.
F2	1.86	-0.016	69.6	14.4	14.7	0.259	Non-filt. meas. used. Stand. param. values. V_c = 7 m/s. Sailmaster.
F3	1.67	-0.073	69.1	12.1	15.1	0.160	
F4	1.54	-0.009	69.7	12.2	15.5	0.304	Tuned parameter values.

Table D.6 - Contd.

Experiment	a_1	a_2	a_3	a_4	b_1	b_2	c_1	c_2	Σa_i
A1	-6.93	6.69	3.50	-3.61	0.51	0.18	-2.02	35.77	-0.35
A2	-15.17	19.33	-2.62	-1.87	0.63	0.52	0.35	113.66	-0.33
A3	-8.60	6.39	4.38	-2.62	0.53	0.26	-2.34	44.87	-0.45
A4	-8.92	6.49	4.88	-2.75	0.48	0.16	-1.79	50.52	-0.30
A5	-8.00	6.67	4.55	-3.59	0.49	0.17	-1.40	49.73	-0.37
A6	-7.23	6.42	4.21	-3.31	0.55	0.16	-0.79	41.84	0.09
A7	-7.00	6.36	4.36	-3.64	0.48	0.09	-1.89	39.41	0.08
A8	-8.29	5.98	4.34	-2.58	0.50	0.18	-2.32	39.92	-0.55
A9	-7.36	5.86	4.03	-2.62	0.51	0.16	-1.97	36.59	-0.09
A10	-9.56	6.81	4.39	-1.97	0.53	0.26	-2.25	40.29	-0.33
A11	-9.16	6.39	4.29	-1.86	0.46	0.22	-2.60	37.18	-0.34
A12	-8.73	7.02	4.66	-3.33	0.29	0.08	-2.89	44.49	-0.38
A13	-9.65	6.81	5.19	-2.67	0.36	0.20	-1.29	44.29	-0.32
A14	-21.78	26.83	-2.30	-3.17	0.50	0.44	-0.54	74.46	-0.42
A15	-7.76	5.70	4.43	-2.61	0.49	0.17	-1.81	-	-0.24
A16	-7.26	6.59	4.46	-4.05	0.42	0.05	-	33.84	-0.26
A17	-7.84	6.75	4.75	-3.89	0.43	0.02	-	-	-0.23
A18	-7.88	6.86	4.67	-3.50	0.45	0.11	-	-	0.15
A19	-8.42	6.56	4.42	-2.96	0.49	0.16	-1.26	45.72	-0.40
A22	-8.04	6.23	4.52	-2.99	0.51	0.16	-1.89	35.94	-0.28
A23	-7.24	6.33	4.12	-3.37	0.50	0.12	-1.82	37.53	-0.16
A24	-8.40	7.15	4.96	-3.79	0.51	0.13	-1.76	40.37	-0.08
A25	-8.06	6.68	4.51	-3.45	0.48	0.13	-1.96	41.91	-0.32
A26	-7.72	6.23	4.27	-2.95	0.49	0.10	-2.20	34.95	-0.17
A27	-7.76	6.63	4.48	-3.73	0.45	0.08	-3.32	41.43	-0.38
A28	-8.13	6.65	4.67	-3.33	0.47	0.10	-1.94	39.40	-0.14
A29	-9.74	8.48	6.22	-5.25	0.29	-0.06	-	-	0.21
A32	-10.51	9.96	4.86	-4.33	0.49	0.12	-0.69	70.44	-0.02
A33	-13.33	16.86	-2.60	-1.14	0.41	0.23	-0.39	100.94	-0.21
A34	-9.25	10.23	-0.26	-0.85	0.48	0.21	-0.03	103.99	-0.13
A36	-11.12	12.52	1.53	-3.00	0.59	0.29	0.45	89.21	-0.07
C1	-7.27	6.10	2.67	-2.07	0.48	0.08	-0.09	95.45	-0.57
C2	-10.20	11.11	2.38	-3.34	0.54	0.26	-0.71	65.62	-0.05
C3	-10.55	12.90	-0.97	-1.57	0.38	0.17	-0.54	89.70	-0.19
C4	-15.46	18.76	-1.80	-2.39	0.40	0.19	0.29	108.85	-0.89
C5	-10.07	8.90	5.69	-4.90	0.41	0.05	-1.54	48.49	-0.38
C6	-11.31	11.45	4.34	-4.95	0.37	0.08	-0.96	61.38	-0.47
D1	-7.32	6.37	3.37	-2.70	0.38	0.02	1.41	112.69	-0.28
D2	-7.57	5.86	4.14	-2.95	0.51	0.12	-1.69	39.59	-0.52
D3	-8.24	6.08	4.67	-2.61	0.52	0.16	-1.30	46.13	-0.10
F1	-7.05	5.88	3.03	-1.67	0.46	0.06	3.88	152.75	0.19
F3	-11.47	13.11	0.48	-2.31	0.58	0.31	-0.07	79.27	-0.19

Table D.7 - Final parameter values of the self-tuning regulator.

EXPERIMENT A1

Date	1976-04-18	Forward draught	8.5 m
Time	15.40	Aft draught	12.5 m
Duration	51 min	Wind direction	NW (3; see App. A)
Position	N 33°09' W 12°37'	Wind velocity	9 m/s (fresh breeze)
ψ_{ref}	206 deg	Wave height	2 m

The forward speed u was measured by Sperry's log, and sometimes that signal had an incorrect value in the computer. The rudder was moving between the sampling events, because the rudder servo was defect. The sway velocity v_1 was not measured during the experiment.

Self-tuning regulator using estimates from the Kalman filter.

The sway velocity v_1 was not used by the Kalman filter.
Tuning time before the experiment started: 0 min (the yaw regulator was not used).

NC1 = 1	NC2 = 1	k = 7	q = 0
T_s = 10 s	V_0 = 8 m/s	IVVC = 3	V_c = 7 m/s

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -6.93 \\ 6.69 \\ 3.50 \\ -3.61 \\ 0.51 \\ 0.18 \\ -2.02 \\ 35.77 \end{bmatrix} \qquad P = \begin{bmatrix} 4.58 & & & & & & & \\ -3.75 & 4.61 & & & & & & \\ -0.37 & -1.45 & 4.26 & & & & & \\ -0.15 & 0.69 & -2.28 & 2.20 & & & & \\ -0.06 & -0.01 & 0.12 & -0.05 & 0.01 & & & \\ -0.09 & 0.05 & -0.01 & 0.05 & 0.01 & 0.01 & & \\ -3.12 & 2.68 & 0.83 & -0.23 & -0.03 & -0.04 & 4.55 & \\ -45.73 & 38.72 & 8.90 & 1.51 & -1.16 & -1.48 & 84.78 & 1714.04 \end{bmatrix}$$

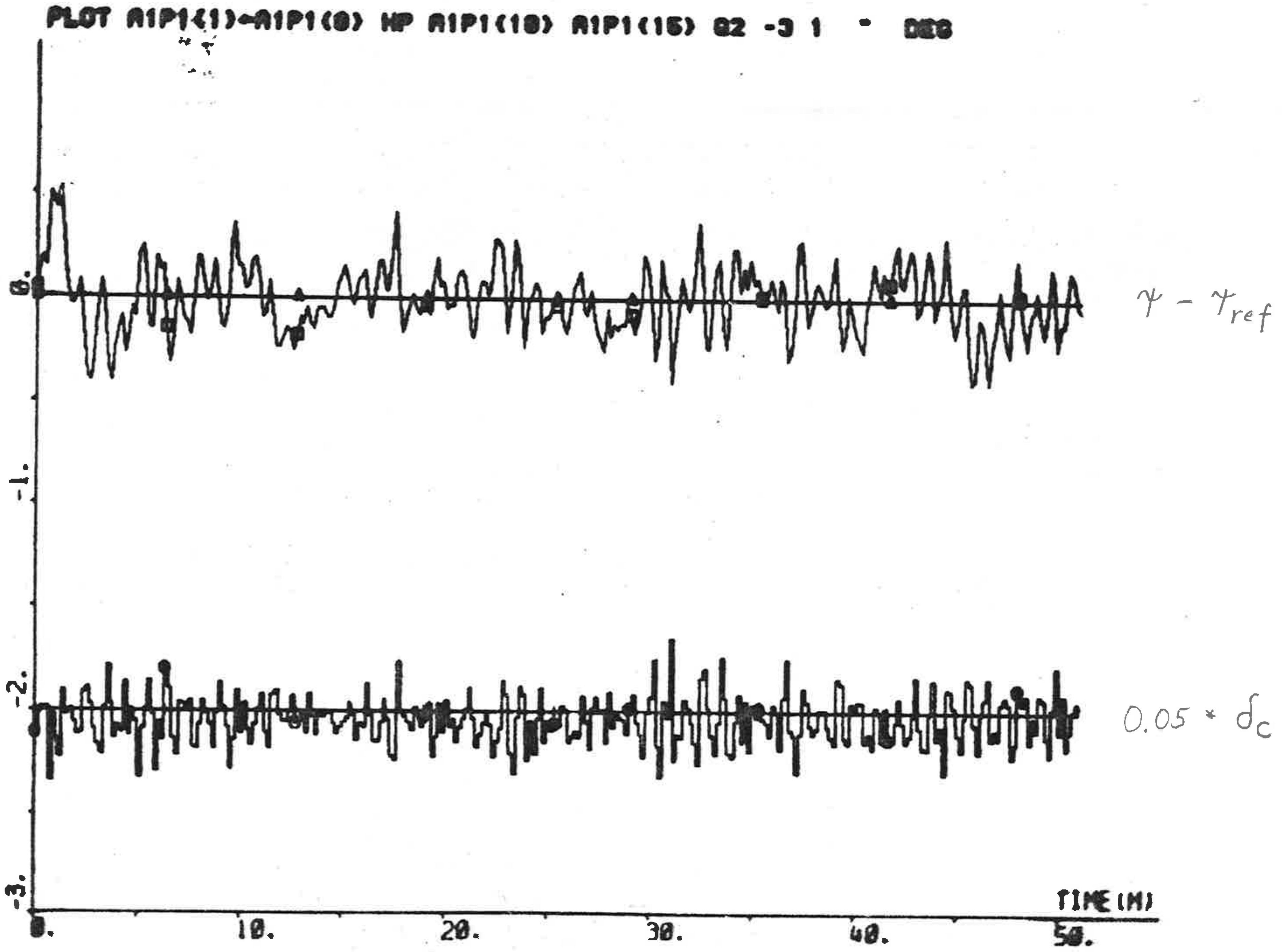
$a_1 + a_2 + a_3 + a_4 = -0.35$

$\hat{\delta}_0 = -0.6$ deg $\quad \hat{d}_v = -$ $\quad \hat{d}_r = -0.001$ deg/s $\quad \hat{d}_\delta = 1.4$ deg

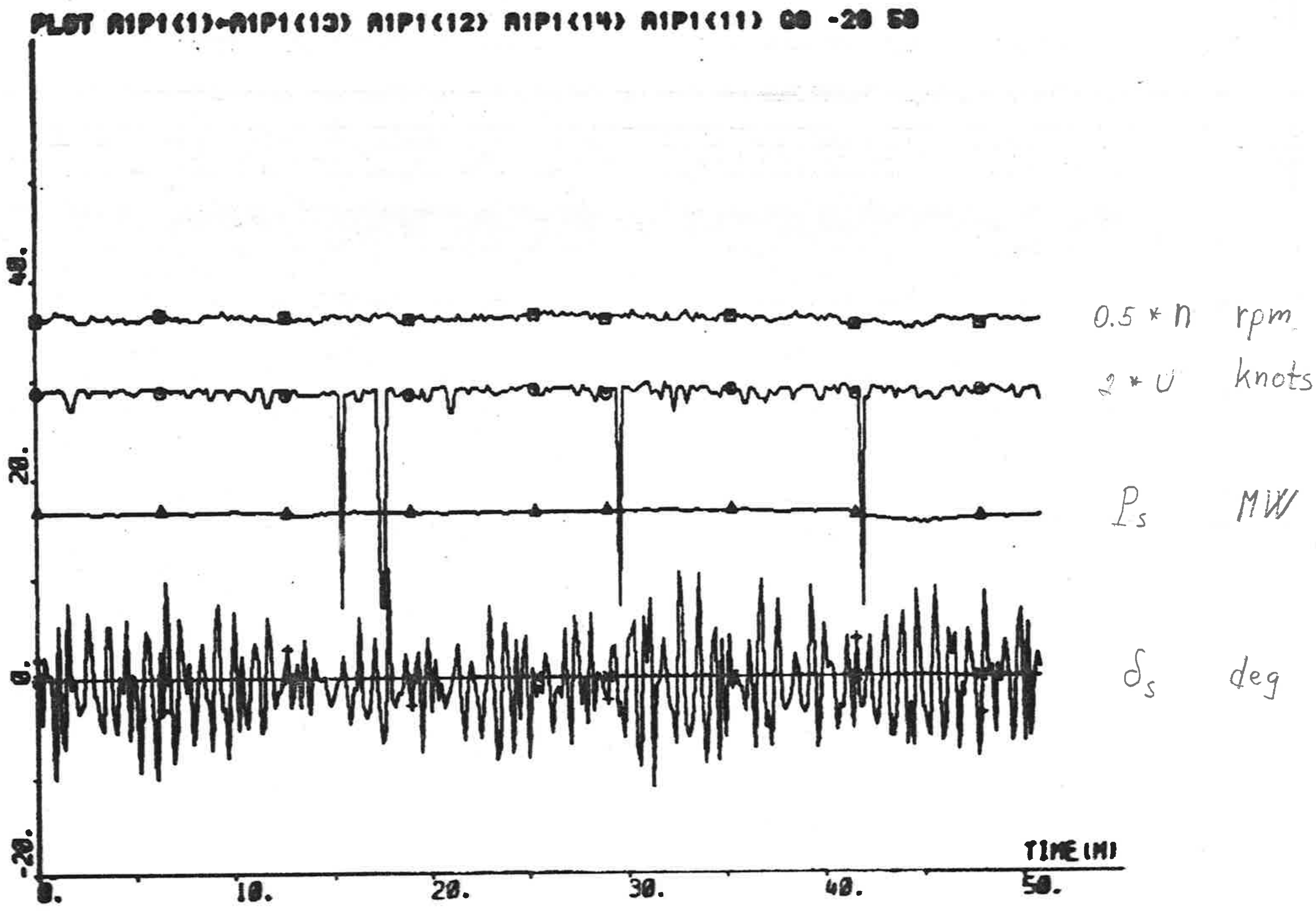
Statistics (mean value and standard deviation)

δ_c	-0.83	± 2.24	deg		P_s	16.4	± 0.3	MW
δ	0.57	± 2.68	deg		ε_v	-		
$\psi - \psi_{ref}$	-0.004	± 0.161	deg		ε_r	0.00	± 0.03	deg/s
n	72.3	± 0.7	rpm		ε_ψ	0.00	± 0.04	deg
u	14.2	± 1.4	knots		ε_δ	0.2	± 1.2	deg

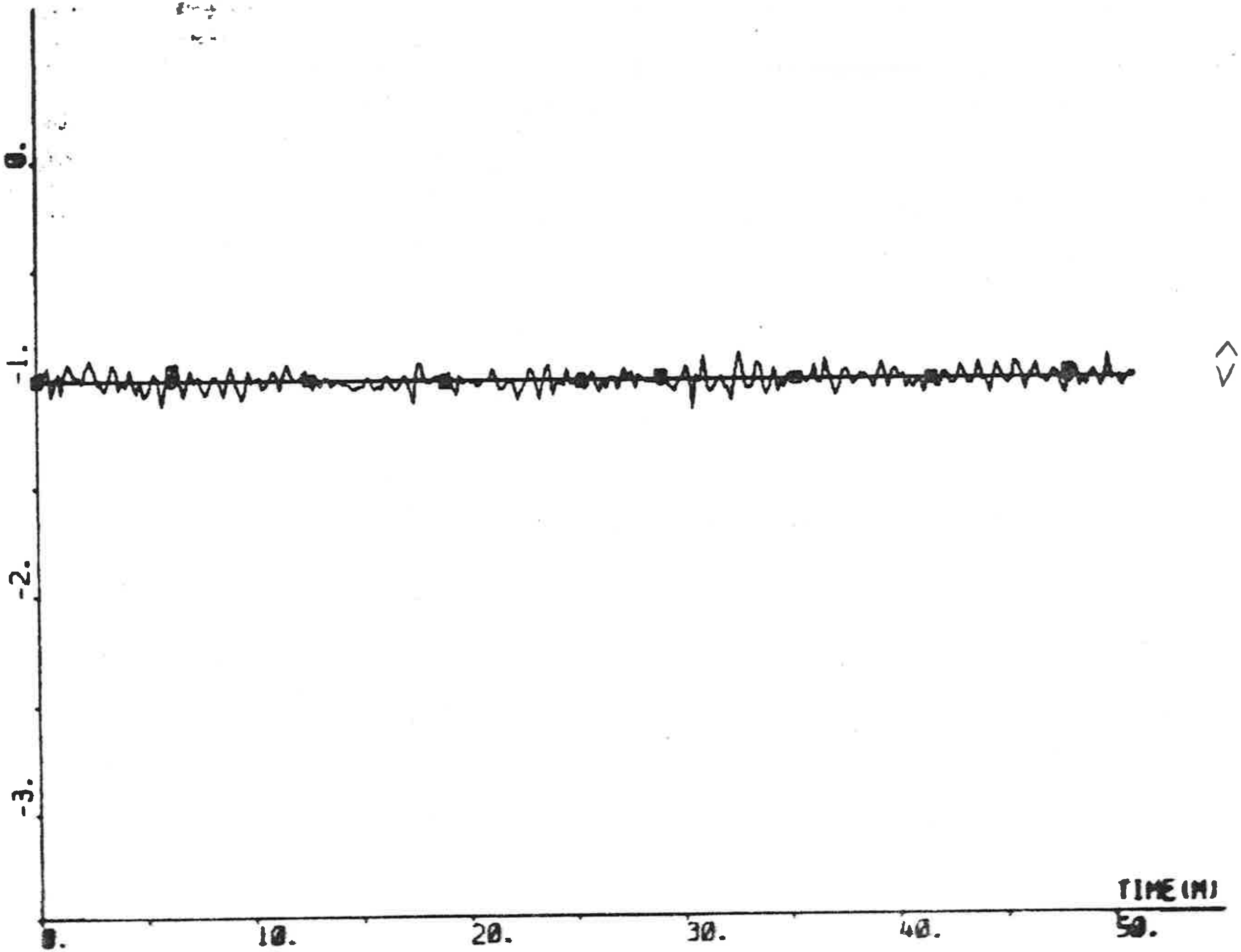
$V_1 = 0.444$

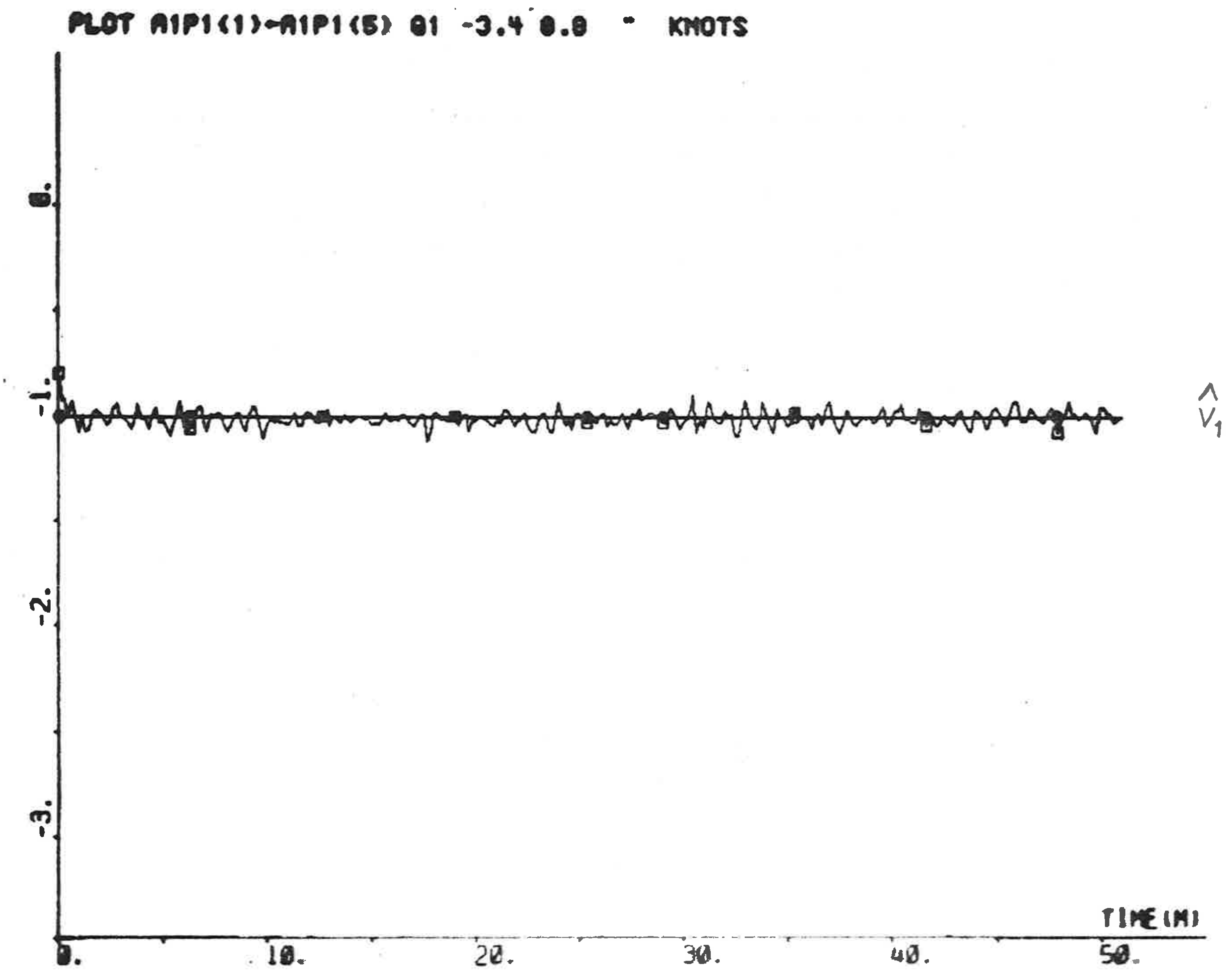


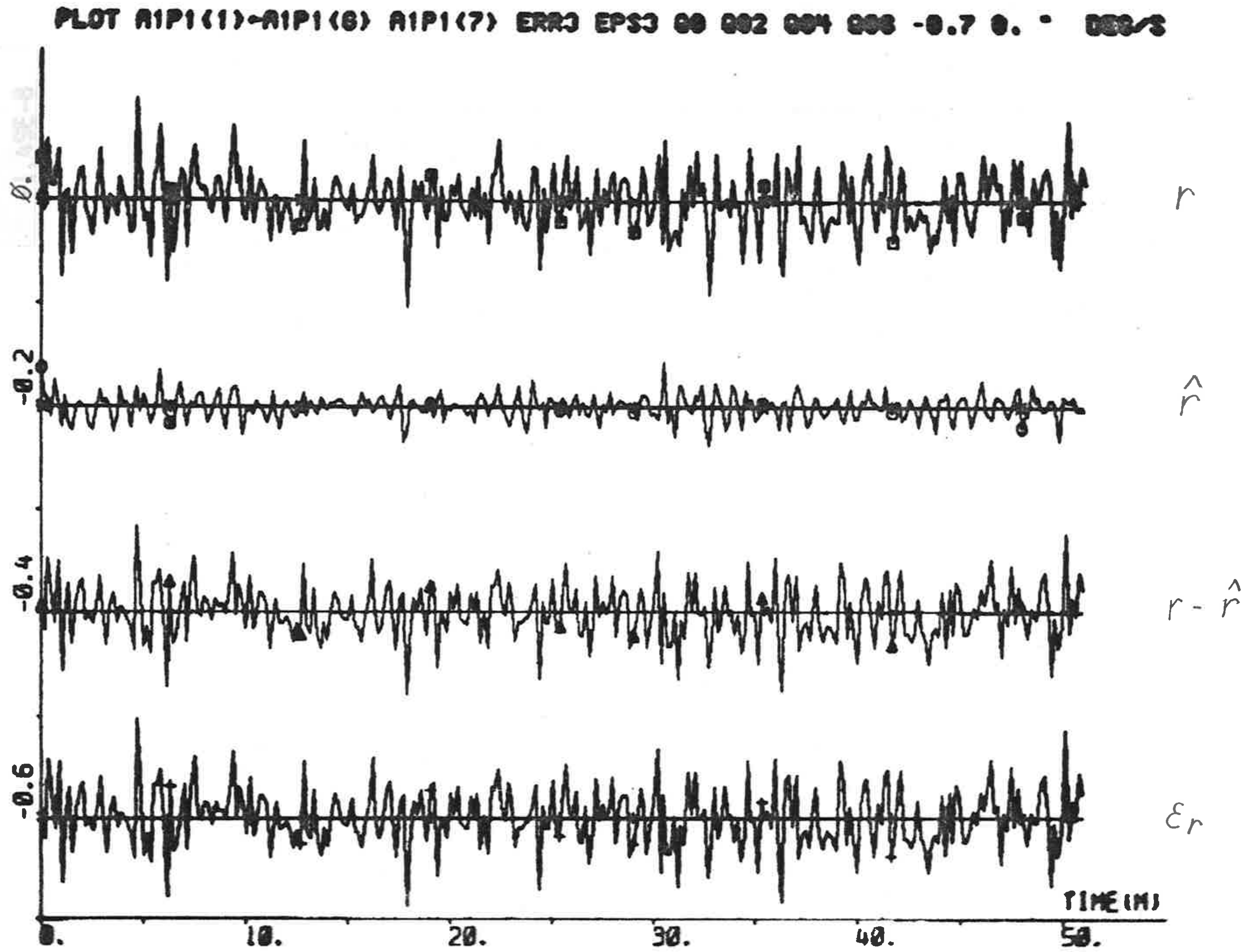
PLOT A1P1(1)-A1P1(8) HP A1P1(10) A1P1(15) 82 -3 1 * DEG
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
ψ - ψref
0.05 * δc

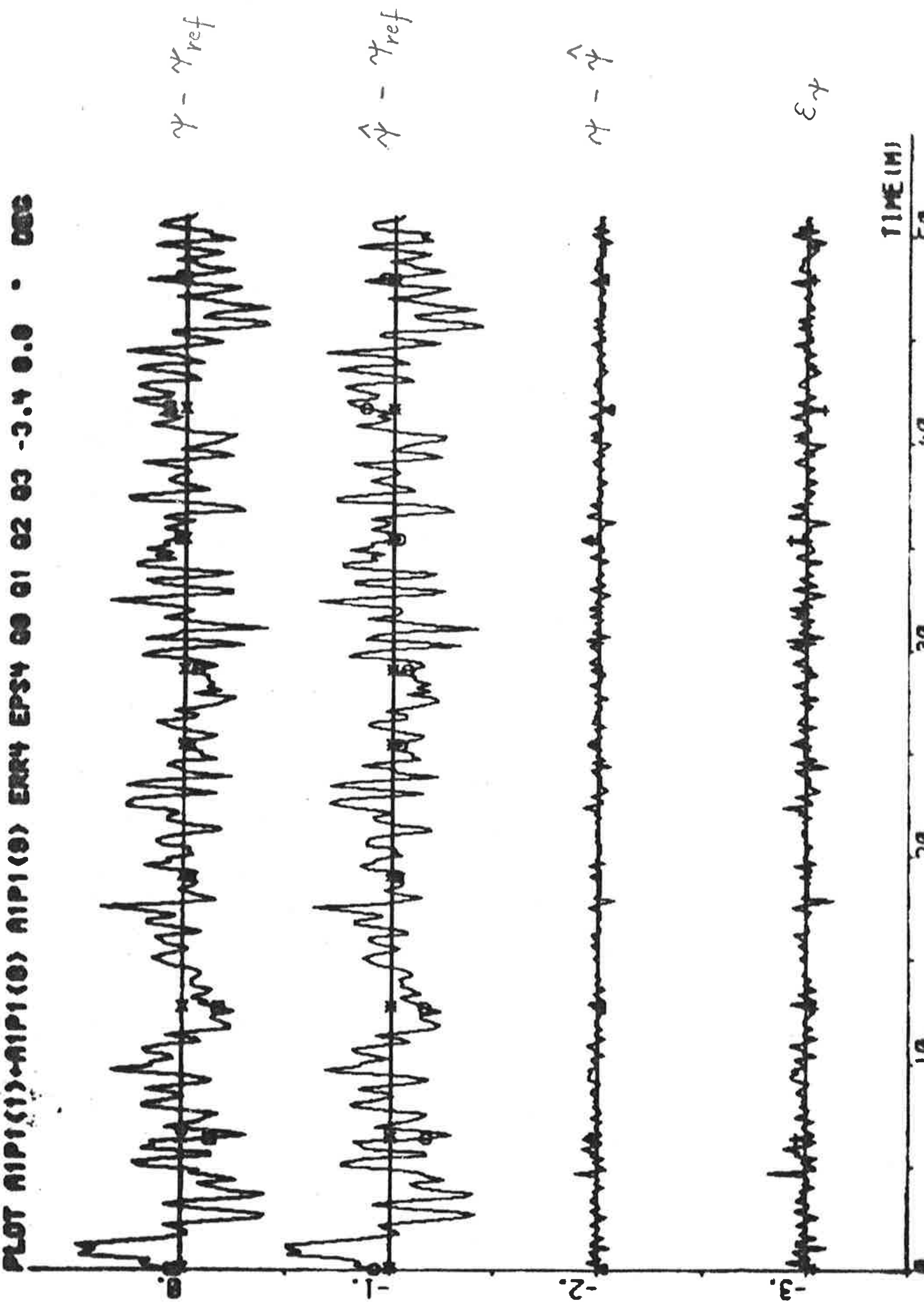

PLOT A1P1(1)+A1P1(13) A1P1(12) A1P1(14) A1P1(11) 00 -20 50
40.
20.
0.
-20.
0.5 * n rpm
2 * U knots
P_s MW
δ_s deg
TIME (M)
0.
10.
20.
30.
40.
50.

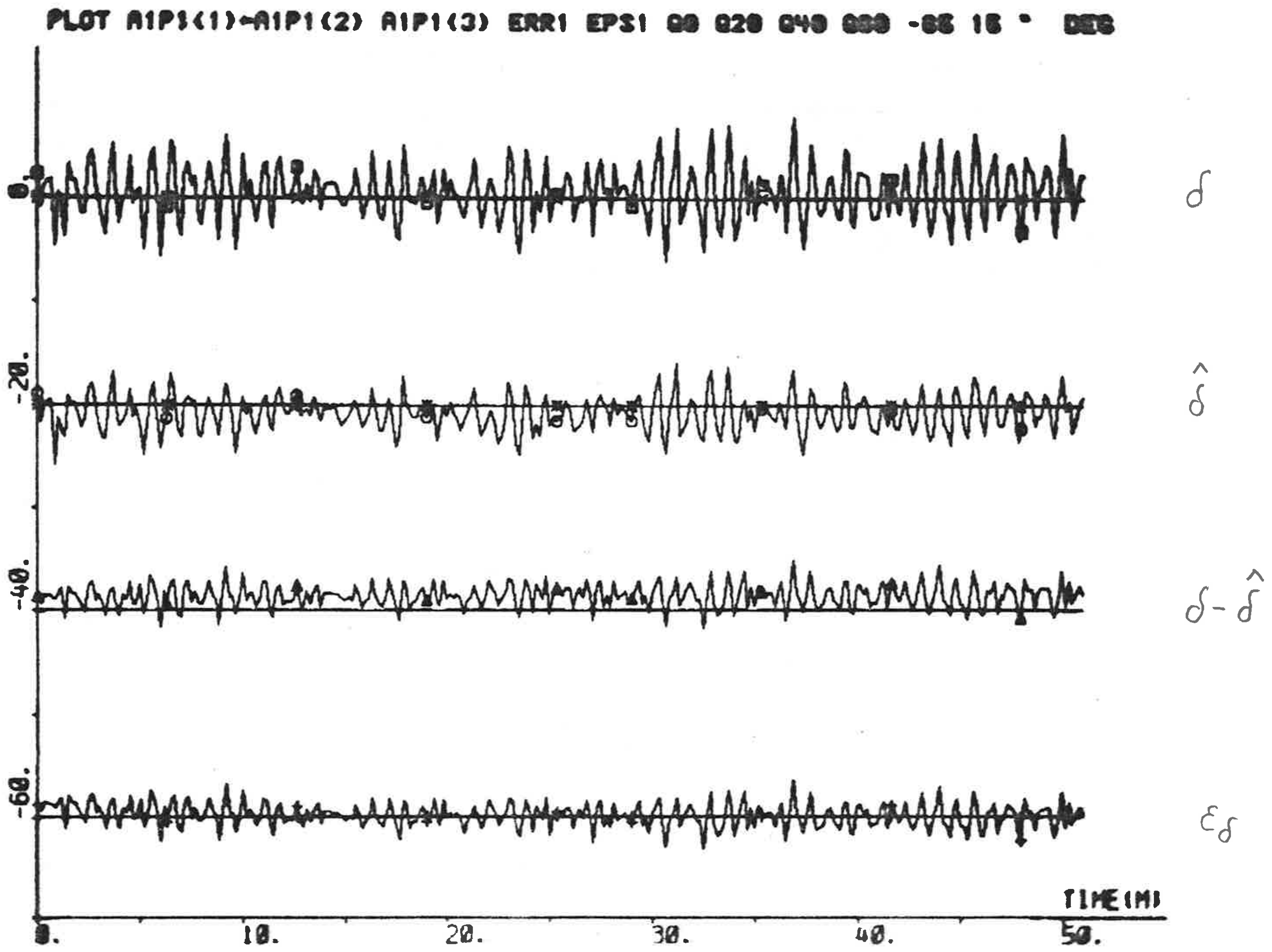
PLOT A1P1(1)-A1P2(2) 01 -3.4 0.0 " KNOTS



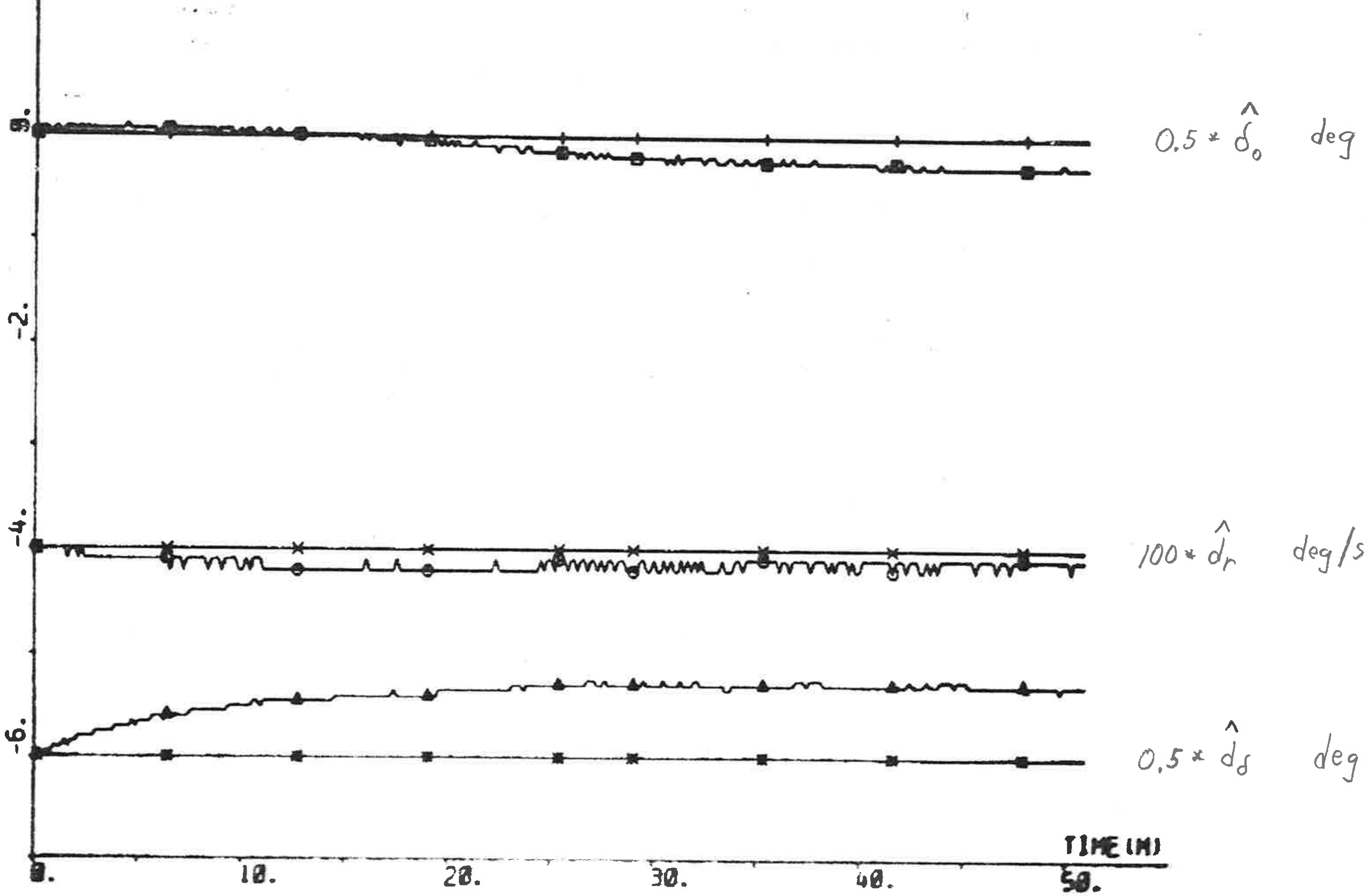

PLOT A1P1(1)-A1P1(5) 01 -3.4 0.0 * KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
$\hat{V}_1$

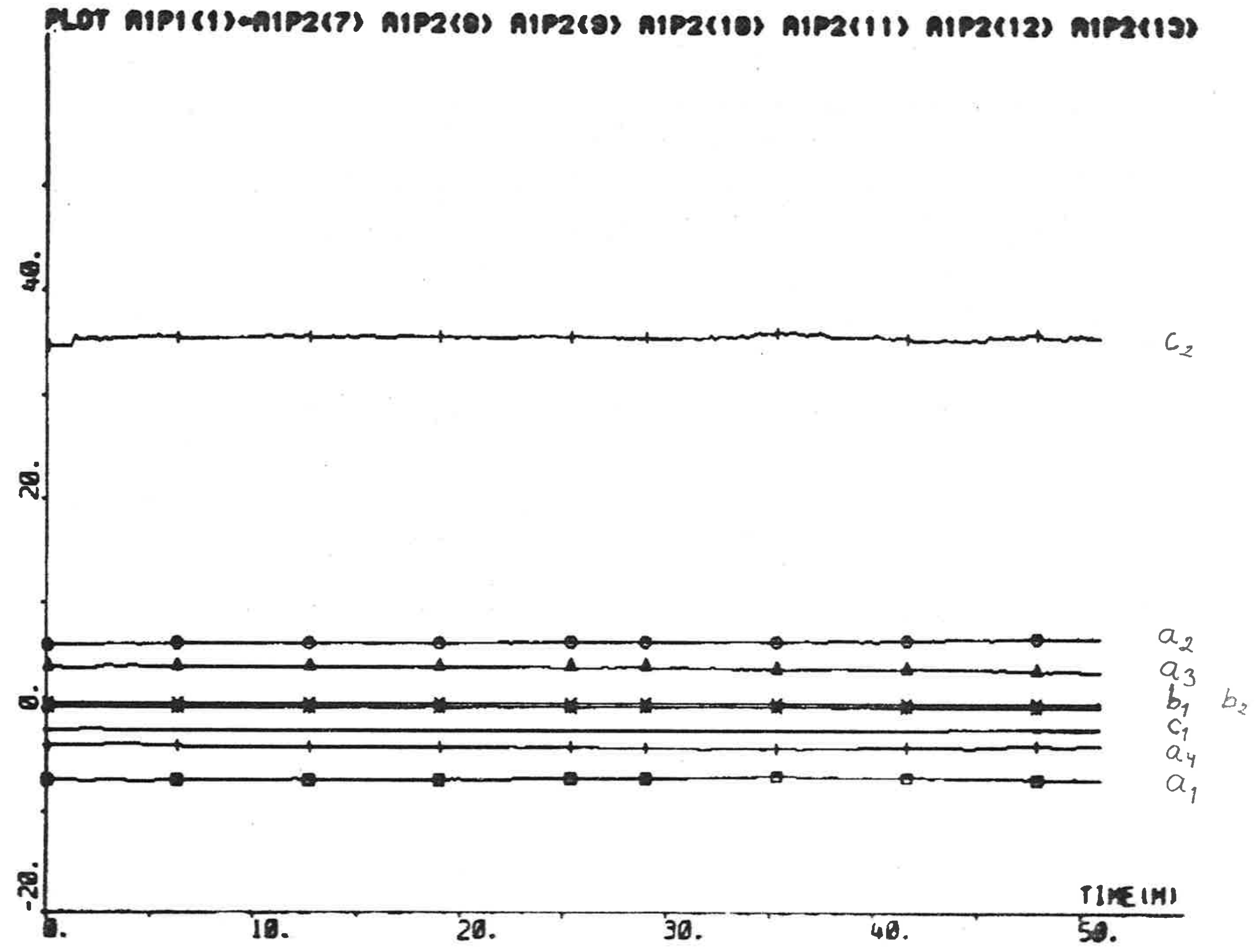

PLOT A1P1(1)-A1P1(6) A1P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. " DEG/S
Ø.
-0.2
-0.4
-0.6
0.
10.
20.
30.
40.
50.
TIME(M)
r
r̂
r - r̂
εr


PLOT A1P1(1)-A1P1(8) A1P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 • DEG
0.
-1.
-2.
-3.
TIME(M)
0.
10.
20.
30.
40.
50.


PLOT A1PS(1)-A1P1(2) A1P1(3) ERR1 EPS1 00 020 040 060 -66 16 " DEG
0.
-20.
-40.
-60.
TIME(M)
0.
10.
20.
30.
40.
50.
δ
δ̂
δ - δ̂
εδ

PLOT A1P1(1)-A1P2(3) A1P2(5) A1P2(6) 00 04 05 -6.5 1.5




PLOT A1P1(1)=A1P2(7) A1P2(8) A1P2(9) A1P2(10) A1P2(11) A1P2(12) A1P2(13)
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME(H)
c_2
a_2
a_3
b_1
b_2
c_1
a_4
a_1

EXPERIMENT A2

Date	1976-04-22	Forward draught	8.5 m
Time	08.19	Aft draught	12.5 m
Duration	26 min	Wind direction	N (5; see App. A)
Position	N 12°39' W 18°29'	Wind velocity	5 m/s (gentle breeze)
ψ_{ref}	180 deg	Wave height	Low swell from N

An incorrect measurement of the yaw rate r was obtained after about 6 min. This measurement was not skipped by the Kalman filter.

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: > 120 min.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 7 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -15.17 \\ 19.33 \\ -2.62 \\ -1.87 \\ 0.63 \\ 0.52 \\ 0.35 \\ 113.66 \end{bmatrix} \qquad P = \begin{bmatrix} 13.56 & & & & & & & \\ -18.18 & 32.91 & & & & & & \\ -0.39 & -14.74 & 29.92 & & & & & \\ 5.72 & -0.62 & -15.50 & 11.07 & & & & \\ -0.33 & 0.12 & 0.62 & -0.43 & 0.03 & & & \\ -0.25 & 0.21 & 0.17 & -0.14 & 0.01 & 0.02 & & \\ -1.85 & 2.54 & 0.28 & -1.04 & 0.03 & 0.00 & 0.86 & \\ 61.97 & -69.20 & -45.68 & 49.88 & -2.82 & -1.84 & 7.66 & 1171.60 \end{bmatrix}$$

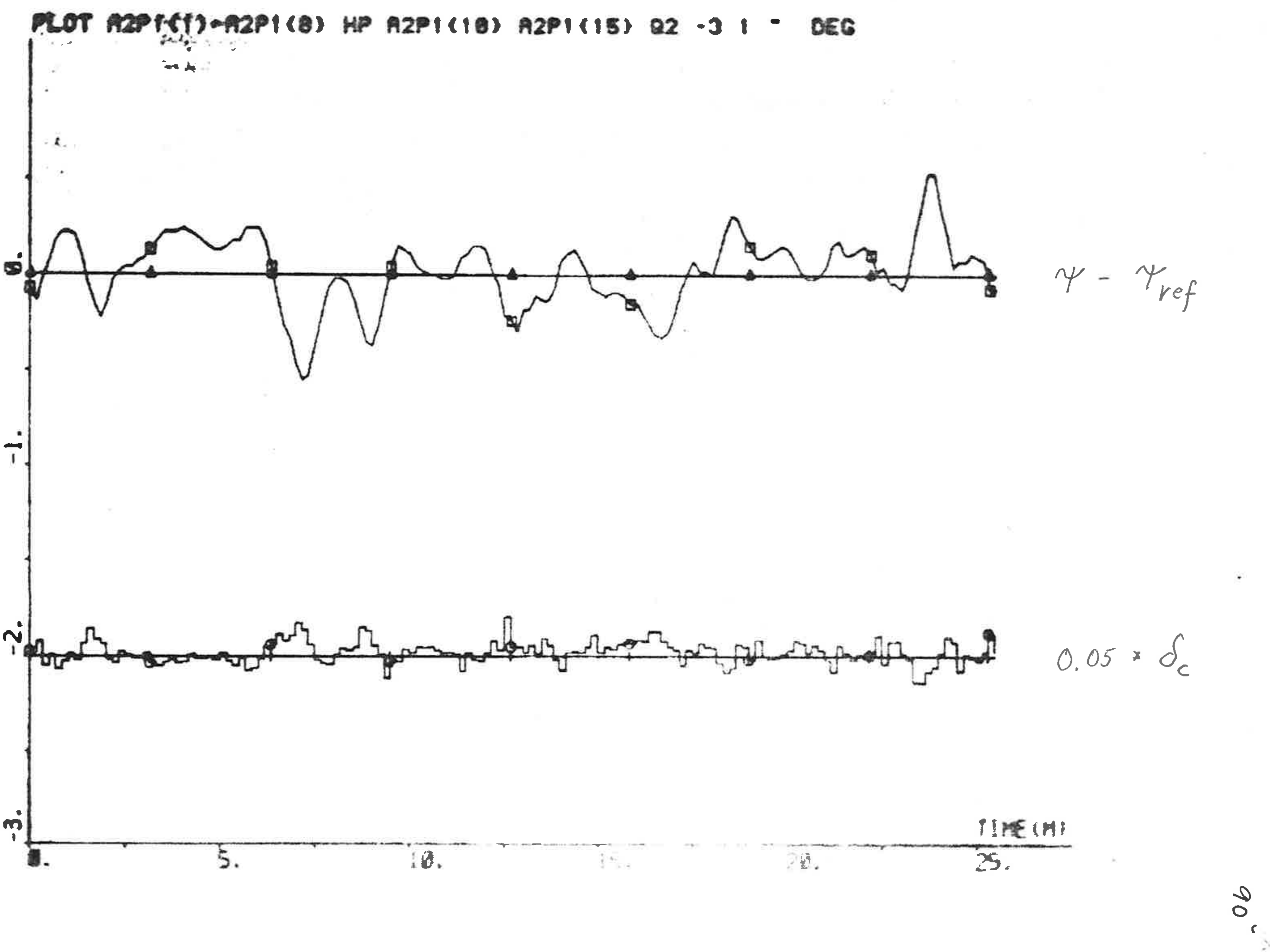
$a_1 + a_2 + a_3 + a_4 = -0.33$

$\hat{\delta}_0 = 0.4$ deg $\hat{d}_v = 0.20$ knots $\hat{d}_r = -0.001$ deg/s $\hat{d}_\delta = 1.3$ deg

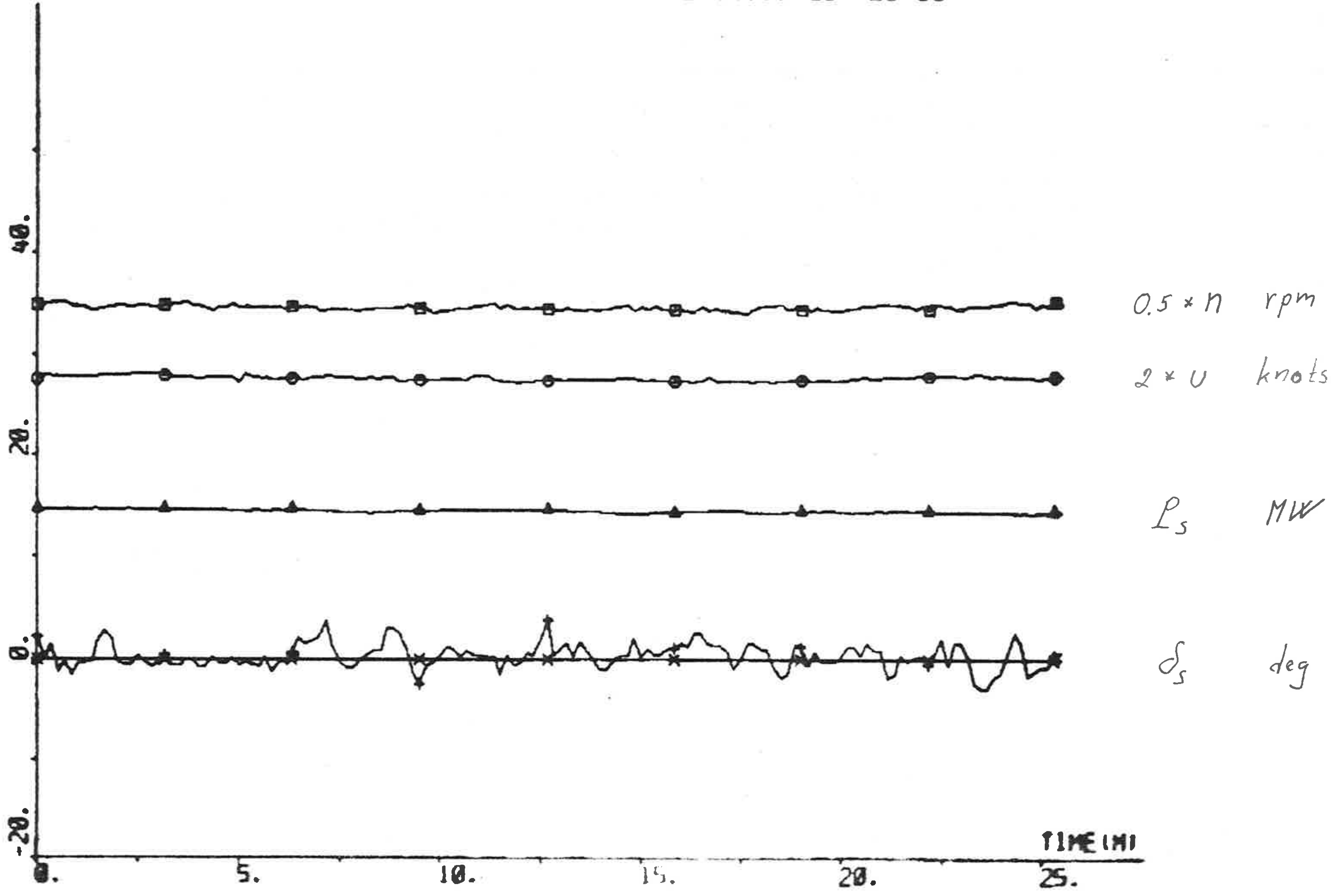
Statistics (mean value and standard deviation)

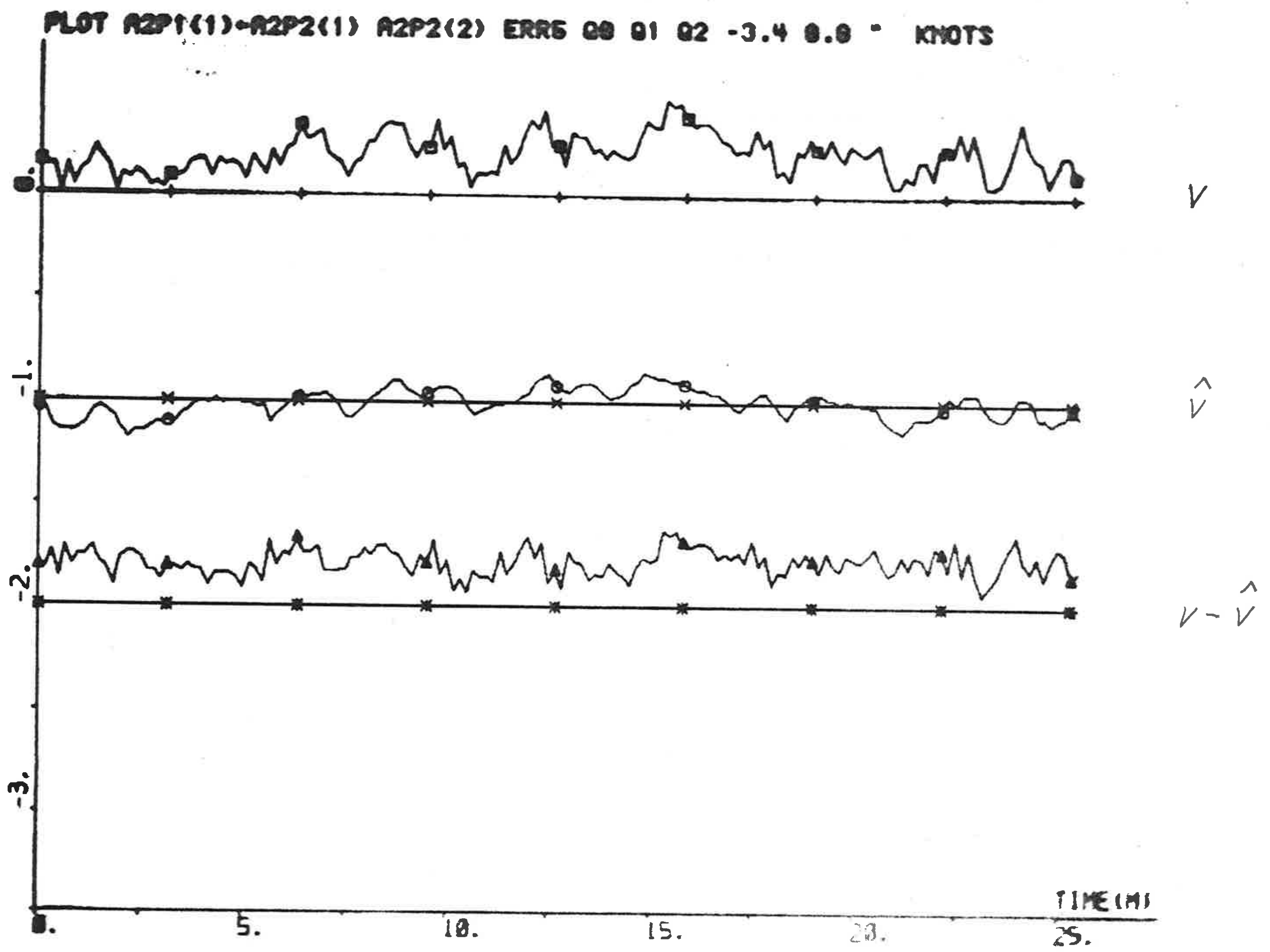
δ_c	0.41	± 1.14	deg	P_s	14.5	± 0.1	MW
δ	1.77	± 1.03	deg	ε_v	0.00	± 0.02	knots
$\psi-\psi_{ref}$	0.017	± 0.182	deg	ε_r	0.00	± 0.02	deg/s
n	69.6	± 0.5	rpm	ε_ψ	0.00	± 0.02	deg
u	13.9	± 0.1	knots	ε_δ	0.0	± 0.5	deg

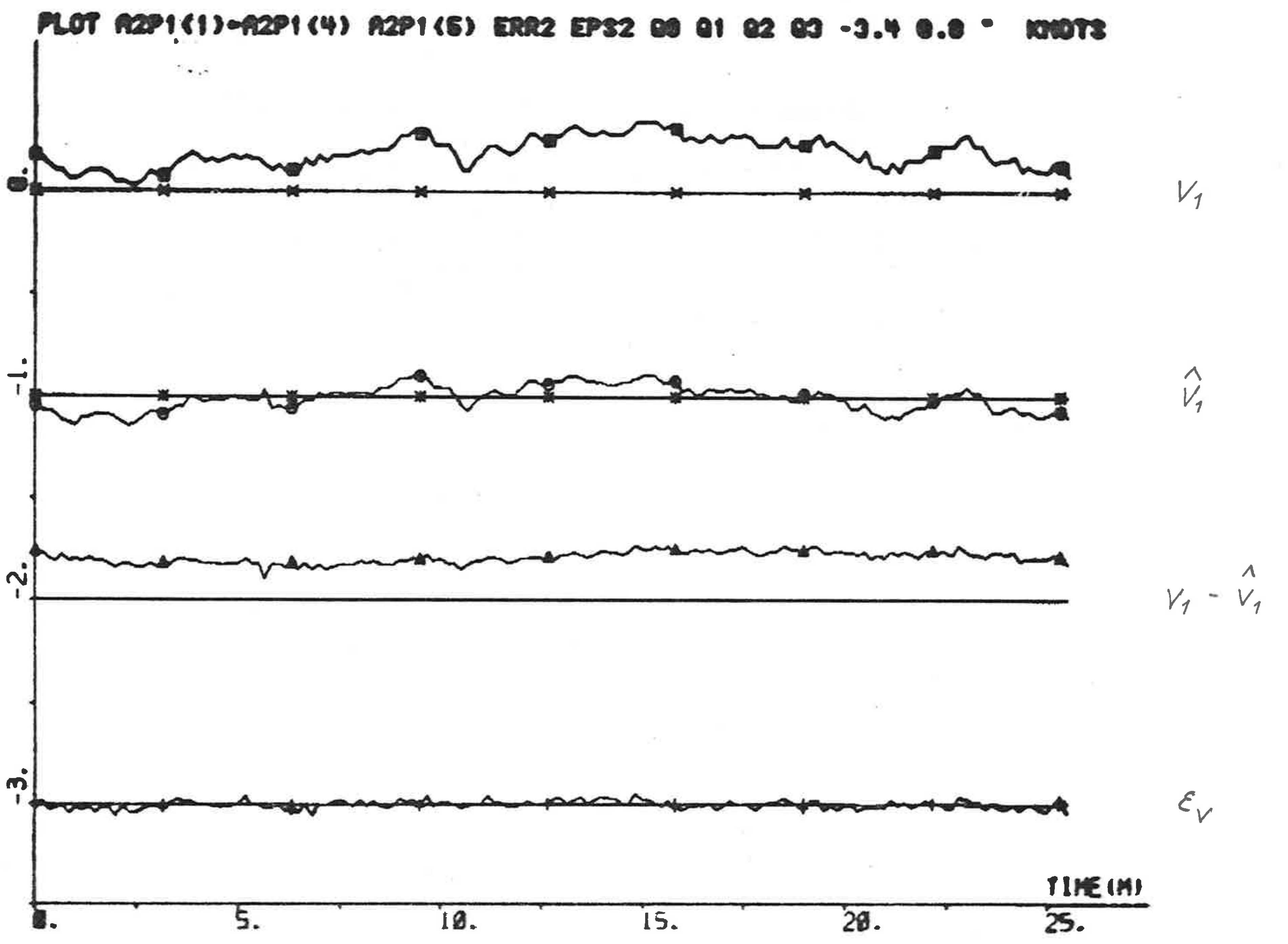
$V_1 = 0.142$

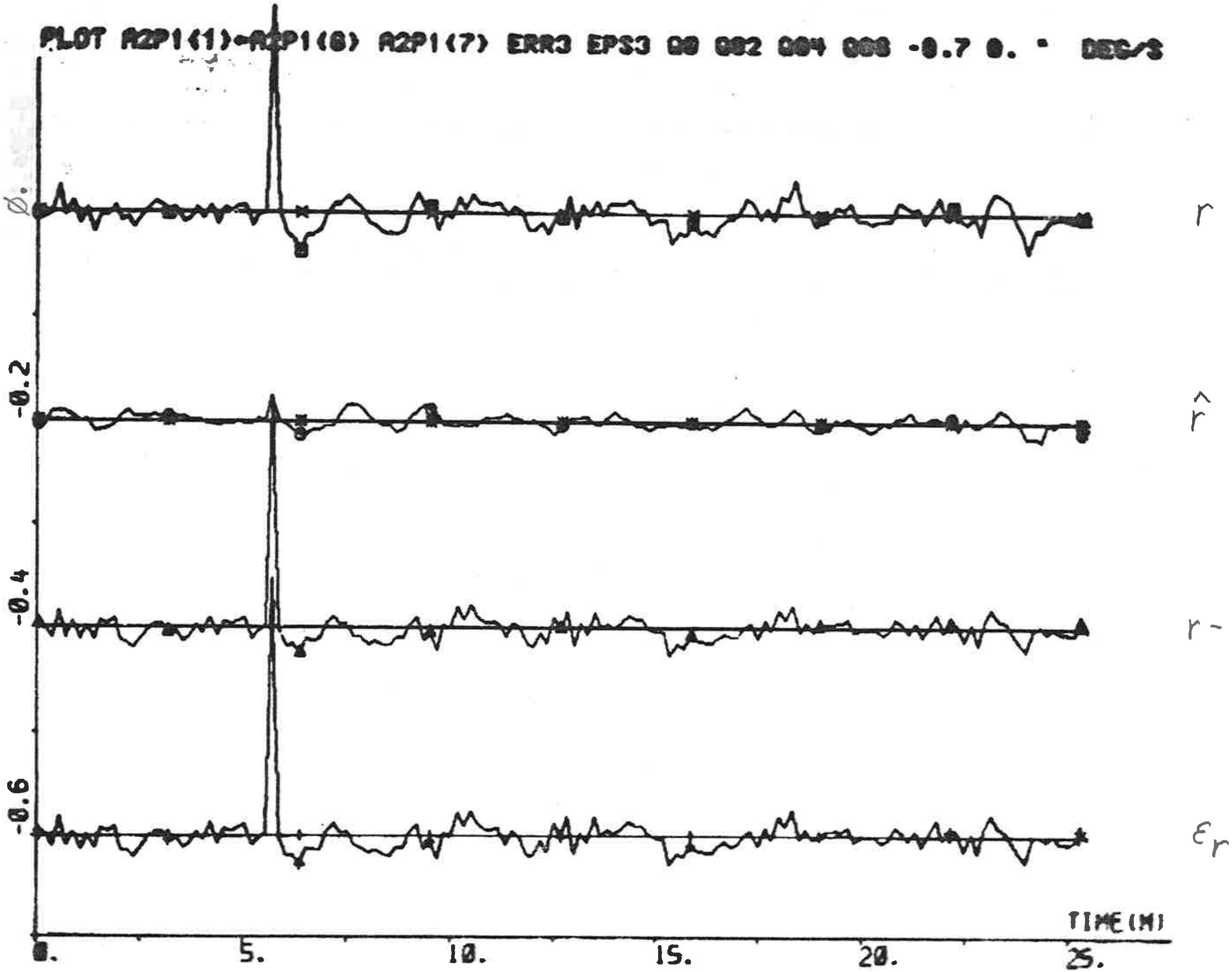

PLOT A2P1(T)-A2P1(8) HP A2P1(18) A2P1(15) 82 -3 1 - DEG
0.
-1.
-2.
-3.
5.
10.
25.
TIME(M)
ψ - ψ_ref
0.05 * δ_c
90°

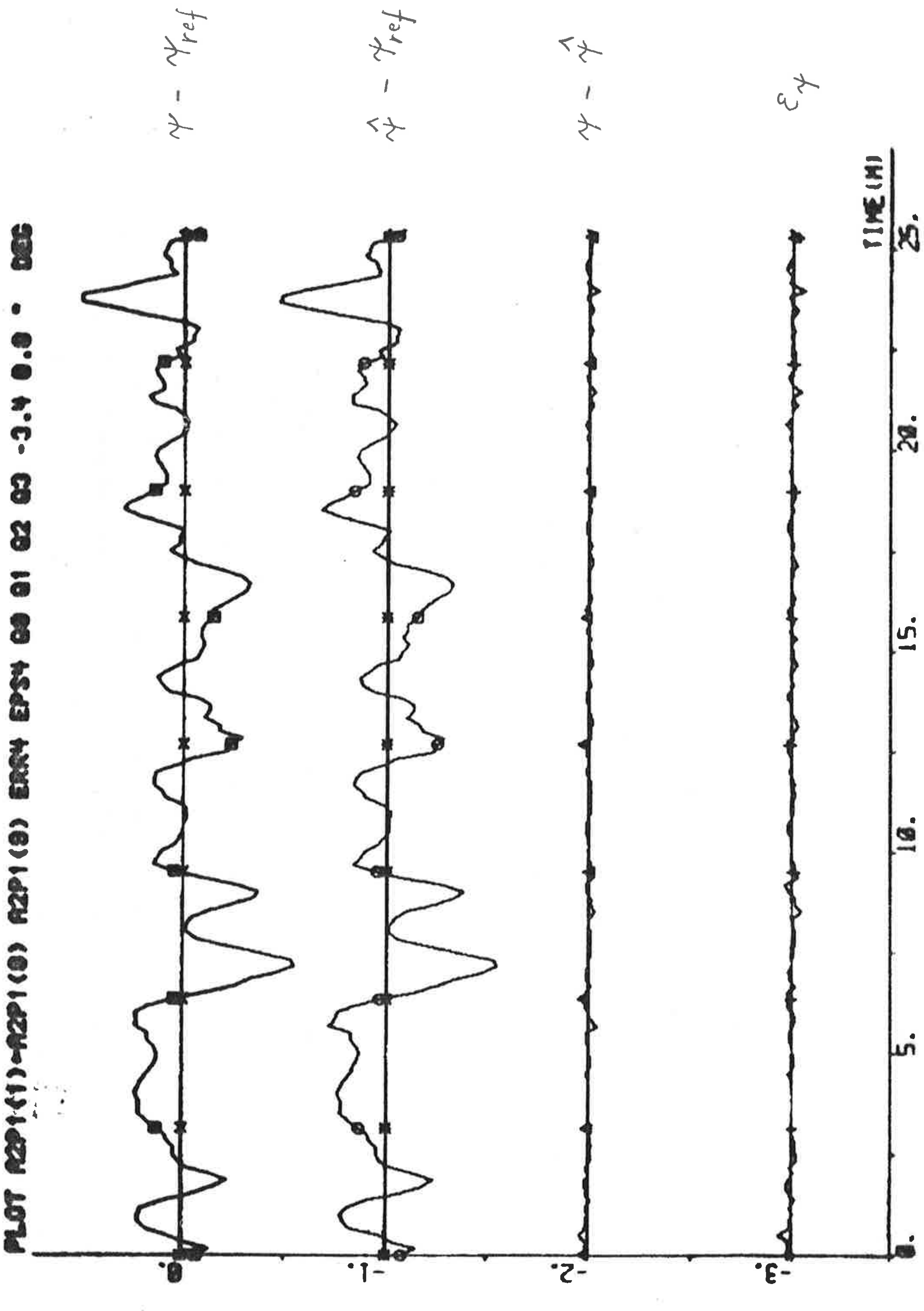
PLOT A2P1(1)-A2P1(13) A2P1(12) A2P1(14) A2P1(11) 00 -20 50

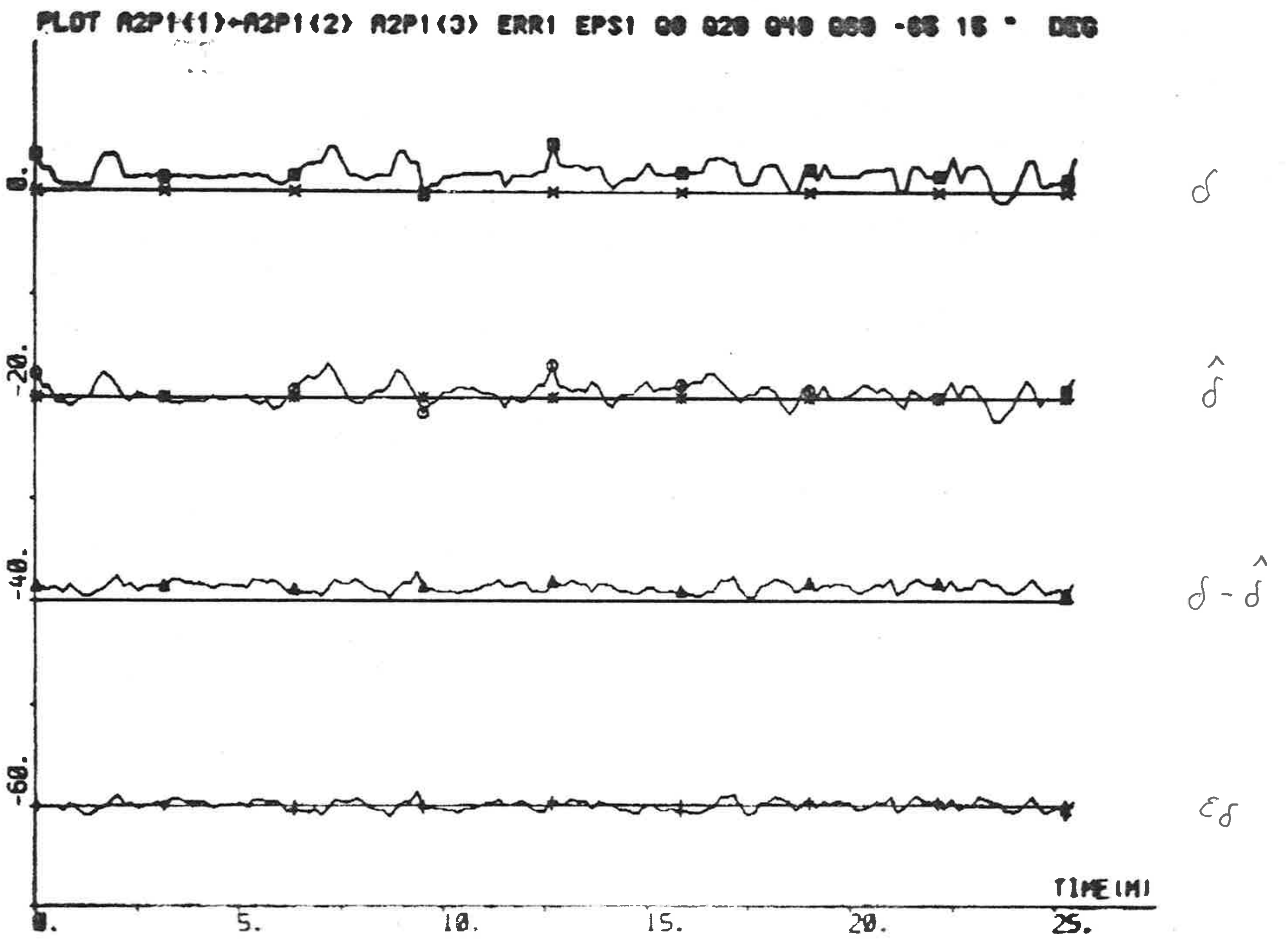


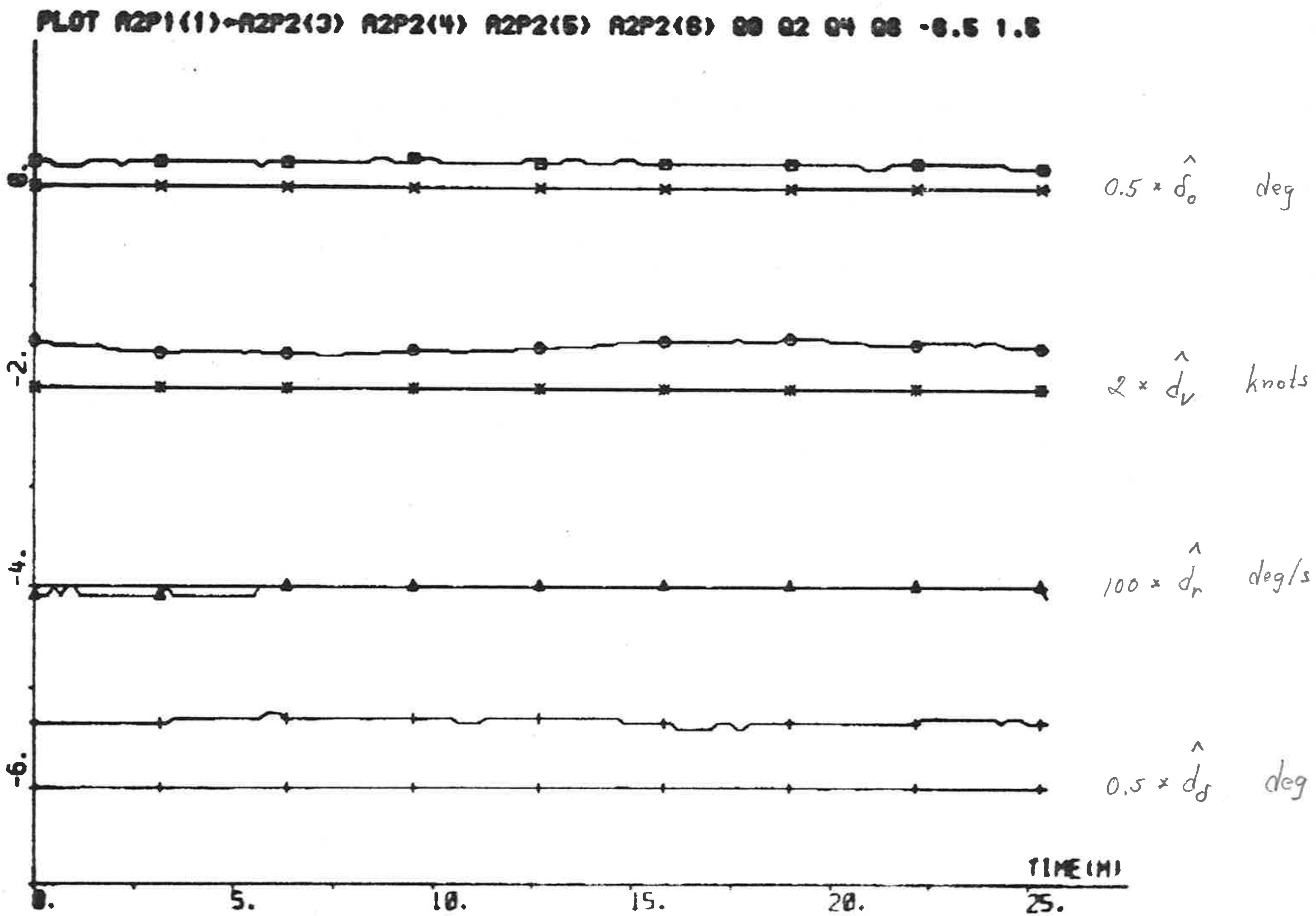

PLOT A2P1(1)-A2P2(1) A2P2(2) ERRS 00 01 02 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V
V̂
V - V̂


PLOT A2P1(1)-A2P1(4) A2P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V1
V̂1
V1 - V̂1
εV

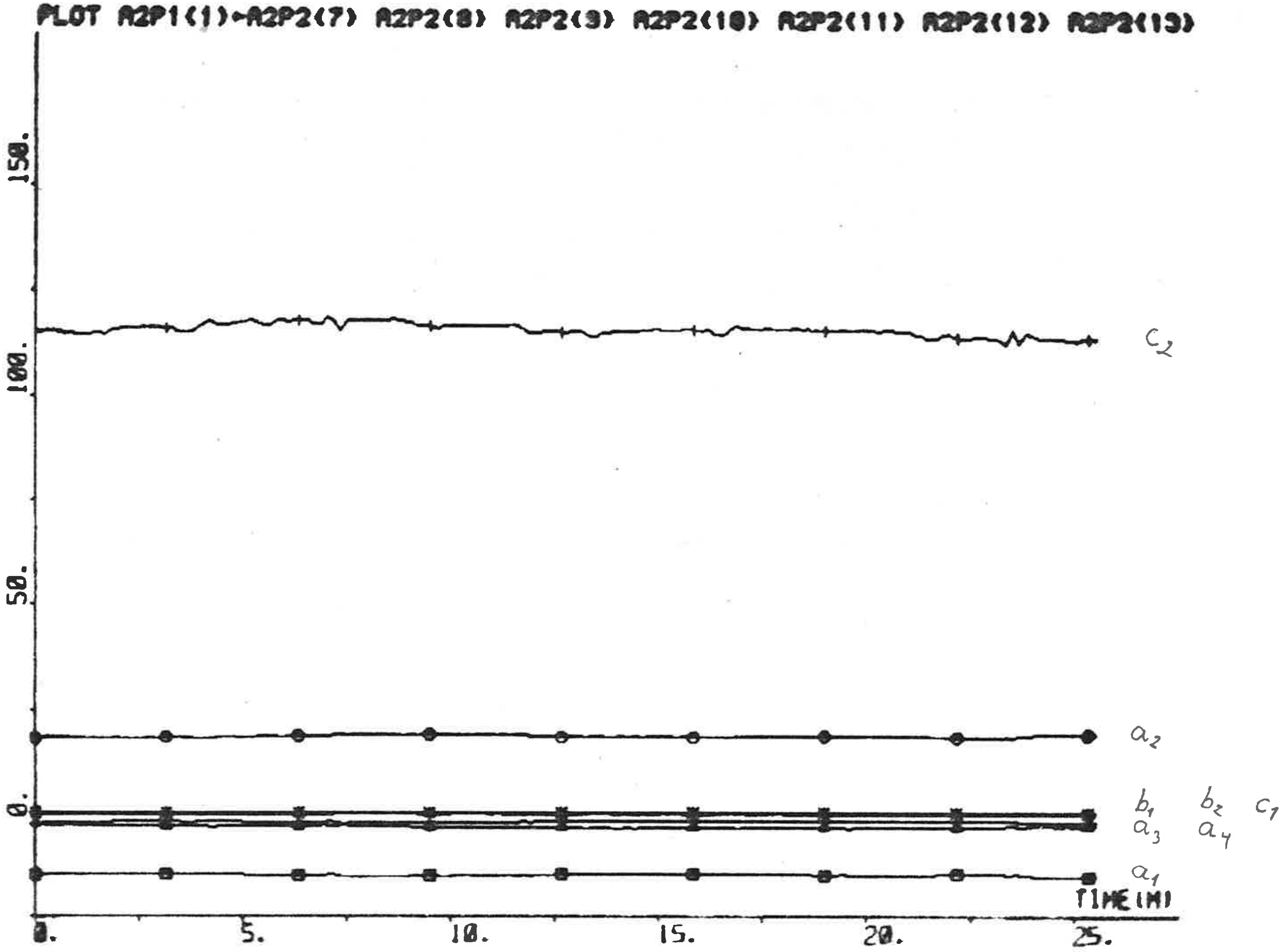

PLOT A2P1(1)-A2P1(6) A2P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. DEG/S
Ø.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A2P1(1)-A2P1(0) A2P1(9) ERR4 EPS4 G0 G1 G2 G3 -3.4 0.0 DEG
TIME (H)
0.
5.
10.
15.
20.
25.
-1.
-2.
-3.


PLOT A2P1(1)+A2P1(2) A2P1(3) ERR1 EPS1 00 020 040 060 -65 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂
εδ



PLOT A2P1(1)-A2P2(3) A2P2(4) A2P2(5) A2P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(H)
$0.5 * \hat{\delta}_o$ deg
$2 * \hat{d}_V$ knots
$100 * \hat{d}_r$ deg/s
$0.5 * \hat{d}_\delta$ deg


PLOT A2P1(1)-A2P2(7) A2P2(8) A2P2(9) A2P2(10) A2P2(11) A2P2(12) A2P2(13)
150.
100.
50.
0.
0.
5.
10.
15.
20.
25.
TIME(H)
c2
a2
b1
b2
c1
a3
a4
a1

EXPERIMENT A3

Date	1976-04-22	Forward draught	8.5 m
Time	09.46	Aft draught	12.5 m
Duration	24 min	Wind direction	N (5; see App. A)
Position	N 12°17' W 18°29'	Wind velocity	10 m/s (fresh breeze)
ψ_{ref}	180 deg	Wave height	Low swell from N

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 k = 5 q = 0

T_s = 10 s V_0 = 7 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.60 \\ 6.39 \\ 4.38 \\ -2.62 \\ 0.53 \\ 0.26 \\ -2.34 \\ 44.87 \end{bmatrix} \qquad P = \begin{bmatrix} 4.93 & & & & & & & \\ -5.58 & 10.51 & & & & & & \\ -1.10 & -4.43 & 10.96 & & & & & \\ 2.10 & -0.68 & -5.65 & 4.56 & & & & \\ -0.14 & -0.04 & 0.33 & -0.15 & 0.03 & & & \\ -0.12 & 0.05 & -0.01 & 0.08 & 0.01 & 0.03 & & \\ -0.53 & 0.85 & 0.22 & -0.57 & -0.02 & -0.03 & 0.67 & \\ 14.78 & -24.57 & -4.88 & 12.45 & -1.00 & 0.36 & 9.76 & 816.84 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.45$

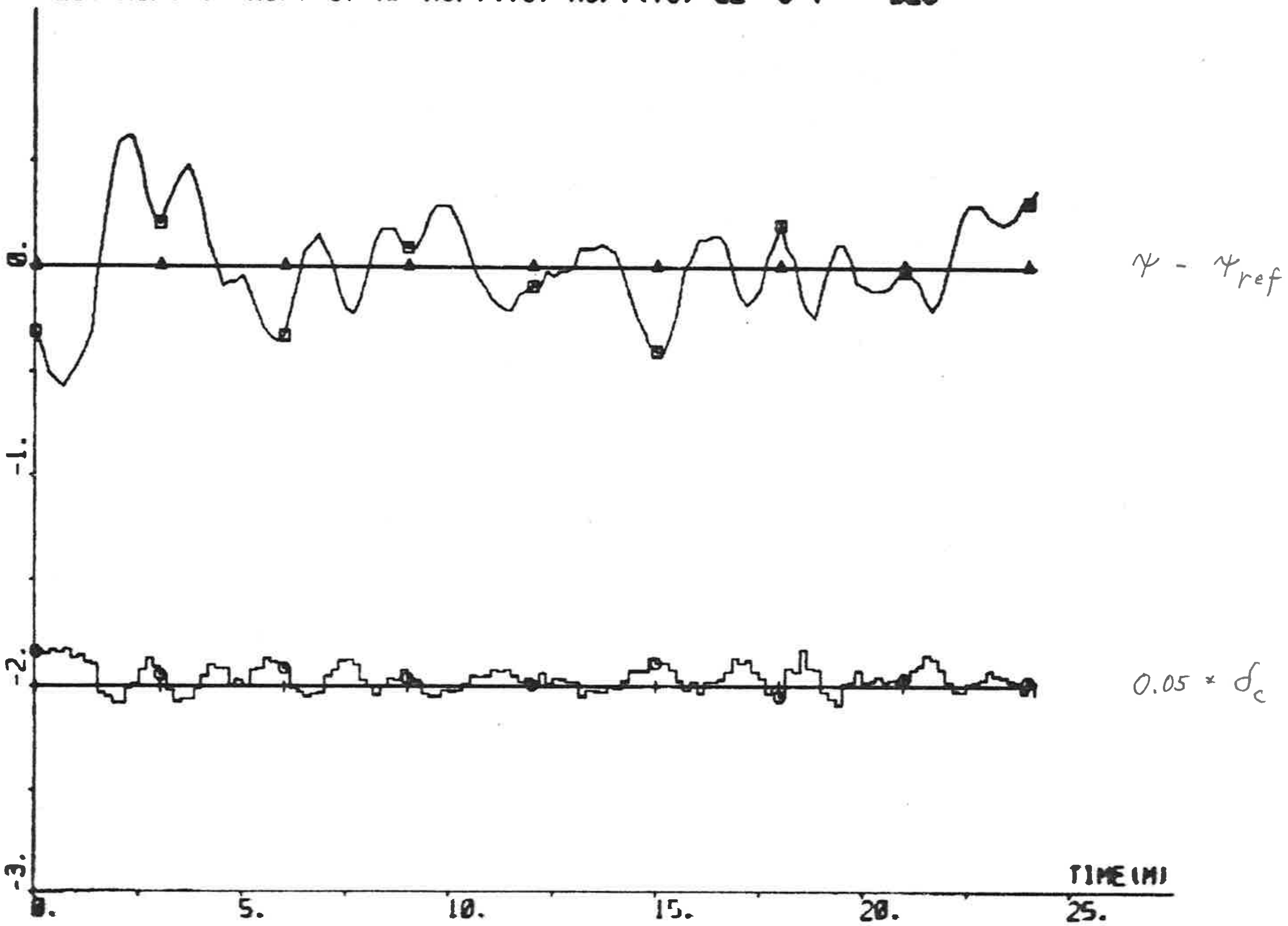
$\hat{\delta}_0 = 0.7$ deg $\hat{d}_v = 0.12$ knots $\hat{d}_r = -0.001$ deg/s $\hat{d}_\delta = 1.4$ deg

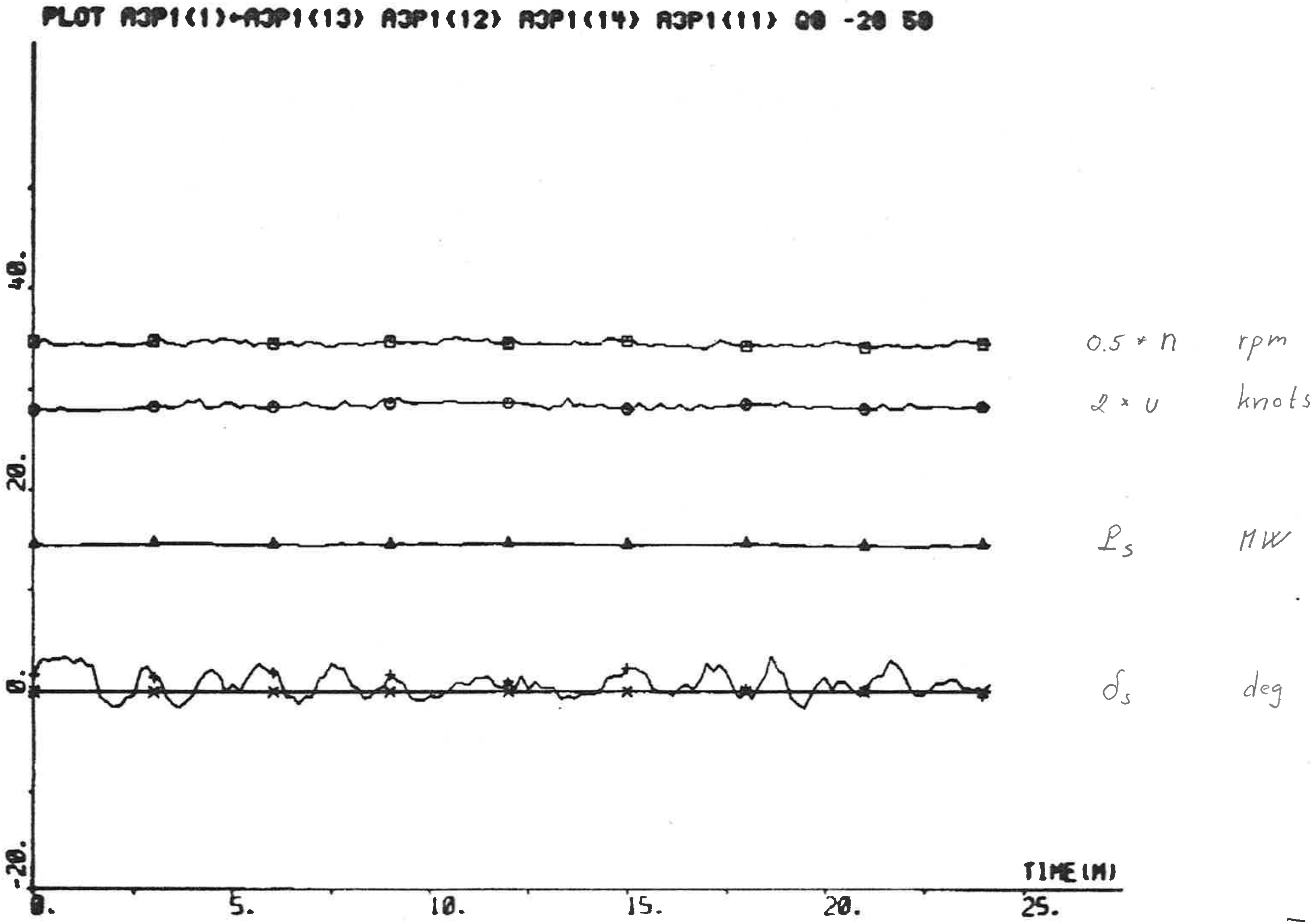
Statistics (mean value and standard deviation)

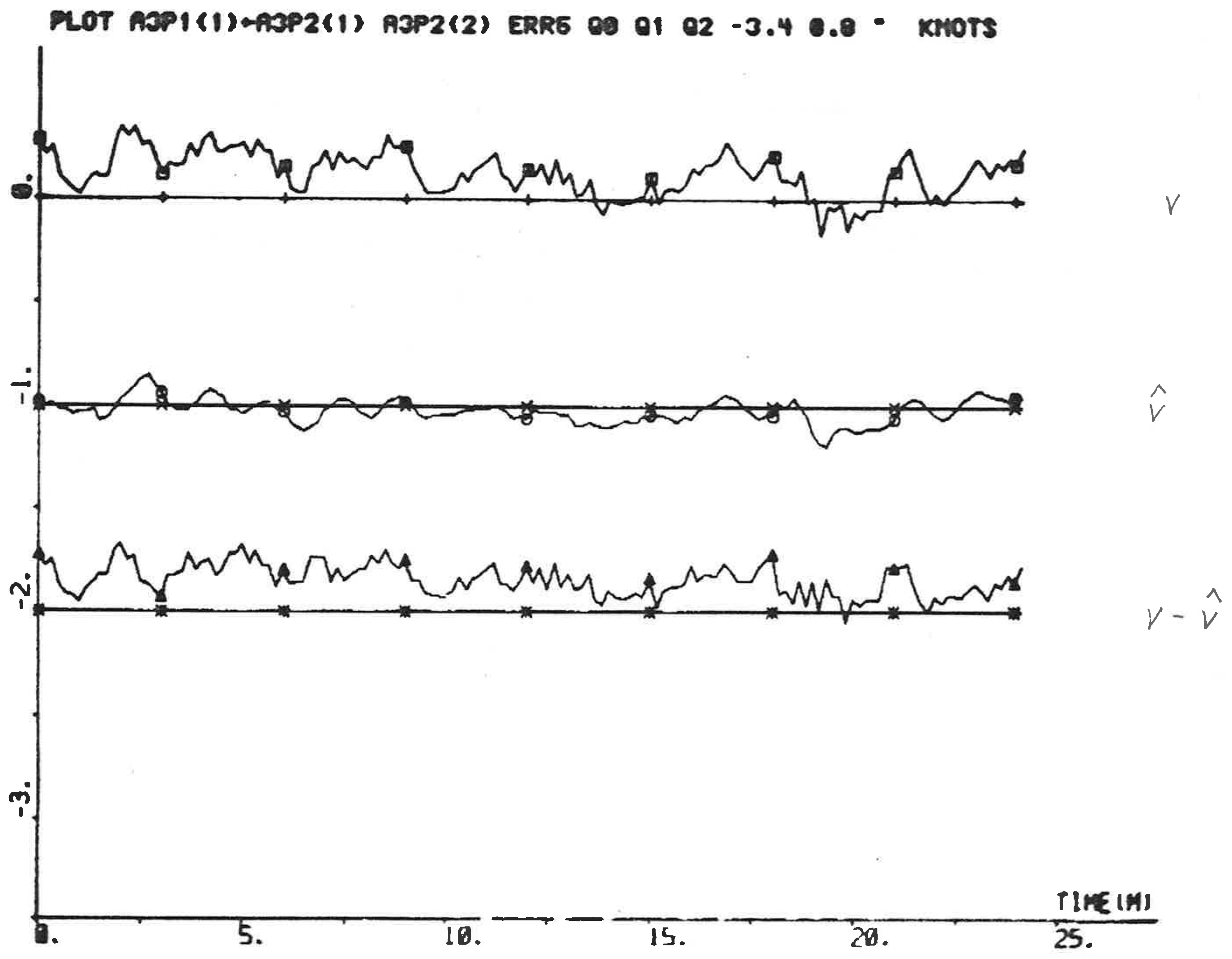
δ_c	0.74 ± 1.20	deg		P_s	14.5 ± 0.1	MW
δ	2.12 ± 1.04	deg		ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.009 ± 0.239	deg		ε_r	0.00 ± 0.01	deg/s
n	69.4 ± 0.4	rpm		ε_ψ	0.00 ± 0.02	deg
u	14.2 ± 0.1	knots		ε_δ	0.0 ± 0.5	deg

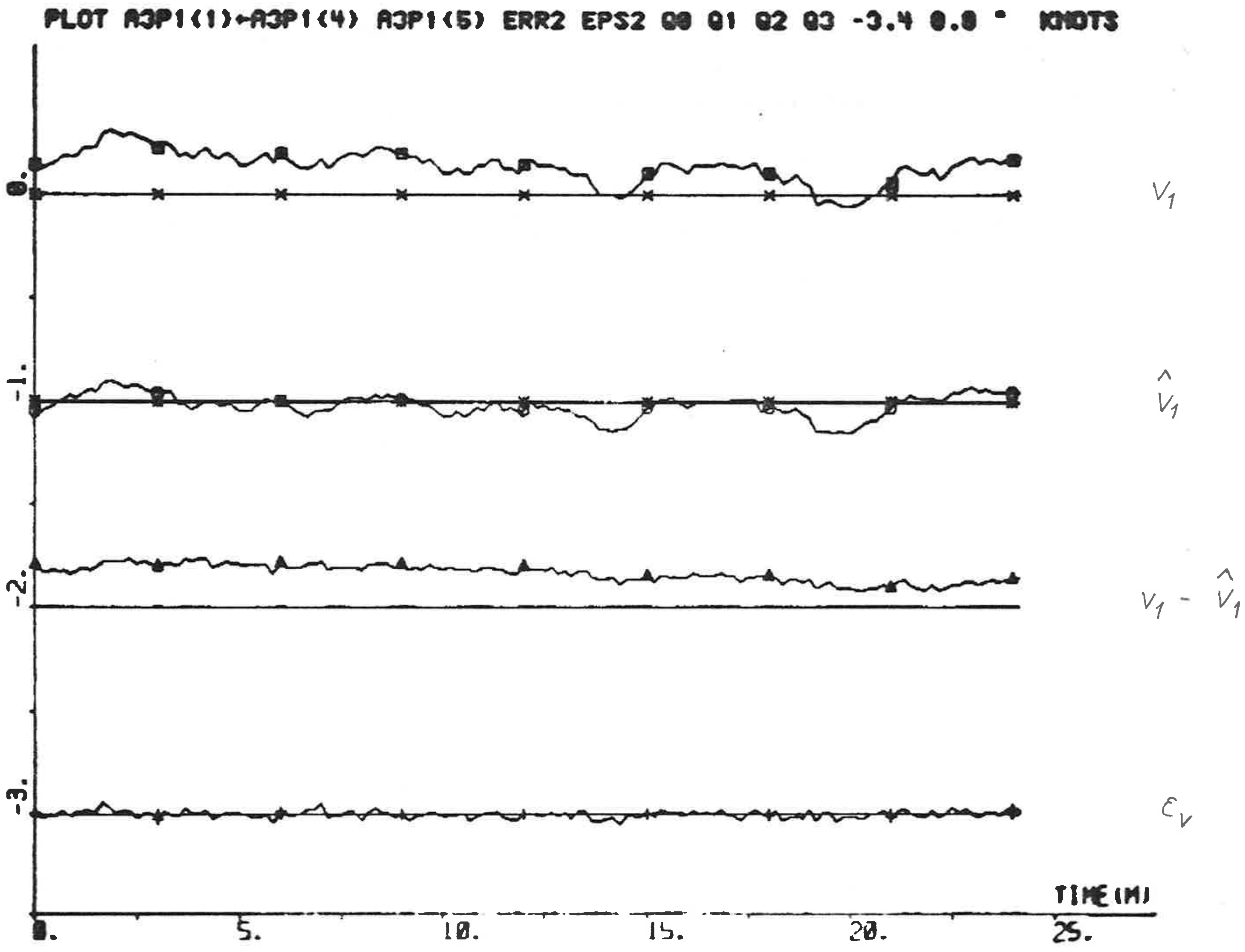
$V_1 = 0.177$

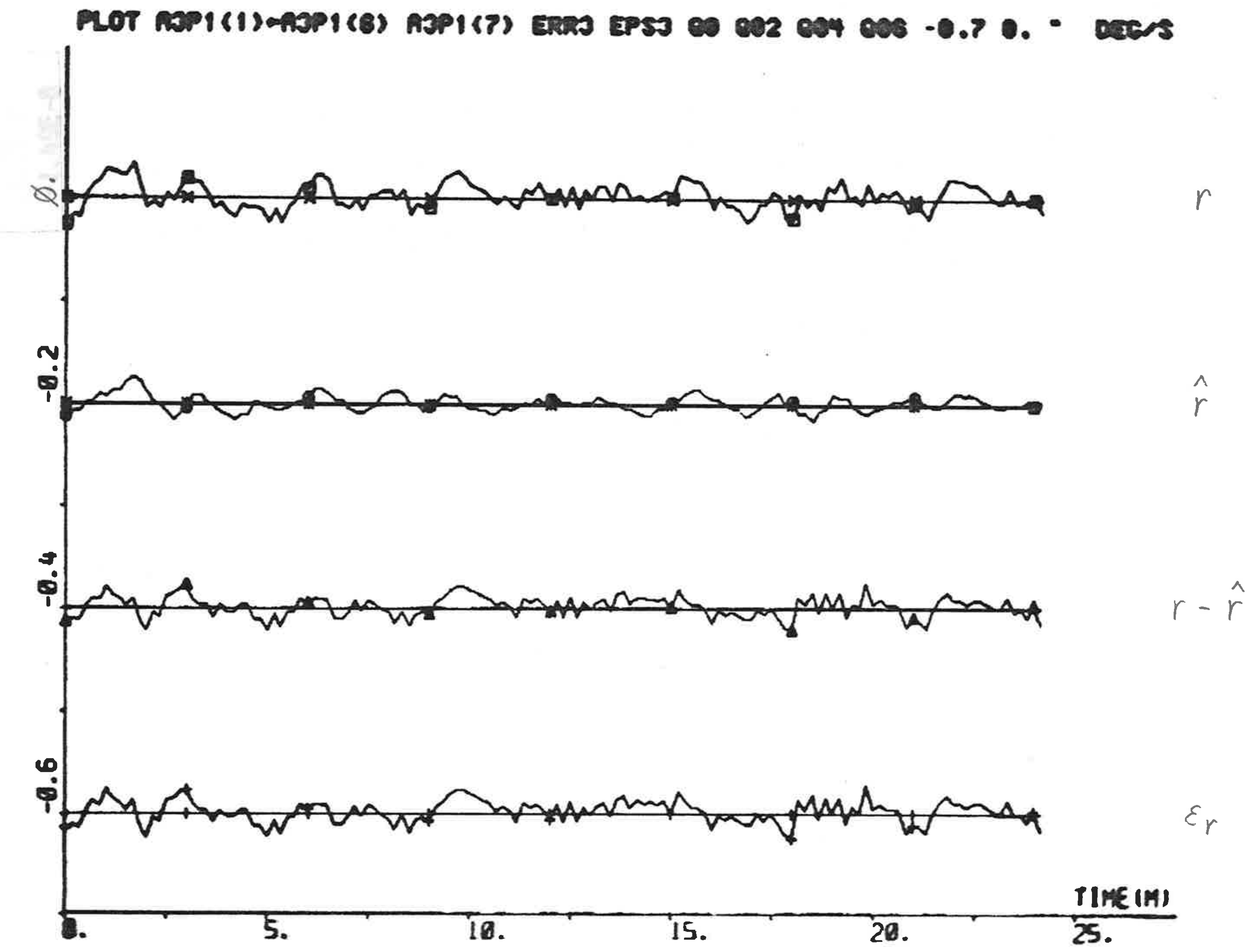
PLOT A3P1(1)-A3P1(8) HP A3P1(10) A3P1(15) 02 -3 1 ° DEG

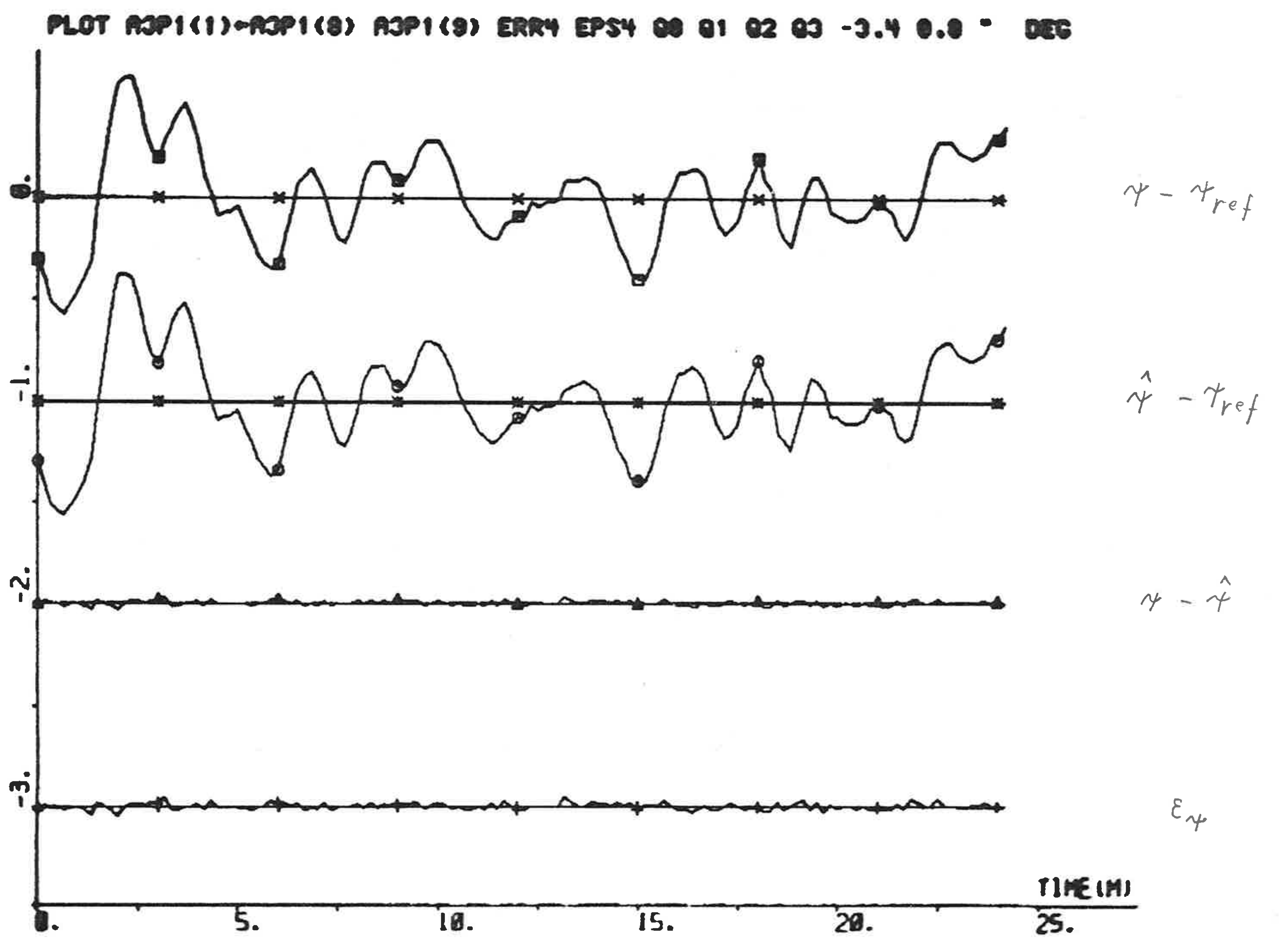


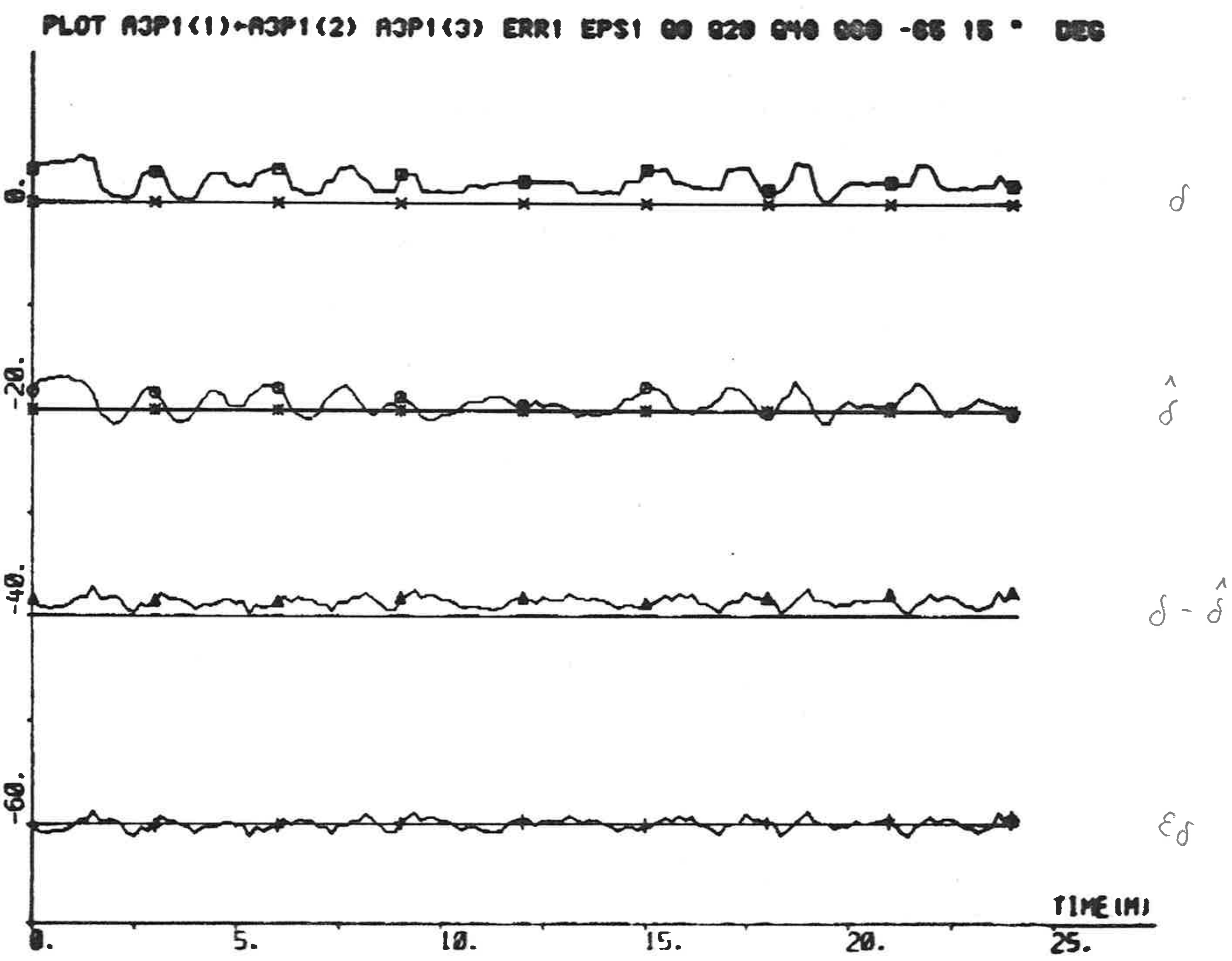

PLOT A3P1(1)+A3P1(13) A3P1(12) A3P1(14) A3P1(11) Q0 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n rpm
2 * U knots
P_s MW
δ_s deg

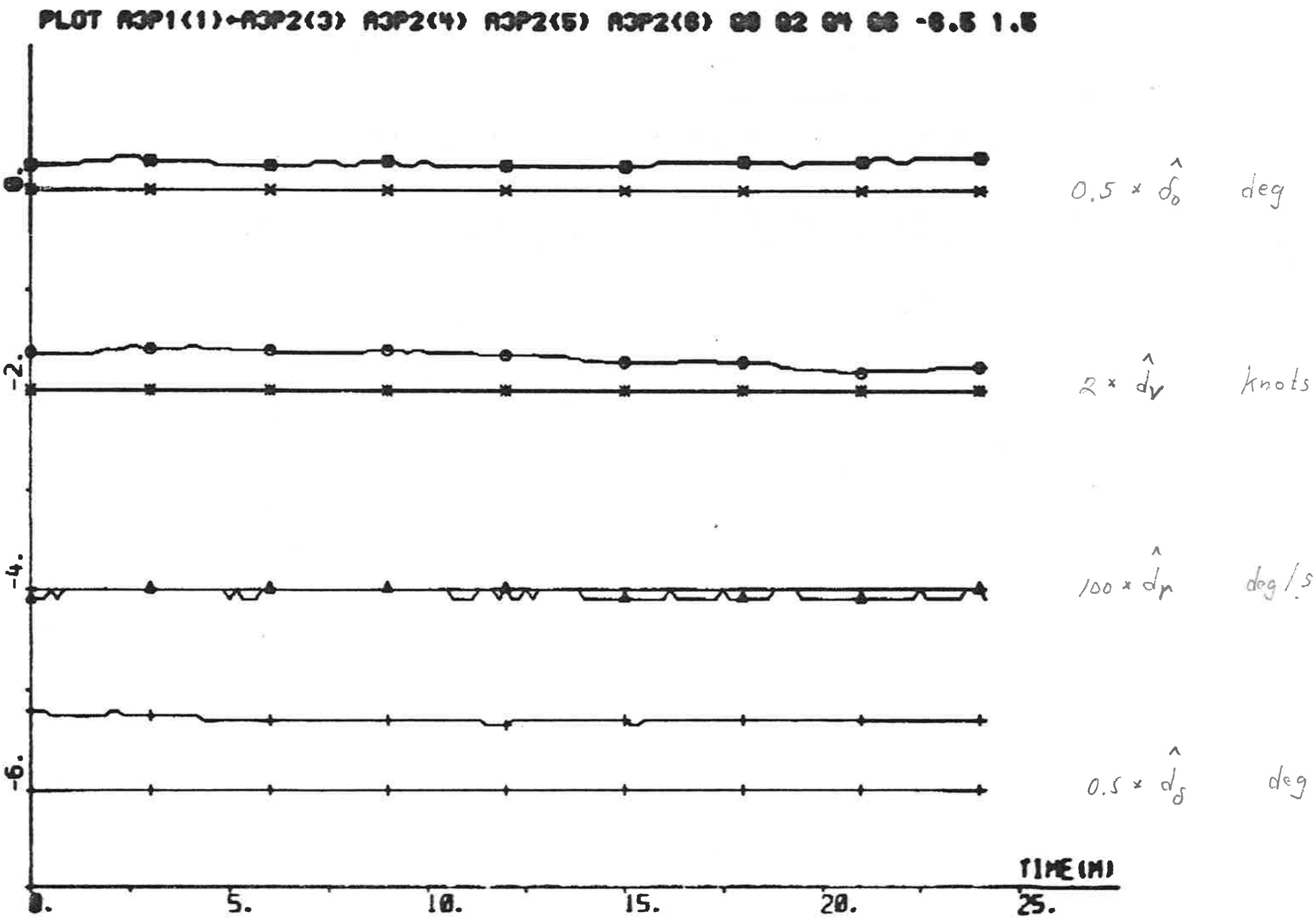

PLOT A3P1(1)+A3P2(1) A3P2(2) ERR6 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V
V̂
V - V̂

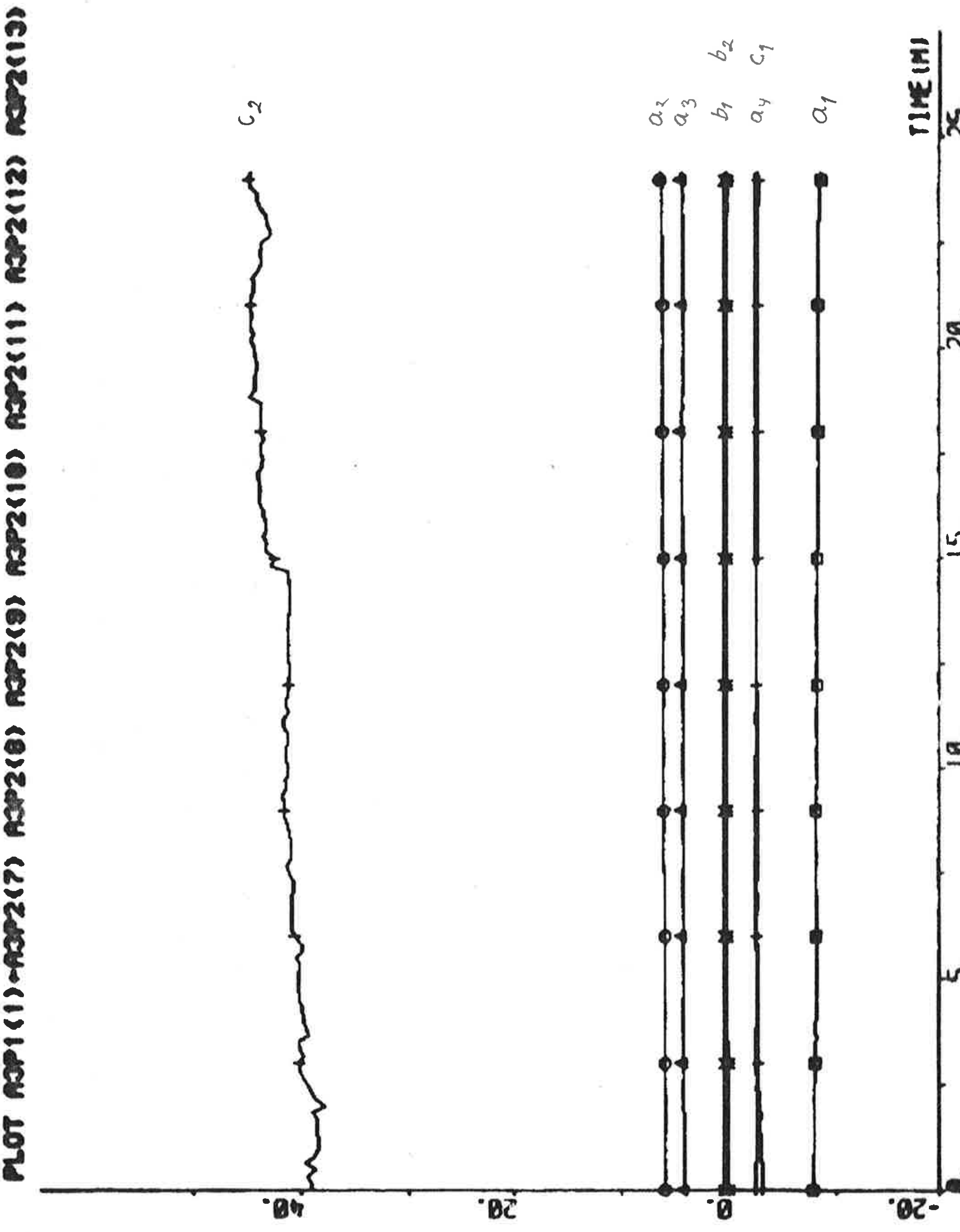

PLOT A3P1(1)-A3P1(4) A3P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT A3P1(1)~A3P1(6) A3P1(7) ERR3 EPS3 G0 G02 G04 G06 -0.7 0. " DEG/S
Ø.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂
εr


PLOT A3P1(1)-A3P1(8) A3P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$\hat{\psi} - \psi_{ref}$
$\psi - \hat{\psi}$
ε_{ψ}


PLOT A3P1(1)-A3P1(2) A3P1(3) ERR1 EPS1 00 020 040 060 -65 15 ° DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
$\hat{\delta}$
$\delta - \hat{\delta}$
ε_δ


PLOT A3P1(1)-A3P2(3) A3P2(4) A3P2(5) A3P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0. 5. 10. 15. 20. 25.
TIME(M)
0.5 × $\hat{d}_o$ deg
2 × $\hat{d}_v$ knots
100 × $\hat{d}_r$ deg/s
0.5 × $\hat{d}_\delta$ deg



PLOT A3P1(1)-A3P2(7) A3P2(8) A3P2(9) A3P2(10) A3P2(11) A3P2(12) A3P2(13)
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(H)
c2
a2
a3
b1
b2
a4
c1
a1

EXPERIMENT A4

Date	1976-04-22	Forward draught	8.5 m
Time	10.53	Aft draught	12.5 m
Duration	24 min	Wind direction	N (5; see App. A)
Position	N 12°01' W 18°28'	Wind velocity	5 m/s (gentle breeze)
ψref	180 deg	Wave height	Low swell from N

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 k = 6 q = 0

T_s = 10 s V_0 = 7 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.92 \\ 6.49 \\ 4.88 \\ -2.75 \\ 0.48 \\ 0.16 \\ -1.79 \\ 50.52 \end{bmatrix} \qquad P = \begin{bmatrix} 4.78 \\ -5.62 & 11.34 \\ -1.02 & -5.32 & 12.23 \\ 2.15 & -0.53 & -6.13 & 4.83 \\ -0.14 & -0.07 & 0.36 & -0.15 & 0.03 \\ -0.10 & 0.02 & 0.00 & 0.08 & 0.01 & 0.03 \\ -0.65 & 1.02 & 0.22 & -0.62 & -0.01 & -0.01 & 0.70 \\ 17.24 & -25.17 & -10.77 & 16.08 & -0.30 & -0.23 & 9.34 & 881.25 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.30$

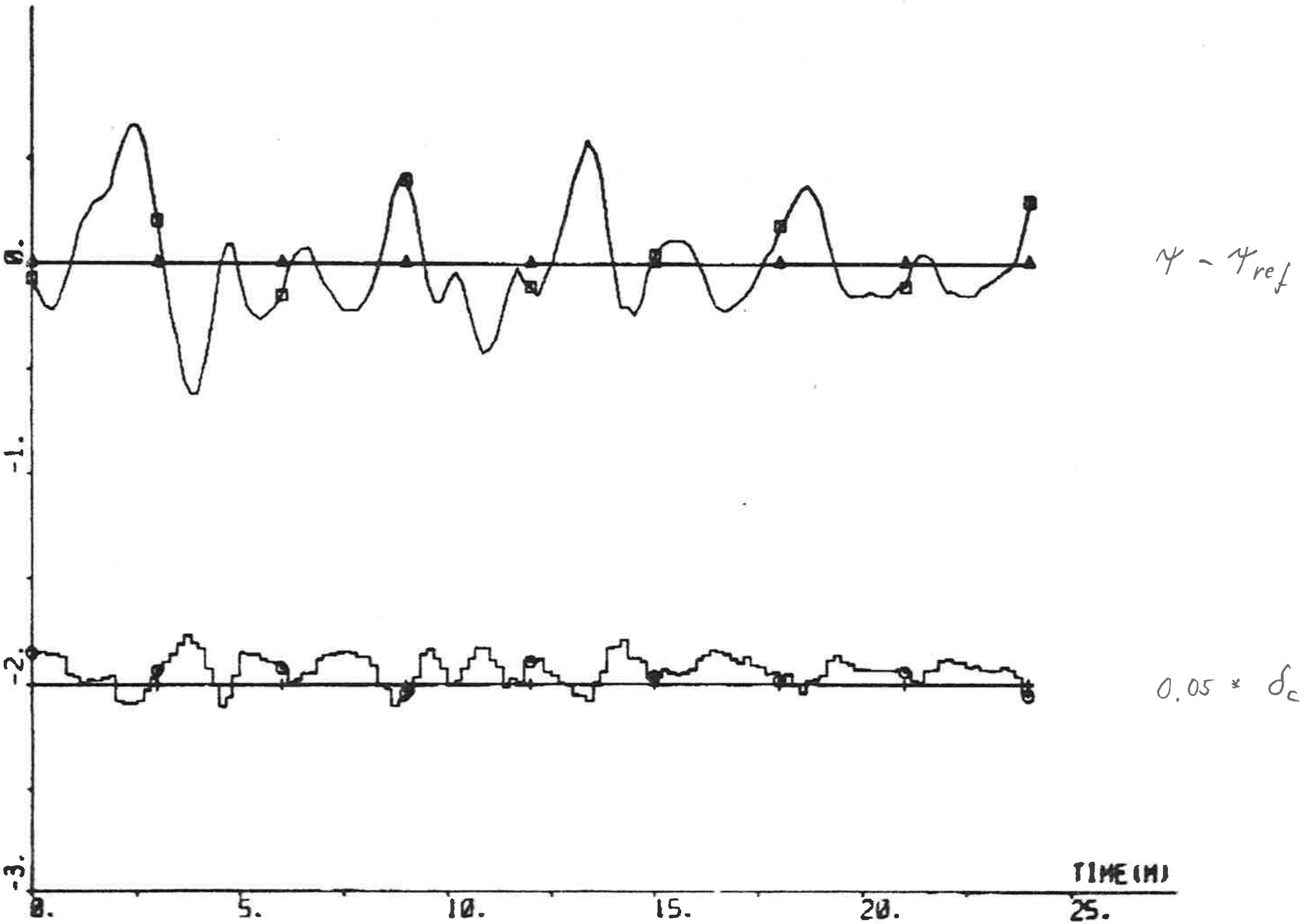
$\hat{\delta}_0$ = 1.1 deg $\hat{d}_v$ = 0.38 knots $\hat{d}_r$ = 0.000 deg/s $\hat{d}_\delta$ = 1.5 deg

Statistics (mean value and standard deviation)

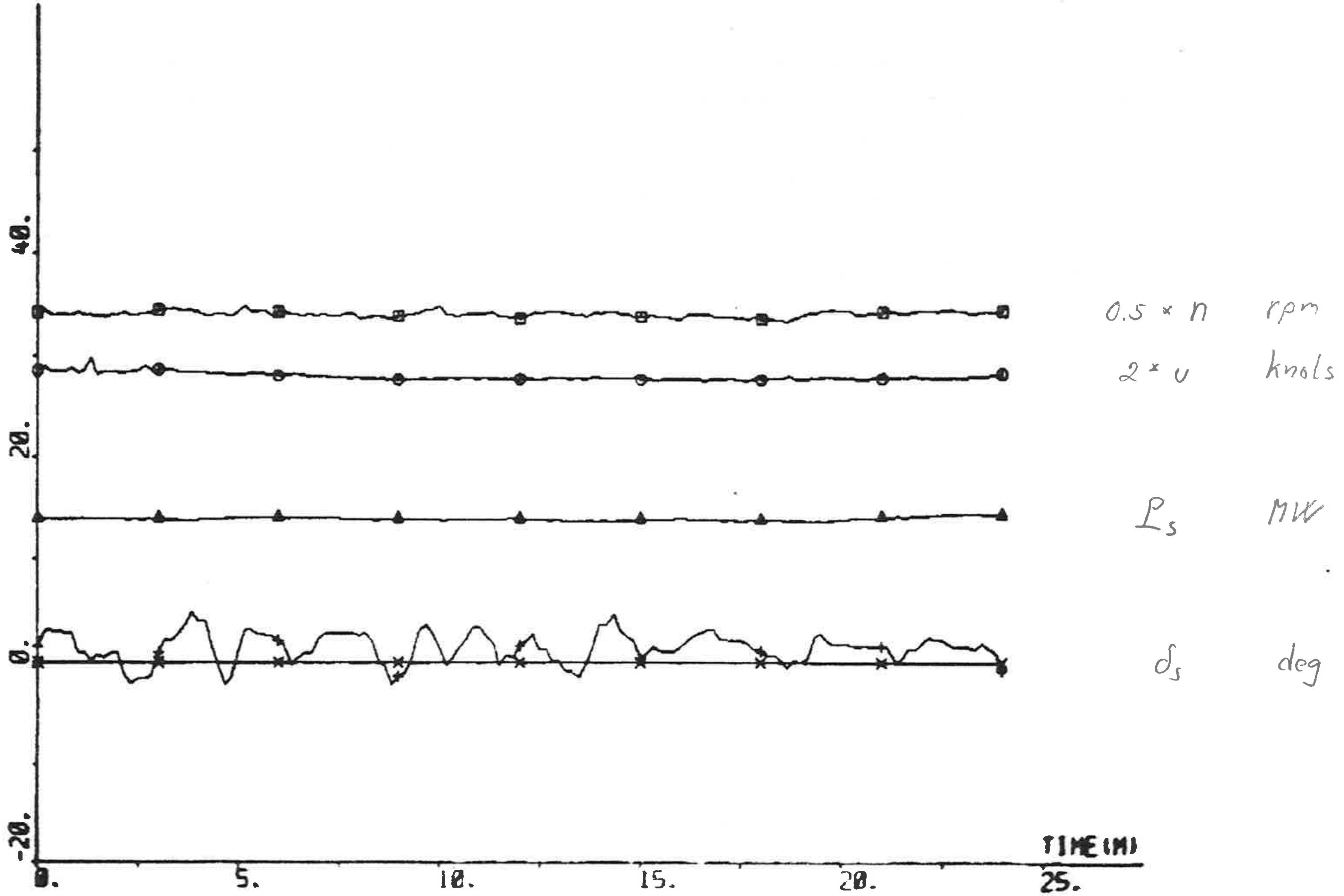
δ_c	1.39 ± 1.41	deg		P_s	14.0 ± 0.2	MW
δ	2.82 ± 1.33	deg		ε_v	0.01 ± 0.02	knots
$\psi-\psi_{ref}$	-0.009 ± 0.246	deg		ε_r	0.00 ± 0.01	deg/s
n	68.5 ± 0.6	rpm		ε_ψ	0.00 ± 0.02	deg
u	14.0 ± 0.2	knots		ε_δ	0.0 ± 0.6	deg

V_1 = 0.226

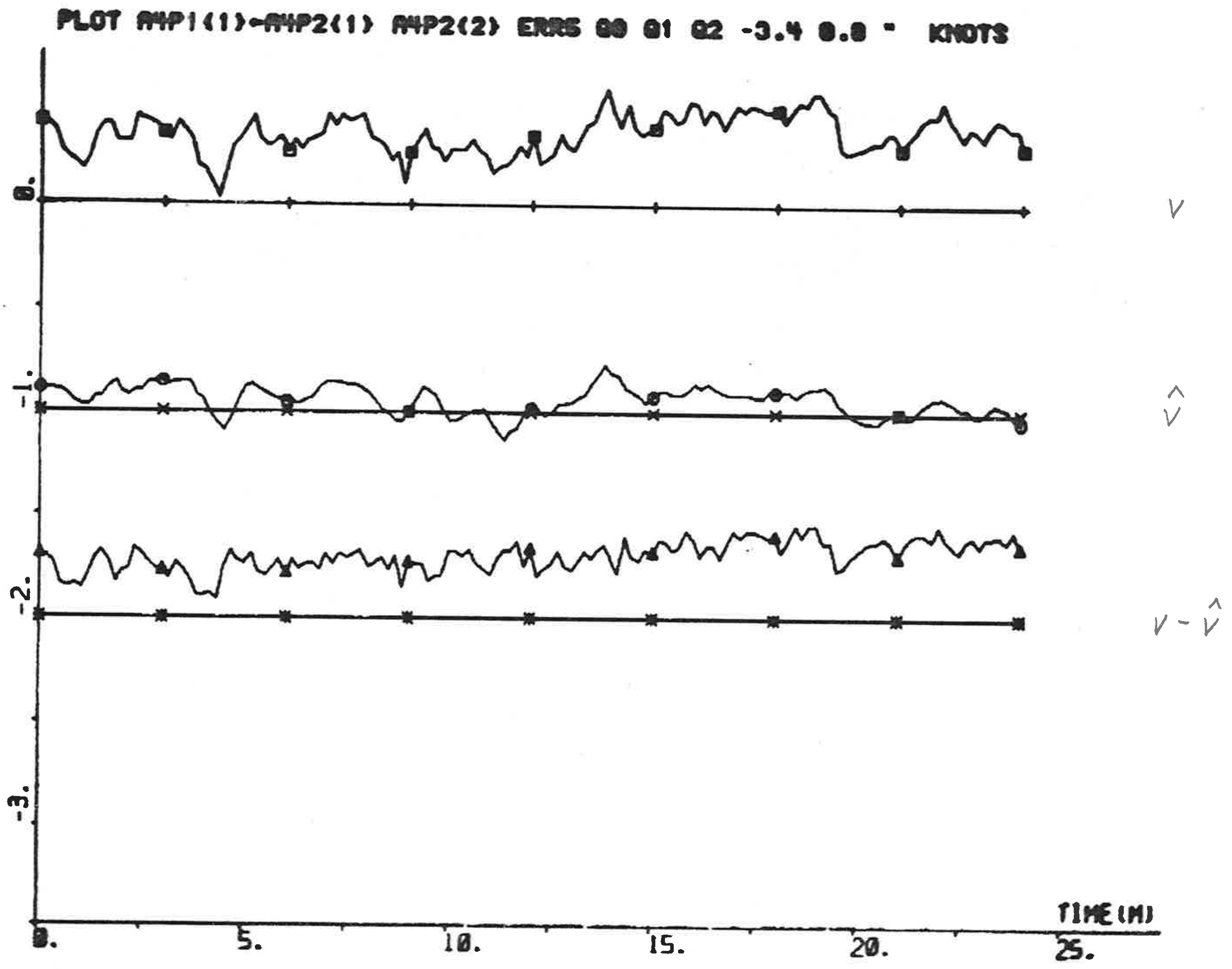
PLOT A4P1(1)-A4P1(8) HP A4P1(10) A4P1(15) 02 -3 1 " DEG

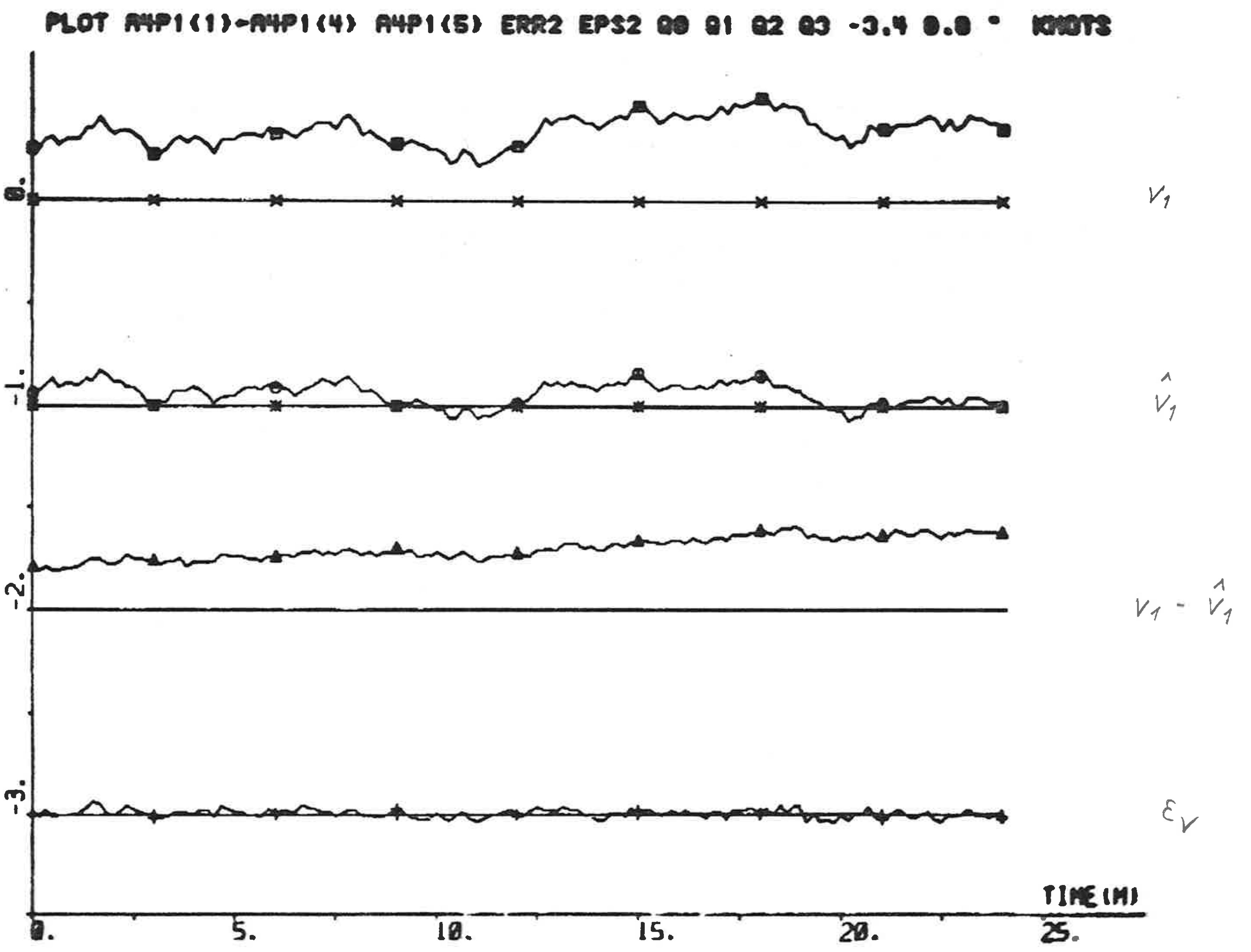


PLOT A4P1(1)+A4P1(13) A4P1(12) A4P1(14) A4P1(11) 00 -20 50

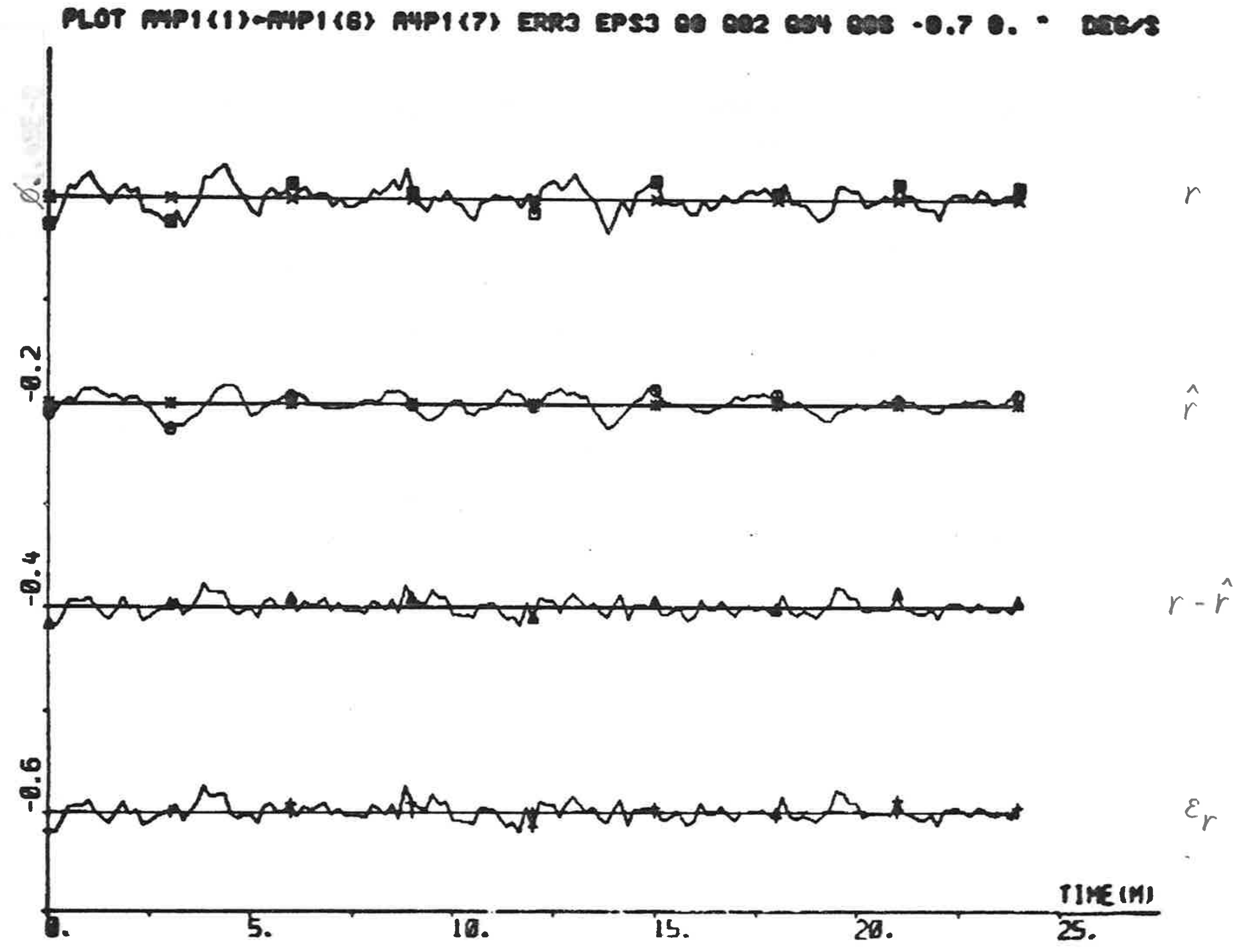


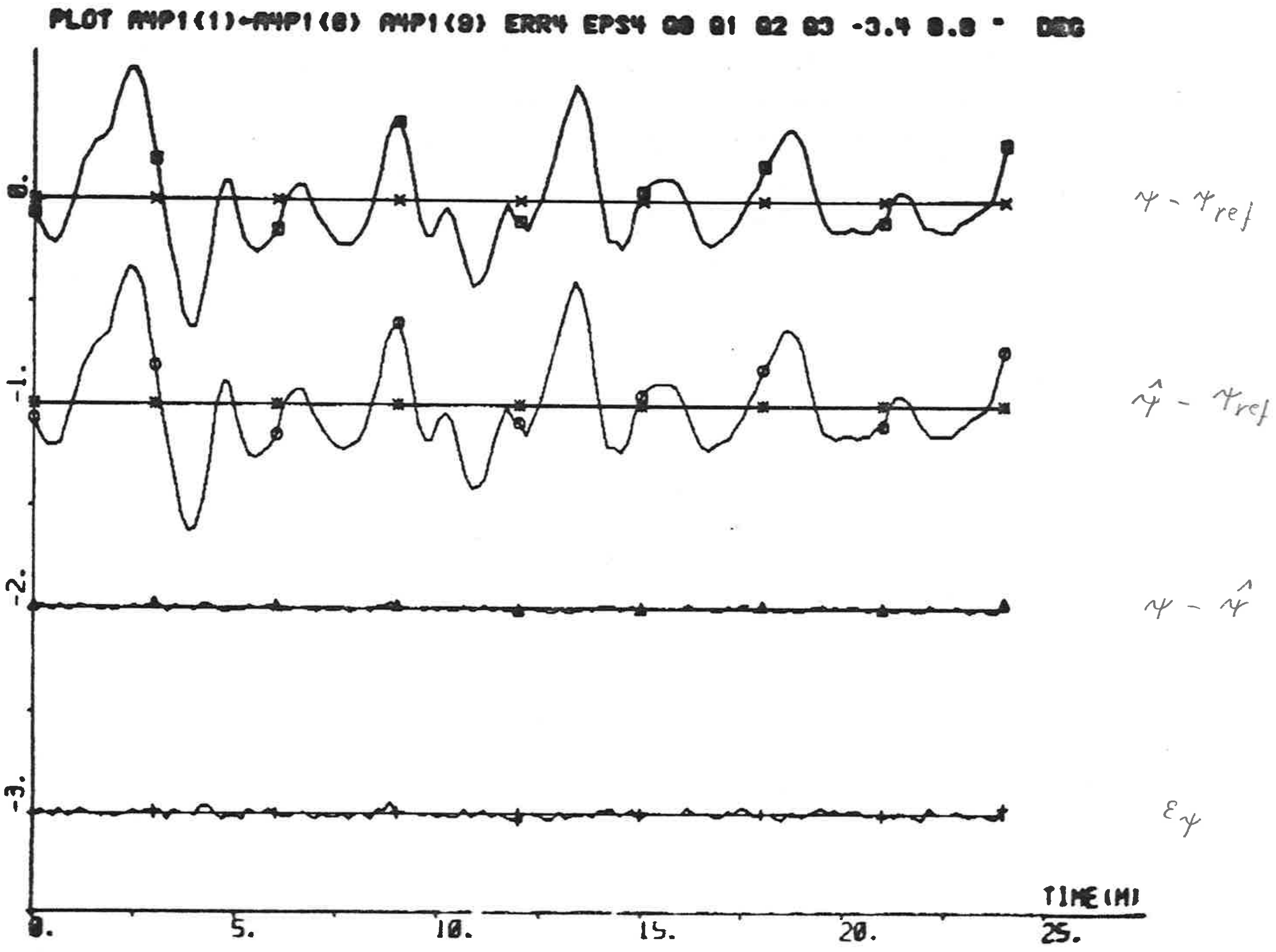
III


PLOT AMP1(1)-AMP2(1) AMP2(2) ERRS 00 01 02 -3.4 0.0 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(H)



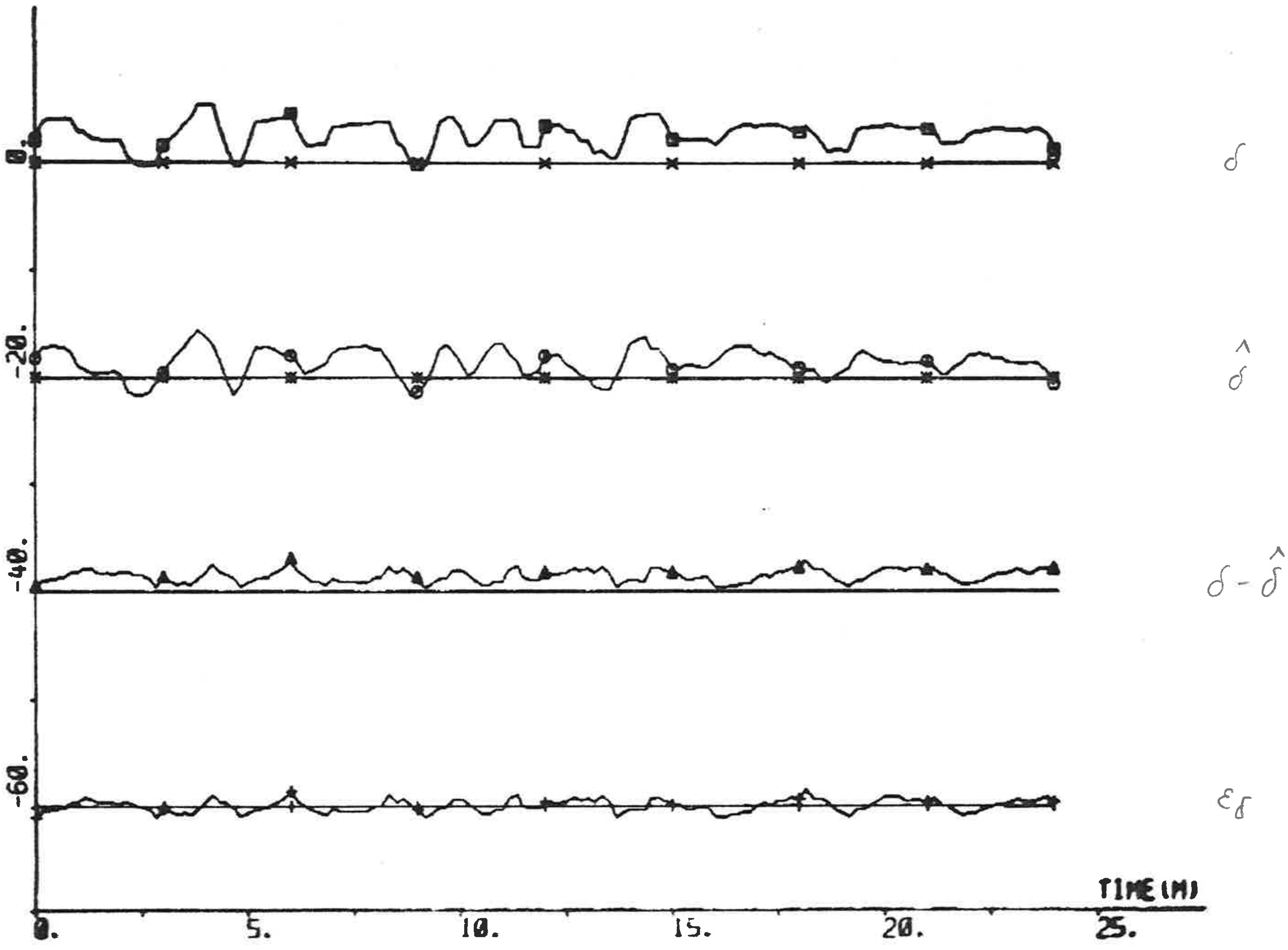
PLOT A4P1(1)-A4P1(4) A4P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 ° KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
v_1
$\hat{v}_1$
$v_1 - \hat{v}_1$
ε_v

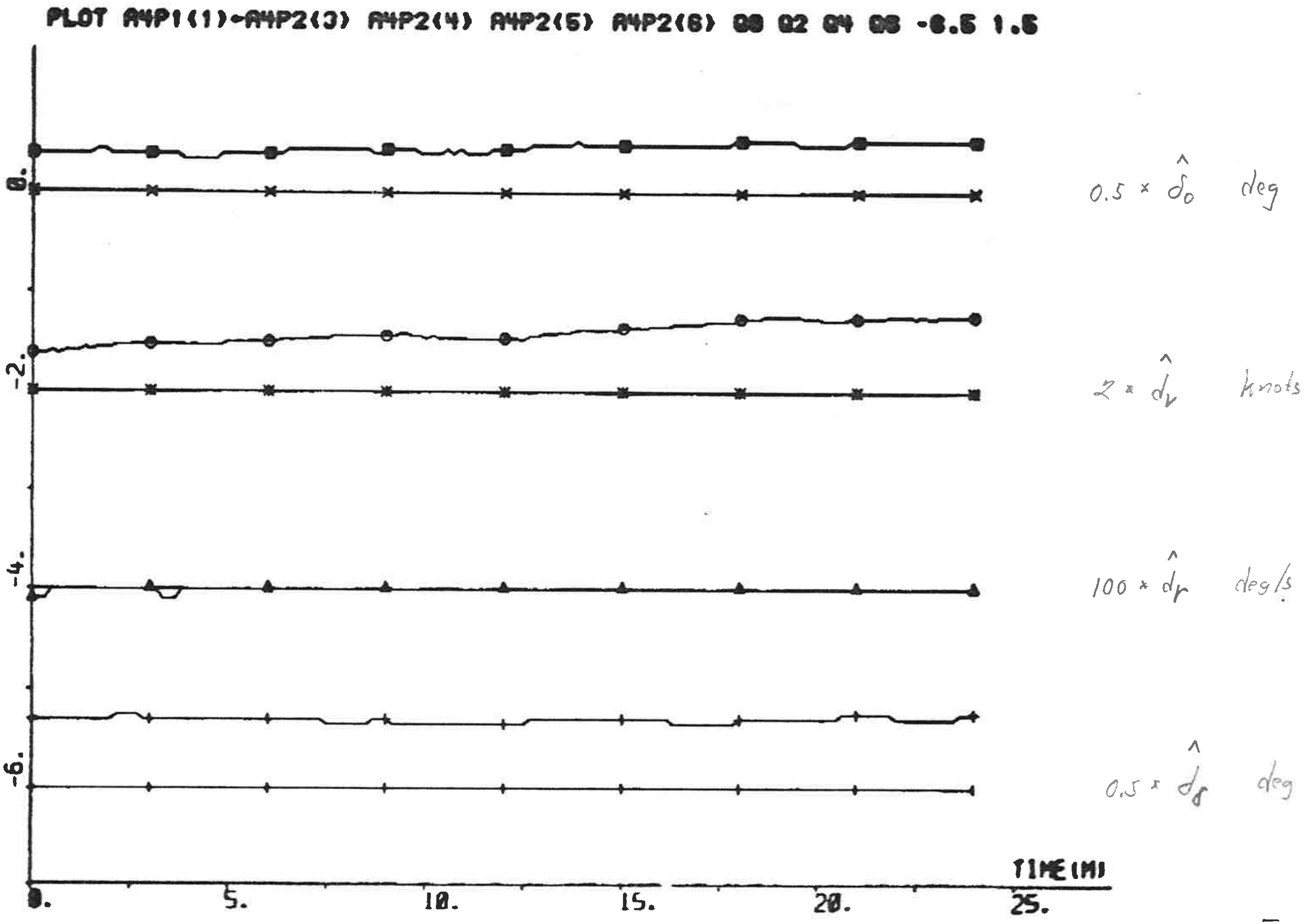

PLOT AMP1(1)-AMP1(6) AMP1(7) ERR3 EPS3 00 002 004 006 -0.7 0. * DEG/S
0.
-0.2
-0.4
-0.6
r
$\hat{r}$
$r - \hat{r}$
ε_r
0.
5.
10.
15.
20.
25.
TIME(M)



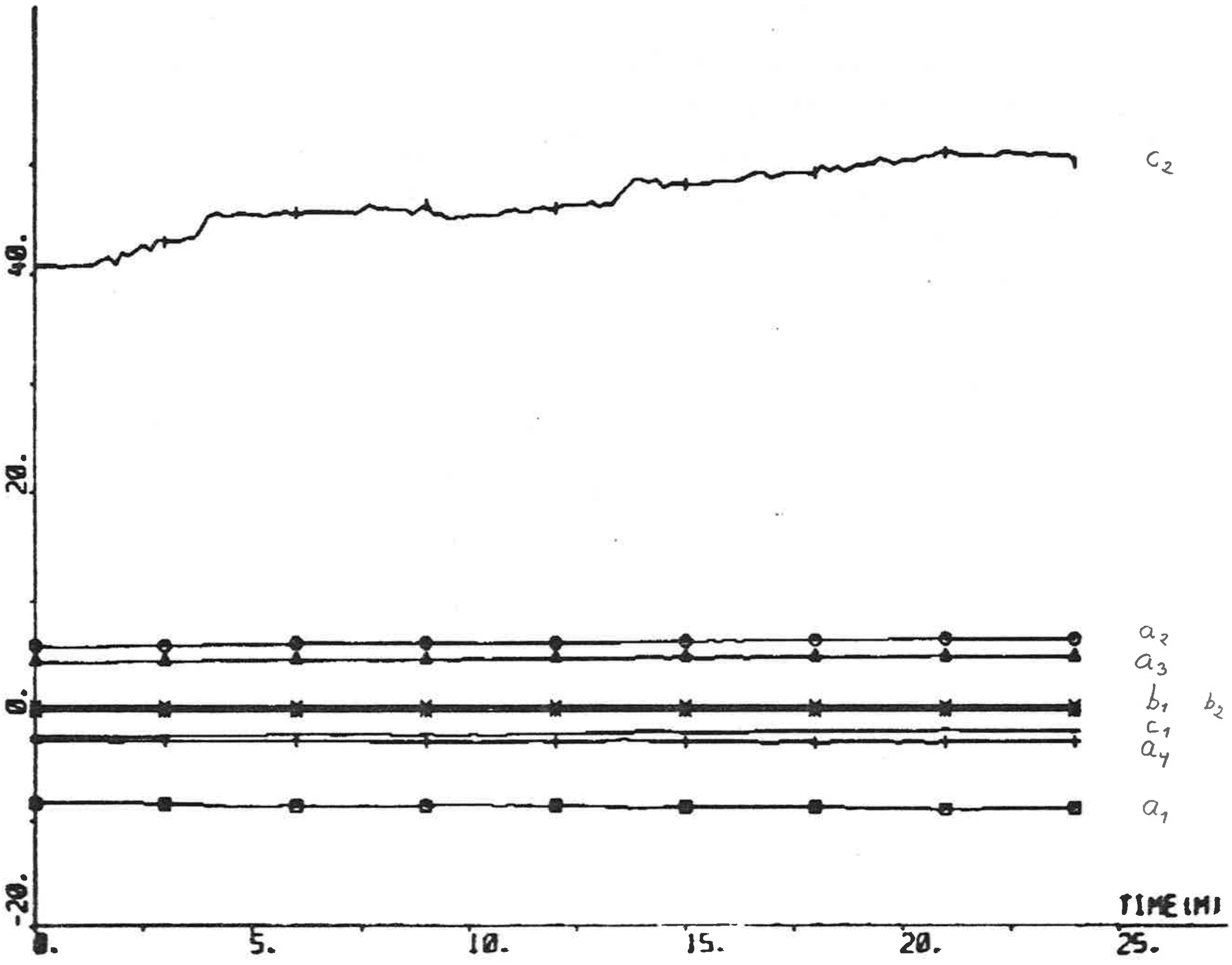
PLOT AMP1(1)-AMP1(8) AMP1(9) ERR4 EPS4 G0 G1 G2 G3 -3.4 0.8 - DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ

PLOT A4P1(1)-A4P1(2) A4P1(3) ERR1 EPS1 00 020 040 060 -65 15 " DEG




PLOT A4P1(1)-A4P2(3) A4P2(4) A4P2(5) A4P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 × $\hat{\delta}_o$ deg
2 × $\hat{d}_v$ knots
100 × $\hat{d}_r$ deg/s
0.5 × $\hat{d}_\delta$ deg

PLOT AMP1(1)-AMP2(7) AMP2(8) AMP2(9) AMP2(10) AMP2(11) AMP2(12) AMP2(13)



EXPERIMENT A5

Date	1976-04-22	Forward draught	8.5 m
Time	11.57	Aft draught	12.5 m
Duration	24 min	Wind direction	N (5; see App. A)
Position	N 11°46' W 18°28'	Wind velocity	4 m/s (gentle breeze)
ψ_{ref}	180 deg	Wave height	Low swell from N

Self-tuning regulator using estimates from the Kalman filter

Tuning time before the experiment started: 30 min.

NC1 = 1   NC2 = 1   k = 7   q = 0

T_s = 10 s V_0 = 7 m/s   IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.00 \\ 6.67 \\ 4.55 \\ -3.59 \\ 0.49 \\ 0.17 \\ -1.40 \\ 49.73 \end{bmatrix}$$

P unknown

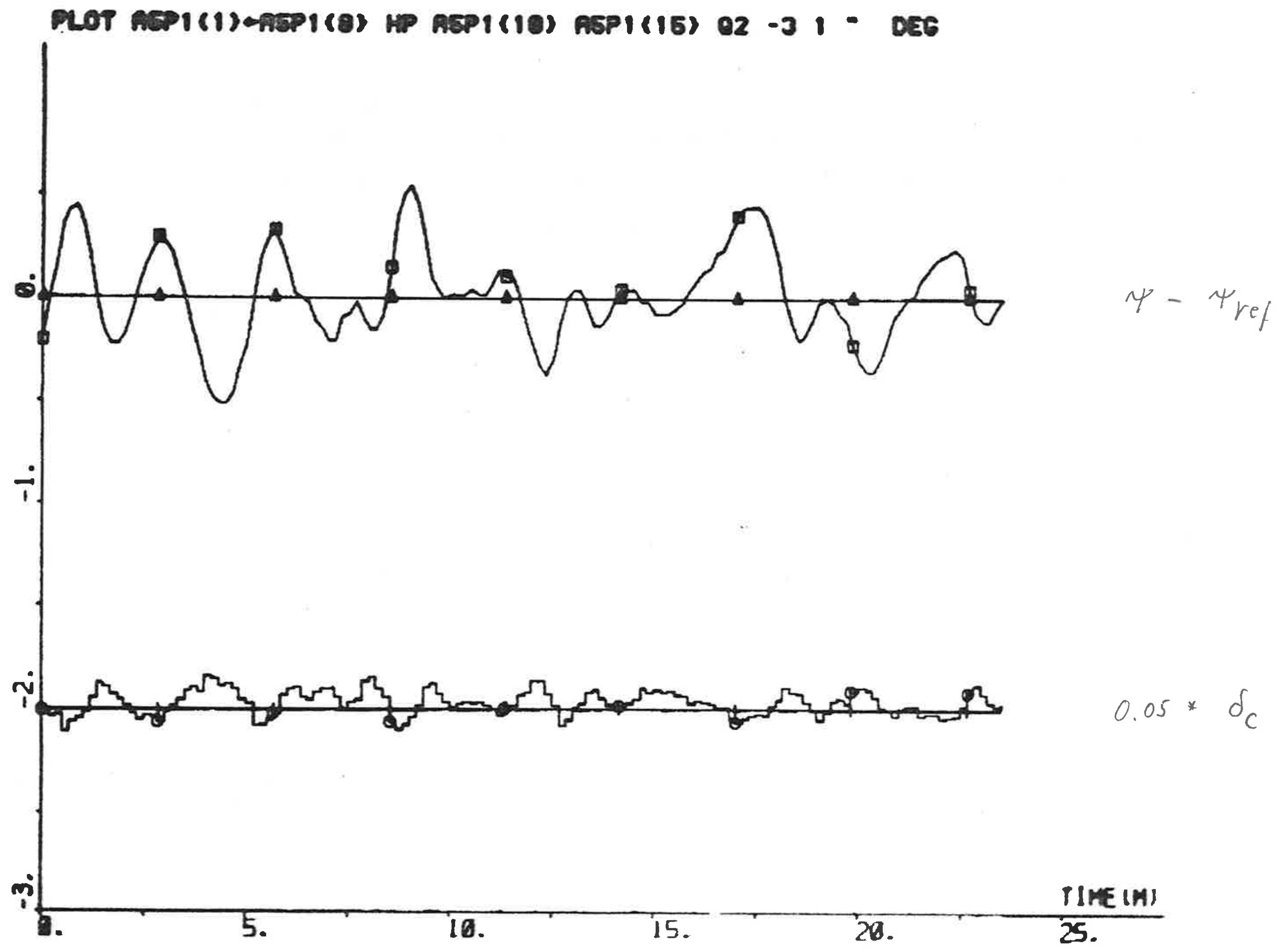
$a_1 + a_2 + a_3 + a_4 = -0.37$

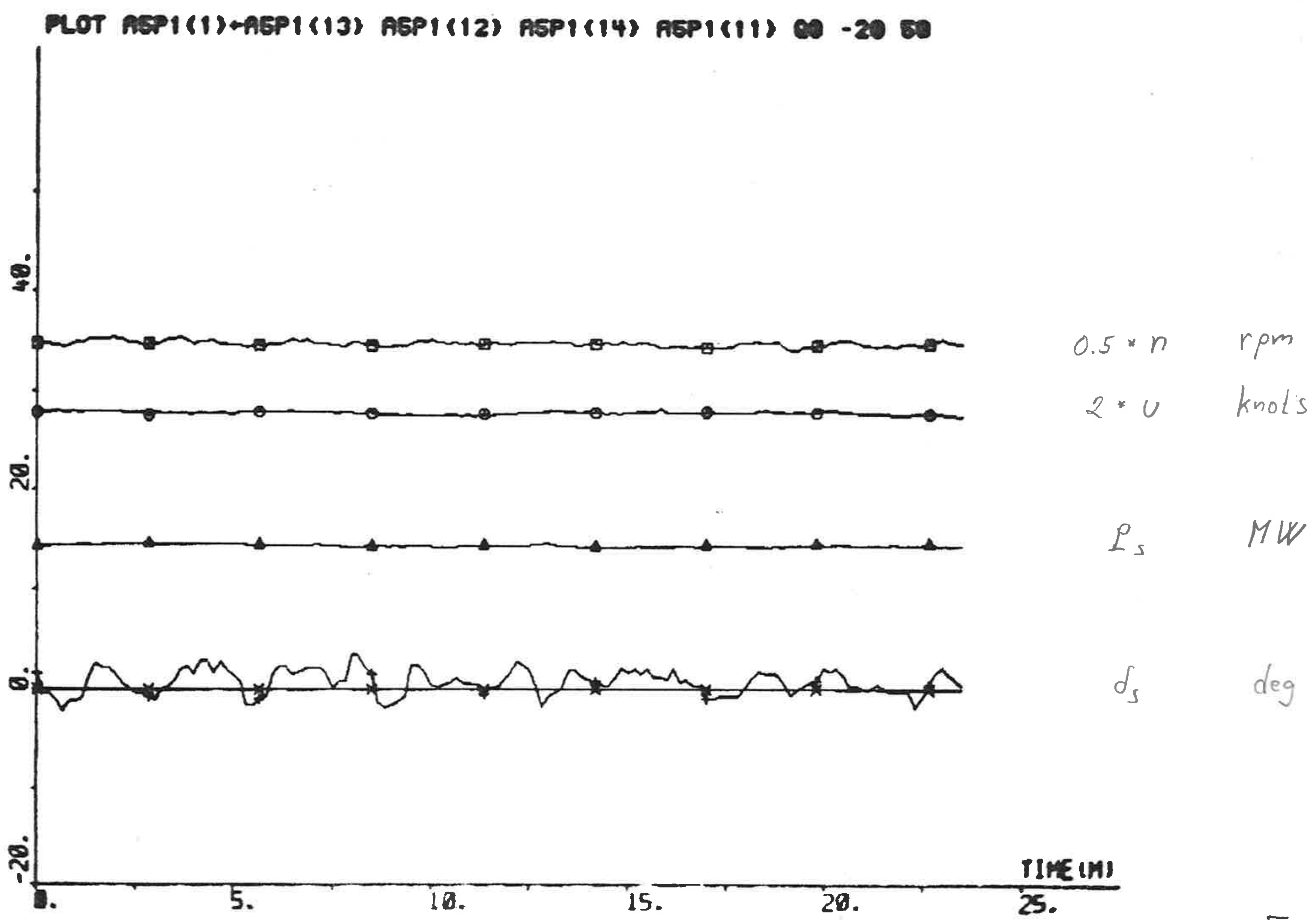
$\hat{\delta}_0 = 0.9$ deg $\hat{d}_v = 0.15$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.5$ deg

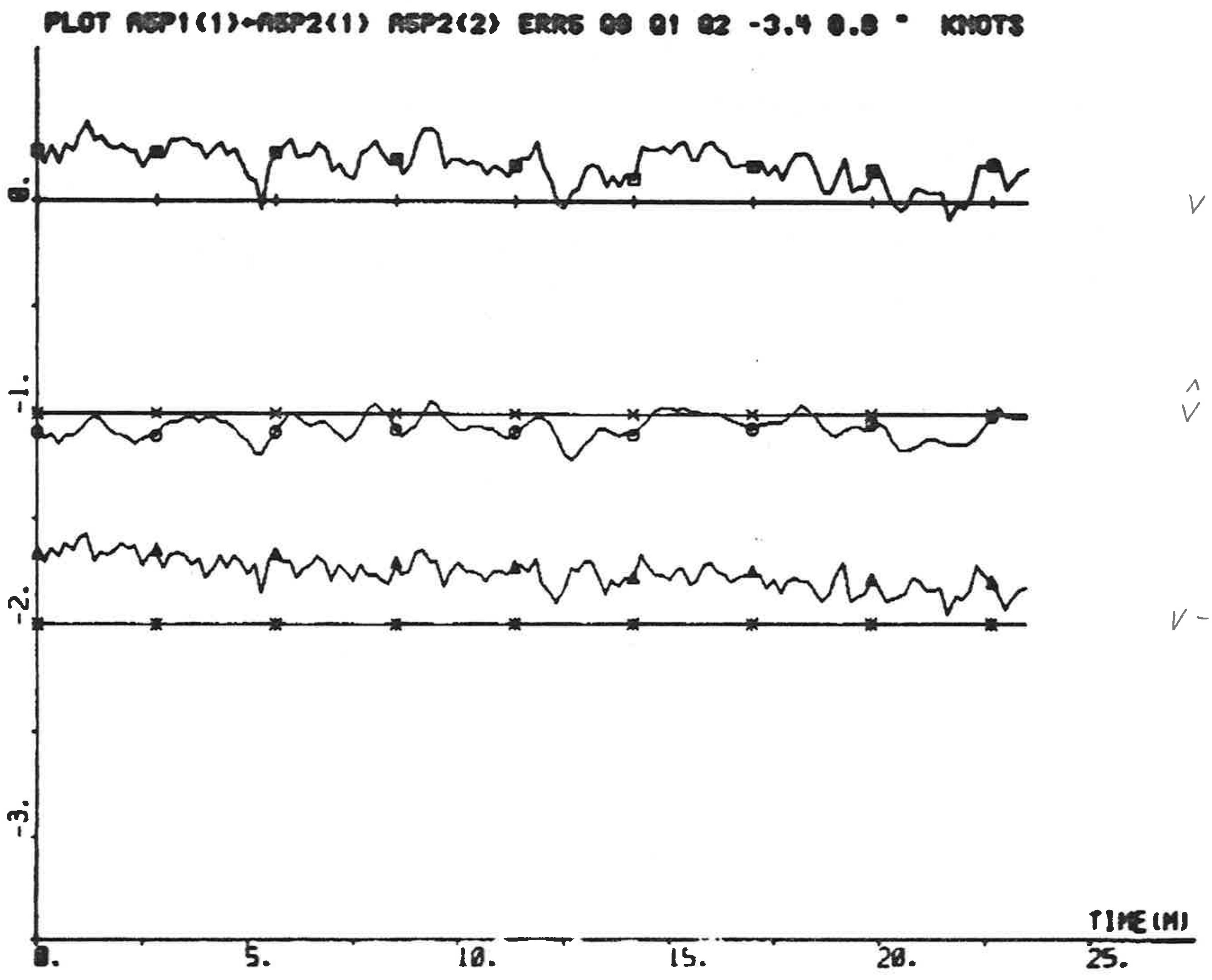
Statistics (mean value and standard deviation)

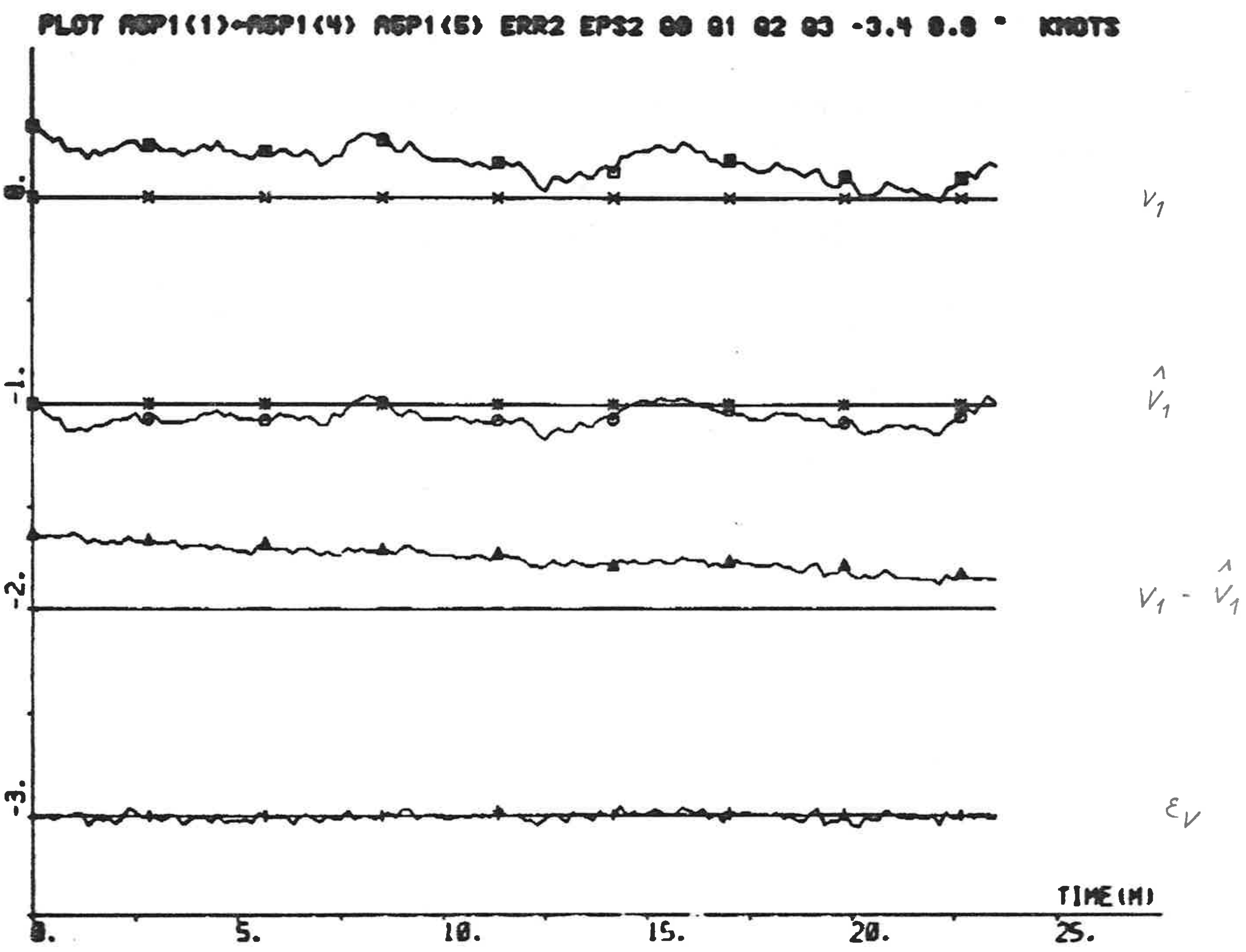
δ_c	0.66 ± 1.17	deg		P_s	14.4 ± 0.1	MW
δ	2.16 ± 1.10	deg		ε_v	-0.01 ± 0.02	knots
$\psi-\psi_{ref}$	0.014 ± 0.219	deg		ε_r	0.00 ± 0.01	deg/s
n	69.7 ± 0.4	rpm		ε_ψ	0.00 ± 0.02	deg
u	14.0 ± 0.1	knots		ε_δ	0.1 ± 0.6	deg

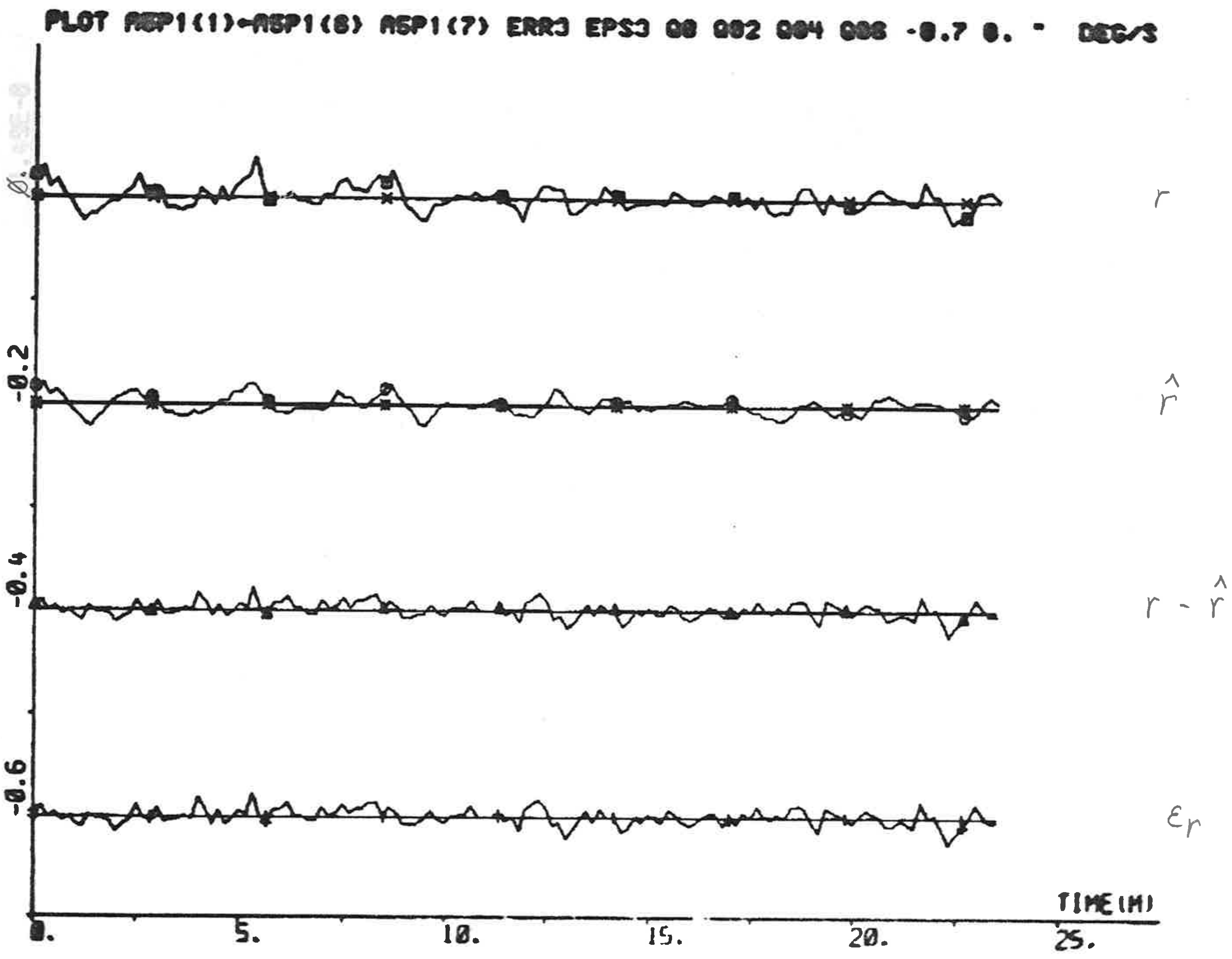
$V_1 = 0.162$

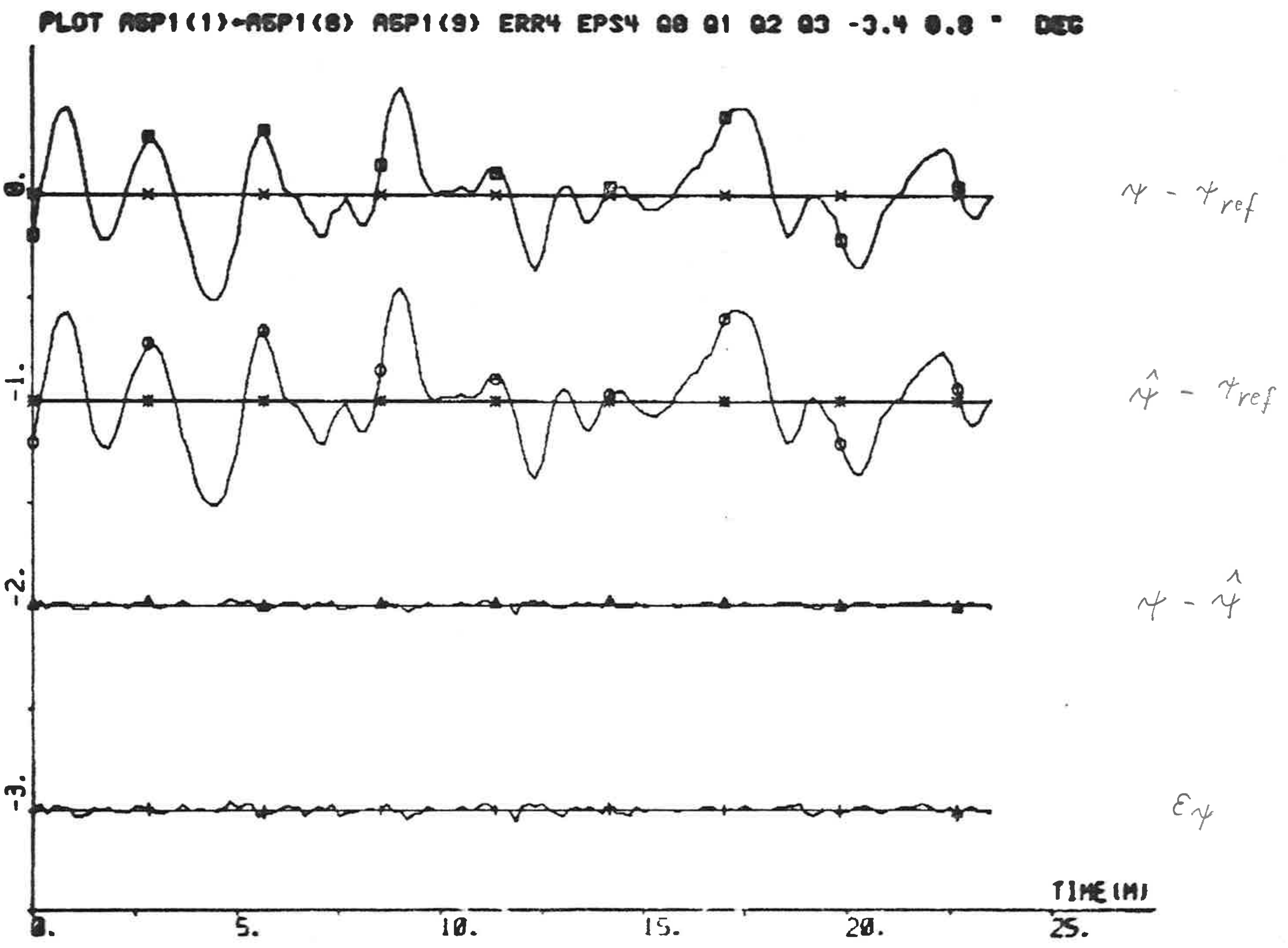

PLOT ASP1(1)-ASP1(8) HP ASP1(10) ASP1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc


PLOT ASP1(1)+ASP1(13) ASP1(12) ASP1(14) ASP1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n
rpm
2 * U
knots
P_s
MW
d_s
deg

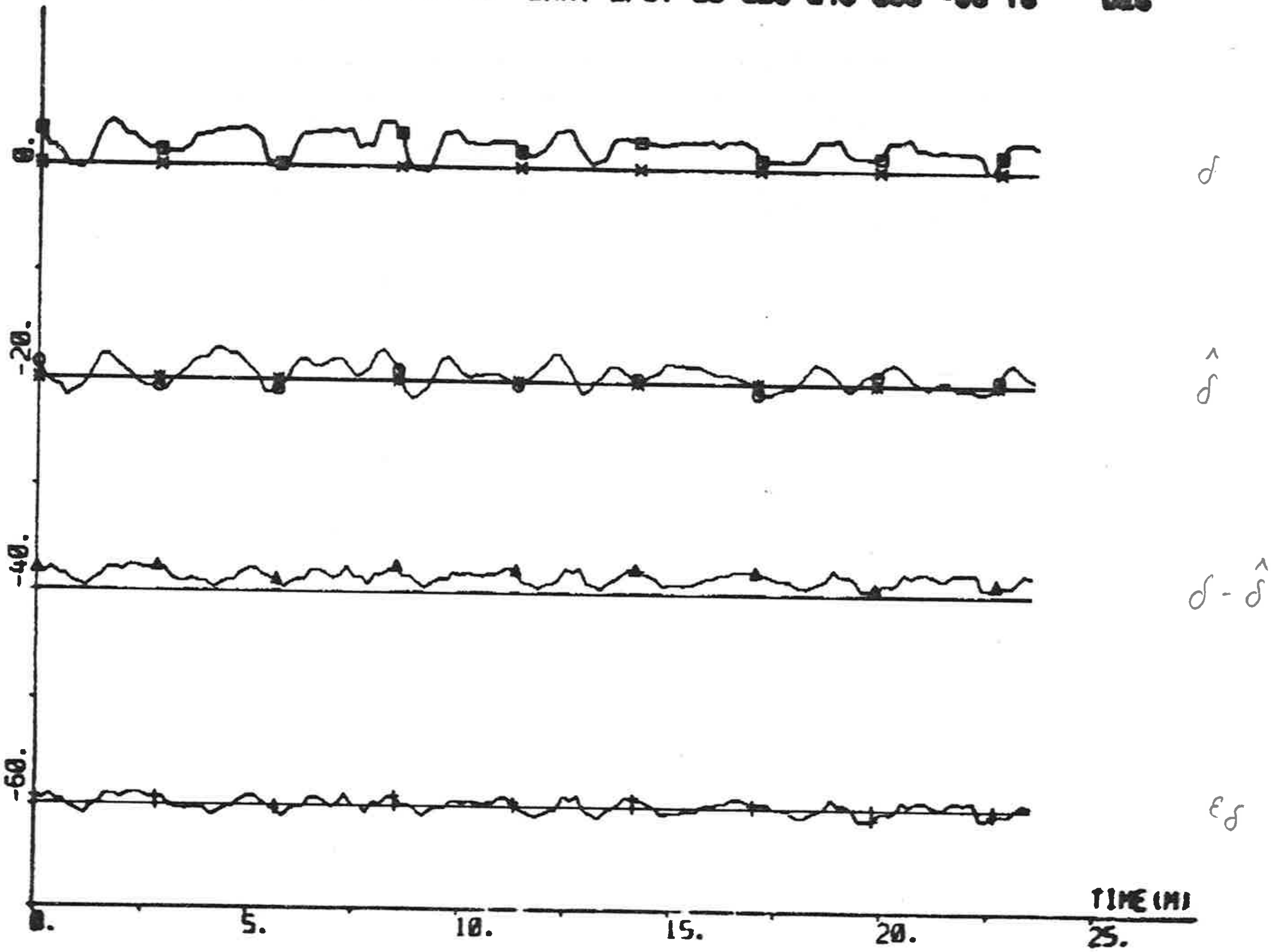

PLOT ASP1(1)-ASP2(1) ASP2(2) ERRS 00 01 02 -3.4 0.8 ° KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

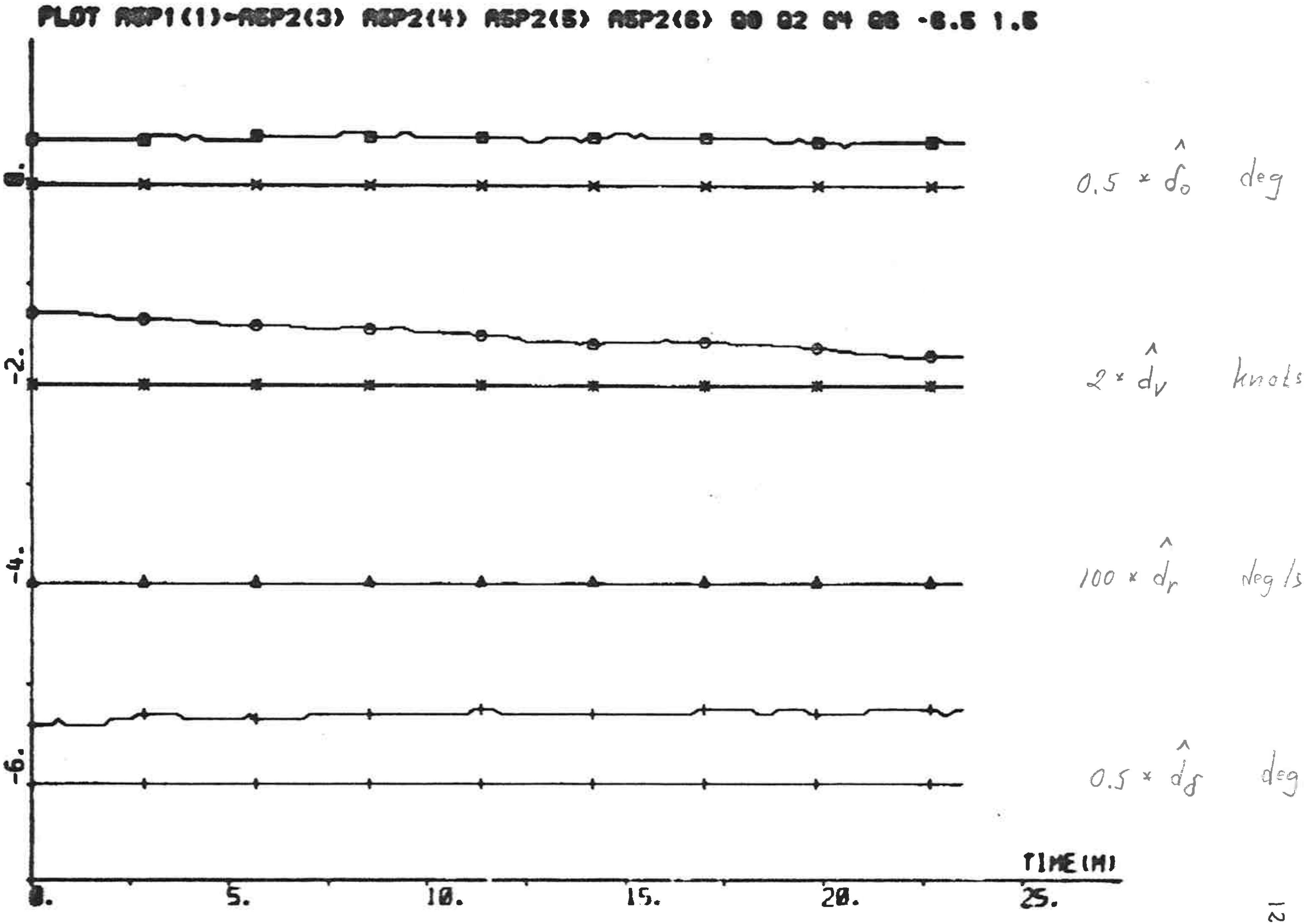

PLOT ASP1(1)-ASP1(4) ASP1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT ASP1(1)-ASP1(8) ASP1(7) ERR3 EPS3 Q0 Q02 Q04 Q06 -0.7 0. " DEG/S
Ø
-0.2
-0.4
-0.6
r
$\hat{r}$
$r - \hat{r}$
ε_r
TIME(H)
0.
5.
10.
15.
20.
25.

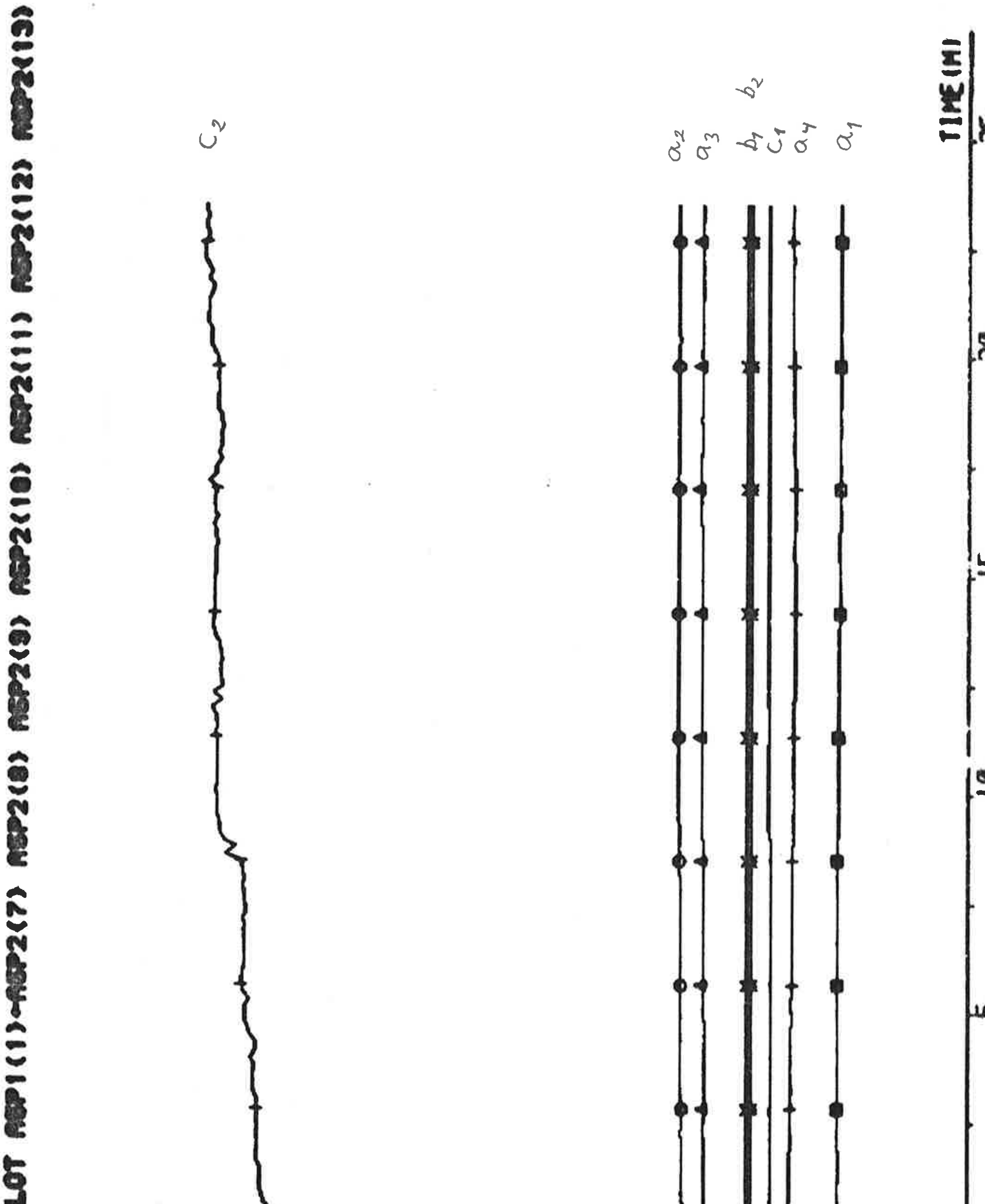

PLOT ASP1(1)-ASP1(8) ASP1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.8 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$\hat{\psi} - \psi_{ref}$
$\psi - \hat{\psi}$
ε_ψ

PLOT RSP1(1)-RSP1(2) RSP1(3) ERR1 EPS1





PLOT ASP1(1)-ASP2(3) ASP2(4) ASP2(5) ASP2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(H)
0.5 * $\hat{d}_\delta$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg


PLOT ASP1(1)-ASP2(7) ASP2(8) ASP2(9) ASP2(10) ASP2(11) ASP2(12) ASP2(13)
TIME(H)
0.
5.
10.
15.
20.
25.
40.
20.
0.
-20.
c_2
a_2
a_3
b_1
b_2
c_1
a_4
a_1

EXPERIMENT A6

Date	1976-04-22	Forward draught	8.5 m
Time	15.05	Aft draught	12.5 m
Duration	24 min	Wind direction	NW (4; see App. A)
Position	N 11°01' W 18°30'	Wind velocity	4 m/s (gentle breeze)
ψ_{ref}	180 deg	Wave height	Moderate swell from N

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 7$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.23 \\ 6.42 \\ 4.21 \\ -3.31 \\ 0.55 \\ 0.16 \\ -0.79 \\ 41.84 \end{bmatrix} \qquad P = \begin{bmatrix} 4.73 & & & & & & & \\ -5.79 & 10.88 & & & & & & \\ -0.95 & -4.87 & 12.01 & & & & & \\ 2.24 & -0.33 & -6.36 & 4.68 & & & & \\ -0.15 & -0.06 & 0.44 & -0.22 & 0.04 & & & \\ -0.14 & 0.11 & 0.01 & 0.03 & 0.01 & 0.03 & & \\ -0.86 & 1.17 & 0.27 & -0.62 & 0.00 & 0.00 & 0.82 & \\ 17.43 & -18.10 & -20.57 & 19.53 & -1.15 & -0.58 & 12.97 & 886.31 \end{bmatrix}$$

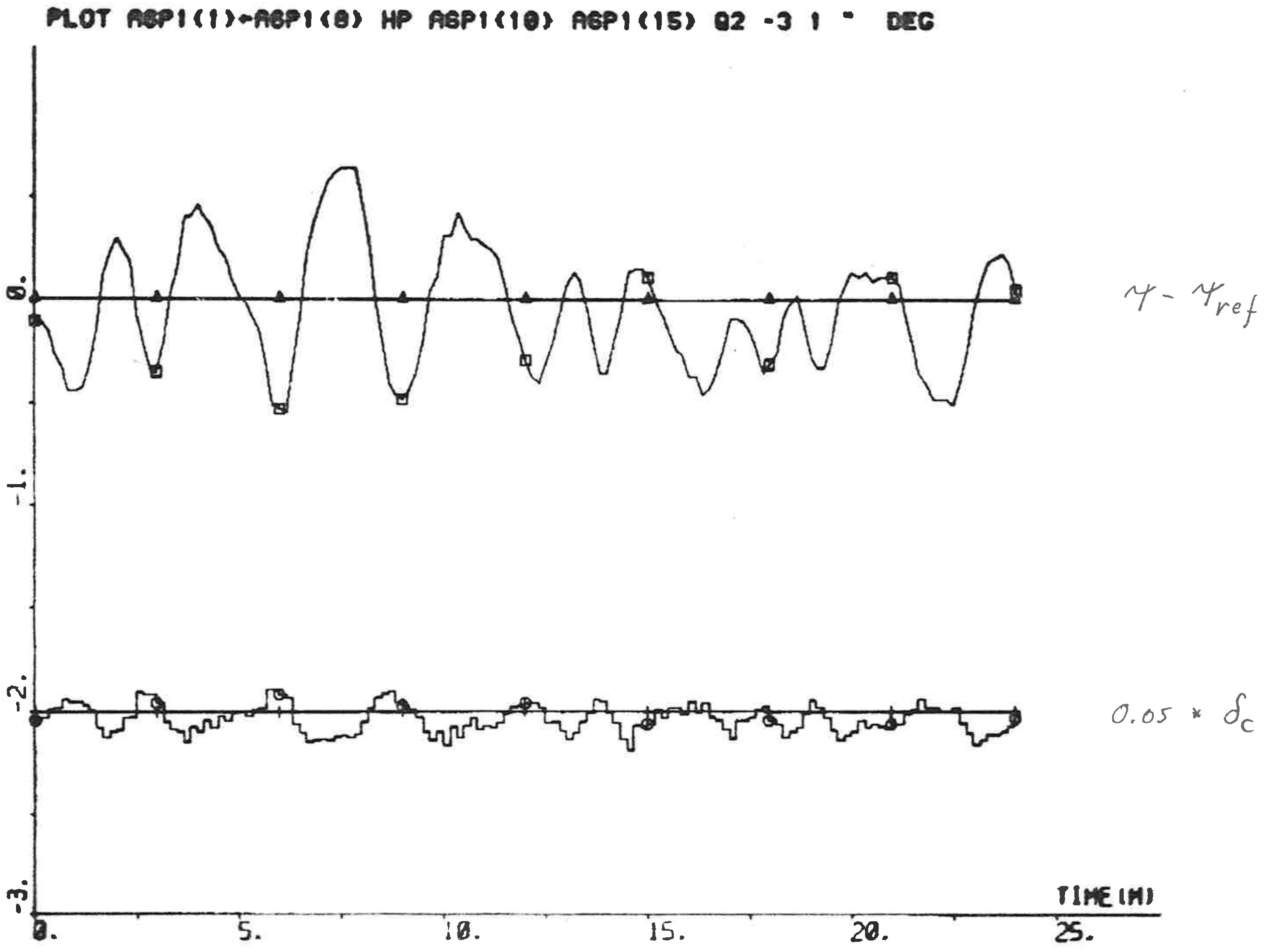
$a_1 + a_2 + a_3 + a_4 = 0.09$

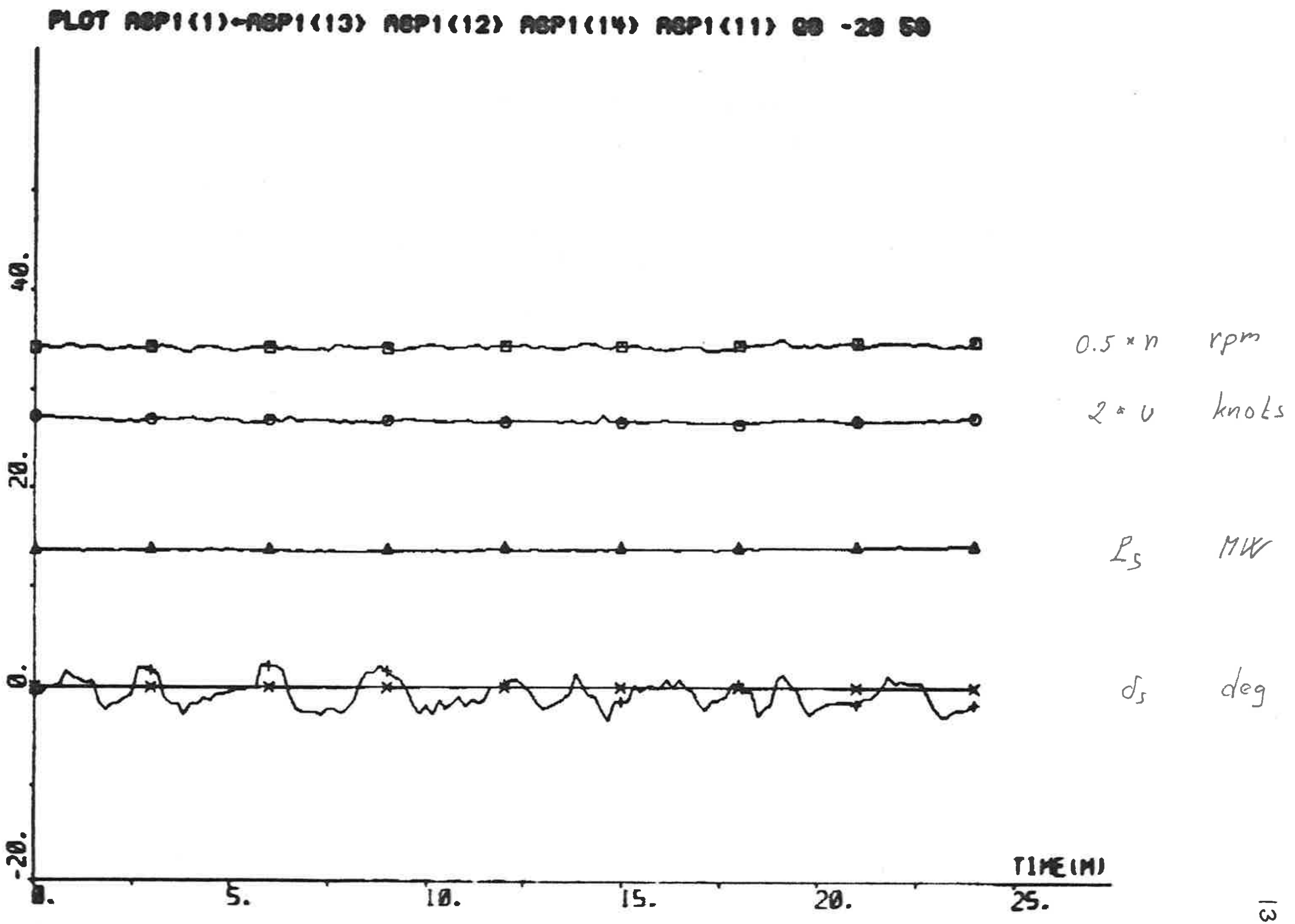
$\hat{\delta}_0 = -0.3$ deg $\hat{d}_v = -0.24$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.4$ deg

Statistics (mean value and standard deviation)

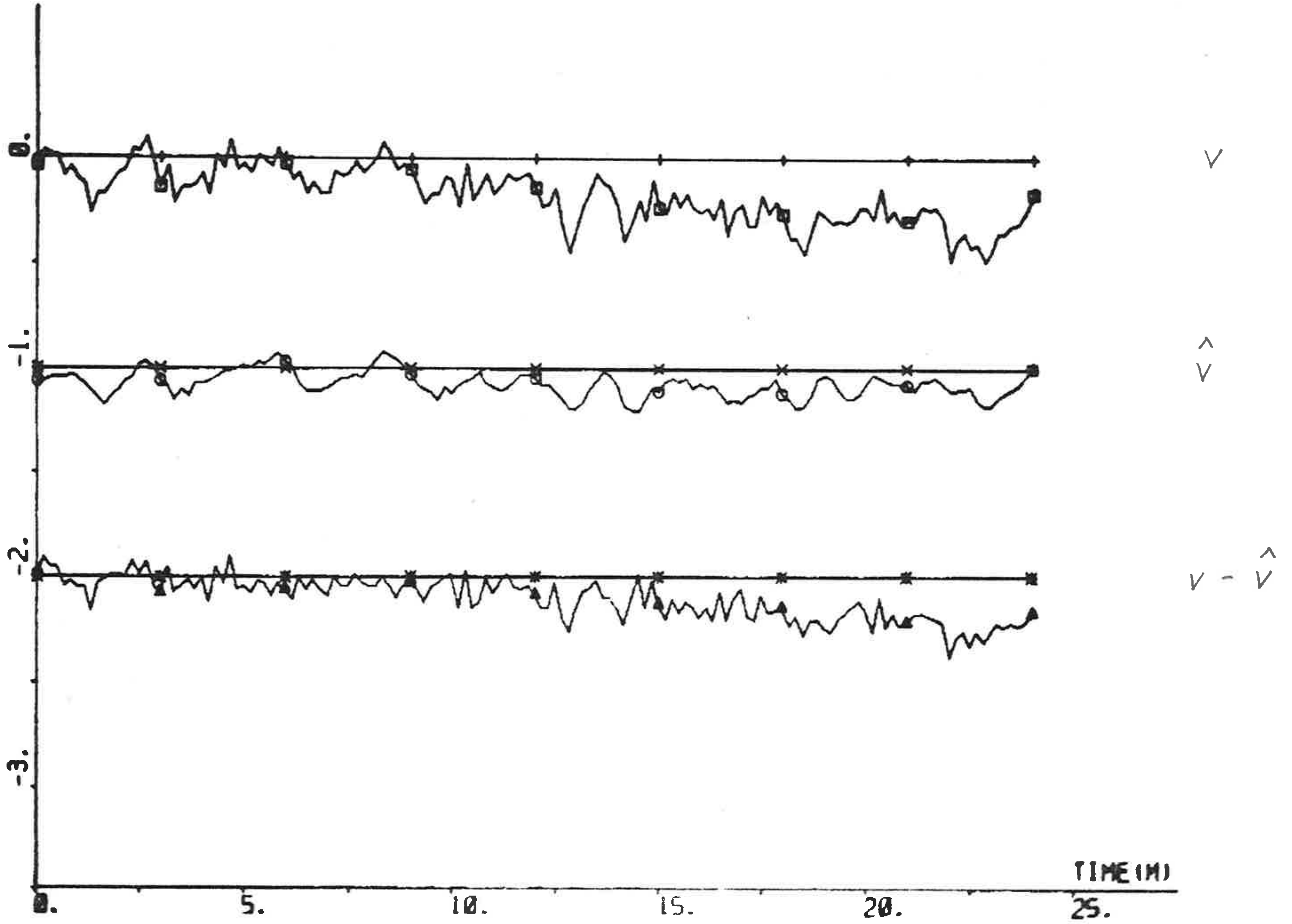
δ_c	−0.73 ± 1.32	deg	P_s	13.9 ± 0.2	MW
δ	0.63 ± 1.27	deg	ε_v	−0.01 ± 0.02	knots
$\psi - \psi_{ref}$	−0.051 ± 0.290	deg	ε_r	0.00 ± 0.01	deg/s
n	69.1 ± 0.5	rpm	ε_ψ	0.00 ± 0.02	deg
u	13.5 ± 0.1	knots	ε_δ	0.0 ± 0.6	deg

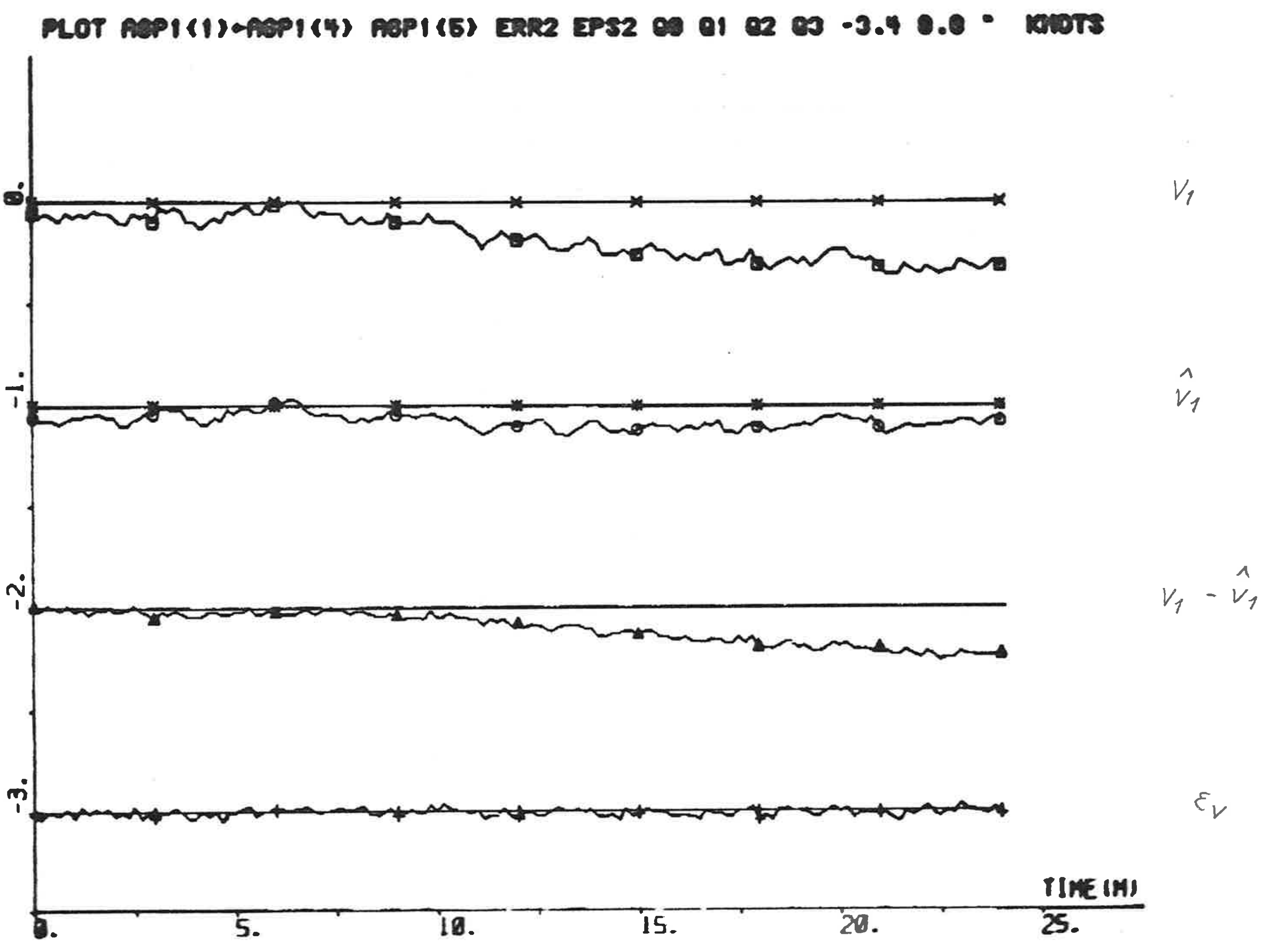
$V_1 = 0.232$

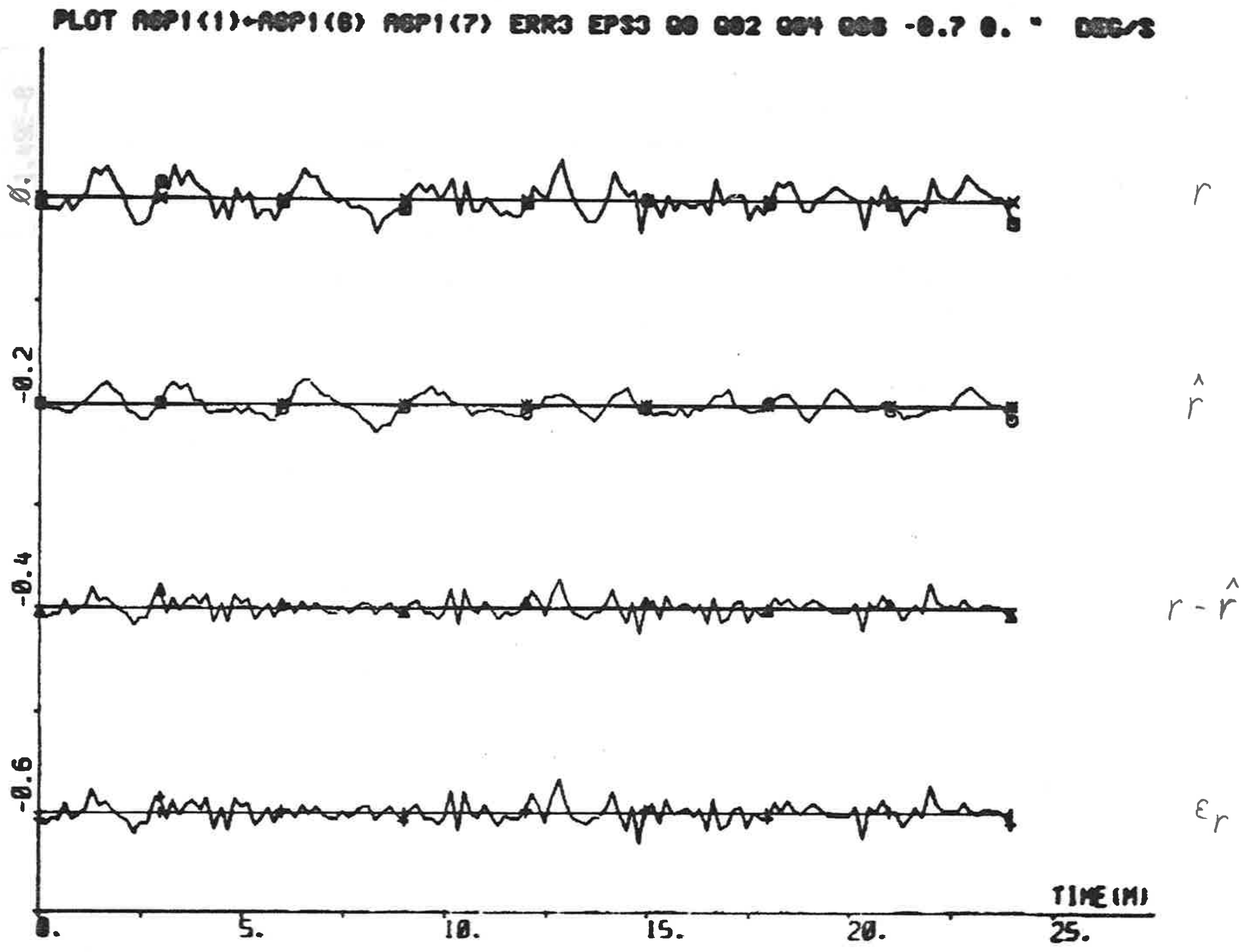

PLOT ASP1(1)-ASP1(8) HP ASP1(10) ASP1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$0.05 * \delta_c$

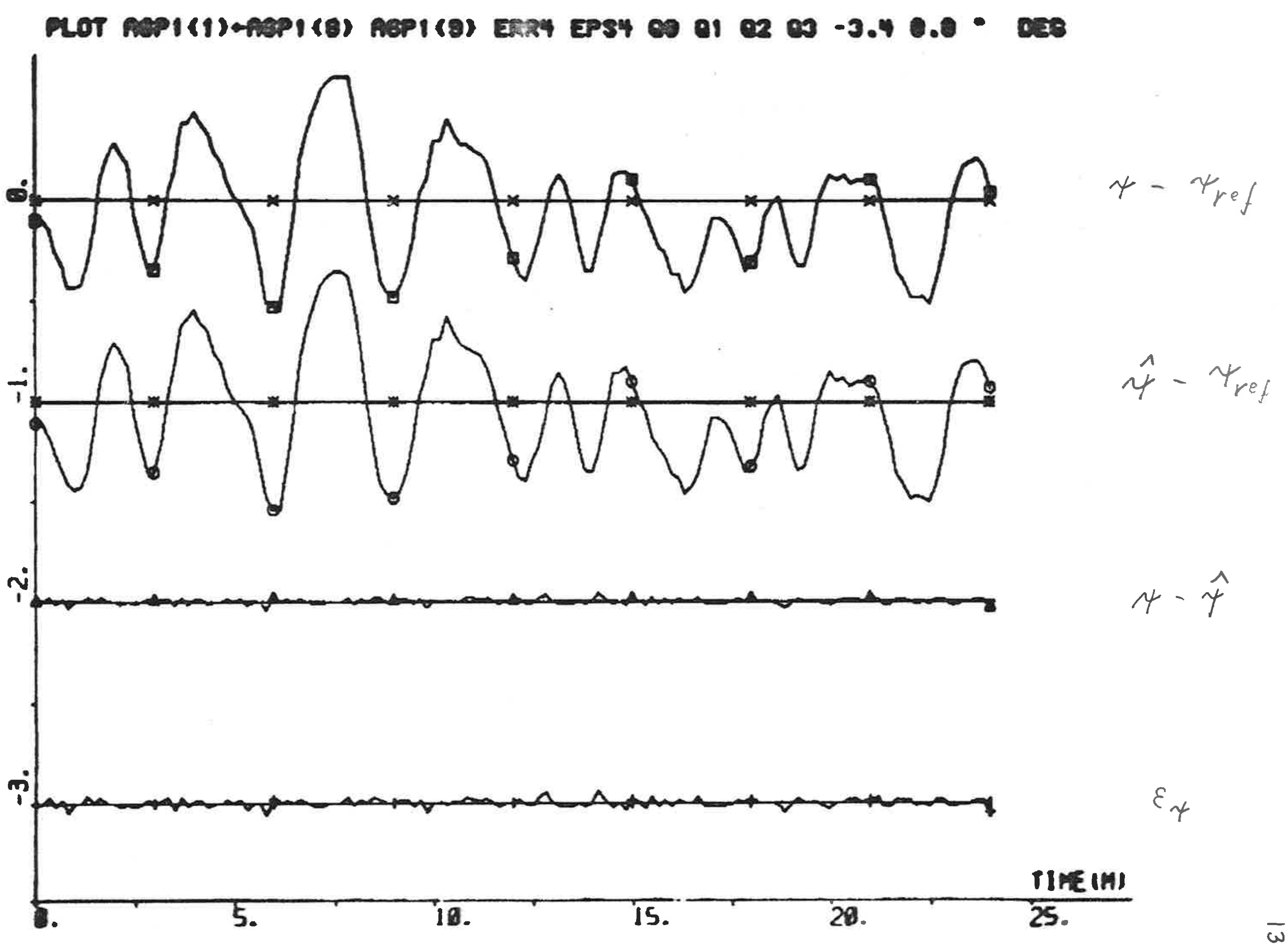

PLOT ASP1(1)-ASP1(13) ASP1(12) ASP1(14) ASP1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n rpm
2 * v knots
P_s MW
δ_s deg

PLOT ASP1(1)-ASP2(1) ASP2(2) ERRS Q0 Q1 Q2 -3.4 0.0 - KNOTS

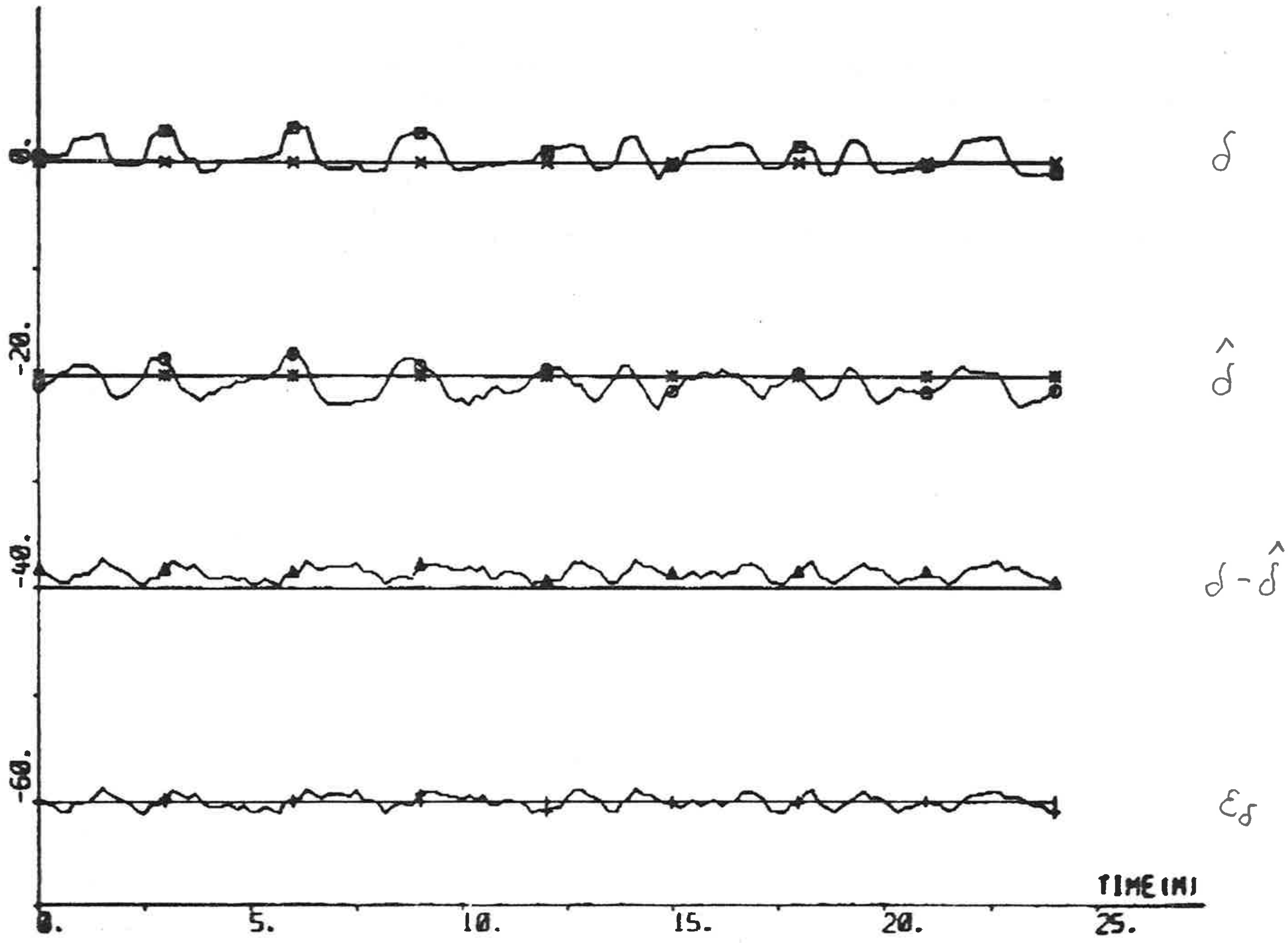


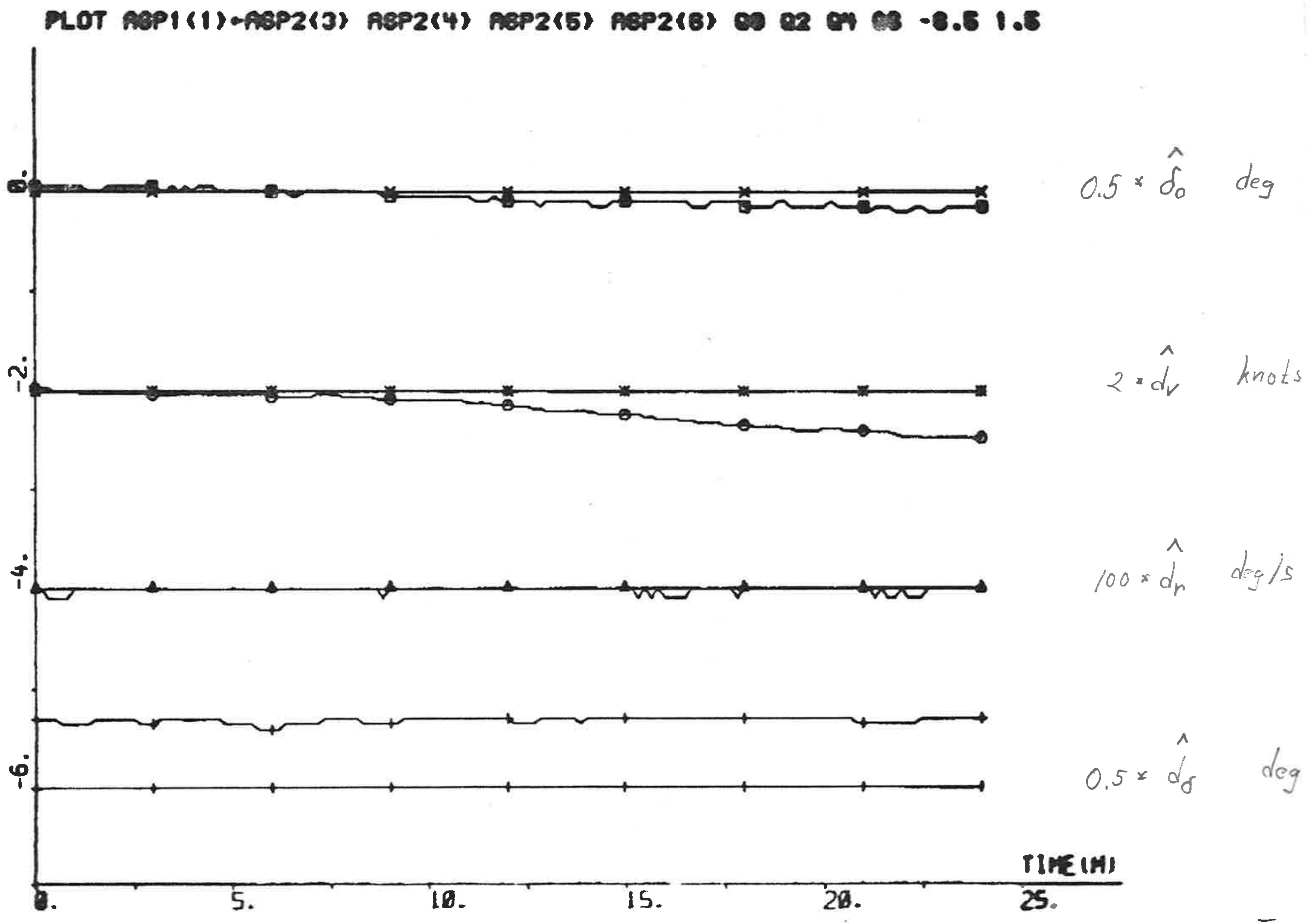

PLOT ASP1(1)+ASP1(4) ASP1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 ° KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(H)

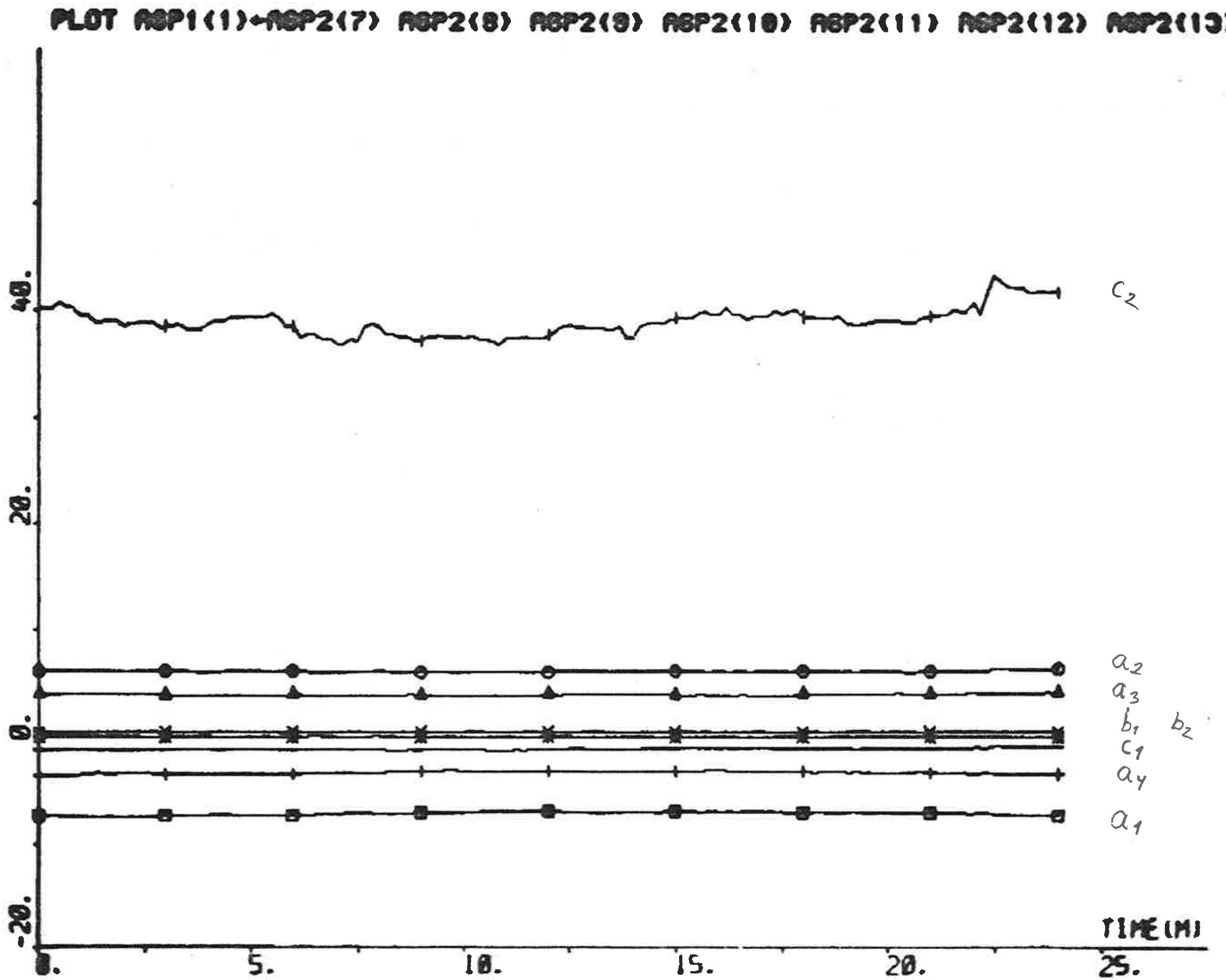

PLOT ASP1(1)-ASP1(6) ASP1(7) ERR3 EPS3 G0 G02 G04 G06 -0.7 0. " DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT ASP1(1)+ASP1(8) ASP1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 ° DEG
0.
-1.
-2.
-3.
TIME(H)
0.
5.
10.
15.
20.
25.
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ

PLOT ASP1(1)-ASP1(2) ASP1(3) ERR1 EPS1 Q0 Q20 Q40 Q60 -05 16 " DEG




PLOT ASP1(1)+ASP2(3) ASP2(4) ASP2(5) ASP2(6) Q0 Q2 Q4 Q6 -6.5 1.5
0.
-2.
-4.
-6.
0.5 * $\hat{\delta}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg
0.
5.
10.
15.
20.
25.
TIME(H)



PLOT ASP1(1)+ASP2(7) ASP2(8) ASP2(9) ASP2(10) ASP2(11) ASP2(12) ASP2(13)
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT A7

Date	1976-04-22	Forward draught	8.5 m
Time	16.09	Aft draught	12.5 m
Duration	25 min	Wind direction	W (3; see App. A)
Position	N 10°47' W 18°29'	Wind velocity	4 m/s (gentle breeze)
ψref	181 deg	Wave height	Moderate swell from N

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1   NC2 = 1   k = 8   q = 0

T_s = 10 s V_0 = 7 m/s   IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.00 \\ 6.36 \\ 4.36 \\ -3.64 \\ 0.48 \\ 0.09 \\ -1.89 \\ 39.41 \end{bmatrix} \qquad P = \begin{bmatrix} 5.91 & & & & & & & \\ -7.08 & 12.98 & & & & & & \\ -1.24 & -5.93 & 15.13 & & & & & \\ 2.70 & -0.15 & -8.00 & 5.82 & & & & \\ -0.16 & -0.05 & 0.43 & -0.21 & 0.03 & & & \\ -0.15 & 0.14 & -0.03 & 0.05 & 0.01 & 0.03 & & \\ -0.88 & 1.10 & 0.41 & -0.64 & 0.02 & -0.02 & 0.80 & \\ 16.96 & -13.50 & -26.26 & 21.56 & -1.22 & -0.80 & 11.86 & 848.17 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = 0.08$

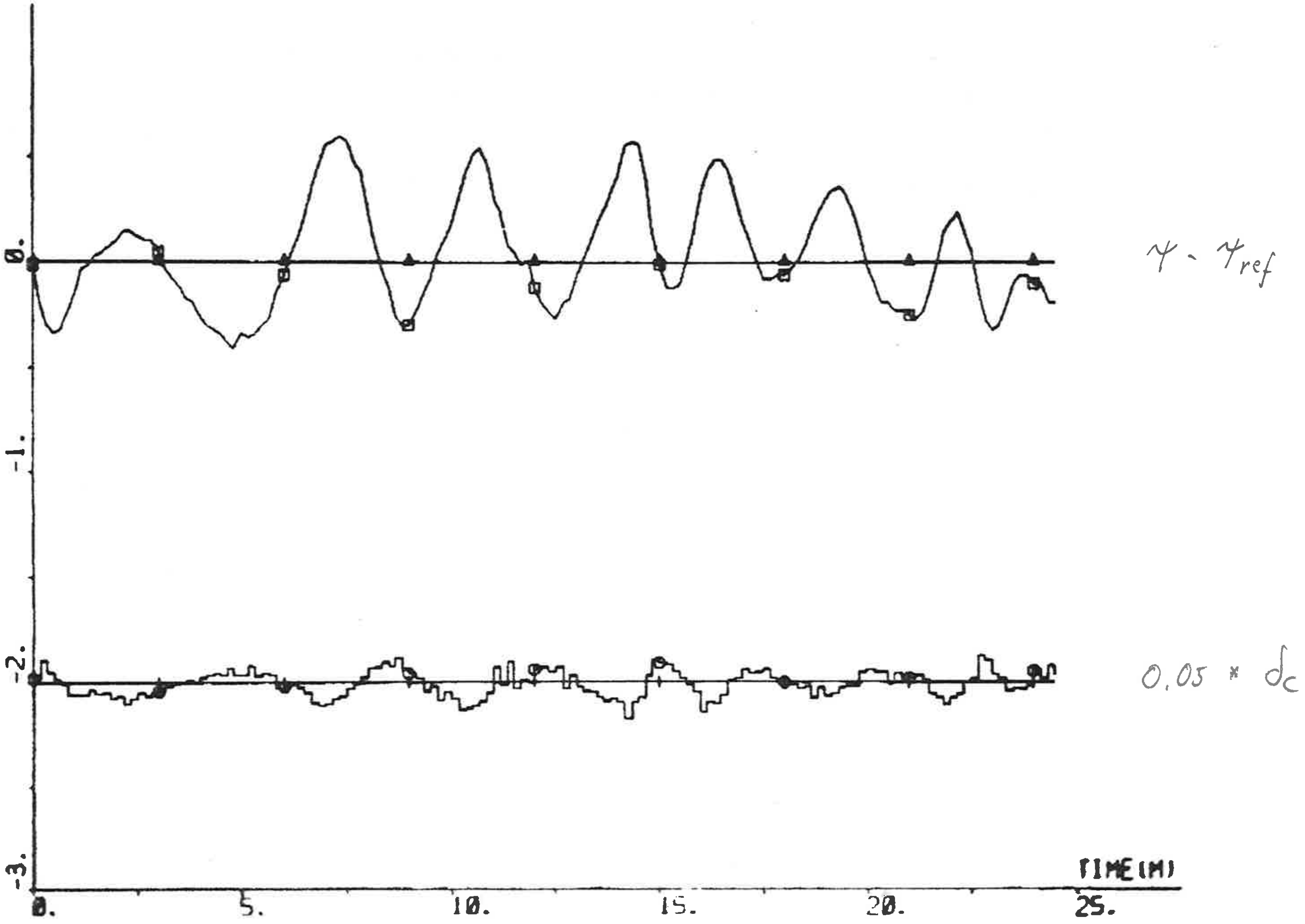
$\hat{\delta}_0 = -0.2$ deg $\hat{d}_v = 0.18$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.5$ deg

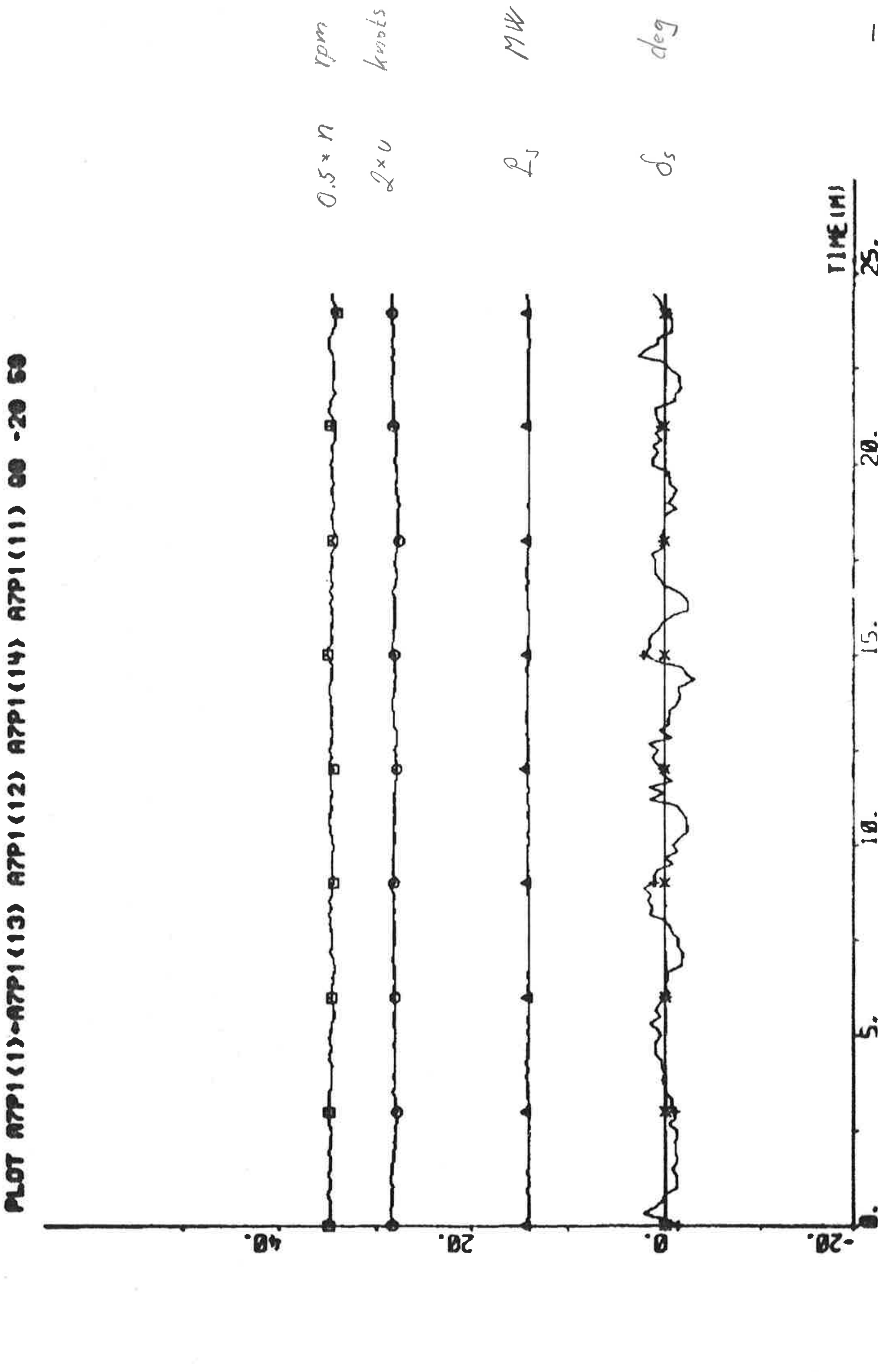
Statistics (mean value and standard deviation)

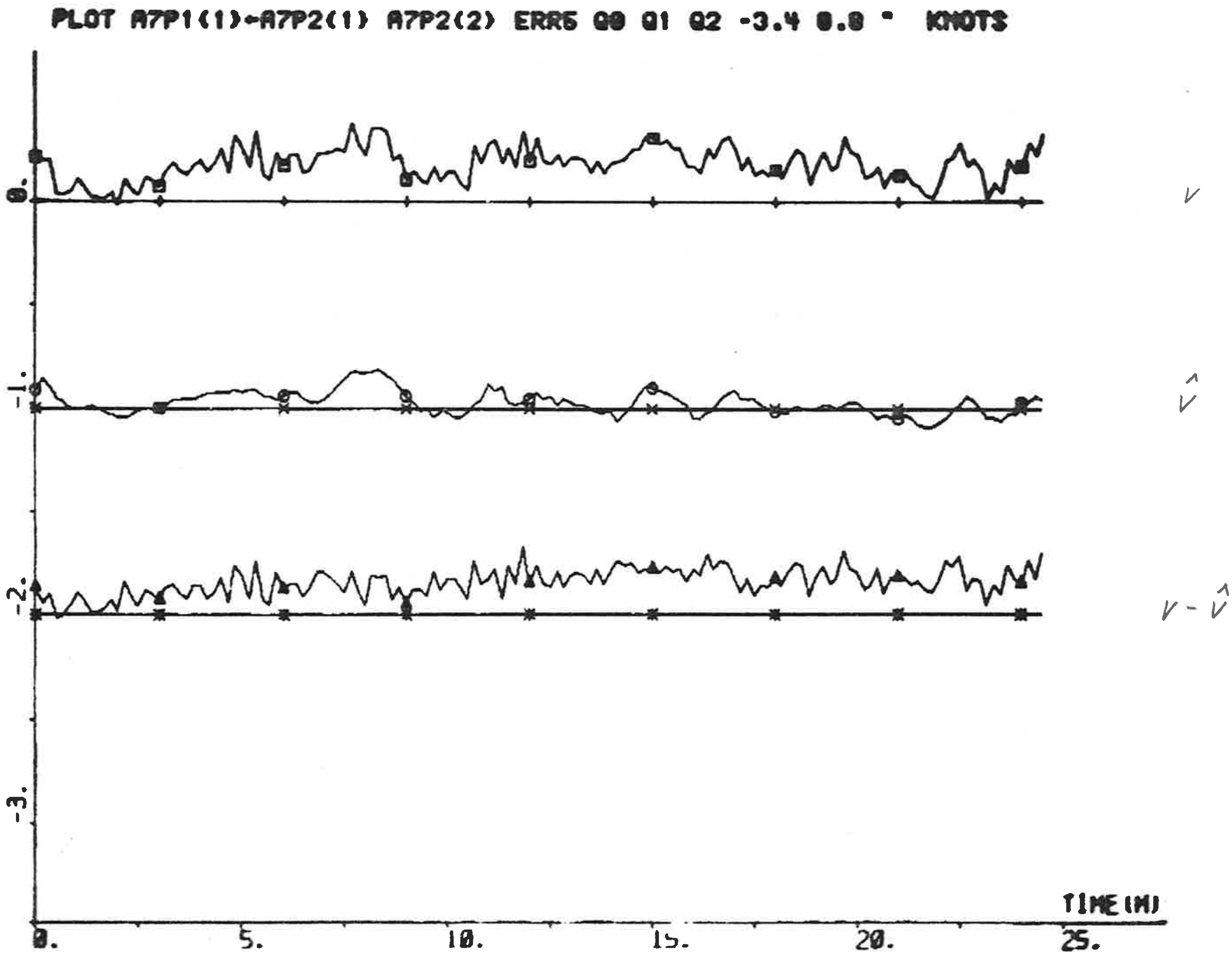
δ_c	-0.17 ± 1.19	deg		P_s	14.2 ± 0.1	MW
δ	1.33 ± 0.98	deg		ε_v	0.01 ± 0.02	knots
$\psi-\psi$ref	0.034 ± 0.260	deg		ε_r	0.00 ± 0.01	deg/s
n	69.5 ± 0.3	rpm		ε_ψ	0.00 ± 0.02	deg
u	14.1 ± 0.1	knots		ε_δ	0.0 ± 0.6	deg

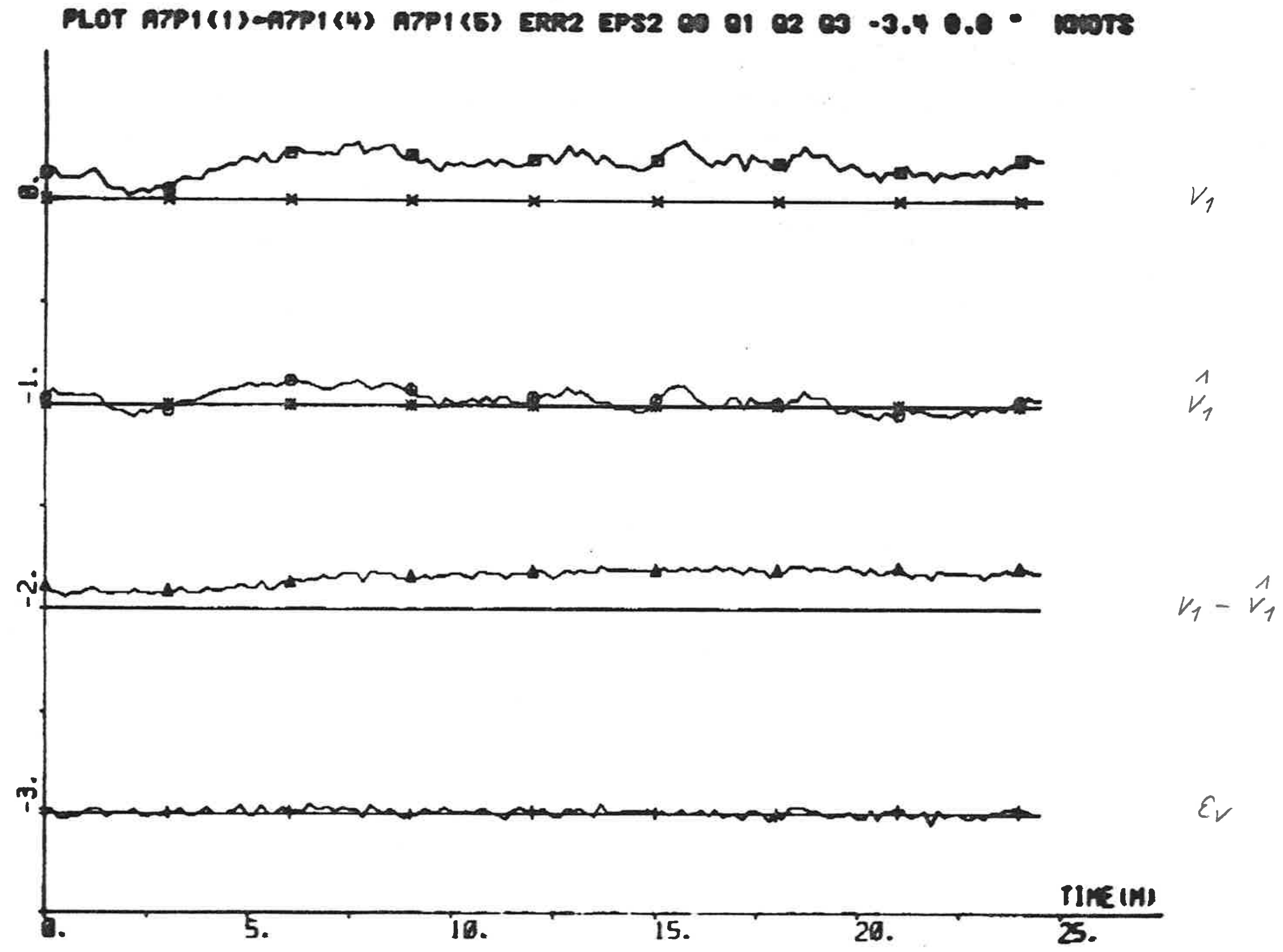
$V_1 = 0.187$

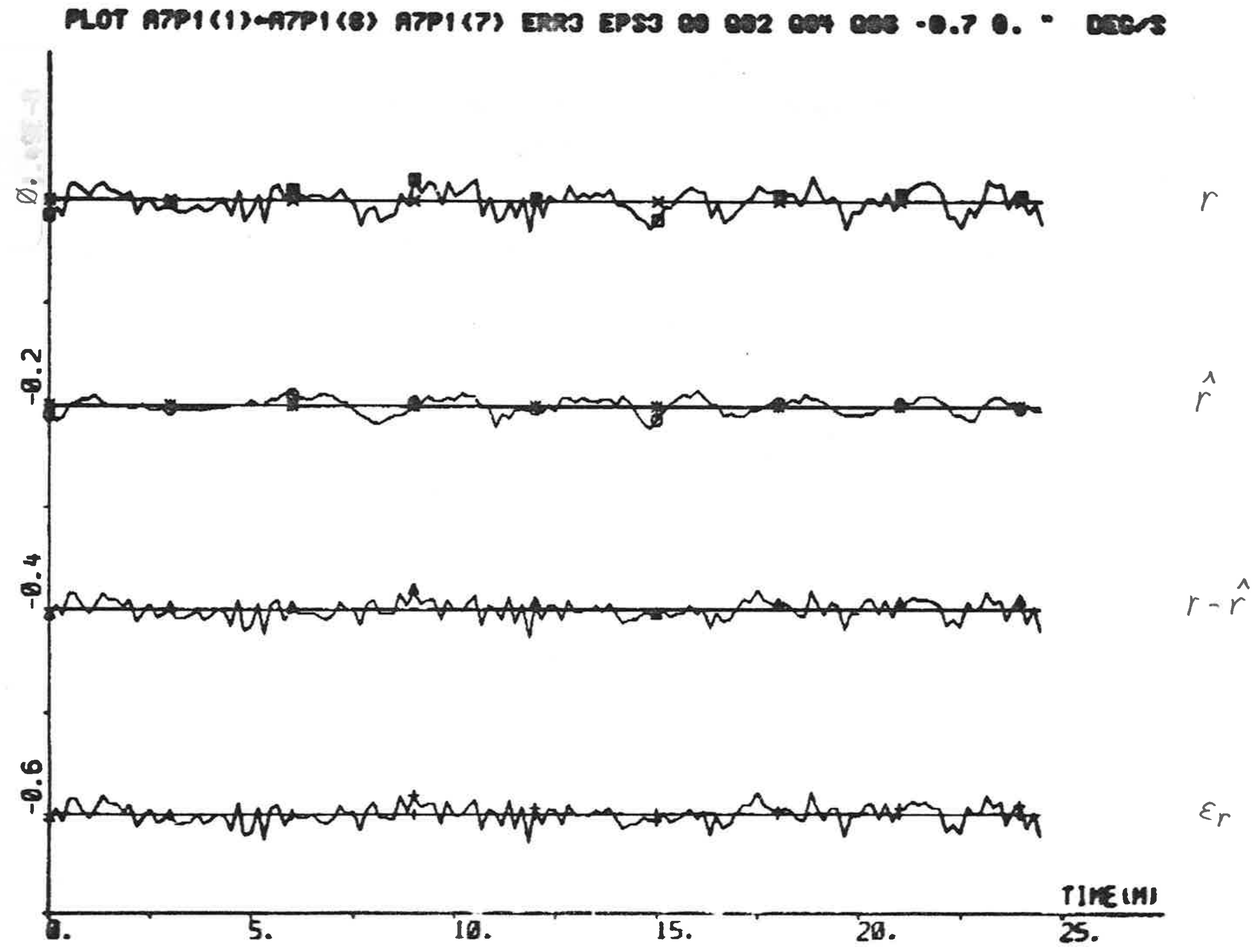
PLOT A7P1(1)-A7P1(8) HP A7P1(18) A7P1(15) Q2 -3 1 " DEG

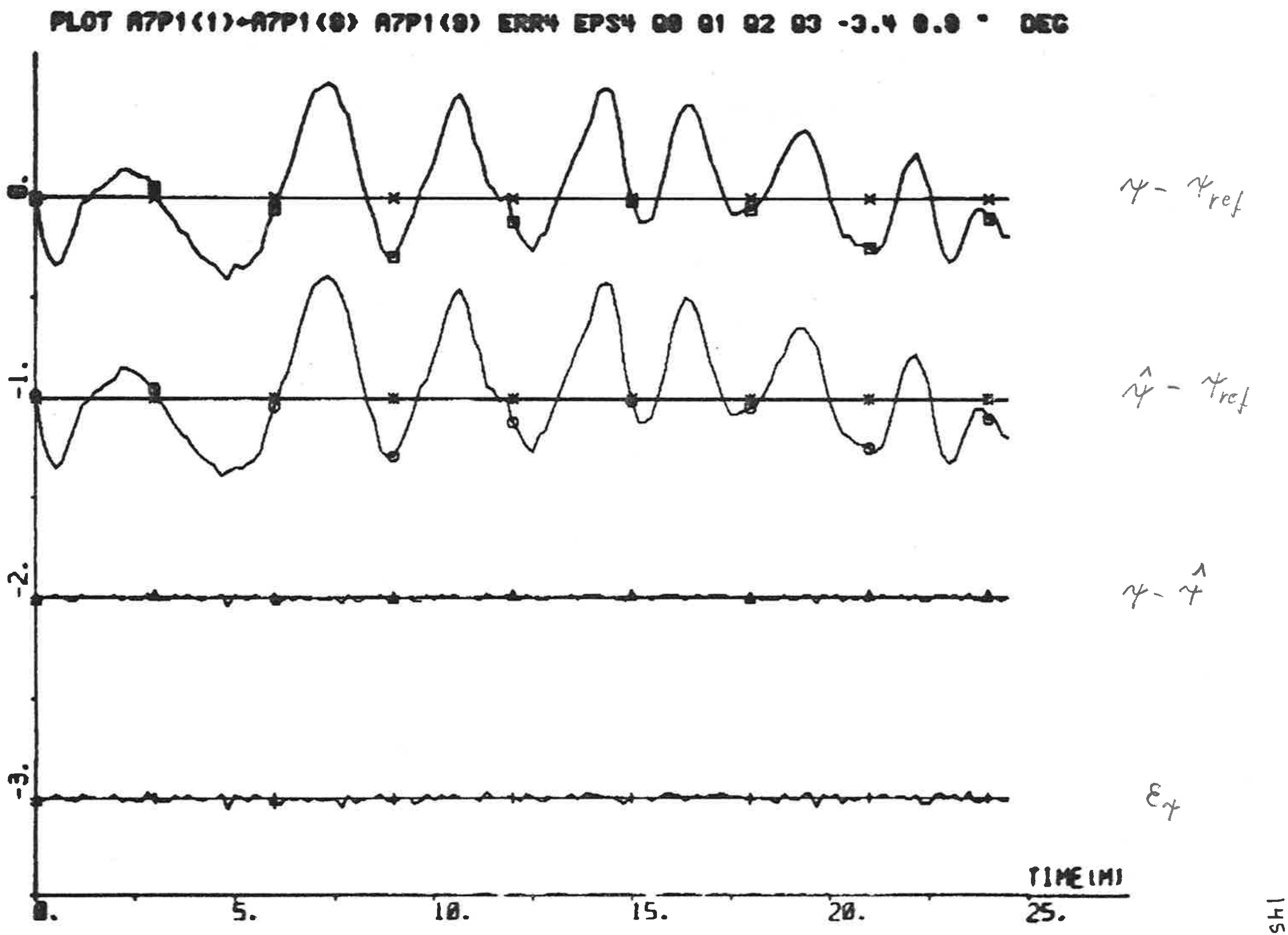


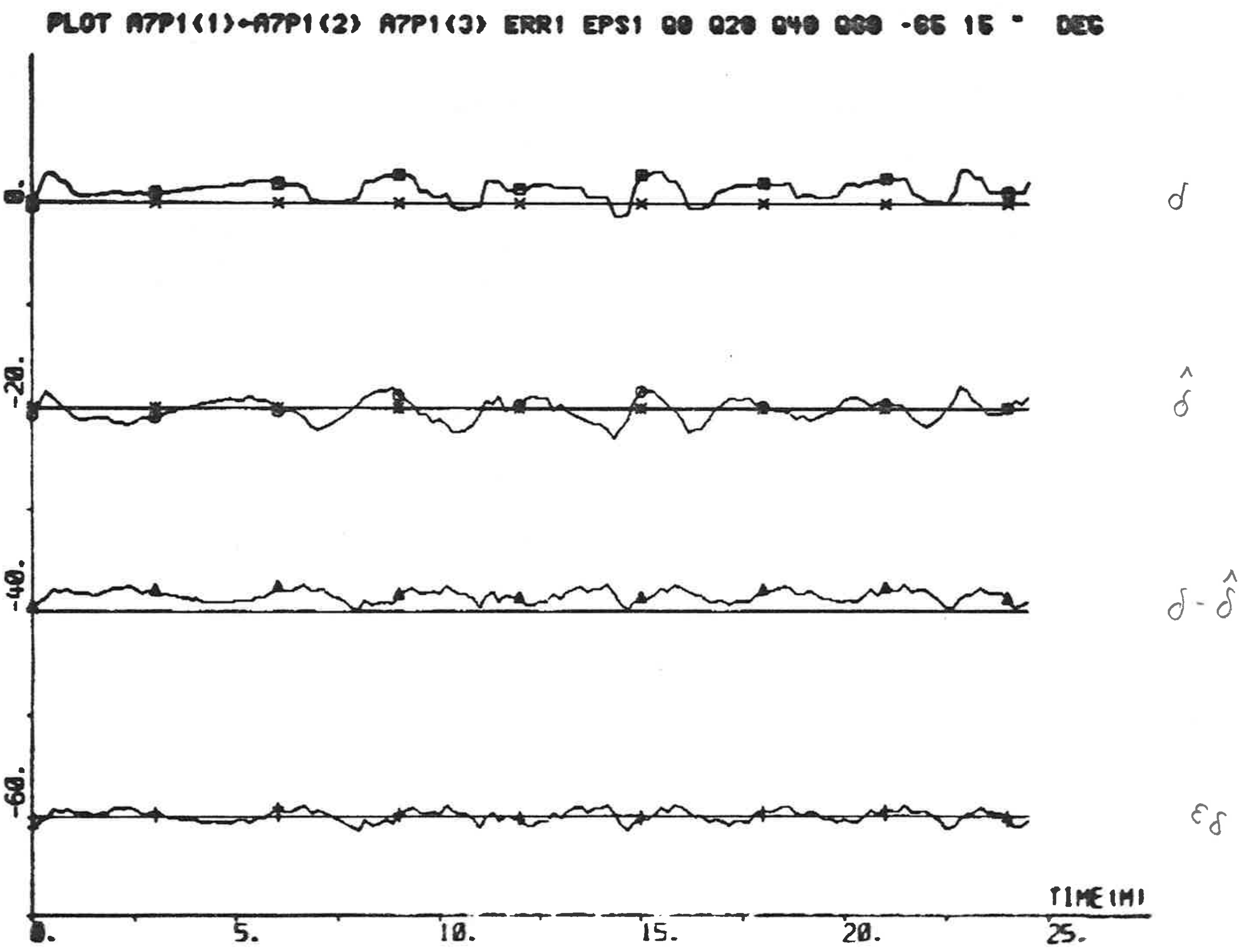

PLOT A7P1(1)-A7P1(13) A7P1(12) A7P1(14) A7P1(11) 00 -20 50
0.5 * n rpm
2 × v knots
MW
deg
TIME(M)
0.
5.
10.
15.
20.
25.
-20.
0.
20.
40.

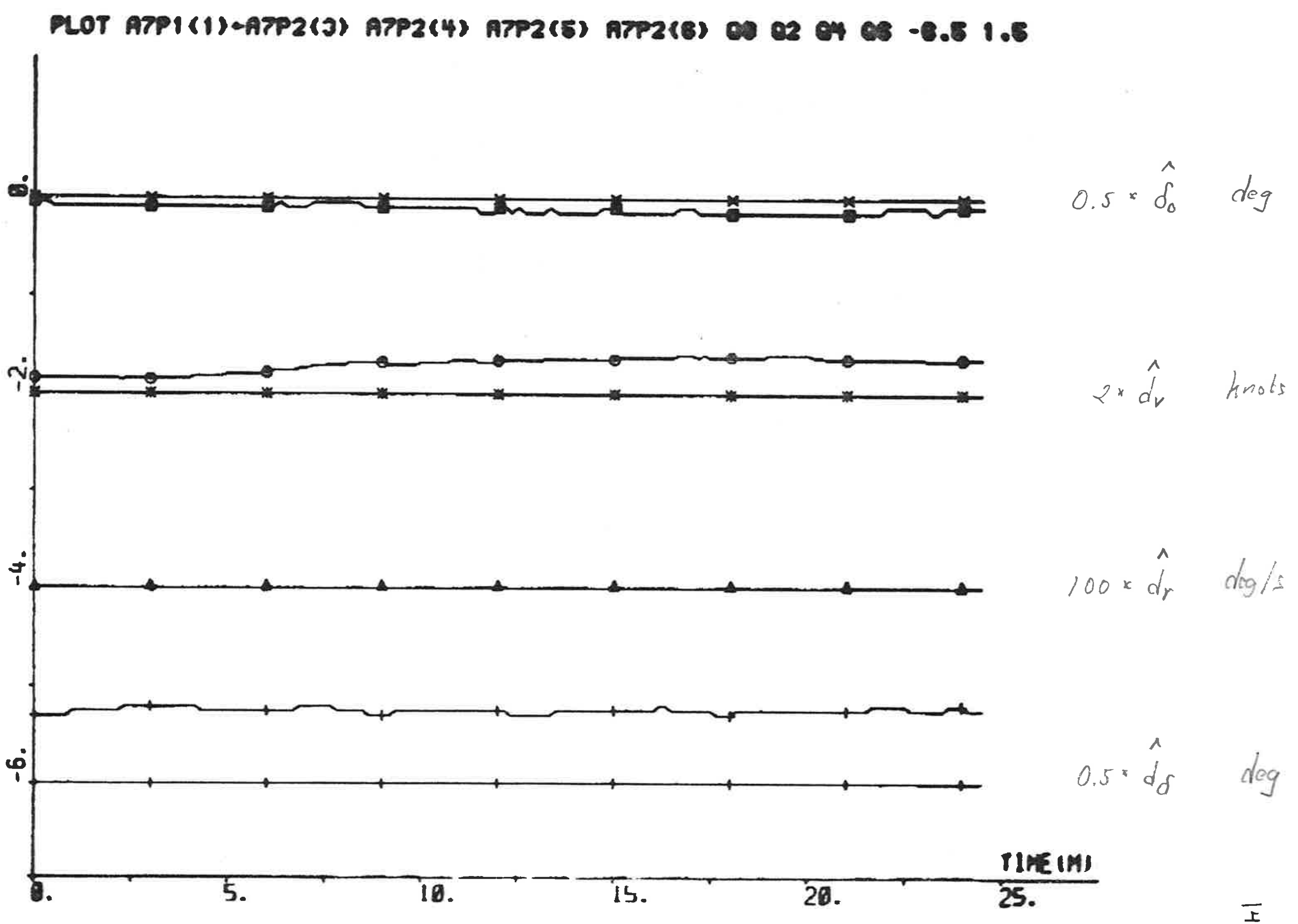

PLOT A7P1(1)-A7P2(1) A7P2(2) ERR6 Q0 Q1 Q2 -3.4 0.0 ° KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A7P1(1)-A7P1(4) A7P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 * KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(H)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT A7P1(1)-A7P1(8) A7P1(7) ERR3 EPS3 G0 G02 G04 G06 -0.7 0. " DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
0.
5.
10.
15.
20.
25.
TIME(M)

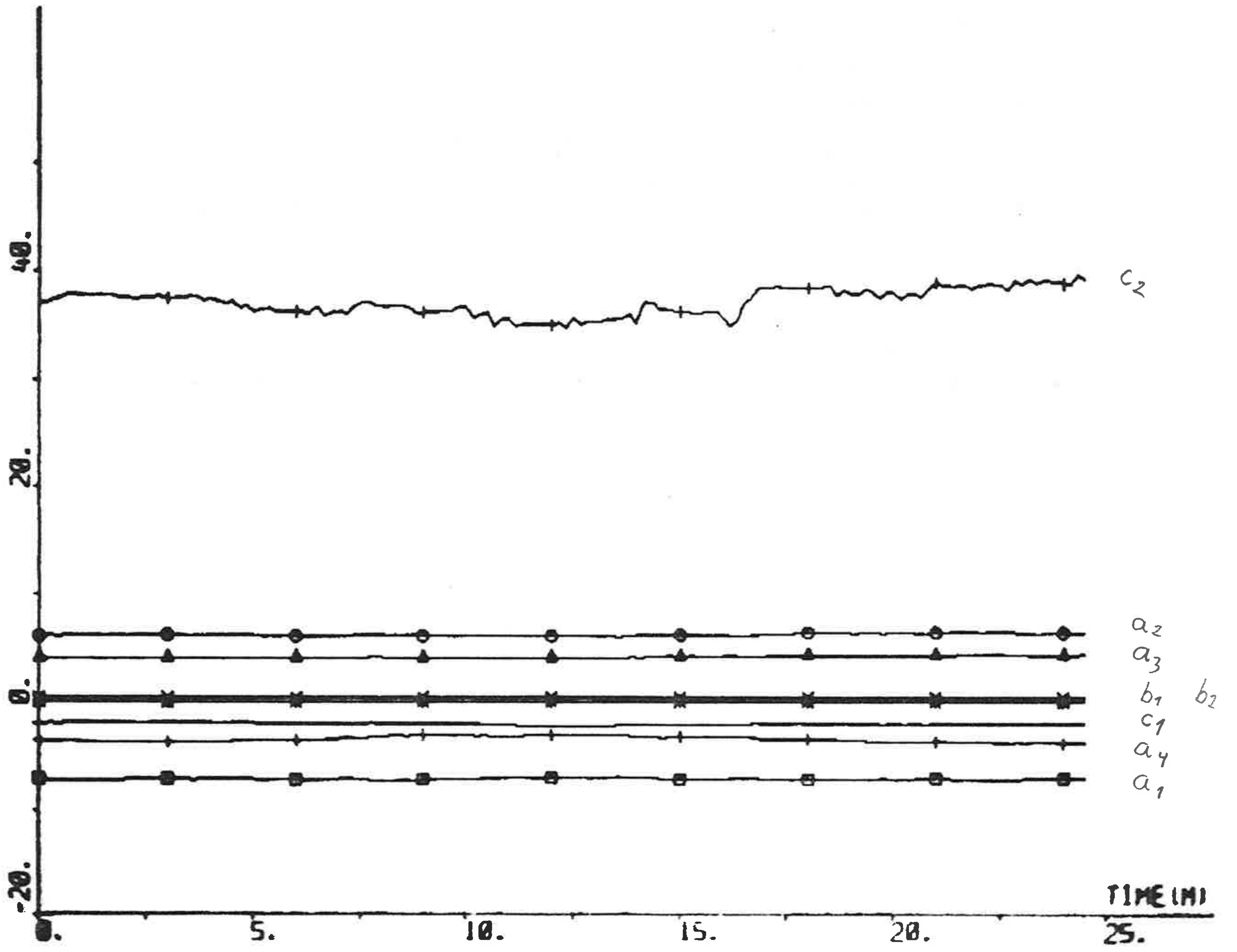

PLOT A7P1(1)-A7P1(8) A7P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A7P1(1)-A7P1(2) A7P1(3) ERR1 EPS1 00 020 040 060 -65 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(H)



PLOT A7P1(1)-A7P2(3) A7P2(4) A7P2(5) A7P2(6) G0 G2 G4 G6 -8.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 × $\hat{\delta}_0$ deg
2 × $\hat{d}_v$ knots
100 × $\hat{d}_r$ deg/s
0.5 × $\hat{d}_\delta$ deg

PLOT A7P1(1)-A7P2(7) A7P2(8) A7P2(9) A7P2(10) A7P2(11) A7P2(12) A7P2(13)



EXPERIMENT A8

Date	1976-04-23	Forward draught	8.5 m
Time	08.56	Aft draught	12.5 m
Duration	24 min	Wind direction	NW (5; see App. A)
Position	N 07°34' W 16°32'	Wind velocity	4 m/s (gentle breeze)
ψ_{ref}	144 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1   NC2 = 1   k = 4   q = 0

T_s = 15 s V_0 = 6 m/s   IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.29 \\ 5.98 \\ 4.34 \\ -2.58 \\ 0.50 \\ 0.18 \\ -2.32 \\ 39.92 \end{bmatrix} \qquad P = \begin{bmatrix} 1.72 \\ -1.87 & 3.80 \\ -0.31 & -1.99 & 4.23 \\ 0.59 & 0.01 & -1.99 & 1.54 \\ -0.08 & 0.01 & 0.15 & -0.07 & 0.01 \\ -0.04 & -0.01 & 0.04 & 0.01 & 0.00 & 0.01 \\ -0.37 & 0.48 & 0.17 & -0.29 & 0.01 & 0.00 & 0.41 \\ 2.99 & -5.18 & -1.70 & 3.09 & -0.36 & -0.02 & 6.79 & 386.28 \end{bmatrix}$$

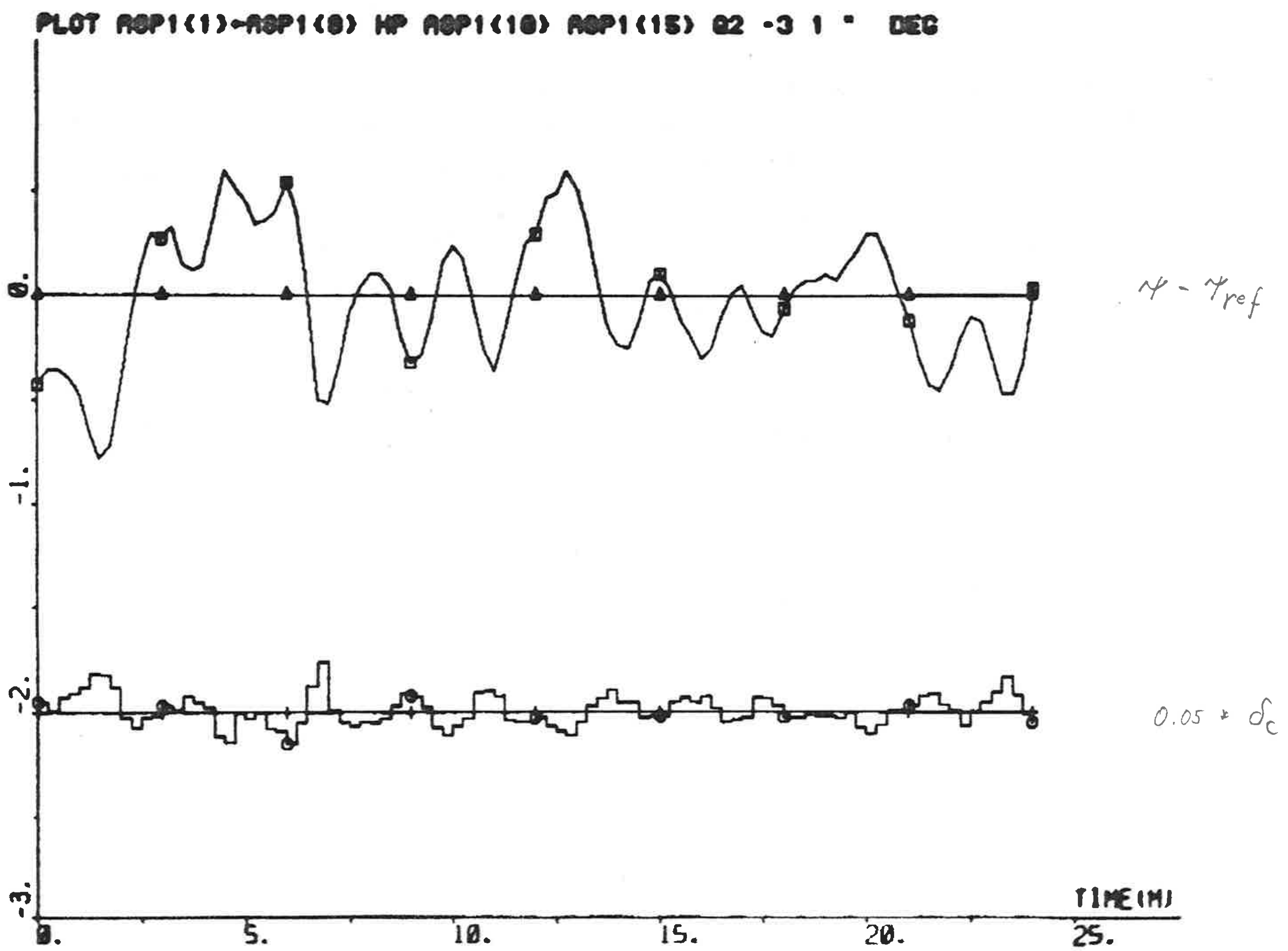
$a_1 + a_2 + a_3 + a_4 = -0.55$

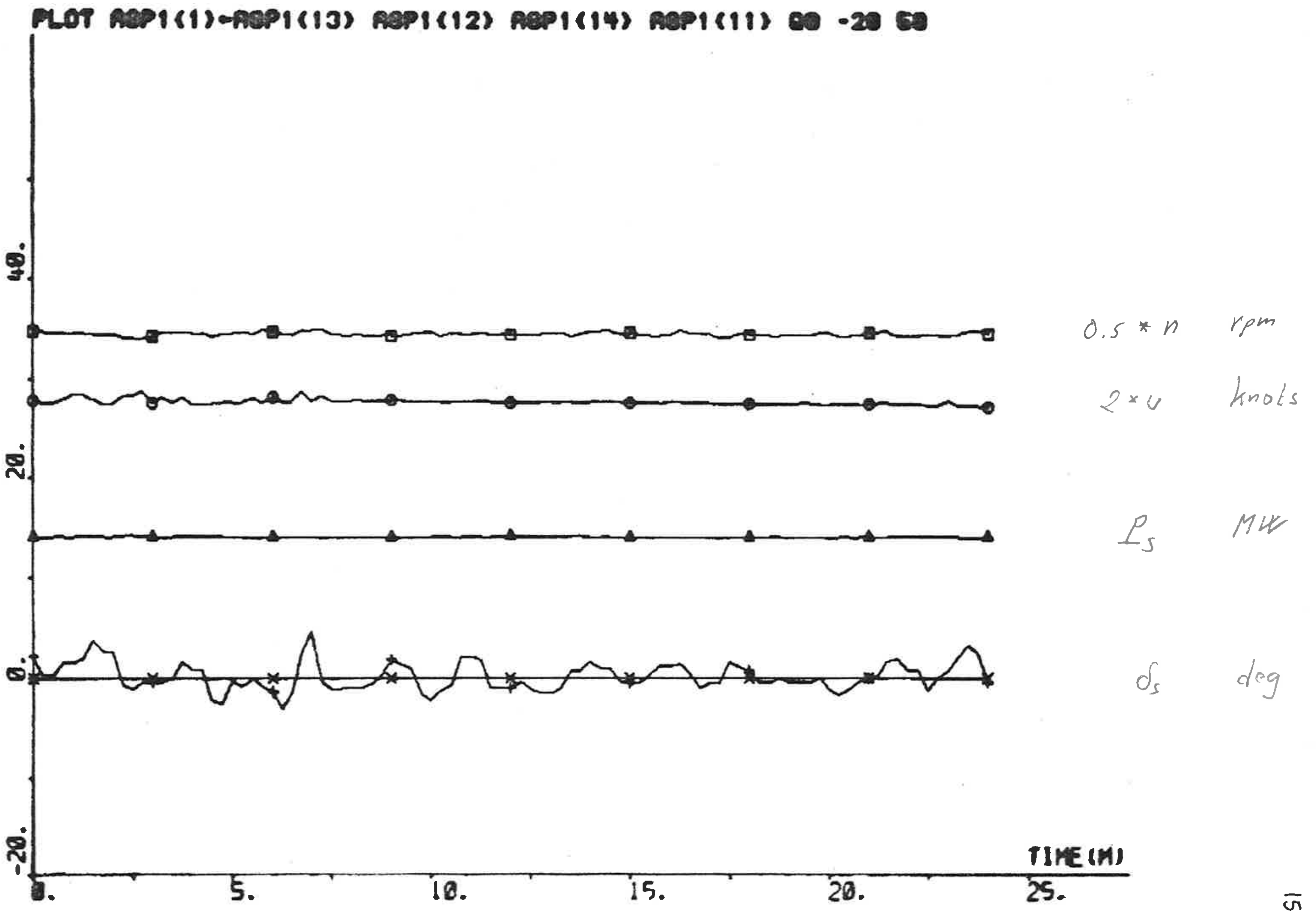
$\hat{\delta}_0 = 0.1$ deg $\hat{d}_v = 0.08$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.4$ deg

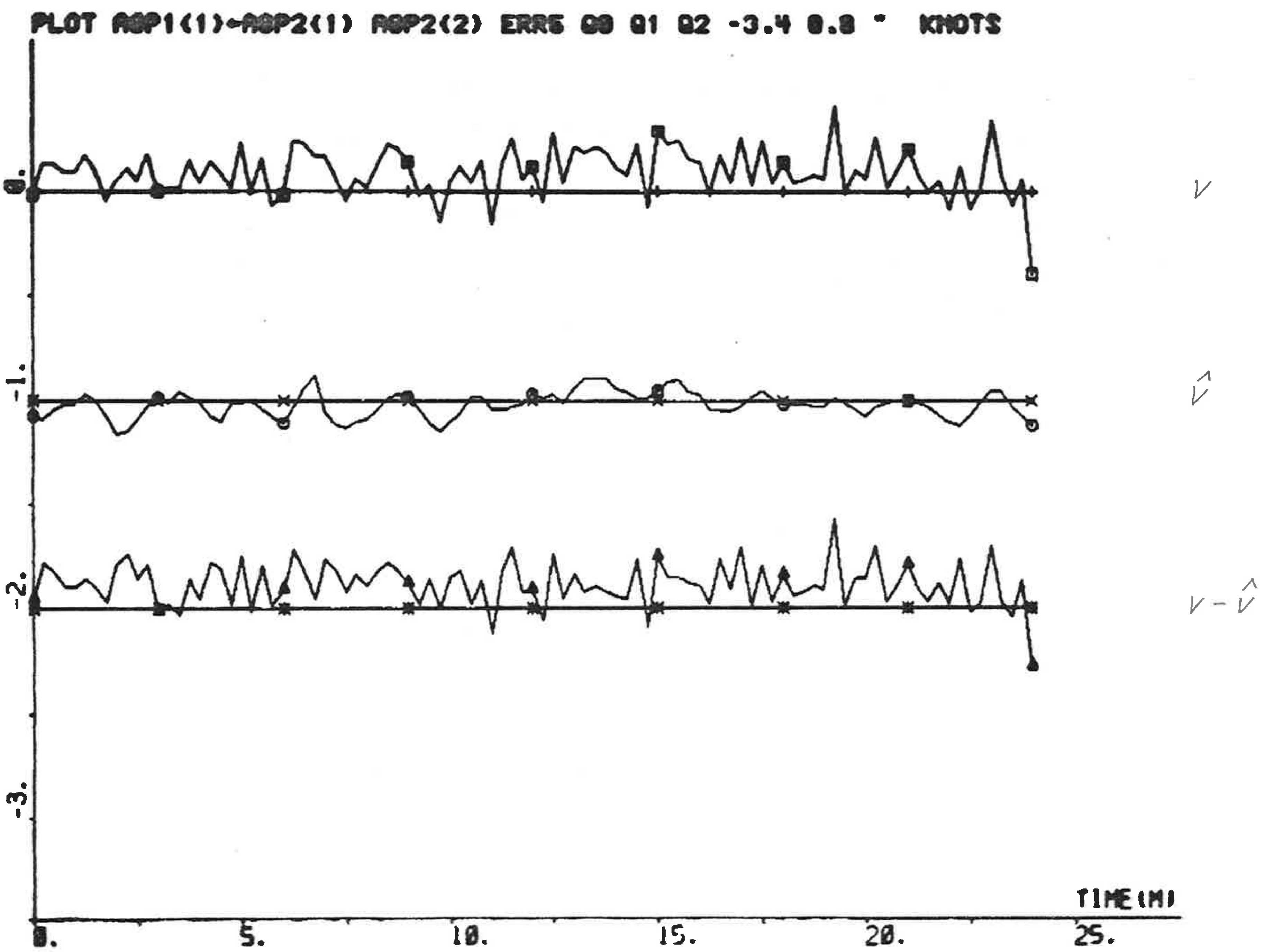
Statistics (mean value and standard deviation)

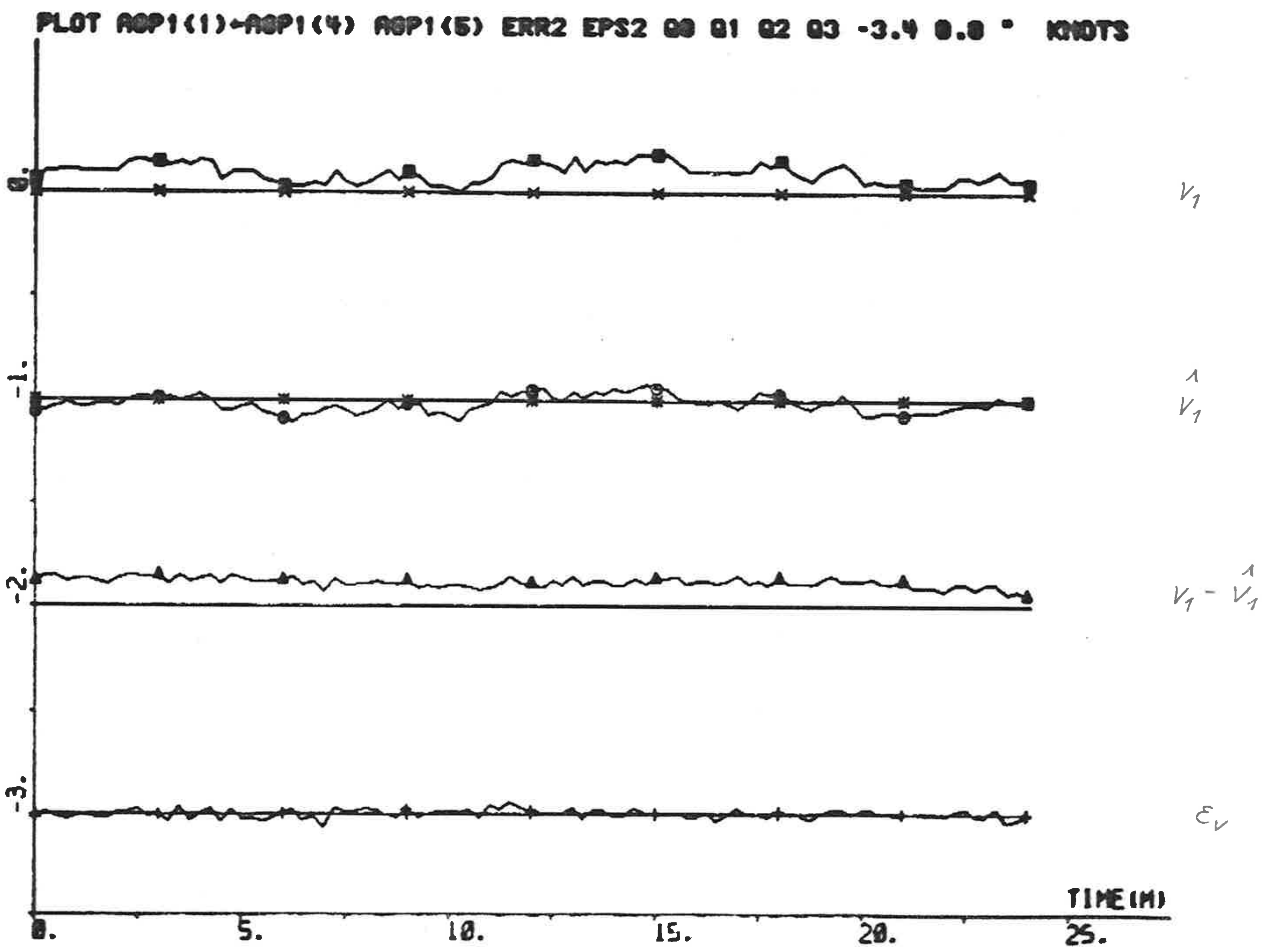
δ_c	0.17 ± 1.46 deg	P_s	14.1 ± 0.1 MW
δ	1.63 ± 1.26 deg	ε_v	0.00 ± 0.02 knots
$\psi-\psi_{ref}$	-0.027 ± 0.309 deg	ε_r	0.00 ± 0.02 deg/s
n	69.2 ± 0.4 rpm	ε_ψ	0.00 ± 0.03 deg
u	13.9 ± 0.1 knots	ε_δ	0.0 ± 0.6 deg

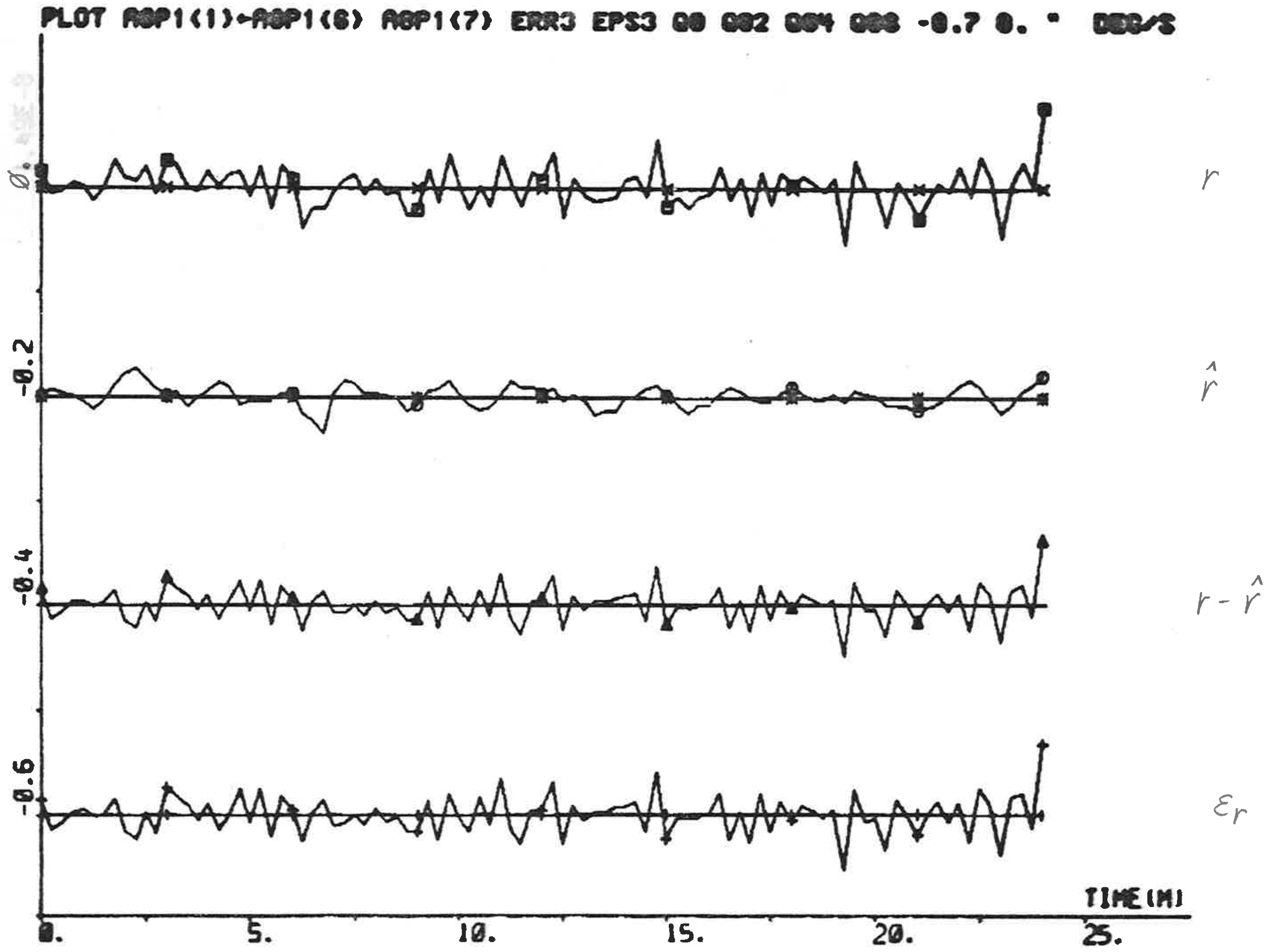
$V_1 = 0.274$

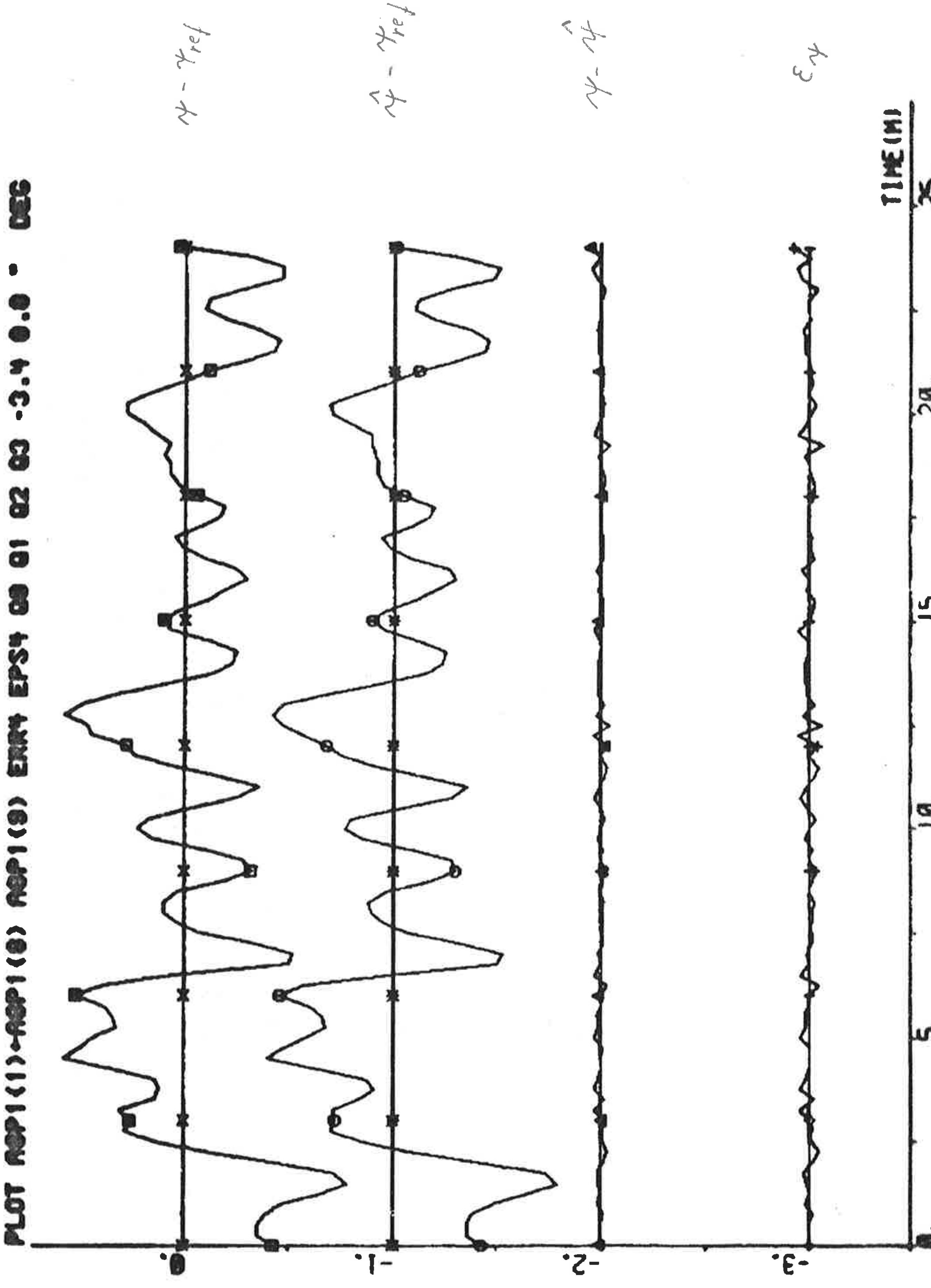

PLOT ASP1(1)-ASP1(8) HP ASP1(10) ASP1(15) Q2 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

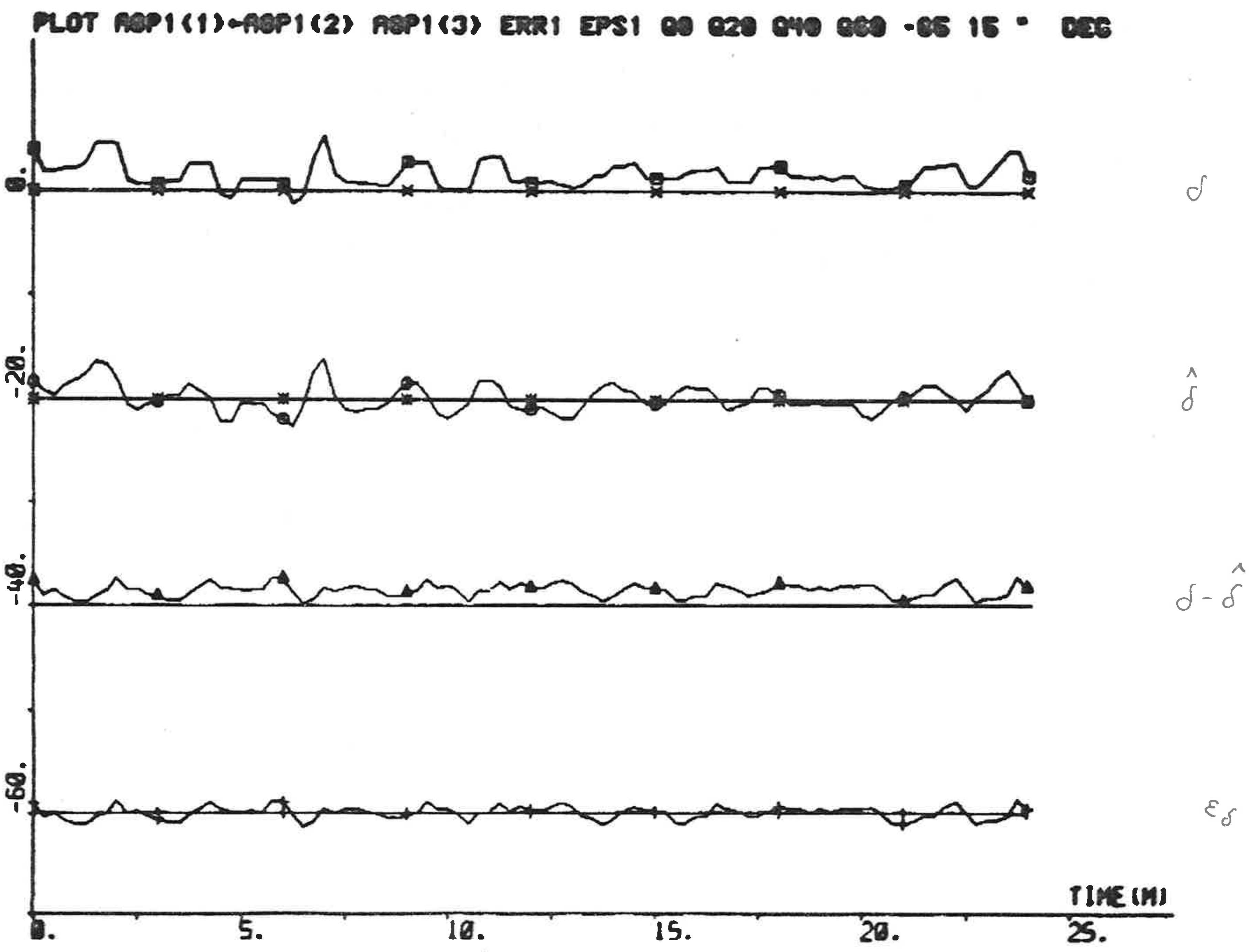

PLOT ASP1(1)-ASP1(13) ASP1(12) ASP1(14) ASP1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n
rpm
2 * v
knots
P_s
MW
δ_s
deg

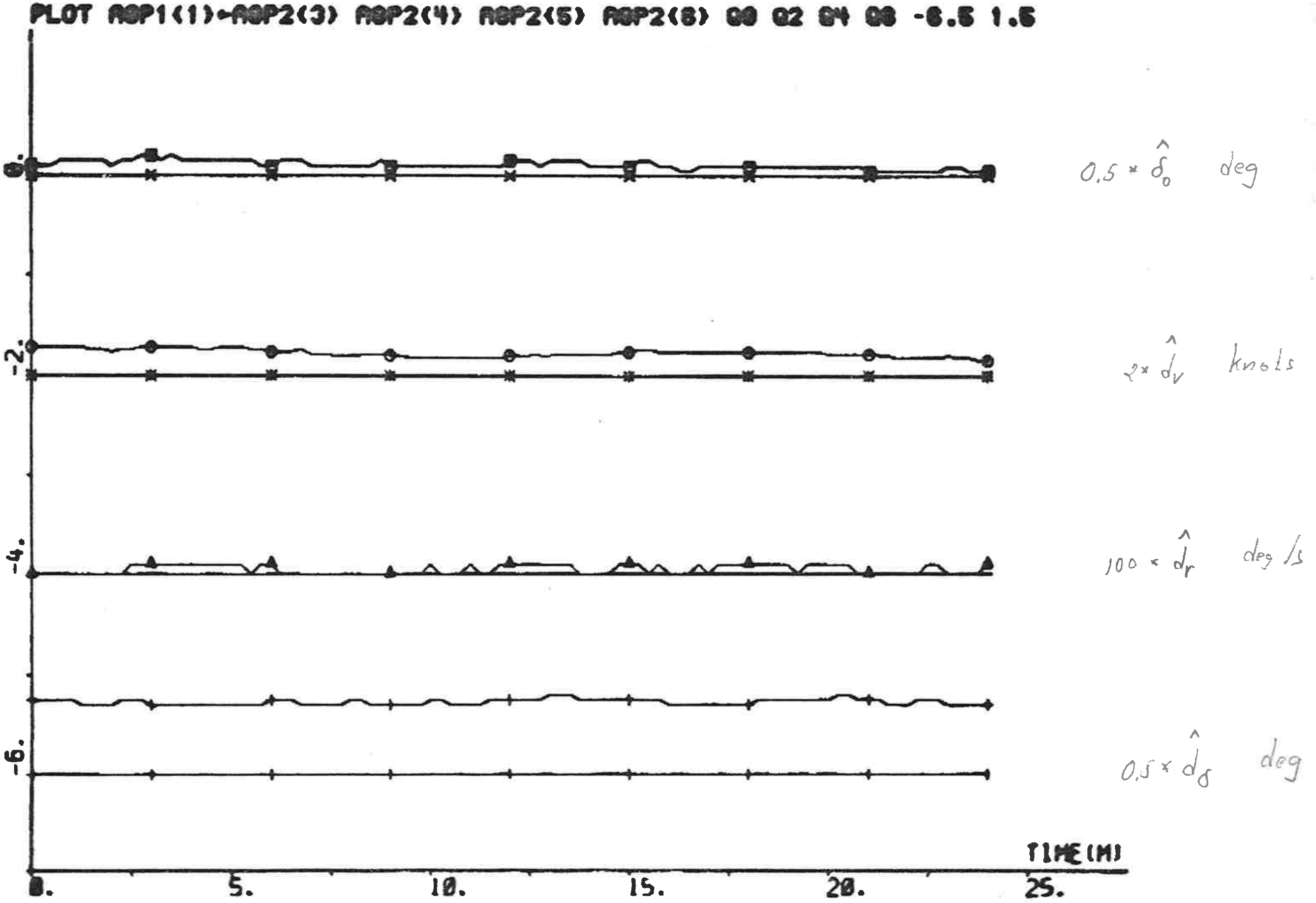

PLOT ASP1(1)-ASP2(1) ASP2(2) ERRS 00 01 02 -3.4 0.8 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

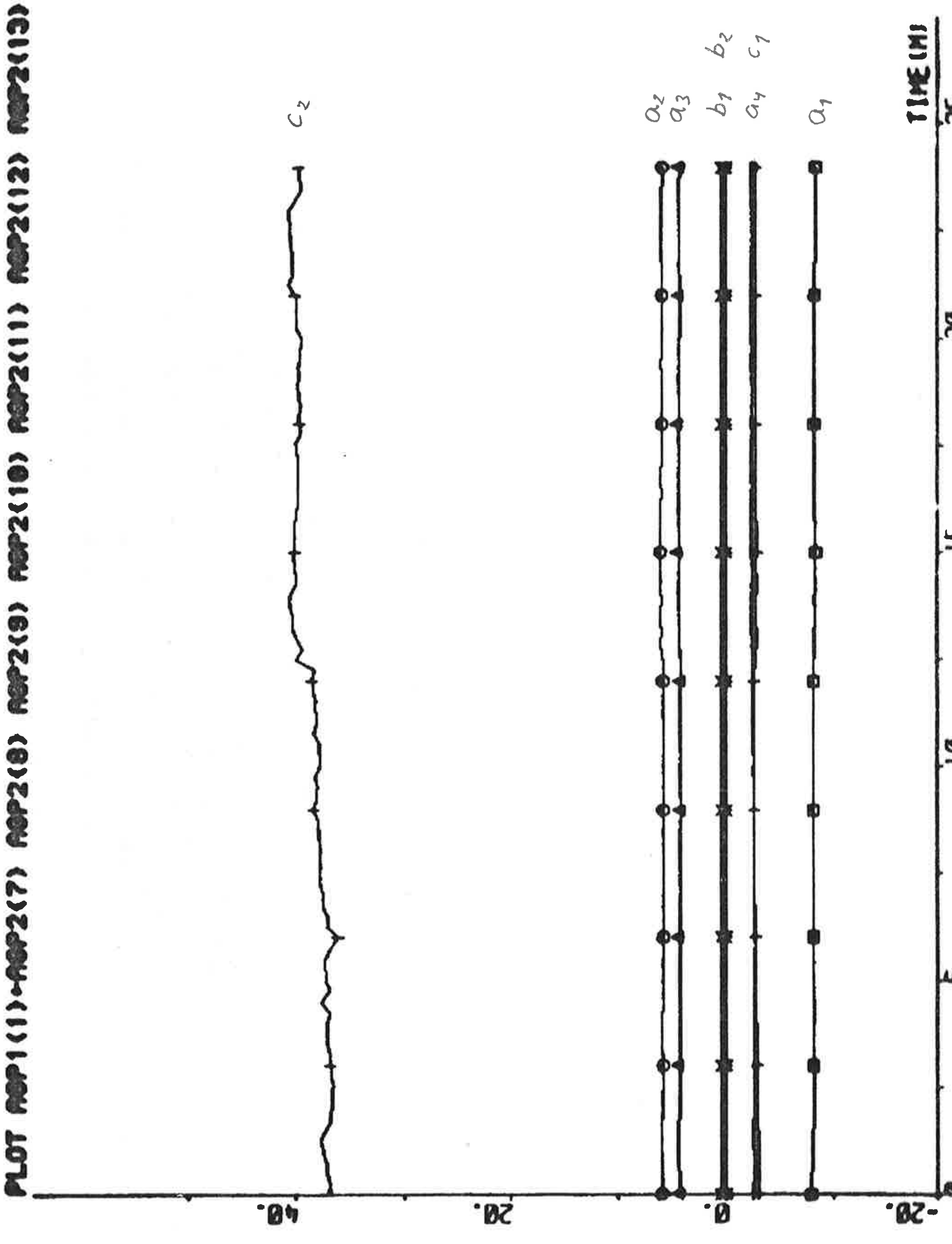

PLOT AGP1(1)-AGP1(4) AGP1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 ° KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT ASP1(1)-ASP1(6) ASP1(7) ERR3 EPS3 00 002 004 008 -0.7 0. " DEG/S
Ø.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂
εr


PLOT ASP1(1)-ASP1(8) ASP1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT ASP1(1)-ASP1(2) ASP1(3) ERR1 EPS1 00 020 040 060 -05 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂
εδ


PLOT ASP1(1)-ASP2(3) ASP2(4) ASP2(5) ASP2(6) 00 02 04 08 -6.5 1.5
0.
-2.
-4.
-6.
0.5 * $\hat{\delta}_0$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg /s
0.5 * $\hat{d}_\delta$ deg
TIME(M)
0.
5.
10.
15.
20.
25.


TIME (M)
0.
5.
10.
15.
20.
25.
-20.
0
20.
40.
c_2
a_2
a_3
b_1
b_2
a_4
c_1
a_1

EXPERIMENT A9

Date	1976-04-23	Forward draught	8.5 m
Time	09.59	Aft draught	12.5 m
Duration	25 min	Wind direction	NW (5; see App. A)
Position	N 07°22' W 16°23'	Wind velocity	4 m/s (gentle breeze)
ψ_{ref}	144 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 k = 5 q = 0

$T_s = 15$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.36 \\ 5.86 \\ 4.03 \\ -2.62 \\ 0.51 \\ 0.16 \\ -1.97 \\ 36.59 \end{bmatrix} \qquad P = \begin{bmatrix} 1.94 & & & & & & & \\ -2.14 & 4.28 & & & & & & \\ -0.24 & -2.39 & 4.78 & & & & & \\ 0.61 & 0.18 & -2.19 & 1.59 & & & & \\ -0.10 & 0.01 & 0.17 & -0.08 & 0.02 & & & \\ -0.05 & -0.01 & 0.05 & 0.01 & 0.00 & 0.02 & & \\ -0.38 & 0.44 & 0.11 & -0.18 & 0.01 & 0.01 & 0.48 & \\ 3.78 & -6.25 & -3.29 & 4.98 & -0.49 & 0.04 & 7.39 & 414.76 \end{bmatrix}$$

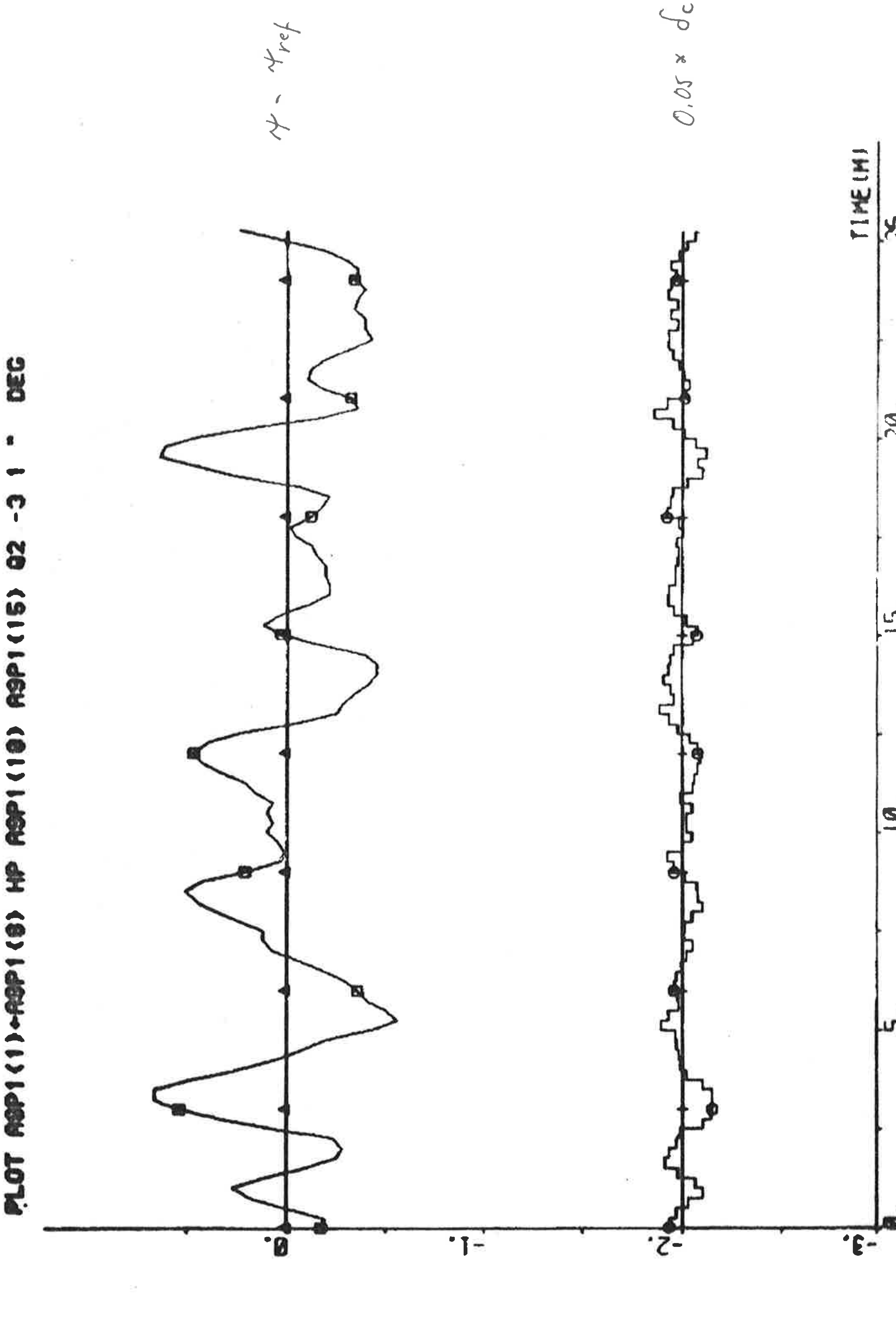
$a_1 + a_2 + a_3 + a_4 = -0.09$

$\hat{\delta}_0 = 0.1$ deg $\hat{d}_v = 0.22$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.4$ deg

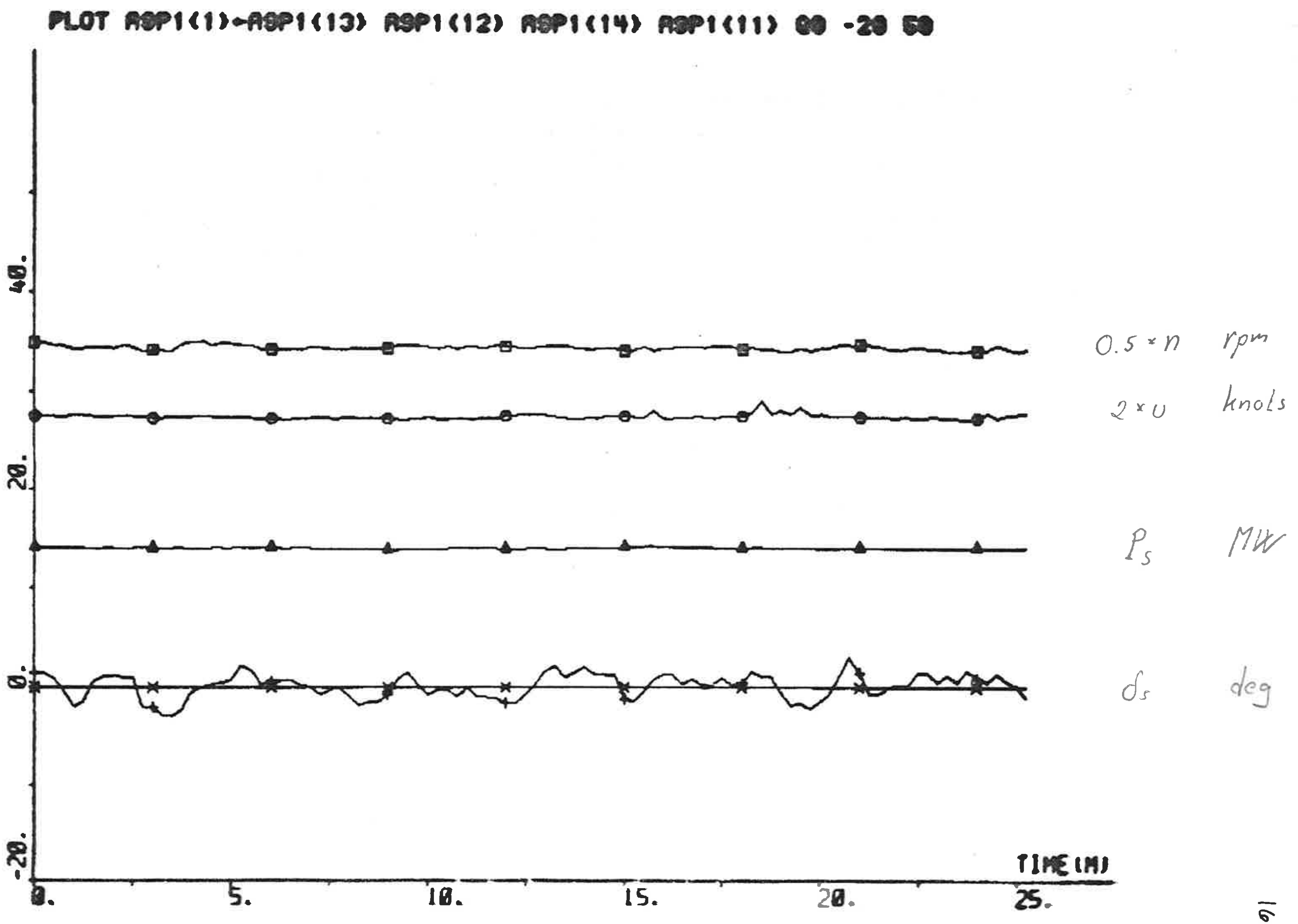
Statistics (mean value and standard deviation)

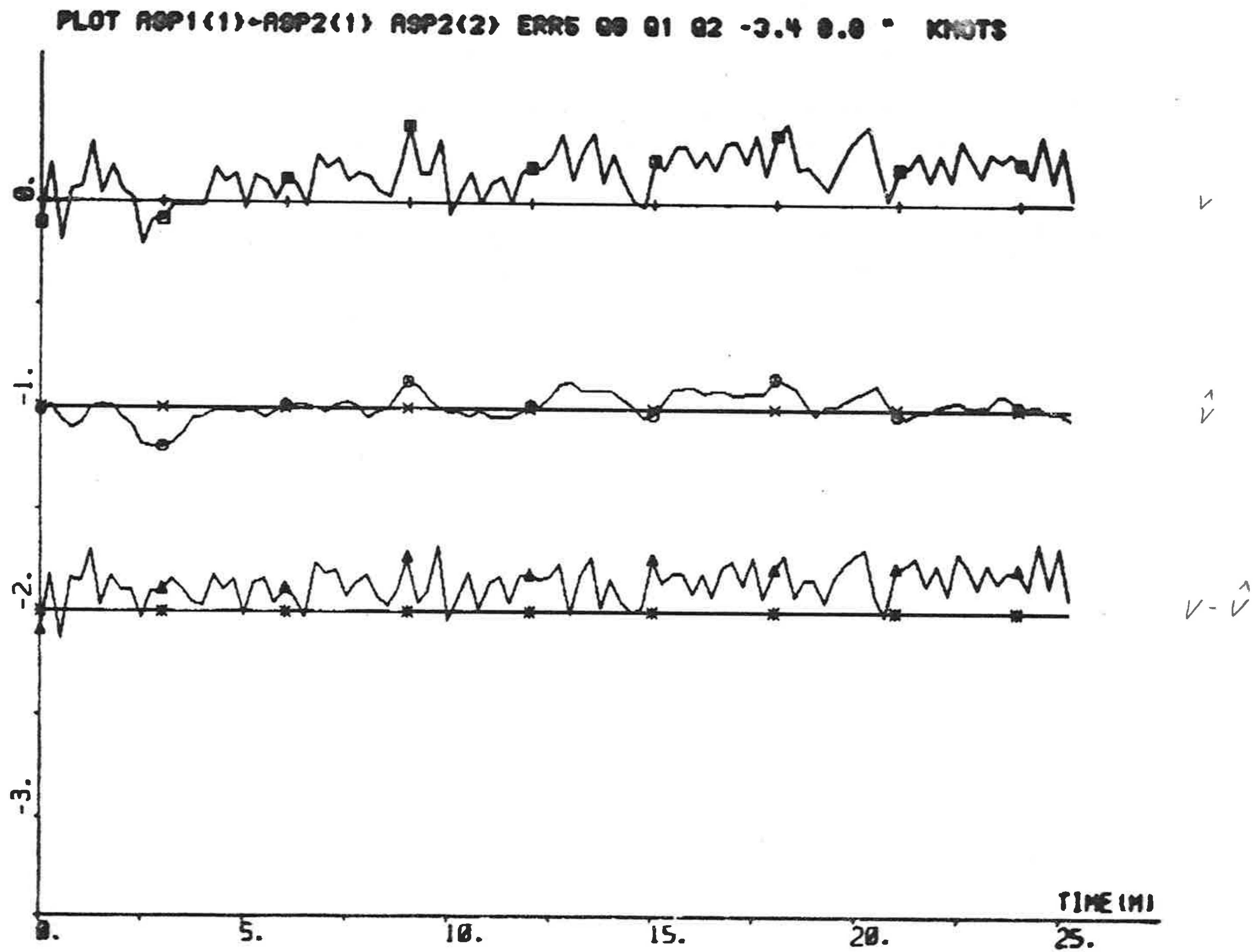
δ_c	0.05 ± 1.24	deg	P_s	14.0 ± 0.1	MW
δ	1.48 ± 1.12	deg	ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	-0.022 ± 0.301	deg	ε_r	0.00 ± 0.02	deg/s
n	69.0 ± 0.4	rpm	ε_ψ	0.00 ± 0.02	deg
u	13.8 ± 0.1	knots	ε_δ	0.0 ± 0.5	deg

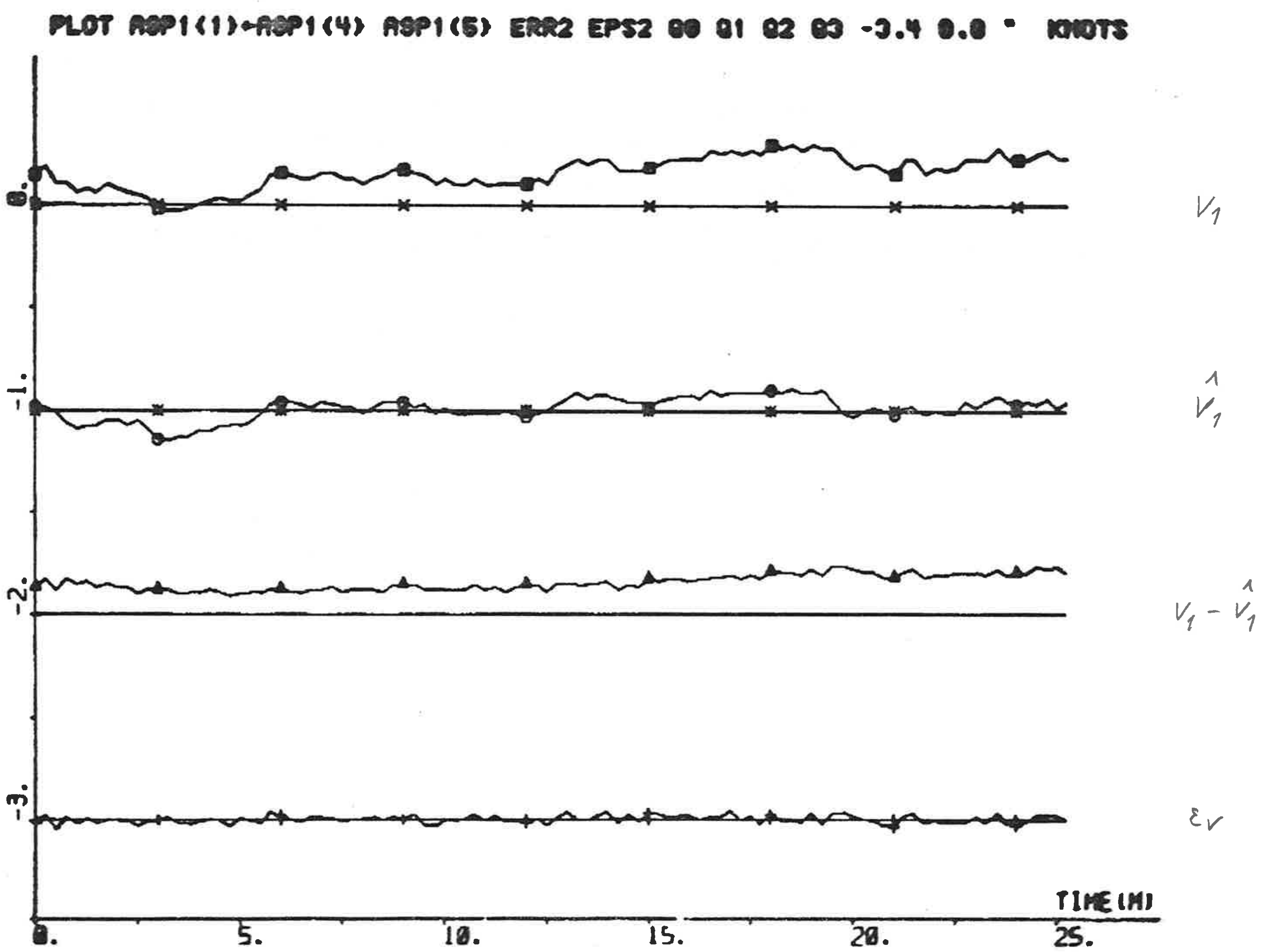
$V_1 = 0.219$

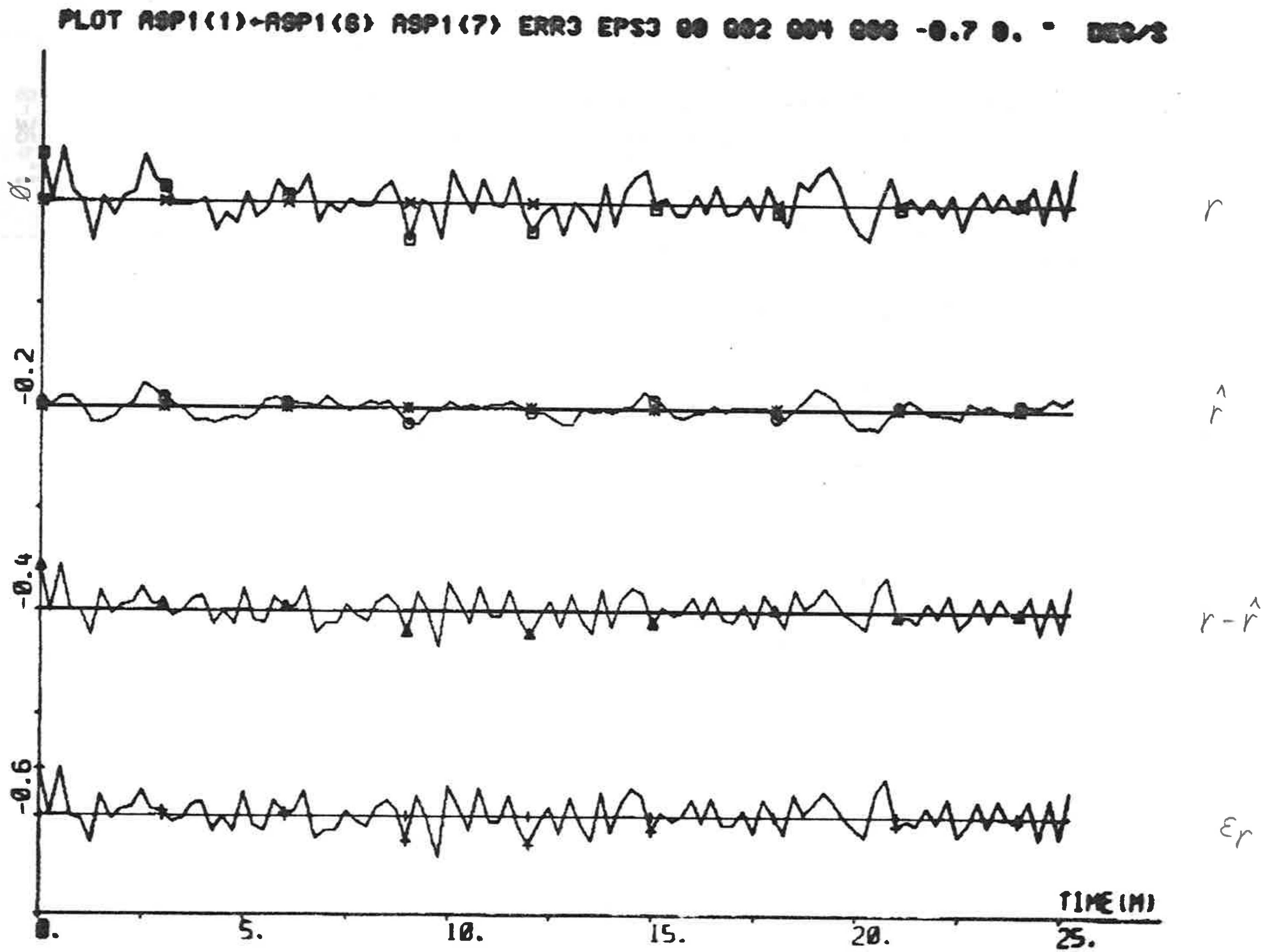


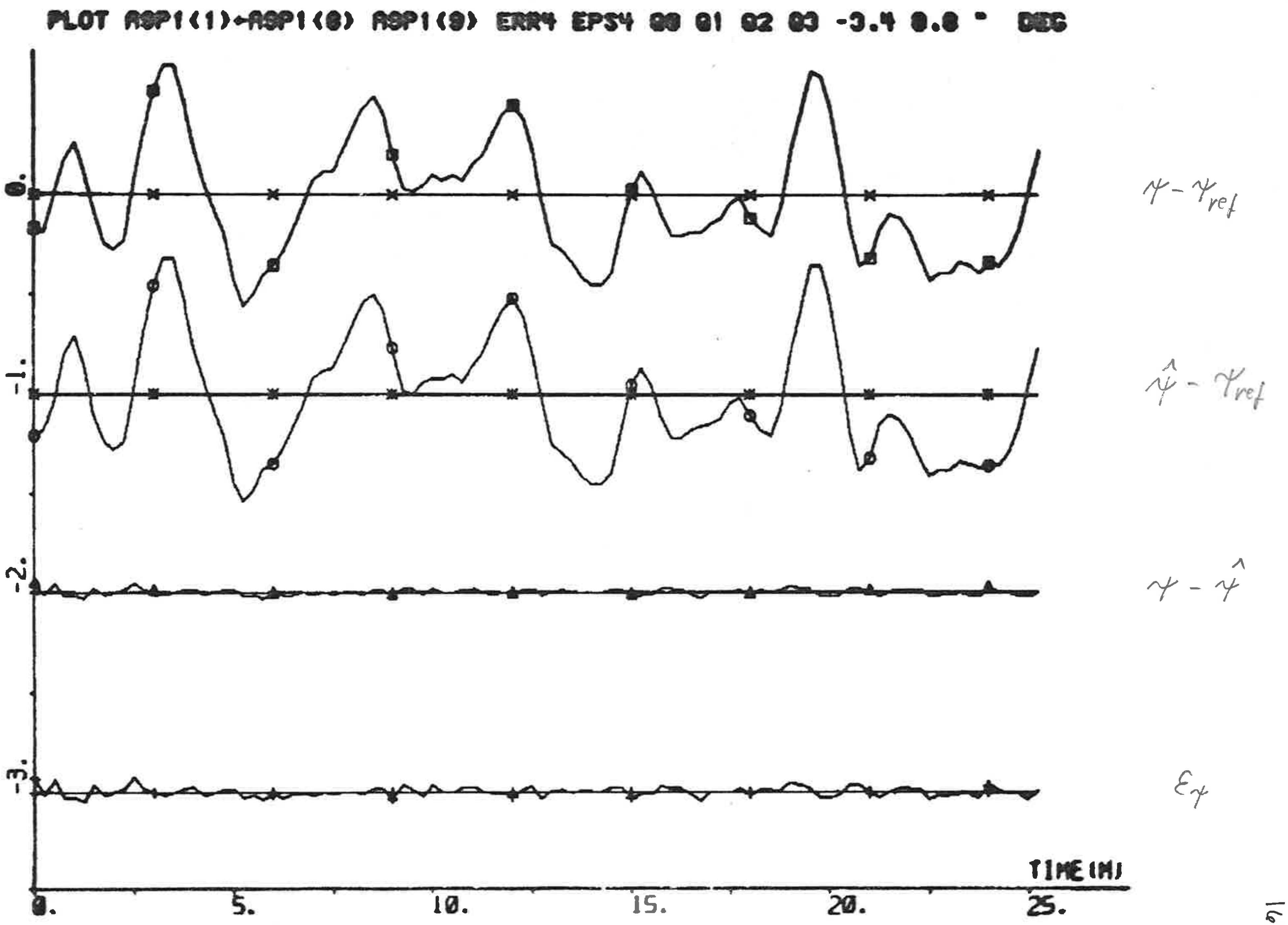
PLOT ASP1(1)-ASP1(9) HP ASP1(10) ASP1(15) 02 -3 1 " DEG
ψ - ψref
0.05 × δc
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

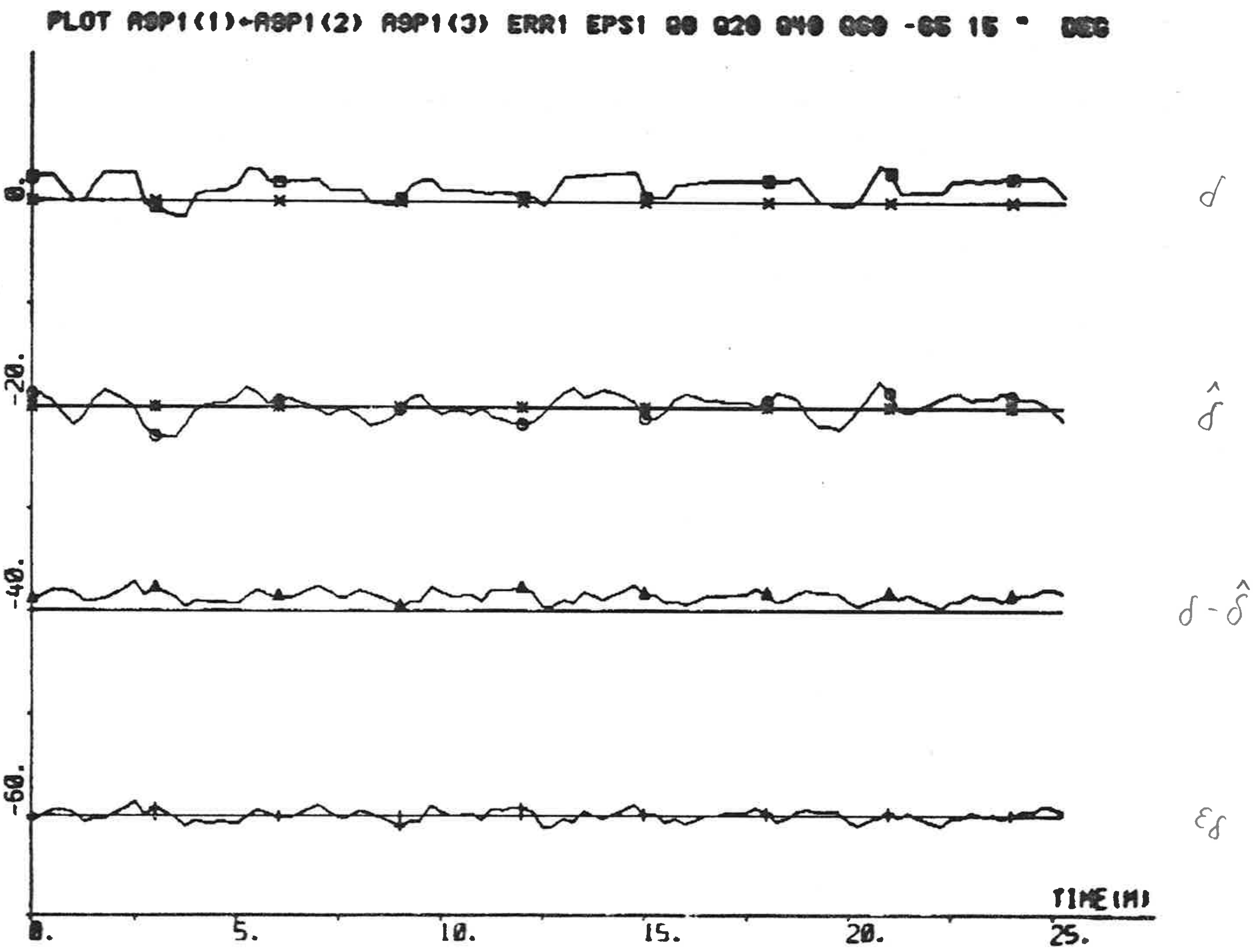

PLOT ASP1(1)-ASP1(13) ASP1(12) ASP1(14) ASP1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME (M)
0.5 * n rpm
2 * U knots
P_s MW
δ_s deg

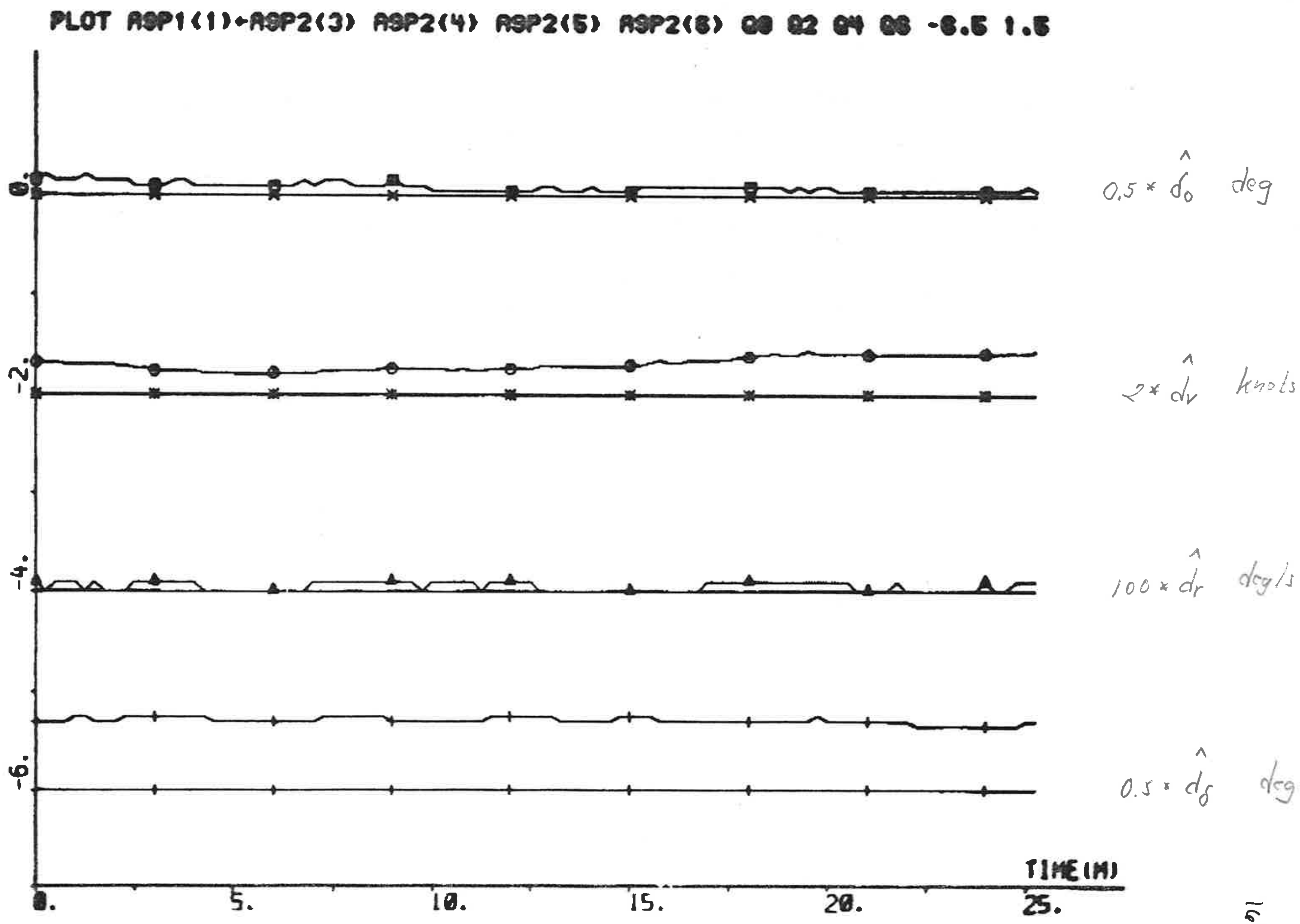

PLOT ASP1(1)-ASP2(1) ASP2(2) ERRS Q0 Q1 Q2 -3.4 0.0 * KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

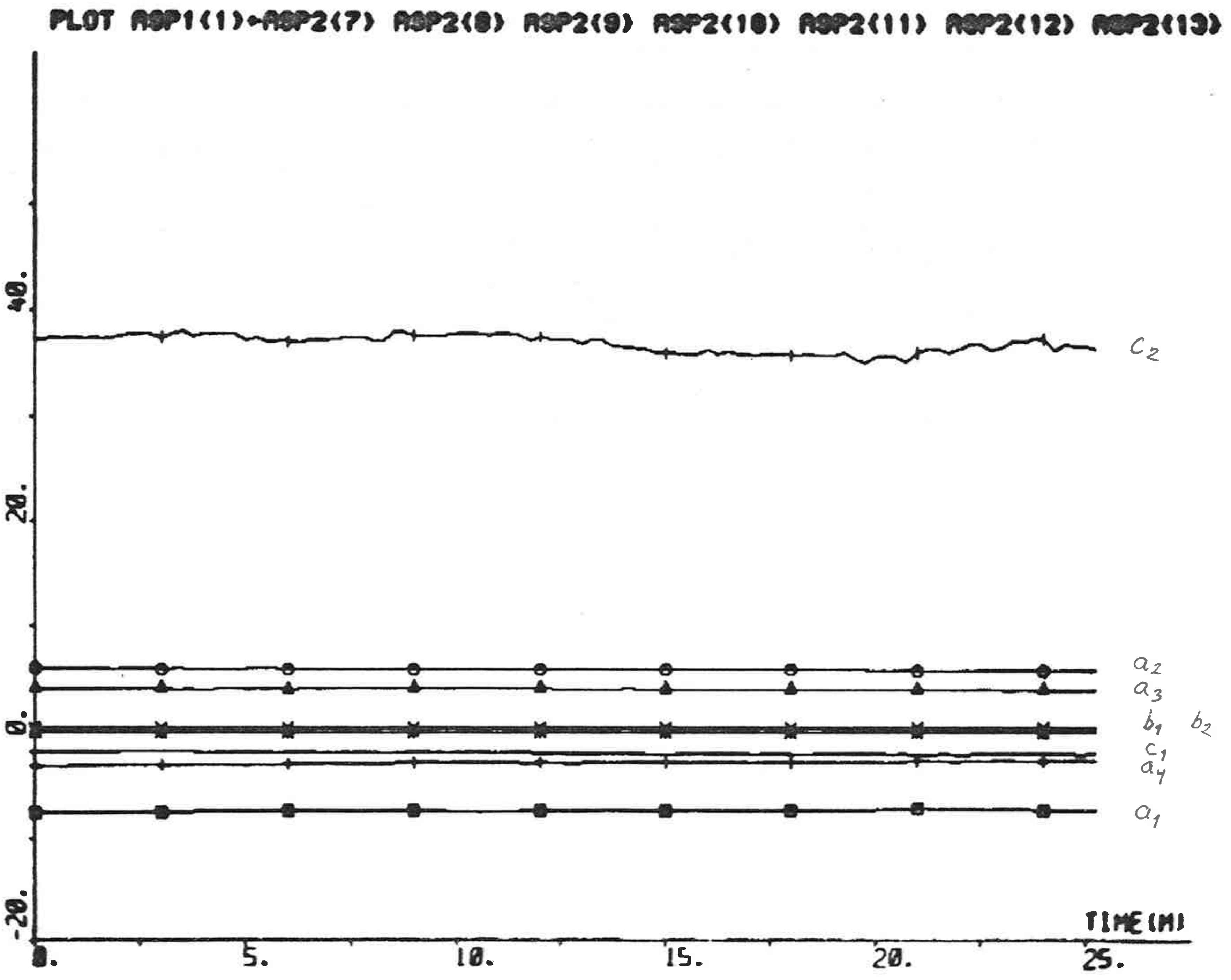

PLOT ASP1(1)+ASP1(4) ASP1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 " KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT ASP1(1)-ASP1(6) ASP1(7) ERR3 EPS3 00 002 004 006 -0.7 0. - DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT ASP1(1)+ASP1(8) ASP1(9) ERR4 EPS4 00 01 02 03 -3.4 0.8 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(H)
$\psi - \psi_{ref}$
$\hat{\psi} - \psi_{ref}$
$\psi - \hat{\psi}$
ε_ψ


PLOT ASP1(1)+ASP1(2) ASP1(3) ERR1 EPS1 00 020 040 060 -65 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂
εδ


PLOT ASP1(1)+ASP2(3) ASP2(4) ASP2(5) ASP2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * d̂o deg
2 * d̂v knots
100 * d̂r deg/s
0.5 * d̂δ deg


PLOT ASP1(1)+ASP2(7) ASP2(8) ASP2(9) ASP2(10) ASP2(11) ASP2(12) ASP2(13)
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT A10

Date	1976-04-23	Forward draught	8.5 m
Time	11.32	Aft draught	12.5 m
Duration	33 min	Wind direction	NW (5; see App. A),
Position	N 07°05' W 16°10'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	144 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -9.56 \\ 6.81 \\ 4.39 \\ -1.97 \\ 0.53 \\ 0.26 \\ -2.25 \\ 40.29 \end{bmatrix} \quad P = \begin{bmatrix} 6.46 & & & & & & & \\ -8.35 & 17.84 & & & & & & \\ -0.32 & -10.89 & 20.44 & & & & & \\ 2.47 & 1.20 & -9.56 & 6.24 & & & & \\ -0.14 & -0.18 & 0.54 & -0.23 & 0.03 & & & \\ -0.13 & 0.10 & -0.04 & 0.07 & 0.01 & 0.02 & & \\ -1.04 & 1.30 & 0.53 & -0.83 & 0.02 & -0.01 & 0.95 & \\ 24.78 & -35.21 & -8.89 & 17.37 & -0.31 & -0.44 & 13.63 & 998.99 \end{bmatrix}$$

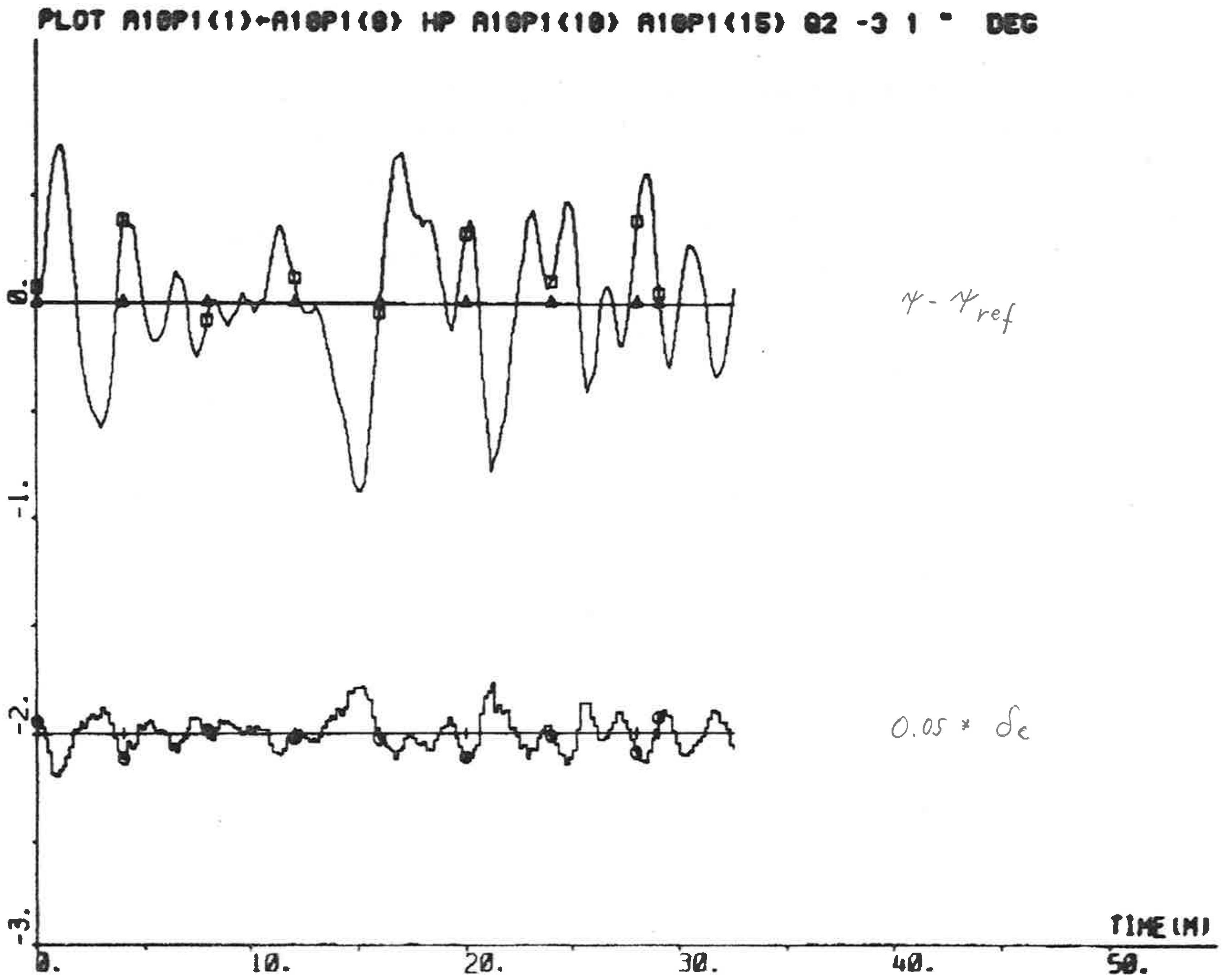
$a_1 + a_2 + a_3 + a_4 = -0.33$

$\hat{\delta}_0 = 0.2$ deg $\hat{d}_v = 0.06$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.3$ deg

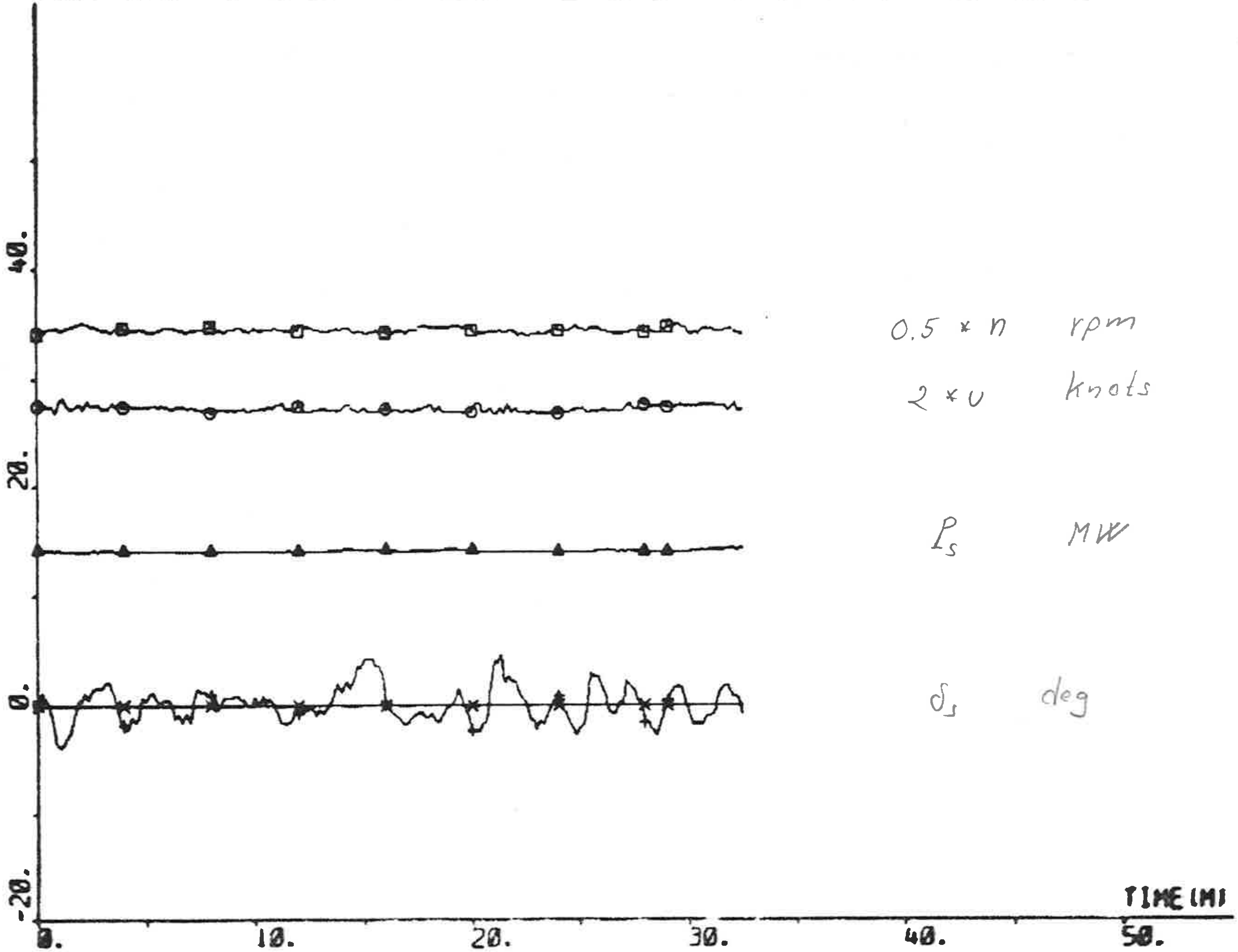
Statistics (mean value and standard deviation)

δ_c	0.08 ± 1.62	deg	P_s	14.1 ± 0.1	MW
δ	1.34 ± 1.45	deg	ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.013 ± 0.344	deg	ε_r	0.01 ± 0.02	deg/s
n	69.0 ± 0.4	rpm	ε_ψ	0.00 ± 0.03	deg
u	13.7 ± 0.1	knots	ε_δ	0.0 ± 0.6	deg

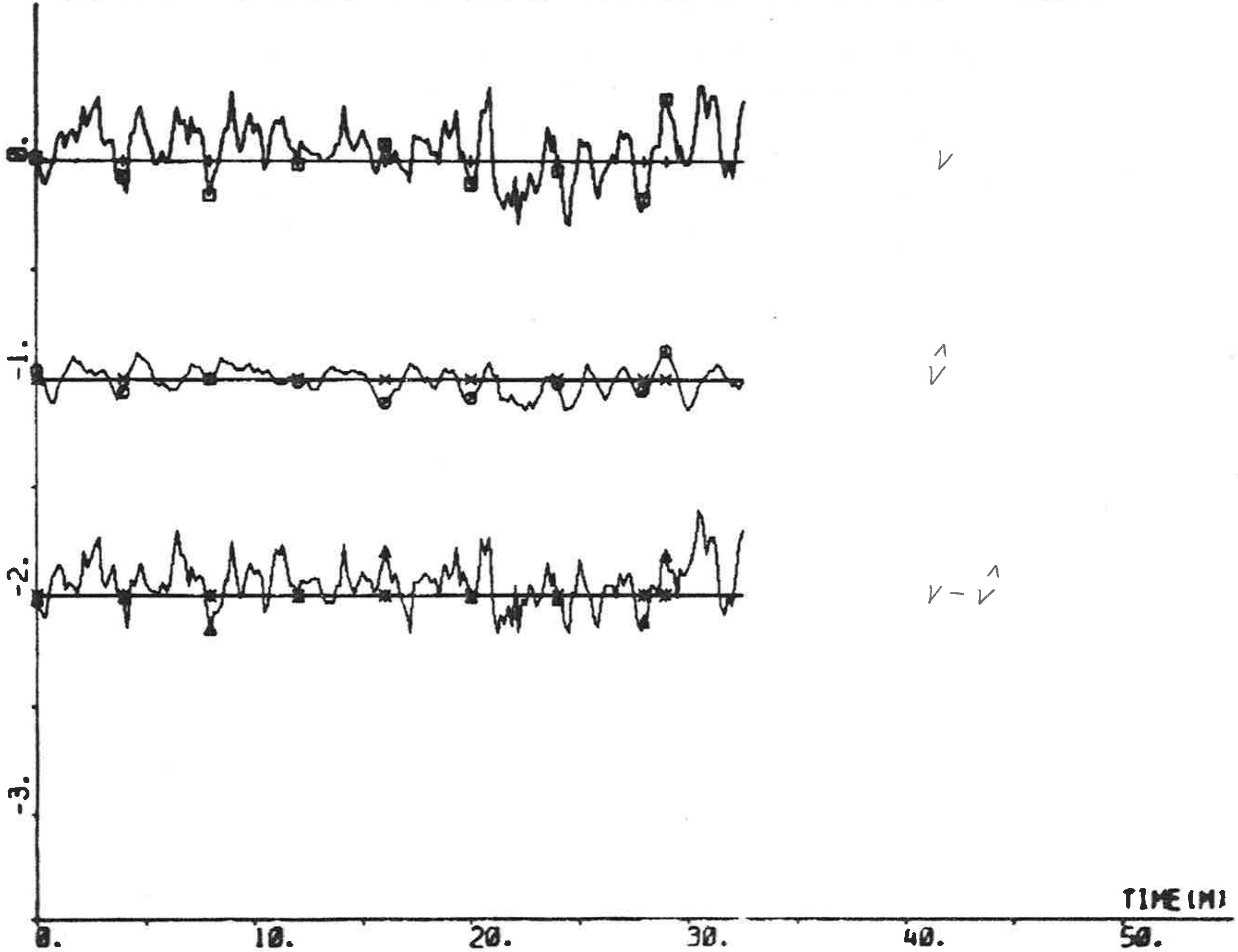
$V_1 = 0.337$

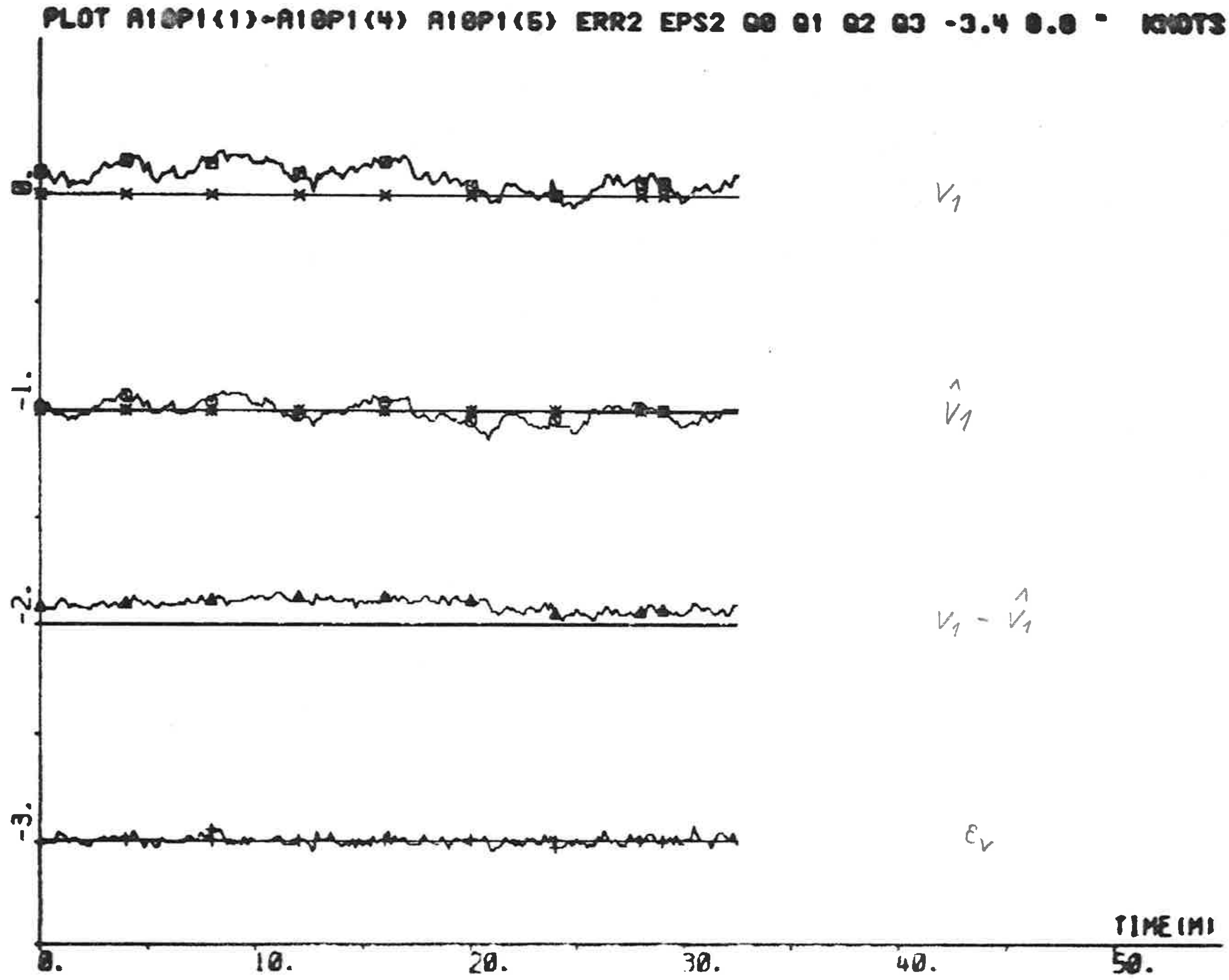

PLOT A1GP1(1)-A1GP1(8) HP A1GP1(10) A1GP1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
ψ - ψref
0.05 * δc

PLOT A10P1(1)-A10P1(13) A10P1(12) A10P1(14) A10P1(11) 00 -20 50

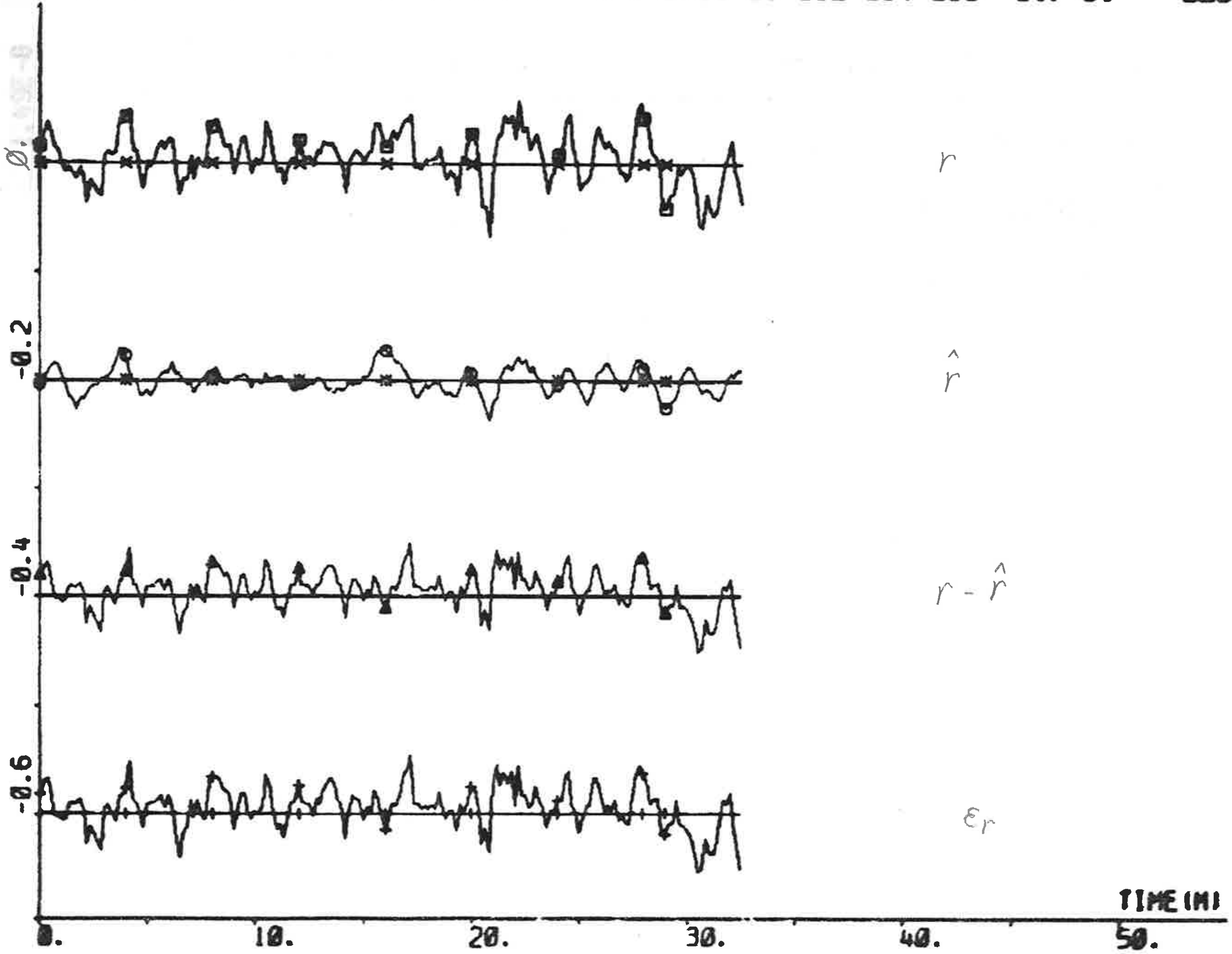


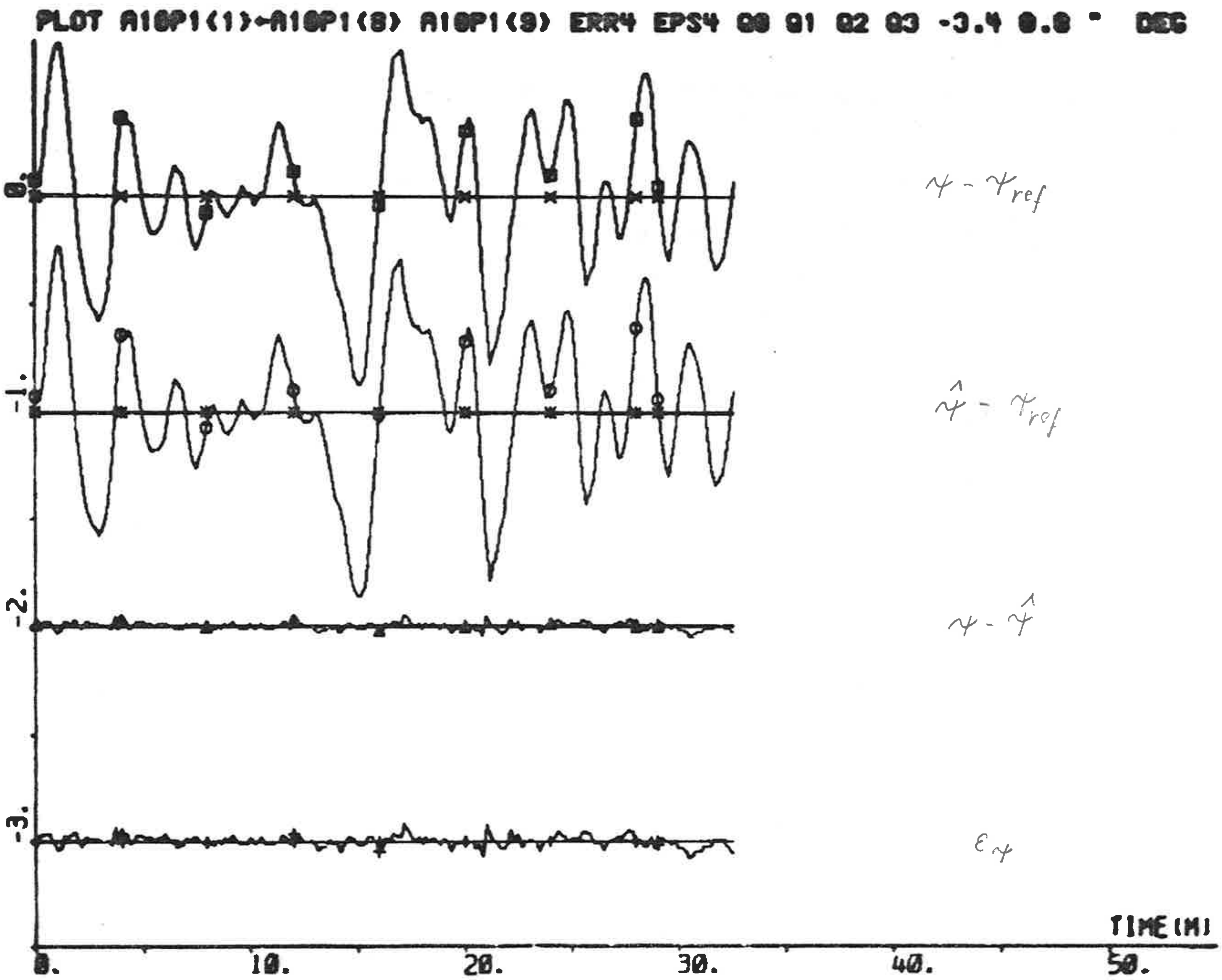
PLOT A10P1(1)-A10P2(1) A10P2(2) ERRS Q0 Q1 Q2 -3.4 0.8 " KNOTS

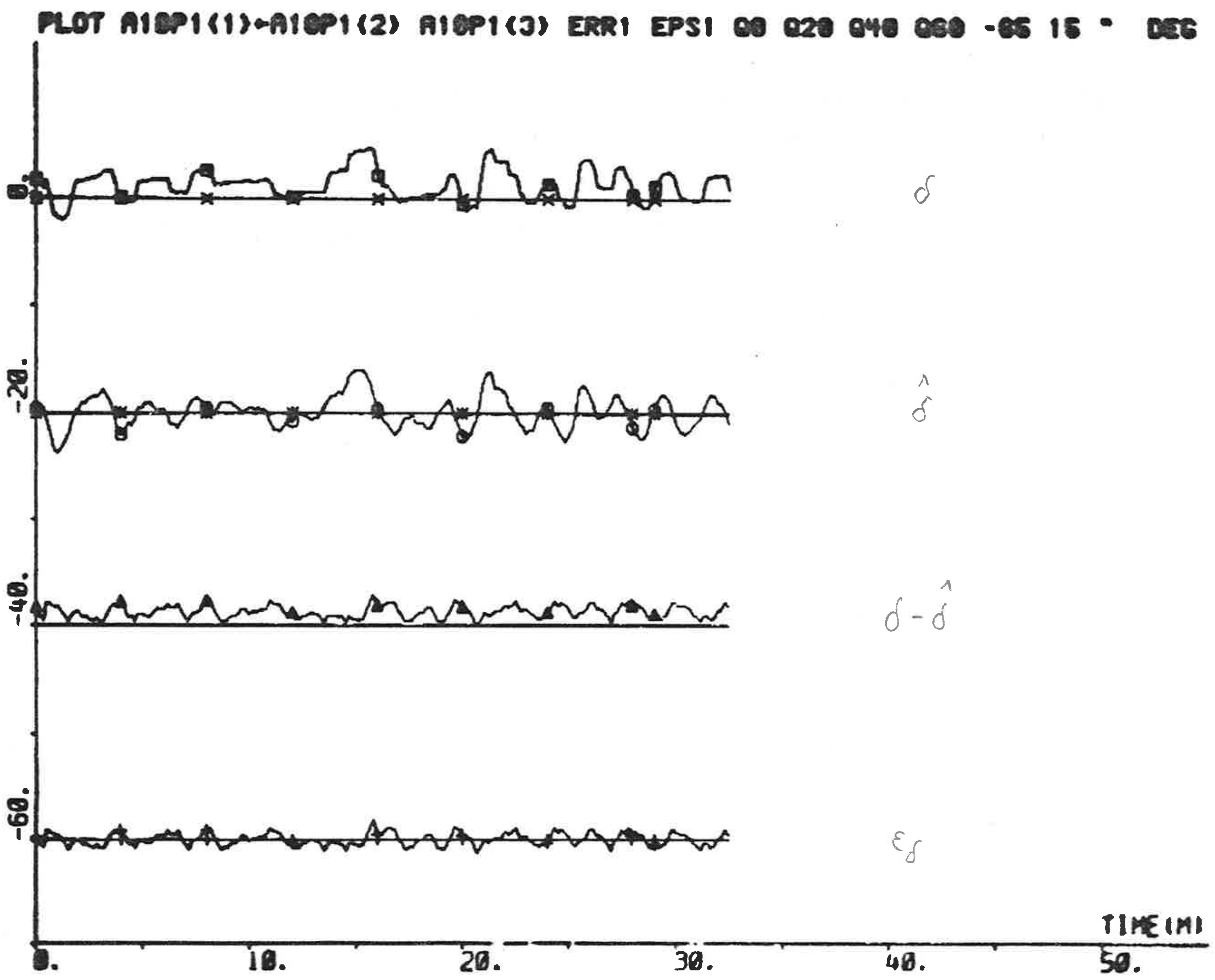


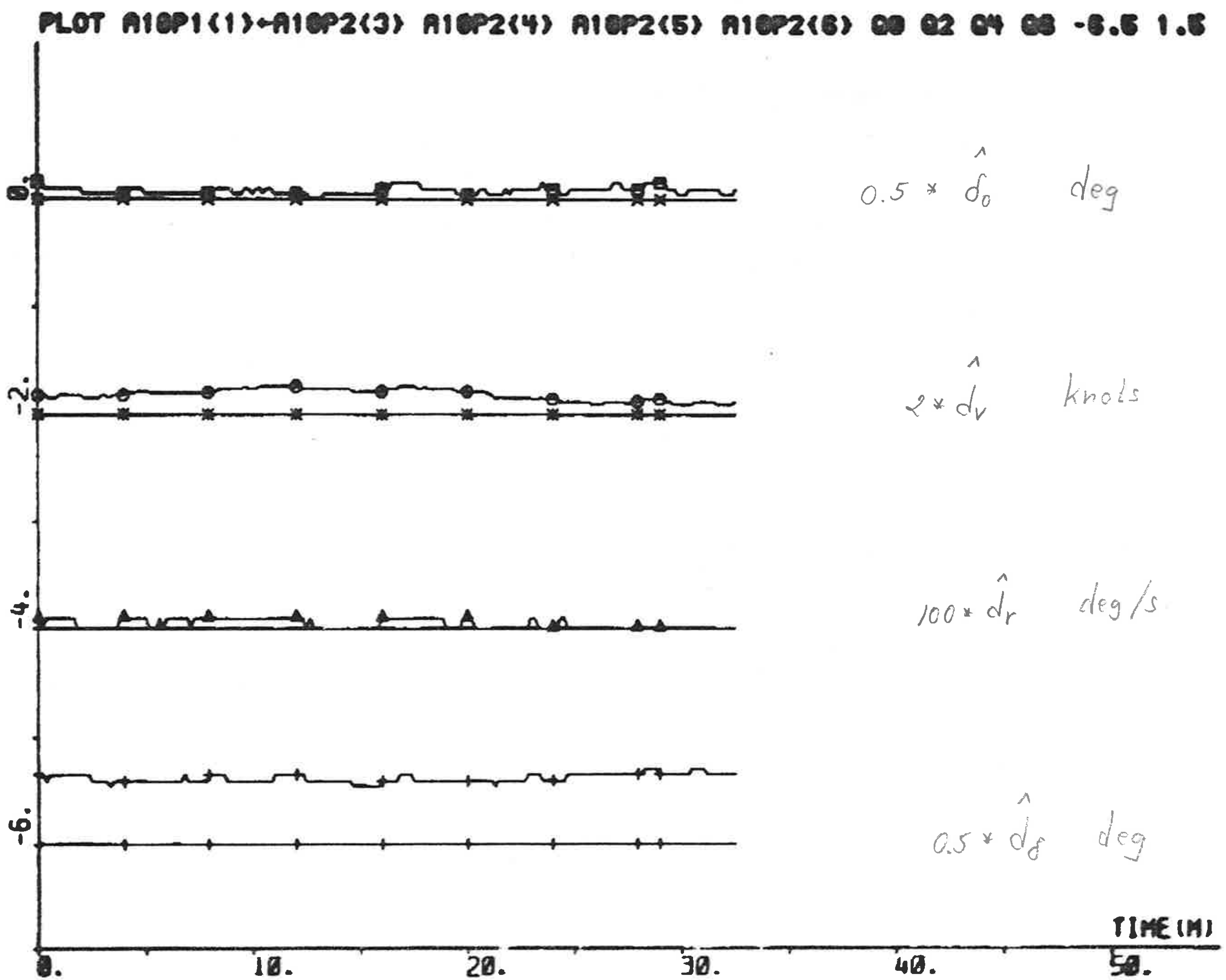

PLOT A10P1(1)-A10P1(4) A10P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_v
TIME(M)
0.
10.
20.
30.
40.
50.

PLOT A10P1(1)-A10P1(6) A10P1(7) ERR3 EPS3 G0 G02 G04 G06 -0.7 0. " DEG/S

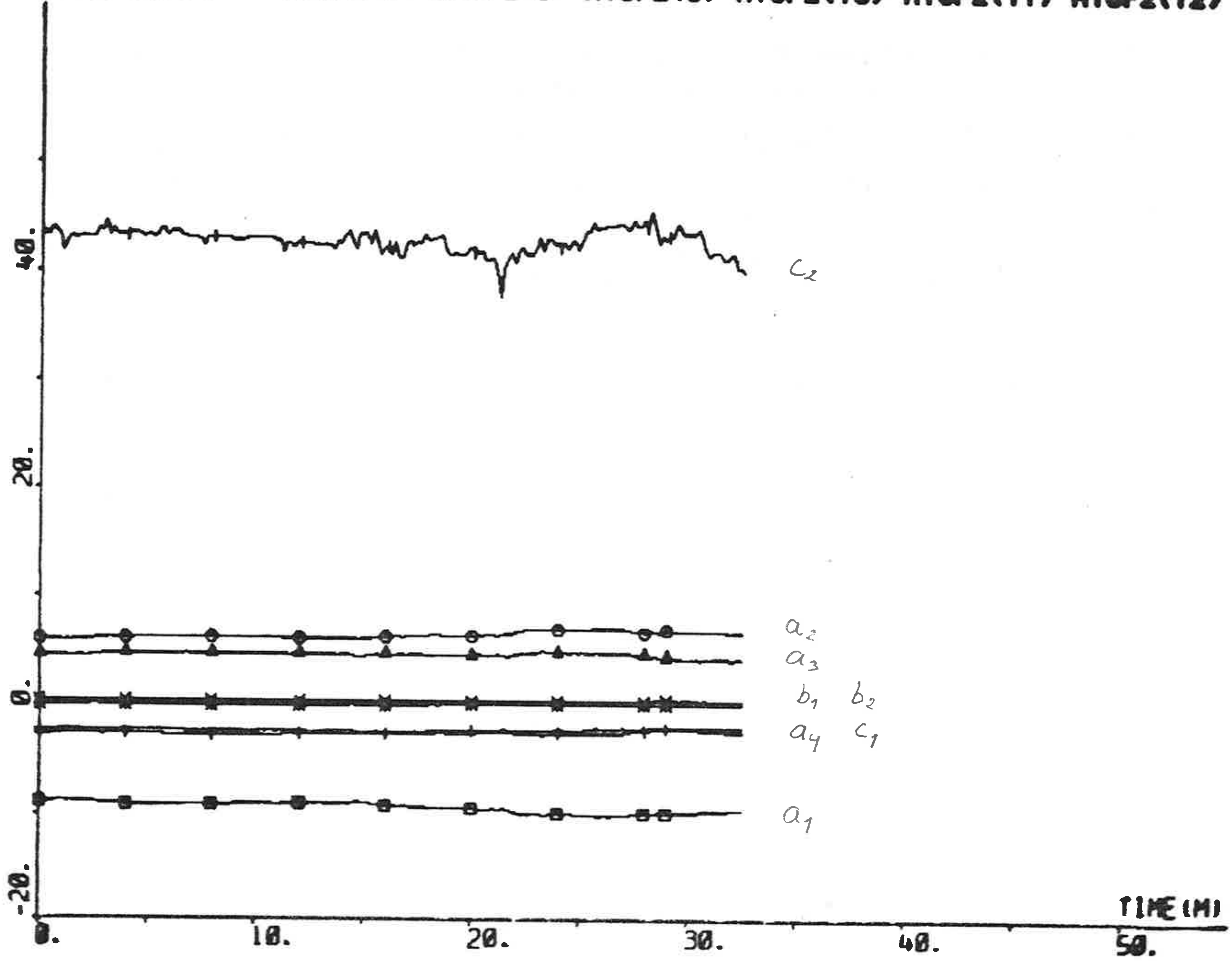



PLOT A10P1(1)-A10P1(8) A10P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 * DEG
0.
-1.
-2.
-3.
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ
TIME(M)
0.
10.
20.
30.
40.
50.


PLOT A10P1(1)-A10P1(2) A10P1(3) ERR1 EPS1 00 020 040 060 -05 15 " DEG
0.
-20.
-40.
-60.
δ
δ̂
δ - δ̂
ε_δ
TIME(M)
0.
10.
20.
30.
40.
50.


PLOT A10P1(1)-A10P2(3) A10P2(4) A10P2(5) A10P2(6) 00 02 04 08 -6.5 1.5
0.
-2.
-4.
-6.
0.5 * $\hat{d}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg
0. 10. 20. 30. 40. 50.
TIME(M)

PLOT A10P1(1)-A10P2(7) A10P2(8) A10P2(9) A10P2(10) A10P2(11) A10P2(12) A1



EXPERIMENT A11

Date	1976-04-23	Forward draught	8.5 m
Time	13.06	Aft draught	12.5 m
Duration	24 min	Wind direction	NW (5; see App. A)
Position	N 06°48' W 15°57'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	145 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 $k = 6$ $q = 0.05$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -9.16 \\ 6.39 \\ 4.29 \\ -1.86 \\ 0.46 \\ 0.22 \\ -2.60 \\ 37.18 \end{bmatrix} \qquad P = \begin{bmatrix} 5.17 & & & & & & & \\ -6.49 & 13.13 & & & & & & \\ -0.84 & -6.88 & 14.72 & & & & & \\ 2.41 & 0.01 & -7.29 & 5.08 & & & & \\ -0.11 & -0.12 & 0.39 & -0.16 & 0.03 & & & \\ -0.07 & 0.04 & -0.04 & 0.08 & 0.00 & 0.02 & & \\ -0.95 & 1.32 & 0.35 & -0.75 & 0.00 & -0.02 & 0.83 & \\ 15.49 & -16.91 & -15.74 & 15.85 & -0.33 & -0.51 & 12.37 & 860.40 \end{bmatrix}$$

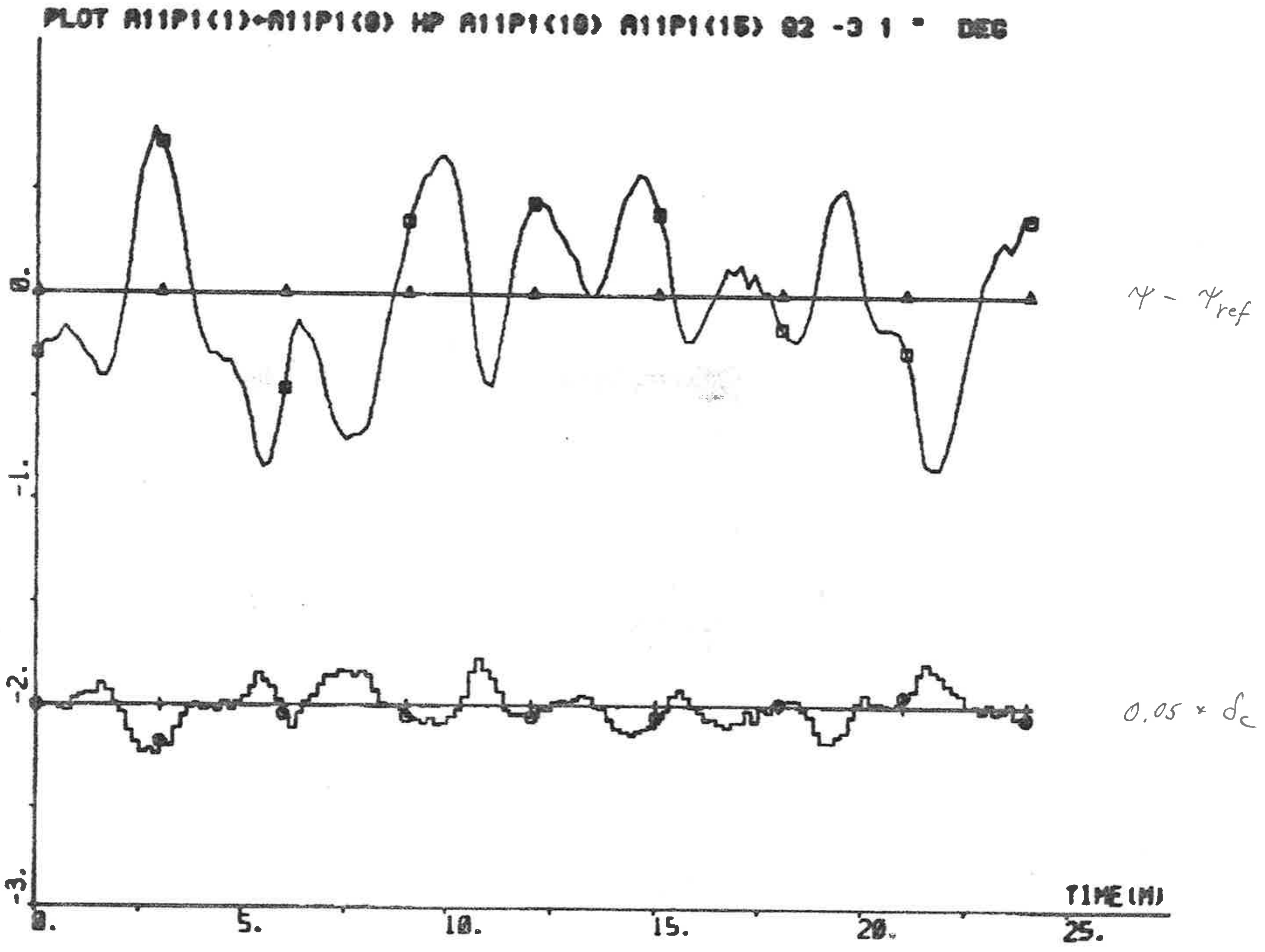
$a_1 + a_2 + a_3 + a_4 = -0.34$

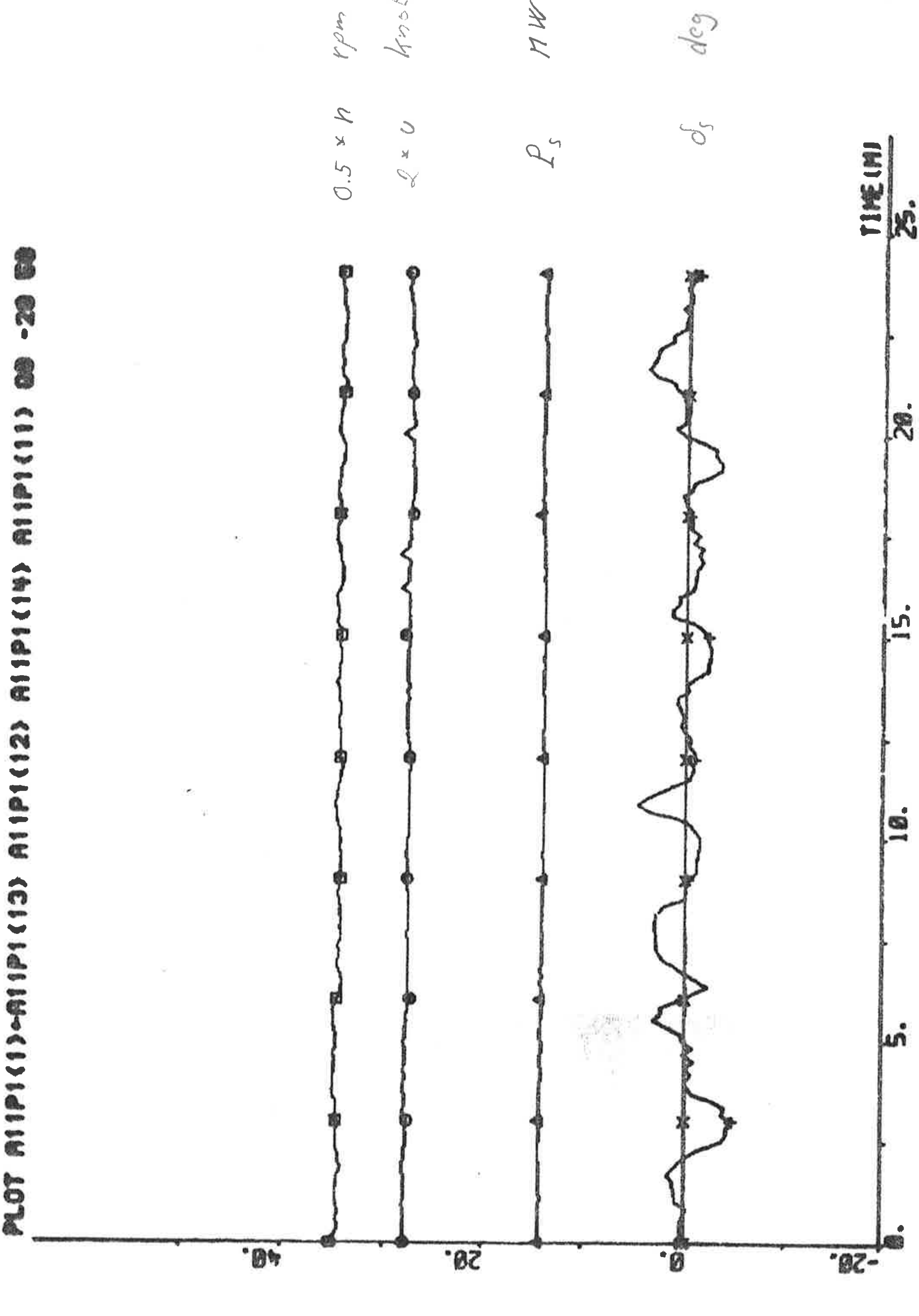
$\hat{\delta}_0 = 0.2$ deg $\hat{d}_v = 0.06$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

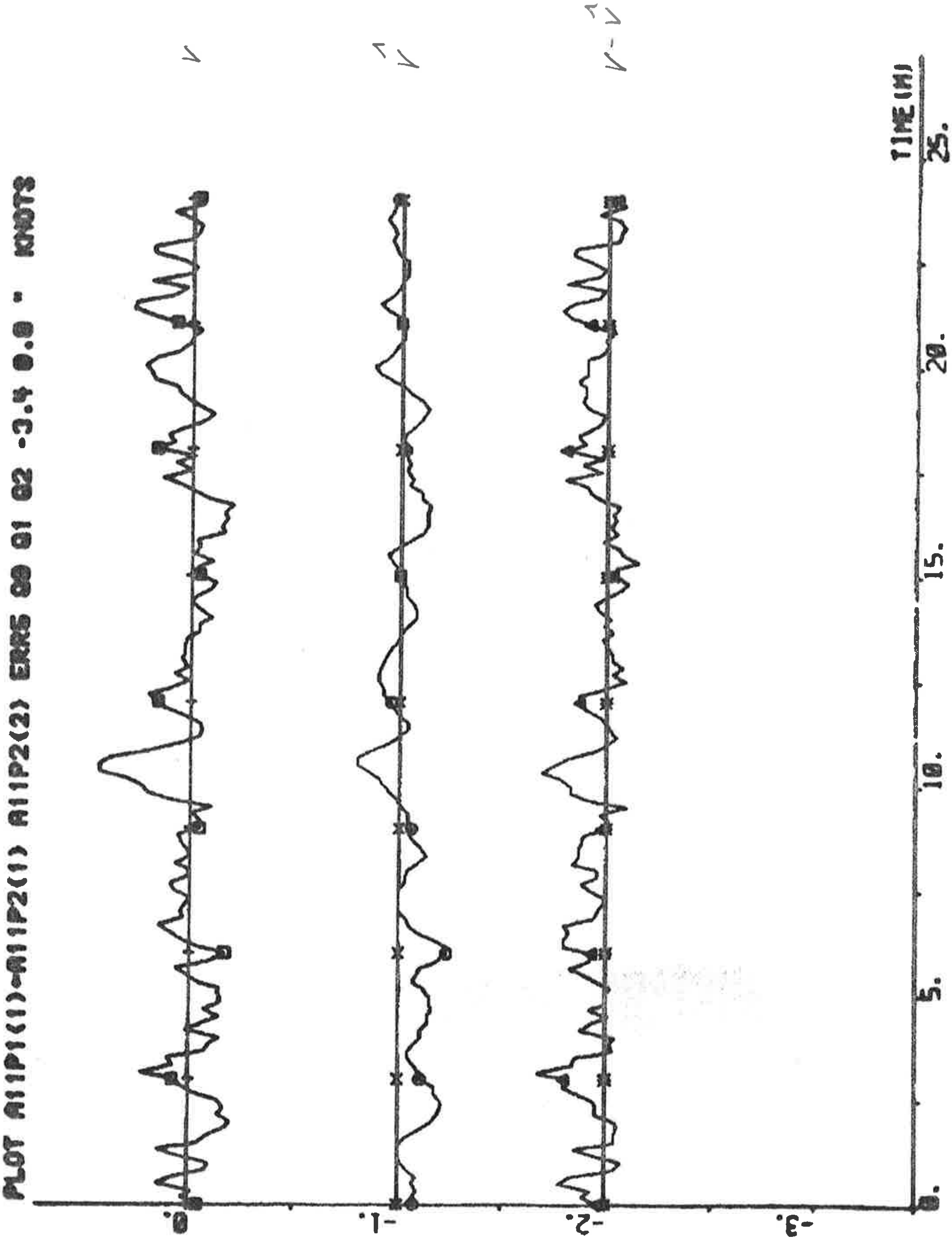
Statistics (mean value and standard deviation)

δ_c	-0.06 ± 1.79 deg	P_s	14.2 ± 0.1 MW
δ	1.33 ± 1.61 deg	ε_v	0.00 ± 0.02 knots
$\psi-\psi_{ref}$	-0.033 ± 0.400 deg	ε_r	0.00 ± 0.02 deg/s
n	69.2 ± 0.4 rpm	ε_ψ	0.00 ± 0.03 deg
u	13.9 ± 0.1 knots	ε_δ	0.1 ± 0.6 deg

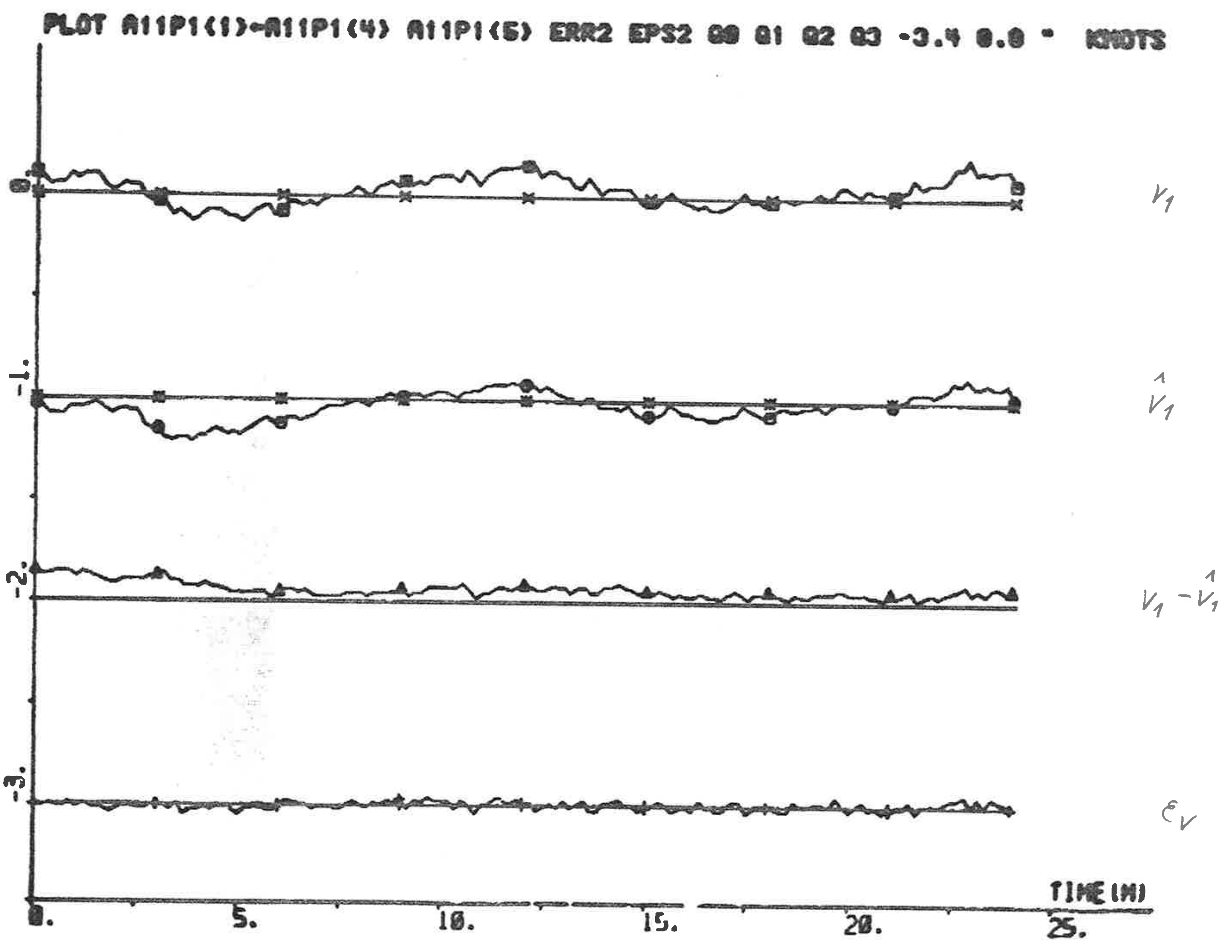
$V_1 = 0.428$

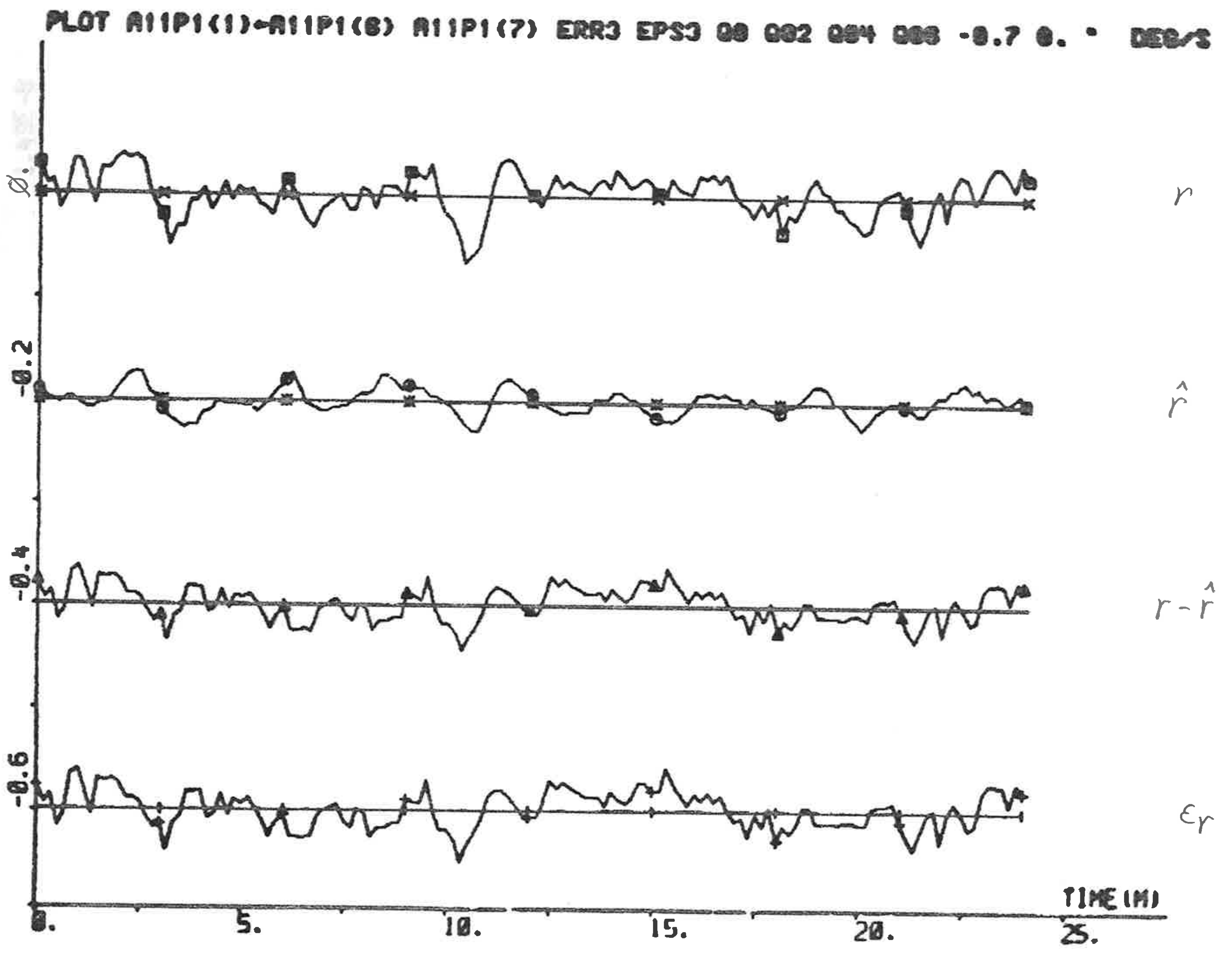

PLOT A11P1(1)+A11P1(8) HP A11P1(10) A11P1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 × δc

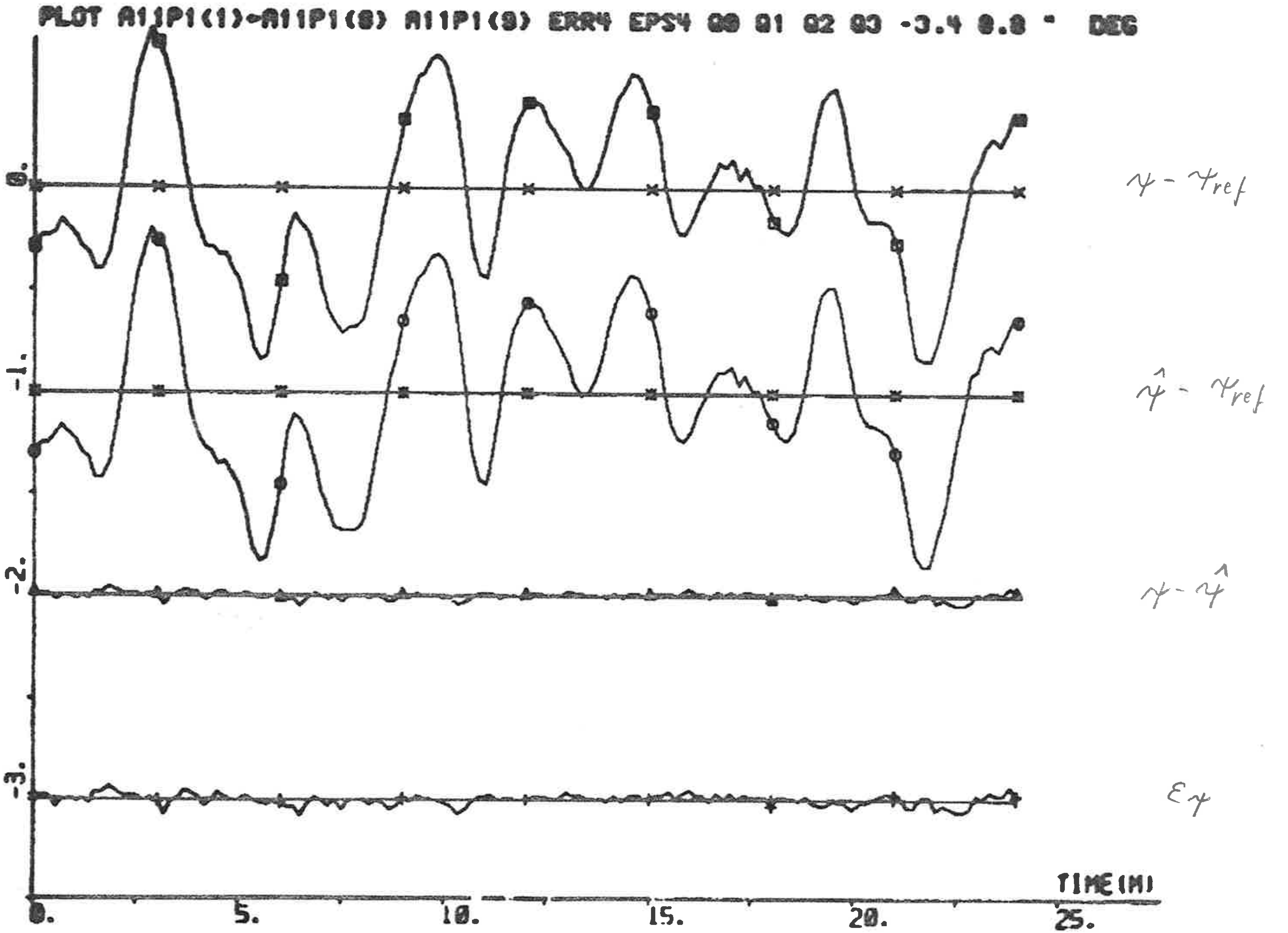

PLOT A11P1(1)-A11P1(13) A11P1(12) A11P1(14) A11P1(11) 00 -20 00
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 × n rpm
2 × v knots
P_s MW
δ_s deg

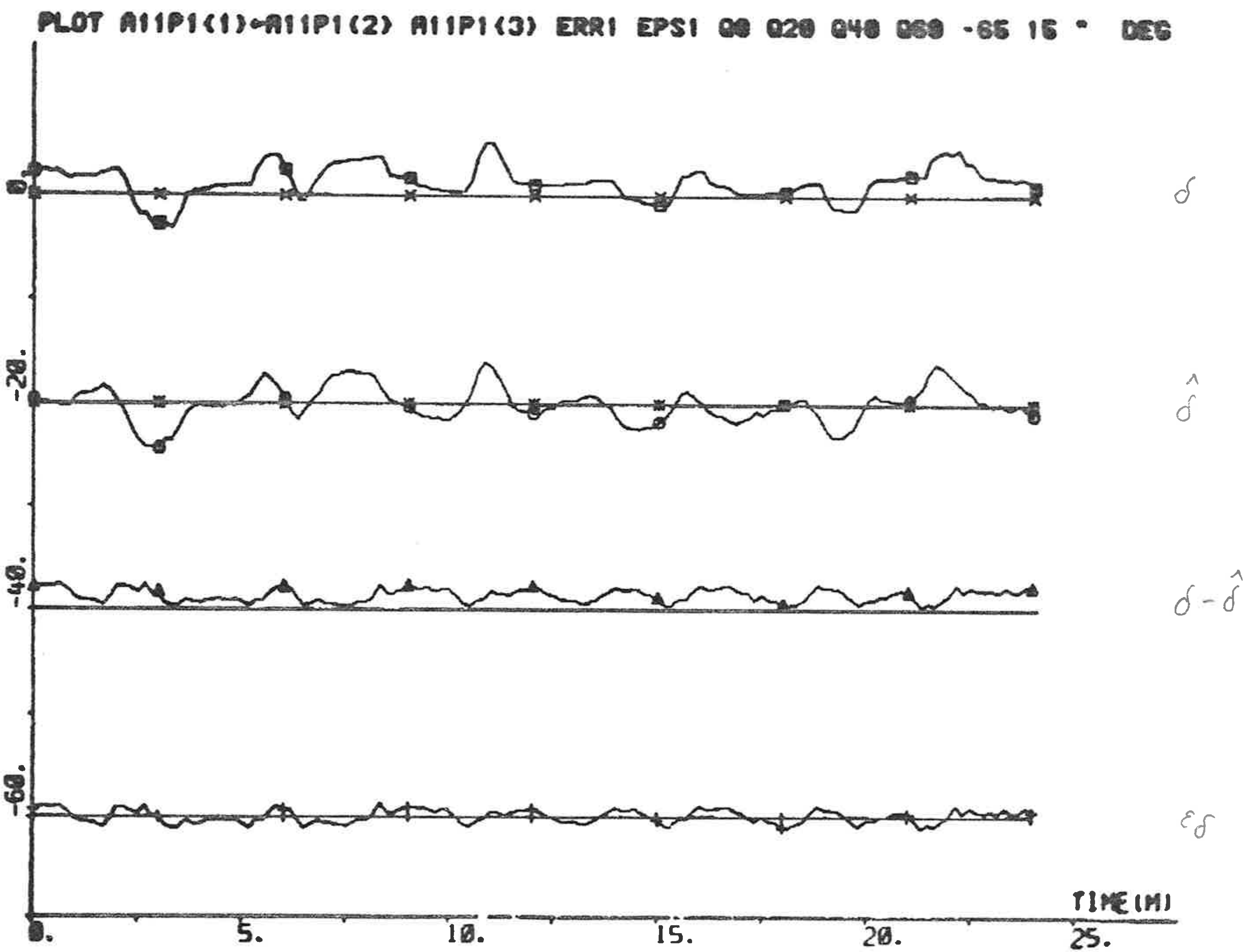


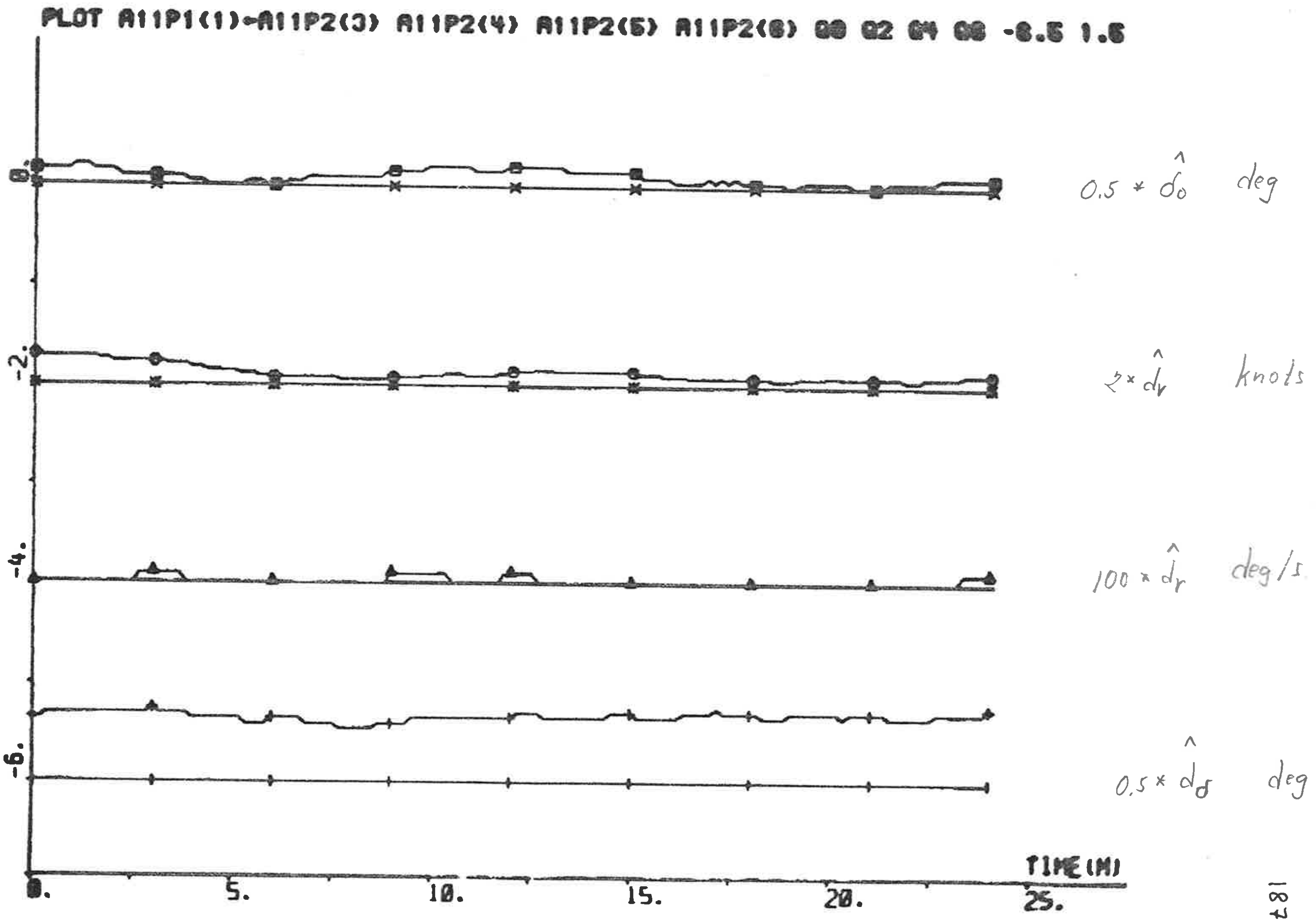
PLOT A11P1(1)-A11P2(1) A11P2(2) ERRS 00 01 02 -3.4 0.0 * KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(H)

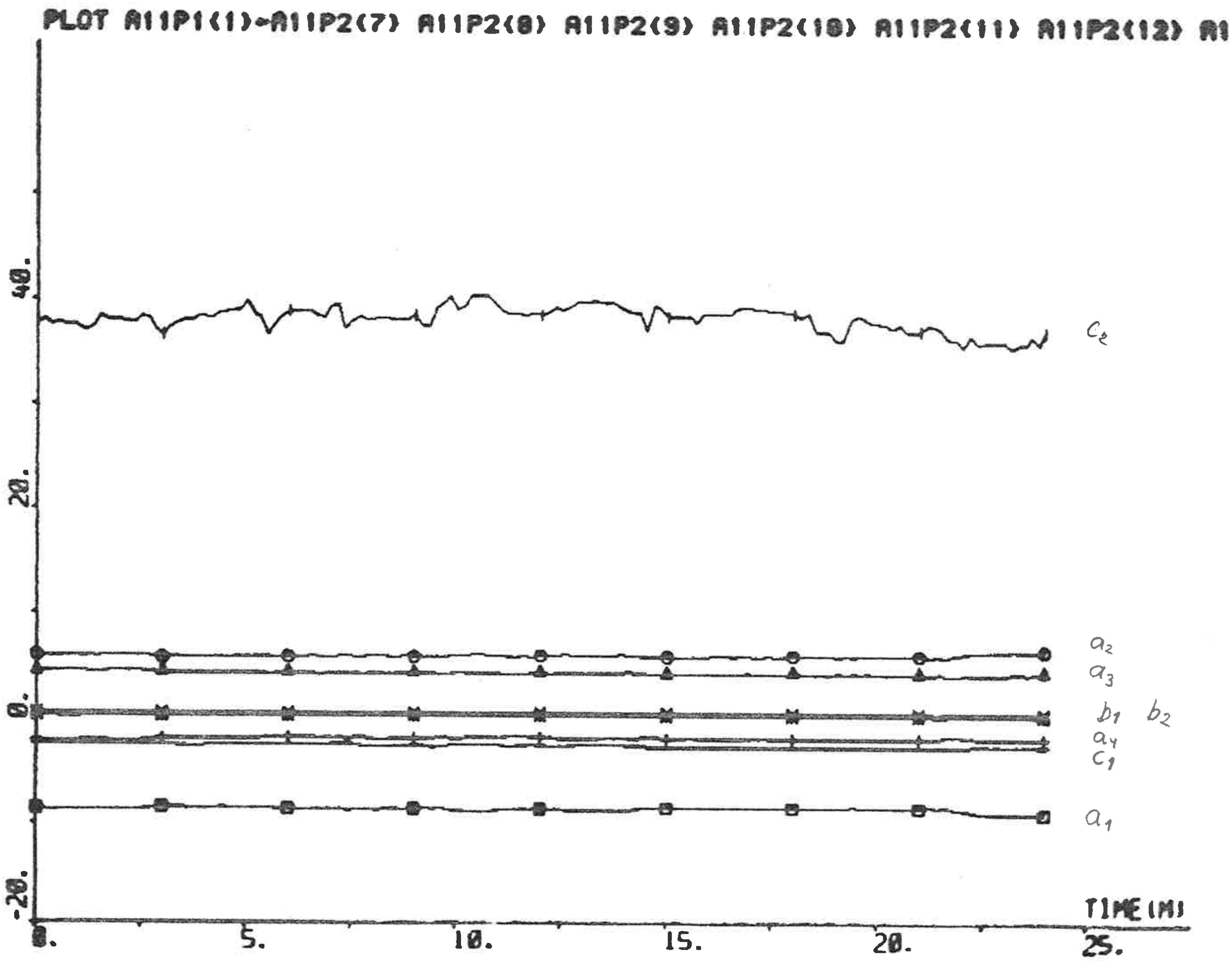

PLOT A11P1(1)-A11P1(4) A11P1(5) ERR2 EPS2 G0 G1 G2 G3 -3.4 0.0 * KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME (H)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT A11P1(1)-A11P1(6) A11P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. * DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME (M)
0.
5.
10.
15.
20.
25.


PLOT A11P1(1)-A11P1(8) A11P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A11P1(1)-A11P1(2) A11P1(3) ERR1 EPS1 Q0 Q20 Q40 Q60 -65 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂
εδ


PLOT A11P1(1)=A11P2(3) A11P2(4) A11P2(5) A11P2(6) 00 02 04 06 -6.5 1.6
0.
-2.
-4.
-6.
0.5 * d̂o deg
2 * d̂v knots
100 * d̂r deg/s
0.5 * d̂δ deg
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A11P1(1)-A11P2(7) A11P2(8) A11P2(9) A11P2(10) A11P2(11) A11P2(12) A1
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
c2
a2
a3
b1
b2
a4
c1
a1

EXPERIMENT A12

Date	1976-04-23	Forward draught	8.5 m
Time	14.09	Aft draught	12.5 m
Duration	26 min	Wind direction	N (5; see App. A)
Position	N 06°35' W 15°48'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	145 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 k = 6 q = 0.1

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.73 \\ 7.02 \\ 4.66 \\ -3.33 \\ 0.29 \\ 0.08 \\ -2.89 \\ 44.49 \end{bmatrix} \qquad P = \begin{bmatrix} 5.36 & & & & & & & \\ -6.80 & 13.38 & & & & & & \\ -0.84 & -6.55 & 14.33 & & & & & \\ 2.47 & -0.08 & -7.15 & 4.95 & & & & \\ -0.10 & -0.10 & 0.37 & -0.16 & 0.03 & & & \\ -0.10 & 0.09 & -0.05 & 0.06 & 0.00 & 0.03 & & \\ -1.01 & 1.34 & 0.26 & -0.58 & -0.01 & 0.01 & 0.92 & \\ 18.54 & -24.21 & -13.08 & 17.88 & -0.34 & -0.27 & 12.52 & 915.41 \end{bmatrix}$$

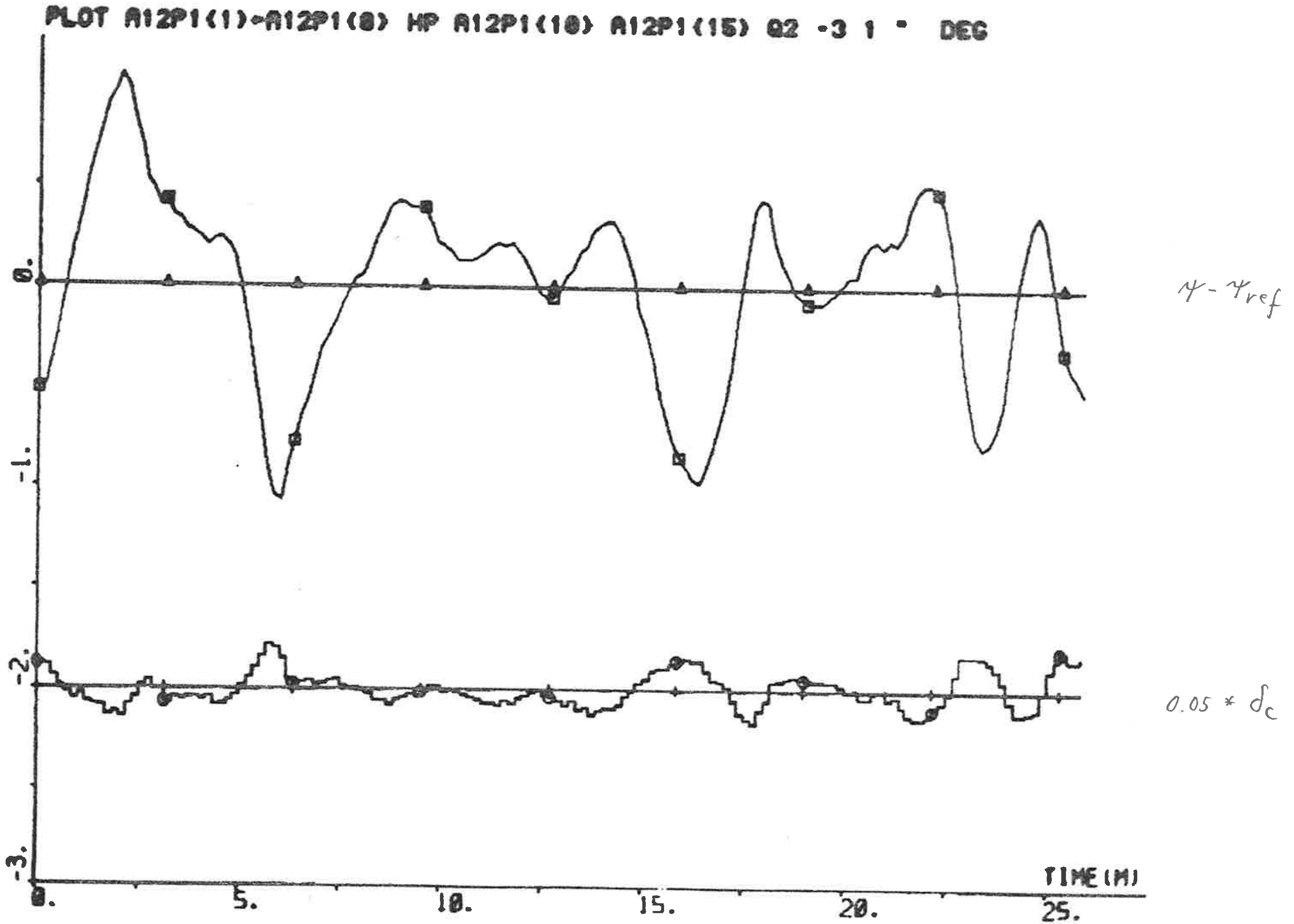
$a_1 + a_2 + a_3 + a_4 = -0.38$

$\hat{\delta}_0 = 0.3$ deg $\hat{d}_v = 0.07$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.3$ deg

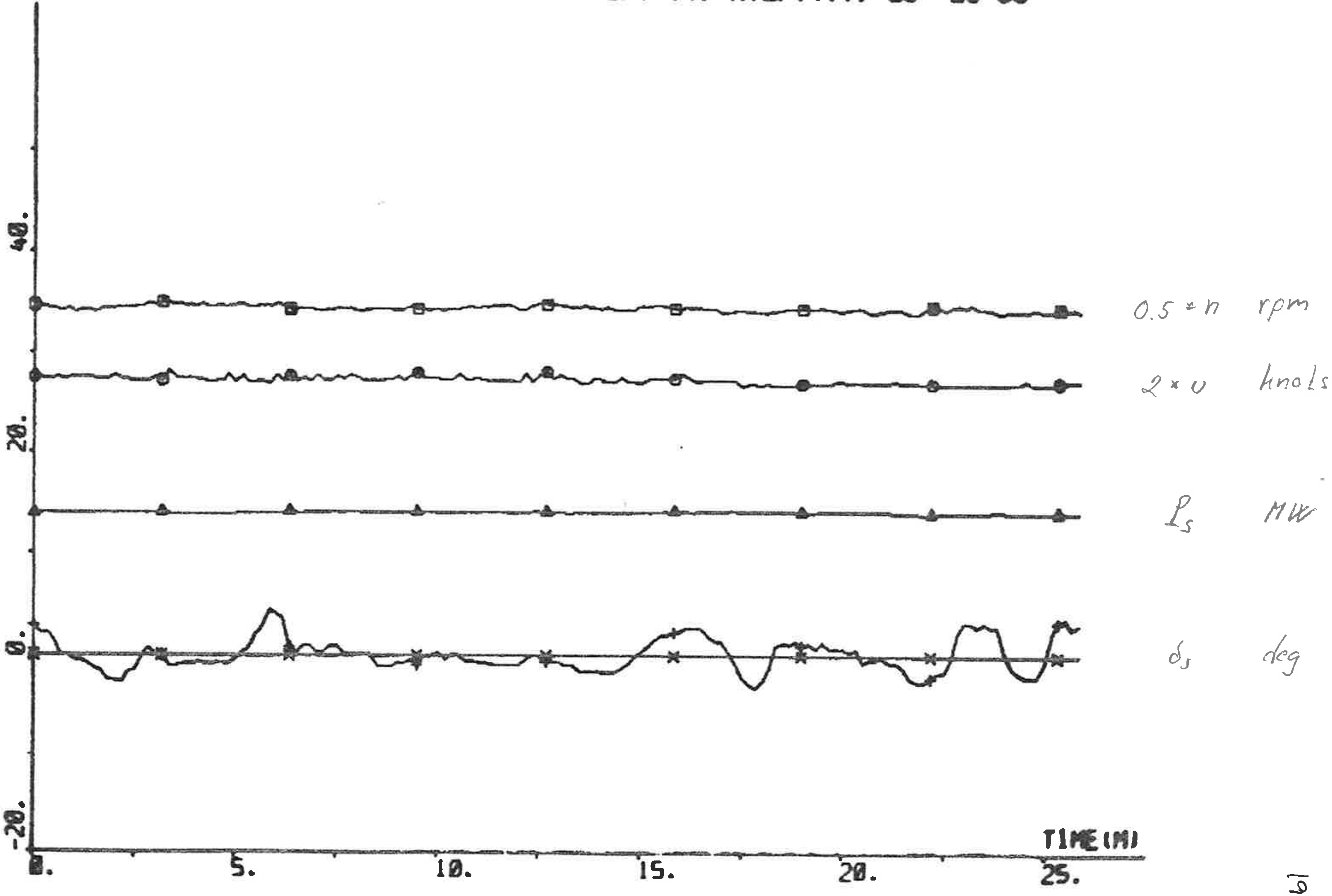
Statistics (mean value and standard deviation)

δ_c	0.05 ± 1.69 deg		P_s	14.2 ± 0.1 MW
δ	1.48 ± 1.41 deg		ε_v	0.00 ± 0.02 knots
$\psi-\psi_{ref}$	0.013 ± 0.444 deg		ε_r	0.00 ± 0.02 deg/s
n	69.2 ± 0.4 rpm		ε_ψ	0.00 ± 0.02 deg
u	13.7 ± 0.1 knots		ε_δ	0.1 ± 0.7 deg

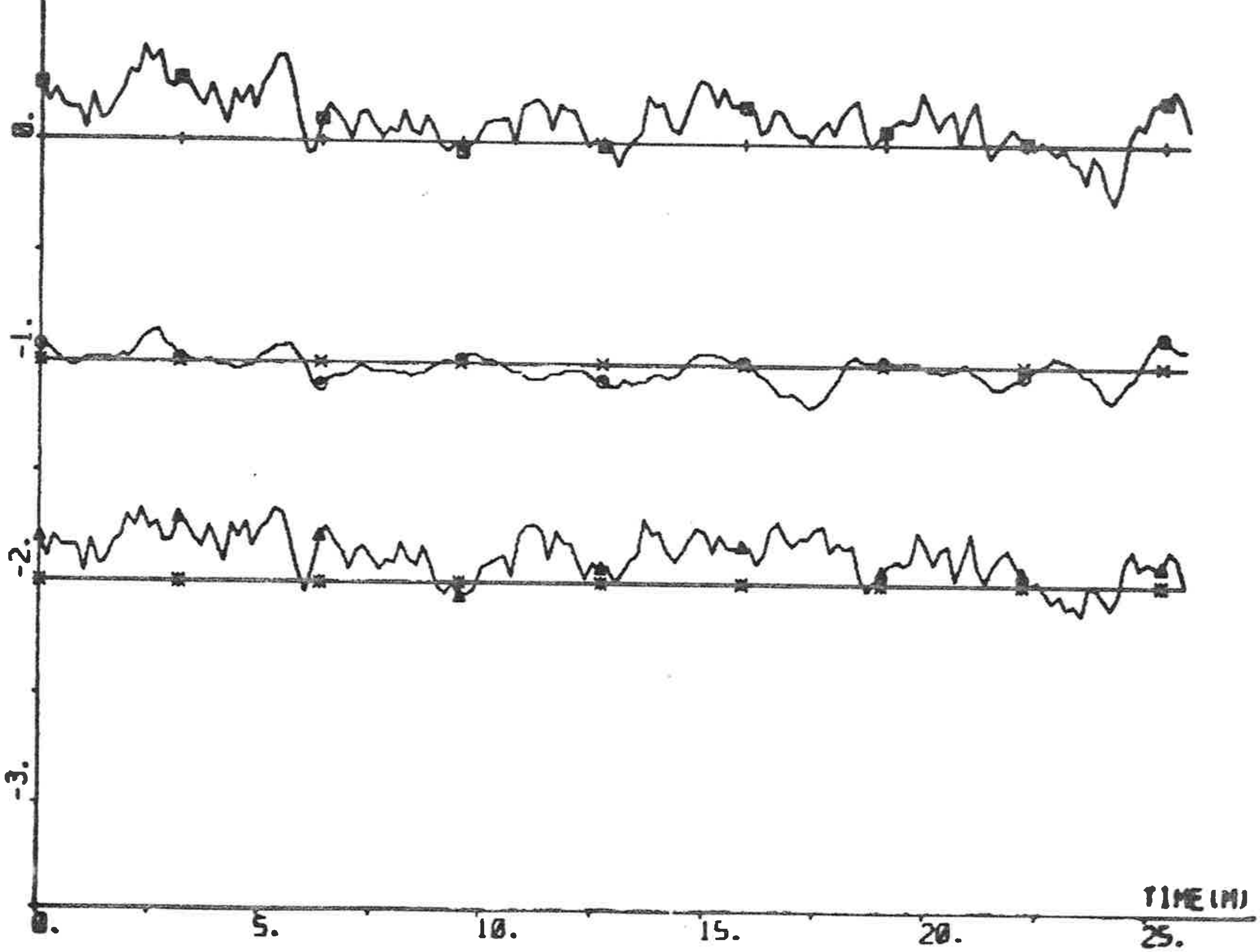
$V_1 = 0.435$

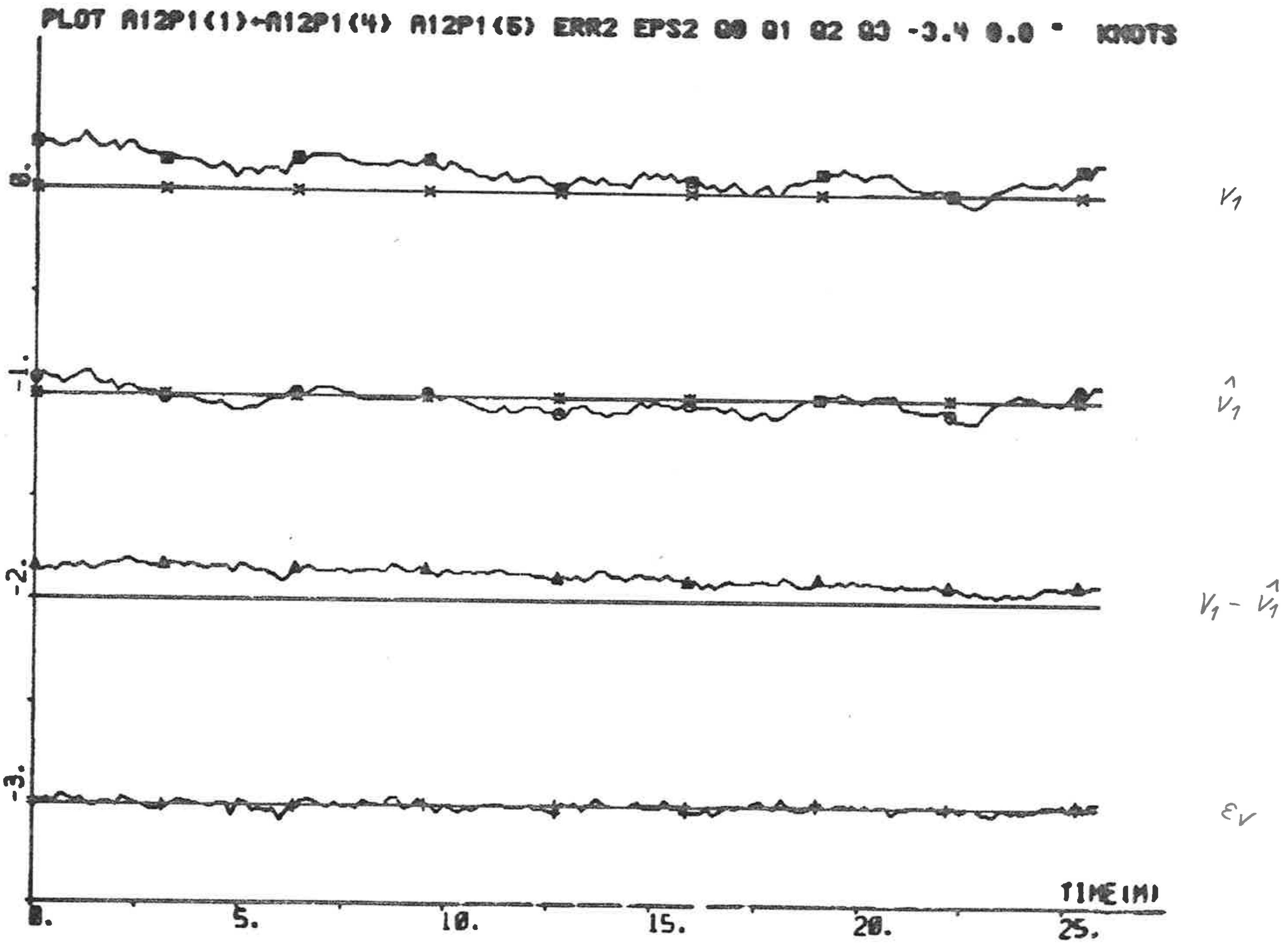

PLOT A12P1(1)-A12P1(8) HP A12P1(10) A12P1(15) Q2 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

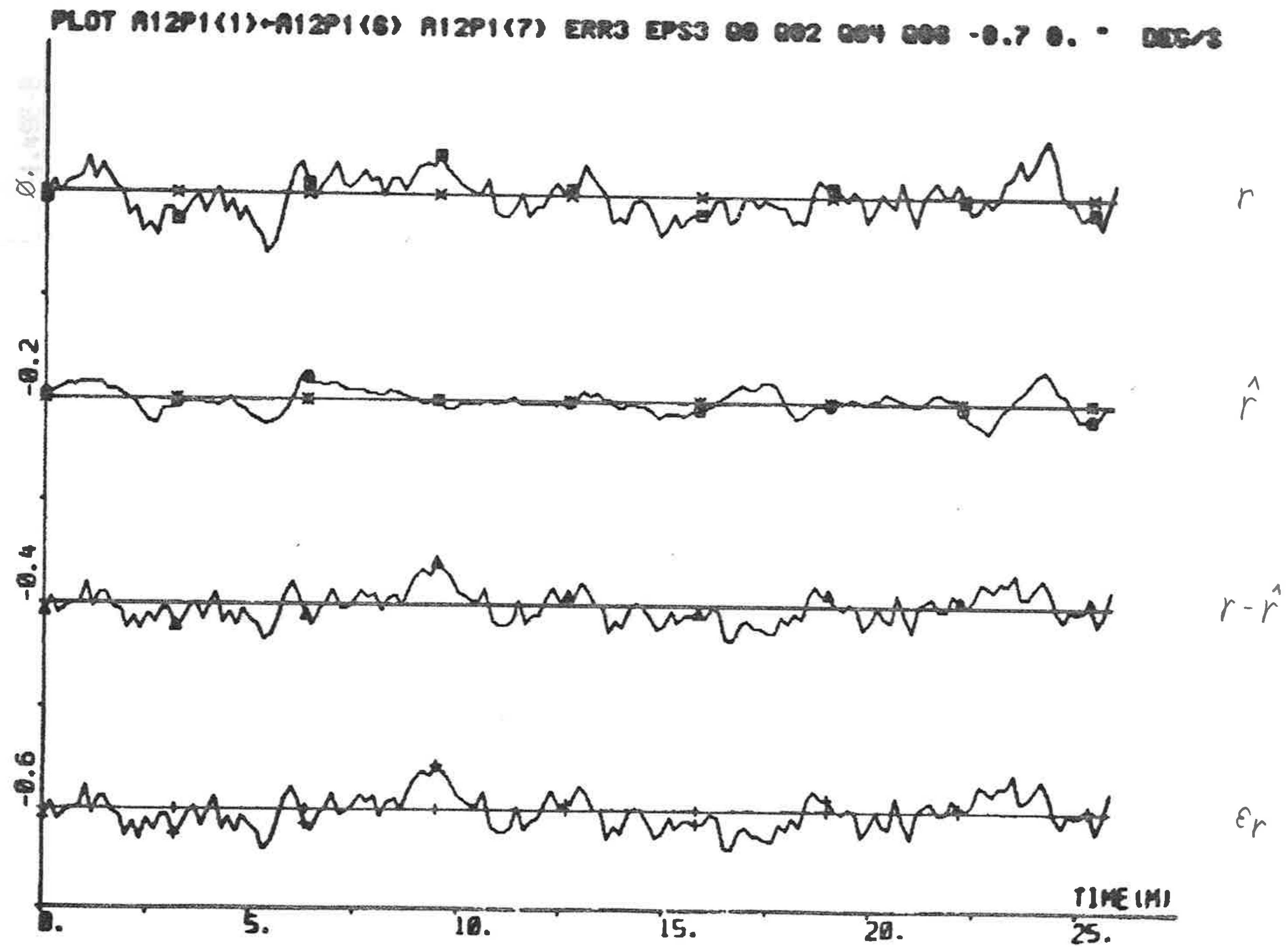
PLOT A12P1(1)-A12P1(13) A12P1(12) A12P1(14) A12P1(11) 00 -20 50



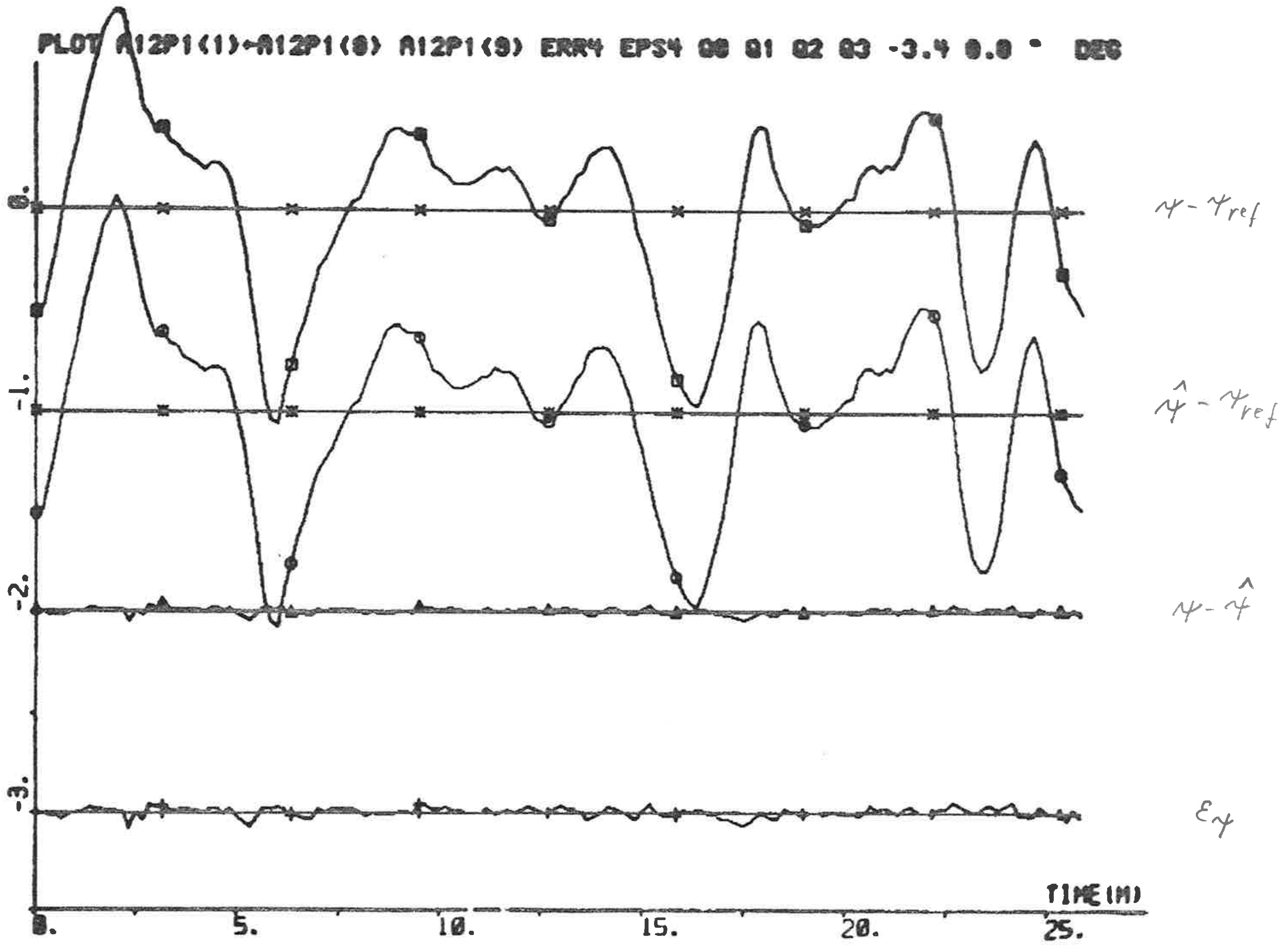
PLOT A12P1(1)+A12P2(1) A12P2(2) ERRS G0 G1 G2 -3.4 0.0 " KNOTS

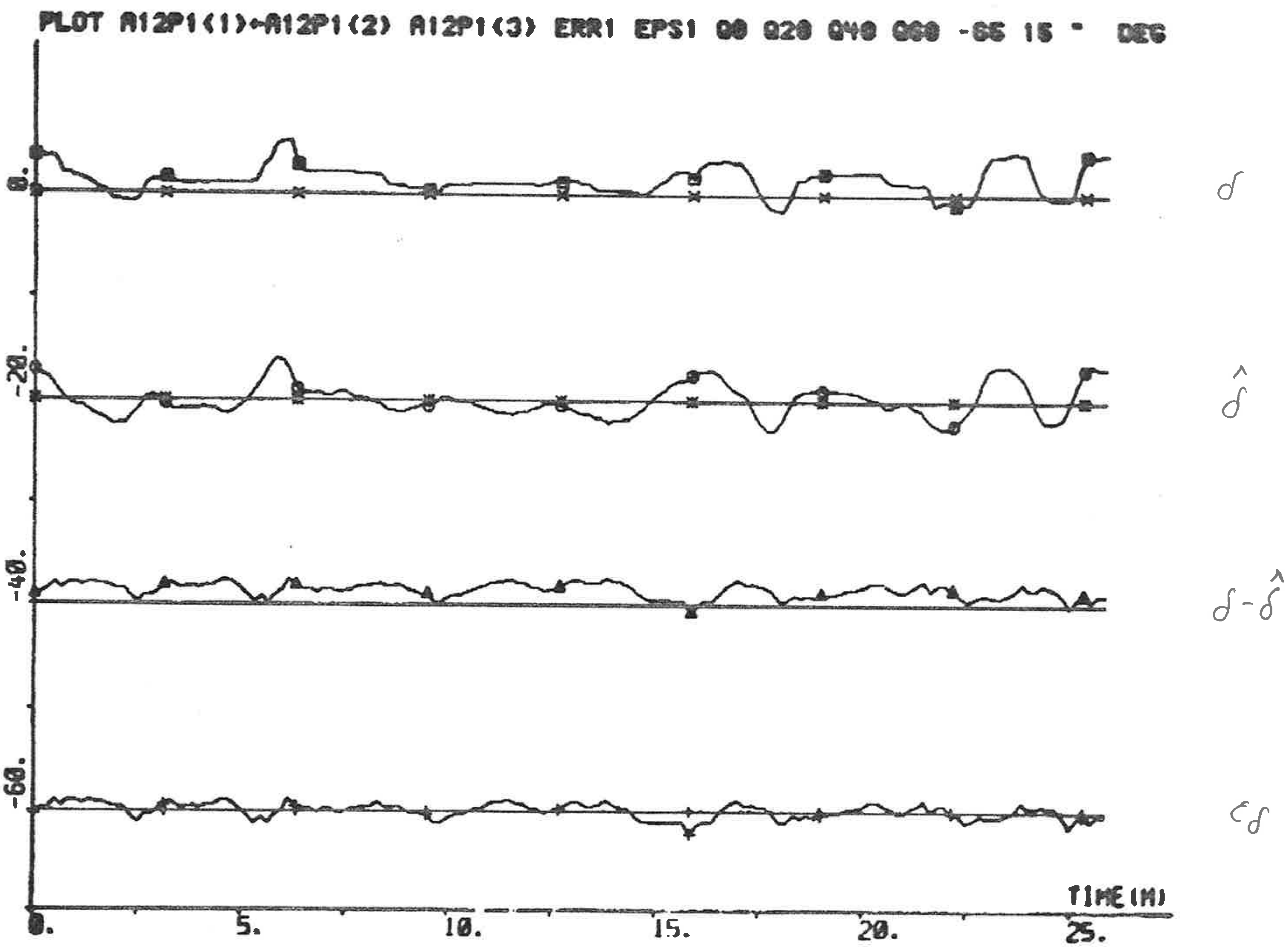


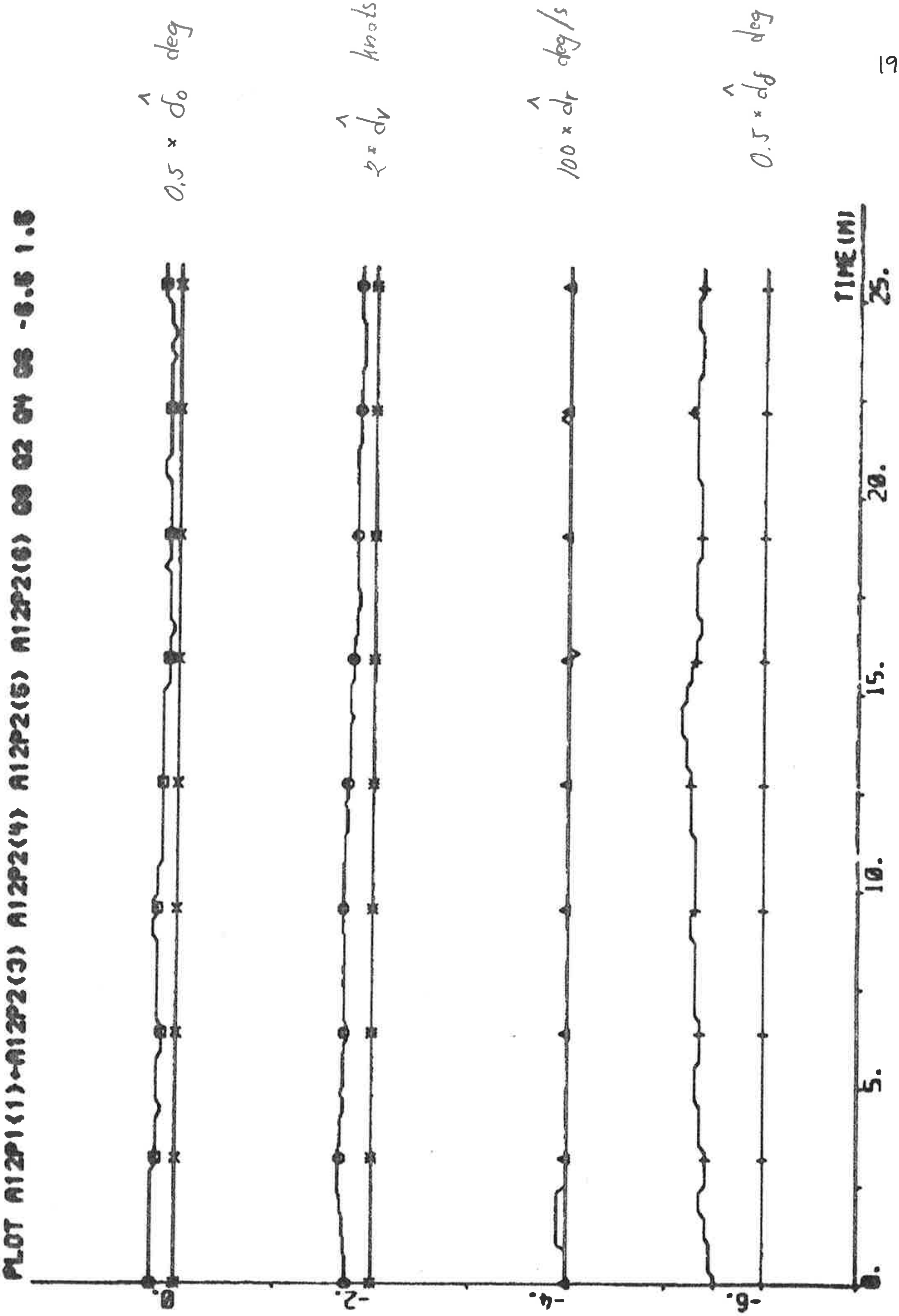

PLOT A12P1(1)+A12P1(4) A12P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V

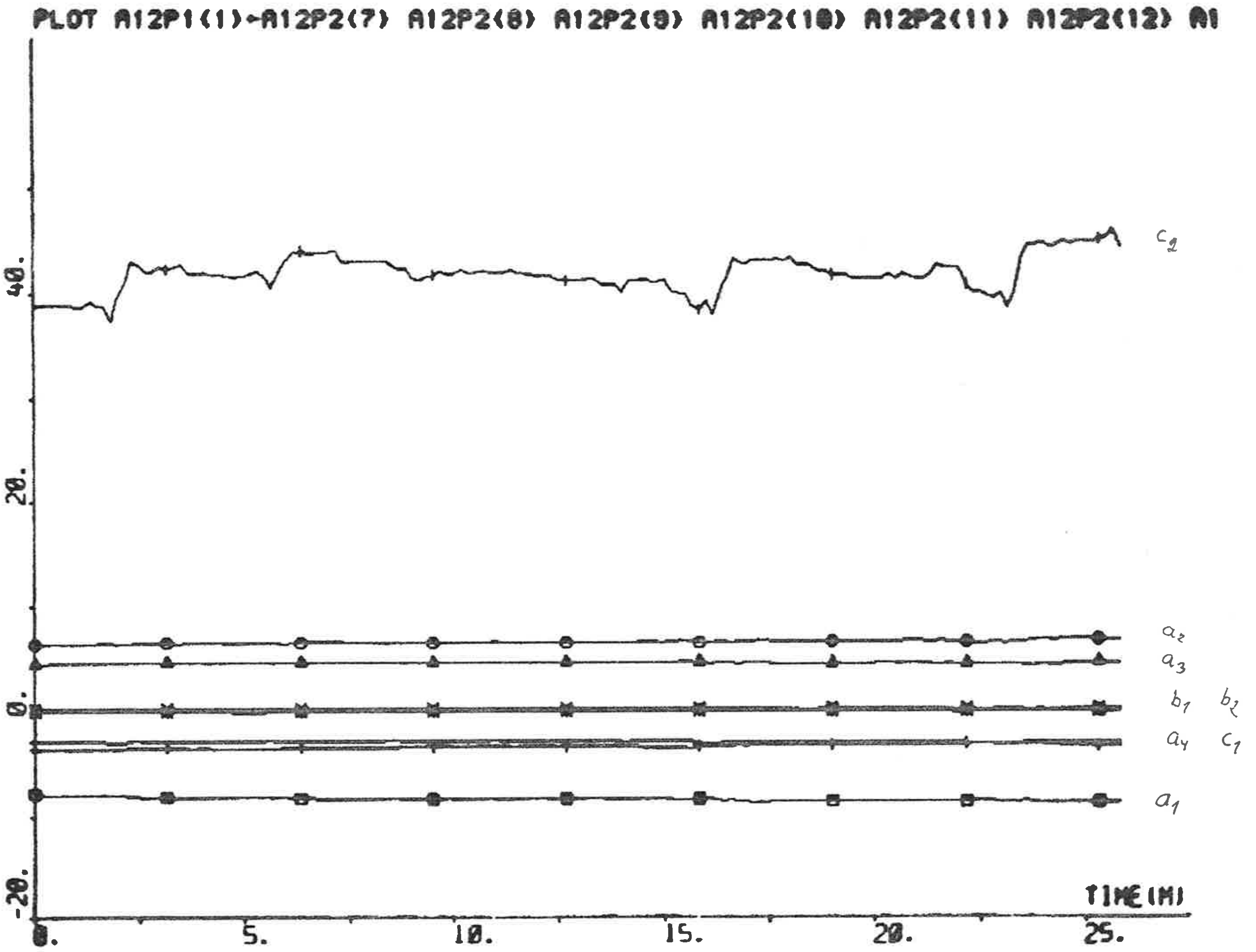


PLOT A12P1(1)-A12P1(6) A12P1(7) ERR3 EPS3 00 002 004 008 -0.7 0. " DEG/S
Ø.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂
εr


PLOT A12P1(1)-A12P1(8) A12P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A12P1(1)-A12P1(2) A12P1(3) ERR1 EPS1 00 020 040 060 -65 15 " DEG
0.
-20.
-40.
-60.
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A12P1(1)-A12P2(3) A12P2(4) A12P2(5) A12P2(6) 00 02 04 06 -6.5 1.5
0.5 × δ̂o deg
2 × d̂v knots
100 × d̂r deg/s
0.5 × d̂f deg
0
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A12P1(1)-A12P2(7) A12P2(8) A12P2(9) A12P2(10) A12P2(11) A12P2(12) AI
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
c2
a2
a3
b1
b2
a4
c1
a1

EXPERIMENT A13

Date	1976-04-23	Forward draught	8.5 m
Time	15.16	Aft draught	12.5 m
Duration	24 min	Wind direction	N (6; see App. A)
Position	N 06°23' W 15°39'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	145 deg	Wave height	-

The speed was reduced during the experiment.

<u>Self-tuning regulator using estimates from the Kalman filter.</u>

Tuning time before the experiment started: 30 min

NC1 = 1   NC2 = 1   k = 6   q = 0.2

T_s = 10 s V_0 = 6 m/s   IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -9.65 \\ 6.81 \\ 5.19 \\ -2.67 \\ 0.36 \\ 0.20 \\ -1.29 \\ 44.29 \end{bmatrix} \qquad P = \begin{bmatrix} 7.06 & & & & & & & \\ -8.75 & 17.57 & & & & & & \\ -1.40 & -8.71 & 19.02 & & & & & \\ 3.37 & -0.36 & -9.28 & 6.54 & & & & \\ -0.21 & -0.20 & 0.70 & -0.30 & 0.06 & & & \\ -0.11 & 0.08 & -0.17 & 0.20 & 0.00 & 0.05 & & \\ -1.21 & 1.57 & 0.52 & -0.89 & 0.00 & -0.01 & 1.01 & \\ 28.62 & -39.14 & -13.65 & 22.95 & -0.80 & 0.14 & 11.93 & 1037.62 \end{bmatrix}$$

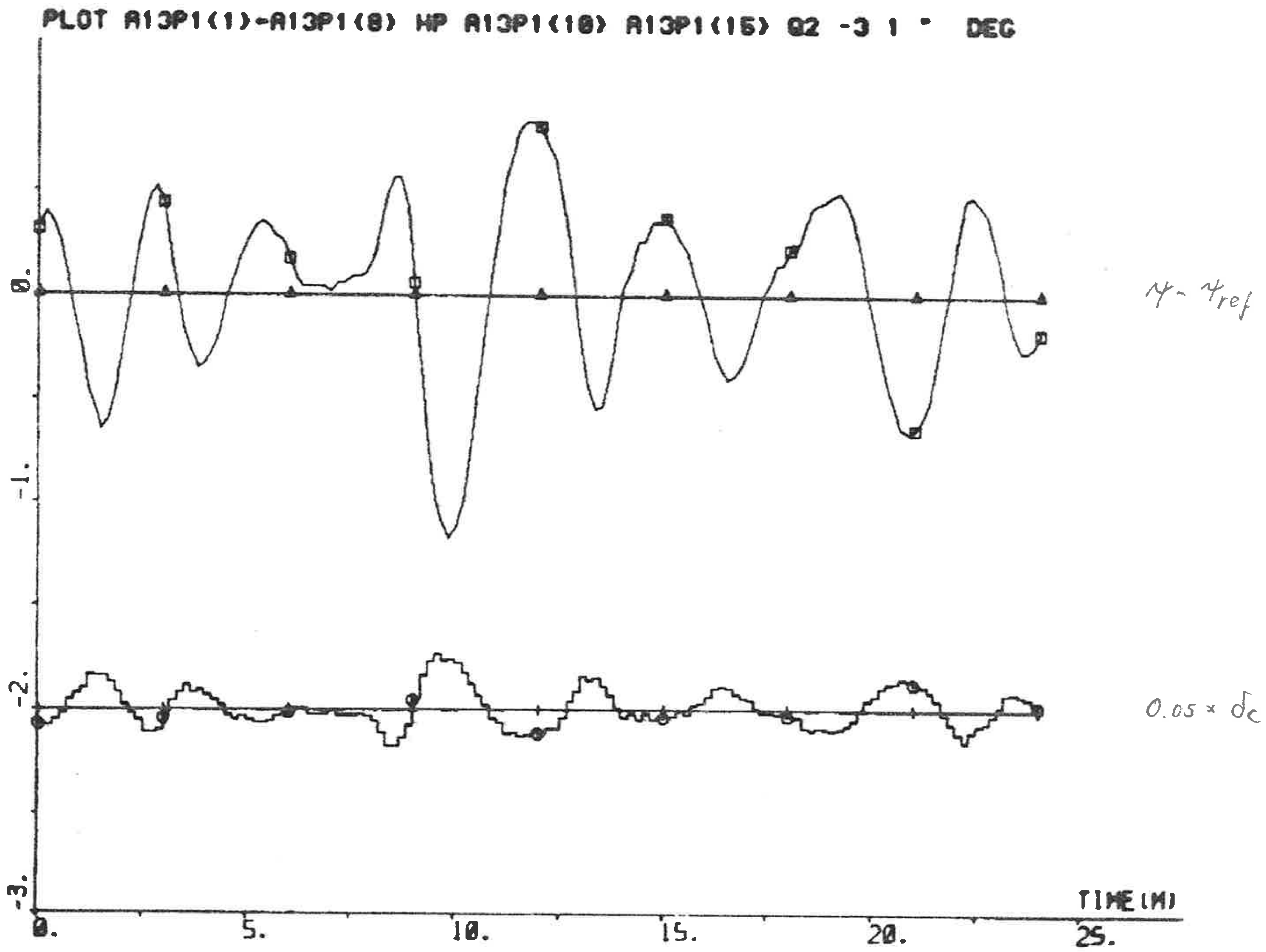
$a_1 + a_2 + a_3 + a_4 = -0.32$

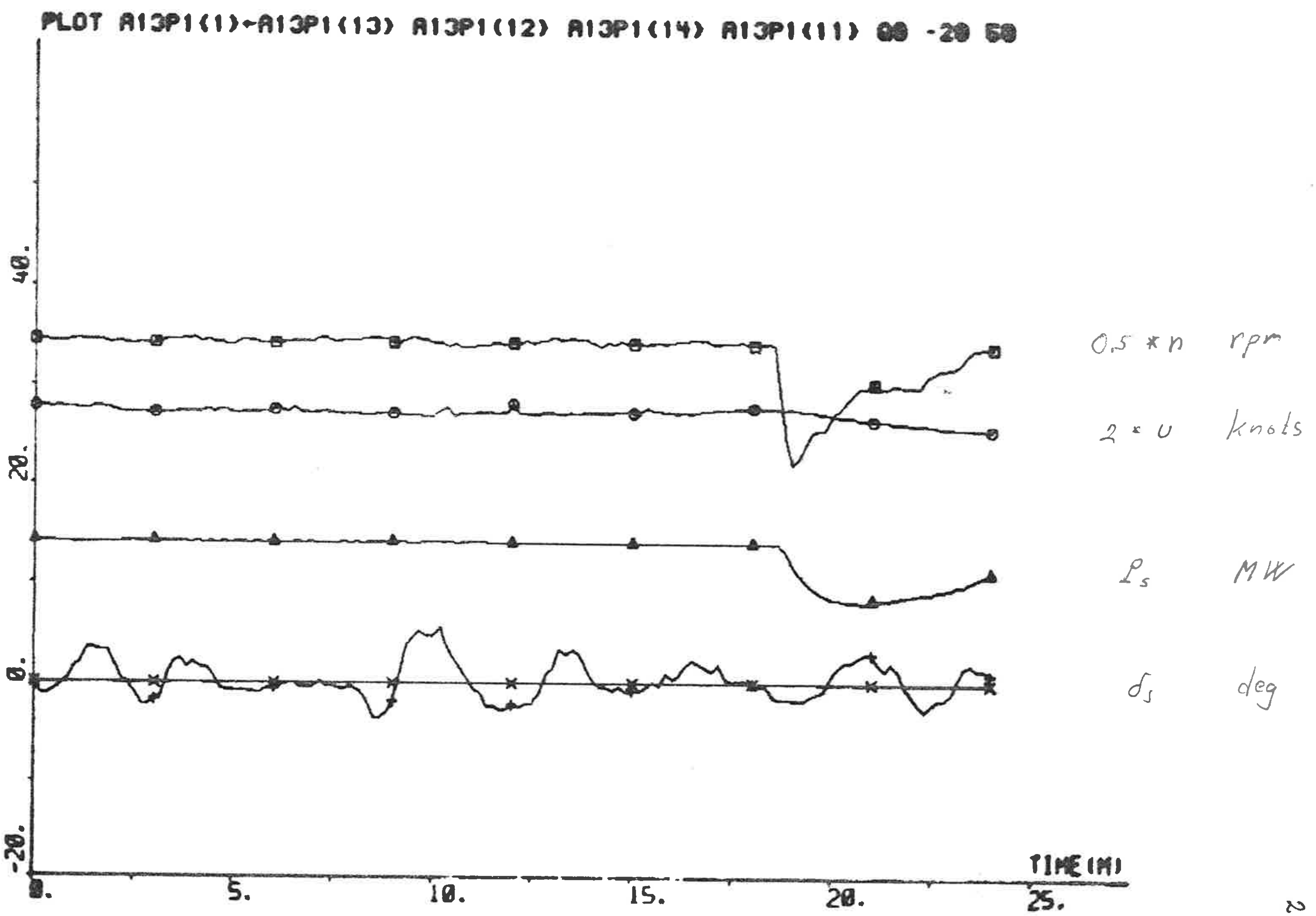
$\hat{\delta}_0 = 0.3$ deg $\hat{d}_v = 0.18$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.3$ deg

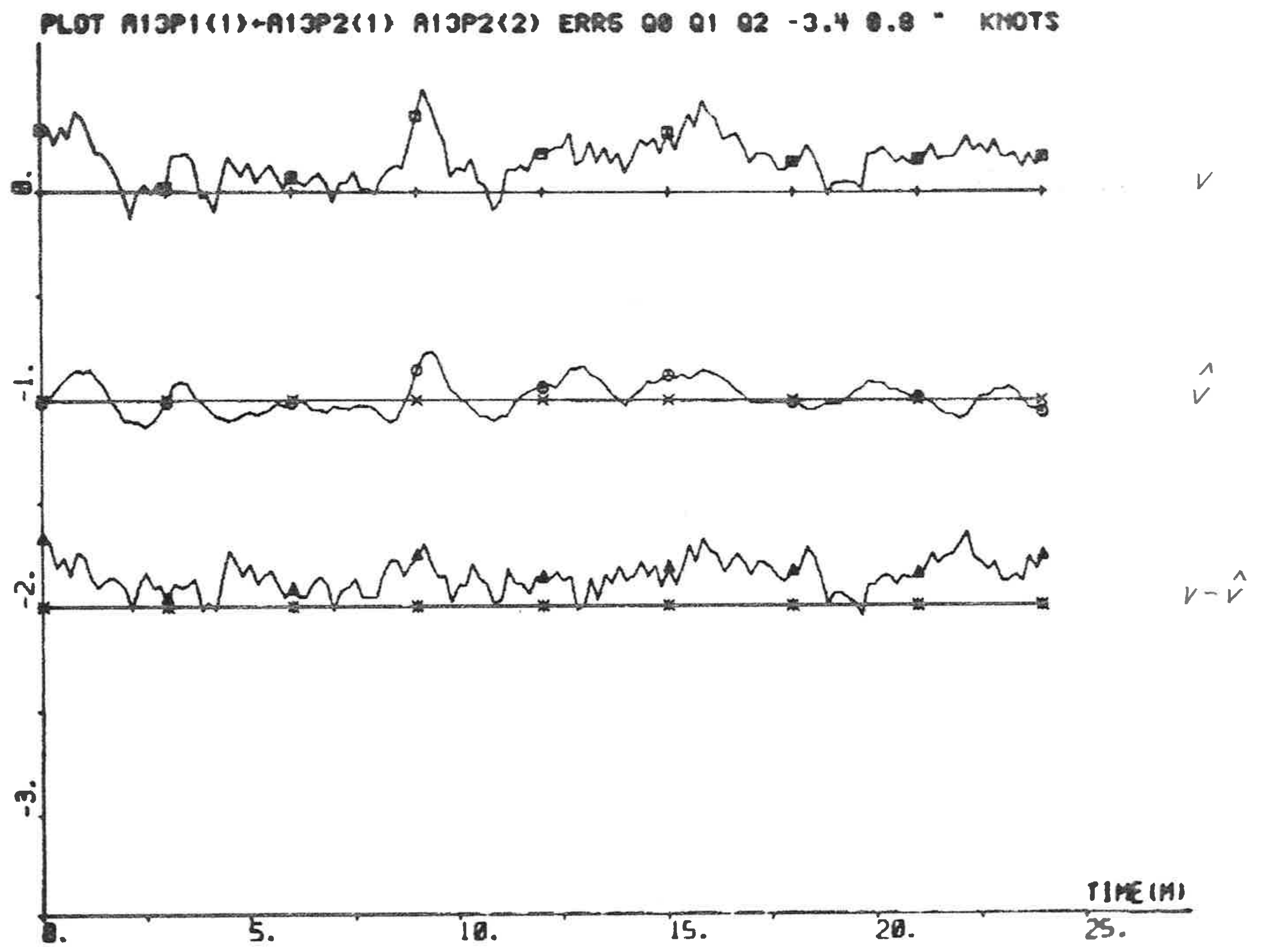
<u>Statistics</u> (mean value and standard deviation)

δ_c	0.24 ± 1.84	deg		P_s	13.1 ± 2.0	MW
δ	1.65 ± 1.69	deg		ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.016 ± 0.420	deg		ε_r	0.00 ± 0.01	deg/s
n	66.7 ± 5.2	rpm		ε_ψ	0.00 ± 0.02	deg
u	13.6 ± 0.3	knots		ε_δ	0.0 ± 0.6	deg

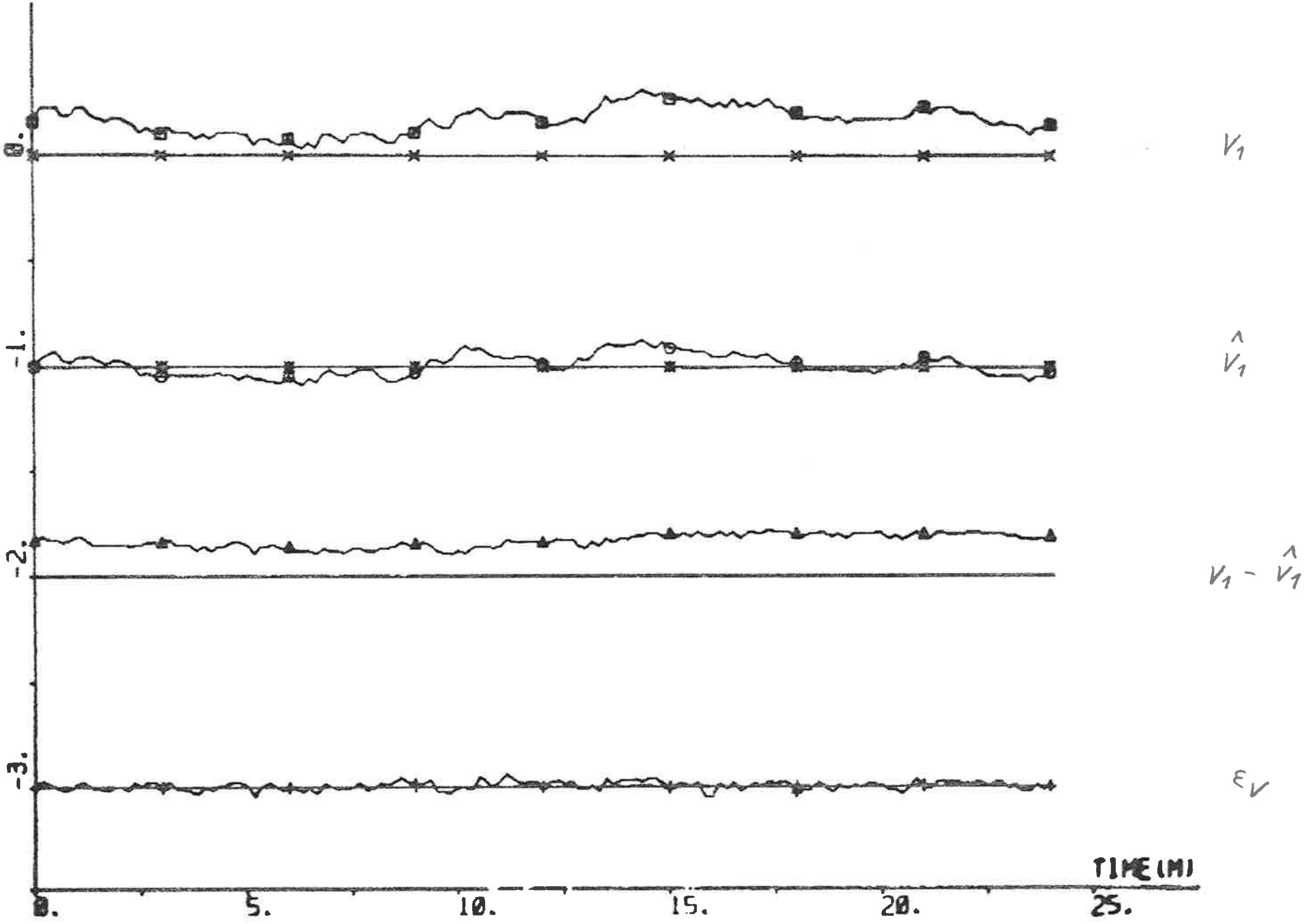
$V_1 = 0.459$

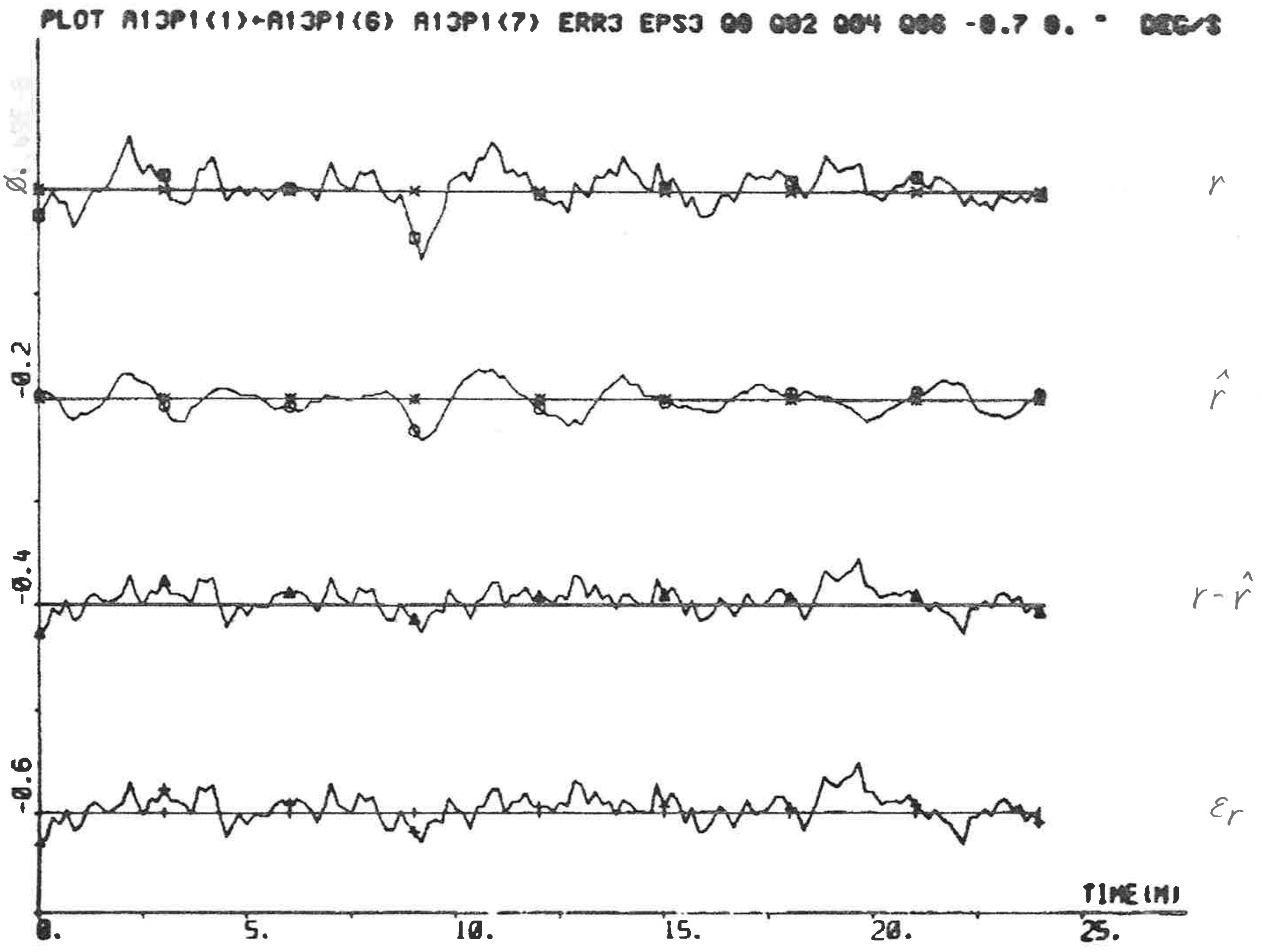

PLOT A13P1(1)-A13P1(8) HP A13P1(10) A13P1(15) Q2 -3 1 ° DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 × δc

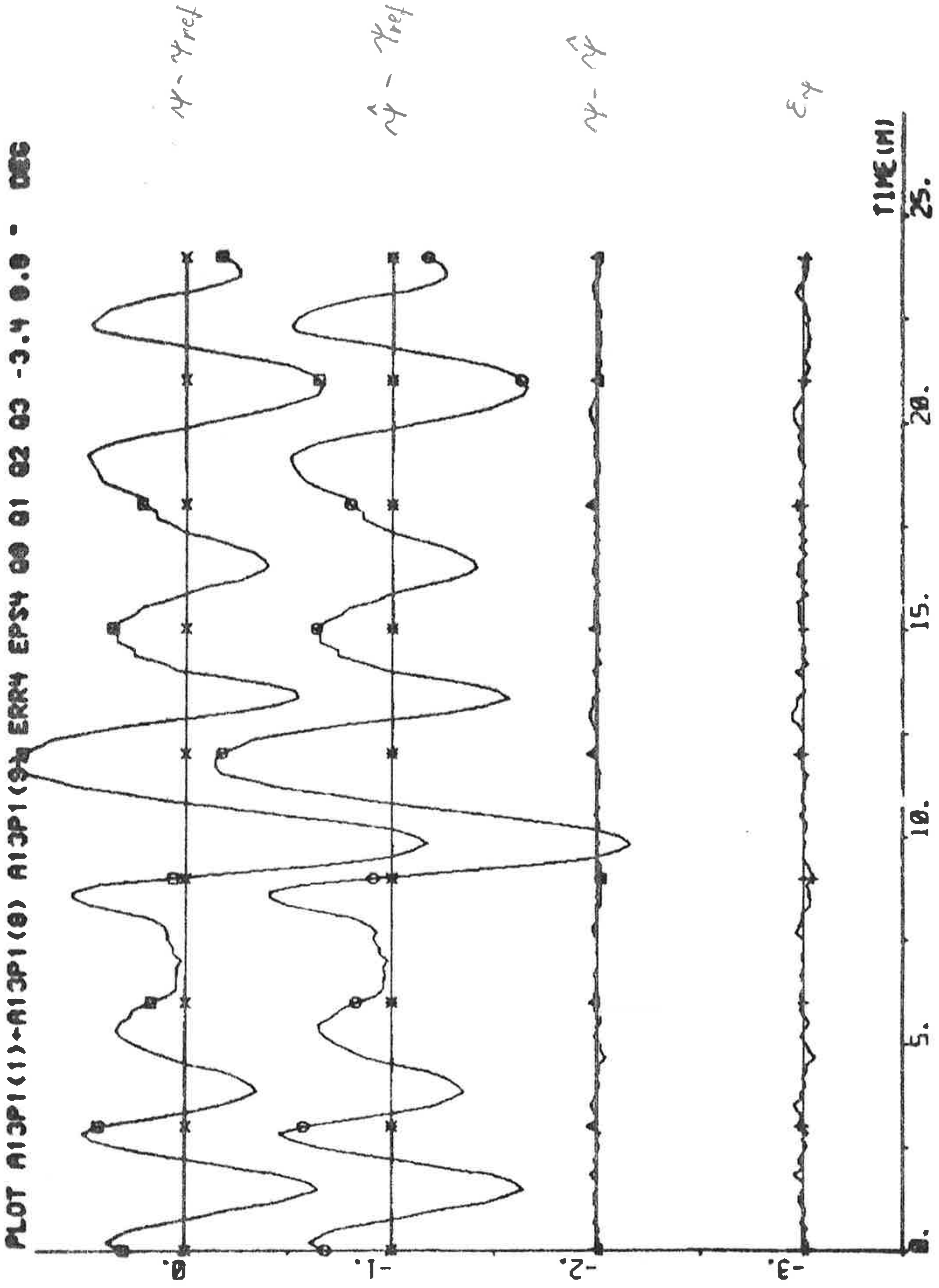

PLOT A13P1(1)-A13P1(13) A13P1(12) A13P1(14) A13P1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n rpm
2 * u knots
P_s MW
δ_s deg

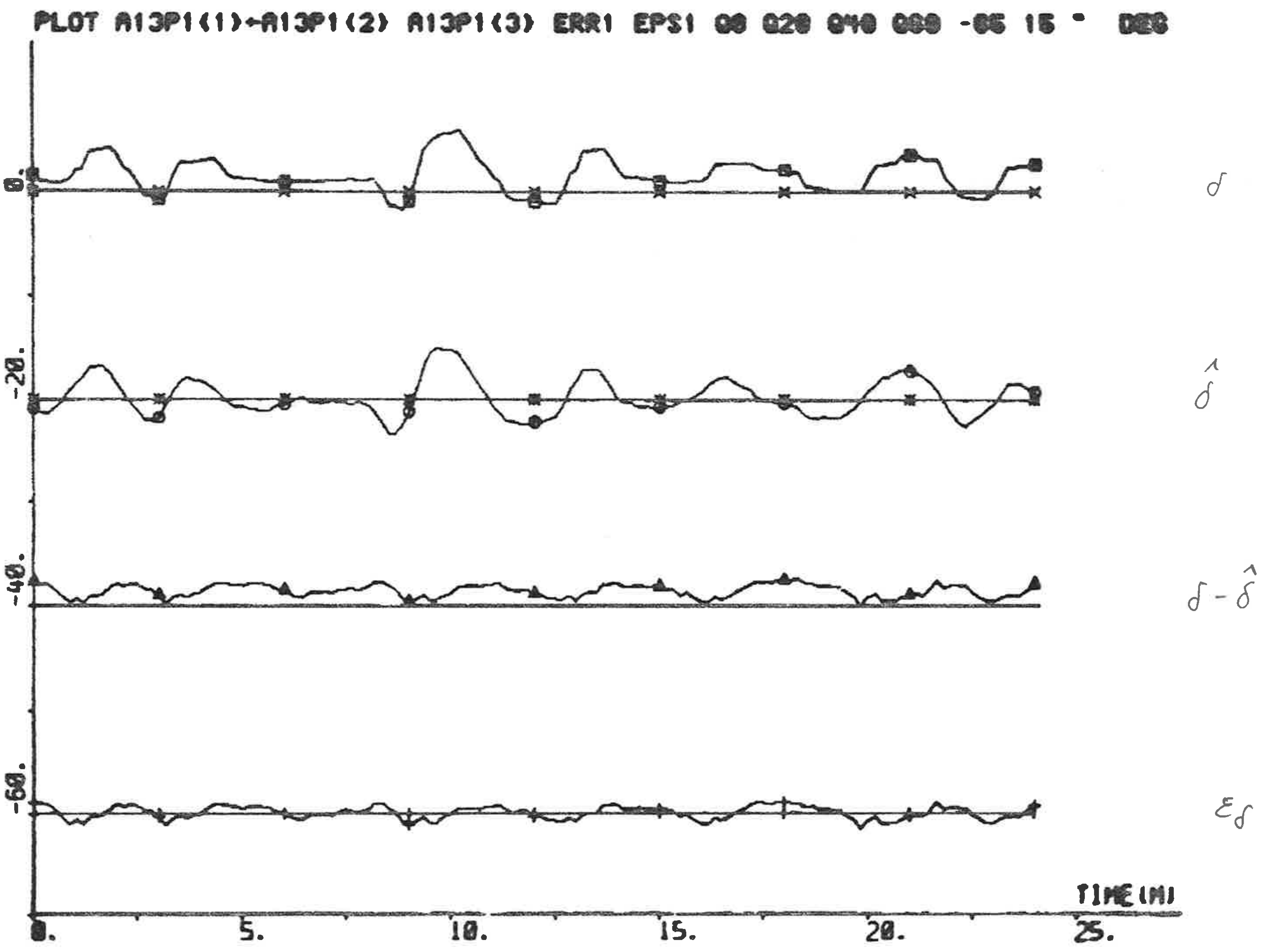

PLOT A13P1(1)-A13P2(1) A13P2(2) ERRS Q0 Q1 Q2 -3.4 0.8 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

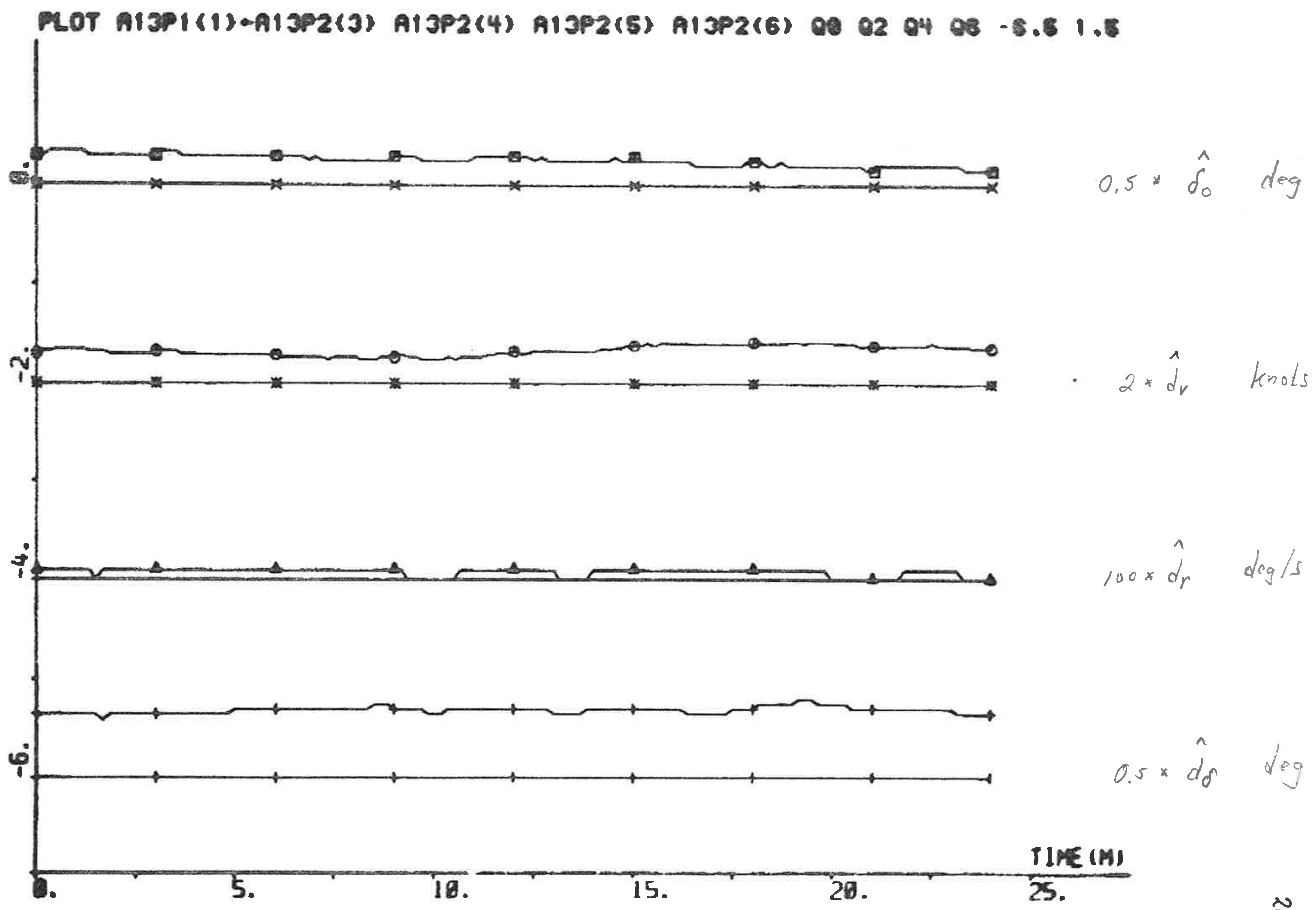
PLOT A13P1(1)+A13P1(4) A13P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 ° KNOTS

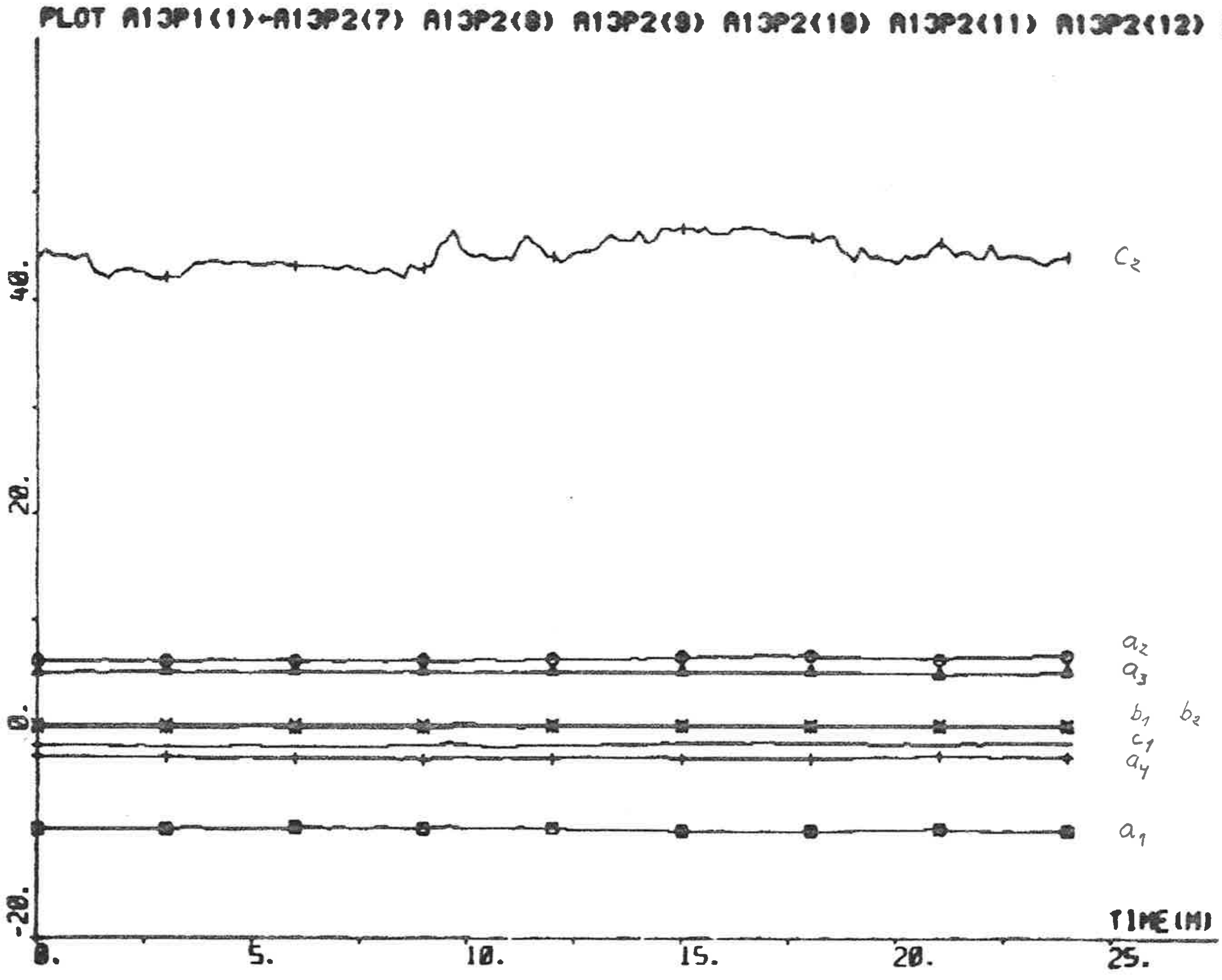



PLOT A13P1(1)-A13P1(6) A13P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A13P1(1)-A13P1(8) A13P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 • DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A13P1(1)+A13P1(2) A13P1(3) ERR1 EPS1 O0 O20 O40 O60 -05 15 DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂
εδ


PLOT A13P1(1)-A13P2(3) A13P2(4) A13P2(5) A13P2(6) Q0 Q2 Q4 Q6 -8.5 1.5
0.
-2.
-4.
-6.
0.5 * $\hat{\delta}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg
0.
5.
10.
15.
20.
25.
TIME (M)


PLOT A13P1(1)-A13P2(7) A13P2(8) A13P2(9) A13P2(10) A13P2(11) A13P2(12) A1
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
C2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT A14

Date	1976-04-24	Forward draught	8.5 m
Time	09.00	Aft draught	12.5 m
Duration	24 min	Wind direction	-
Position	N 02°57' W 13°06'	Wind velocity	0 m/s (calm)
ψ_{ref}	149 deg	Wave height	Swell

The number of propeller revolutions n was temporarily reduced immediately before the experiment started.

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: > 120 min

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -21.78 \\ 26.83 \\ -2.30 \\ -3.17 \\ 0.50 \\ 0.44 \\ -0.54 \\ 74.46 \end{bmatrix} \qquad P = \begin{bmatrix} 9.74 & & & & & & & \\ -13.35 & 27.01 & & & & & & \\ 6.72 & -23.68 & 32.92 & & & & & \\ -0.71 & 8.66 & -16.41 & 10.76 & & & & \\ 0.06 & -0.29 & 0.41 & -0.19 & 0.01 & & & \\ -0.09 & 0.11 & -0.07 & 0.05 & 0.00 & 0.004 & & \\ -2.04 & 2.77 & -0.52 & -0.50 & 0.00 & 0.01 & 1.32 & \\ -0.41 & 12.41 & -12.94 & 5.35 & 0.09 & -0.21 & 22.80 & 866.35 \end{bmatrix}$$

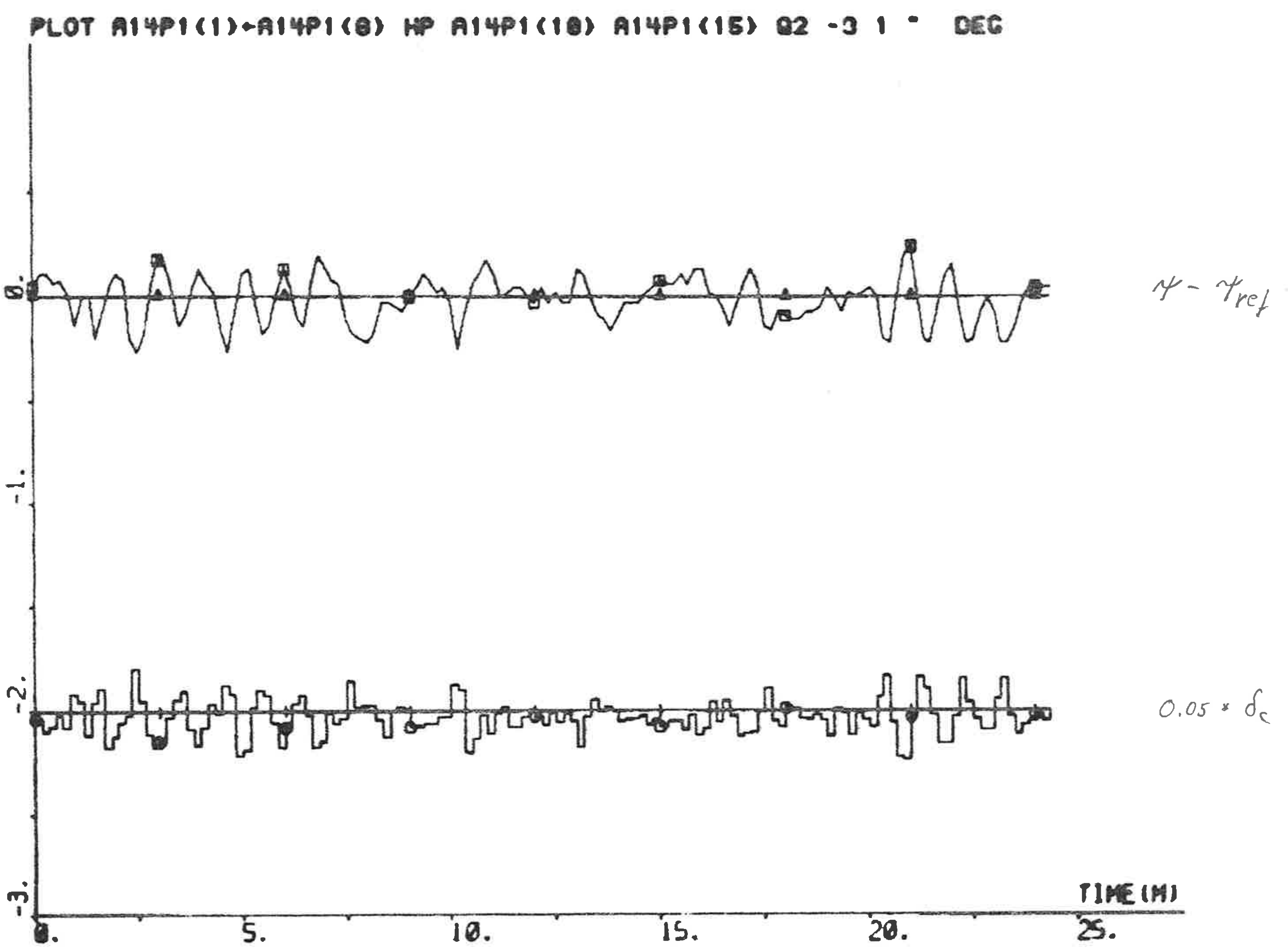
$a_1 + a_2 + a_3 + a_4 = -0.42$

$\hat{\delta}_0 = -0.6$ deg $\hat{d}_v = -0.01$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

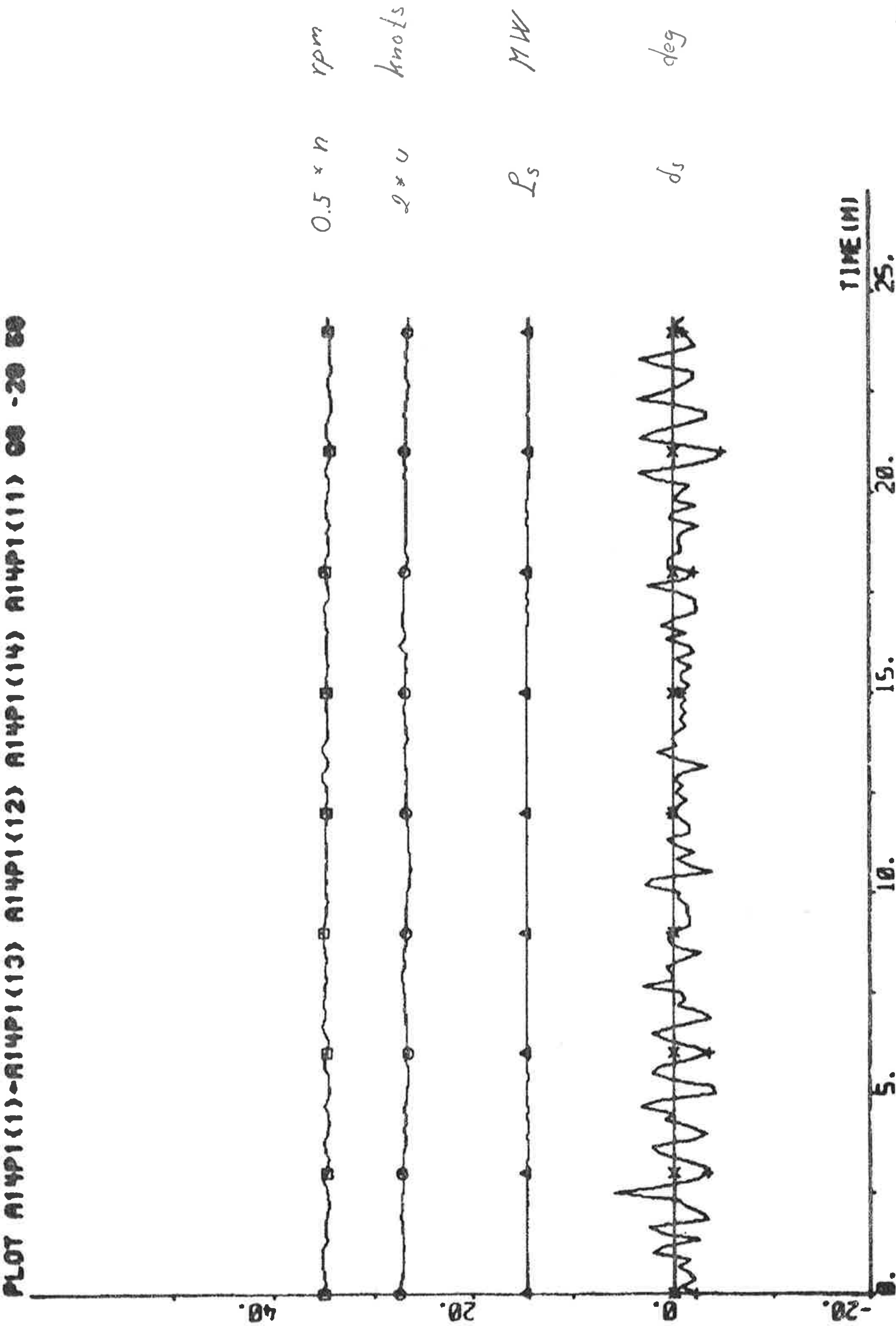
Statistics (mean value and standard deviation)

δ_c	-0.61	± 1.66	deg	P_s	14.6	± 0.1	MW
δ	0.90	± 1.43	deg	ε_v	-0.01	± 0.02	knots
$\psi-\psi_{ref}$	-0.017	± 0.111	deg	ε_r	0.00	± 0.03	deg/s
n	69.7	± 0.4	rpm	ε_ψ	0.00	± 0.03	deg
u	13.5	± 0.1	knots	ε_δ	0.0	± 0.5	deg

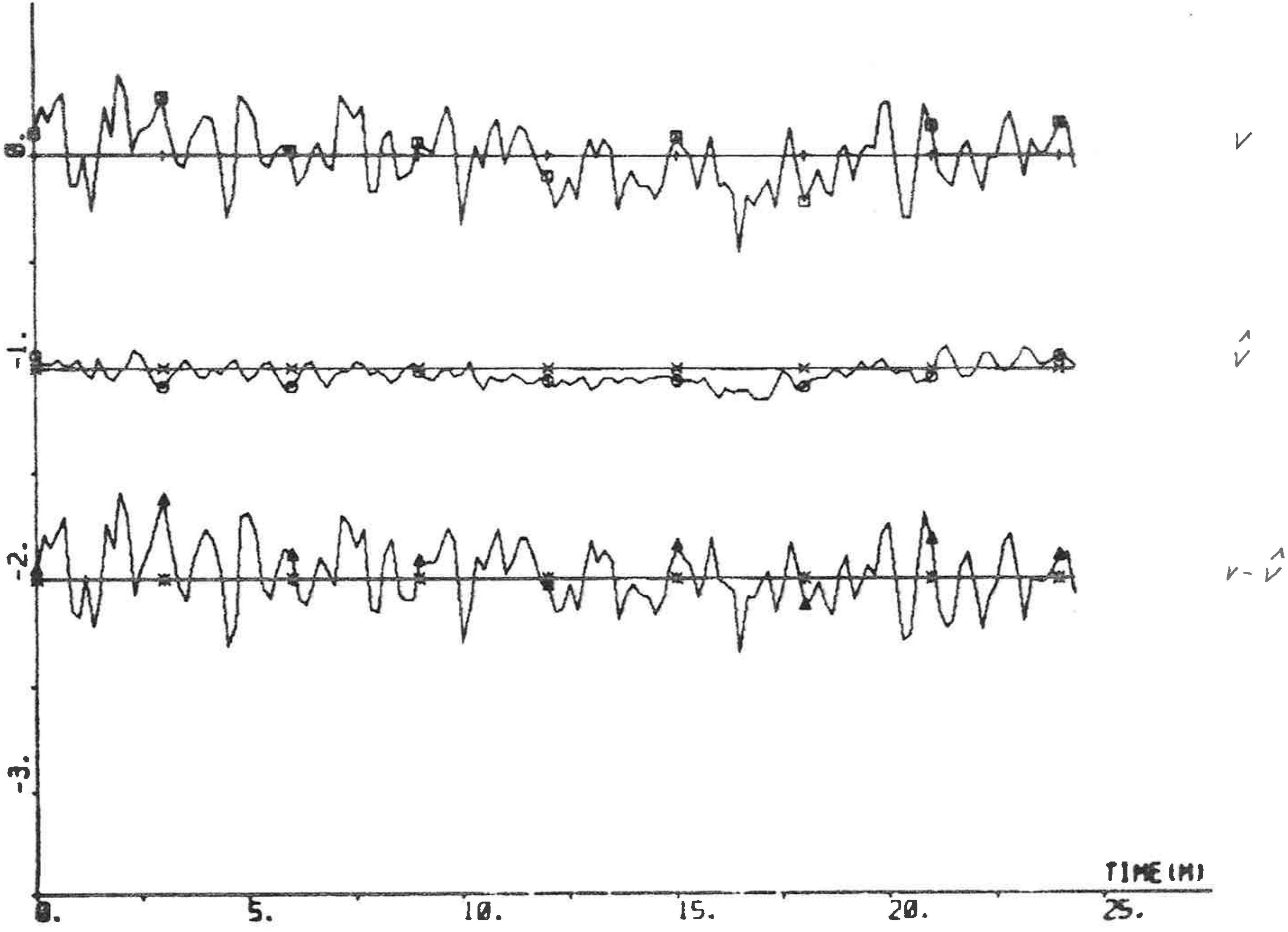
$V_1 = 0.242$

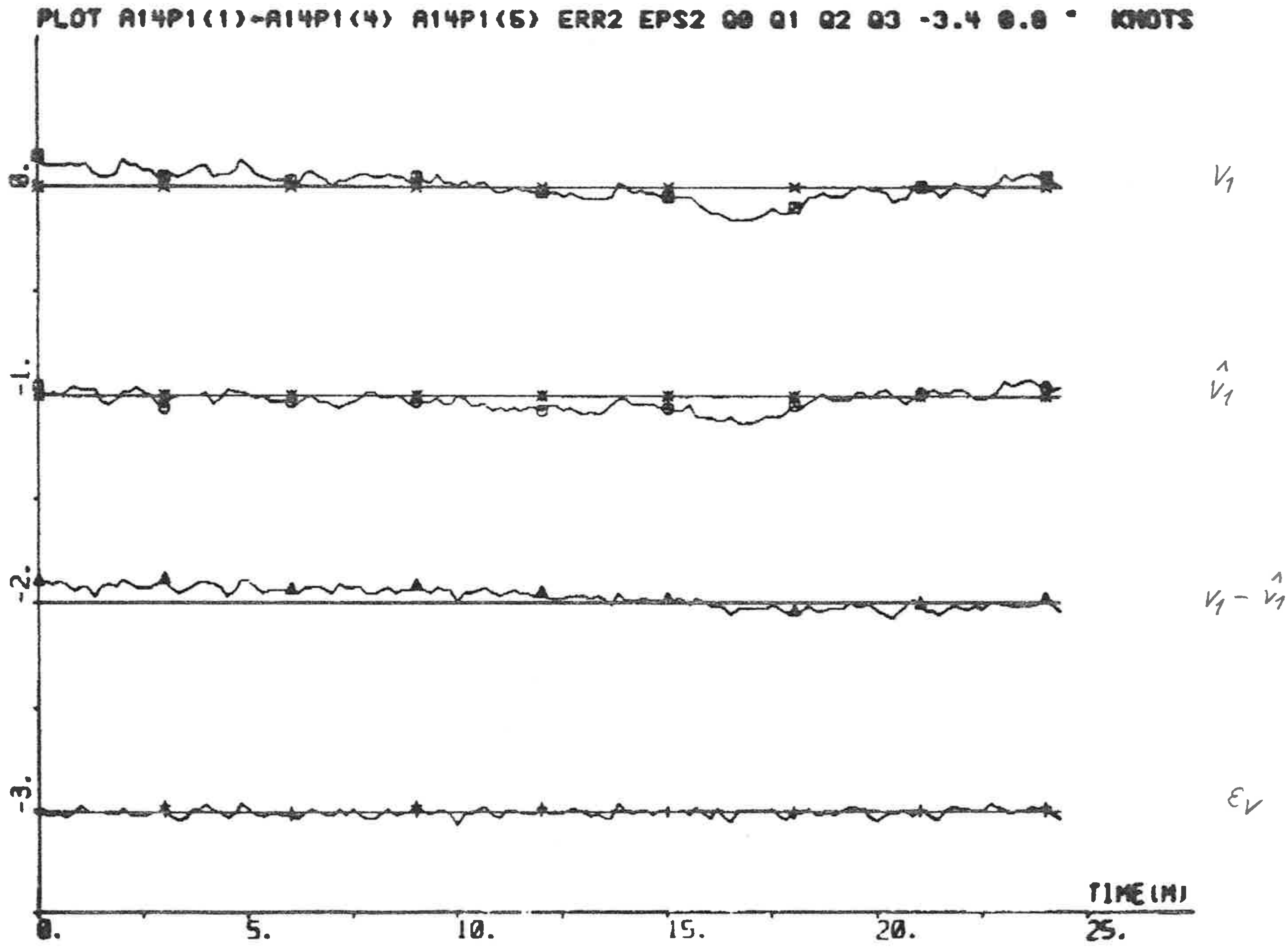


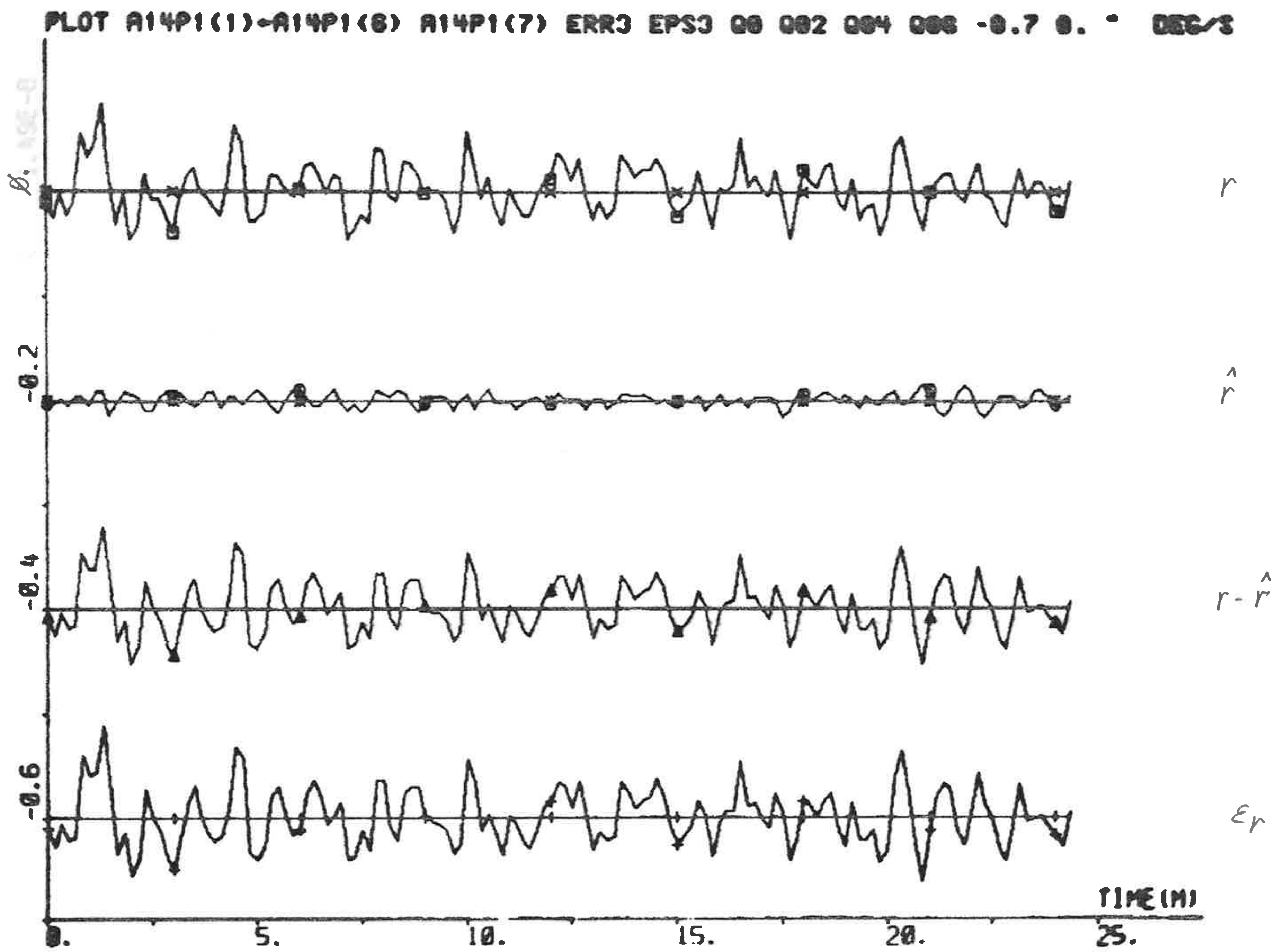
PLOT A14P1(1)-A14P1(8) HP A14P1(10) A14P1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

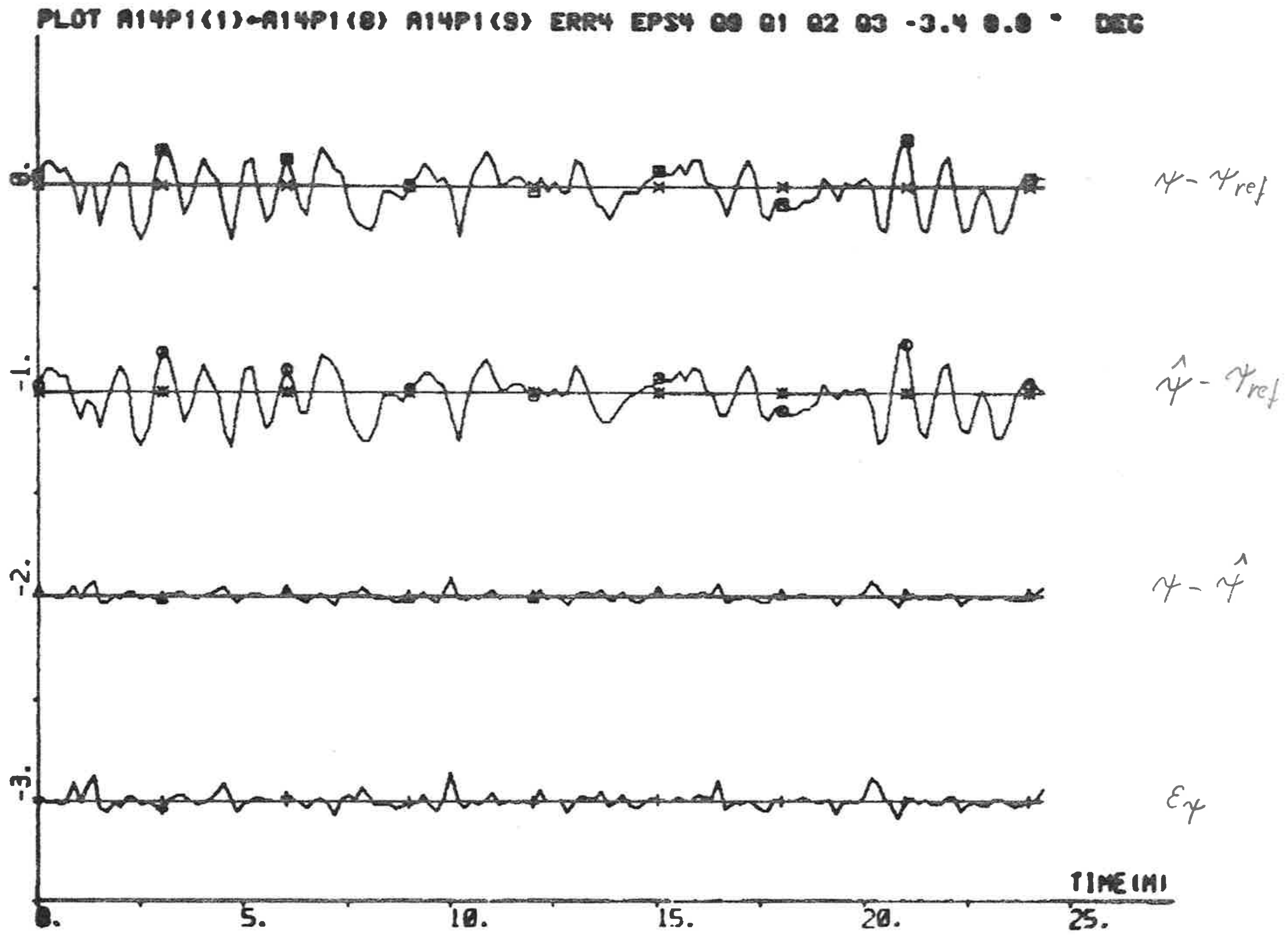

PLOT A14P1(1)-A14P1(13) A14P1(12) A14P1(14) A14P1(11)
0.5 * n rpm
2 * u knots
Ls MW
ds deg
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)

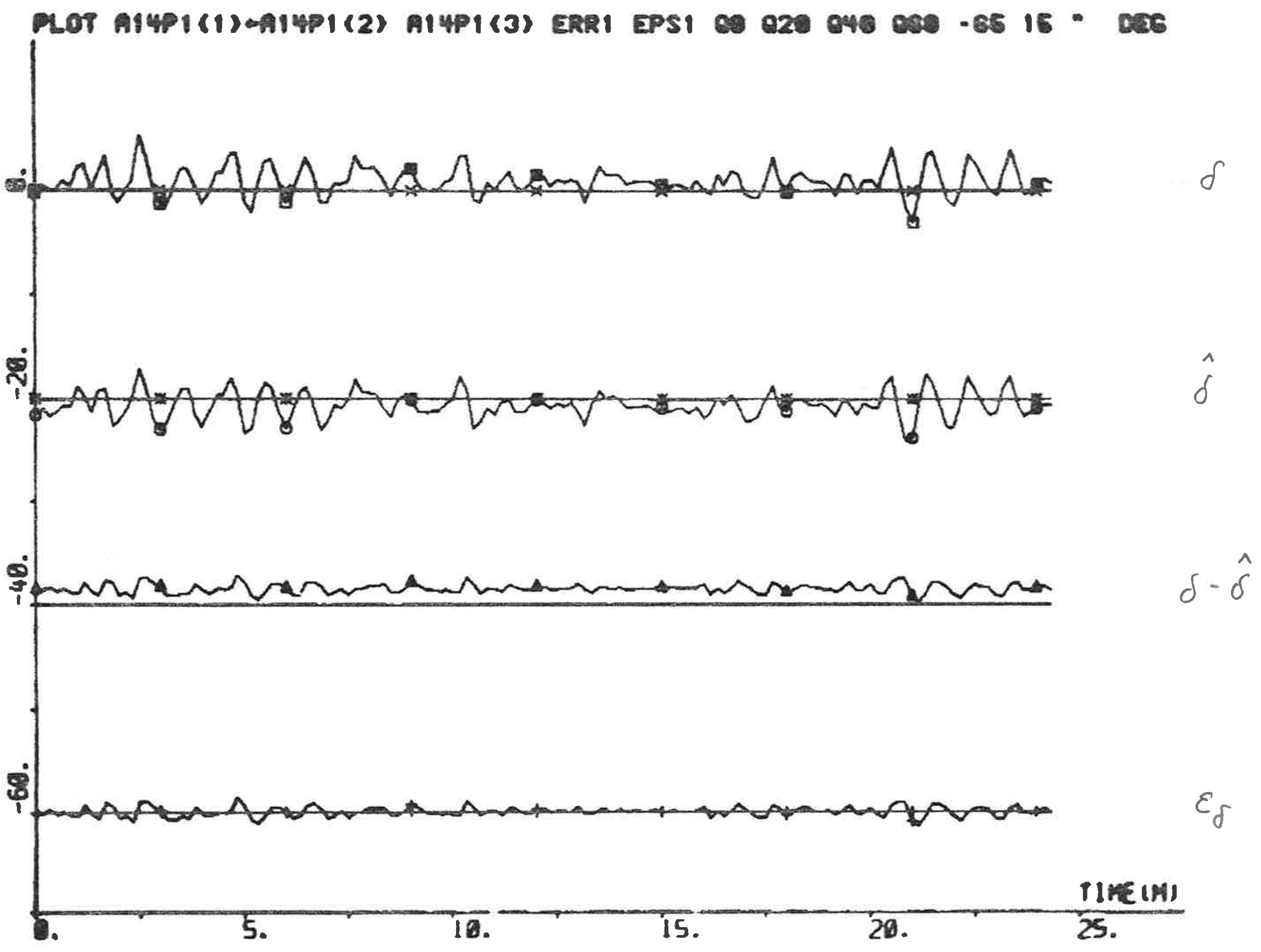
PLOT A14P1(1)-A14P2(1) A14P2(2) ERRS Q0 Q1 Q2 -3.4 0.0 " KNOTS

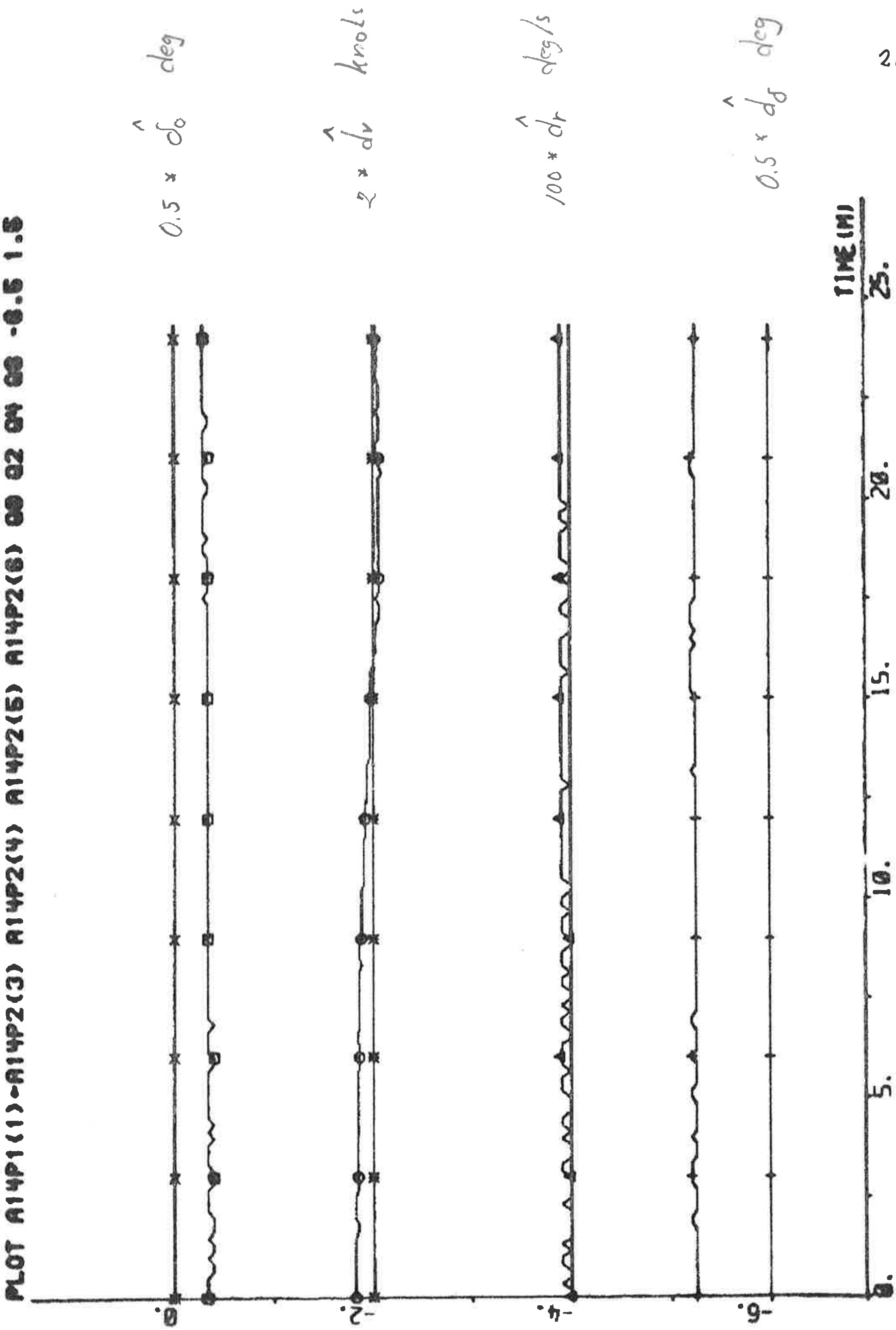


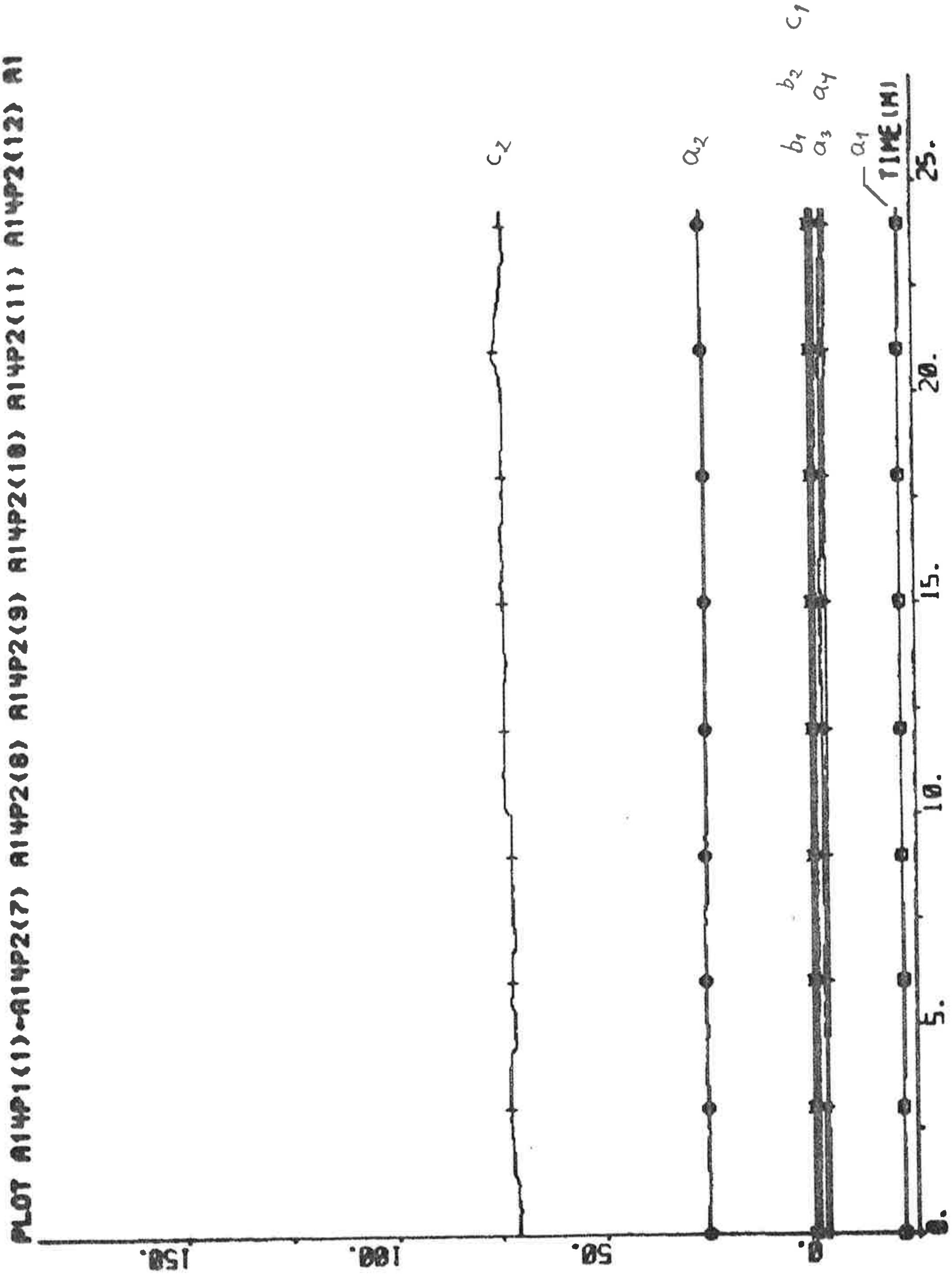

PLOT A14P1(1)-A14P1(4) A14P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT A14P1(1)-A14P1(6) A14P1(7) ERR3 EPS3 Q0 Q02 Q04 Q06 -0.7 0. DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A14P1(1)-A14P1(8) A14P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A14P1(1)-A14P1(2) A14P1(3) ERR1 EPS1 Q0 Q20 Q40 Q60 -65 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂
ε_δ


PLOT A14P1(1)-A14P2(3) A14P2(4) A14P2(5) A14P2(6) 00 02 04 06 -0.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * $\hat{\delta}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg


PLOT A14P1(1)-A14P2(7) A14P2(8) A14P2(9) A14P2(10) A14P2(11) A14P2(12) A1
0.
50.
100.
150.
0.
5.
10.
15.
20.
25.
TIME(H)
c2
a2
b1
a3
b2
a4
c1
a1

EXPERIMENT A15

Date	1976-04-24	Forward draught	8.5 m
Time	10.09	Aft draught	12.5 m
Duration	25 min	Wind direction	-
Position	N 02°45' W 12°57'	Wind velocity	0 m/s (calm)
ψ_{ref}	149 deg	Wave height	Swell

<u>Self-tuning regulator using estimates from the Kalman filter.</u>

Tuning time before the experiment started: 30 min.

NC1 = 1　　NC2 = 0　　k = 7　　q = 0

T_s = 10 s　　V_0 = 6 m/s　　IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \end{bmatrix} = \begin{bmatrix} -7.76 \\ 5.70 \\ 4.43 \\ -2.61 \\ 0.49 \\ 0.17 \\ -1.81 \end{bmatrix} \qquad P = \begin{bmatrix} 3.74 & & & & & & \\ -5.01 & 11.78 & & & & & \\ 0.55 & -8.18 & 14.43 & & & & \\ 1.11 & 1.15 & -7.13 & 5.49 & & & \\ 0.08 & -0.39 & 0.41 & -0.09 & 0.03 & & \\ -0.02 & 0.05 & -0.22 & 0.21 & 0.00 & 0.02 & \\ -0.86 & 1.03 & 0.34 & -0.53 & -0.02 & 0.01 & 0.45 \end{bmatrix}$$

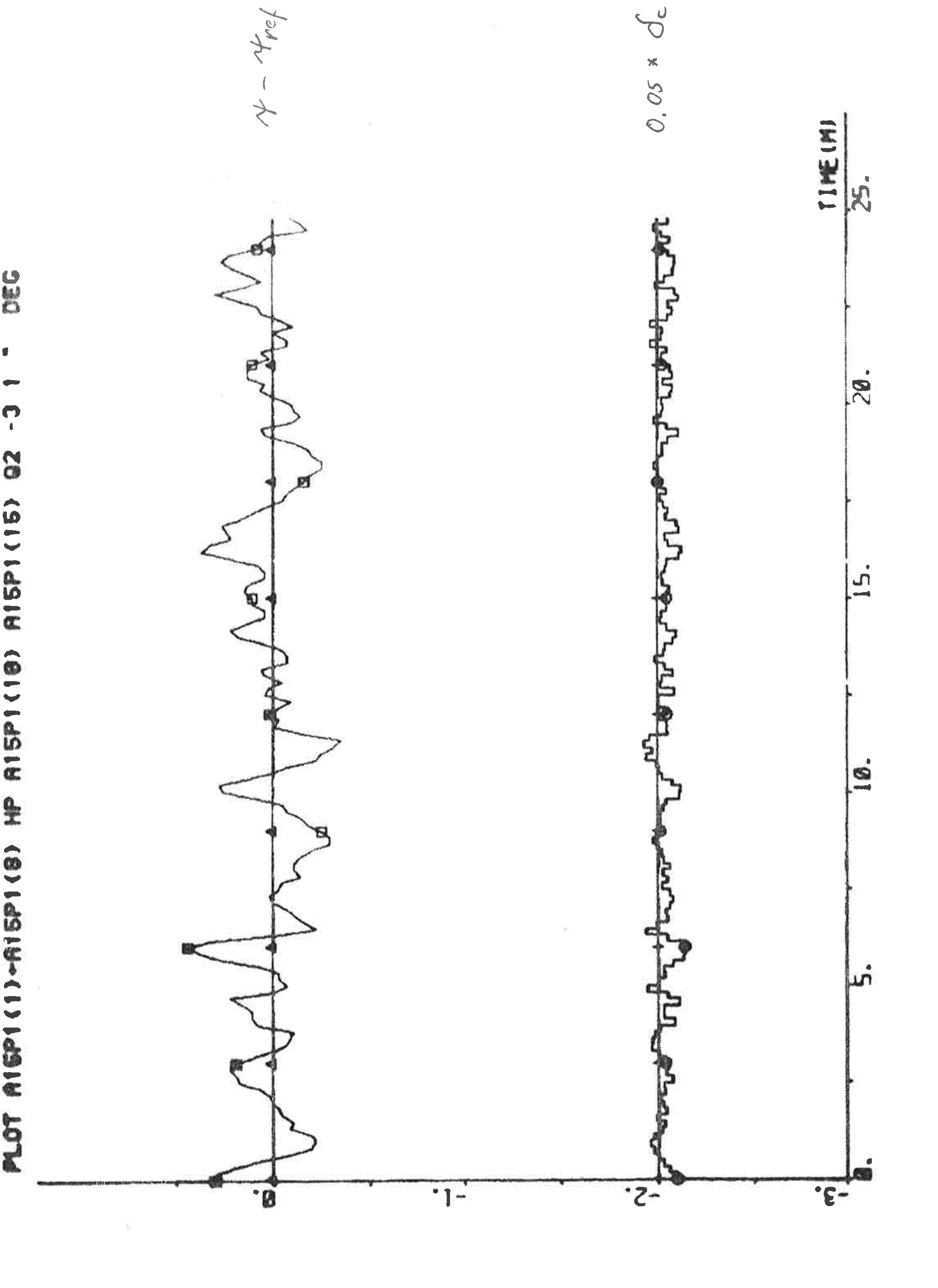
$a_1 + a_2 + a_3 + a_4 = -0.24$

$\hat{\delta}_0 = -0.6$ deg　　$\hat{d}_v = 0.07$ knots　　$\hat{d}_r = 0.000$ deg/s　　$\hat{d}_\delta = 1.6$ deg

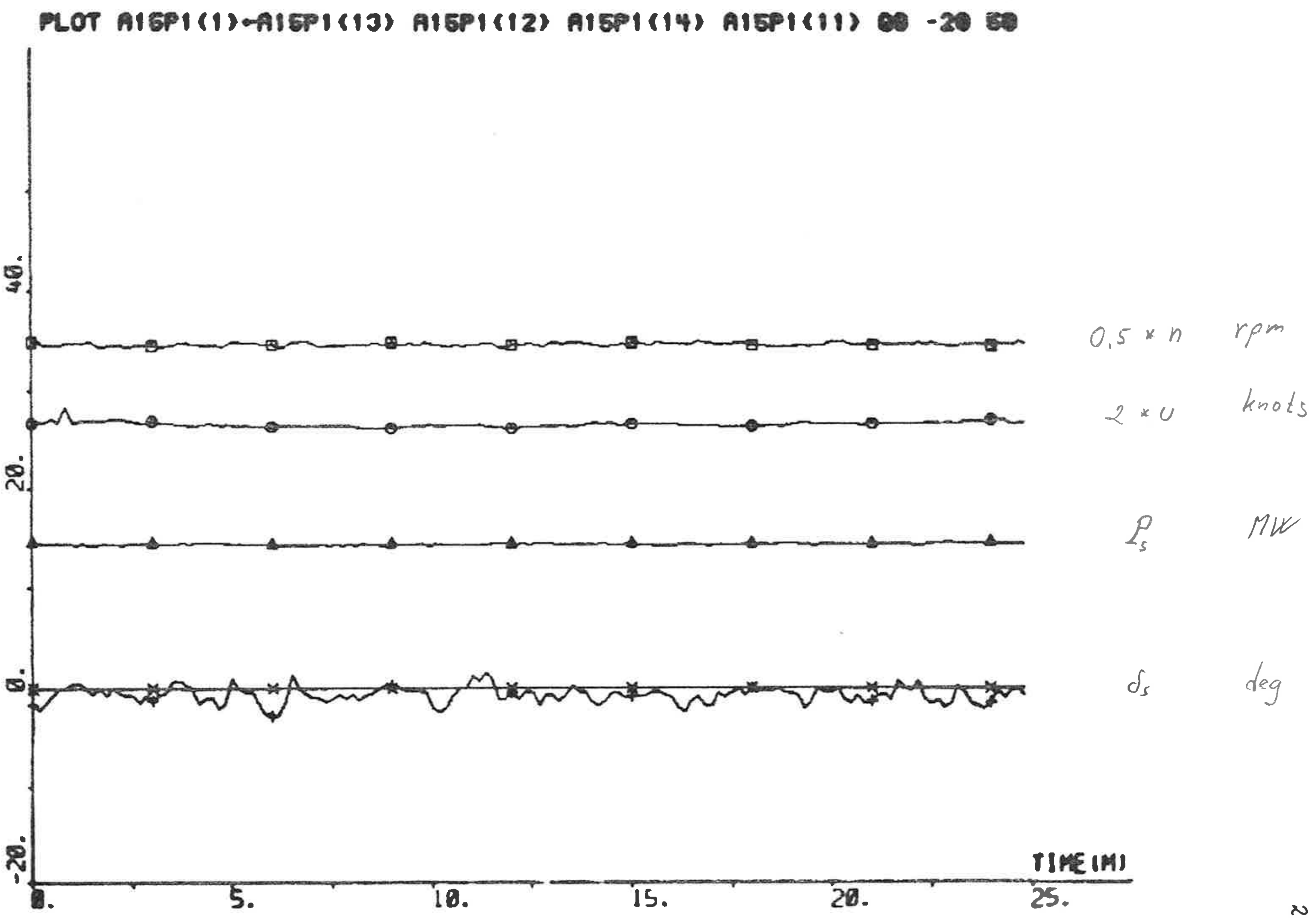
<u>Statistics</u> (mean value and standard deviation)

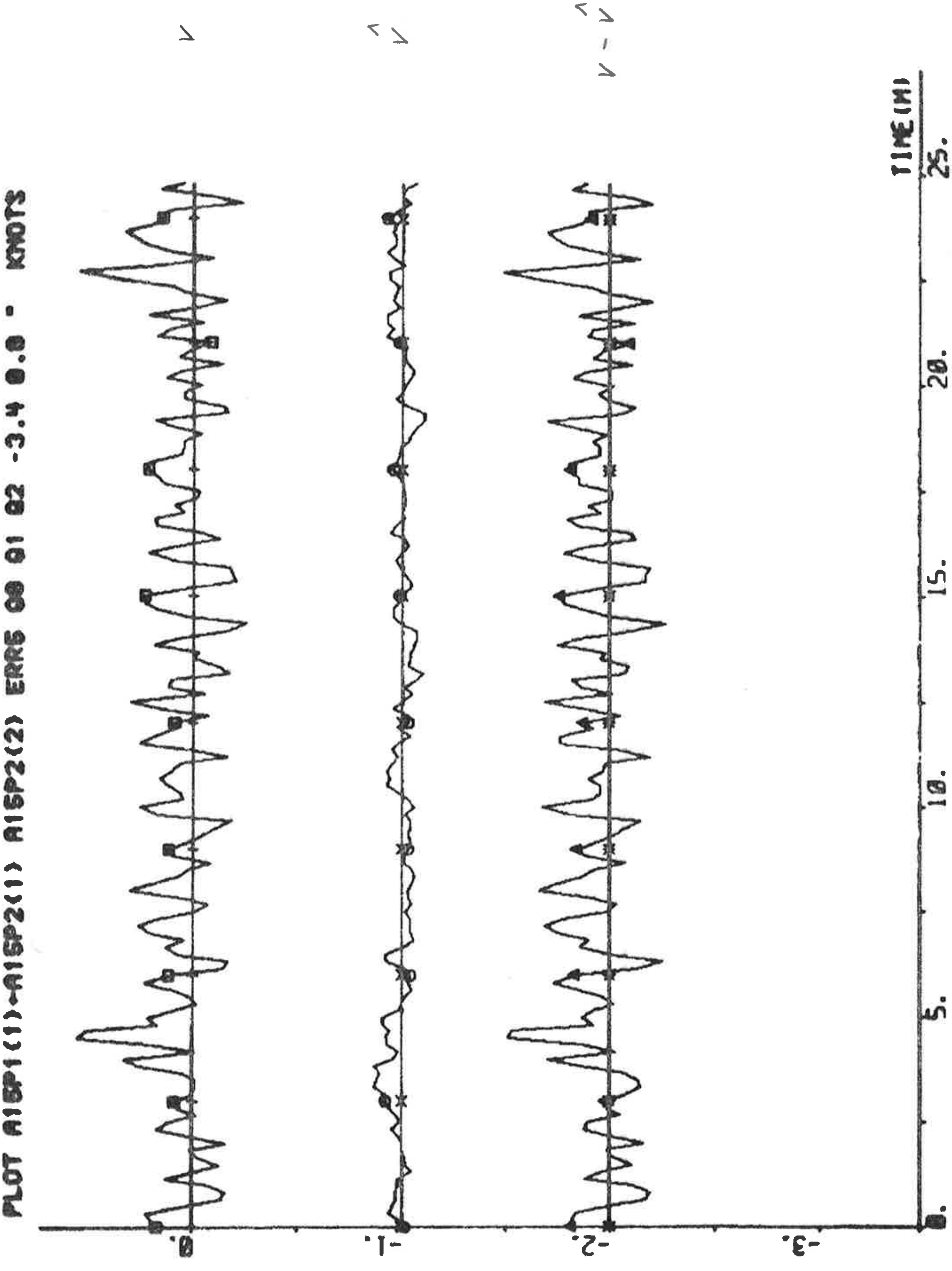
δ_c	-0.68 ± 0.82	deg	P_s	14.4 ± 0.1	MW
δ	0.88 ± 0.70	deg	ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.015 ± 0.158	deg	ε_r	0.00 ± 0.03	deg/s
n	69.4 ± 0.3	rpm	ε_ψ	0.00 ± 0.04	deg
u	13.3 ± 0.1	knots	ε_δ	0.0 ± 0.4	deg

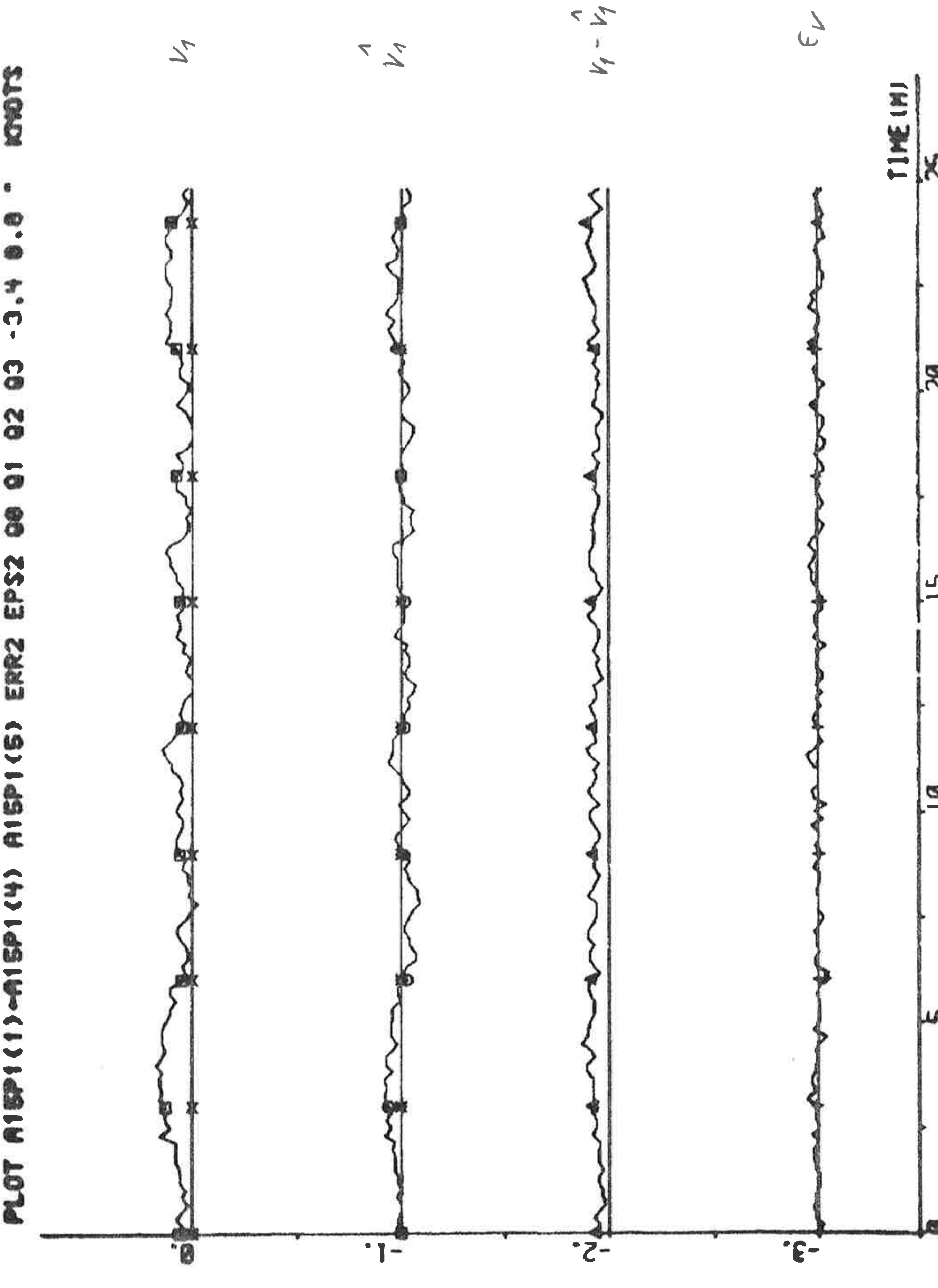
$V_1 = 0.081$



PLOT A15P1(1)-A15P1(8) HP A15P1(10) A15P1(15) 02 -3 1 " DEG
ψ - ψref
0.05 * δc
TIME(M)
0.
5.
10.
15.
20.
25.
.0
-1.
-2.
-3.


PLOT A15P1(1)-A15P1(13) A15P1(12) A15P1(14) A15P1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0,5 * n rpm
2 * U knots
P_s MW
δ_s deg


PLOT A1SP1(1)-A1SP2(1) A1SP2(2) ERRS 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A1SP1(1)-A1SP1(4) A1SP1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.8 ' KNOTS
TIME(H)
0.
5.
10.
15.
20.
25.
0.
-1.
-2.
-3.

CODEN: LUTFD2/(TFRT-7110)/01-587(1976)

THE SEA STRATUS EXPERIMENTS, APRIL 1976
PART II

CLAES KÄLLSTRÖM

Lund Institute of Technology
Department of Automatic Control
September 1976

THE SEA STRATUS EXPERIMENTS, APRIL 1976

PART II

CLAES KÄLLSTRÖM

TABLE OF CONTENTS

	Page
PART I	
1. INTRODUCTION	6
2. MEASUREMENT EQUIPMENT	8
3. AUTOPILOT	10
3.1 Kalman Filter	12
3.2 Self-tuning Regulator	17
3.3 PID-regulator	21
3.4 Yaw Regulator	22
4. DISCUSSION OF THE EXPERIMENTS	27
4.1 Kalman Filter Testing	28
4.2 Straight Course Keeping	32
4.3 Yawing	37
4.4 Experiments for Identification	38
5. CONCLUSIONS	40
6. ACKNOWLEDGEMENTS	42
7. REFERENCES	43
APPENDIX A - NOTATIONS	44
APPENDIX B - STANDARD PARAMETER VALUES	50
APPENDIX C - PROGRAM LISTINGS	56
APPENDIX D - EXPERIMENTS	67
A1	79
A2	89
A3	99
A4	109
A5	119
A6	129
A7	139

		Page
	A8	149
	A9	159
	A10	169
	A11	179
	A12	189
	A13	199
	A14	209
	A15	219
	A16	229
	A17	239
	A18	249
	A19	259
	A20	269
	A21	278
PART II		
	A22	288
	A23	298
	A24	308
	A25	318
	A26	328
	A27	338
	A28	348
	A29	358
	A30	368
	A31	377
	A32	386
	A33	396

	Page
A34	406
A35	416
A36	425
B1	435
B2	441
B3	447
C1	453
C2	463
C3	473
C4	483
C5	493
C6	503
D1	513
D2	523
D3	533
E1	543
E2	552
E3	561
E4	571
F1	580
F2	581
F3	582
F4	583

EXPERIMENT A22

Date	1976-04-25	Forward draught	8.5 m
Time	11.14	Aft draught	12.5 m
Duration	24 min	Wind direction	SE (1; see App. A)
Position	S 01°39' W 09°50'	Wind velocity	13 m/s (strong breeze)
ψ_{ref}	141 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter

The rudder angle δ was not used by the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.04 \\ 6.23 \\ 4.52 \\ -2.99 \\ 0.51 \\ 0.16 \\ -1.89 \\ 35.94 \end{bmatrix} \qquad P = \begin{bmatrix} 4.01 & & & & & & & \\ -4.83 & 10.86 & & & & & & \\ -0.07 & -6.92 & 13.00 & & & & & \\ 1.10 & 0.75 & -6.22 & 4.74 & & & & \\ -0.07 & -0.17 & 0.33 & -0.10 & 0.03 & & & \\ -0.04 & -0.04 & -0.04 & 0.12 & 0.00 & 0.02 & & \\ -0.51 & 0.67 & 0.17 & -0.32 & -0.01 & -0.01 & 0.81 & \\ 7.52 & -9.92 & -5.56 & 8.39 & 0.02 & -0.21 & 15.47 & 744.94 \end{bmatrix}$$

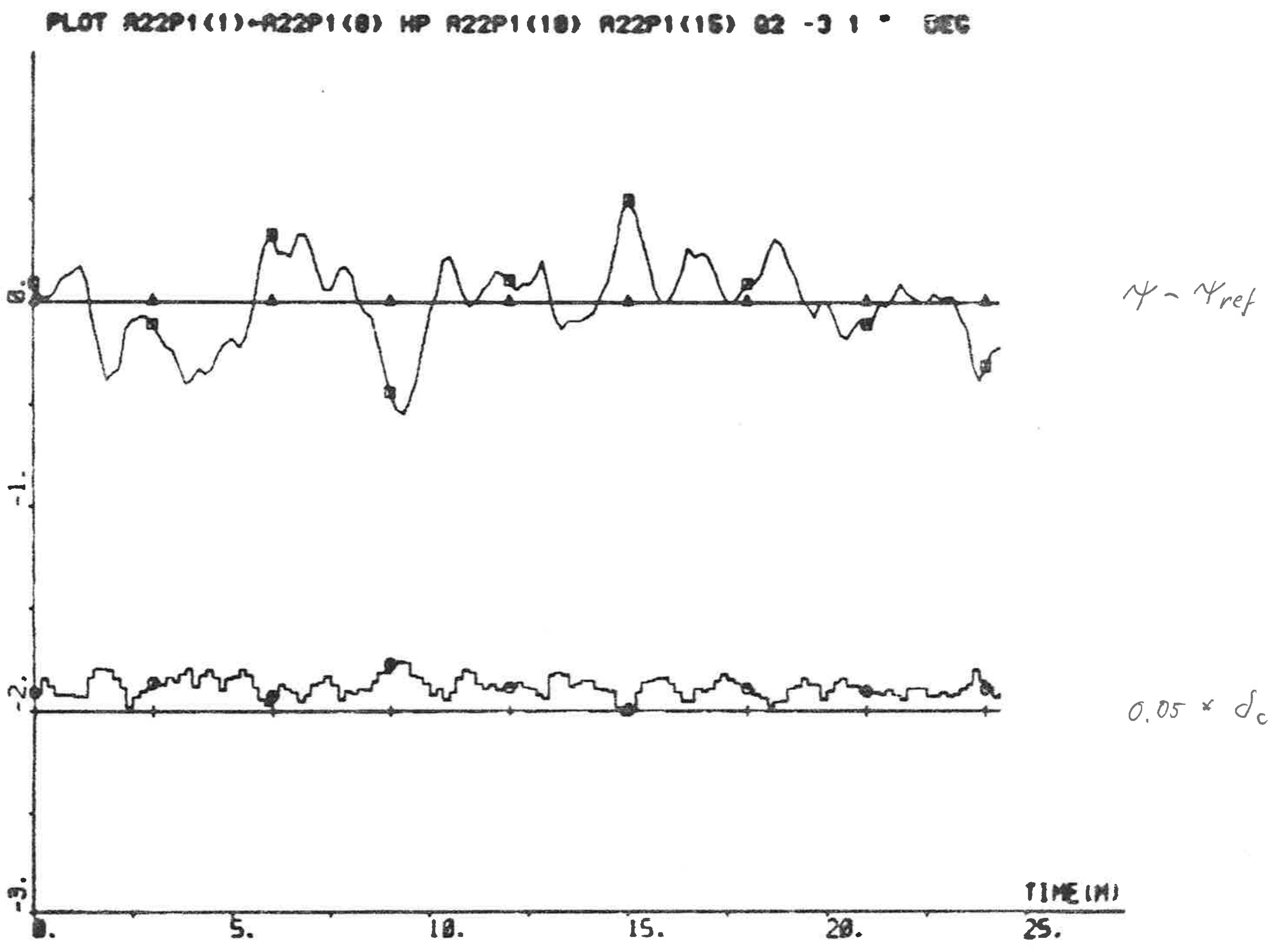
$a_1 + a_2 + a_3 + a_4 = -0.28$

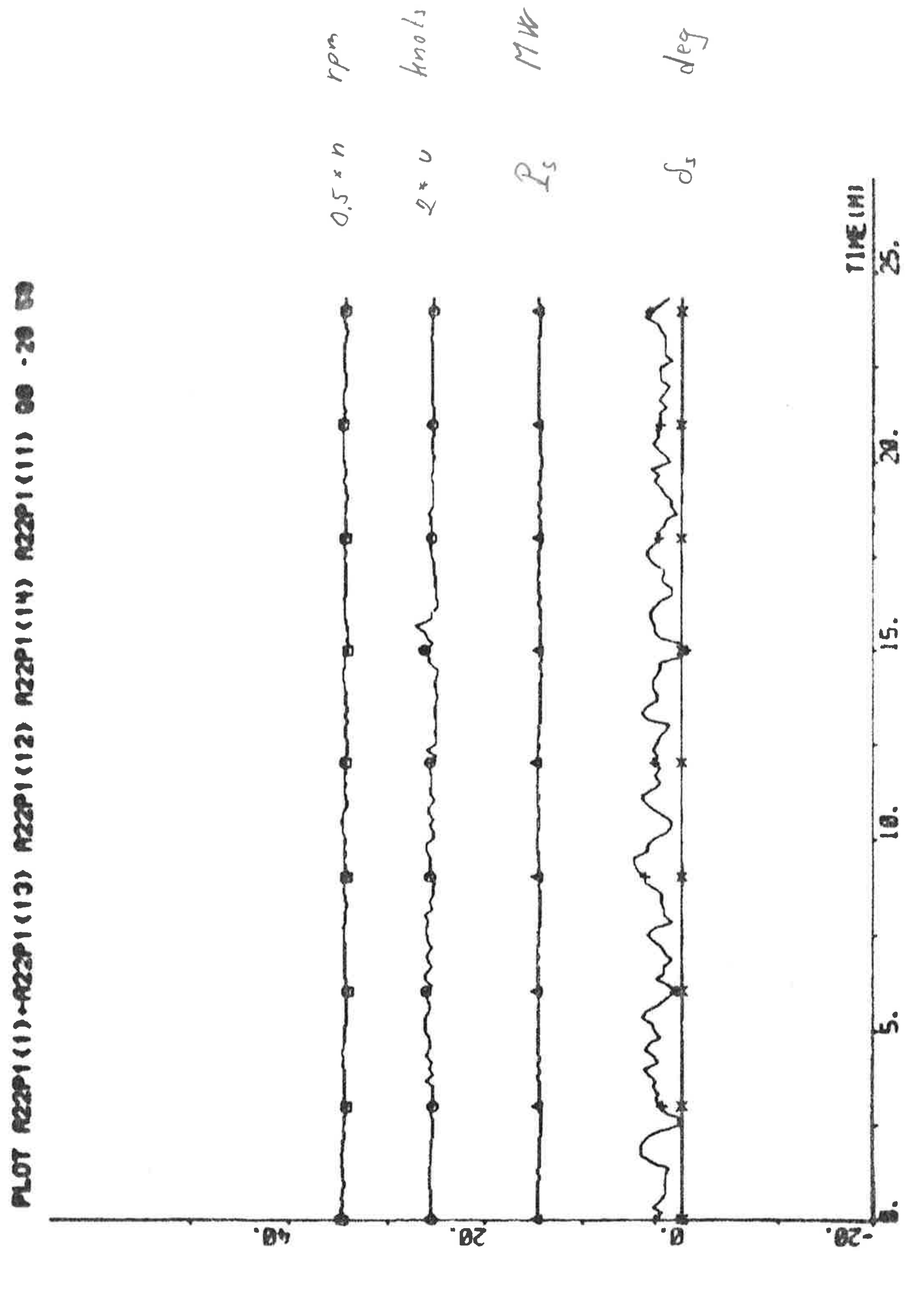
$\hat{\delta}_0 = 1.8$ deg $\hat{d}_v = 0.27$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = -$

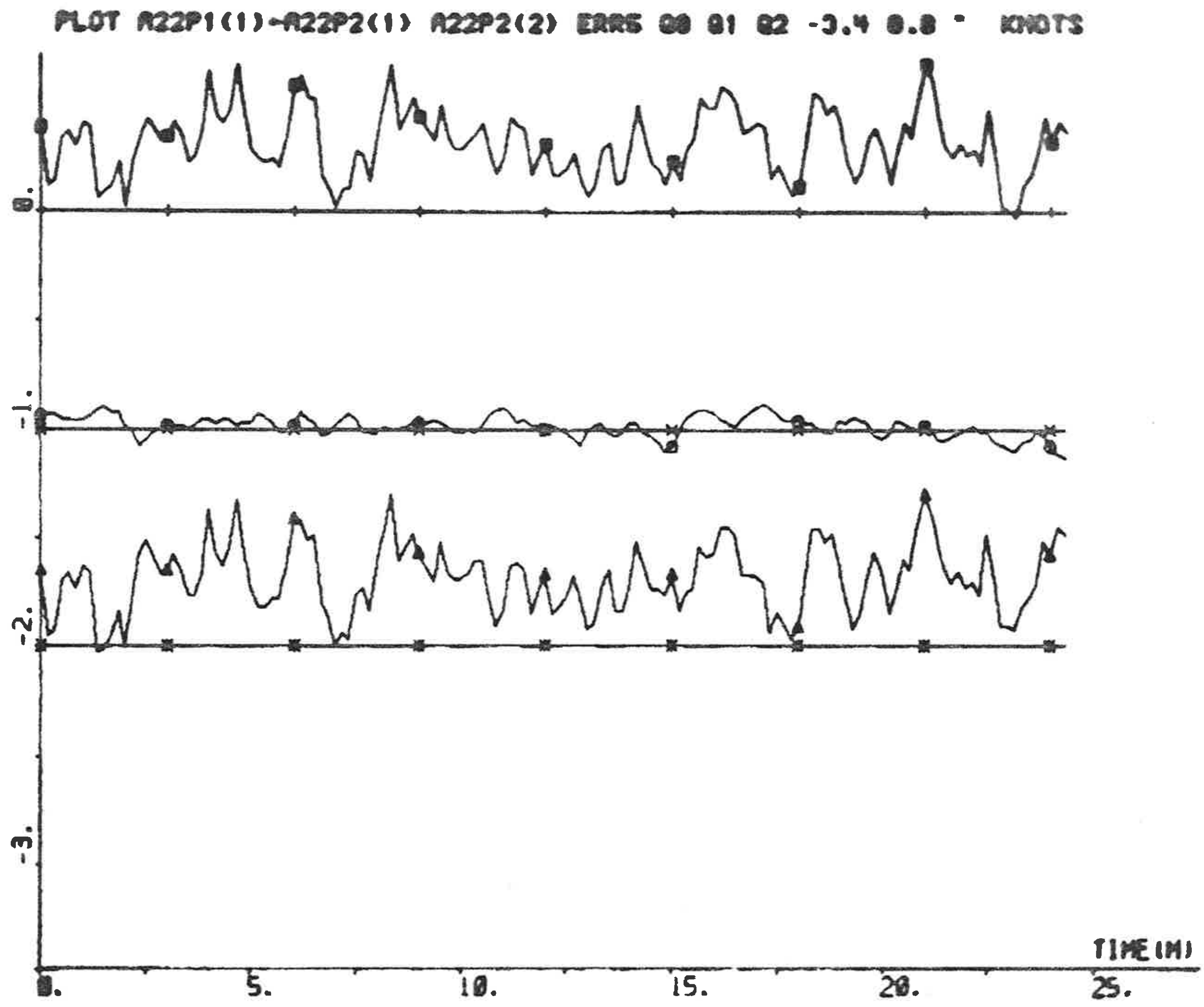
Statistics (mean value and standard deviation)

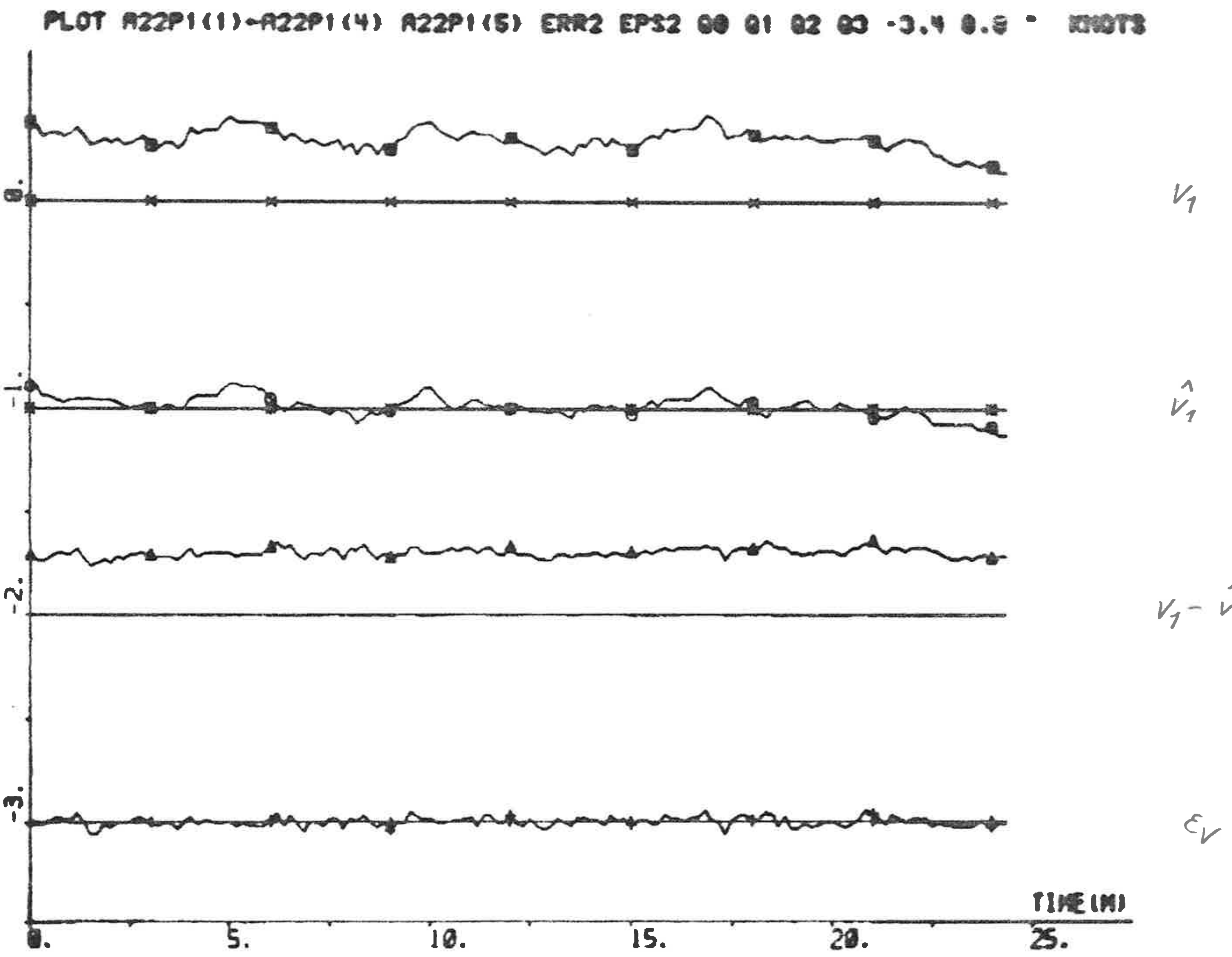
δ_c	2.32 ± 0.95	deg		P_s	14.5 ± 0.1	MW
δ	3.82 ± 0.80	deg		ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	-0.006 ± 0.204	deg		ε_r	0.00 ± 0.03	deg/s
n	68.9 ± 0.3	rpm		ε_ψ	-0.01 ± 0.03	deg
u	12.8 ± 0.2	knots		ε_δ	-	

$V_1 = 0.117$

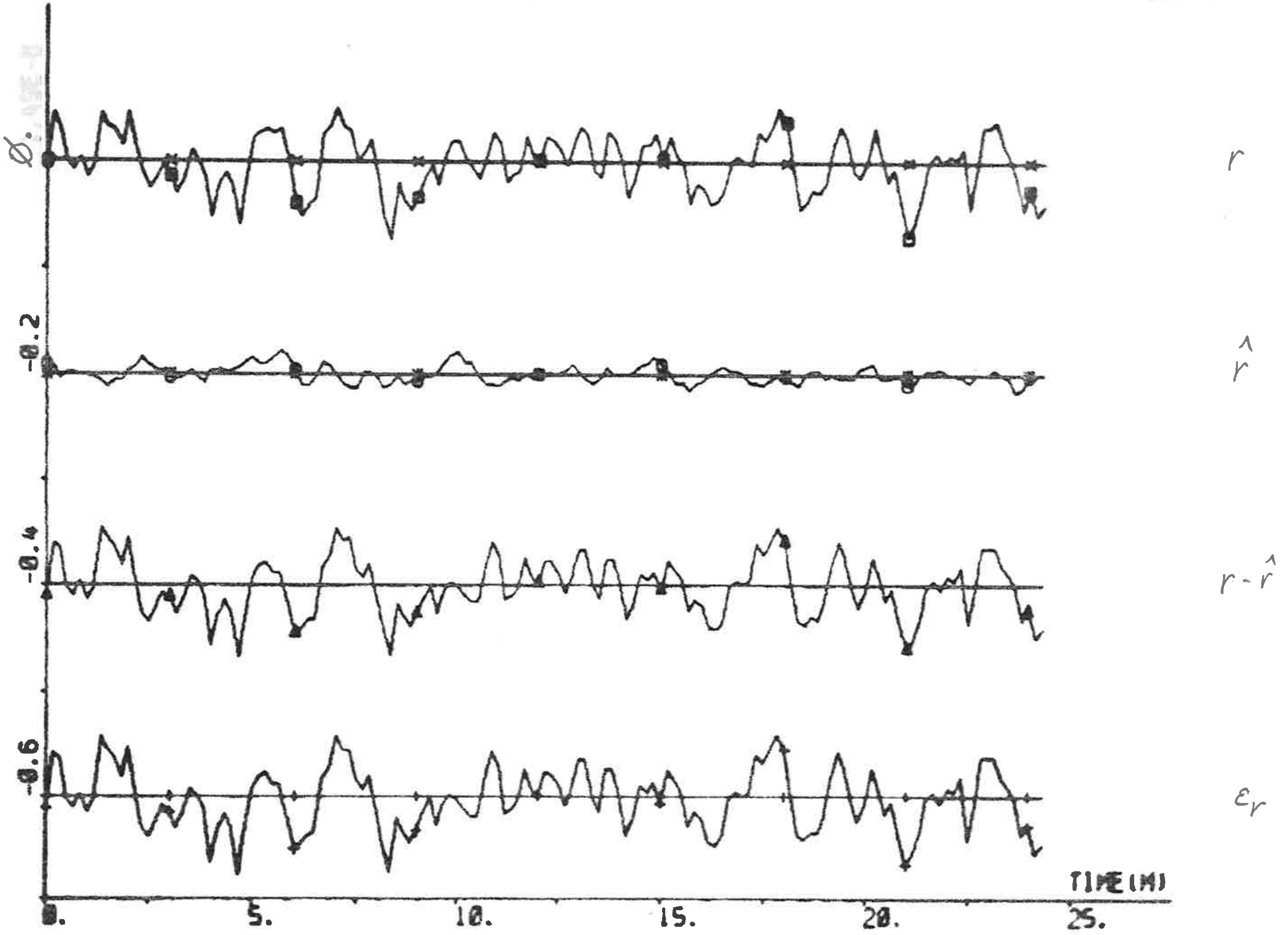

PLOT A22P1(1)-A22P1(8) HP A22P1(10) A22P1(15) 02 -3 1 * DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$0.05 * \delta_c$

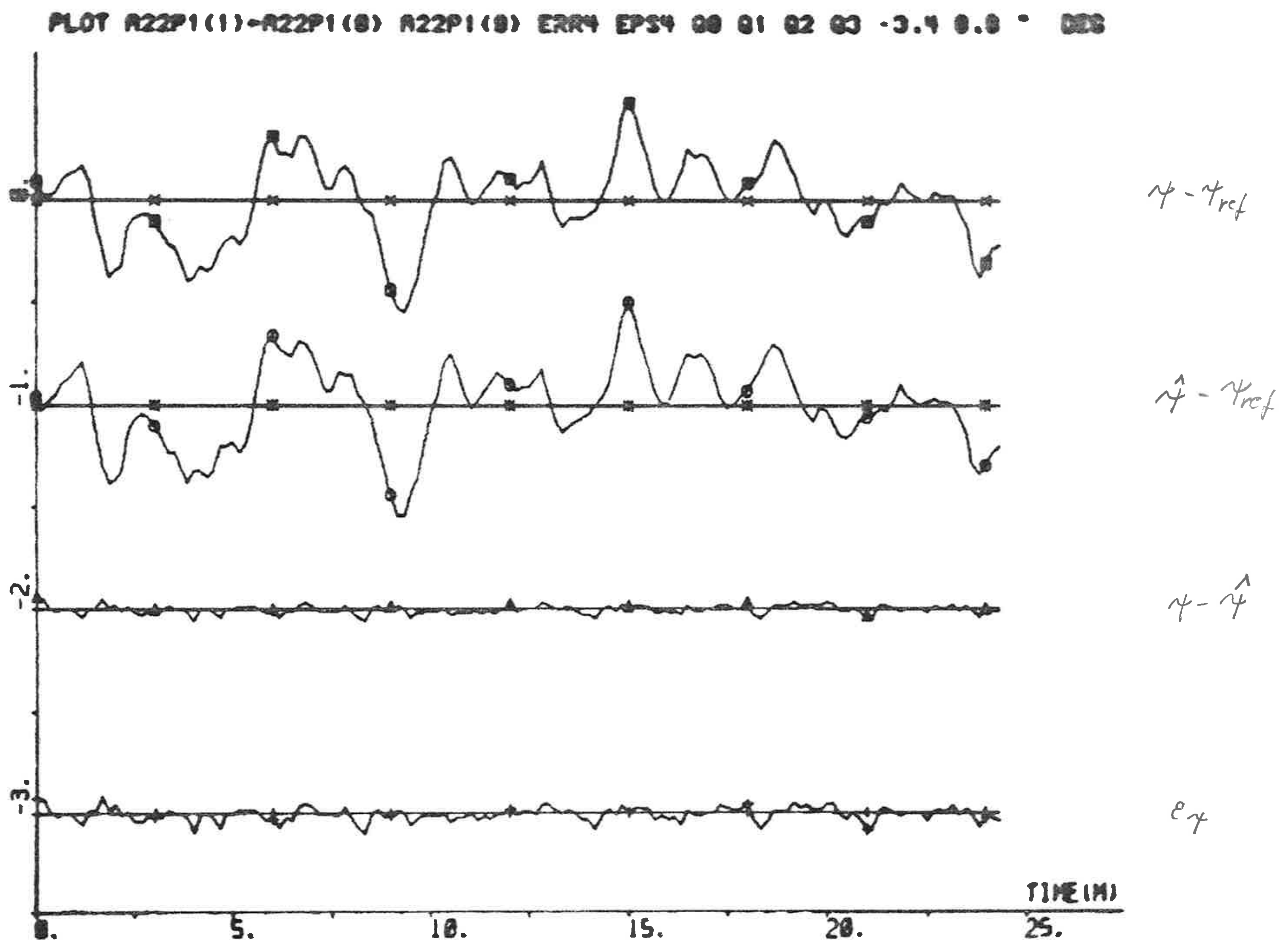

PLOT A22P1(1)-A22P1(13) A22P1(12) A22P1(14) A22P1(11)
0.5 * n rpm
2 * u knots
P_s MW
δ_s deg
TIME (H)
0.
5.
10.
15.
20.
25.
-20.
0.
20.
40.


PLOT A22P1(1)-A22P2(1) A22P2(2) ERRS 00 01 02 -3.4 0.8 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

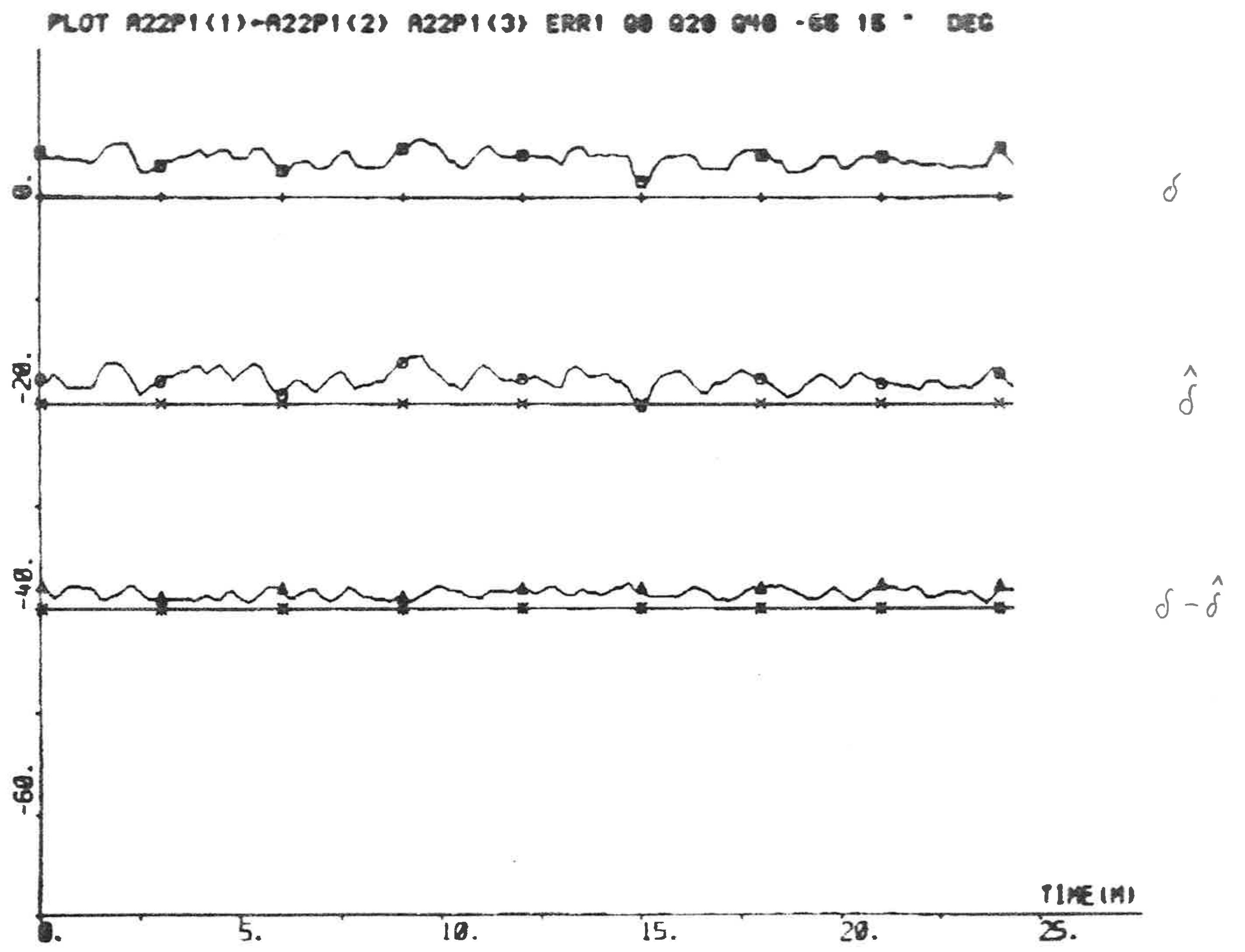

PLOT A22P1(1)-A22P1(4) A22P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V

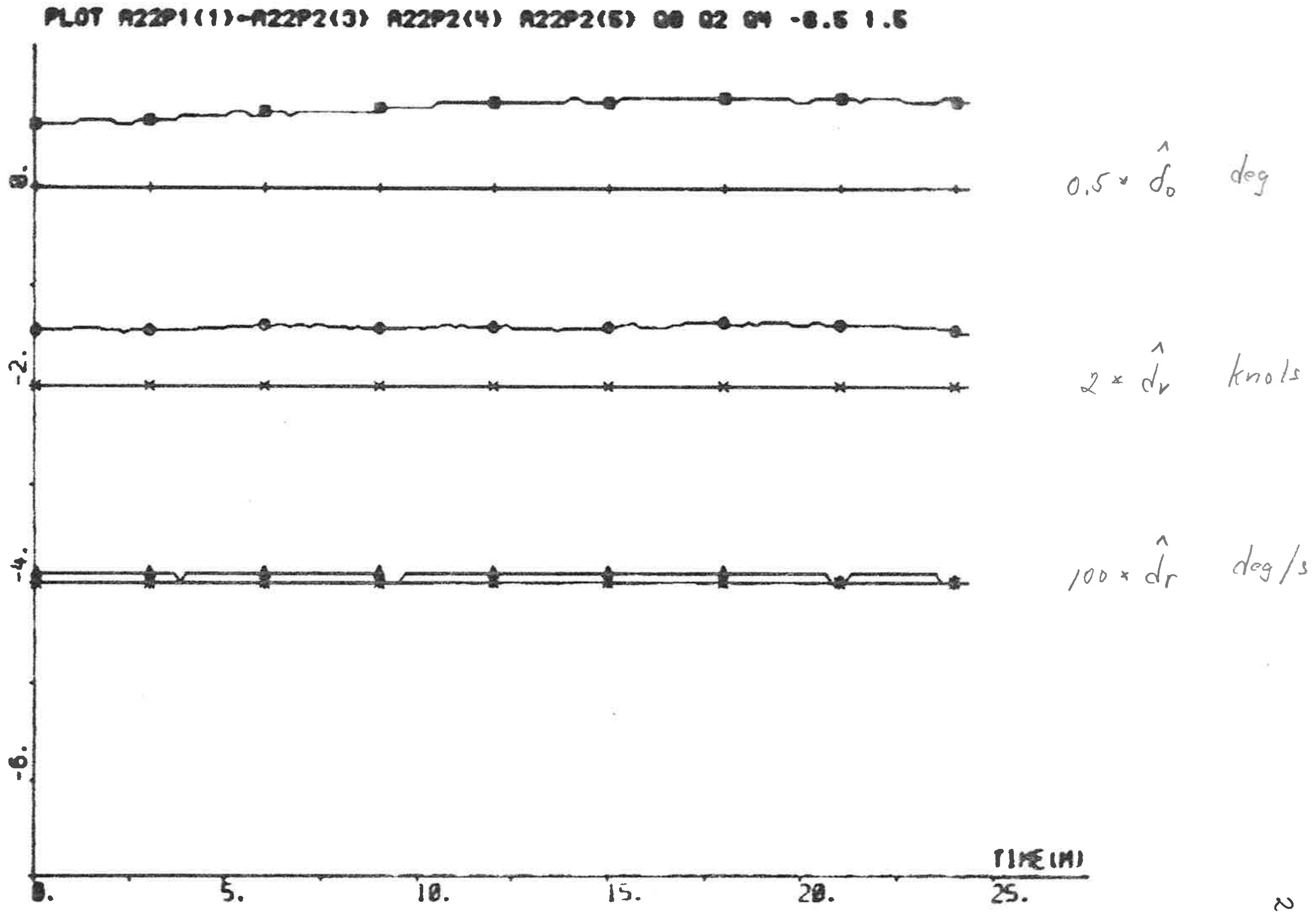
PLOT A22P1(1)-A22P1(6) A22P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. ° DEG/S



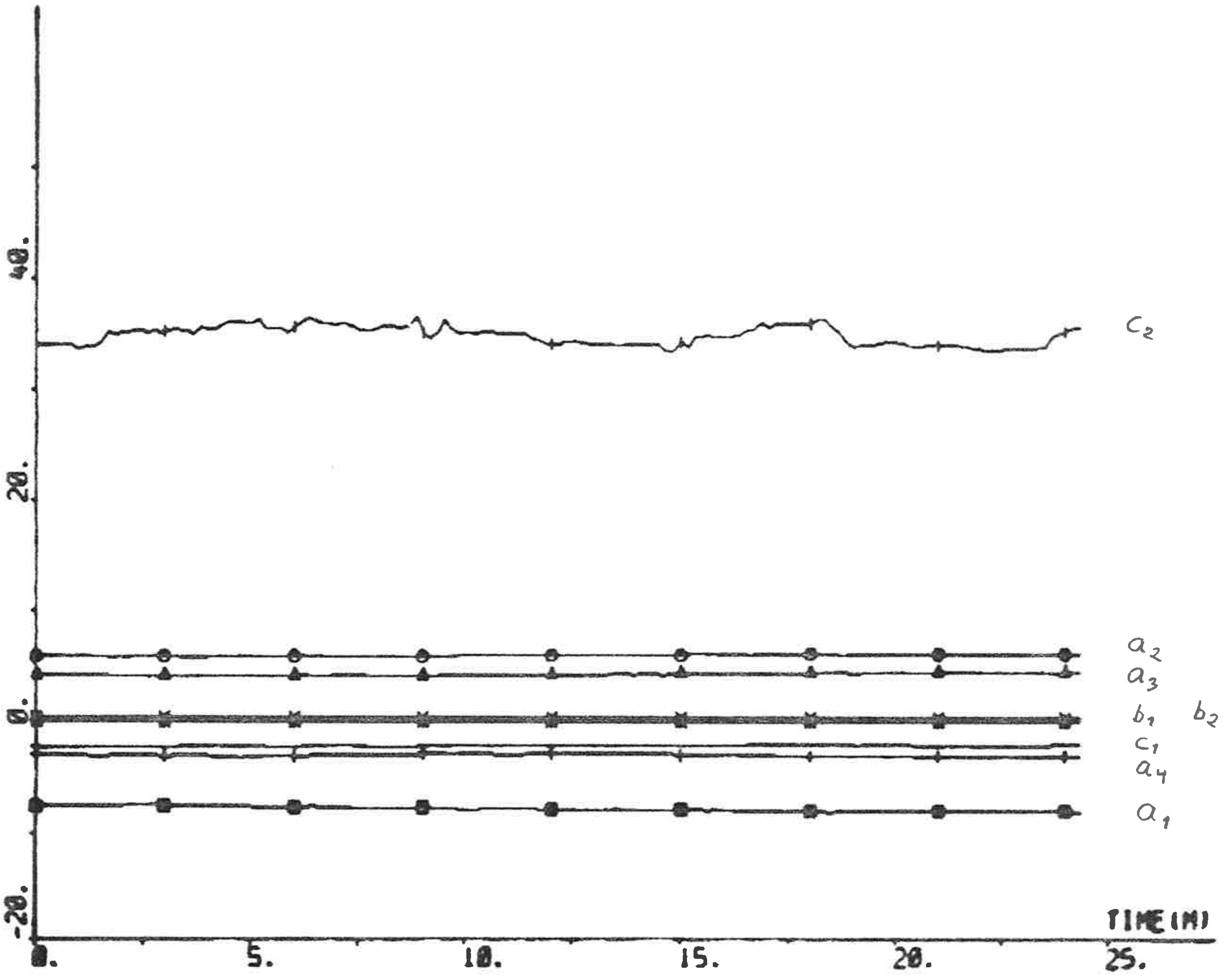


PLOT A22P1(1)-A22P1(0) A22P1(0) ERR4 EPS4 00 01 02 03 -3.4 0.0 DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$\hat{\psi} - \psi_{ref}$
$\psi - \hat{\psi}$
e_ψ


PLOT A22P1(1)-A22P1(2) A22P1(3) ERR1 00 020 040 -66 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂


PLOT A22P1(1)-A22P2(3) A22P2(4) A22P2(5) 00 02 04 -8.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * $\hat{d}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s

PLOT A22P1(1)-A22P2(7) A22P2(8) A22P2(9) A22P2(10) A22P2(11) A22P2(12) A8



EXPERIMENT A23

Date	1976-04-25	Forward draught	8.5 m
Time	13.28	Aft draught	12.5 m
Duration	25 min	Wind direction	SE (1; see App. A)
Position	S 02°02' W 09°33'	Wind velocity	13 m/s (strong breeze)
ψ_{ref}	141 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter

The sway velocity v_1 was not used by the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.24 \\ 6.33 \\ 4.12 \\ -3.37 \\ 0.50 \\ 0.12 \\ -1.82 \\ 37.53 \end{bmatrix} \qquad P = \begin{bmatrix} 6.02 & & & & & & & \\ -6.95 & 13.83 & & & & & & \\ -0.65 & -7.97 & 15.99 & & & & & \\ 1.79 & 0.91 & -7.59 & 5.45 & & & & \\ 0.01 & -0.32 & 0.46 & -0.14 & 0.04 & & & \\ 0.02 & -0.02 & -0.15 & 0.18 & 0.00 & 0.03 & & \\ -3.79 & 3.37 & 1.52 & -0.74 & -0.03 & -0.07 & 6.81 & \\ -41.09 & 26.99 & 19.96 & 1.18 & -0.25 & -1.28 & 112.93 & 2271.61 \end{bmatrix}$$

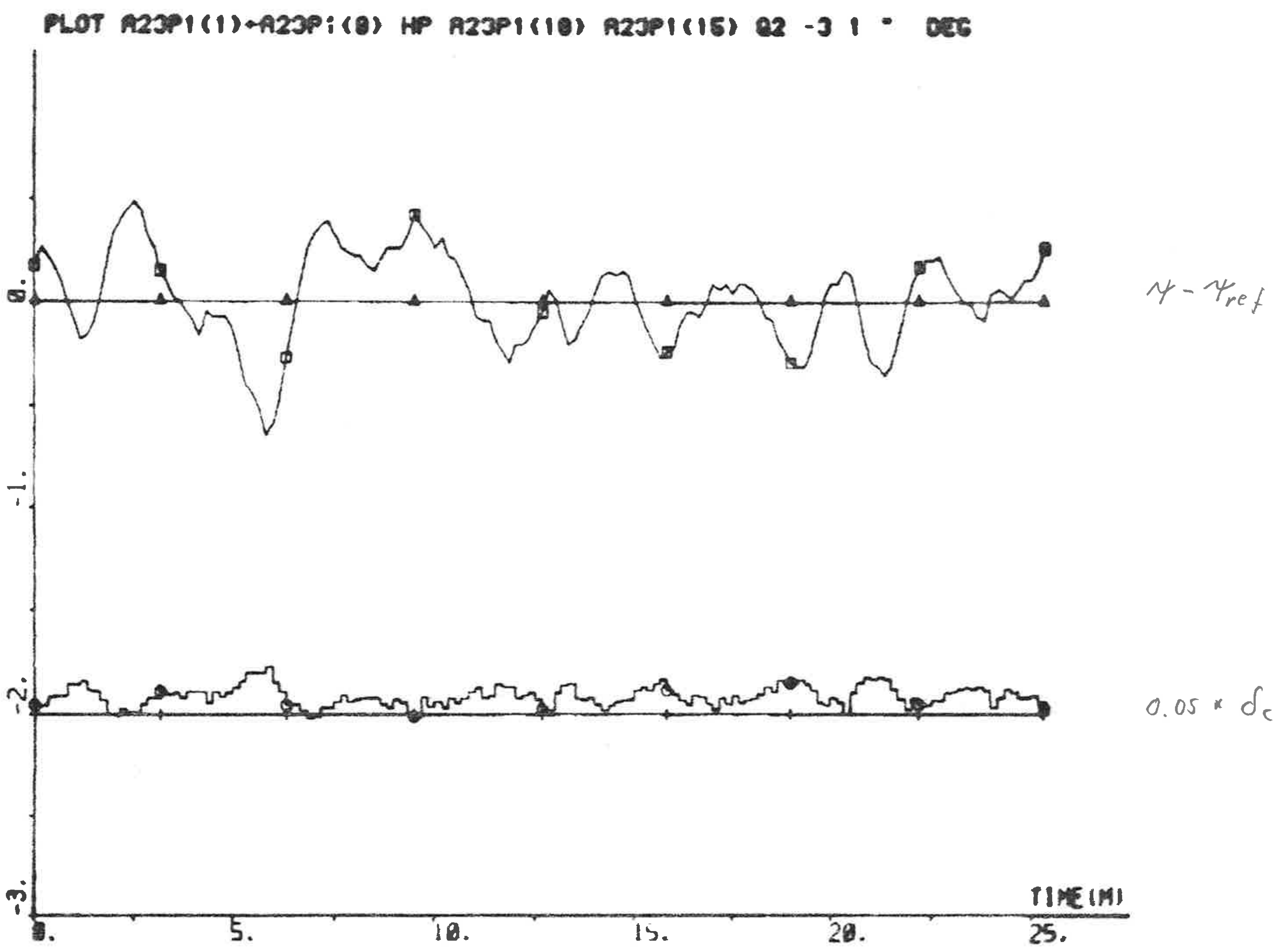
$a_1 + a_2 + a_3 + a_4 = -0.16$

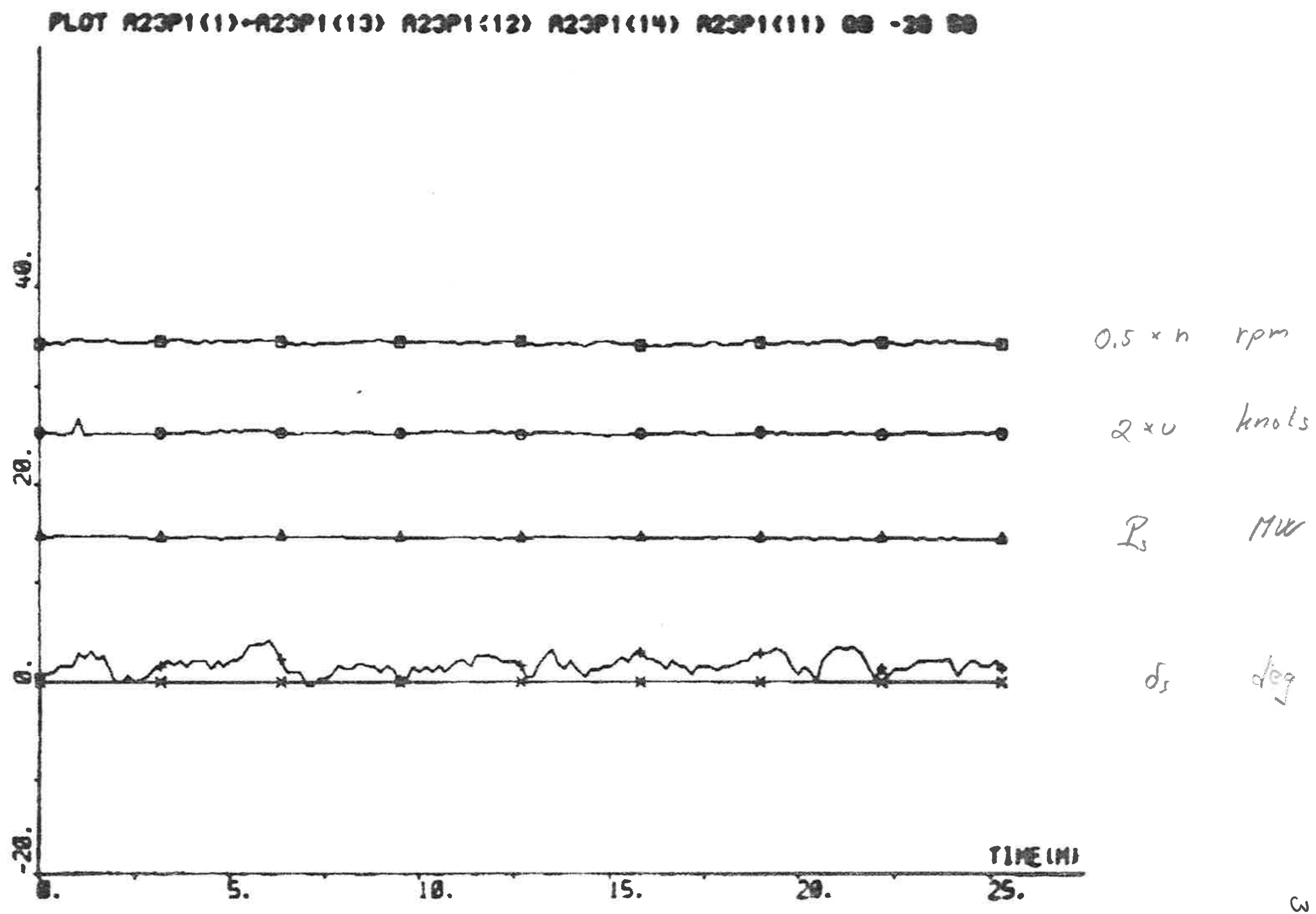
$\hat{\delta}_0 = 1.6$ deg $\hat{d}_v = -$ $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.4$ deg

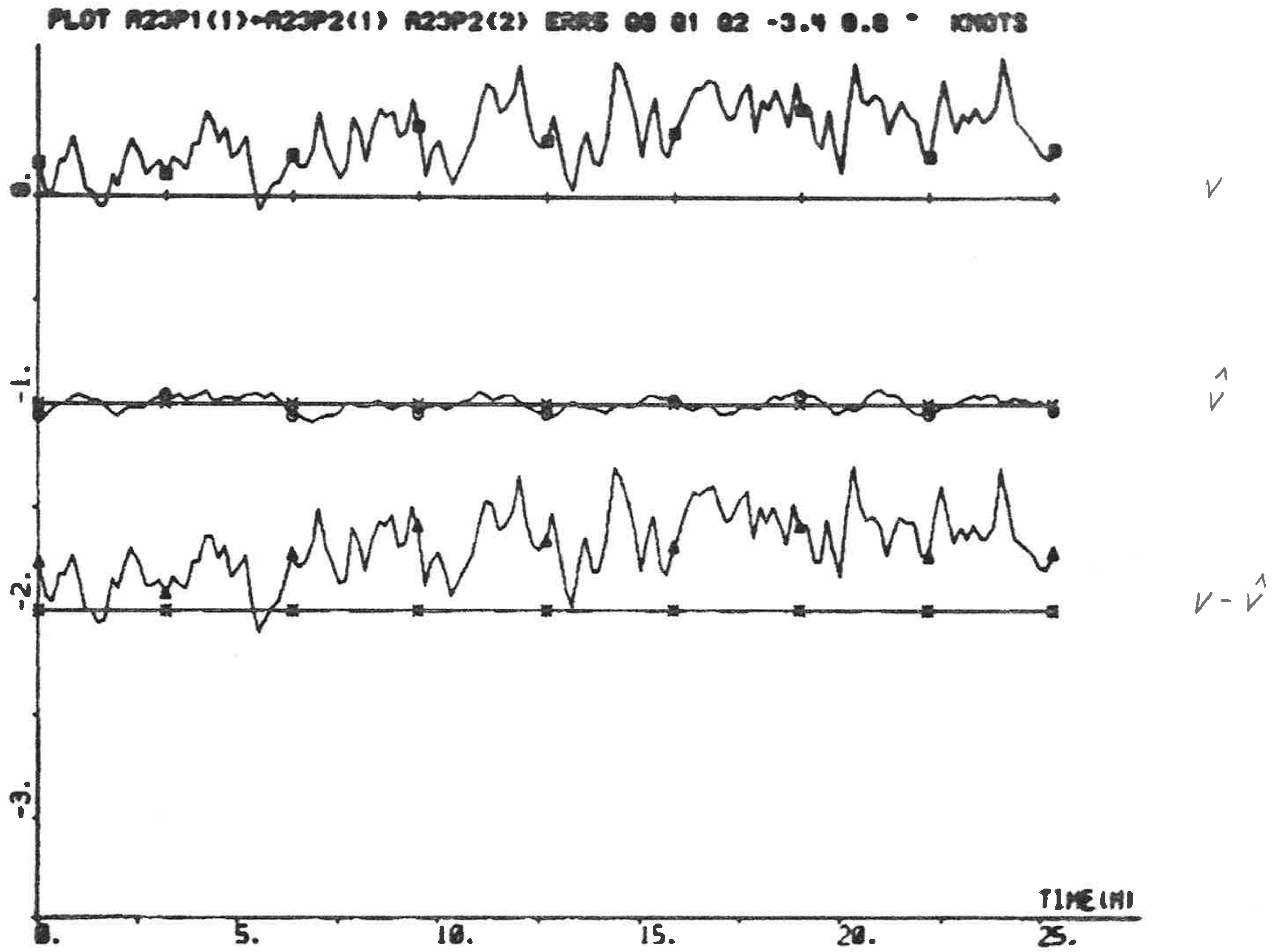
Statistics (mean value and standard deviation)

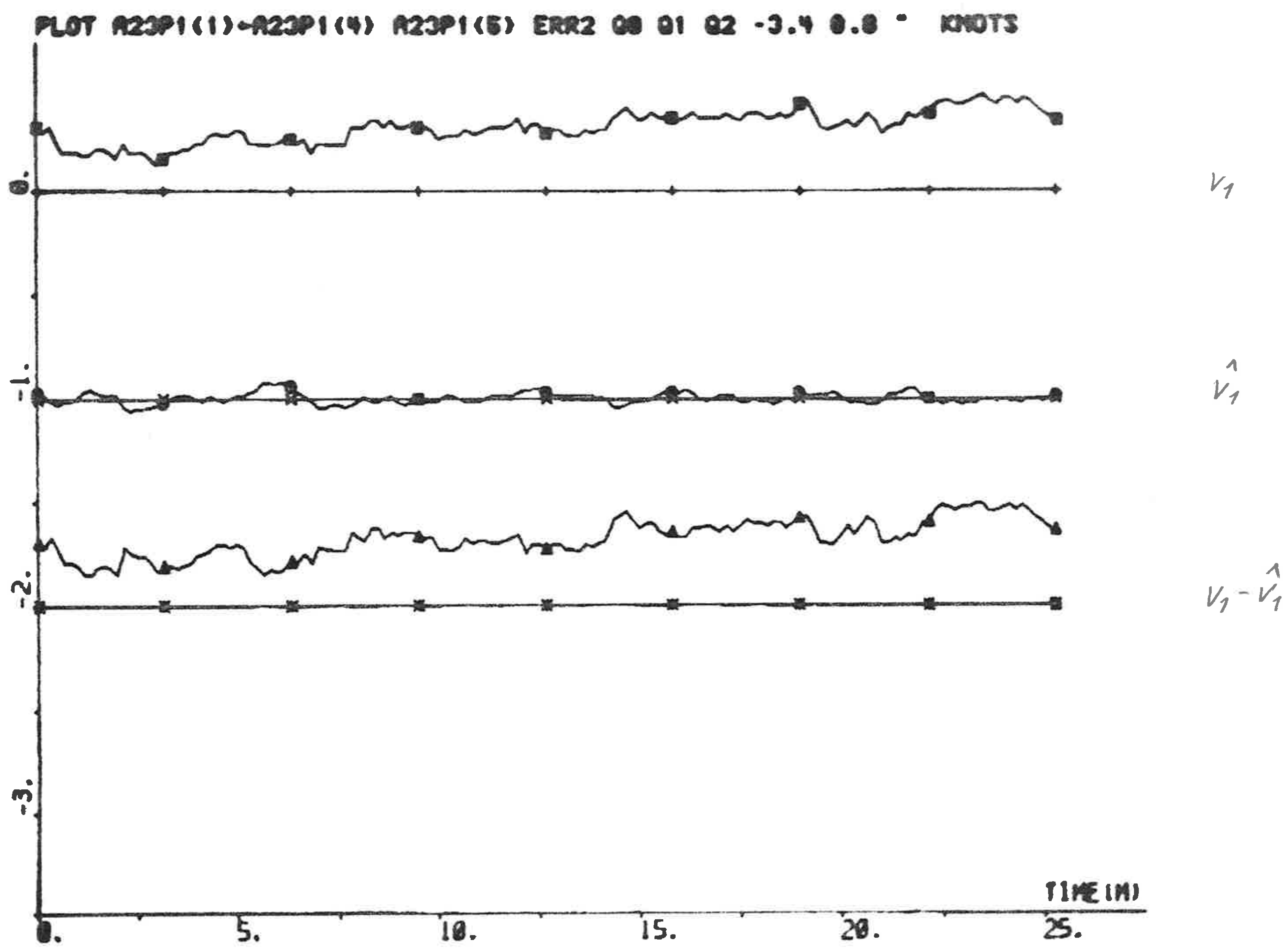
δ_c	1.71 ± 0.94	deg		P_s	14.5 ± 0.1	MW
δ	3.18 ± 0.72	deg		ε_v	-	
$\psi-\psi_{ref}$	0.015 ± 0.217	deg		ε_r	0.00 ± 0.03	deg/s
n	69.0 ± 0.3	rpm		ε_ψ	0.00 ± 0.03	deg
u	12.6 ± 0.1	knots		ε_δ	0.0 ± 0.5	deg

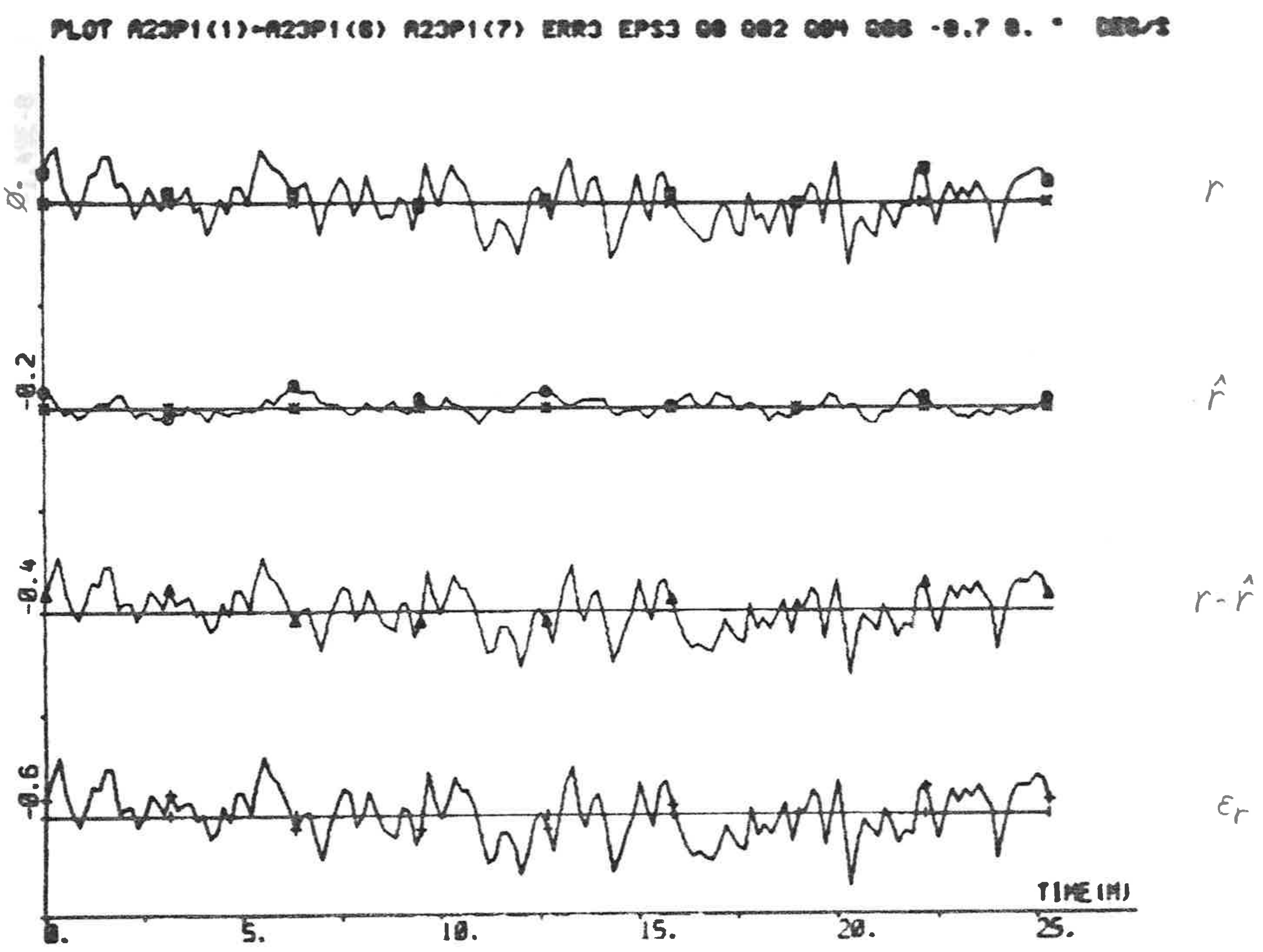
$V_1 = 0.121$

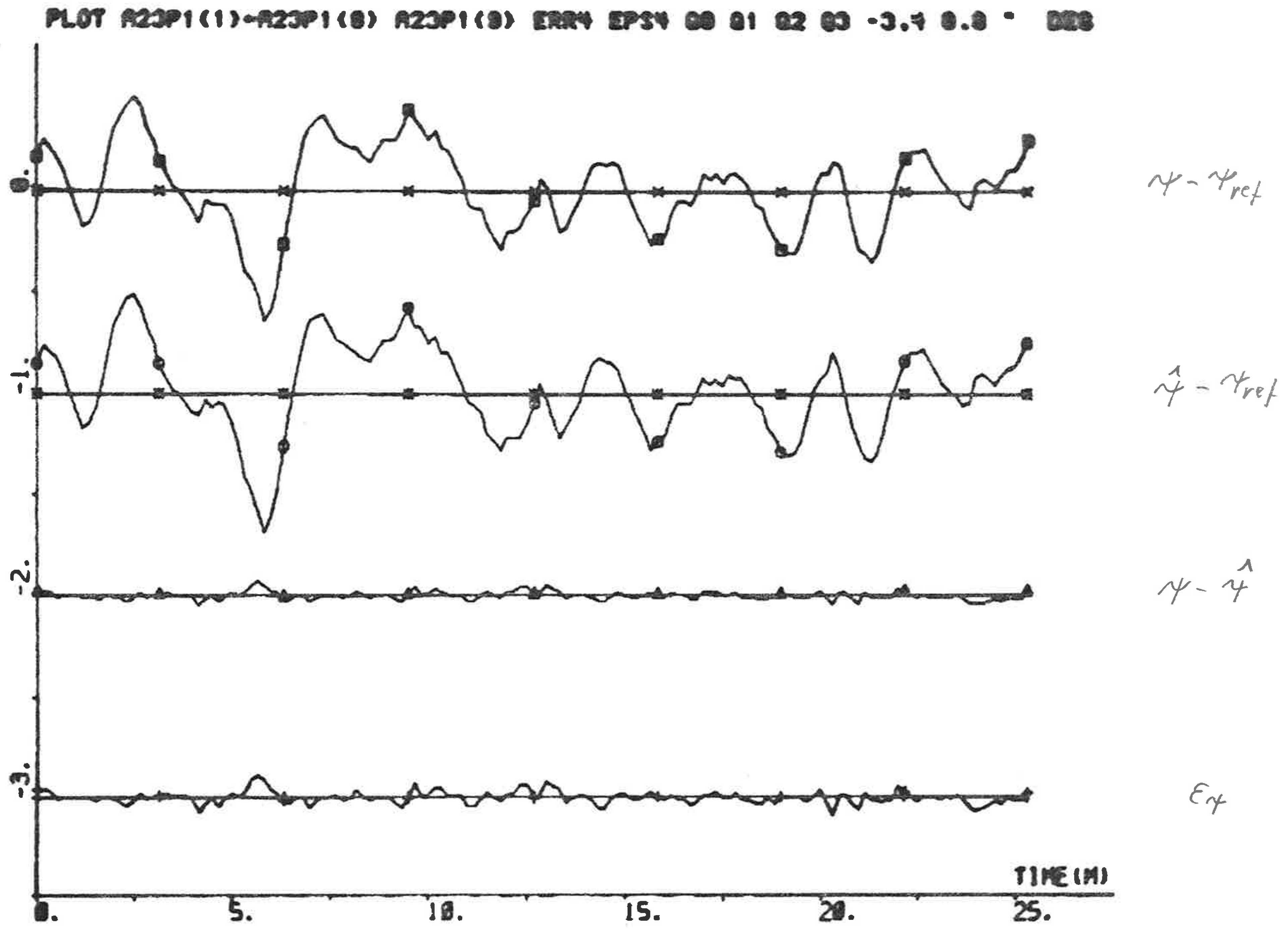

PLOT A23P1(1)-A23P1(8) HP A23P1(10) A23P1(15) Q2 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$0.05 * \delta_c$


PLOT A23P1(1)-A23P1(13) A23P1(12) A23P1(14) A23P1(11) 00 -30 00
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 × n rpm
2 × v knots
P_s MW
δ_s deg

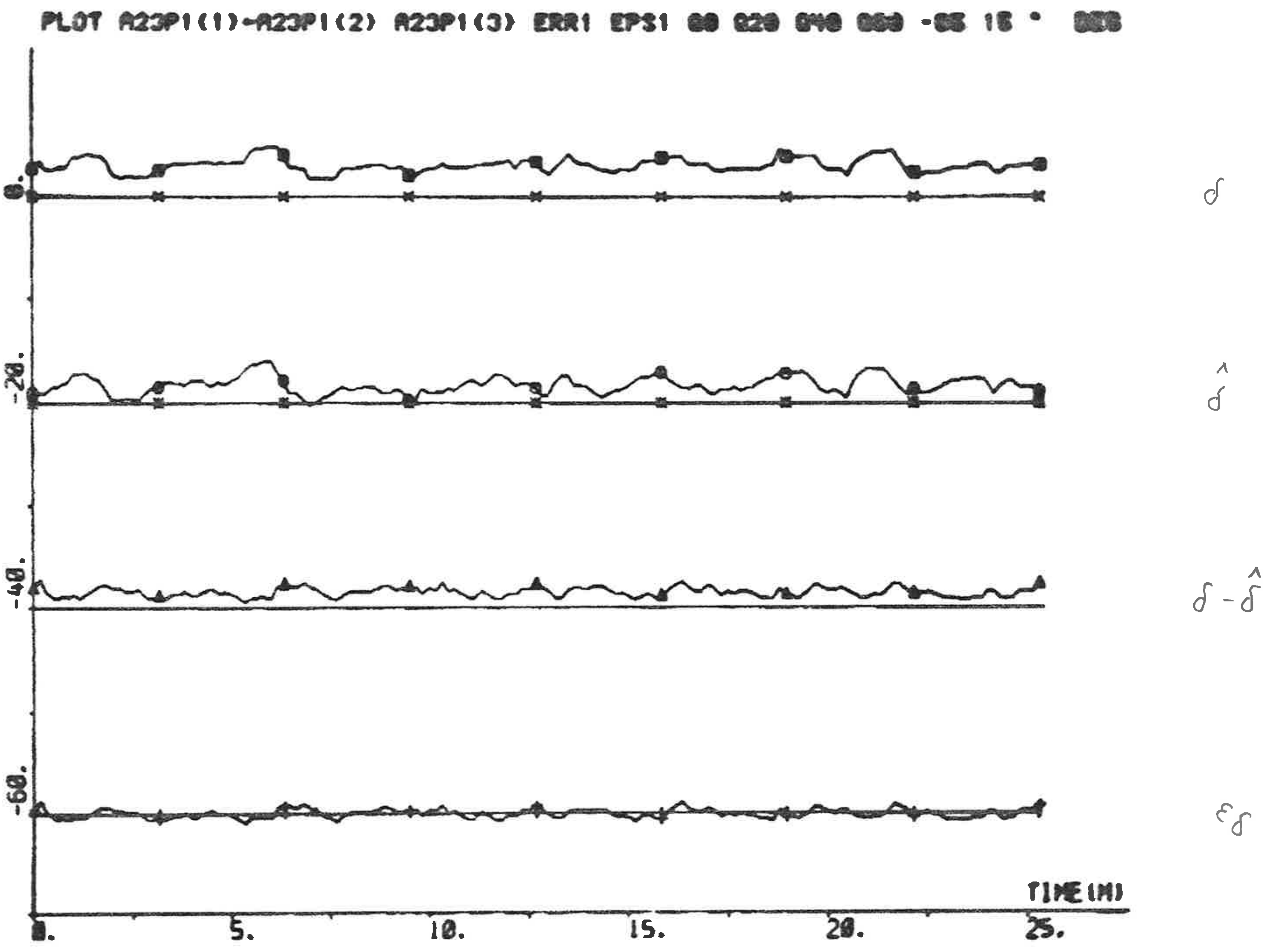

PLOT A23P1(1)-A23P2(1) A23P2(2) ERRS 00 01 02 -3.4 0.8 ° KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.

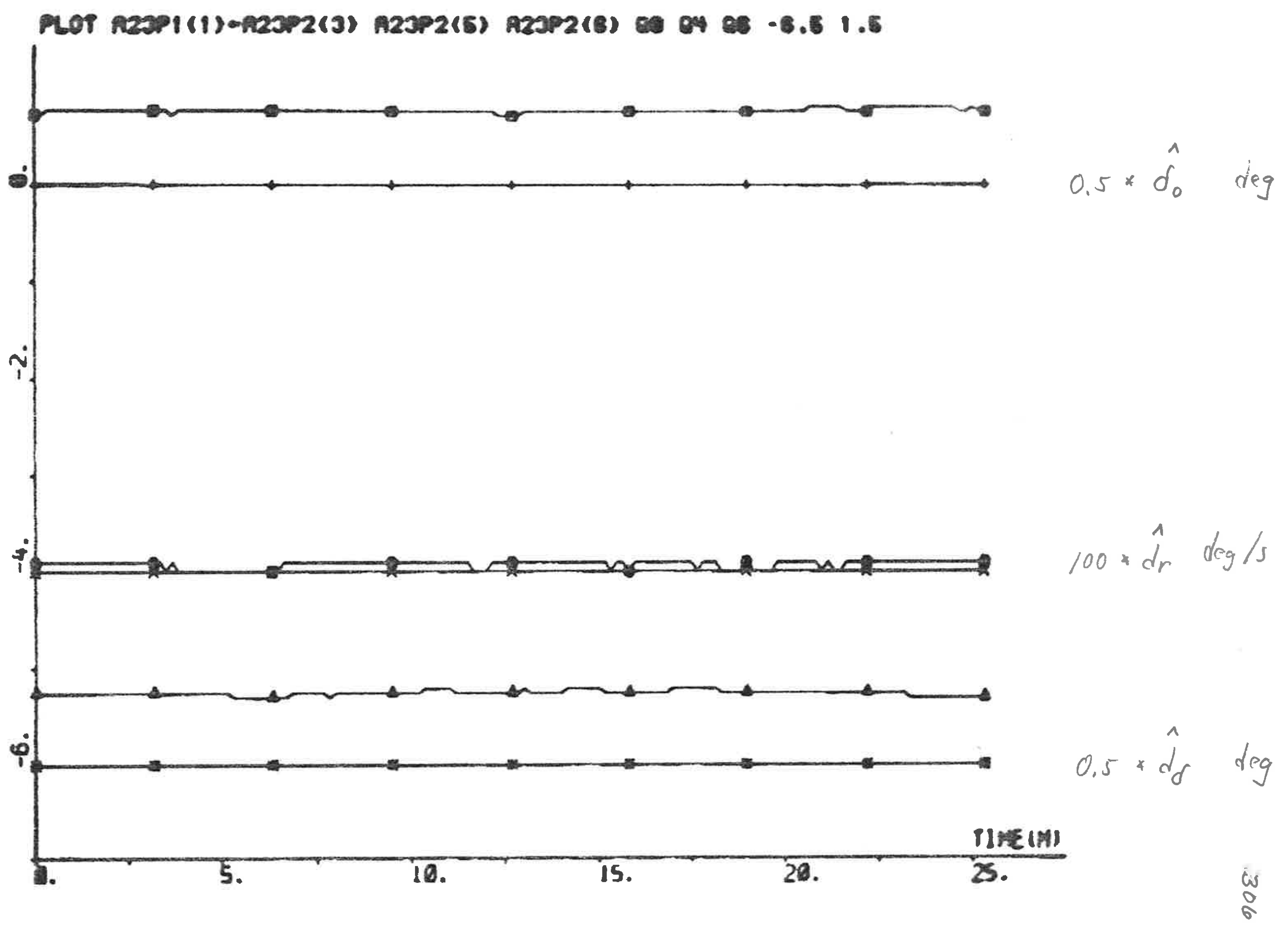

PLOT A23P1(1)-A23P1(4) A23P1(5) ERR2 Q0 Q1 Q2 -3.4 0.8 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$

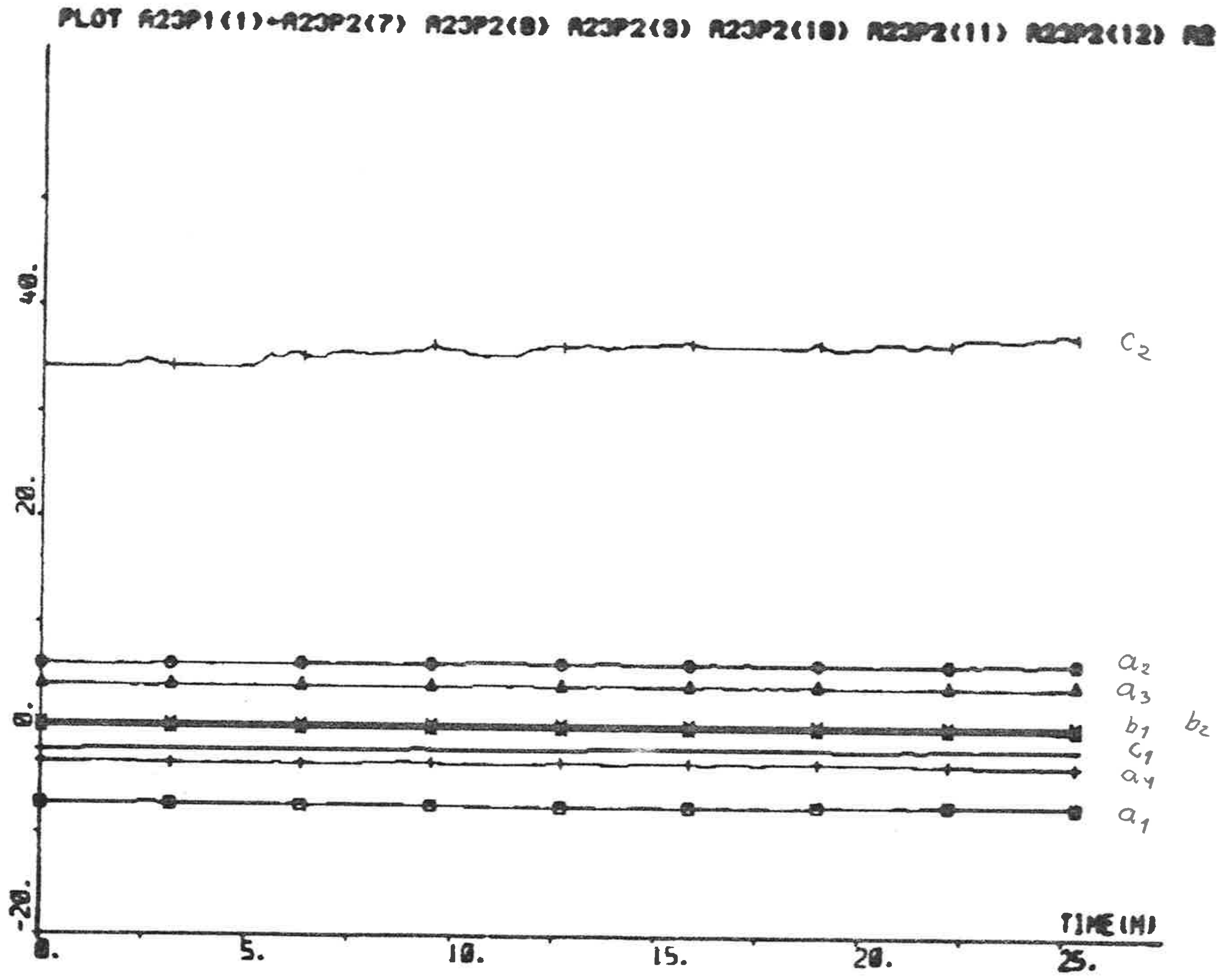

PLOT A23P1(1)-A23P1(6) A23P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. * DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME(M)
0.
5.
10.
15.
20.
25.



PLOT A23P1(1)-A23P1(8) A23P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A23P1(1)-A23P1(2) A23P1(3) ERR1 EPS1 00 020 040 060 -05 15
0.
-20.
-40.
-60.
TIME(M)
0.
5.
10.
15.
20.
25.
δ
δ̂
δ - δ̂
δ3


PLOT A23P1(1)-A23P2(3) A23P2(5) A23P2(6) G8 G4 G6 -6.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
$0.5 * \hat{\delta}_o$ deg
$100 * \hat{d}_r$ deg/s
$0.5 * \hat{d}_\delta$ deg
306


PLOT A23P1(1)-A23P2(7) A23P2(8) A23P2(9) A23P2(10) A23P2(11) A23P2(12) AB
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(H)
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT A24

Date	1976-04-25	Forward draught	8.5 m
Time	14.30	Aft draught	12.5 m
Duration	25 min	Wind direction	SE (1; see App. A)
Position	S 02°13' W 09°26'	Wind velocity	14 m/s (moderate gale)
ψ_{ref}	141 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter

The yaw rate r was not used by the Kalman filter.

Tuning time before the experiment started: 30 min

NC1 = 1 NC2 = 1 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.40 \\ 7.15 \\ 4.96 \\ -3.79 \\ 0.51 \\ 0.13 \\ -1.76 \\ 40.37 \end{bmatrix} \qquad P = \begin{bmatrix} 5.59 \\ -7.19 & 15.43 \\ -1.02 & -8.40 & 18.01 \\ 2.85 & -0.11 & -8.85 & 6.35 \\ -0.12 & -0.32 & 0.74 & -0.30 & 0.07 \\ 0.02 & -0.07 & -0.17 & 0.24 & 0.00 & 0.05 \\ -1.70 & 2.40 & 0.56 & -1.35 & -0.04 & -0.08 & 1.82 \\ 38.35 & -57.33 & -13.04 & 30.46 & -0.15 & 0.43 & 0.22 & 1378.53 \end{bmatrix}$$

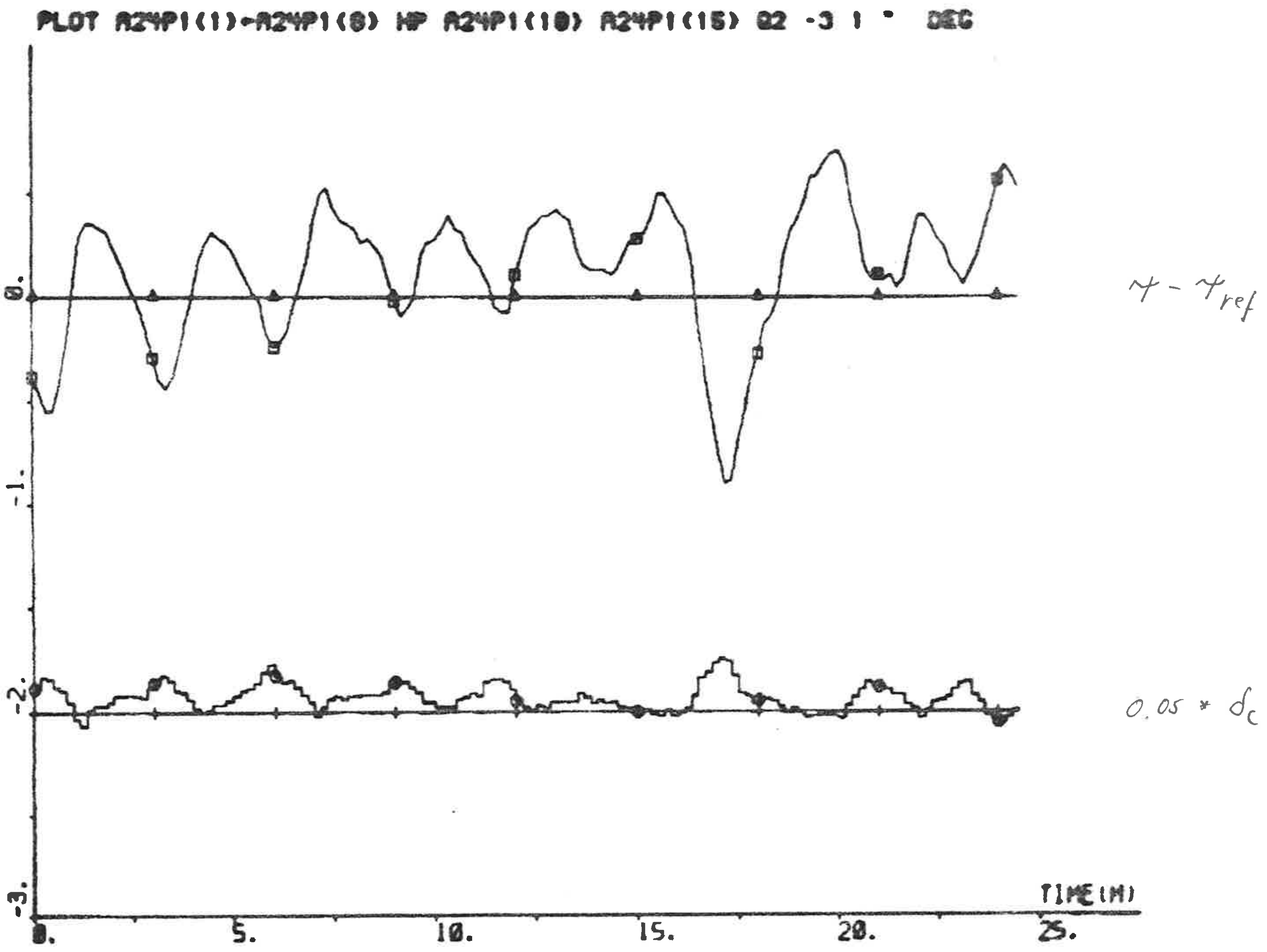
$a_1 + a_2 + a_3 + a_4 = -0.08$

$\hat{\delta}_0 = 1.4$ deg $\hat{d}_v = 0.15$ knots $\hat{d}_r = -$ $\hat{d}_\delta = 1.7$ deg

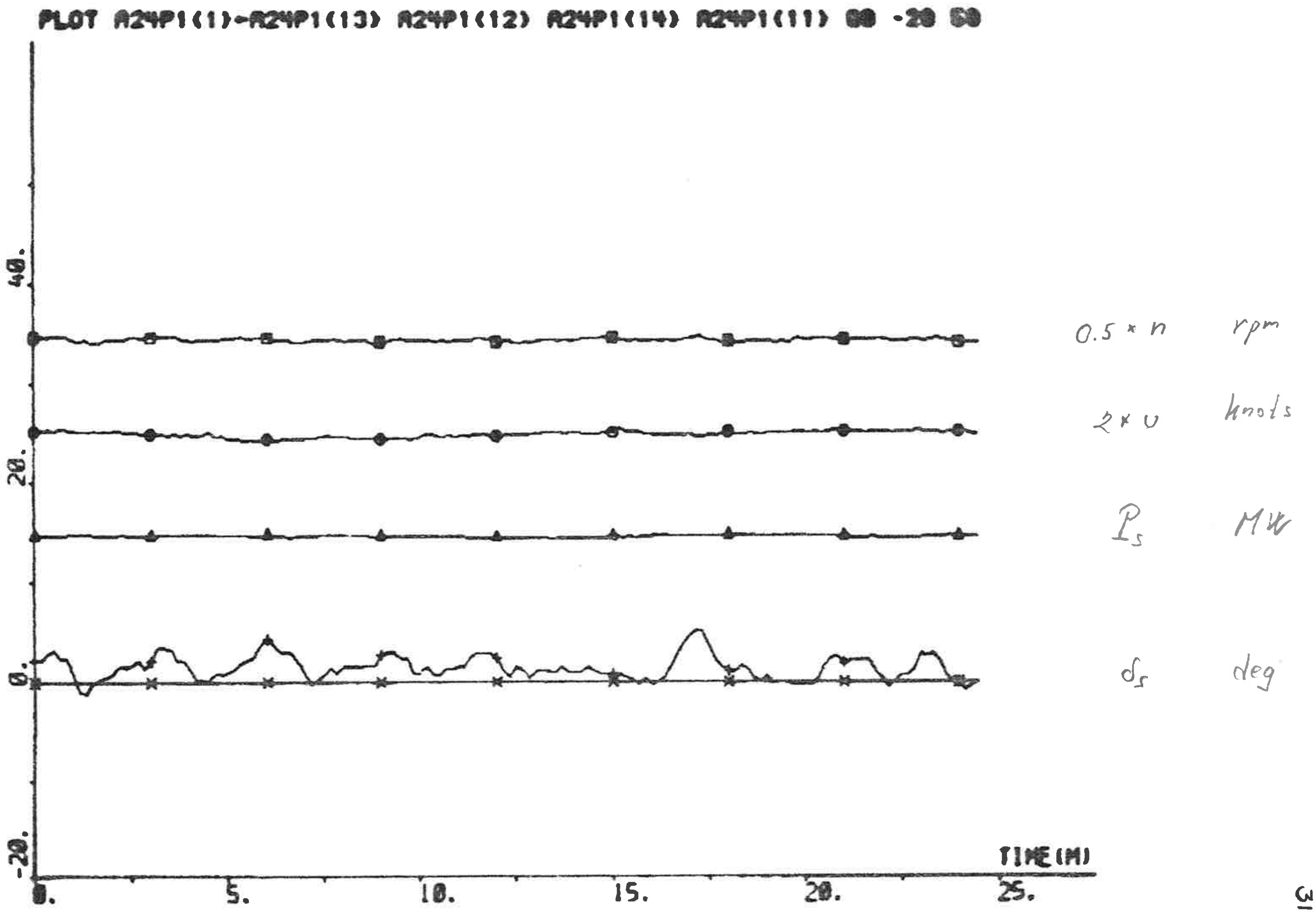
Statistics (mean value and standard deviation)

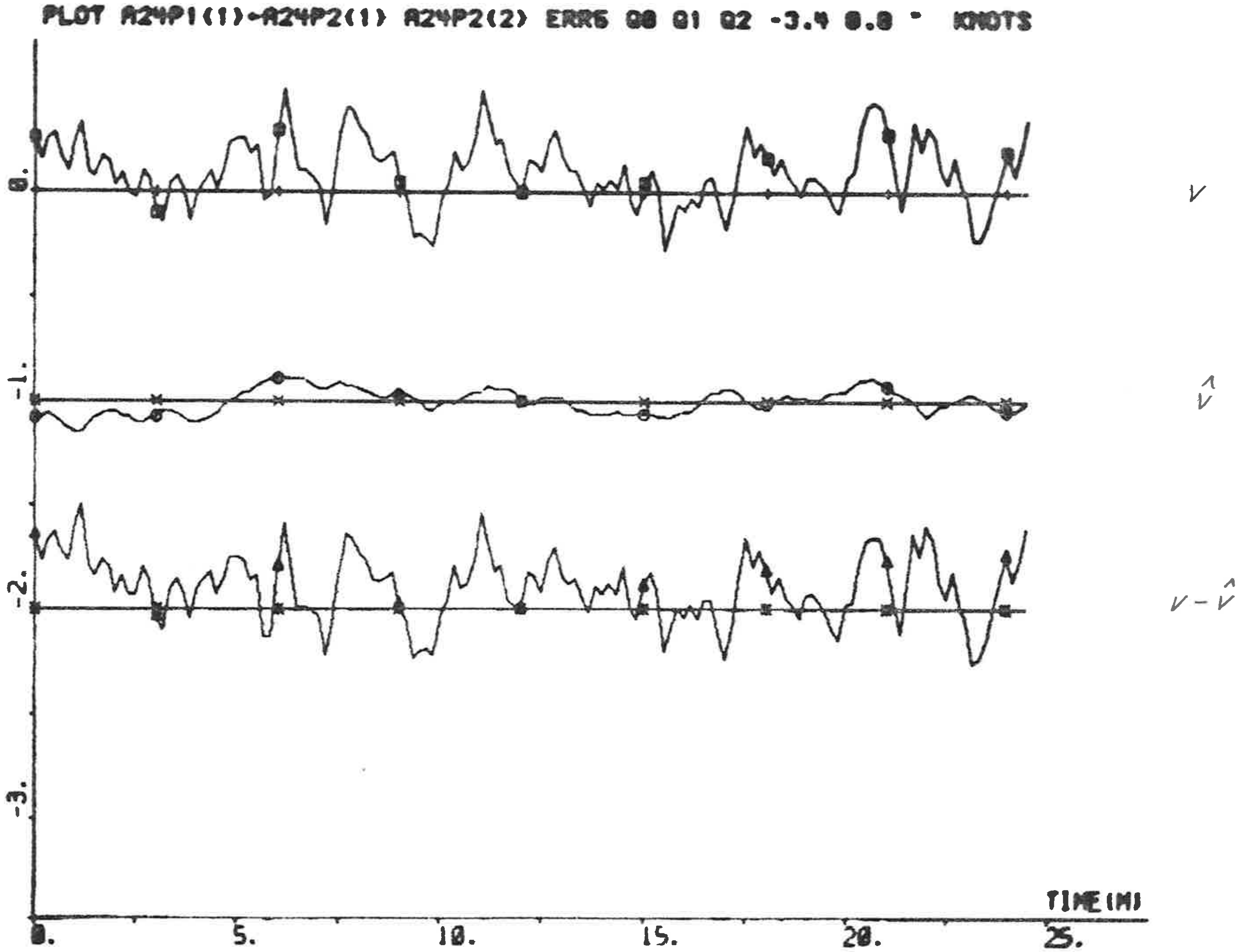
δ_c	1.34 ± 1.25 deg		P_s	14.5 ± 0.1 MW
δ	2.96 ± 1.06 deg		ε_v	0.00 ± 0.02 knots
$\psi-\psi_{ref}$	0.130 ± 0.317 deg		ε_r	-
n	68.9 ± 0.3 rpm		ε_ψ	0.00 ± 0.05 deg
u	12.5 ± 0.1 knots		ε_δ	0.1 ± 0.5 deg

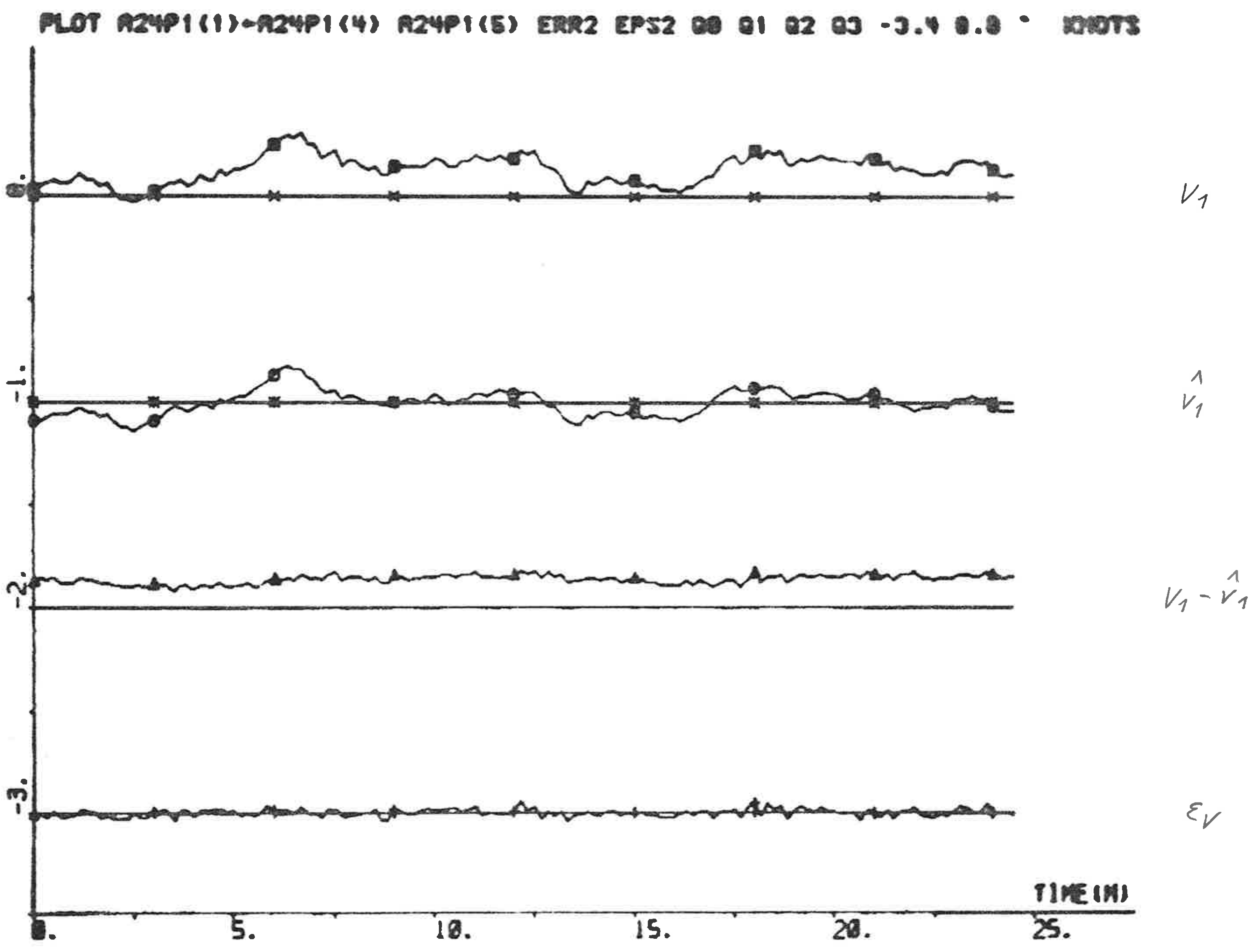
$V_1 = 0.248$



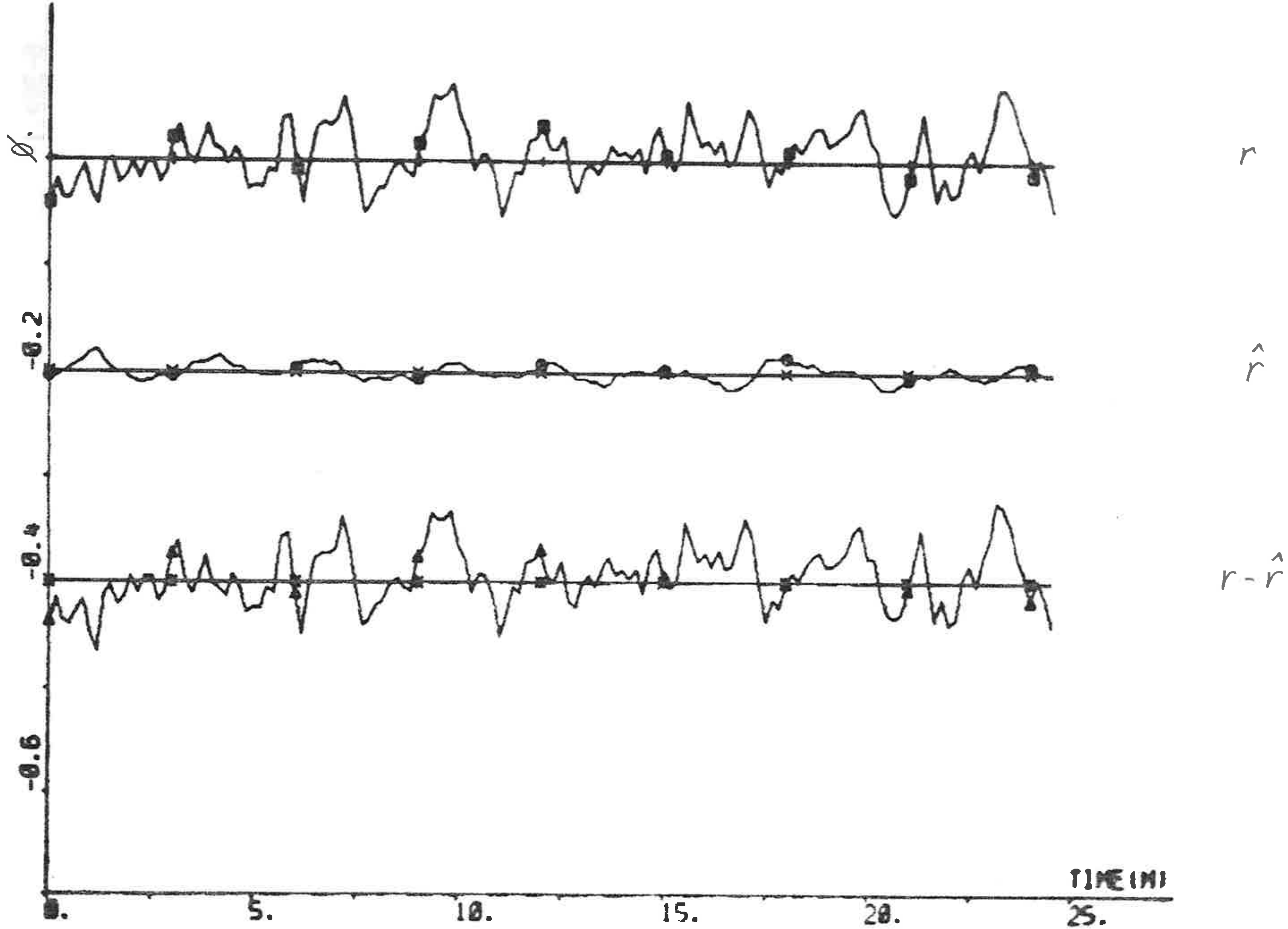
PLOT A24P1(1)-A24P1(8) HP A24P1(10) A24P1(15) 82 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

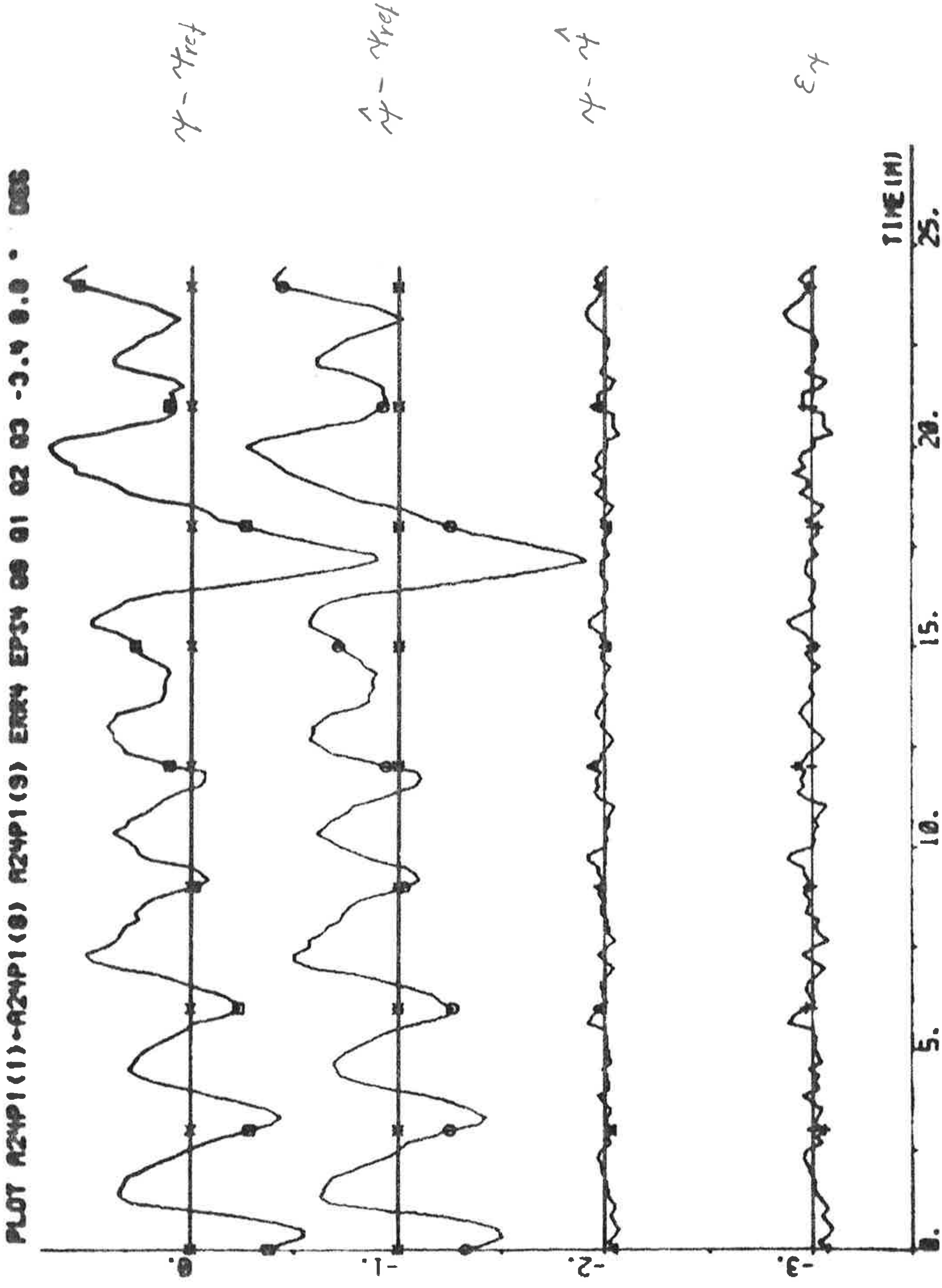

PLOT A24P1(1)-A24P1(13) A24P1(12) A24P1(14) A24P1(11) 00 -20 60
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n rpm
2 * v knots
Ps MW
δs deg

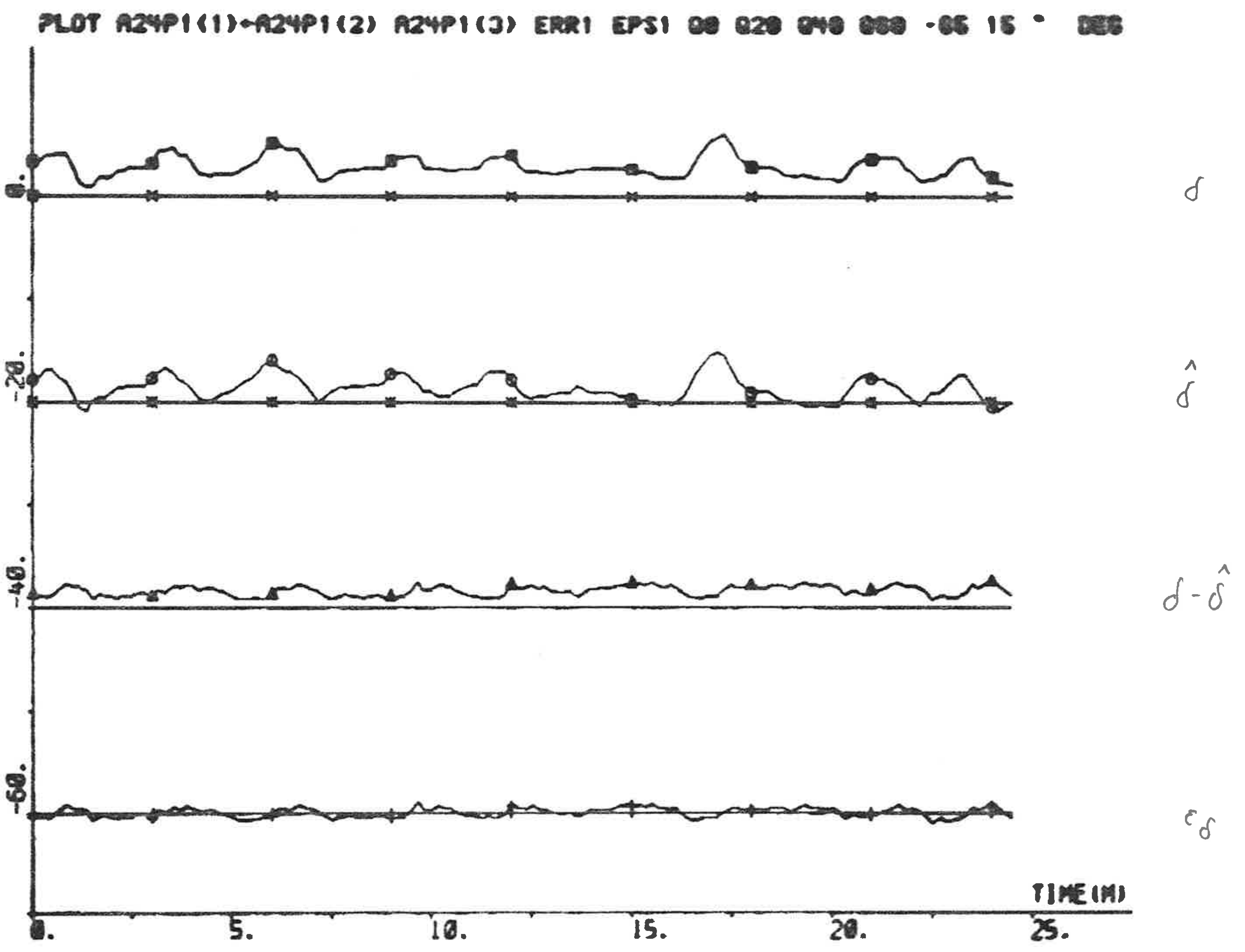

PLOT A24P1(1)-A24P2(1) A24P2(2) ERR6 Q0 Q1 Q2 -3.4 0.0 ° KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A24P1(1)-A24P1(4) A24P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V

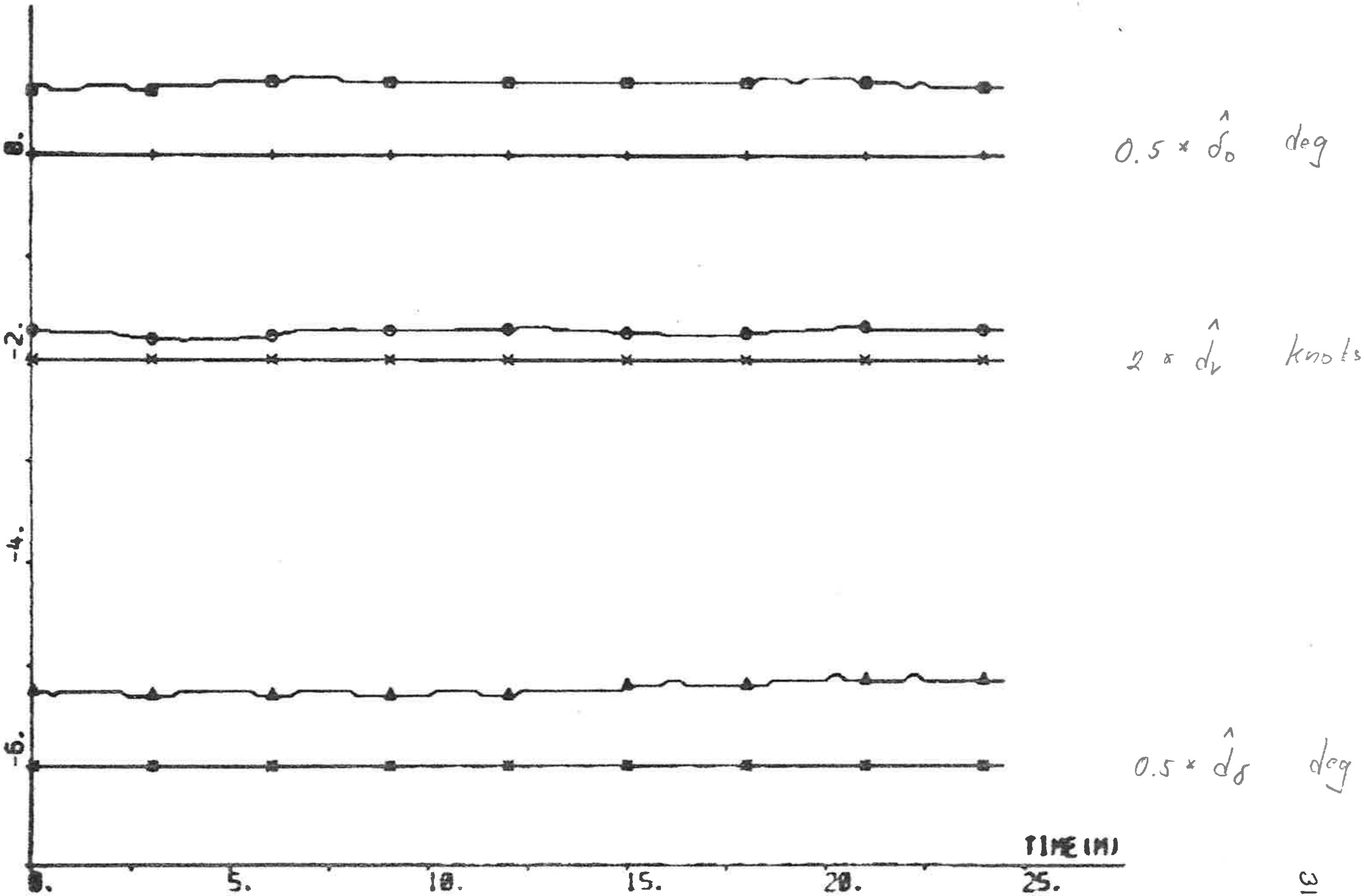
PLOT A24P1(1)+A24P1(8) A24P1(7) ERR3 00 002 004 -0.7 0. ° DEG/S

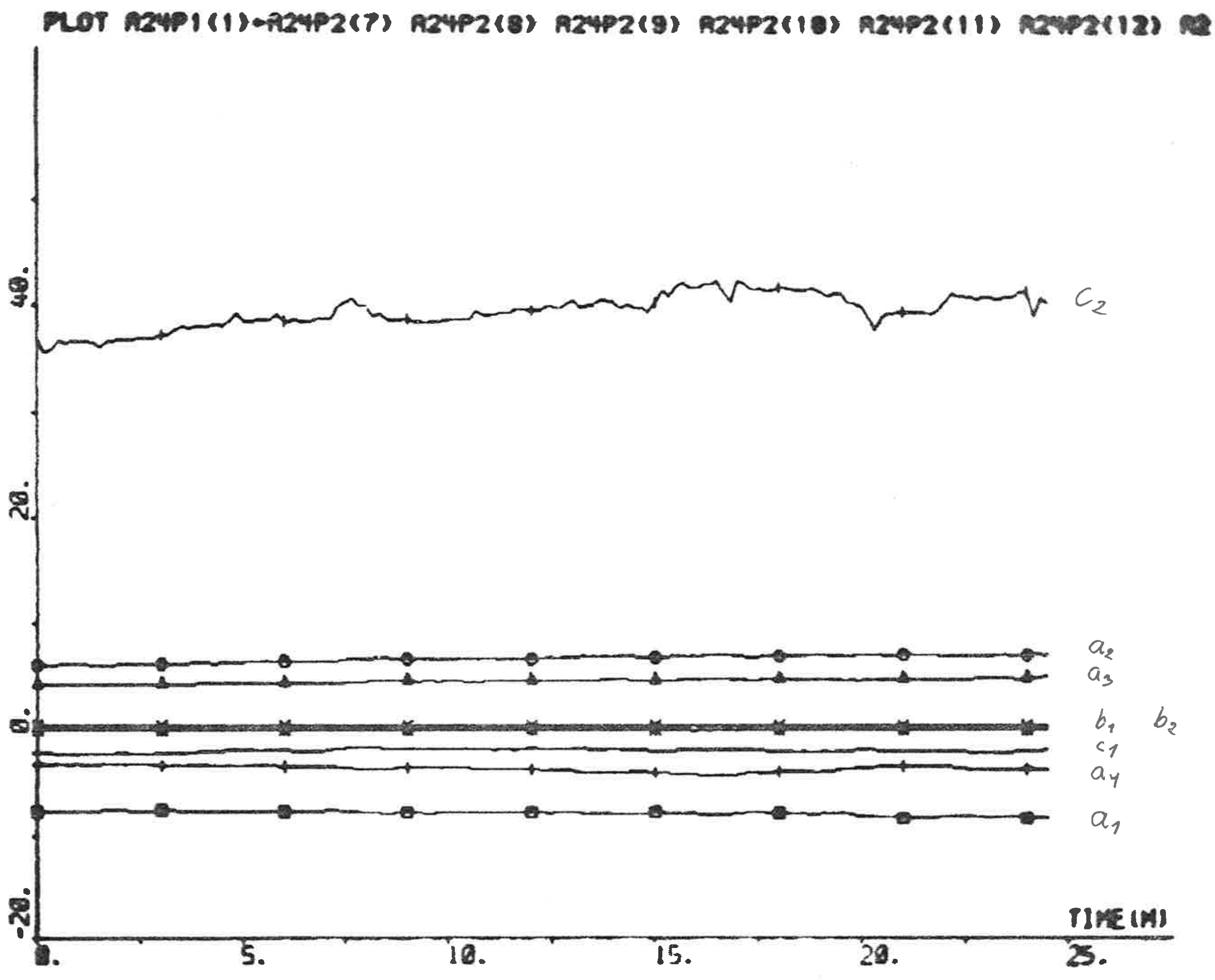



PLOT A24P1(1)-A24P1(8) A24P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 • DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A24P1(1)+A24P1(2) A24P1(3) ERR1 EPS1 00 020 040 060 -06 15 ° DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)

PLOT A24P1(1)-A24P2(3) A24P2(4) A24P2(6) 60 02 06 -6.5 1.5




PLOT R24P1(1)-R24P2(7) R24P2(8) R24P2(9) R24P2(10) R24P2(11) R24P2(12) R2
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT A25

Date	1976-04-25	Forward draught	8.5 m
Time	15.33	Aft draught	12.5 m
Duration	25 min	Wind direction	SE (1; see App. A)
Position	S 02°23' W 09°18'	Wind velocity	14 m/s (moderate gale)
ψ_{ref}	141 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter

After 9.5 min of the experiment, the heading angle ψ was not any longer used by the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.06 \\ 6.68 \\ 4.51 \\ -3.45 \\ 0.48 \\ 0.13 \\ -1.96 \\ 41.91 \end{bmatrix} \qquad P = \begin{bmatrix} 4.58 & & & & & & & \\ -6.04 & 12.90 & & & & & & \\ 0.24 & -8.04 & 14.45 & & & & & \\ 1.53 & 0.89 & -6.96 & 4.97 & & & & \\ -0.08 & -0.12 & 0.34 & -0.13 & 0.04 & & & \\ -0.11 & 0.08 & -0.04 & 0.07 & 0.01 & 0.03 & & \\ -0.27 & 0.54 & 0.11 & -0.38 & -0.01 & -0.01 & 0.97 & \\ 10.37 & -15.36 & -1.46 & 6.10 & -0.01 & -0.29 & 17.04 & 790.91 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.32$

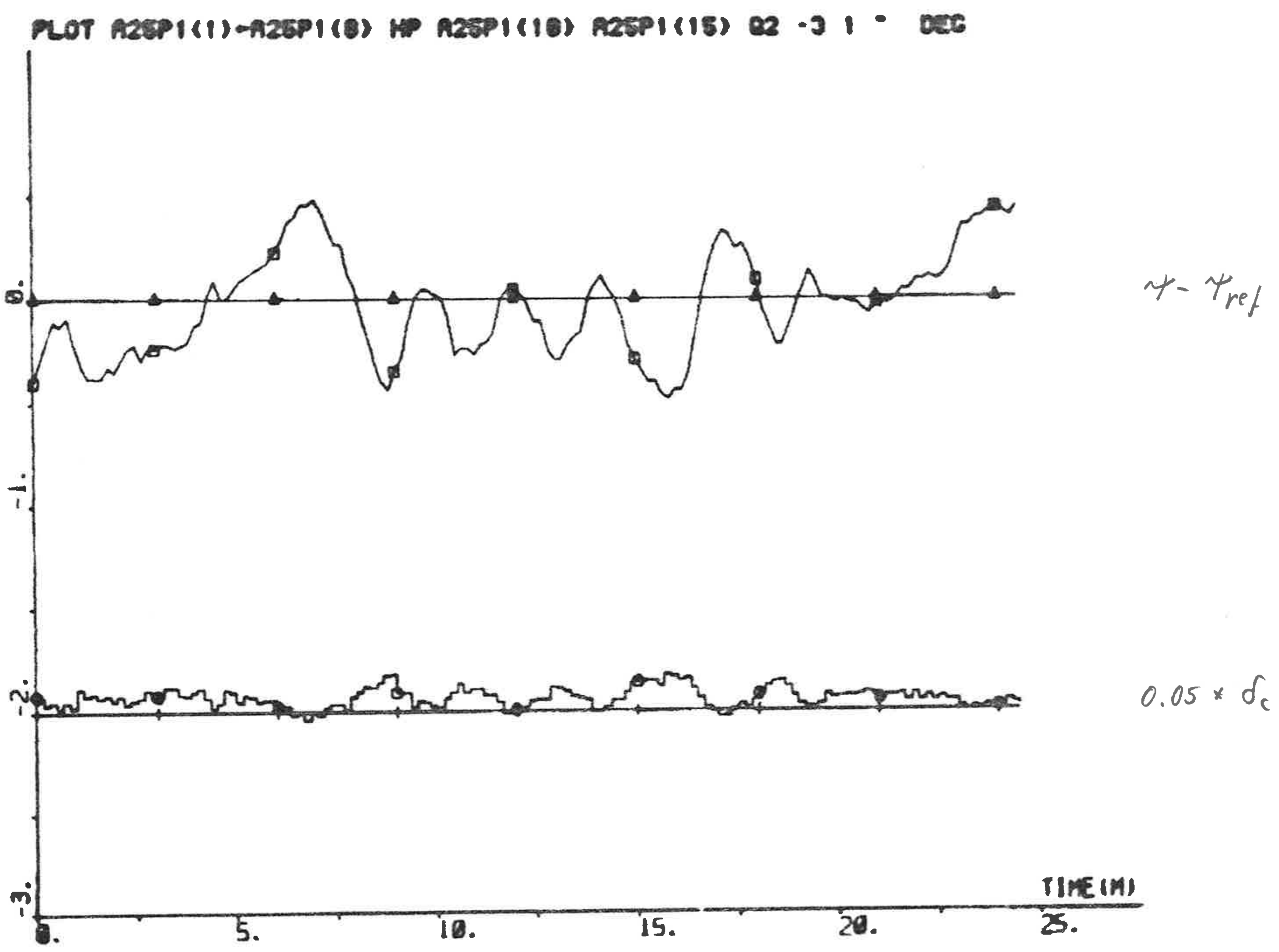
$\hat{\delta}_0 = 1.2$ deg $\hat{d}_v = 0.17$ knots $\hat{d}_r = 0.002$ deg/s $\hat{d}_\delta = 1.8$ deg

Statistics (mean value and standard deviation)

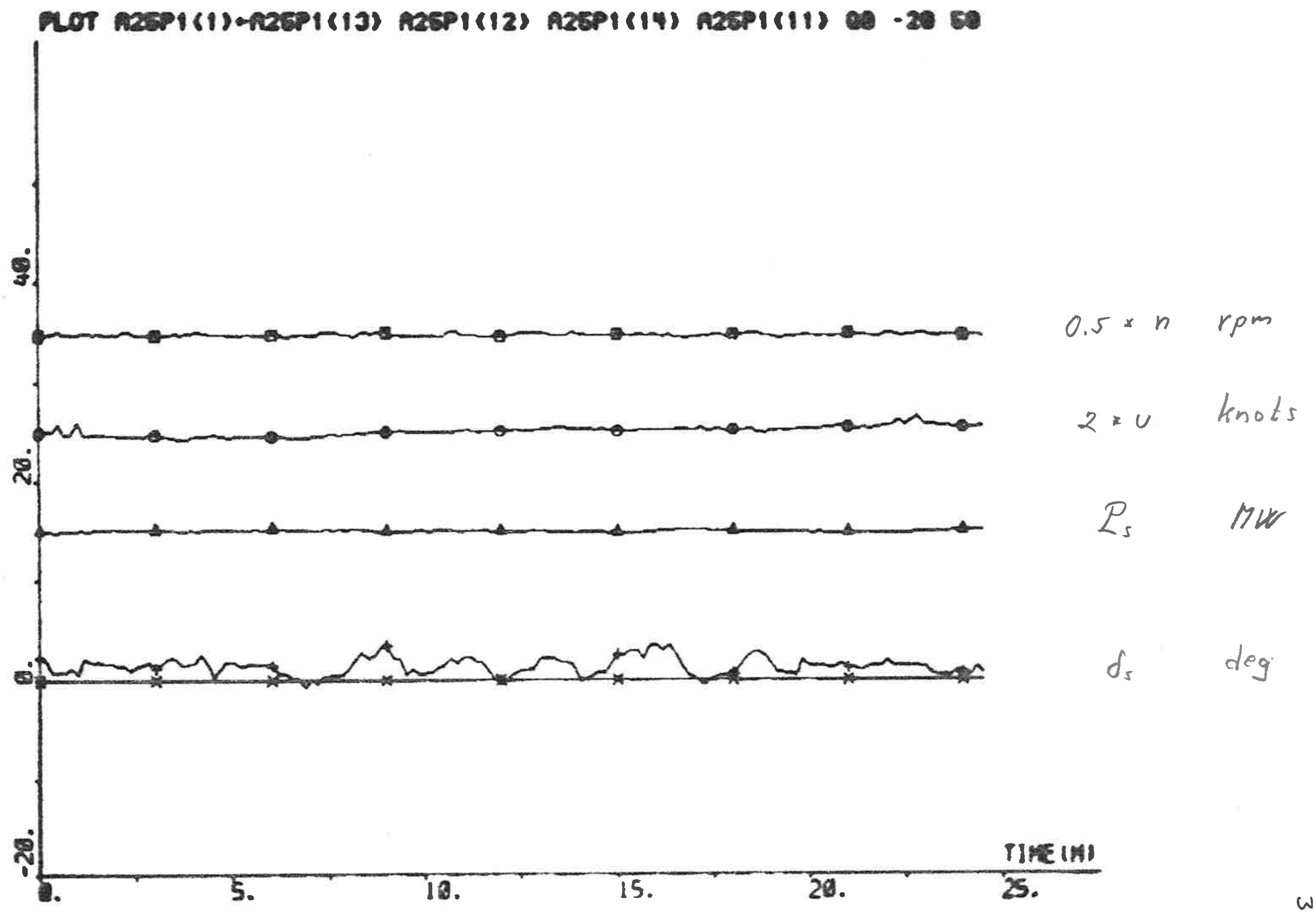
The residual values are computed for the part 9.5 - 25 min.

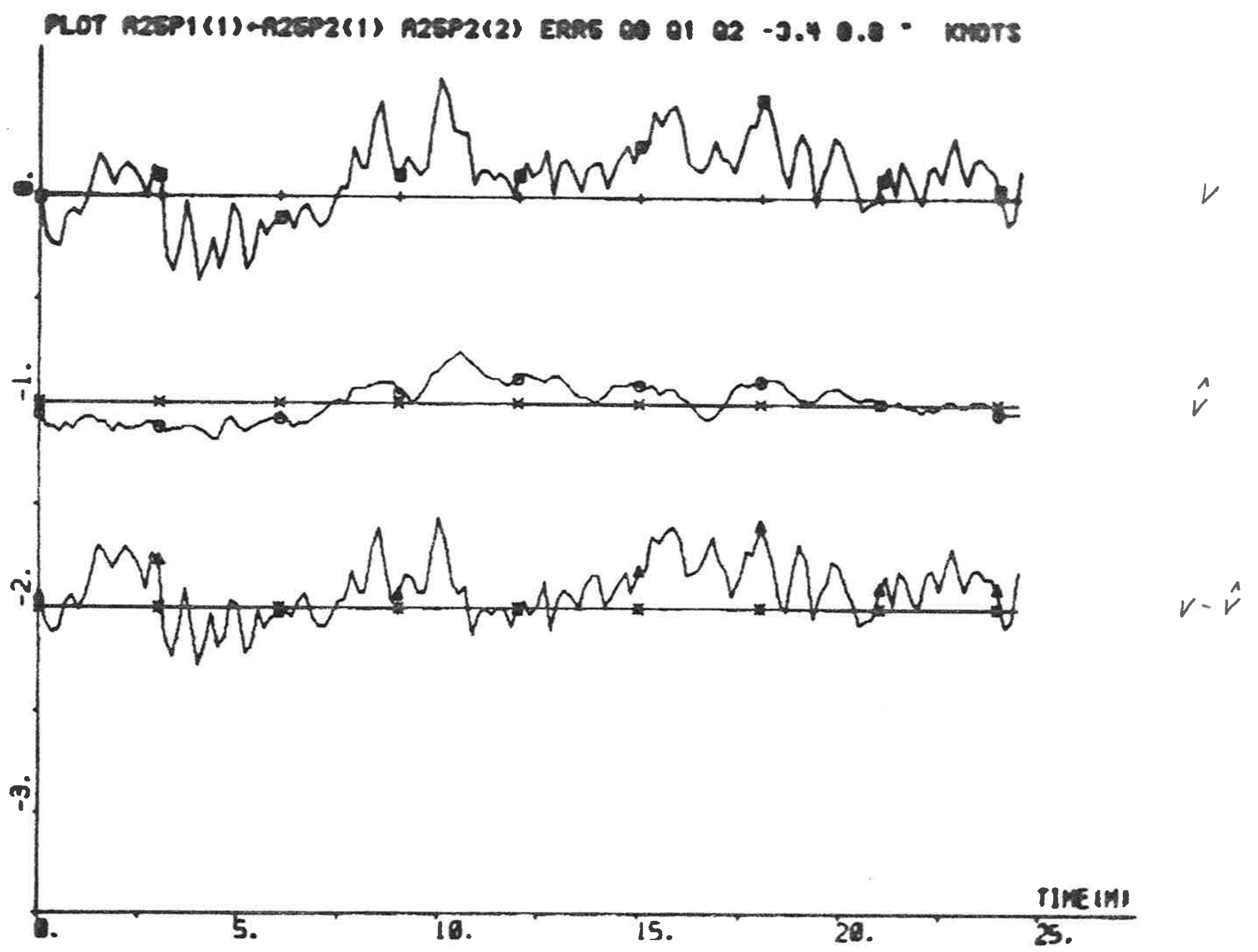
δ_c	1.25 ± 0.90	deg	P_s	14.9 ± 0.1	MW
δ	2.97 ± 0.70	deg	ε_v	0.01 ± 0.02	knots
$\psi-\psi_{ref}$	-0.034 ± 0.240	deg	ε_r	0.00 ± 0.02	deg/s
n	69.6 ± 0.3	rpm	ε_ψ	-	
u	12.5 ± 0.2	knots	ε_δ	0.1 ± 0.5	deg

$V_1 = 0.126$

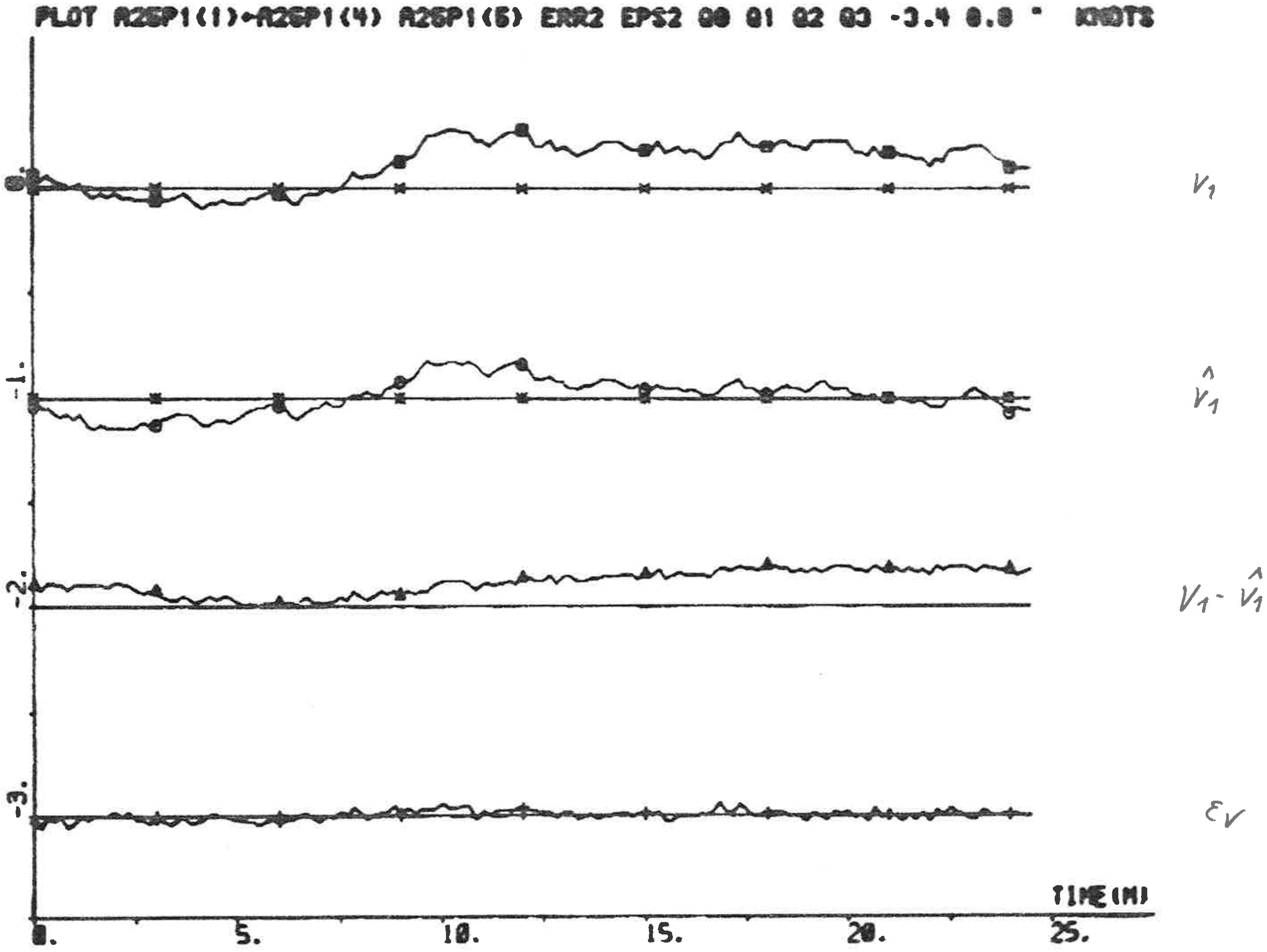


PLOT A25P1(1)-A25P1(8) HP A25P1(10) A25P1(15) 02 -3 1 * DEG
$\psi - \psi_{ref}$
$0.05 * \delta_c$
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

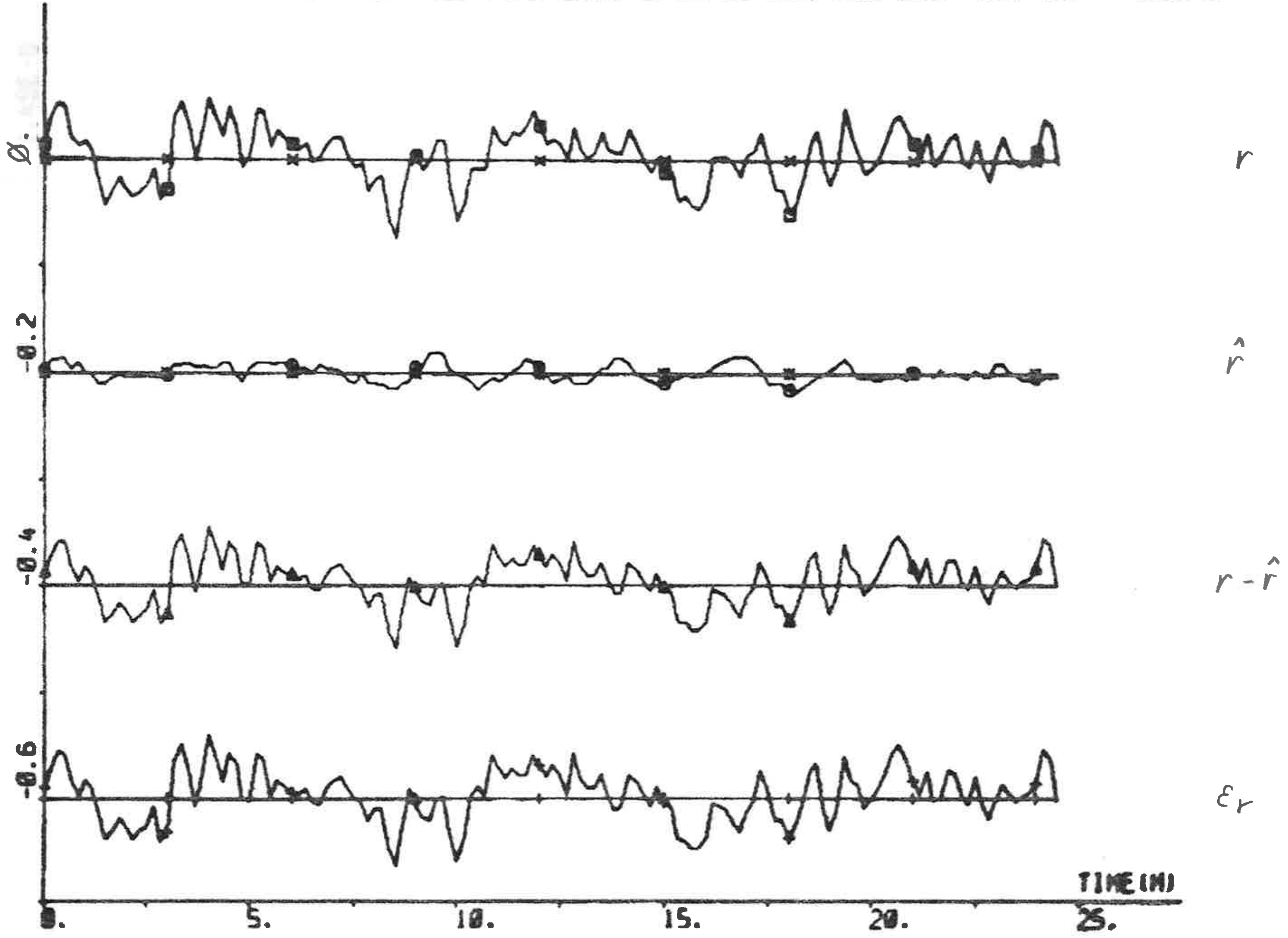

PLOT A2SP1(1)+A2SP1(13) A2SP1(12) A2SP1(14) A2SP1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 × n rpm
2 × U knots
P_s MW
δ_s deg

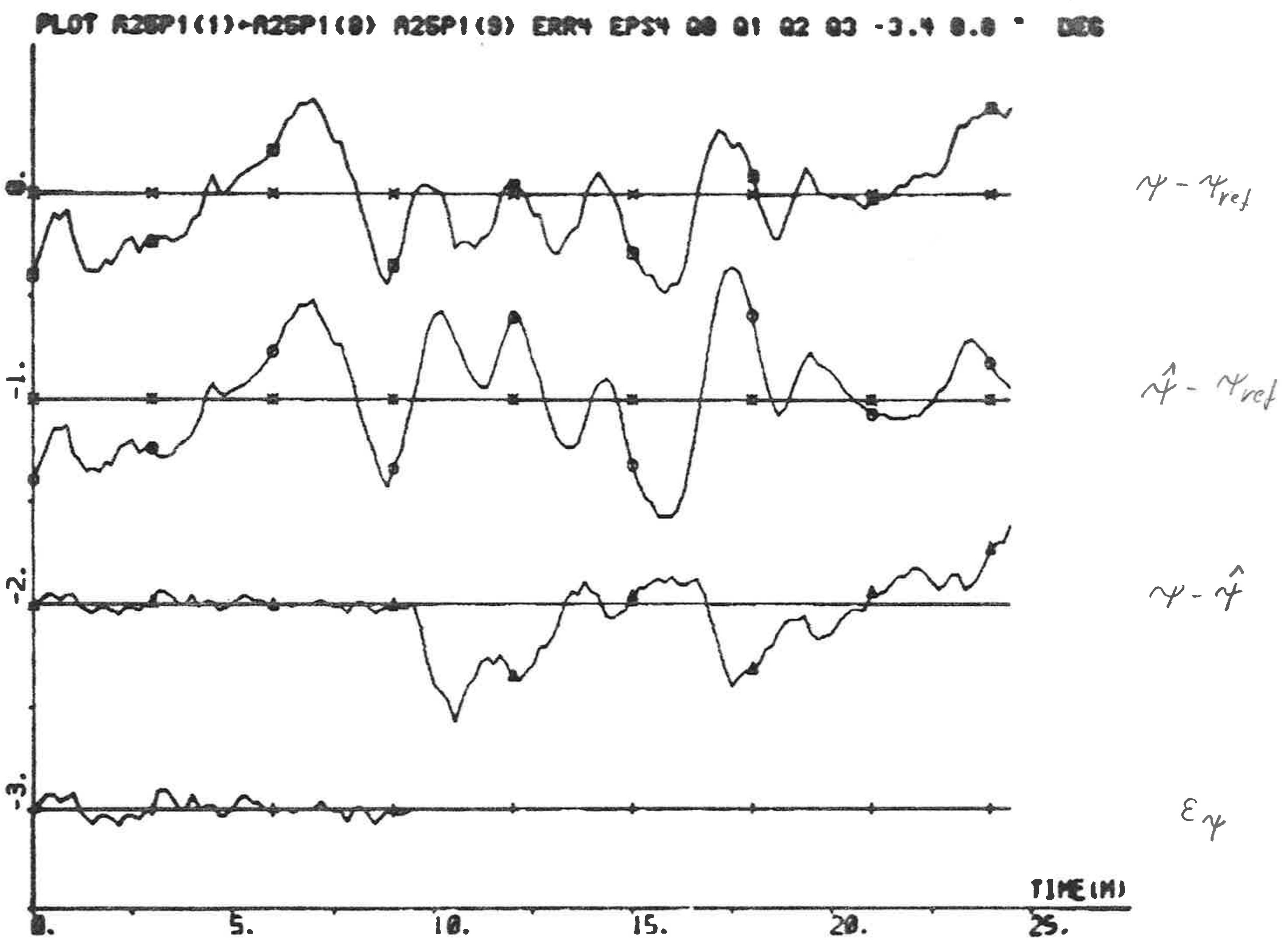


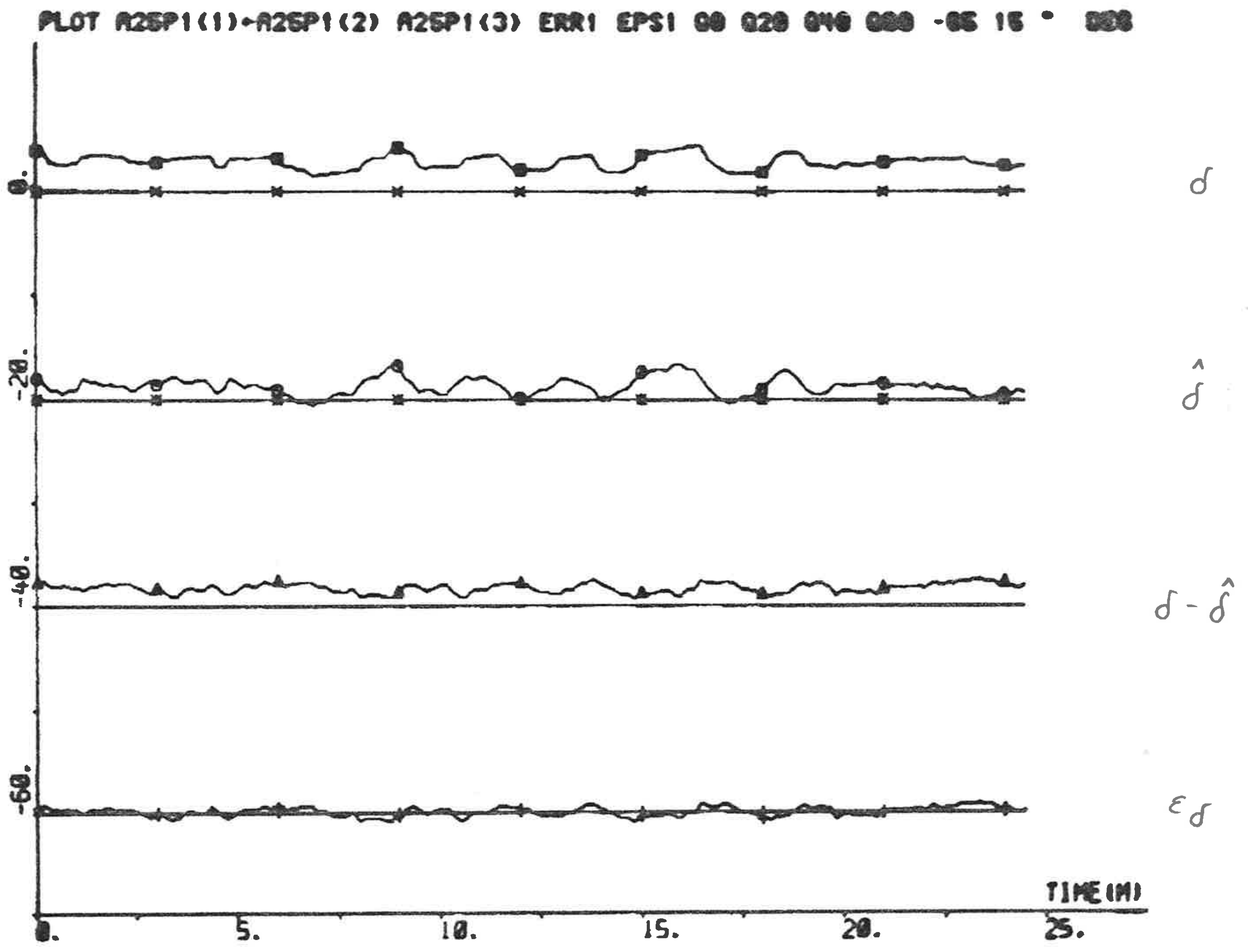
PLOT A2SP1(1)-A2SP2(1) A2SP2(2) ERR6 Q0 Q1 Q2 -3.4 0.8 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

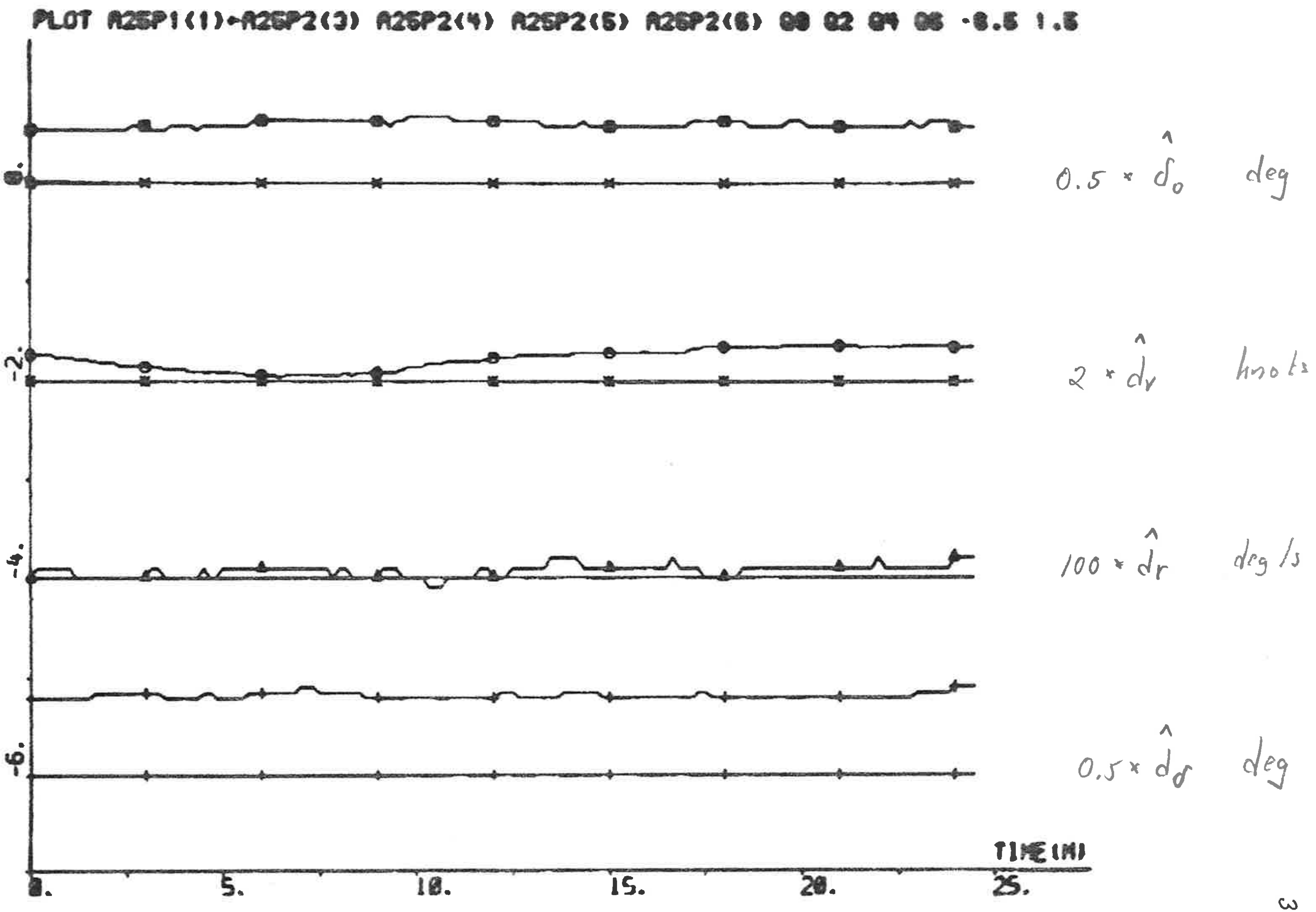

PLOT A2SP1(1)-A2SP1(4) A2SP1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(H)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
εV

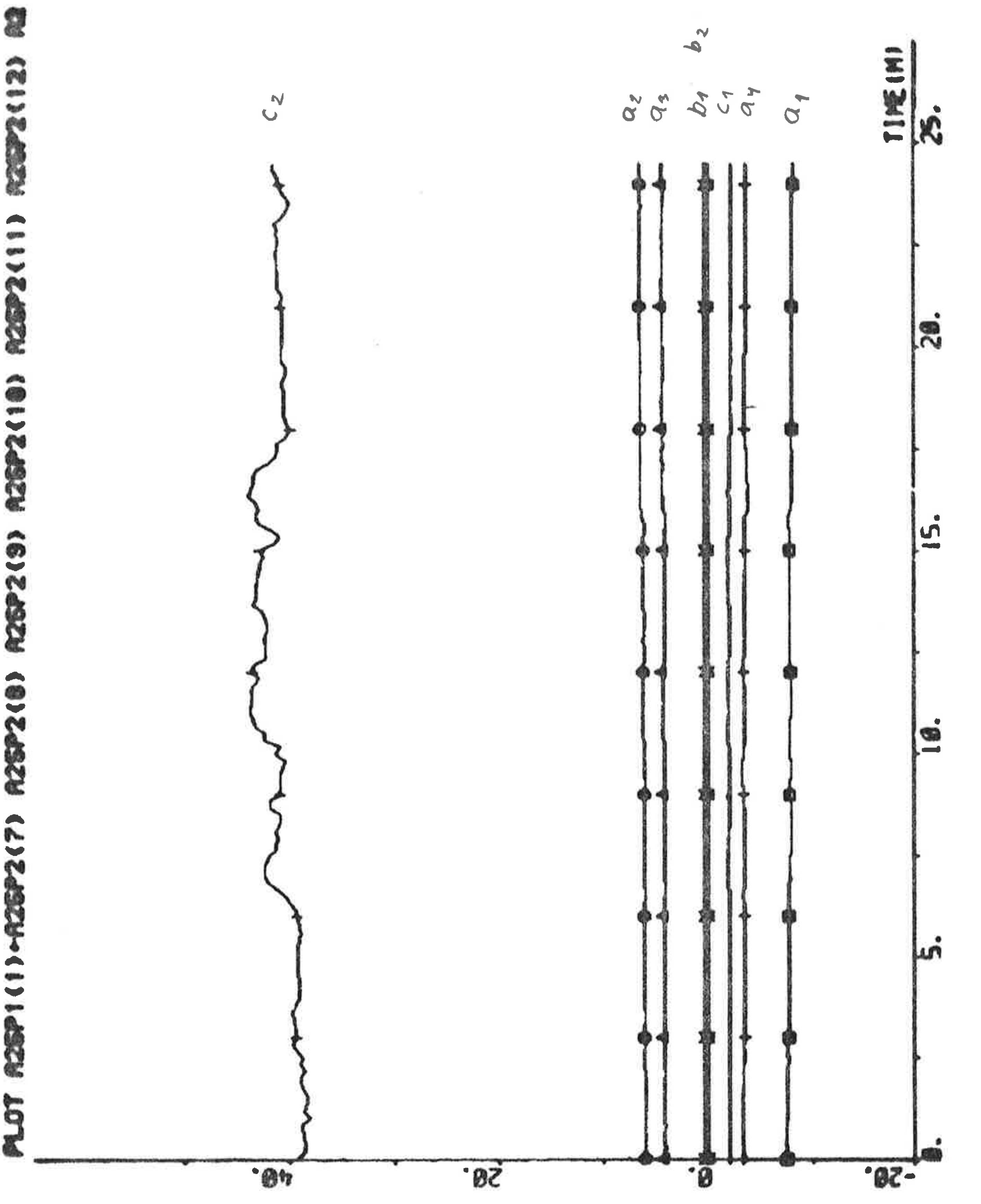
PLOT A2SP1(1)-A2SP1(6) A2SP1(7) ERR3 EPS3




PLOT A2SP1(1)-A2SP1(8) A2SP1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A2SP1(1)-A2SP1(2) A2SP1(3) ERR1 EPS1 00 020 040 060 -05 15 • 008
0.
-20.
-40.
-60.
δ
δ̂
δ - δ̂
ε δ
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A2SP1(1)-A2SP2(3) A2SP2(4) A2SP2(5) A2SP2(6) 00 02 04 06 -8.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * $\hat{\delta}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg


PLOT A2SP1(1)-A2SP2(7) A2SP2(8) A2SP2(9) A2SP2(10) A2SP2(11) A2SP2(12)
TIME(M)
0.
5.
10.
15.
20.
25.
40.
20.
0.
-20.
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT A26

Date	1976-04-26	Forward draught	8.5 m
Time	08.58	Aft draught	12.5 m
Duration	27 min	Wind direction	SE (1; see App. A)
Position	S 05°25' W 07°03'	Wind velocity	6 m/s (moderate breeze)
ψ_{ref}	144 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

The sway velocity v_1, the yaw rate r and the rudder angle δ were not used by the Kalman filter. The correct filter gain K was used.

Tuning time before the experiment started: 30 min.

NC1 = 1   NC2 = 1   k = 7   q = 0

T_s = 10 s V_0 = 6 m/s   IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.72 \\ 6.23 \\ 4.27 \\ -2.95 \\ 0.49 \\ 0.10 \\ -2.20 \\ 34.95 \end{bmatrix} \qquad P = \begin{bmatrix} 9.67 & & & & & & & \\ -10.89 & 19.94 & & & & & & \\ -2.76 & -8.52 & 21.97 & & & & & \\ 3.77 & -0.40 & -10.60 & 7.64 & & & & \\ -0.03 & -0.44 & 0.73 & -0.25 & 0.04 & & & \\ 0.05 & -0.05 & -0.20 & 0.23 & 0.00 & 0.03 & & \\ -7.91 & 7.29 & 3.69 & -2.26 & 0.07 & -0.06 & 12.53 & \\ -33.47 & 16.16 & 19.07 & 7.24 & 0.27 & -1.59 & 128.31 & 2165.90 \end{bmatrix}$$

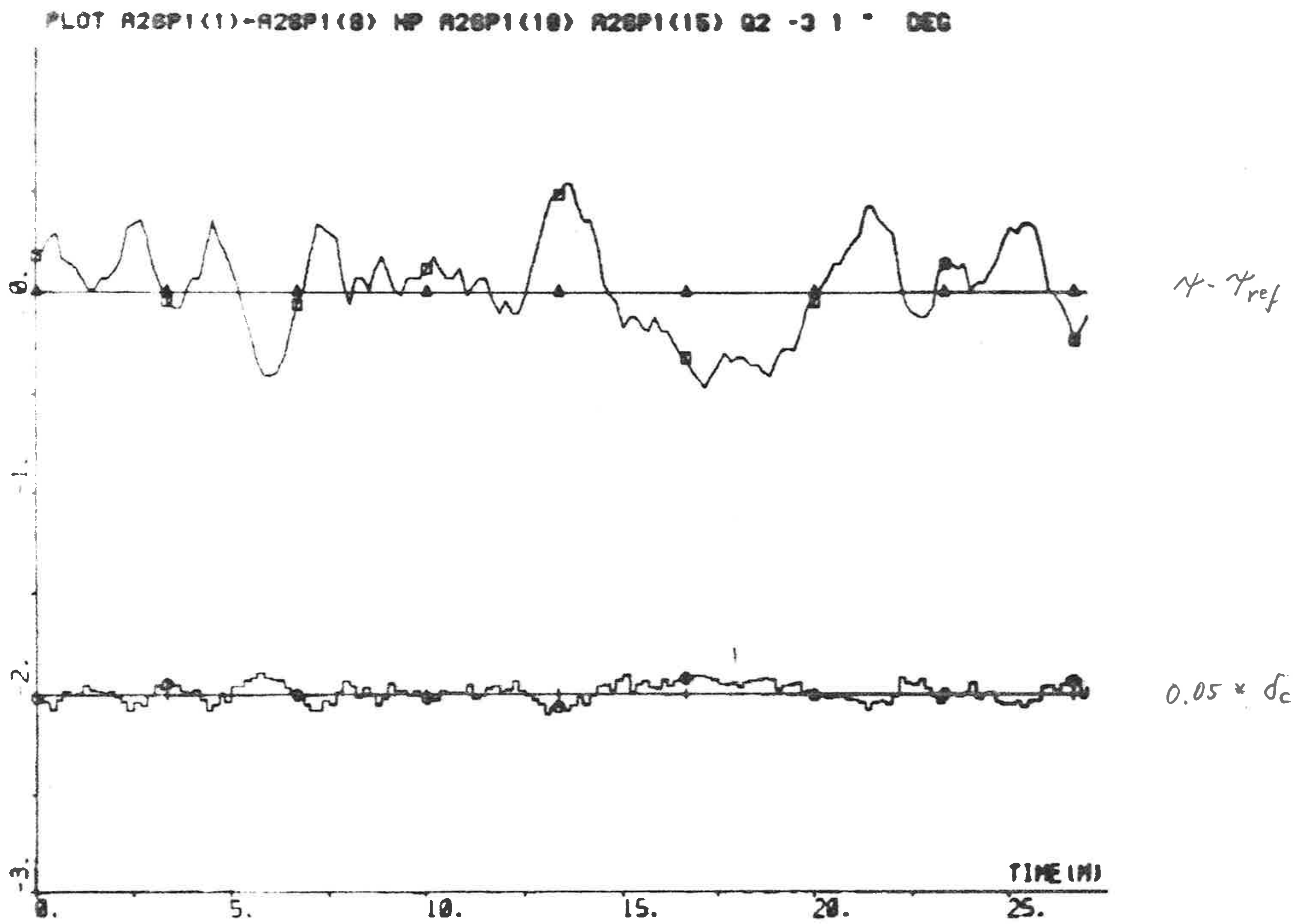
$a_1 + a_2 + a_3 + a_4 = -0.17$

$\hat{\delta}_0 = 0.2$ deg $\hat{d}_v = -$ $\hat{d}_r = -$ $\hat{d}_\delta = -$

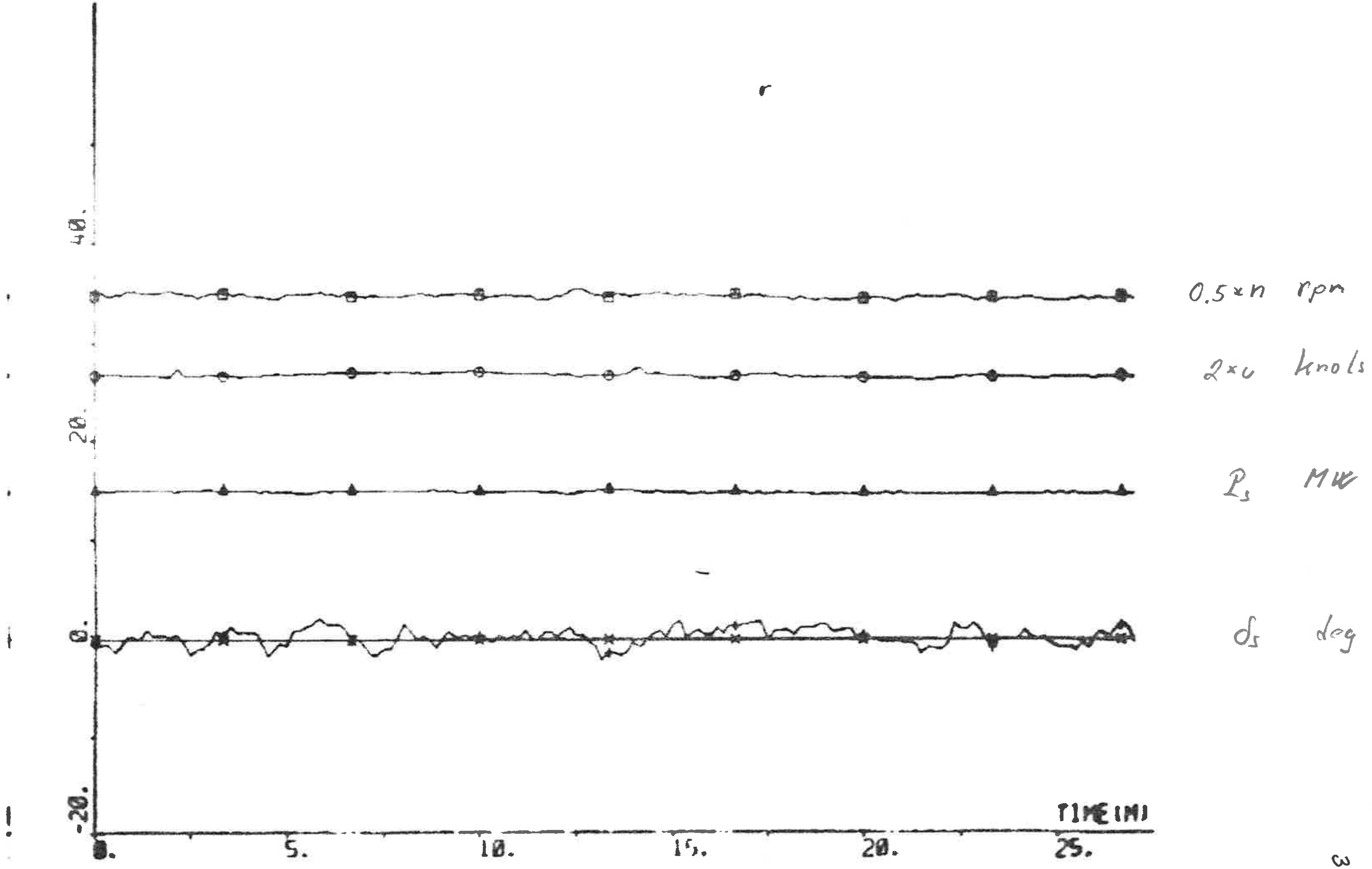
Statistics (mean value and standard deviation)

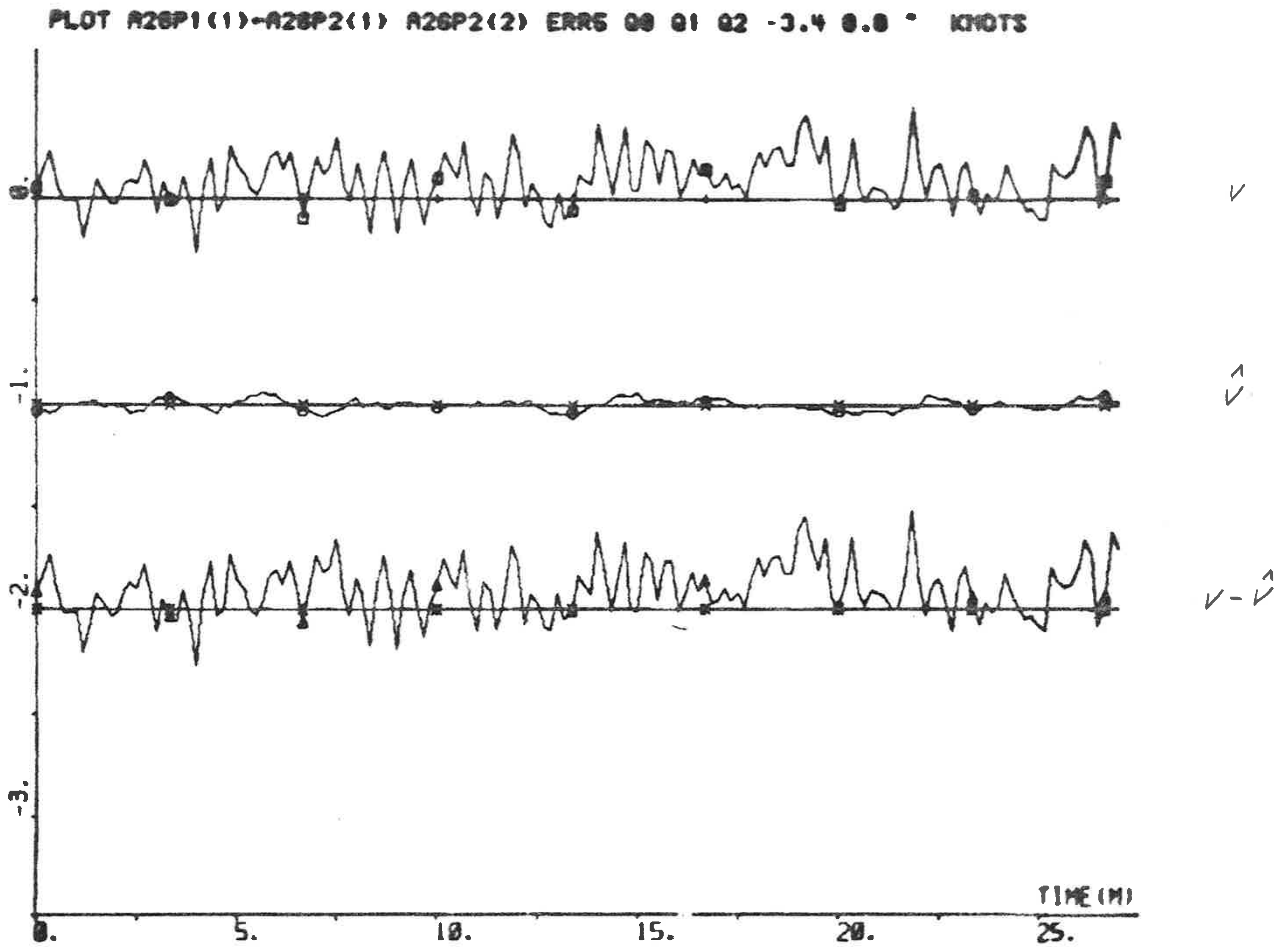
δ_c	0.24 ± 0.89 deg		P_s	14.9 ± 0.1 MW
δ	1.83 ± 0.72 deg		ε_v	-
$\psi-\psi_{ref}$	0.030 ± 0.230 deg		ε_r	-
n	69.7 ± 0.4 rpm		ε_ψ	0.00 ± 0.03 deg
u	13.4 ± 0.1 knots		ε_δ	-

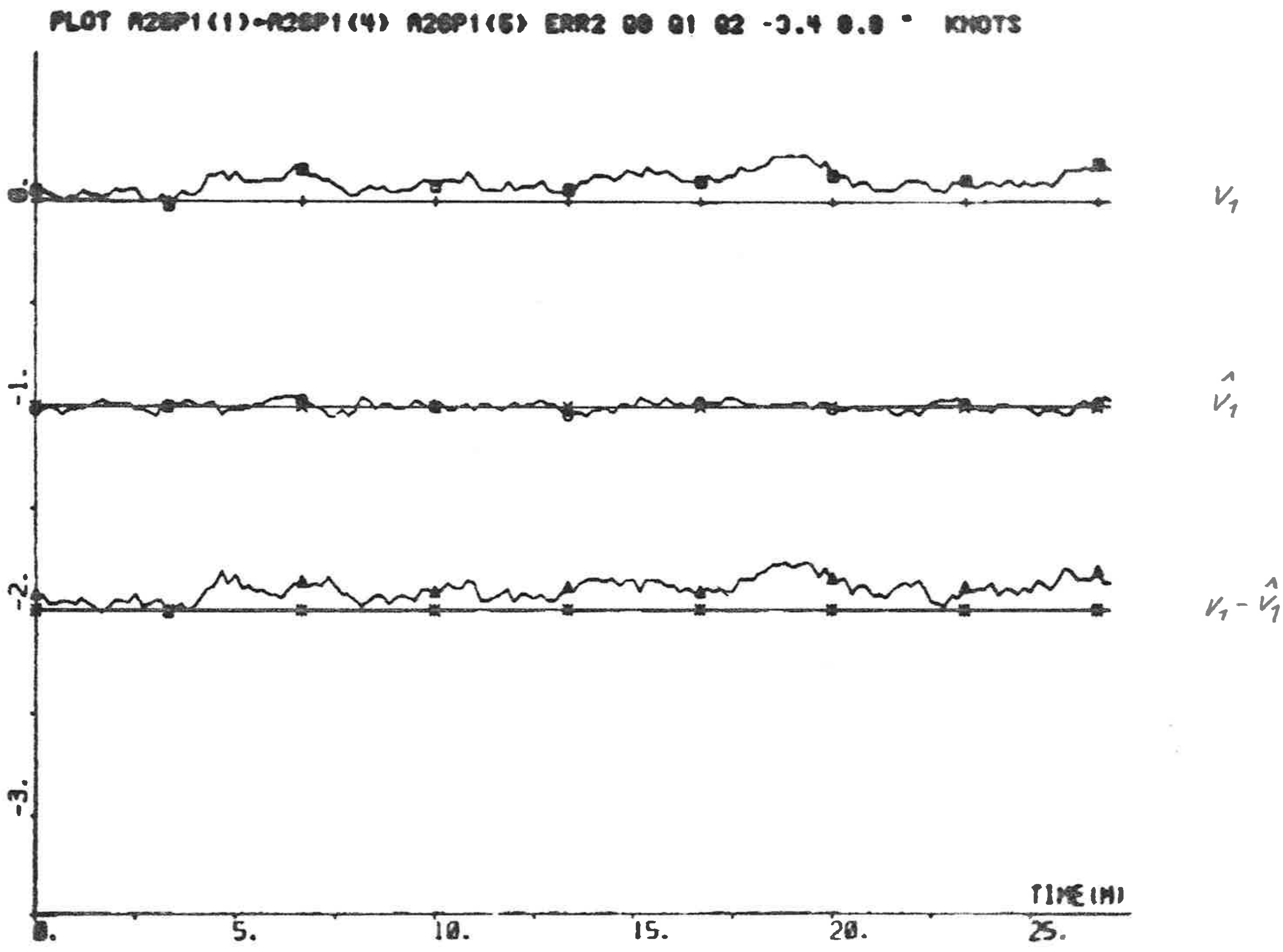
$V_1 = 0.120$

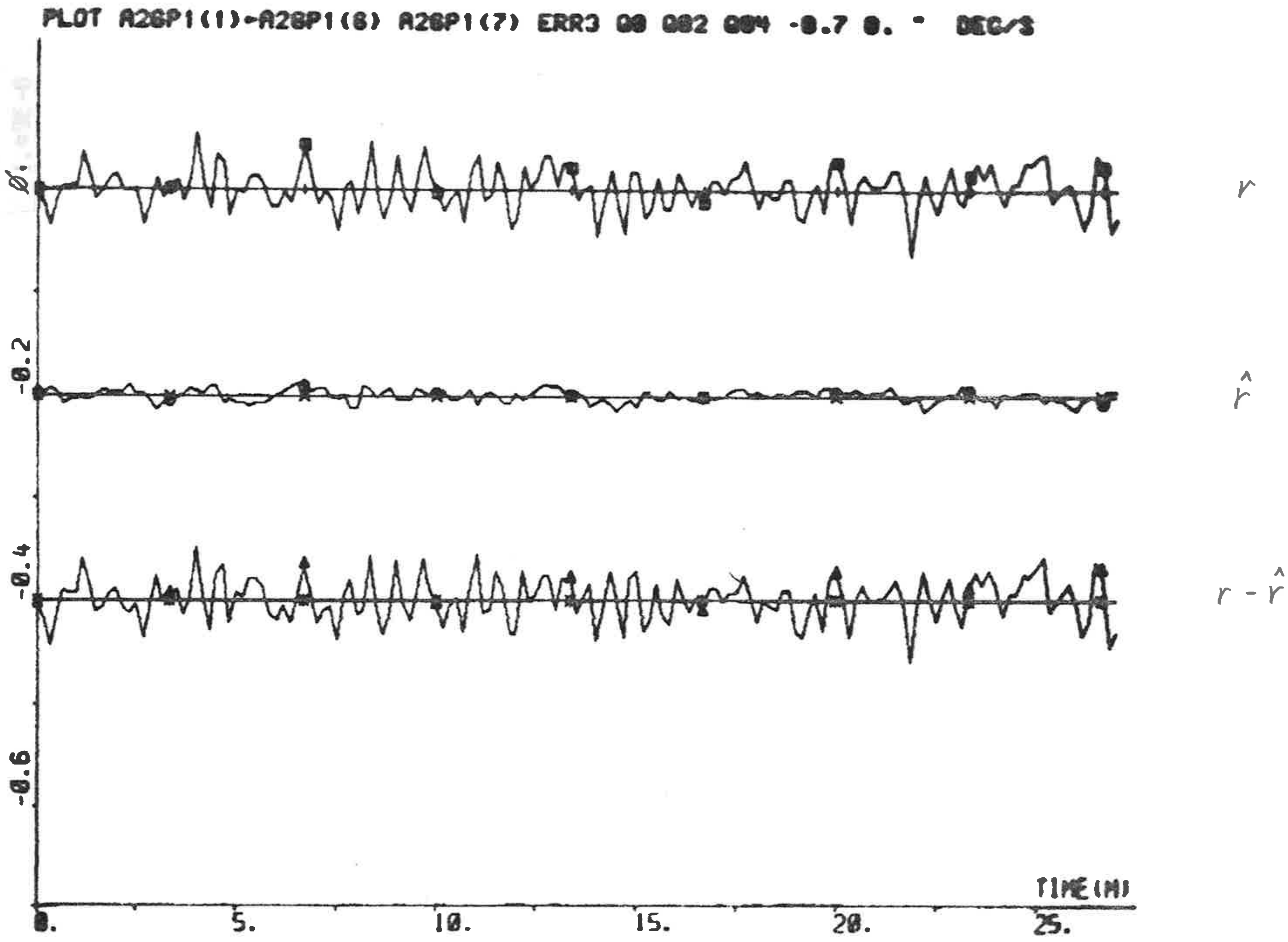

PLOT A2BP1(1)-A2BP1(8) HP A2BP1(10) A2BP1(15) Q2 -3 1 - DEG
ψ - ψref
0.05 * δc
TIME(M)
0.
5.
10.
15.
20.
25.
0.
-1.
-2.
-3.

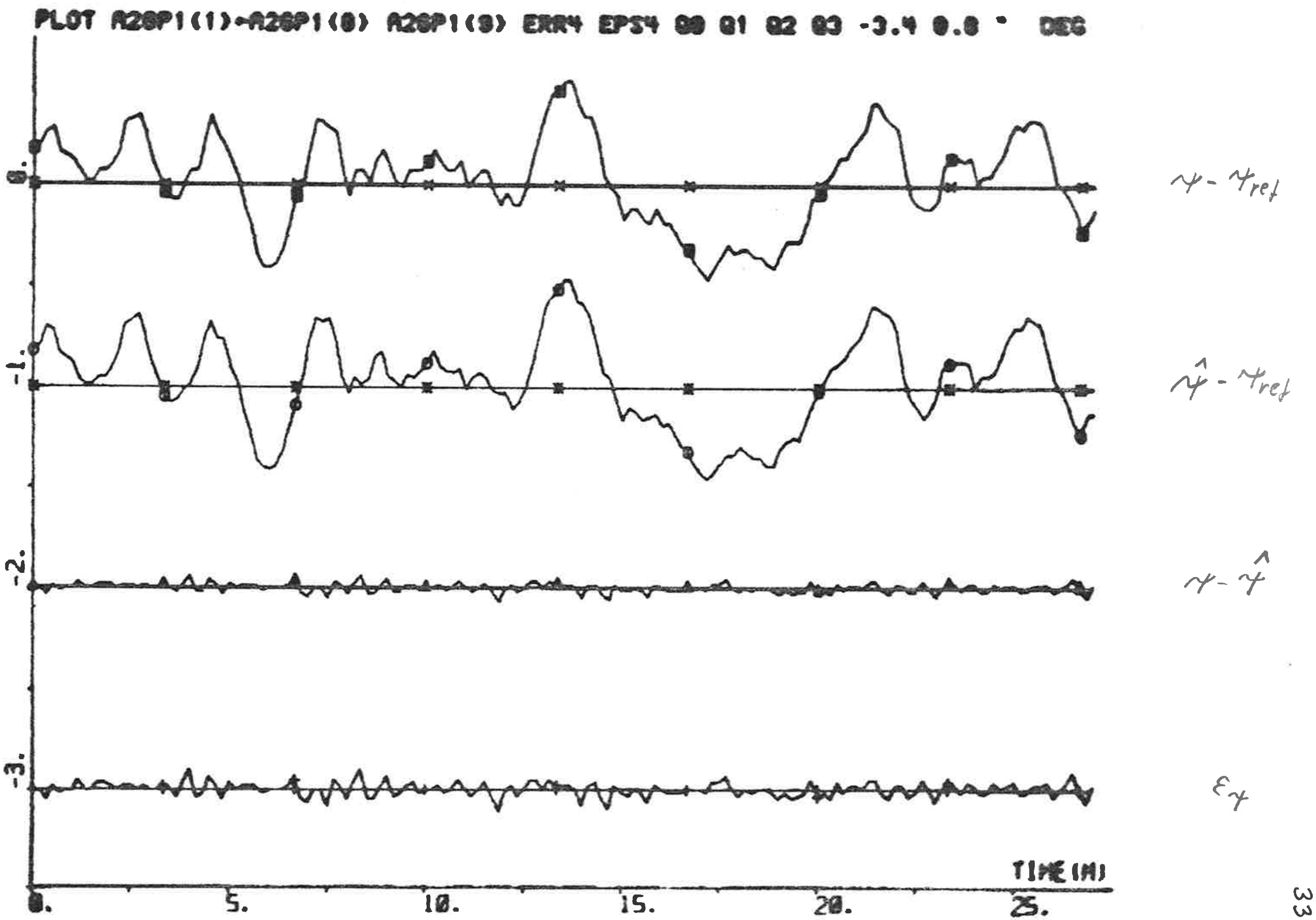
PLOT A28P1(1)-A28P1(13) A28P1(12) A28P1(14) A28P1(11) 00 -20 50

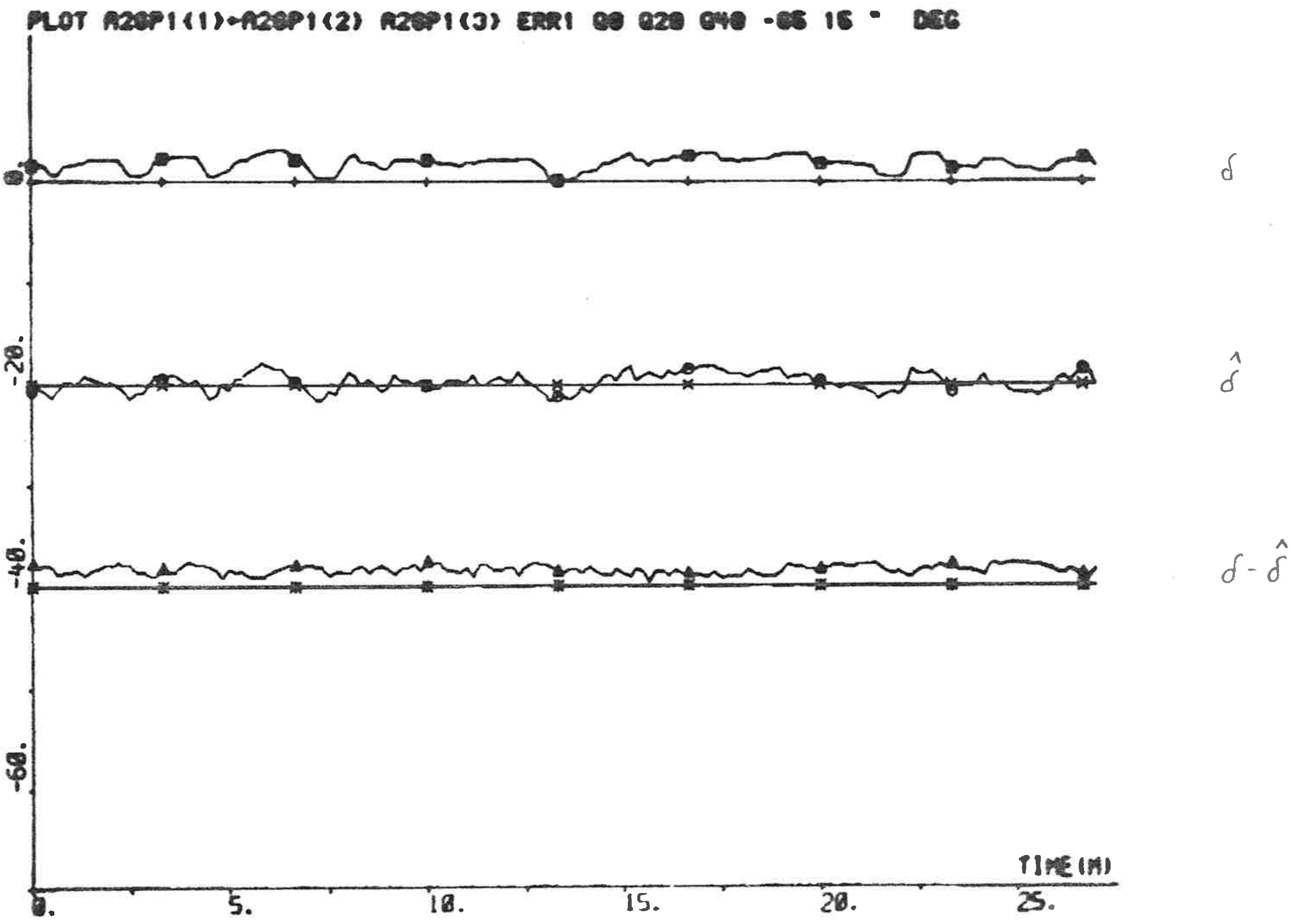


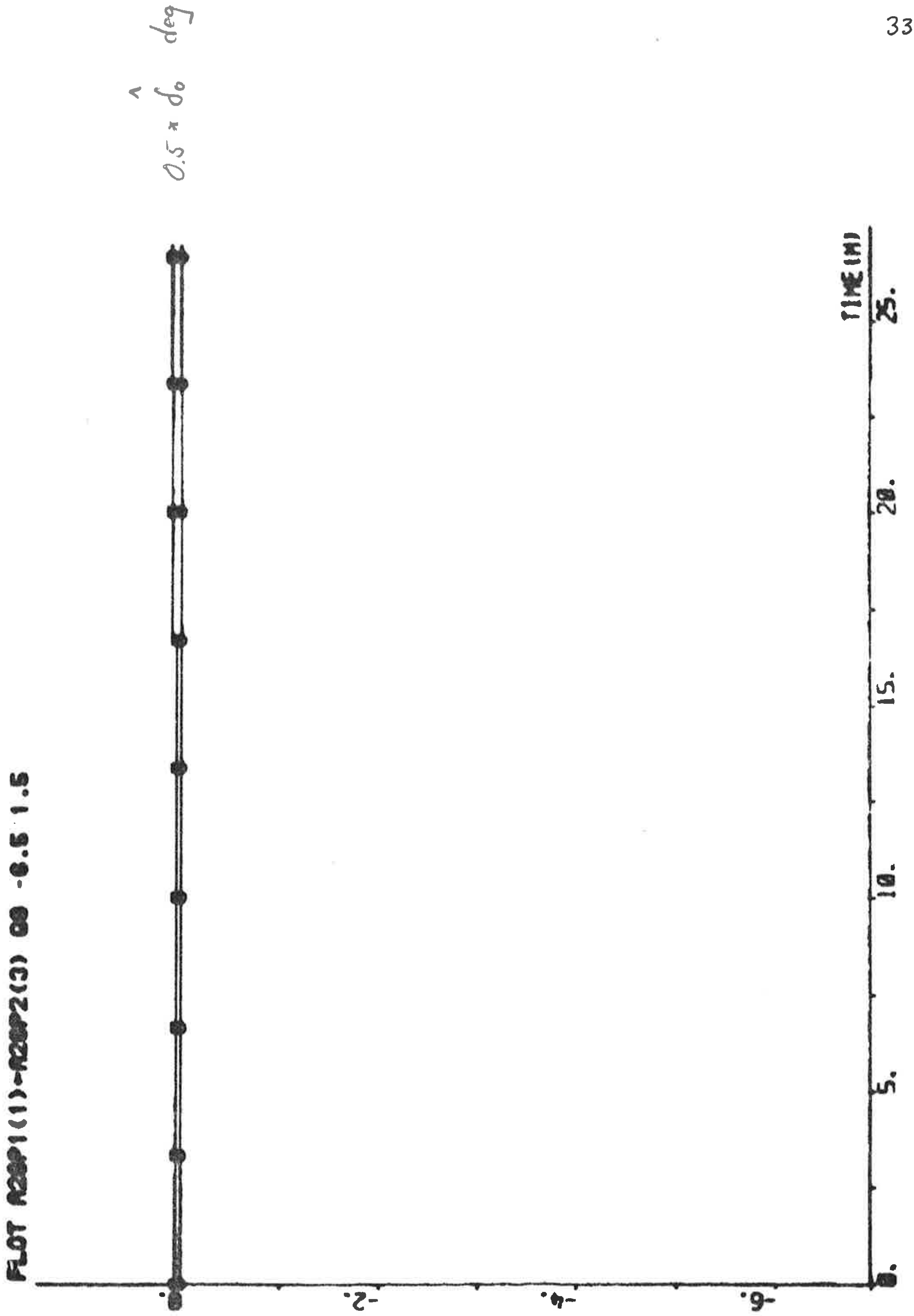

PLOT A20P1(1)-A20P2(1) A20P2(2) ERRS 00 01 02 -3.4 0.0 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A2SP1(1)-A2SP1(4) A2SP1(5) ERR2 00 01 02 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
TIME(H)
0.
5.
10.
15.
20.
25.

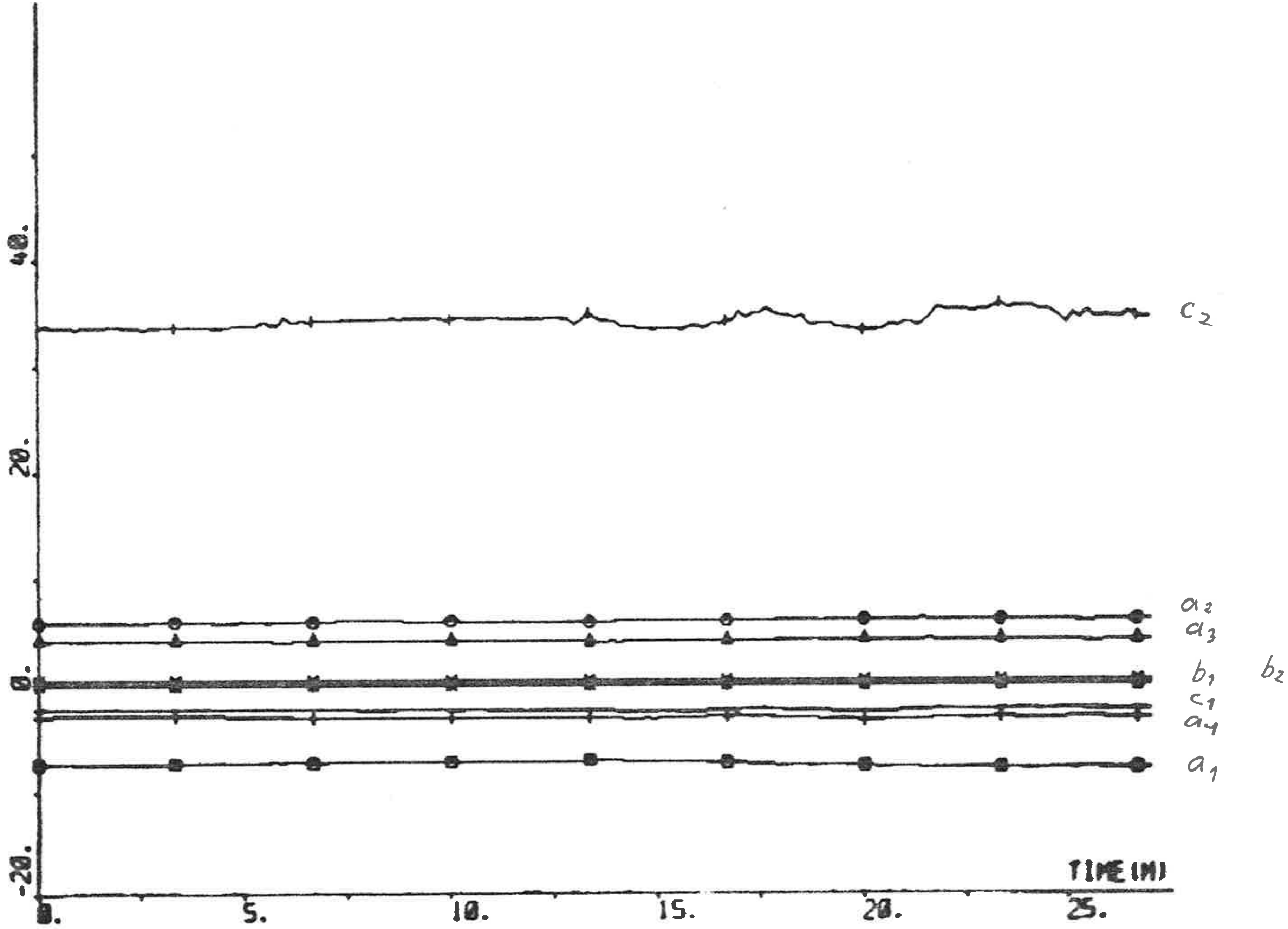

PLOT A28P1(1)-A28P1(6) A28P1(7) ERR3 08 082 084 -0.7 0. DEG/S
Ø.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂


PLOT A2SP1(1)-A2SP1(0) A2SP1(3) ERR4 EPS4 00 01 02 03 -3.4 0.8 DEG
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A20P1(1)-A20P1(2) A20P1(3) ERR1 00 020 040 -06 16 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
$\hat{\delta}$
$\delta - \hat{\delta}$


PLOT A2BP1(1)-A2BP2(3) 08 -0.5 1.5
0.5 × $\hat{\delta}_0$ deg
TIME(M)
0.
5.
10.
15.
20.
25.
-2.
-4.
-6.

PLOT A20P1(1)-A20P2(7) A20P2(8) A20P2(9) A20P2(10) A20P2(11) A20P2(12) A2



EXPERIMENT A27

Date	1976-04-26	Forward draught	8.5 m
Time	10.58	Aft draught	12.5 m
Duration	22 min	Wind direction	SE (1; see App. A)
Position	S 05°46' W 06°47'	Wind velocity	7 m/s (moderate breeze)
ψ_{ref}	143 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

The sway velocity v_1, the yaw rate r and the rudder angle δ were not used by the Kalman filter.

Tuning time before the experiment started: 30 min.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.76 \\ 6.63 \\ 4.48 \\ -3.73 \\ 0.45 \\ 0.08 \\ -3.32 \\ 41.43 \end{bmatrix} \qquad P = \begin{bmatrix} 8.62 & & & & & & & \\ -9.82 & 17.35 & & & & & & \\ -2.84 & -6.15 & 17.88 & & & & & \\ 3.91 & -1.25 & -9.09 & 6.79 & & & & \\ -0.11 & -0.26 & 0.61 & -0.22 & 0.05 & & & \\ 0.03 & -0.05 & -0.17 & 0.22 & 0.01 & 0.03 & & \\ -5.54 & 5.46 & 2.32 & -1.75 & 0.04 & -0.04 & 7.35 & \\ 2.63 & -23.88 & 2.03 & 21.41 & -1.46 & -1.31 & 75.43 & 2667.92 \end{bmatrix}$$

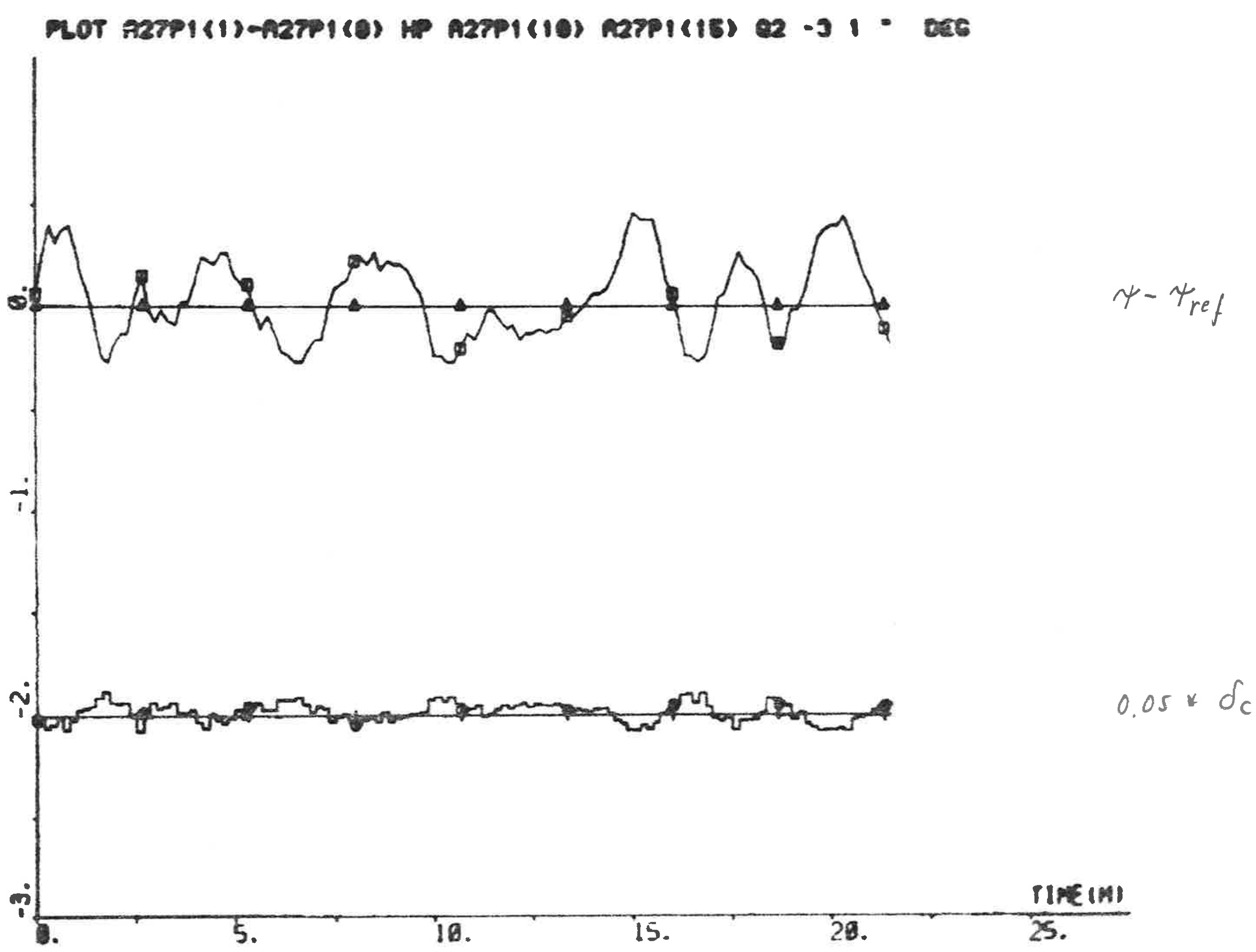
$a_1 + a_2 + a_3 + a_4 = -0.38$

$\hat{\delta}_0 = 0.3$ deg $\hat{d}_v$ = - $\hat{d}_r$ = - $\hat{d}_\delta$ = -

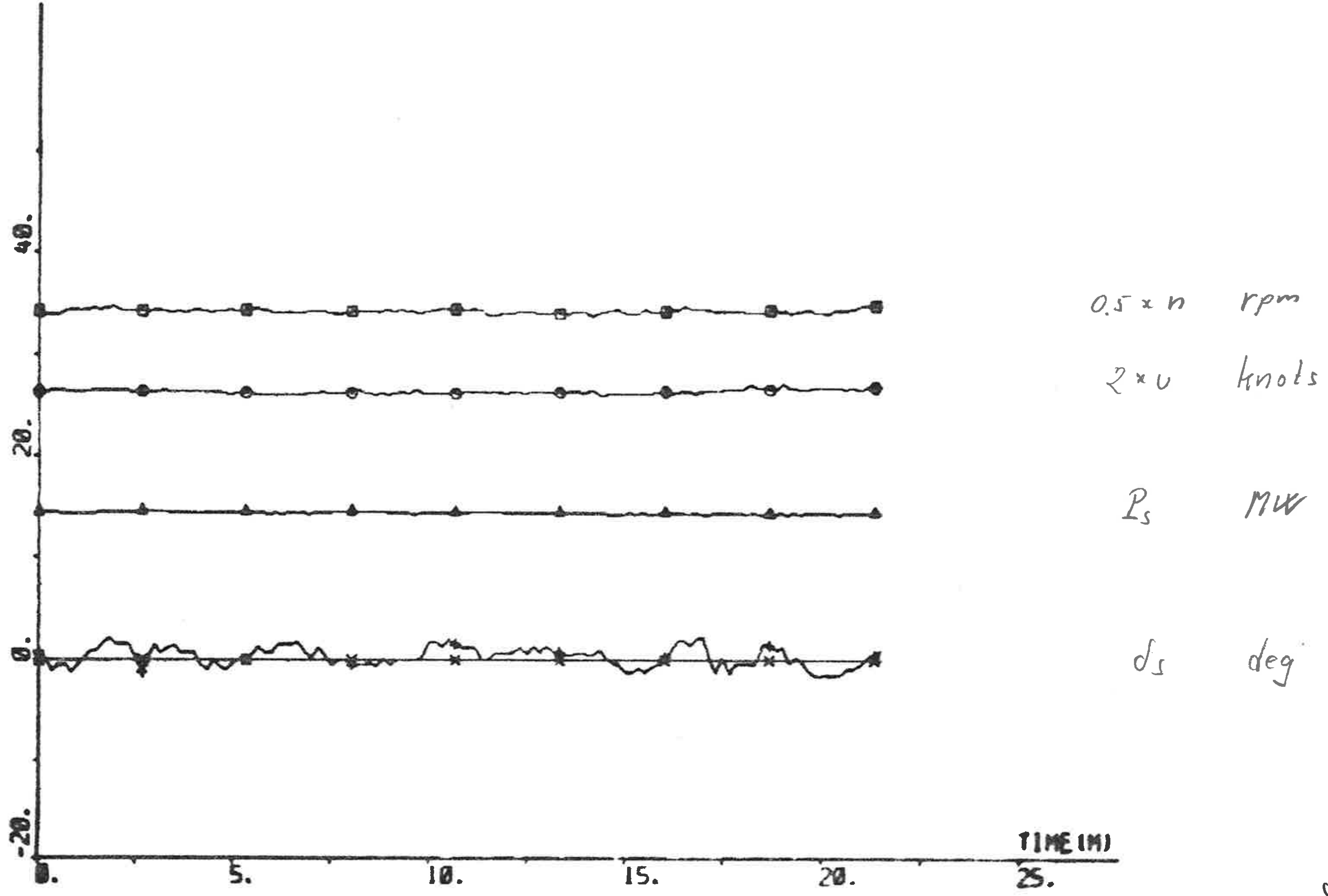
Statistics (mean value and standard deviation)

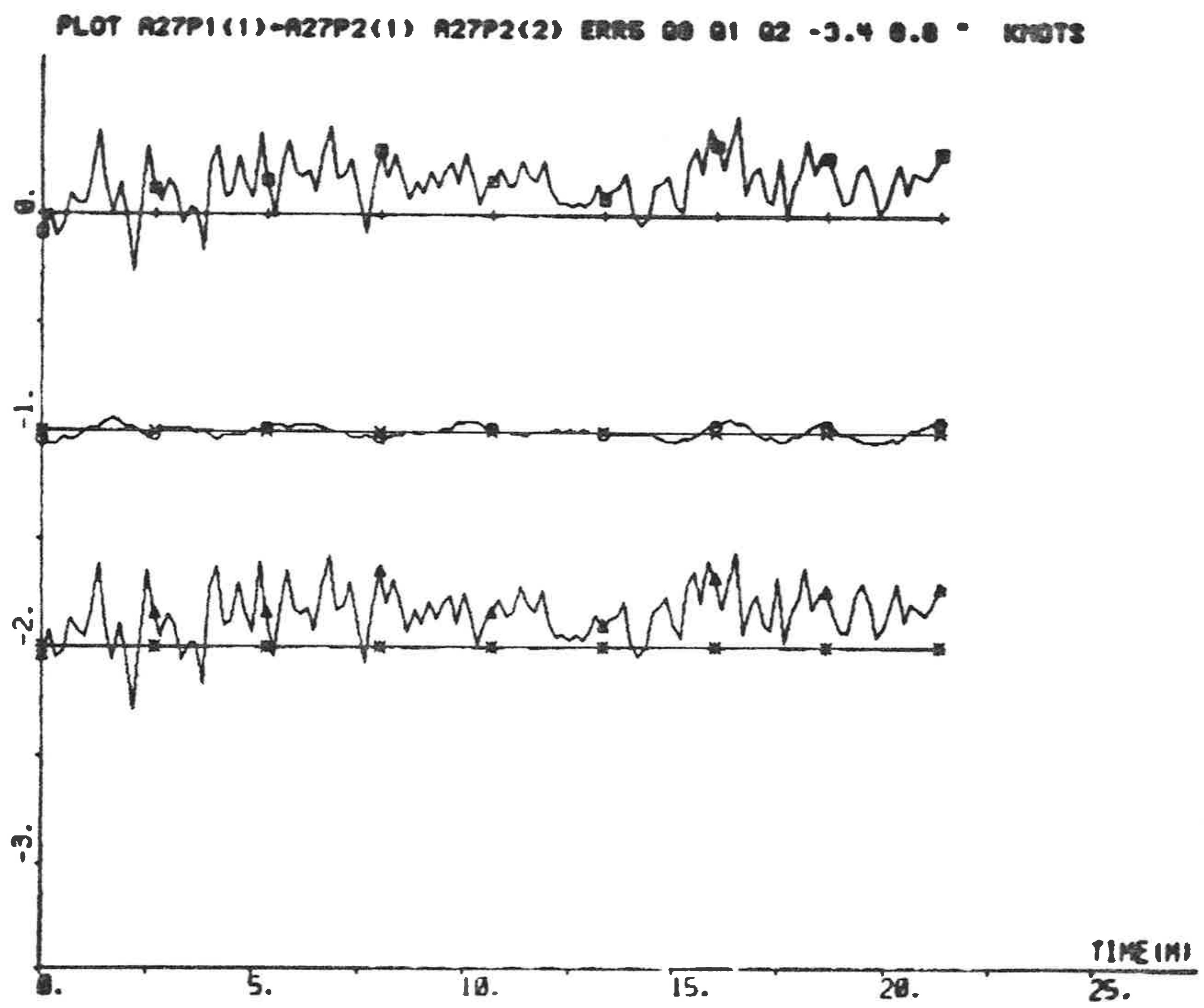
δ_c	0.30 ± 0.92 deg		P_s	14.4 ± 0.1 MW
δ	1.84 ± 0.79 deg		ε_v	-
$\psi-\psi_{ref}$	0.043 ± 0.197 deg		ε_r	-
n	68.9 ± 0.4 rpm		ε_ψ	0.00 ± 0.03 deg
u	13.2 ± 0.1 knots		ε_δ	-

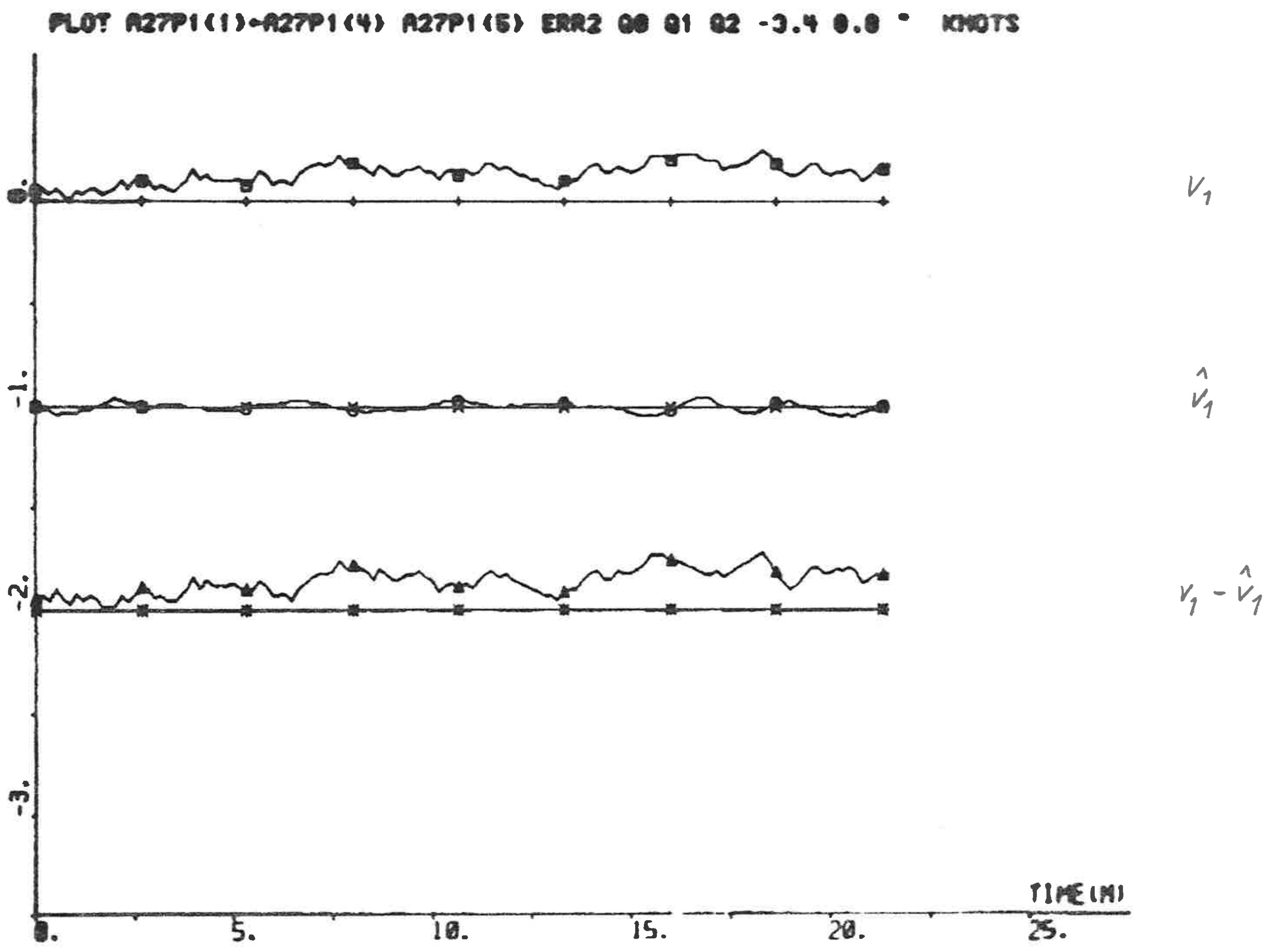
V_1 = 0.111

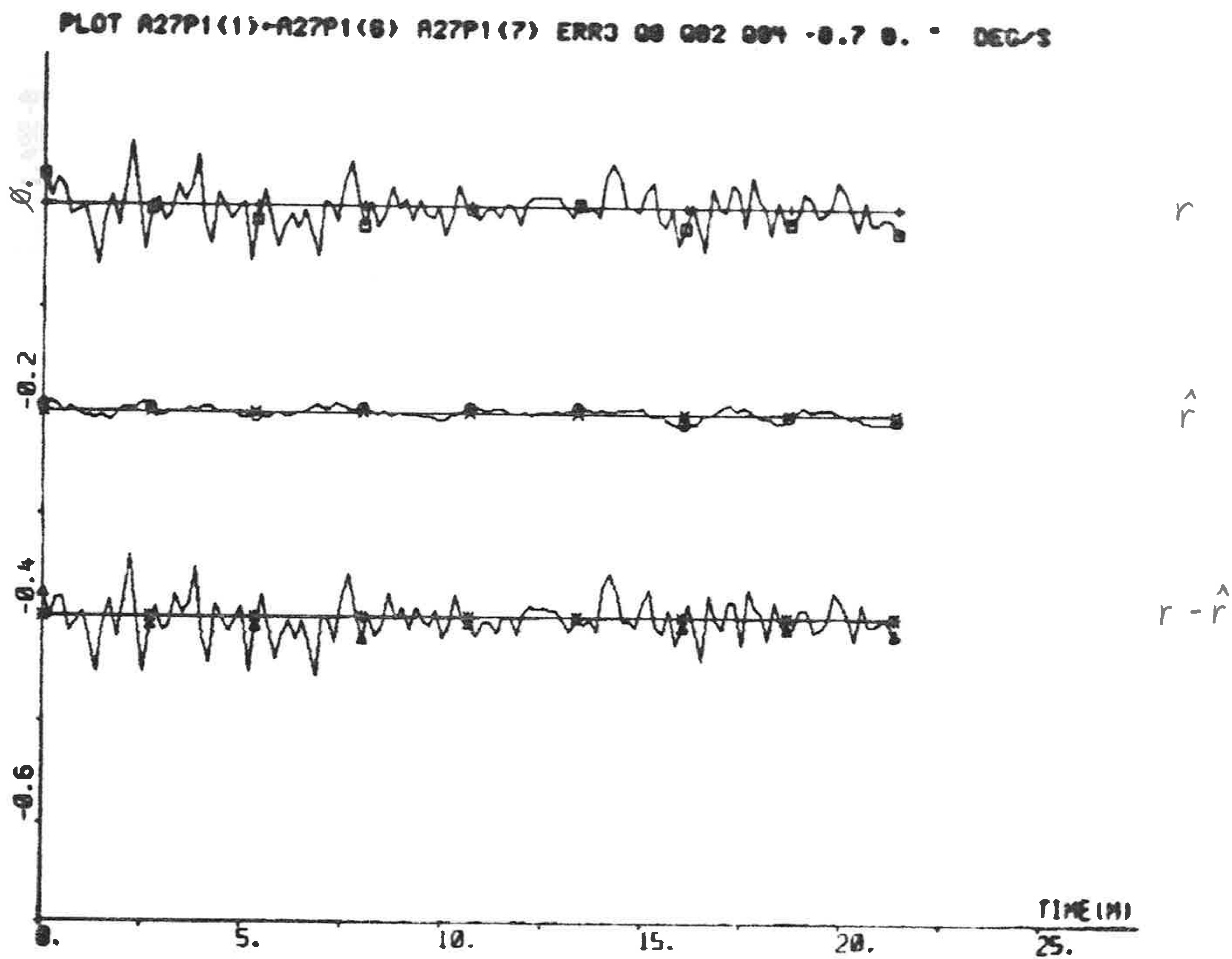

PLOT A27P1(1)-A27P1(8) HP A27P1(10) A27P1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

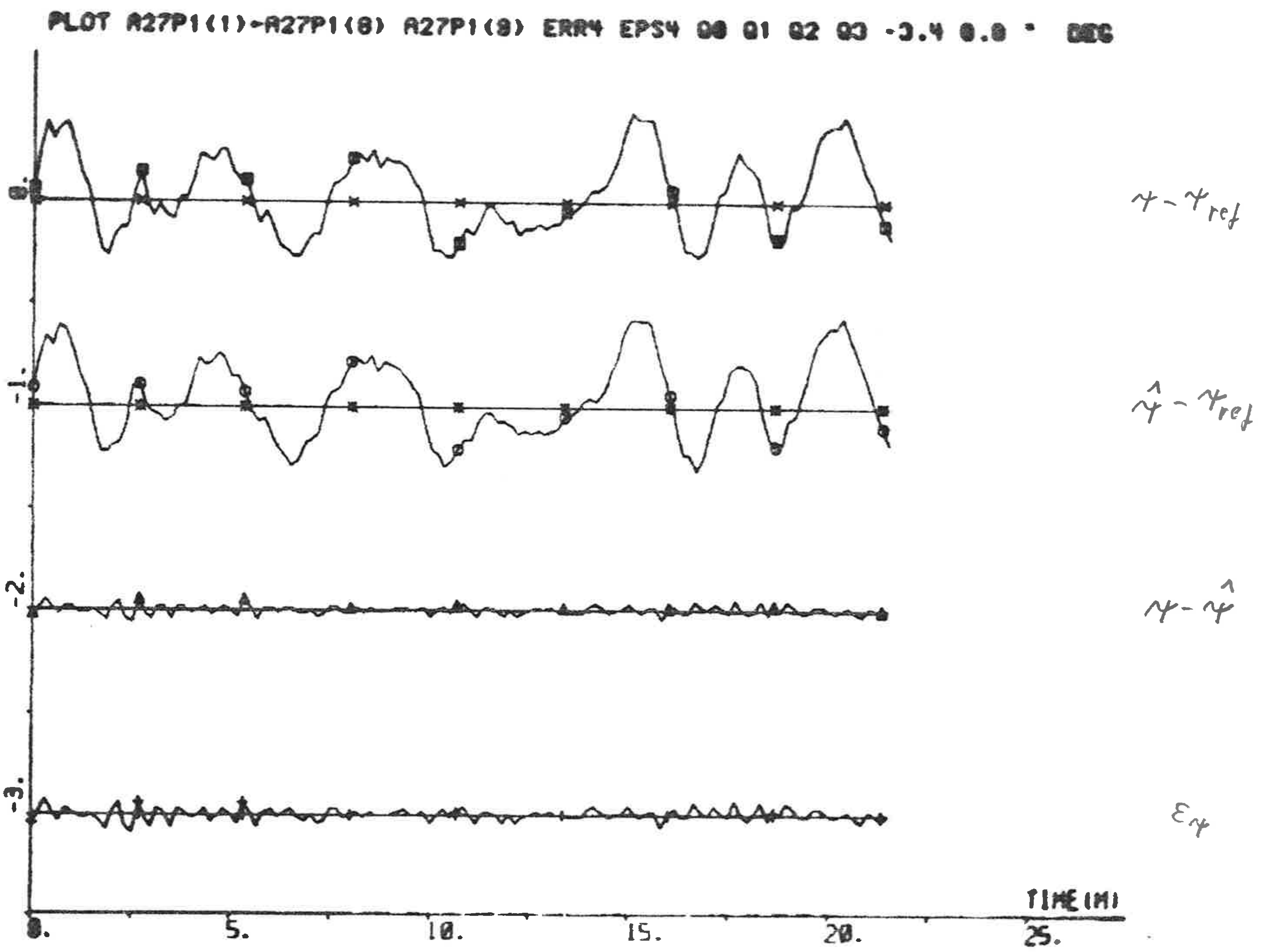
PLOT A27P1(1)-A27P1(13) A27P1(12) A27P1(14) A27P1(11) 60 -20 50

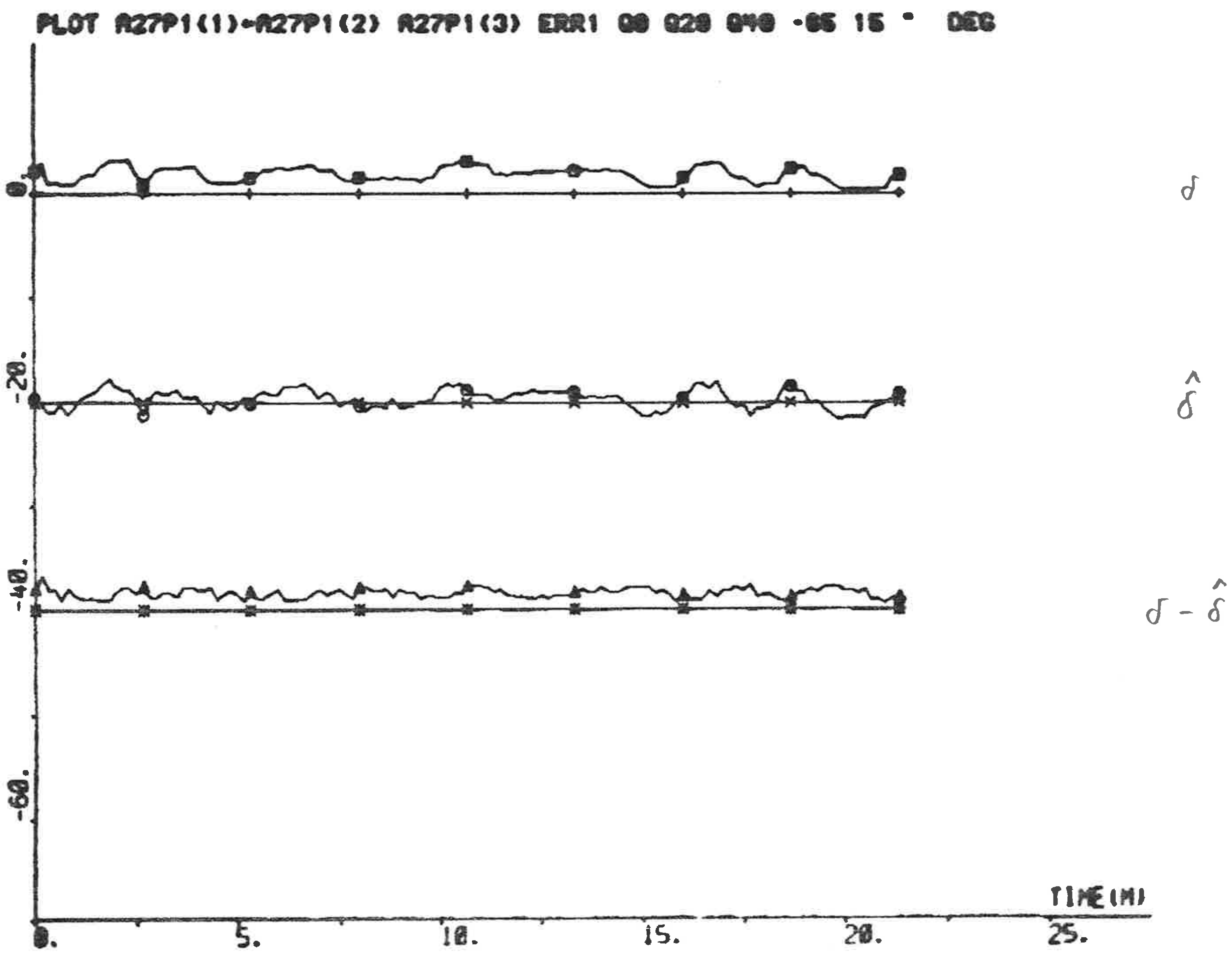


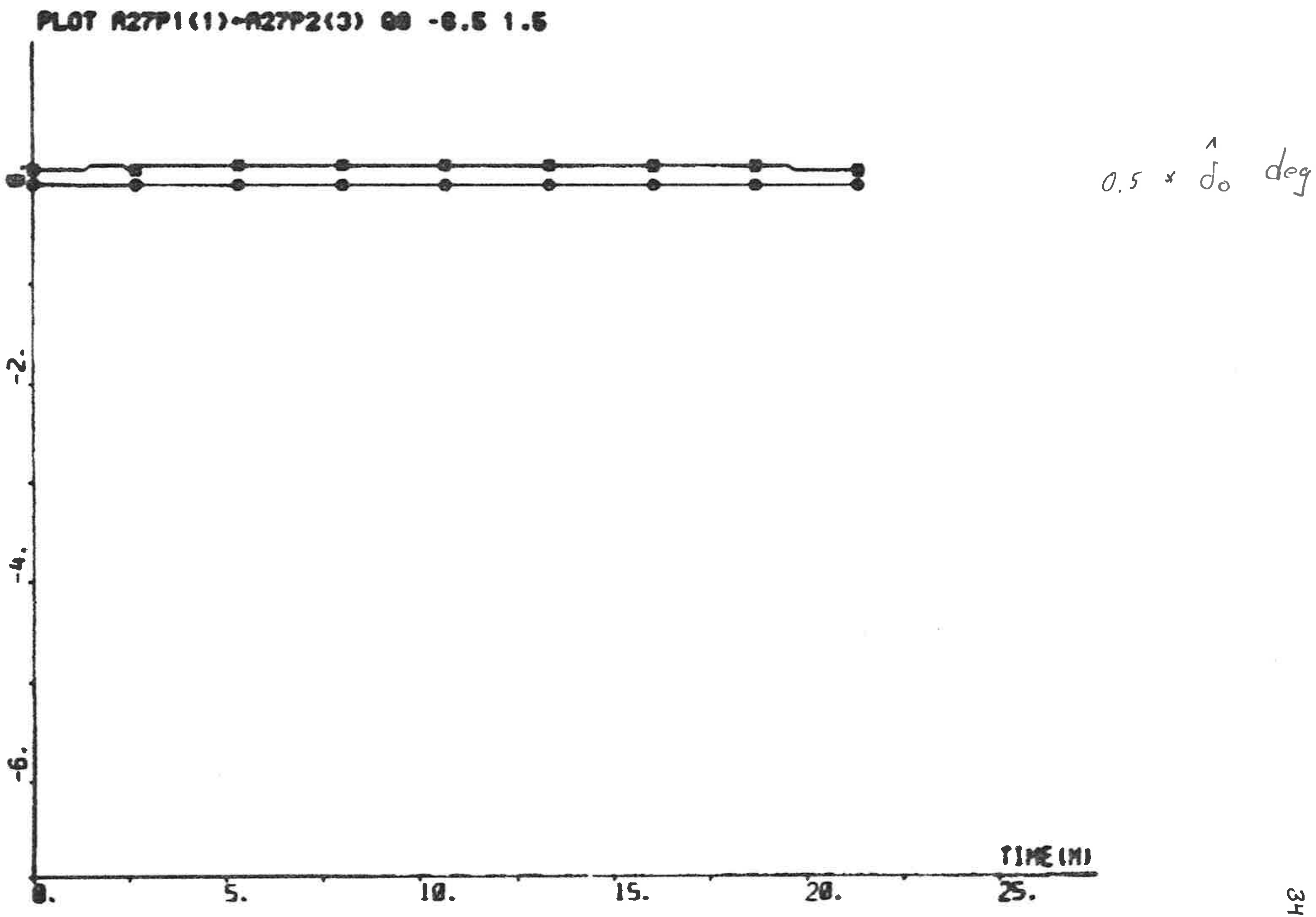

PLOT A27P1(1)-A27P2(1) A27P2(2) ERRS 00 01 02 -3.4 0.8 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

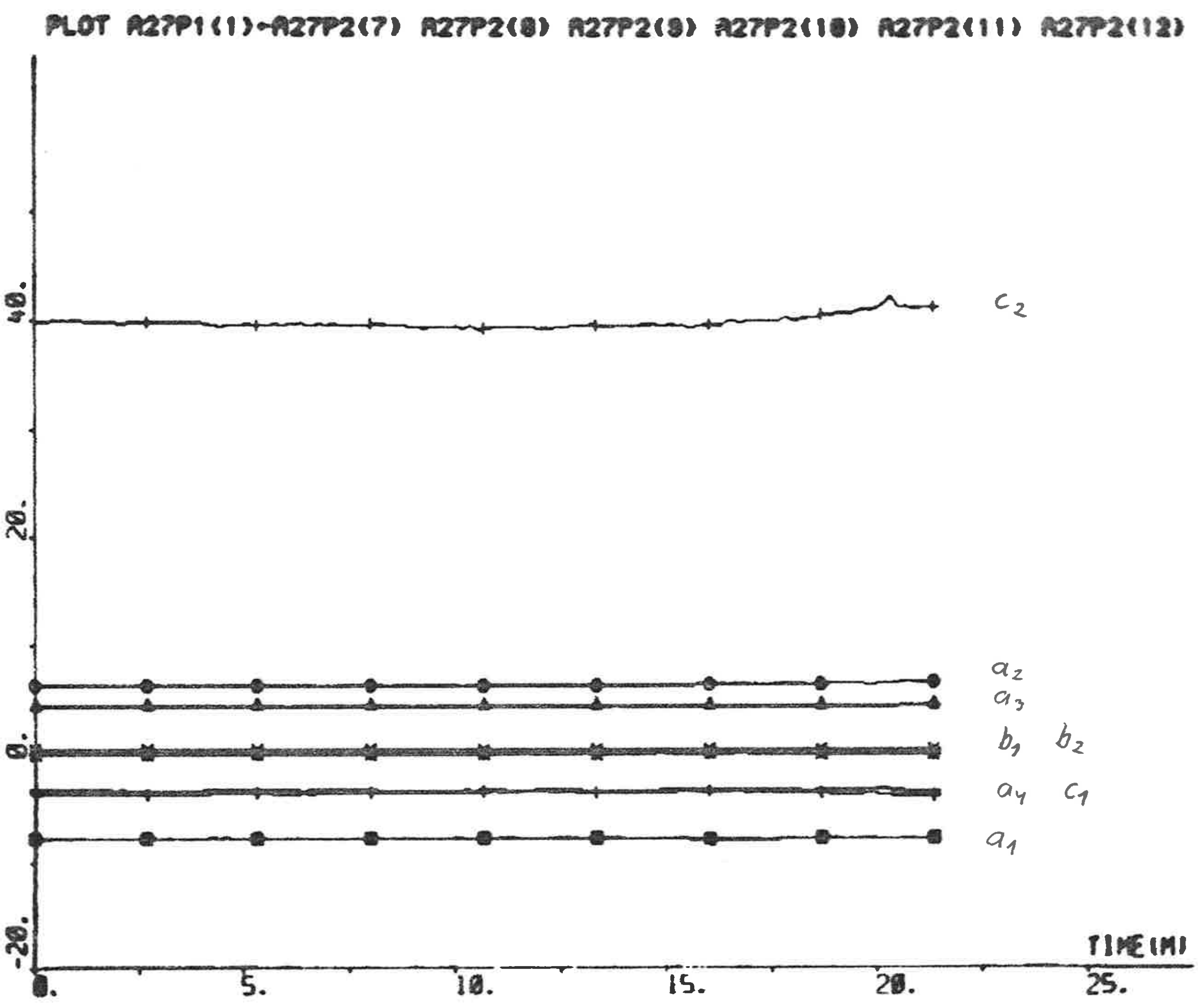

PLOT A27P1(1)-A27P1(4) A27P1(5) ERR2 Q0 Q1 Q2 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$


PLOT A27P1(1)-A27P1(8) A27P1(7) ERR3 00 002 004 -0.7 0. - DEG/S
0.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂


PLOT A27P1(1)-A27P1(8) A27P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 * DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A27P1(1)-A27P1(2) A27P1(3) ERR1 00 020 040 -05 15 DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂


PLOT A27P1(1)-A27P2(3) 00 -6.5 1.5
0.5 * $\hat{\delta}_0$ deg
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A27P1(1)-A27P2(7) A27P2(8) A27P2(9) A27P2(10) A27P2(11) A27P2(12) A2
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
c2
a2
a3
b1 b2
a4 c1
a1

EXPERIMENT A28

Date	1976-04-26	Forward draught	10.9 m
Time	12.52	Aft draught	12.9 m
Duration	24 min	Wind direction	SE (1; see App. A)
Position	S 06°06' W 06°32'	Wind velocity	4 m/s (gentle breeze)
ψ_{ref}	143 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter

Tuning time before the experiment started: 30 min

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.13 \\ 6.65 \\ 4.67 \\ -3.33 \\ 0.47 \\ 0.10 \\ -1.94 \\ 39.40 \end{bmatrix} \qquad P = \begin{bmatrix} 3.92 & & & & & & & \\ -5.51 & 12.92 & & & & & & \\ 0.54 & -8.61 & 15.22 & & & & & \\ 1.55 & 0.86 & -7.45 & 5.55 & & & & \\ 0.07 & -0.34 & 0.33 & -0.07 & 0.02 & & & \\ 0.02 & 0.02 & -0.17 & 0.16 & 0.00 & 0.02 & & \\ -0.75 & 1.00 & 0.19 & -0.48 & -0.01 & 0.01 & 0.79 & \\ 1.67 & -2.97 & -2.81 & 3.37 & 1.03 & -0.40 & 13.89 & 682.35 \end{bmatrix}$$

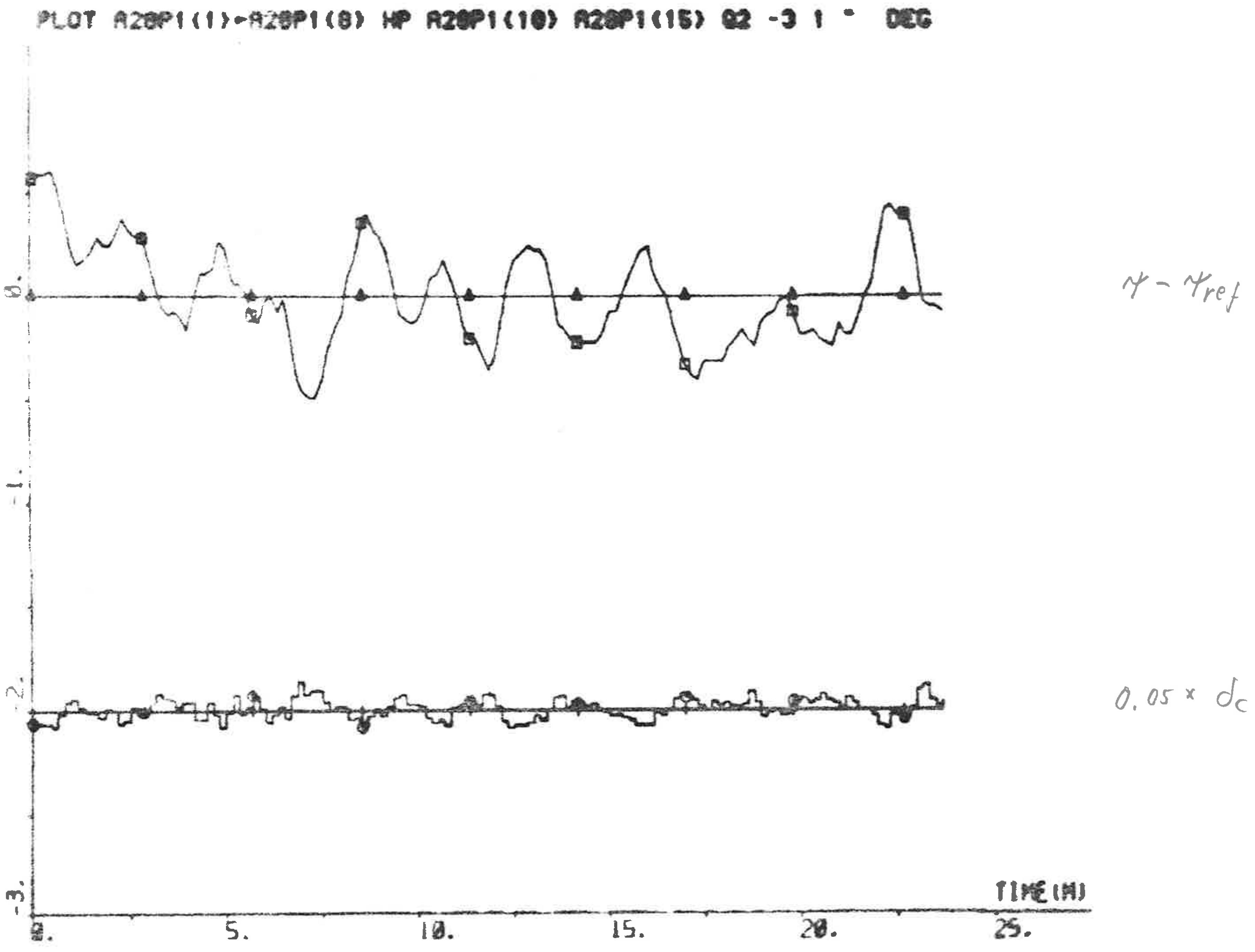
$a_1 + a_2 + a_3 + a_4 = -0.14$

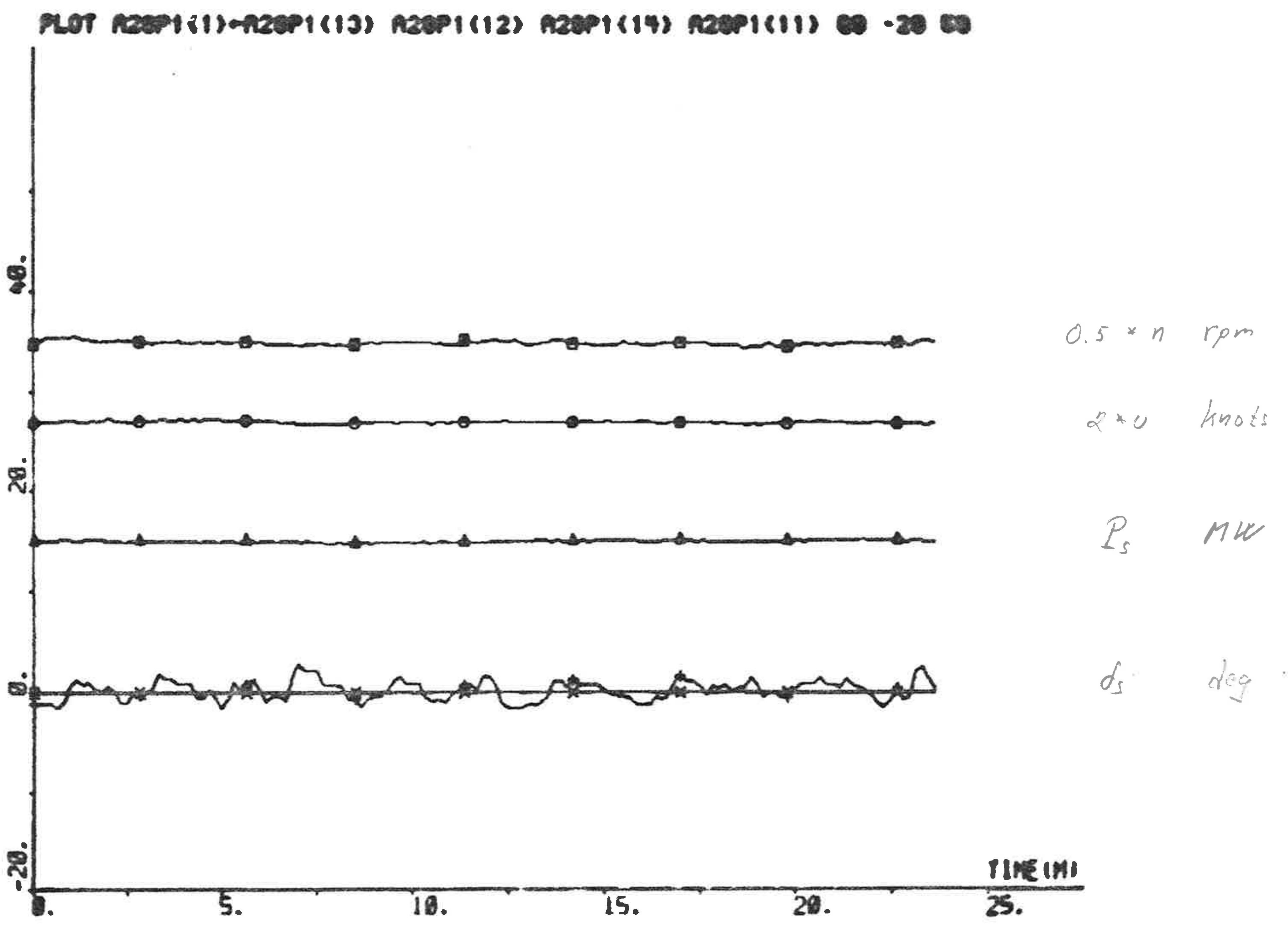
$\hat{\delta}_0 = 0.3$ deg $\hat{d}_v = 0.19$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

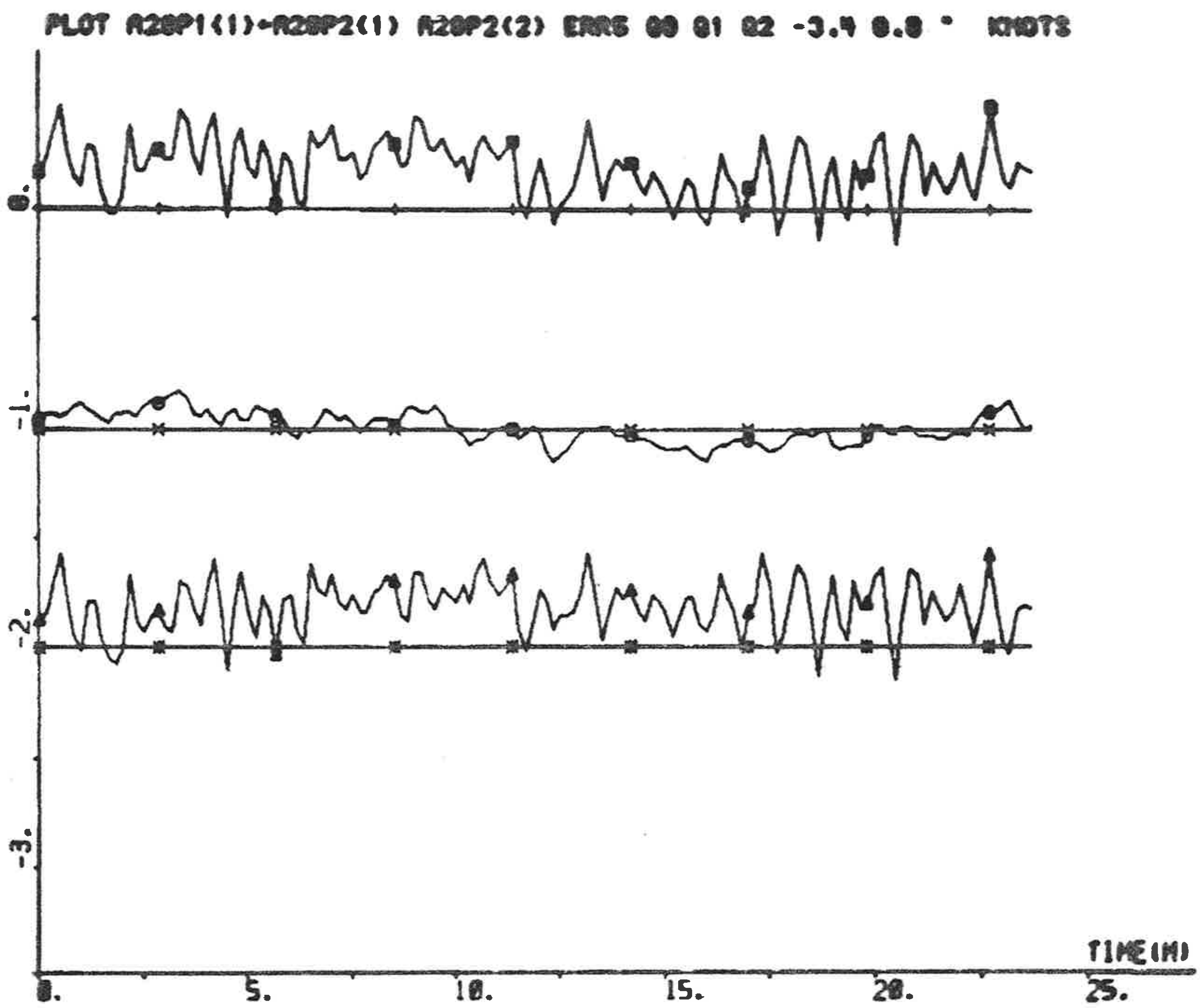
Statistics (mean value and standard deviation)

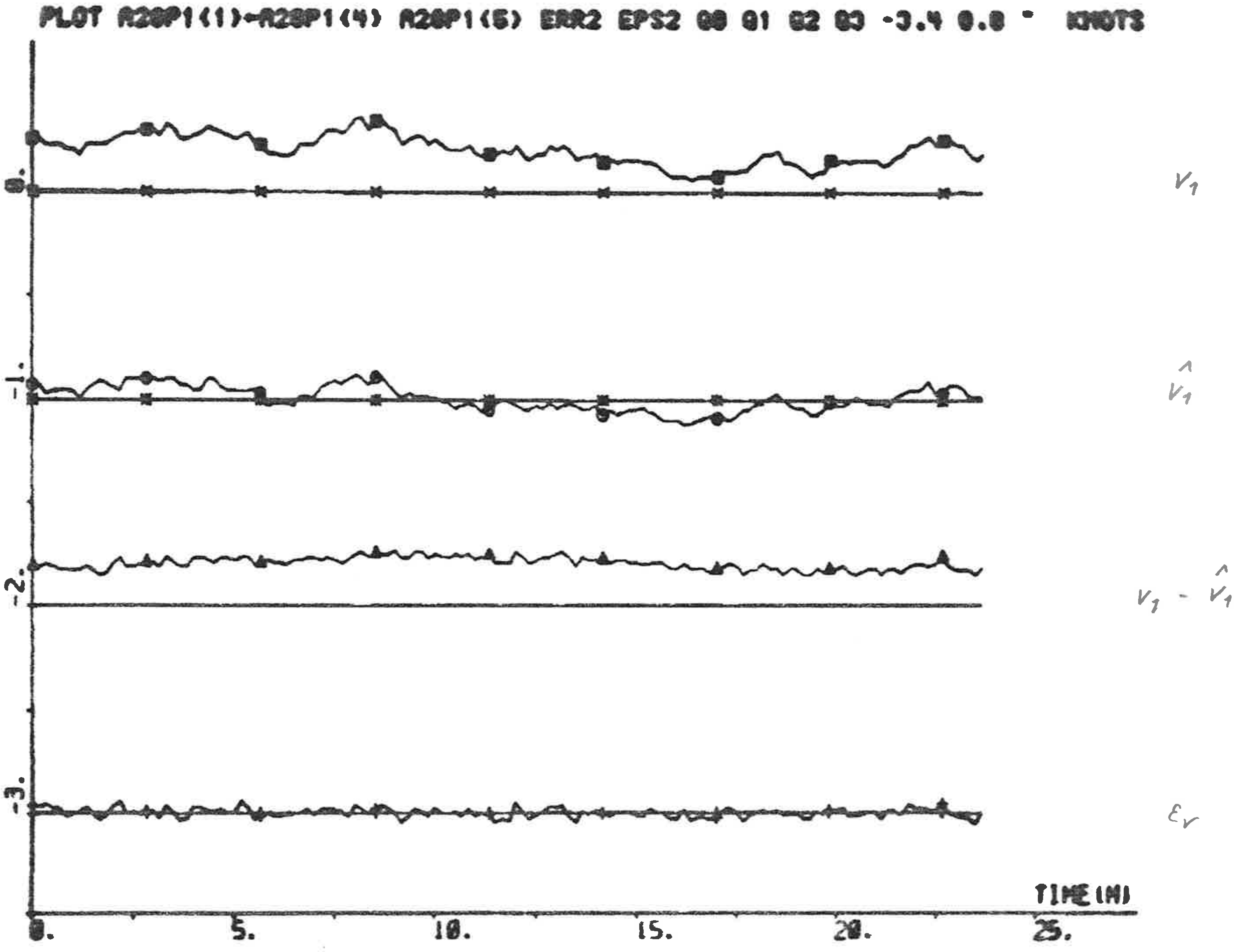
δ_c	0.16 ± 0.95	deg		P_s	15.0 ± 0.1	MW
δ	1.72 ± 0.87	deg		ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.006 ± 0.239	deg		ε_r	0.00 ± 0.02	deg/s
n	69.9 ± 0.4	rpm		ε_ψ	0.00 ± 0.03	deg
u	13.5 ± 0.1	knots		ε_δ	0.0 ± 0.5	deg

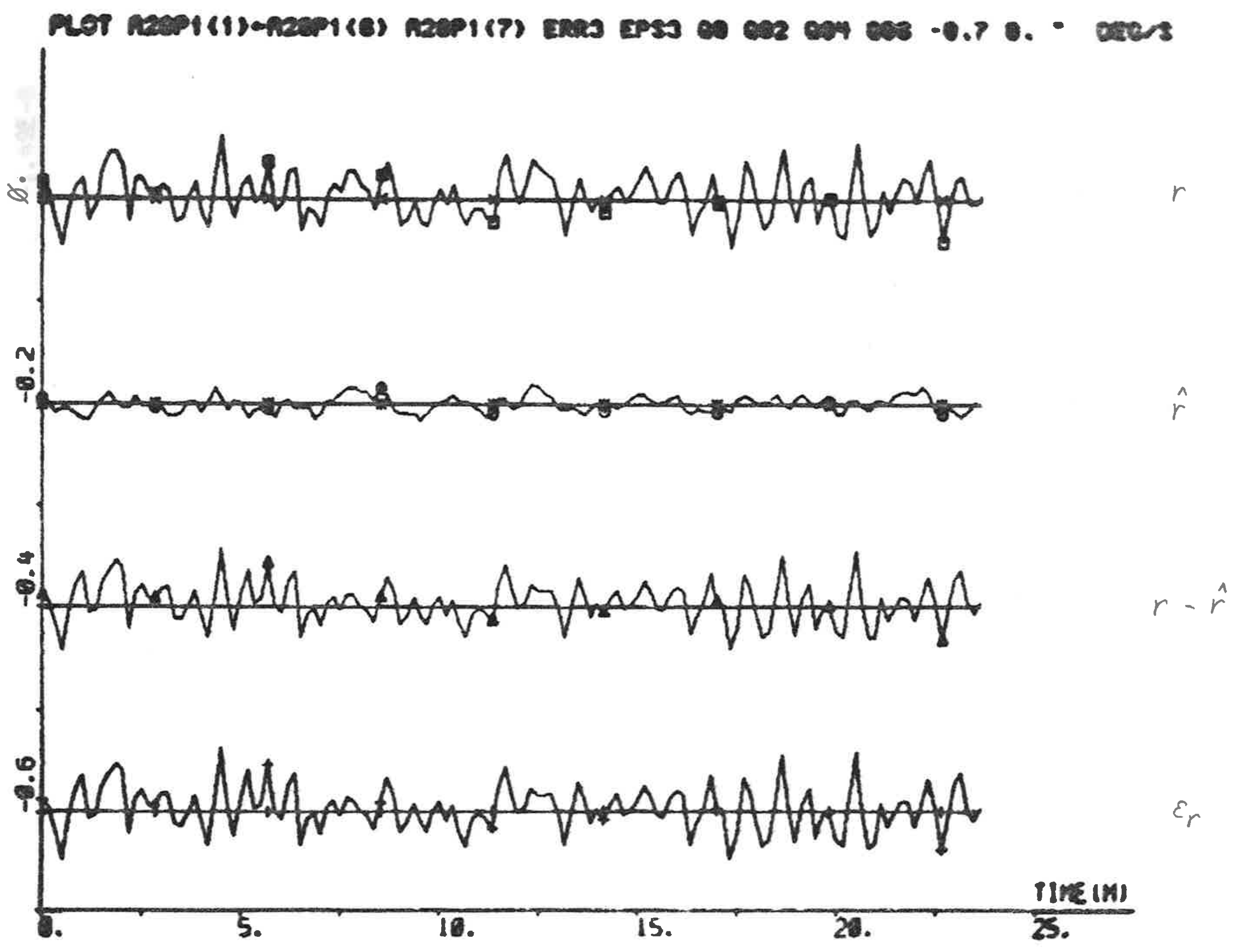
$V_1 = 0.132$

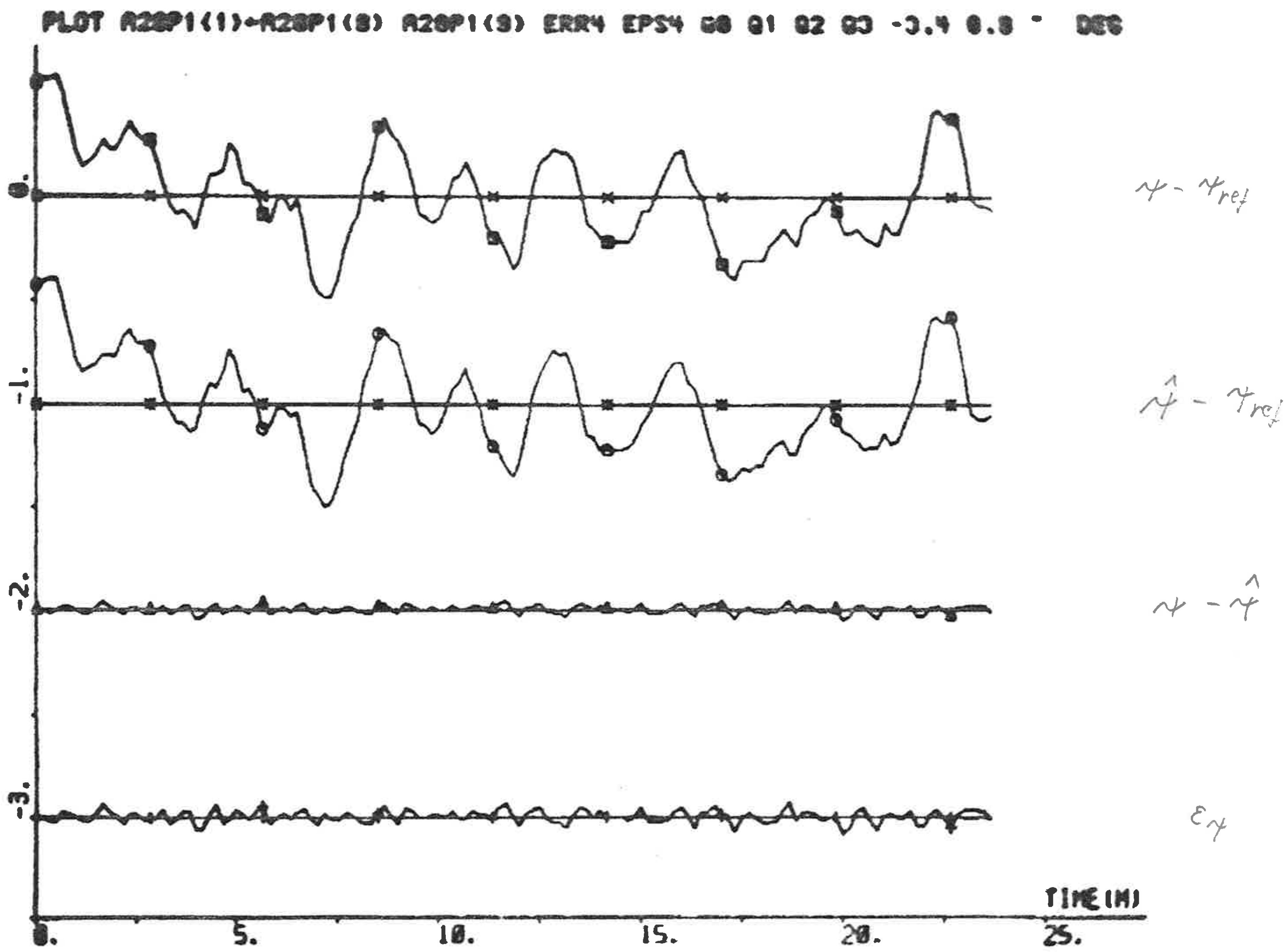

PLOT A20P1(1)-A20P1(8) HP A20P1(10) A20P1(15) Q2 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 × δc

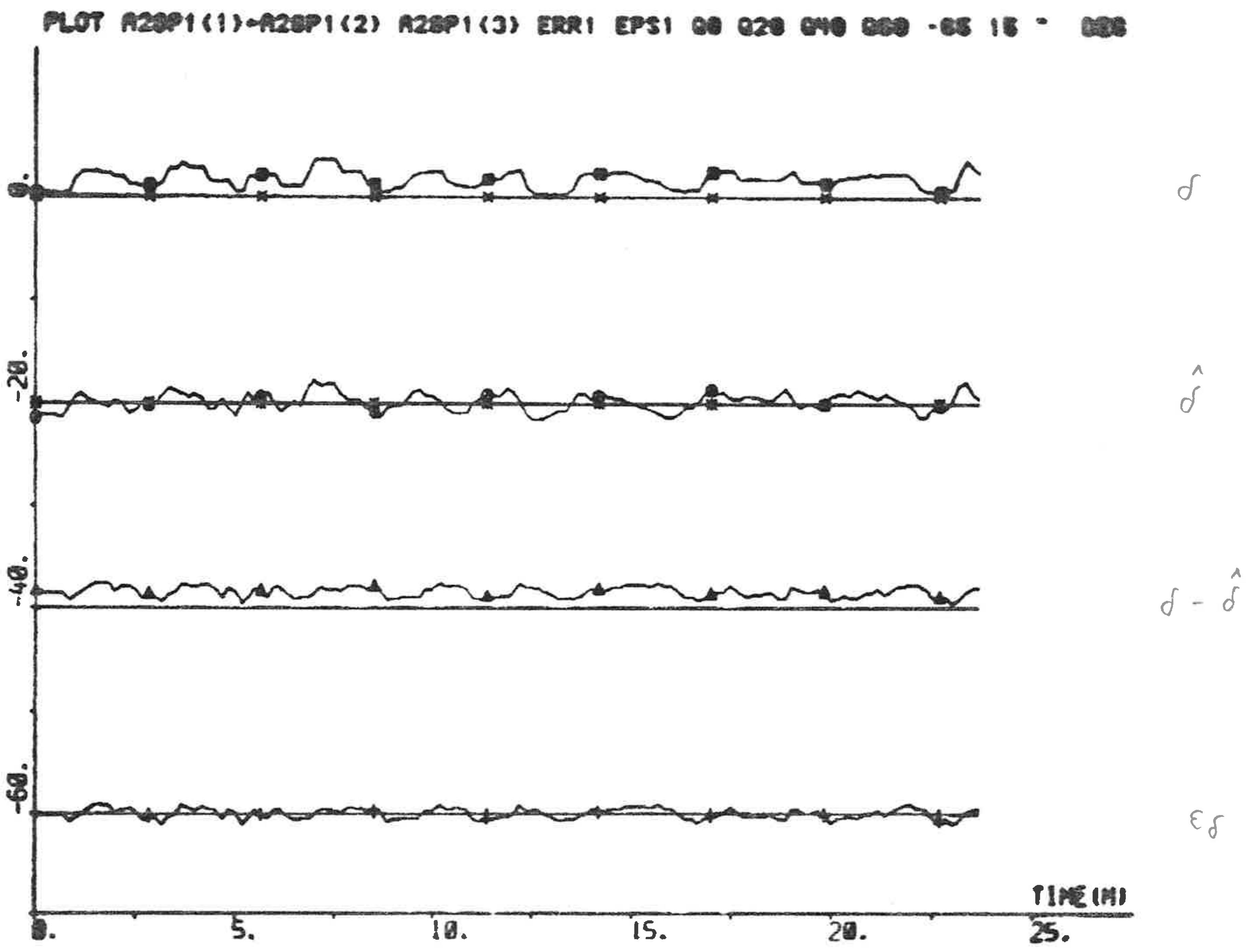

PLOT A20P1(1)-A20P1(13) A20P1(12) A20P1(14) A20P1(11) 60 -20 60
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n rpm
2 * u knots
P_s MW
δ_s deg

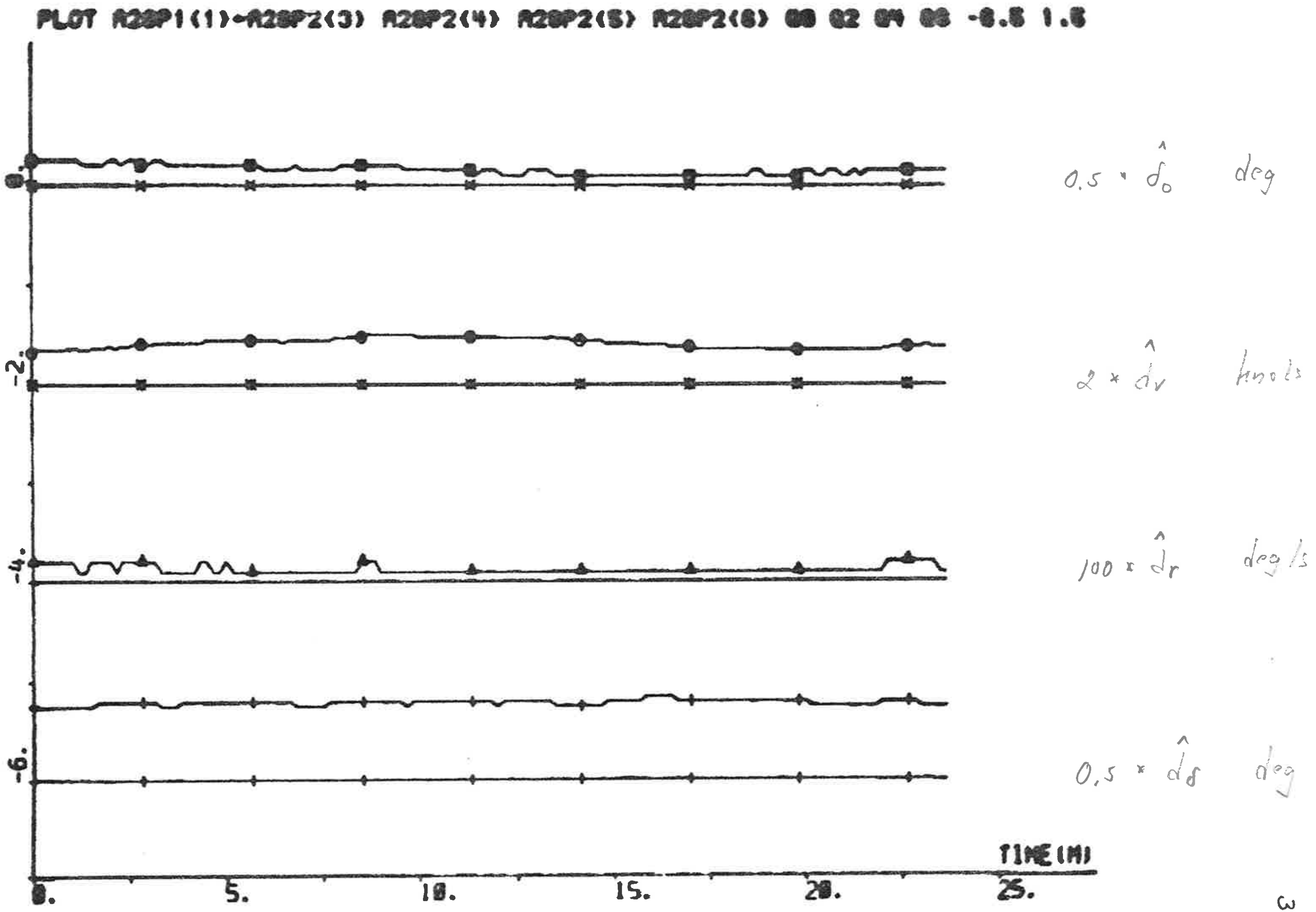

PLOT A28P1(1)-A28P2(1) A28P2(2) ERRS 00 01 02 -3.4 0.8 ° KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

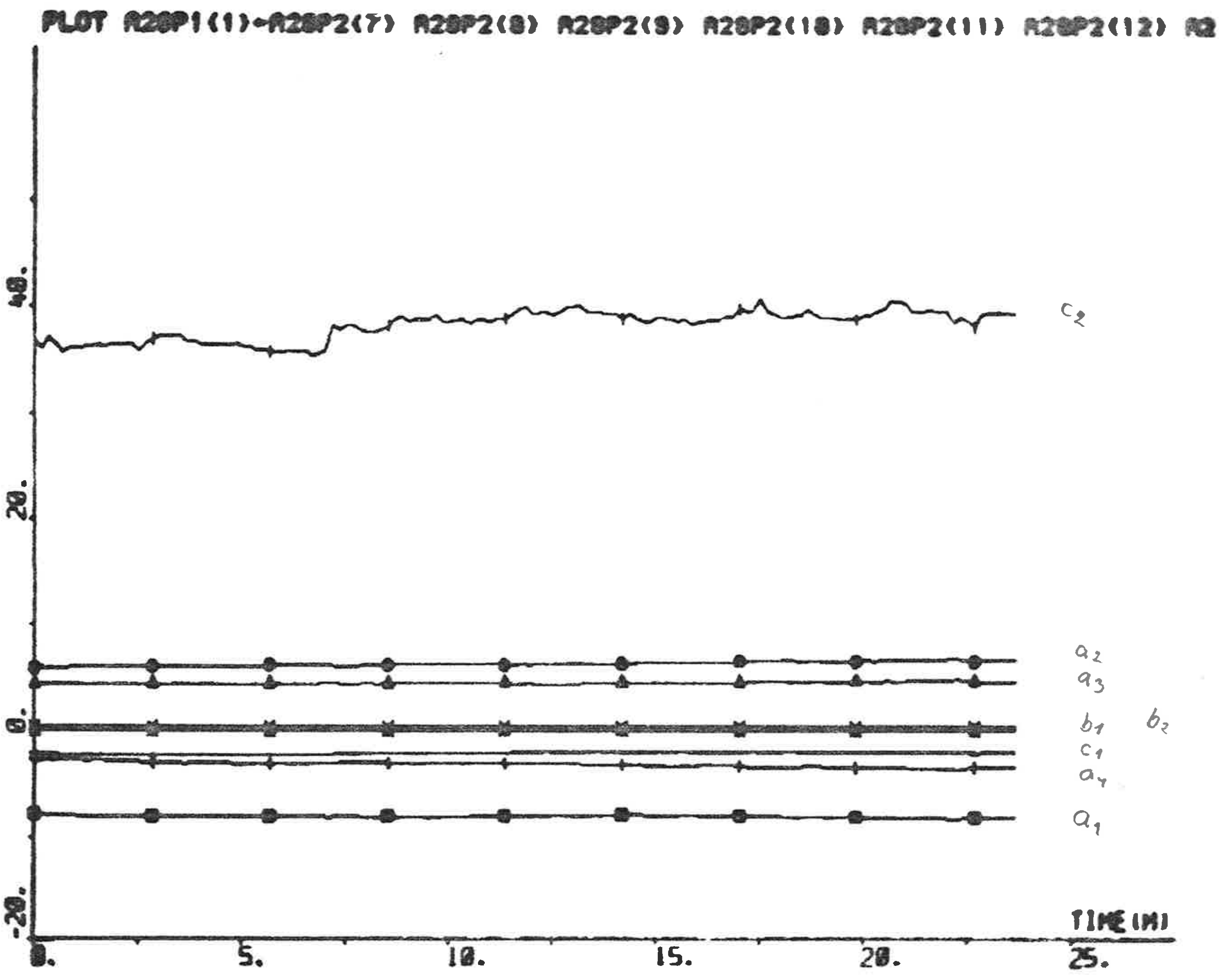

PLOT A20P1(1)-A20P1(4) A20P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 " KNOTS
0.
-1.
-2.
-3.
TIME(H)
0.
5.
10.
15.
20.
25.


PLOT R20P1(1)-R20P1(6) R20P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. " DEG/S
0.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂
εr


PLOT A2SP1(1)-A2SP1(8) A2SP1(3) ERR4 EPS4 G0 G1 G2 G3 -3.4 0.8 - DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A2BP1(1)-A2BP1(2) A2BP1(3) ERR1 EPS1 00 Q20 Q40 Q60 -05 15
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(H)


PLOT A2SP1(1)-A2SP2(3) A2SP2(4) A2SP2(5) A2SP2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.5 * $\hat{d}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A20P1(1)-A20P2(7) A20P2(8) A20P2(9) A20P2(10) A20P2(11) A20P2(12) A2
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT A29

Date	1976-04-26	Forward draught	10.9 m
Time	13.58	Aft draught	12.9 m
Duration	24 min	Wind direction	SE (1; see App. A)
Position	S 06°18' W 06°24'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	143 deg	Wave height	-

Self-tuning regulator using non-filtered measurements

Tuning time before the experiment started: 30 min.

NC1 = 0 NC2 = 0 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -9.74 \\ 8.98 \\ 6.22 \\ -5.25 \\ 0.29 \\ -0.06 \end{bmatrix} \qquad P = \begin{bmatrix} 1.46 & & & & & \\ -1.98 & 6.56 & & & & \\ -0.10 & -5.46 & 10.48 & & & \\ 0.85 & 0.59 & -5.04 & 4.00 & & \\ -0.01 & -0.34 & 0.47 & -0.11 & 0.05 & \\ 0.07 & -0.07 & -0.30 & 0.33 & 0.00 & 0.04 \end{bmatrix}$$

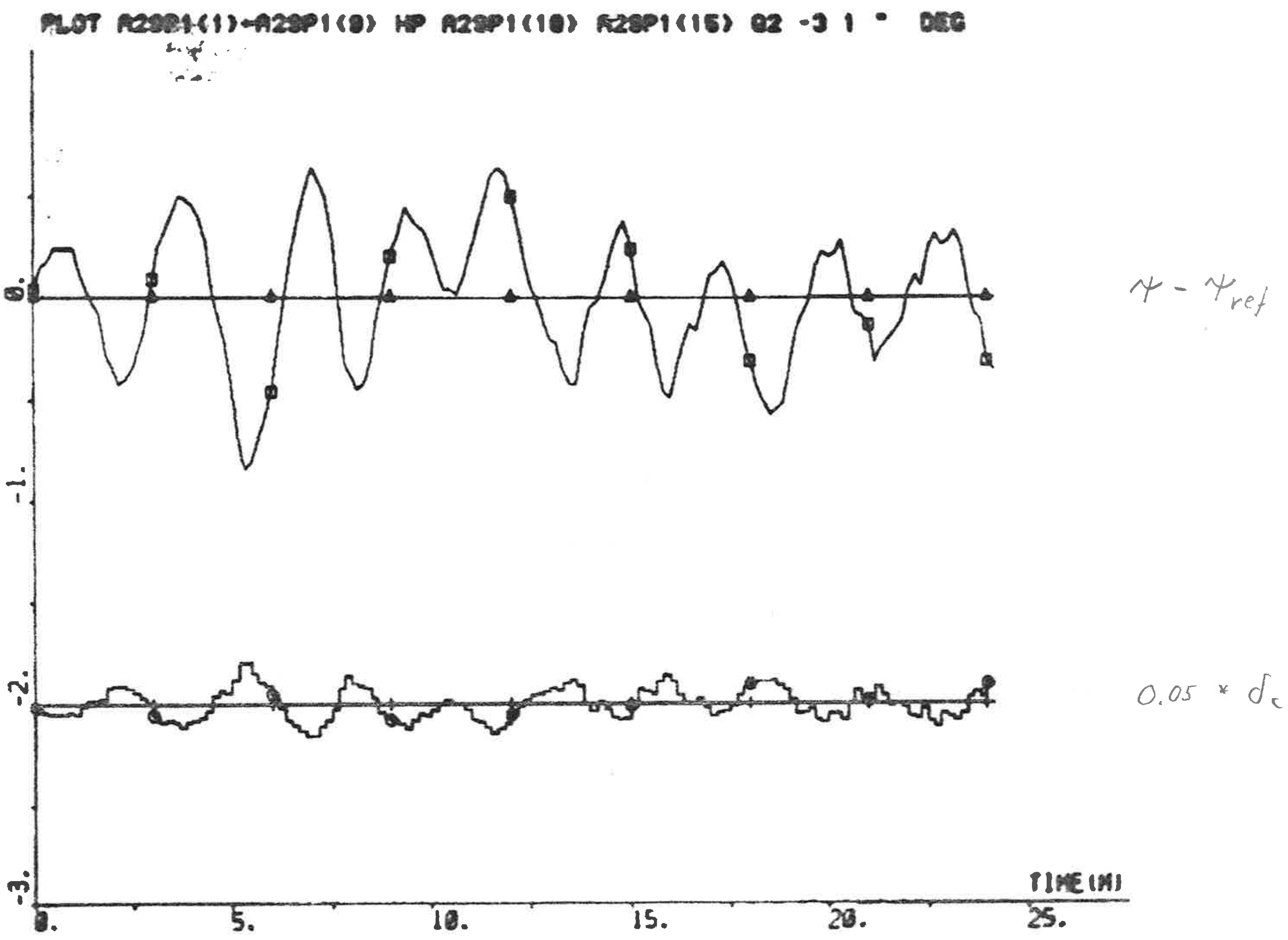
$a_1 + a_2 + a_3 + a_4 = 0.21$

$\hat{\delta}_0 = 0.1$ deg $\hat{d}_v = 0.17$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.6$ deg

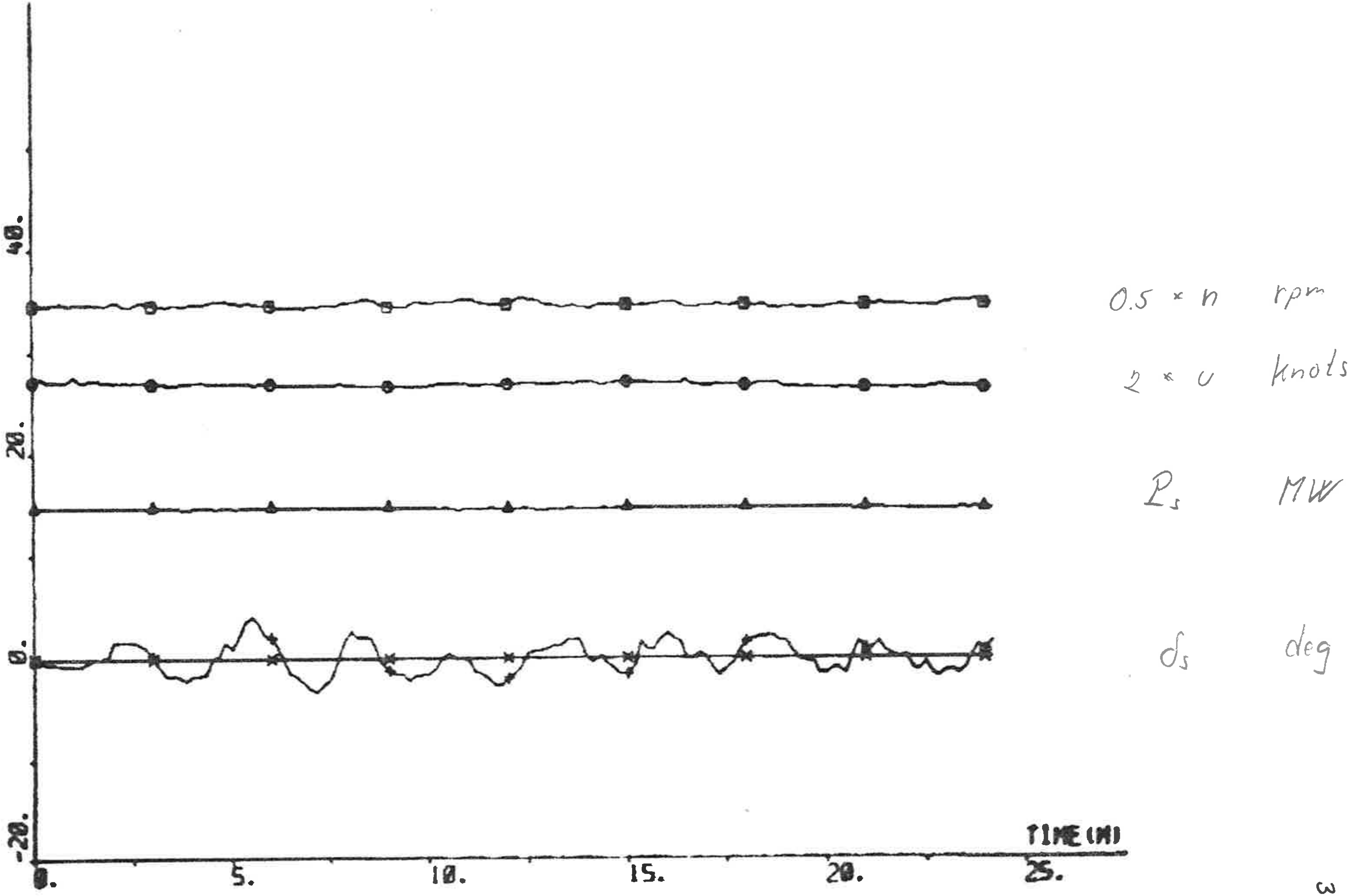
Statistics (mean value and standard deviation)

δ_c	-0.01 ± 1.51	deg		P_s	14.6 ± 0.1	MW
δ	1.53 ± 1.27	deg		ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.001 ± 0.324	deg		ε_r	0.00 ± 0.02	deg/s
n	69.5 ± 0.4	rpm		ε_ψ	0.00 ± 0.03	deg
u	13.4 ± 0.1	knots		ε_δ	0.0 ± 0.5	deg

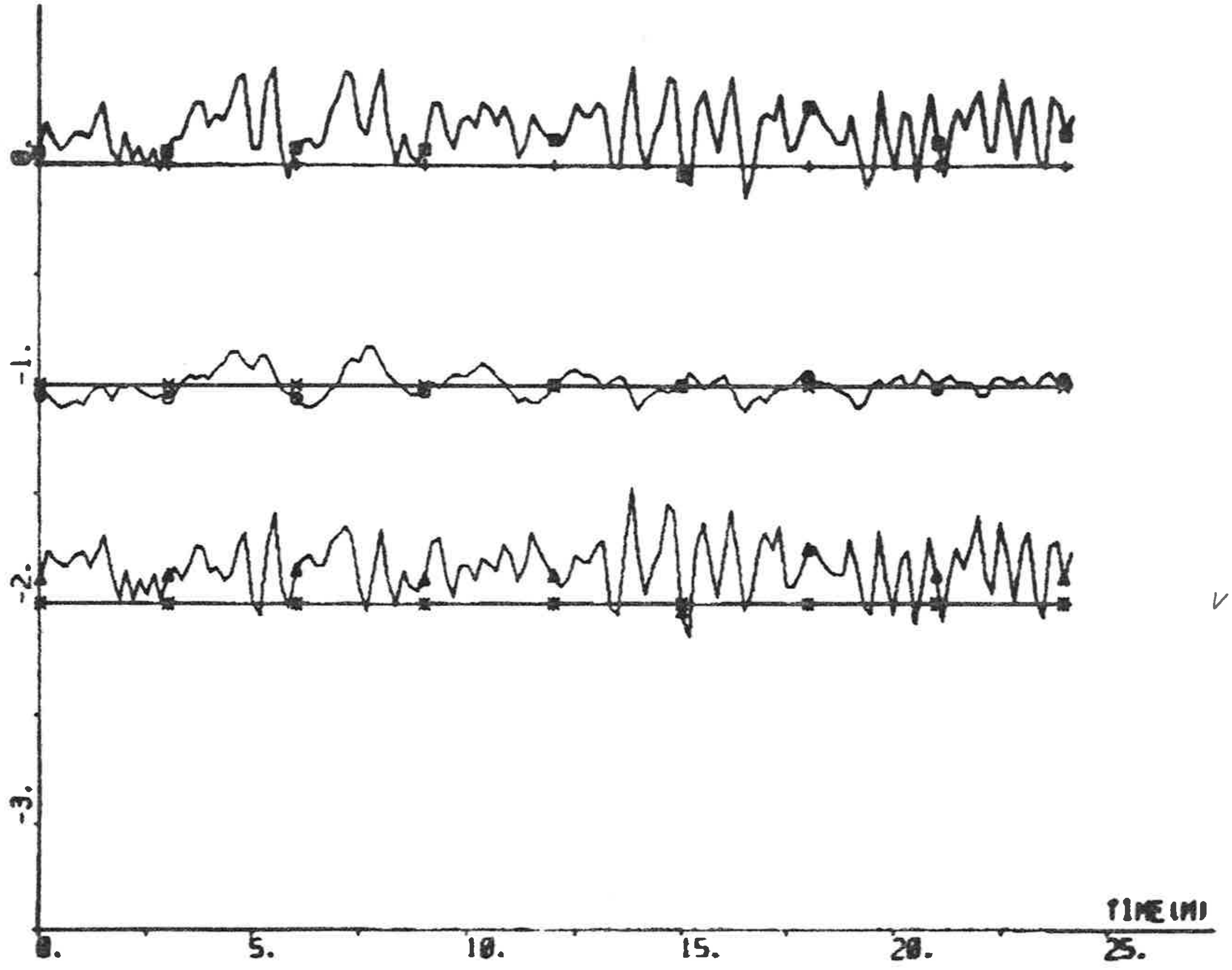
$V_1 = 0.295$

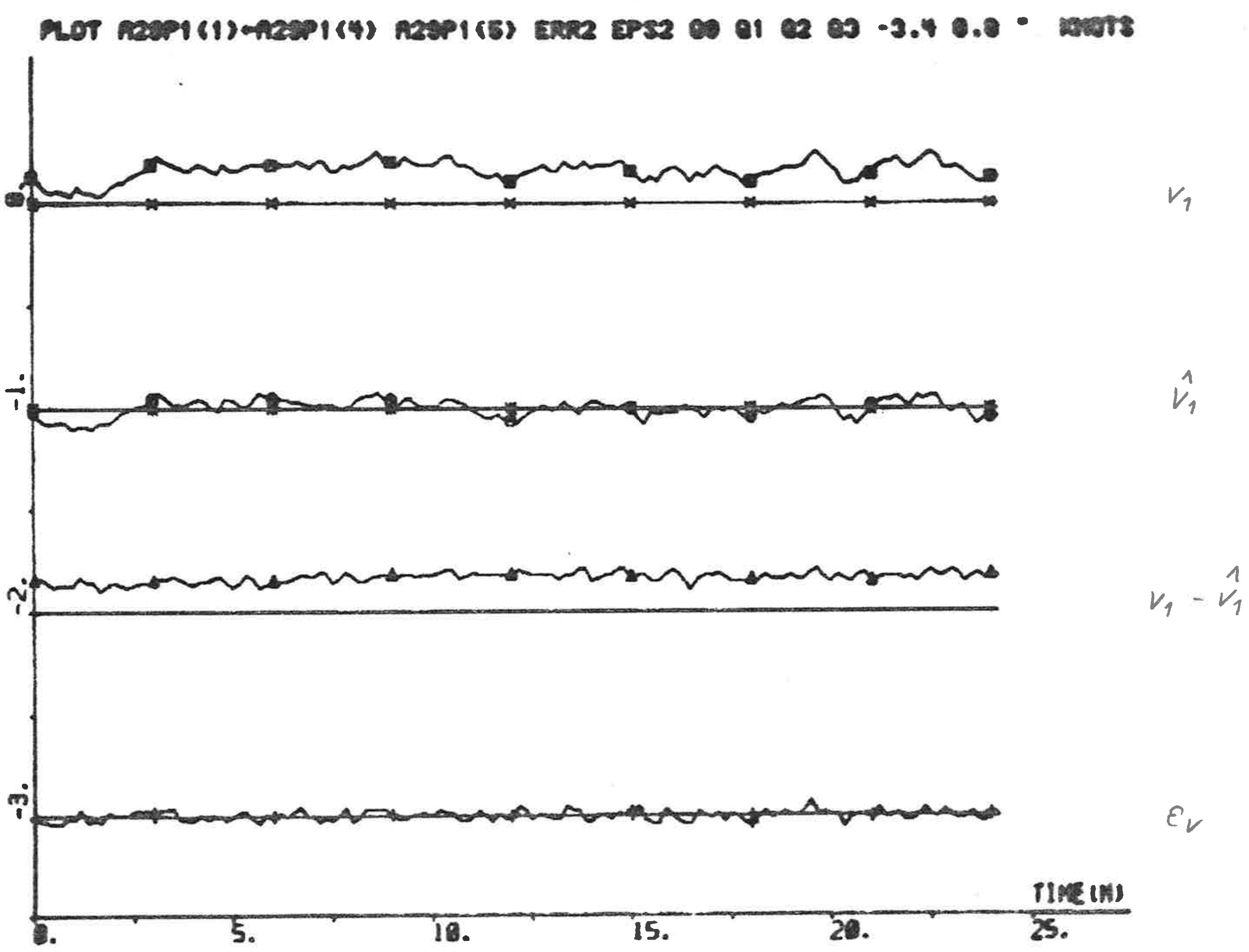

PLOT A29B1(1)-A29P1(9) HP A29P1(10) A29P1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

PLOT A29P1(1)-A29P1(13) A29P1(12) A29P1(14) A29P1(11) 60 -20 50

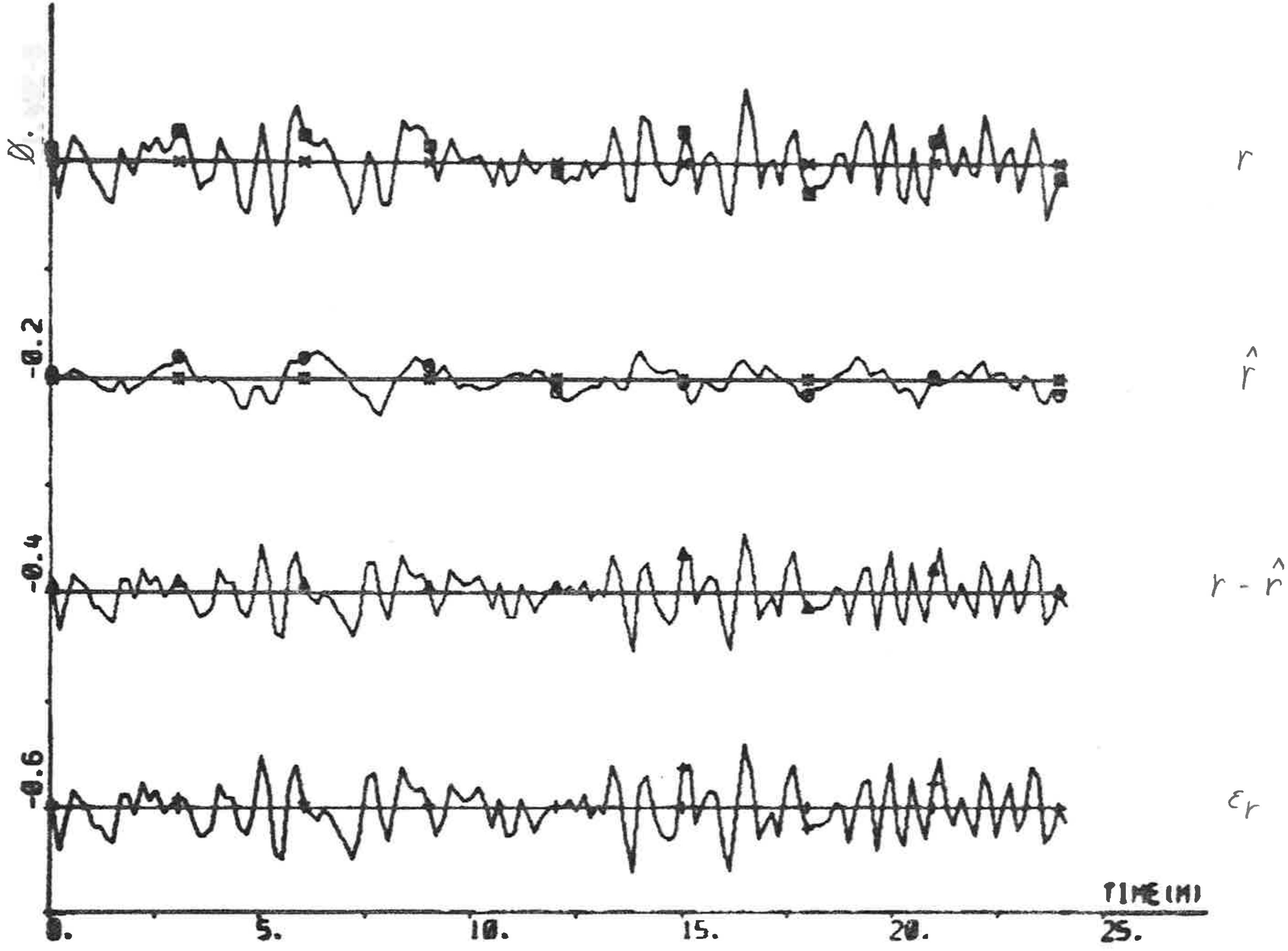


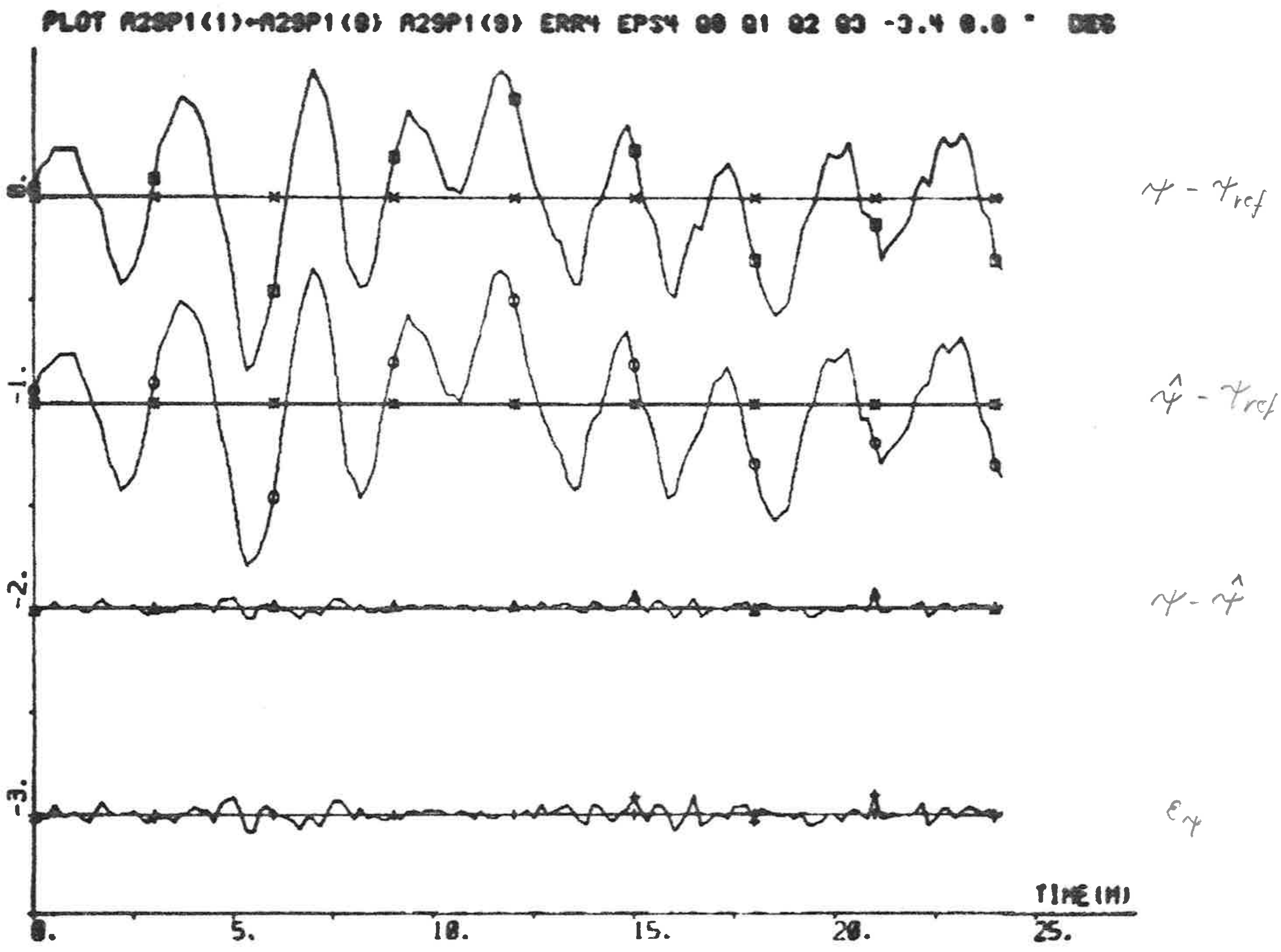
PLOT A2SP1(1)-A2SP2(1) A2SP2(2) ERRS Q0 Q1 Q2 -3.4 0.0 ° KNOTS

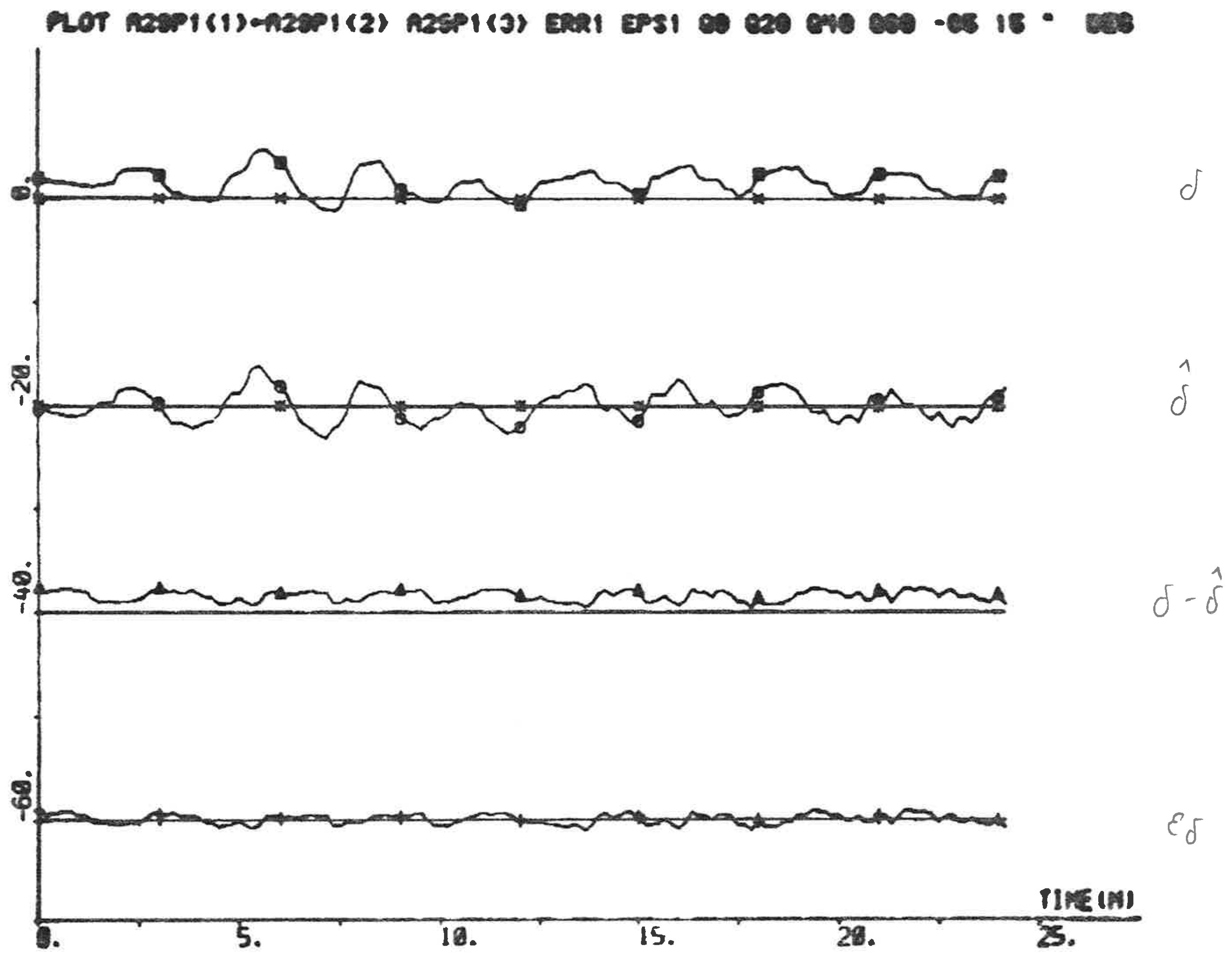


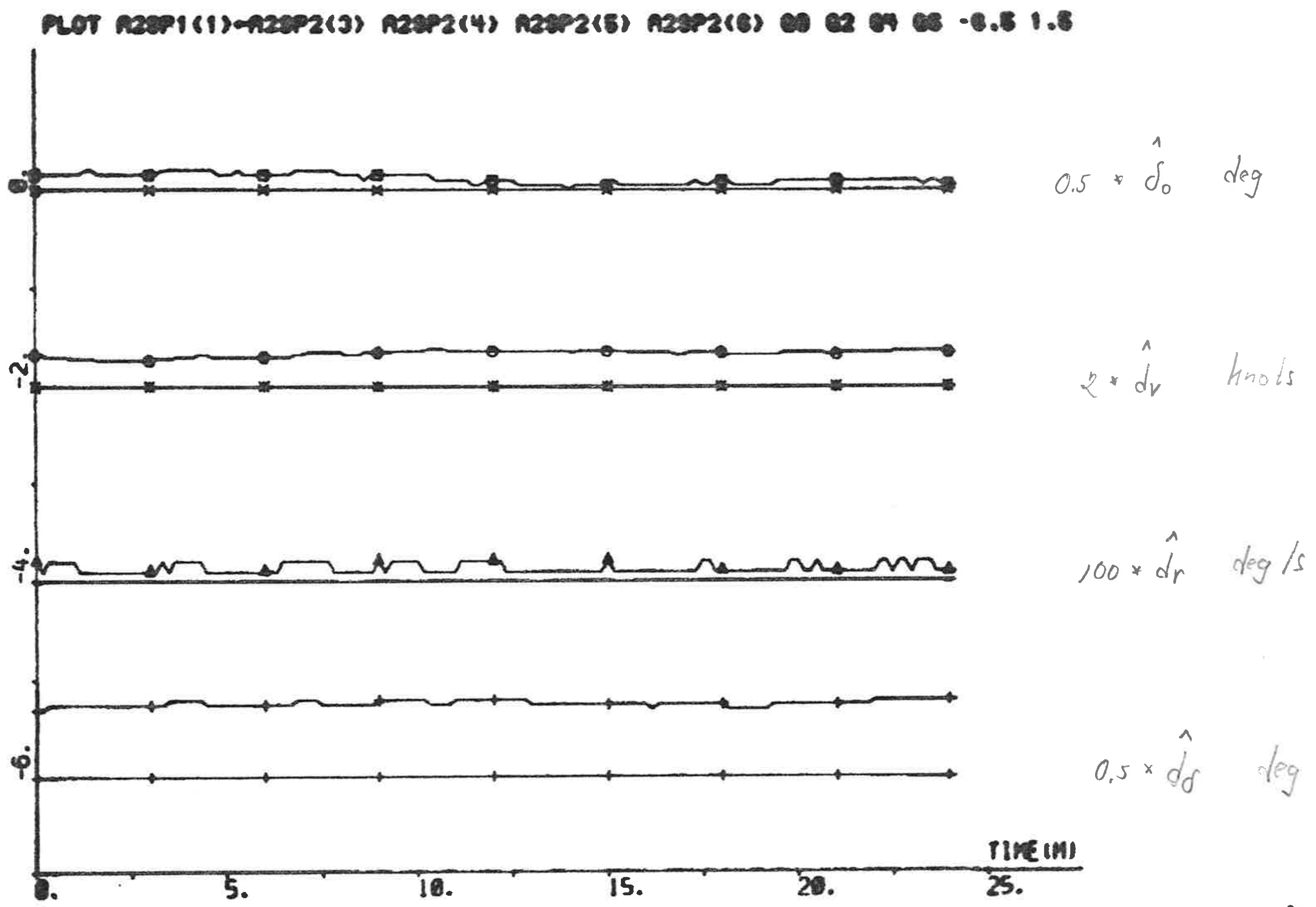

PLOT A29P1(1)-A29P1(4) A29P1(5) ERR2 EPS2 G0 G1 G2 G3 -3.4 0.0 * KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V

PLOT A29P1(1)-A29P1(8) A29P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. ° DEG/S

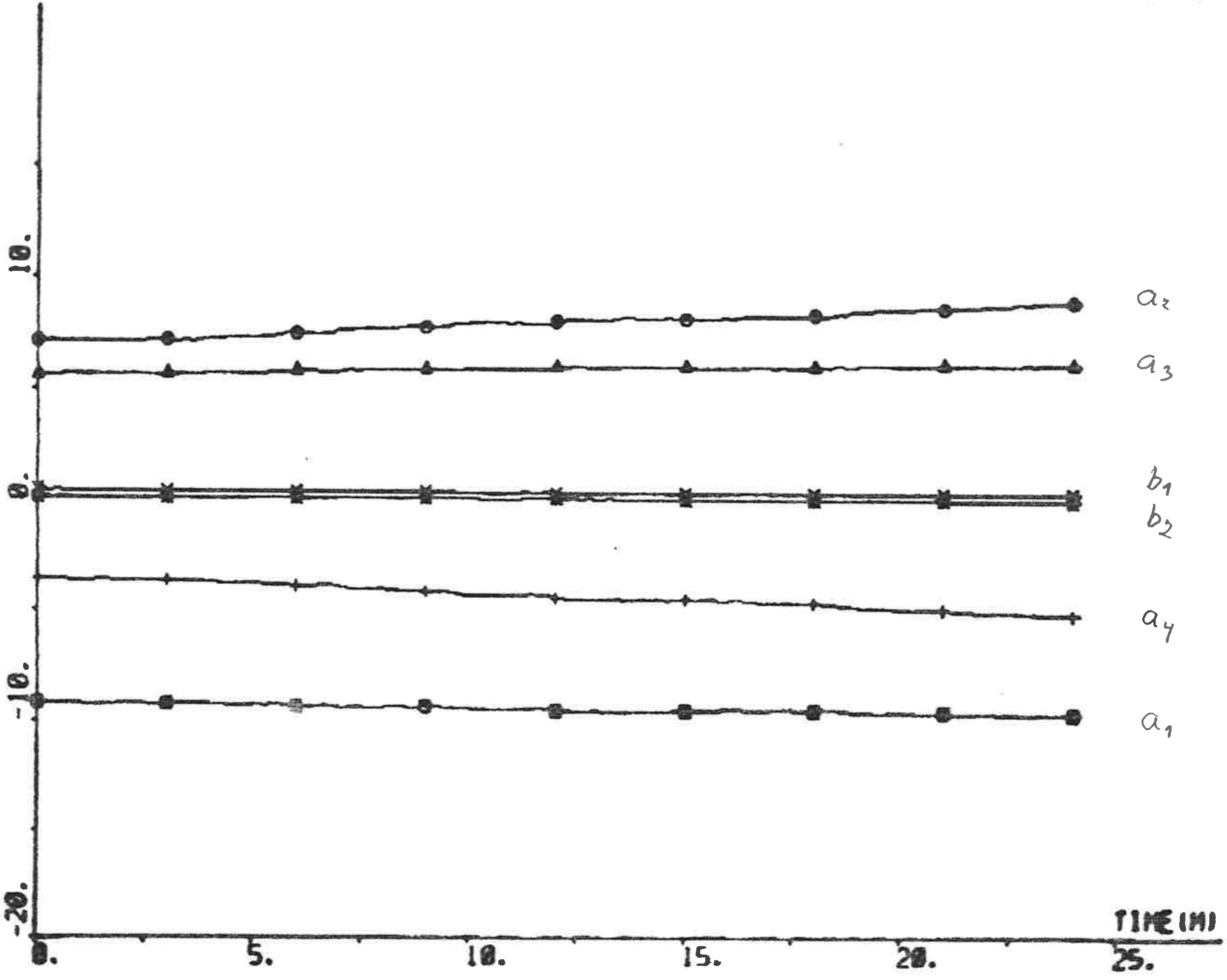



PLOT A29P1(1)-A29P1(9) A29P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A2SP1(1)-A2SP1(2) A2SP1(3) ERR1 EPS1 00 020 040 060 -05 15
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(H)
δ
δ̂
δ - δ̂
εδ


PLOT A2SP1(1)-A2SP2(3) A2SP2(4) A2SP2(5) A2SP2(6) 00 02 04 06 -0.5 1.6
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * δ̂o deg
2 * d̂v knots
100 * d̂r deg/s
0.5 * d̂δ deg

PLOT A20P1(1)+A20P2(7) A20P2(8) A20P2(9) A20P2(10) A20P2(11) A20P2(12) -2



EXPERIMENT A30

Date	1976-04-26	Forward draught	10.9 m
Time	15.12	Aft draught	12.9 m
Duration	25 min	Wind direction	SE (1; see App. A)
Position	S 06°32' W 06°13'	Wind velocity	5 m/s (gentle breeze)
ψ_{ref}	143 deg	Wave height	-

PID-regulator using estimates from the Kalman filter.

$k_P = 3$ $k_D = 120$ s $k_I = 0.02$ 1/s

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

The parameters were manually tuned before the experiment started.

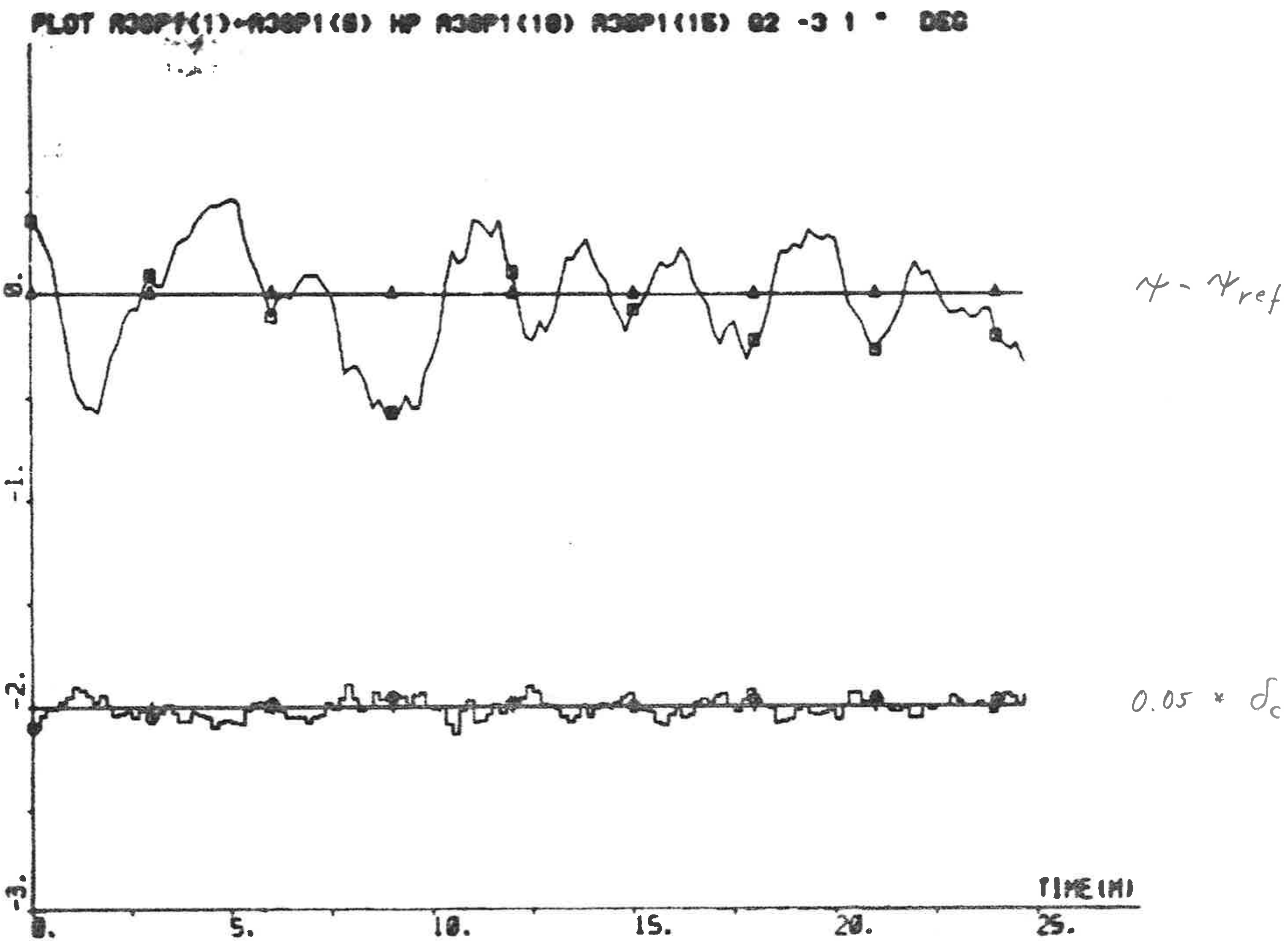
Final values:

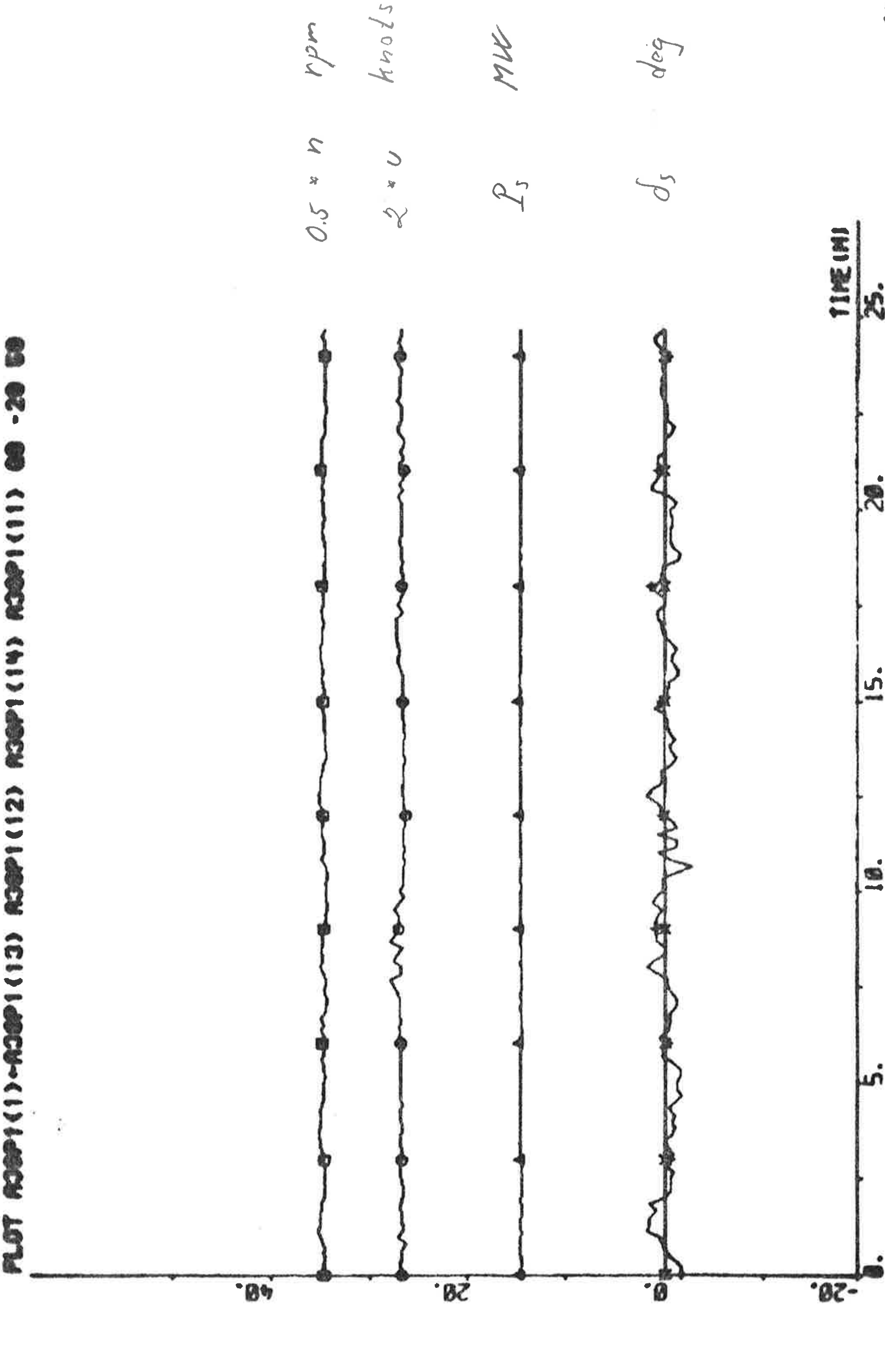
$\hat{\delta}_0 = 0.0$ deg $\hat{d}_v = 0.16$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

Statistics (mean value and standard deviation)

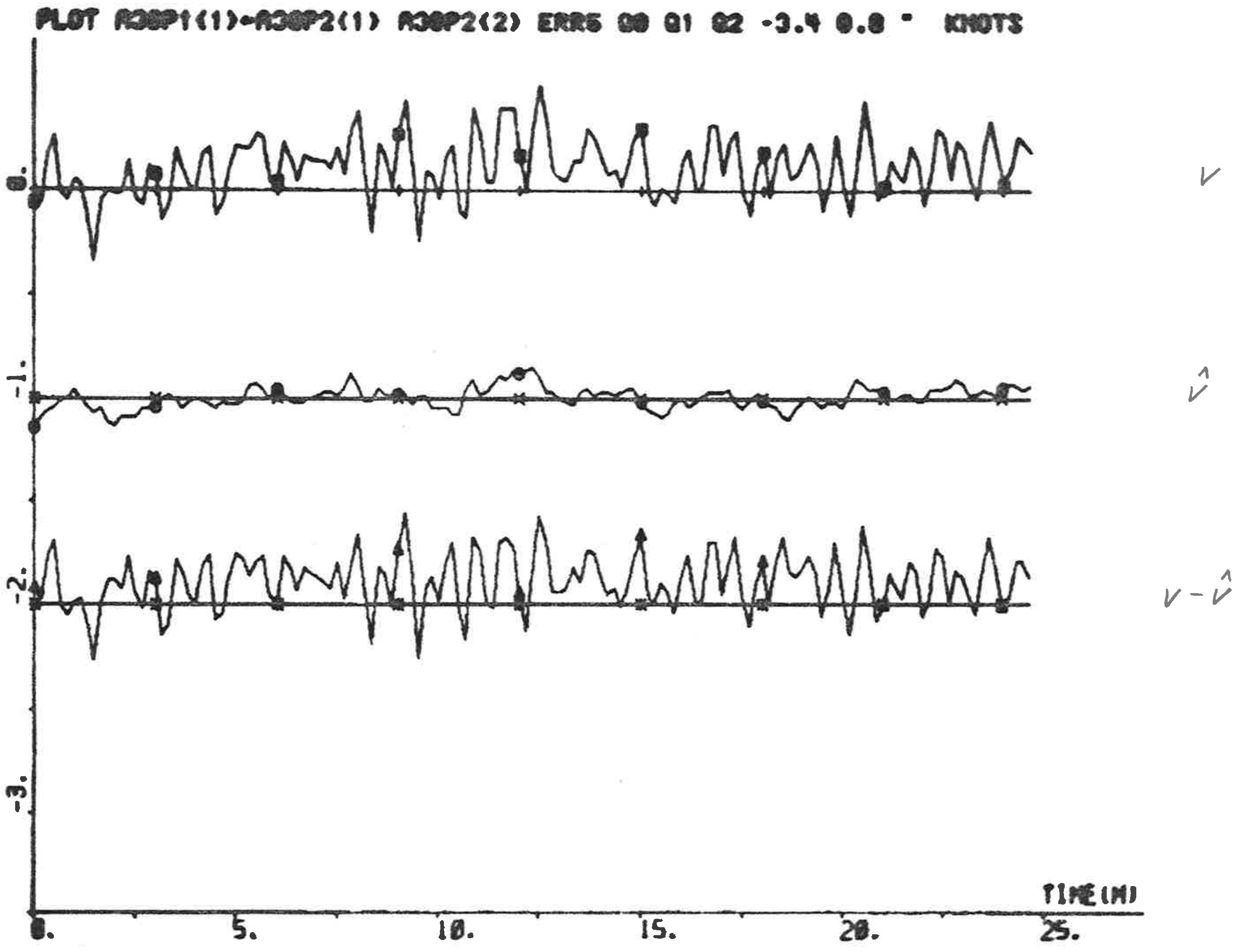
δ_c	-0.10 ± 0.89	deg	P_s	14.6 ± 0.1	MW
δ	1.44 ± 0.71	deg	ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	-0.026 ± 0.256	deg	ε_r	0.00 ± 0.02	deg/s
n	69.6 ± 0.4	rpm	ε_ψ	0.00 ± 0.03	deg
u	13.5 ± 0.1	knots	ε_δ	0.0 ± 0.5	deg

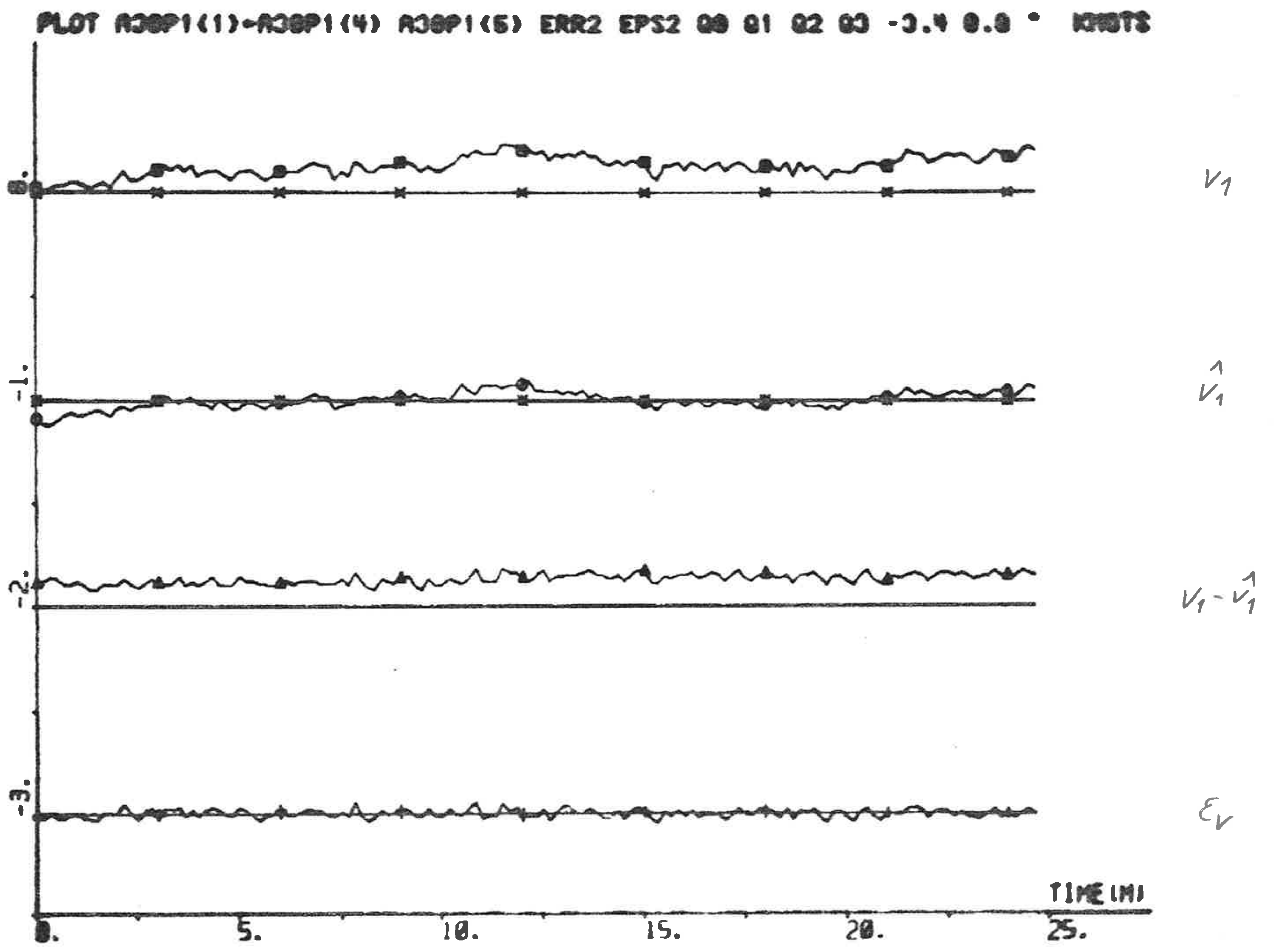
$V_1 = 0.132$

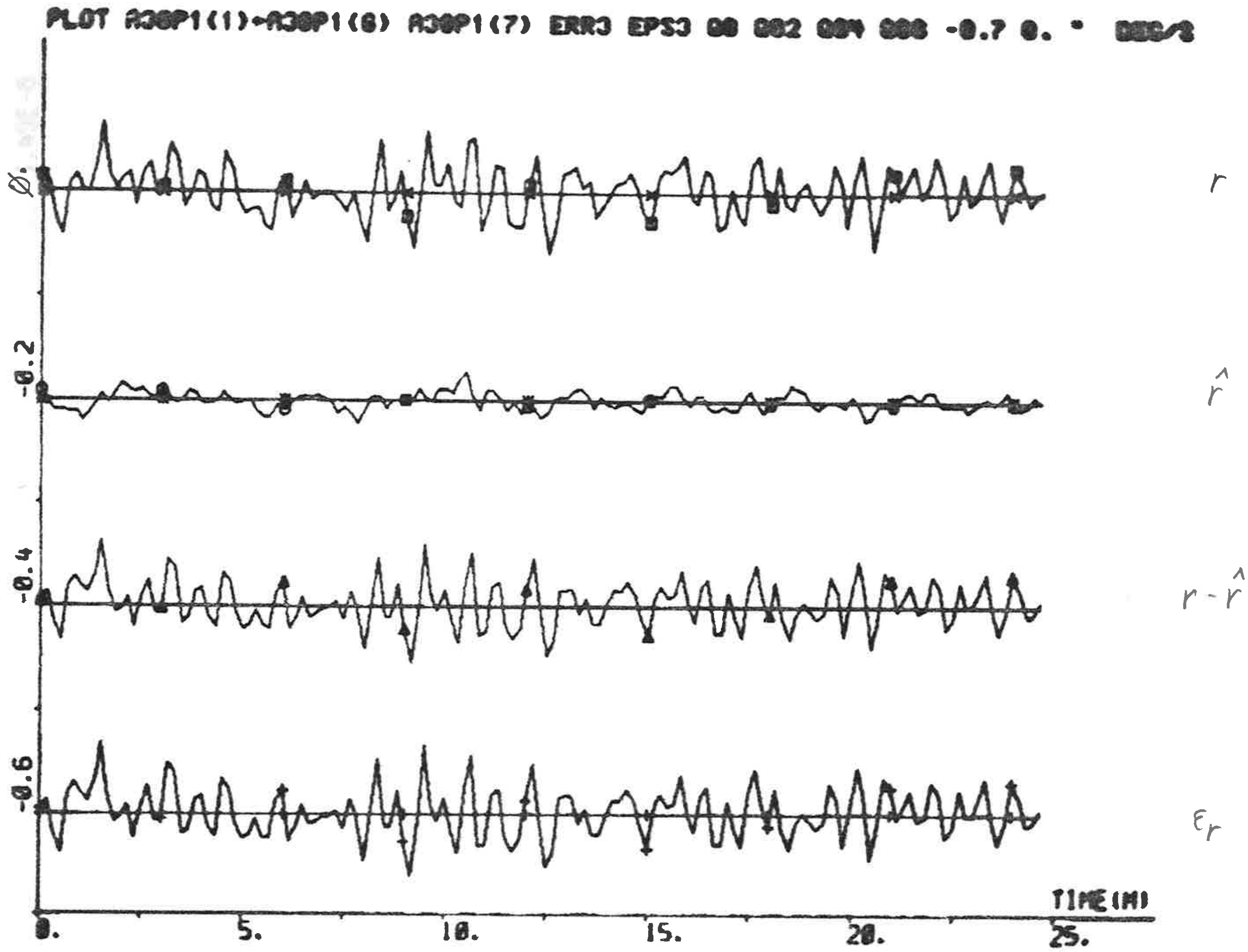

PLOT A3SP1(1)-A3SP1(8) HP A3SP1(10) A3SP1(15) 02 -3 1 * DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

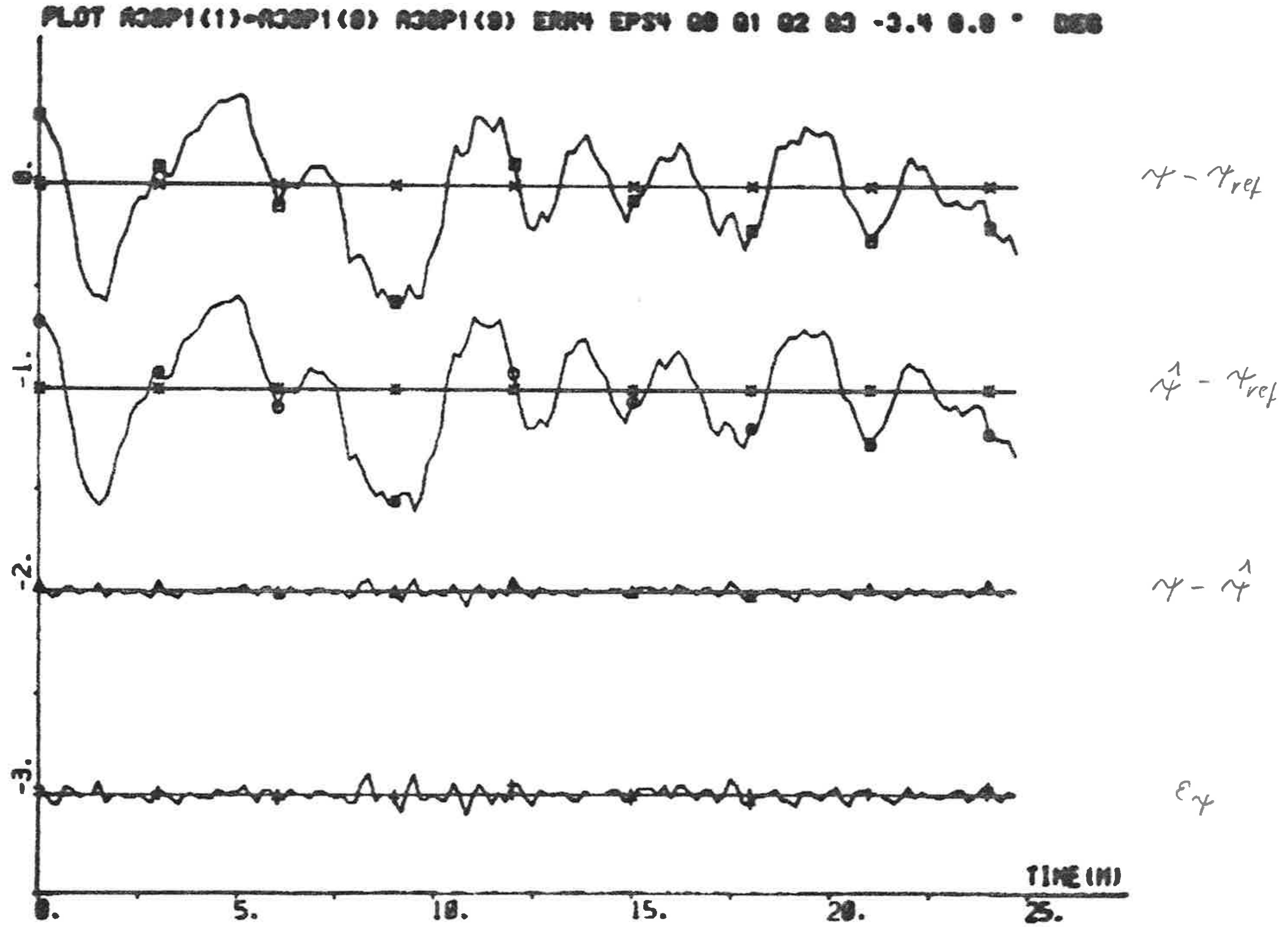


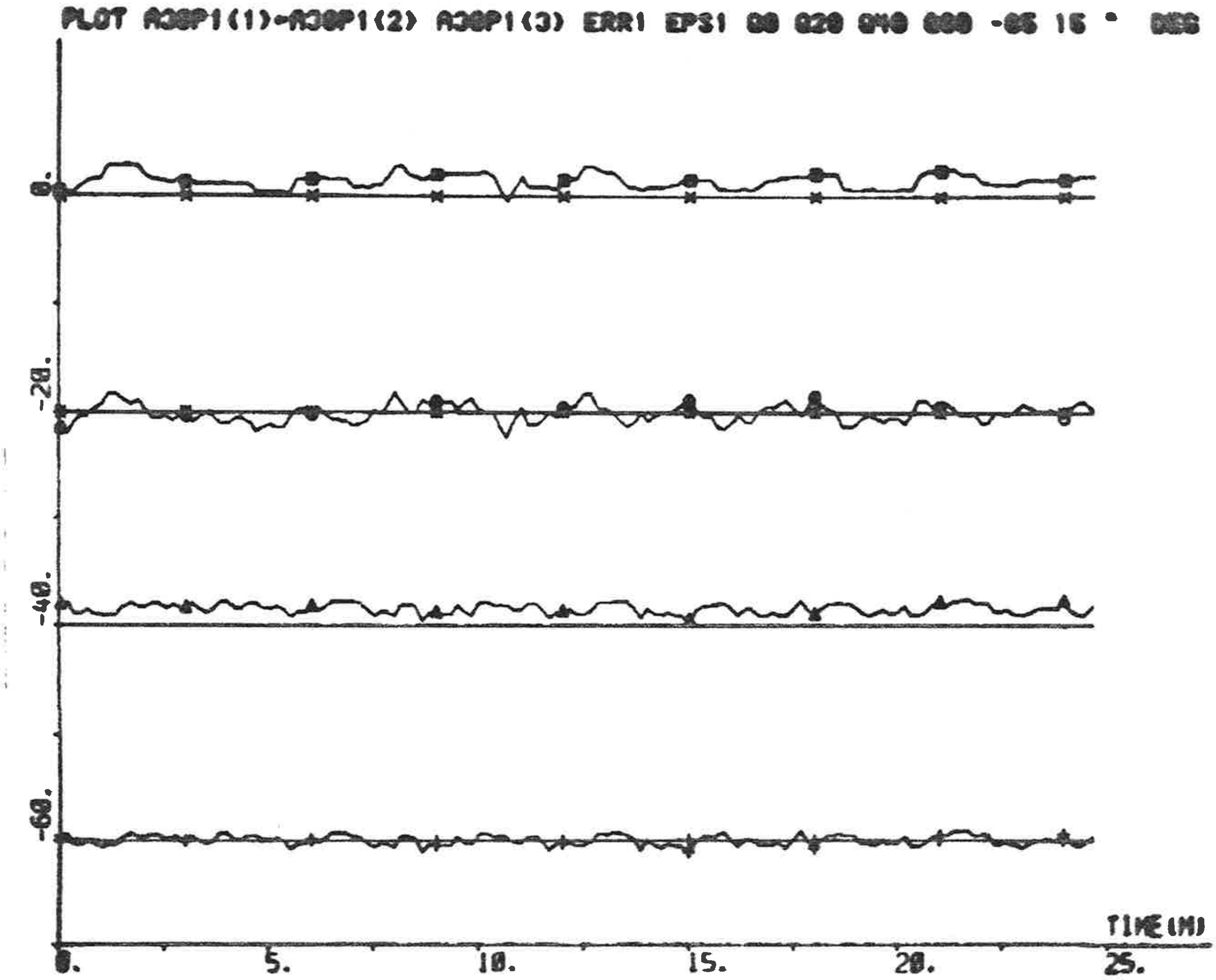
PLOT ADSP1(1)-ADSP1(13) ADSP1(12) ADSP1(14) ADSP1(11)
0.5 * n rpm
2 * v knots
P_s MW
δ_s deg
TIME(H)
0.
5.
10.
15.
20.
25.
-20.
0.
20.
40.

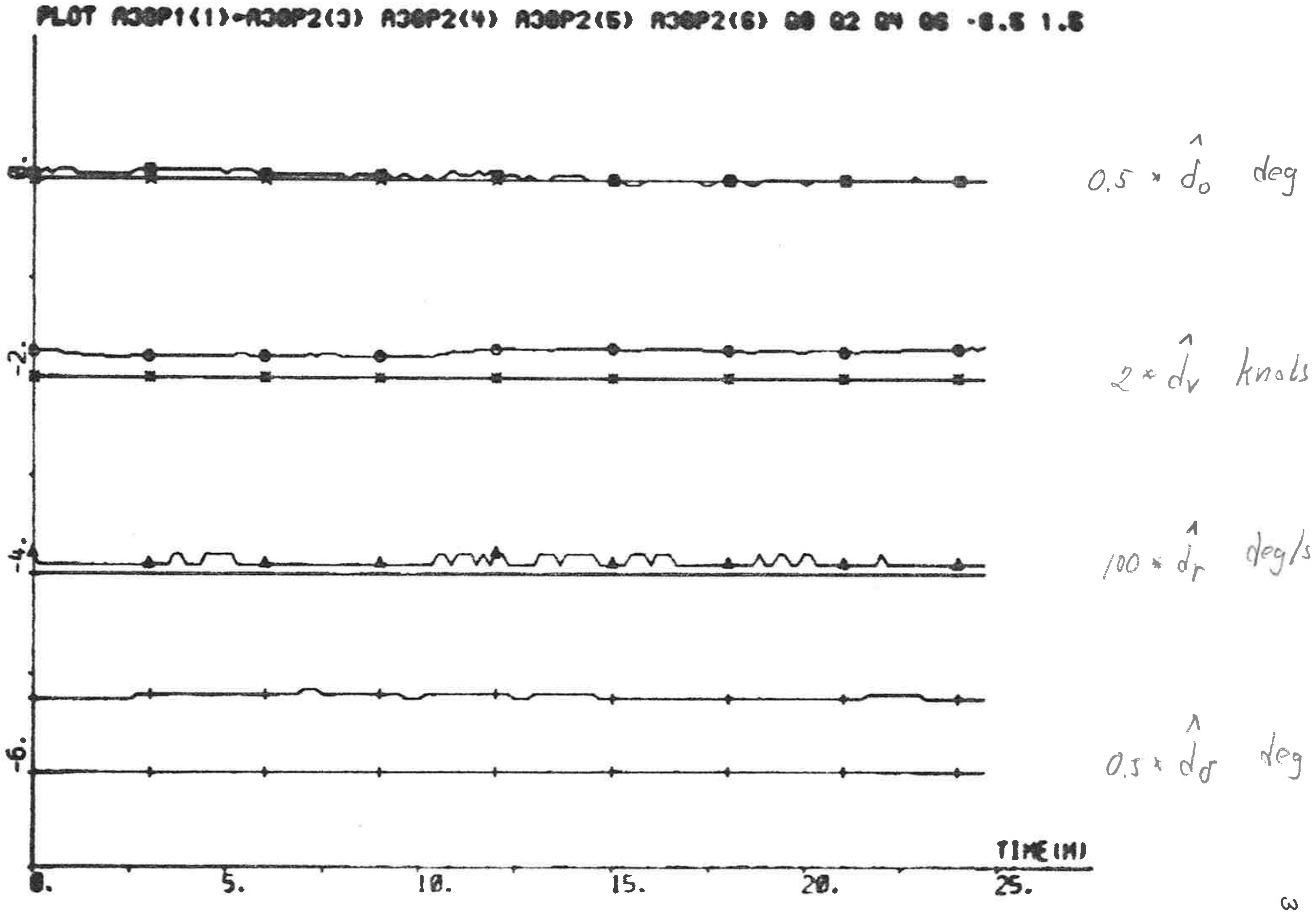

PLOT A30P1(1)-A30P2(1) A30P2(2) ERR5 Q0 Q1 Q2 -3.4 0.8 " KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT A30P1(1)-A30P1(4) A30P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 * KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT A30P1(1)-A30P1(6) A30P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. * DEG/S
Ø.
-0.2
-0.4
-0.6
TIME(M)
0.
5.
10.
15.
20.
25.
r
r̂
r - r̂
εr


PLOT R38P1(1)-R38P1(8) R38P1(8) ERR4 EPS4 00 01 02 03 -3.4 0.0 ° DEG
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A30P1(1)-A30P1(2) A30P1(3) ERR1 EPS1 00 020 040 060 -05 15 * DEG
0.
-20.
-40.
-60.
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A30P1(1)-A30P2(3) A30P2(4) A30P2(5) A30P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * d̂o deg
2 * d̂v knots
100 * d̂r deg/s
0.5 * d̂δ deg

EXPERIMENT A31

Date	1976-04-26	Forward draught	10.9 m
Time	16.05	Aft draught	12.9 m
Duration	24 min	Wind direction	SE (1; see App. A)
Position	S 06°42' W 06°06'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	143 deg	Wave height	-

PID-regulator using non-filtered measurements.

$k_P = 2$ $k_D = 100$ s $k_I = 0.02$ 1/s

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

The parameters were manually tuned before the experiment started.

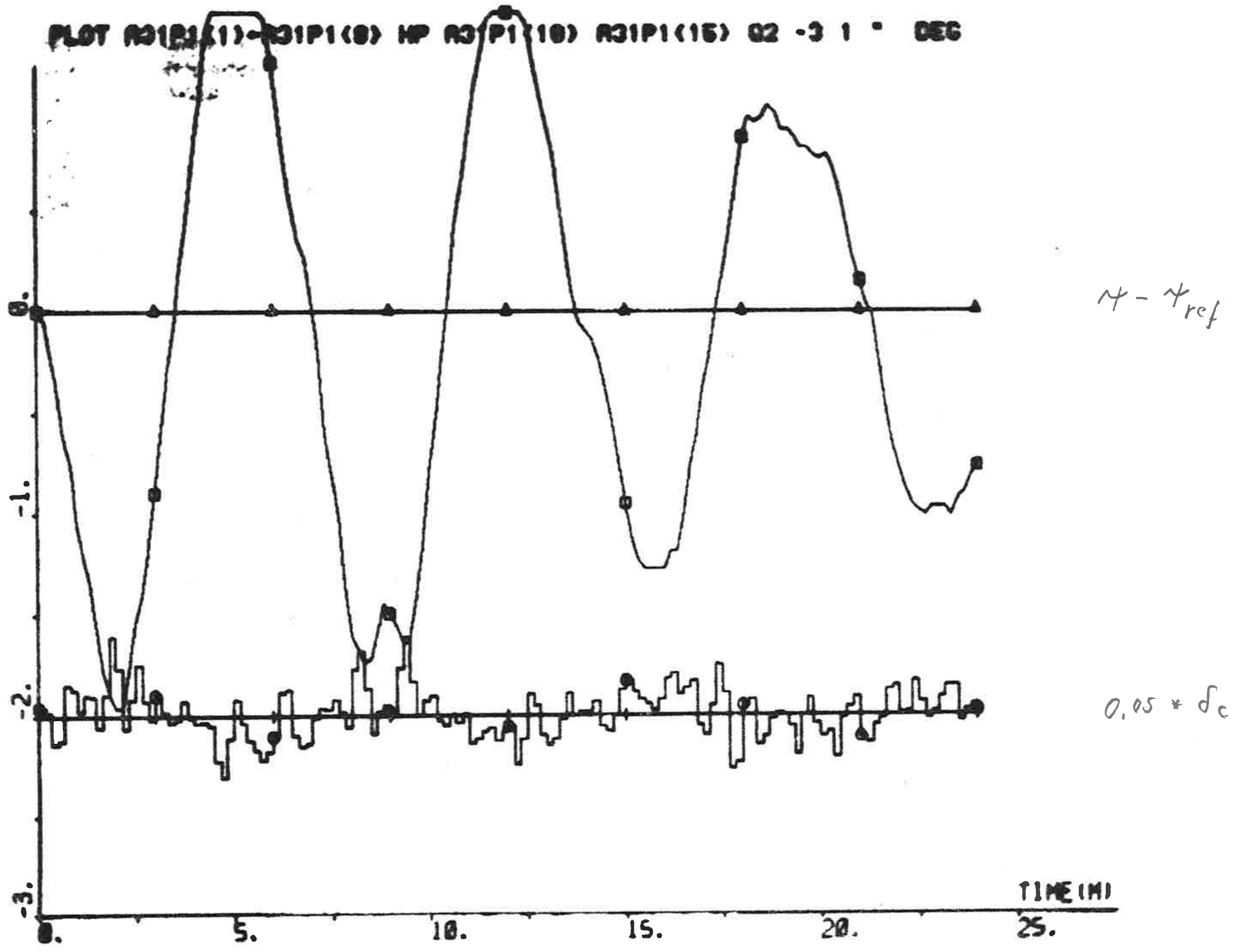
Final values:

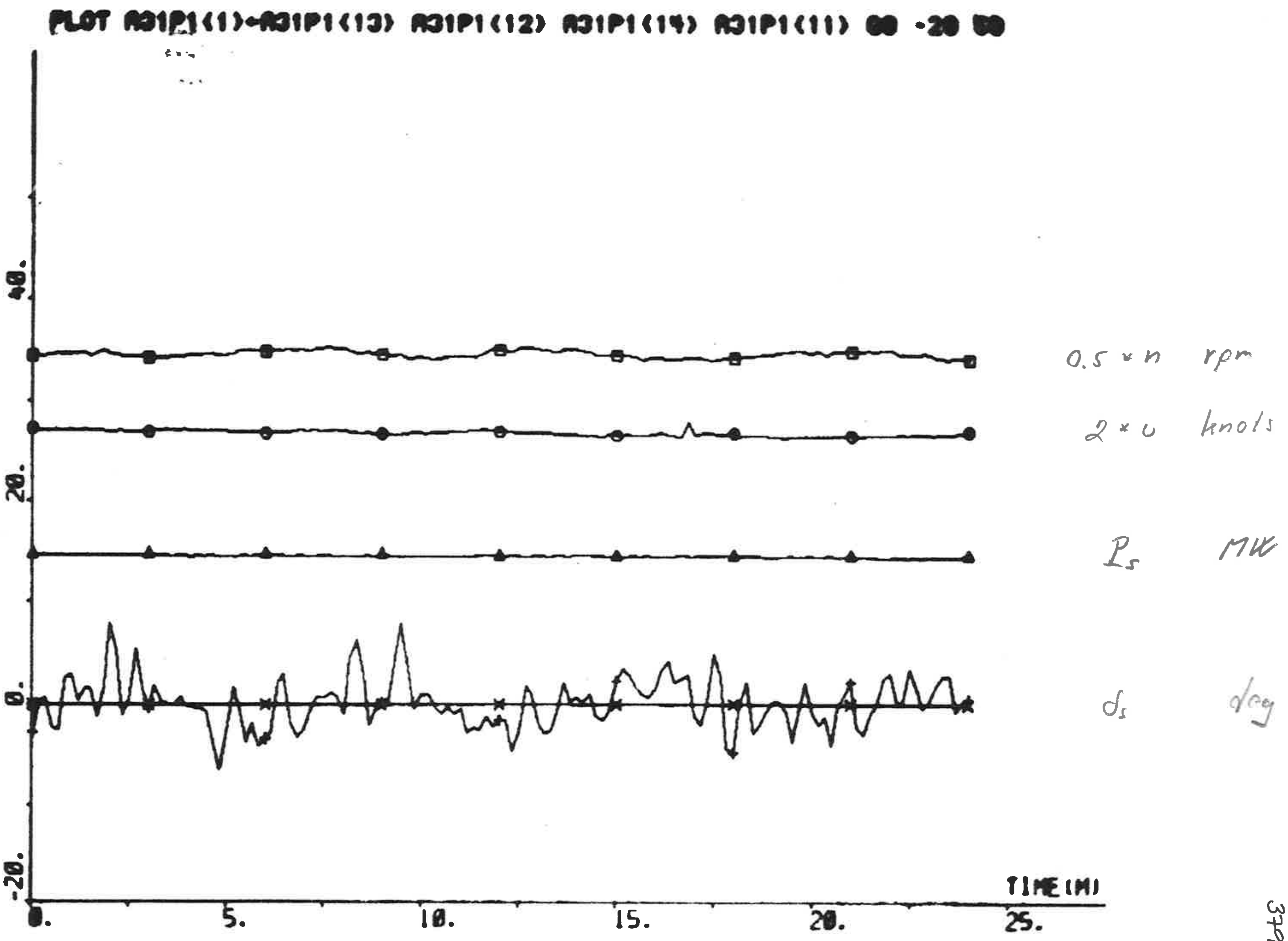
$\hat{\delta}_0 = 0.0$ deg $\hat{d}_v = 0.11$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

Statistics (mean value and standard deviation)

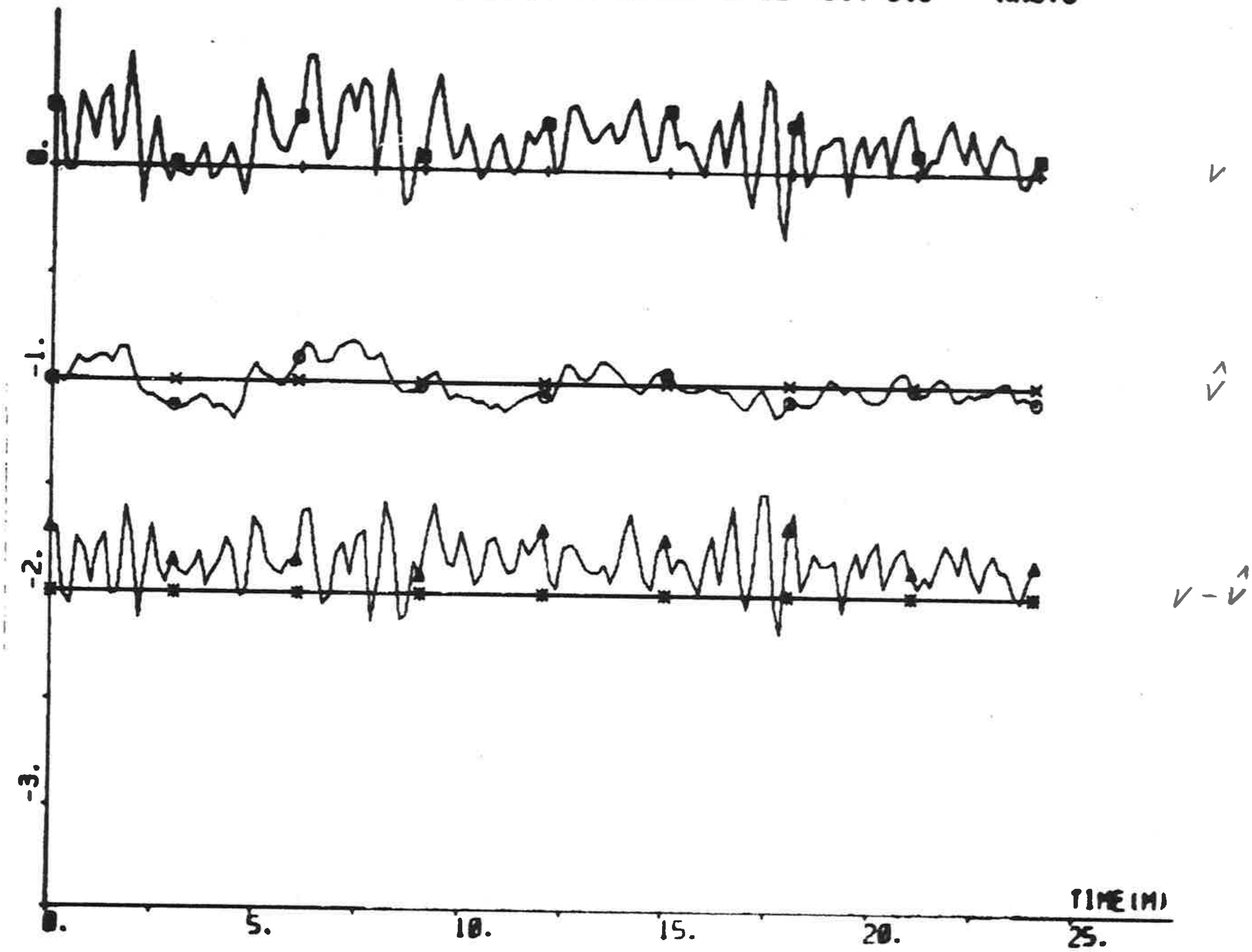
δ_c	0.22 ± 2.41	deg	P_s	14.5 ± 0.1	MW
δ	1.67 ± 2.05	deg	ε_v	0.00 ± 0.03	knots
$\psi-\psi_{ref}$	-0.103 ± 1.085	deg	ε_r	0.00 ± 0.02	deg/s
n	69.4 ± 0.6	rpm	ε_ψ	0.00 ± 0.03	deg
u	13.4 ± 0.1	knots	ε_δ	0.0 ± 0.6	deg

$V_1 = 1.672$

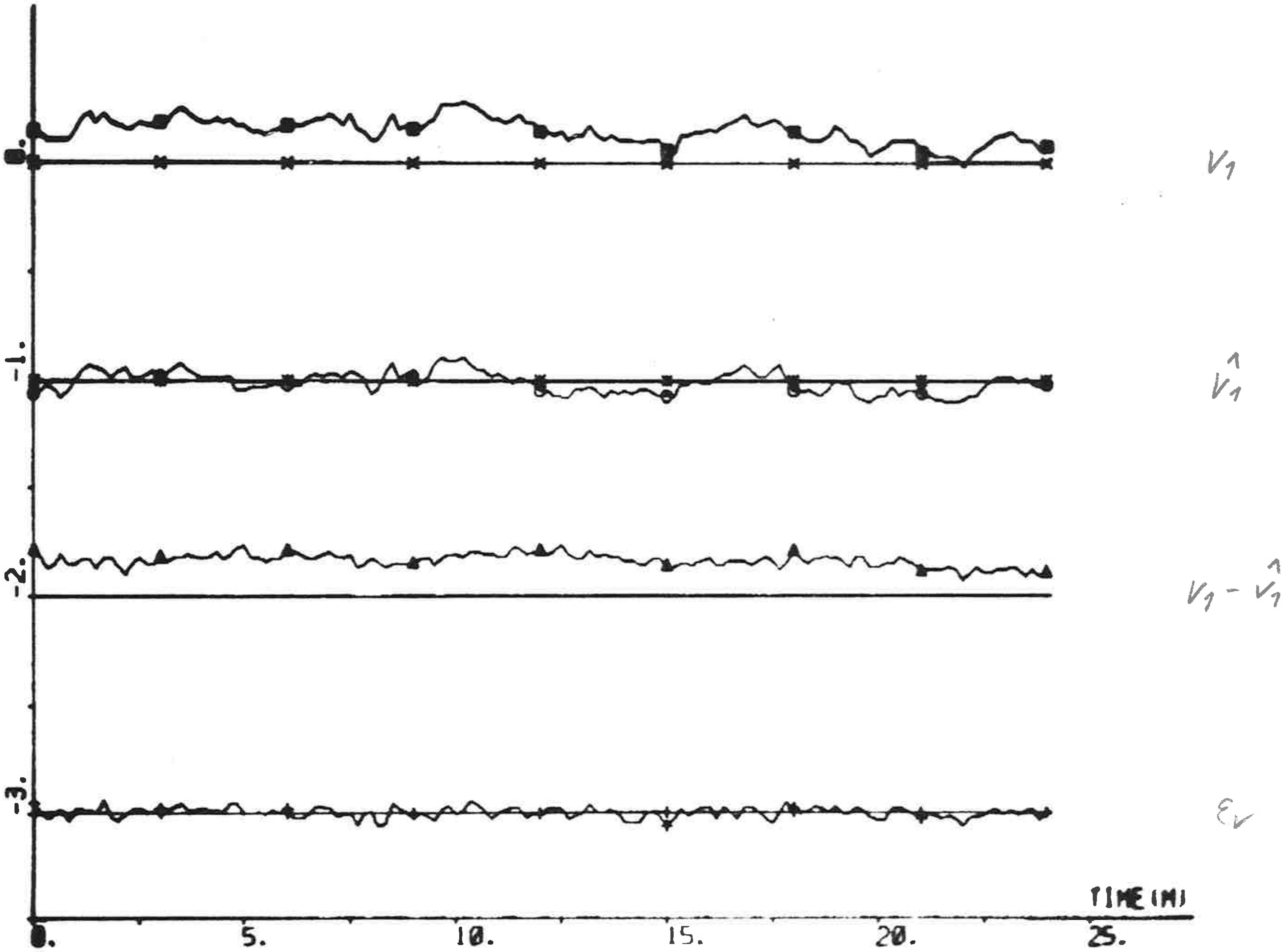

PLOT A31P1(1)-A31P1(8) HP A31P1(10) A31P1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
ψ - ψref
0.05 * δc

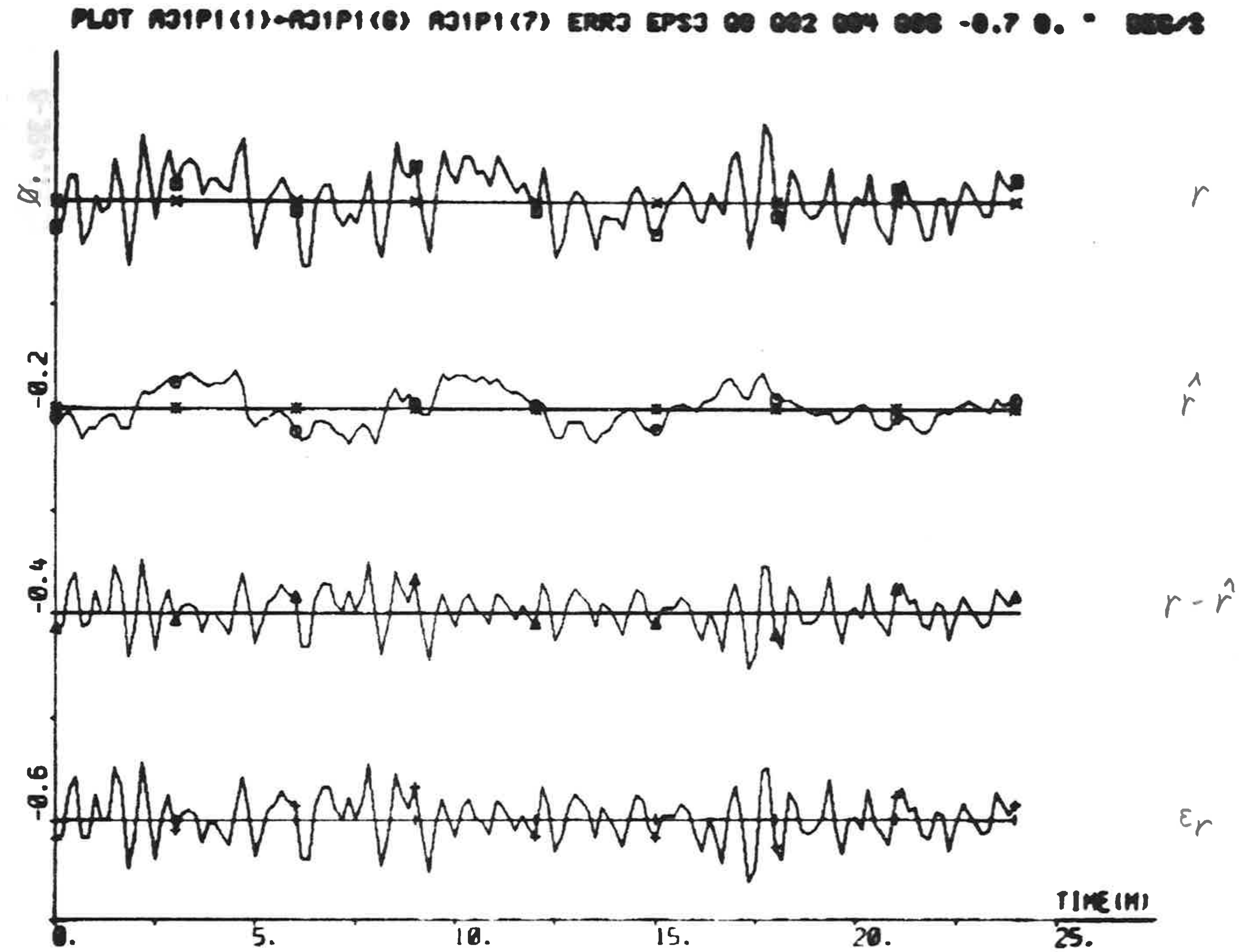

PLOT R31P1(1)-R31P1(13) R31P1(12) R31P1(14) R31P1(11) 00 -20 00
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n rpm
2 * u knots
P_s MW
δ_s deg

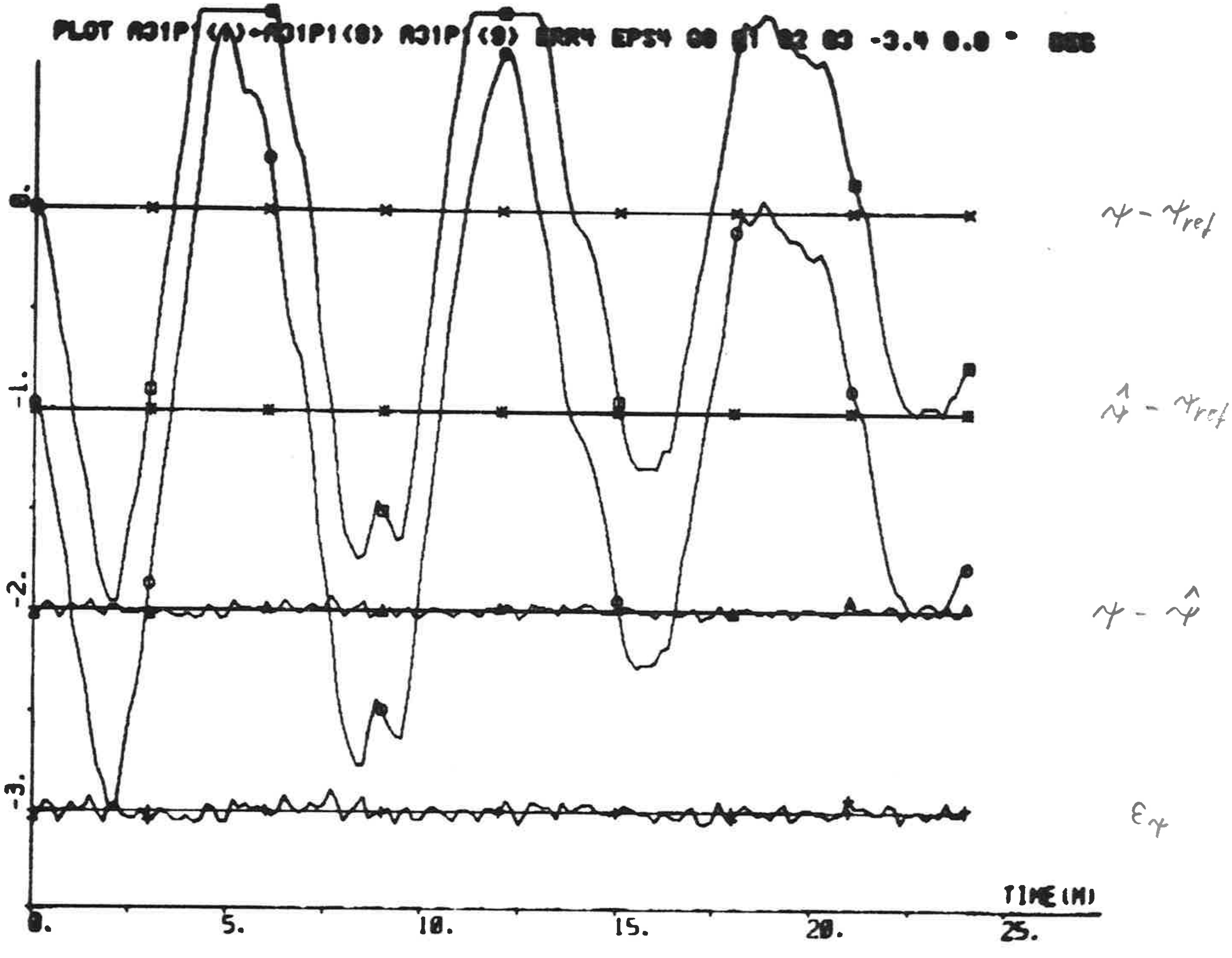
PLOT A31P1(1)-A31P2(1) A31P2(2) ERRS 00 01 02 -3.4 0.0 - KNOTS

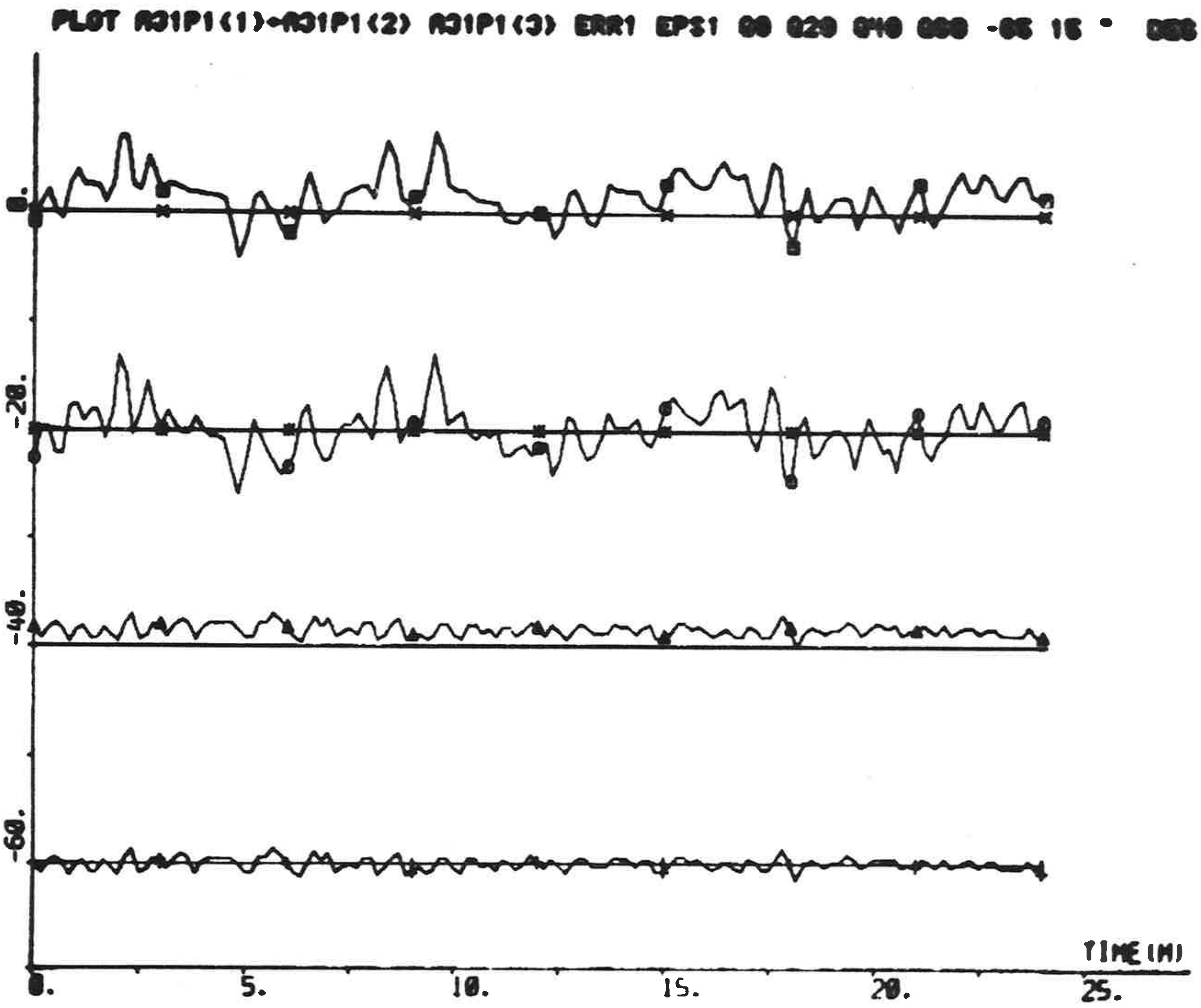


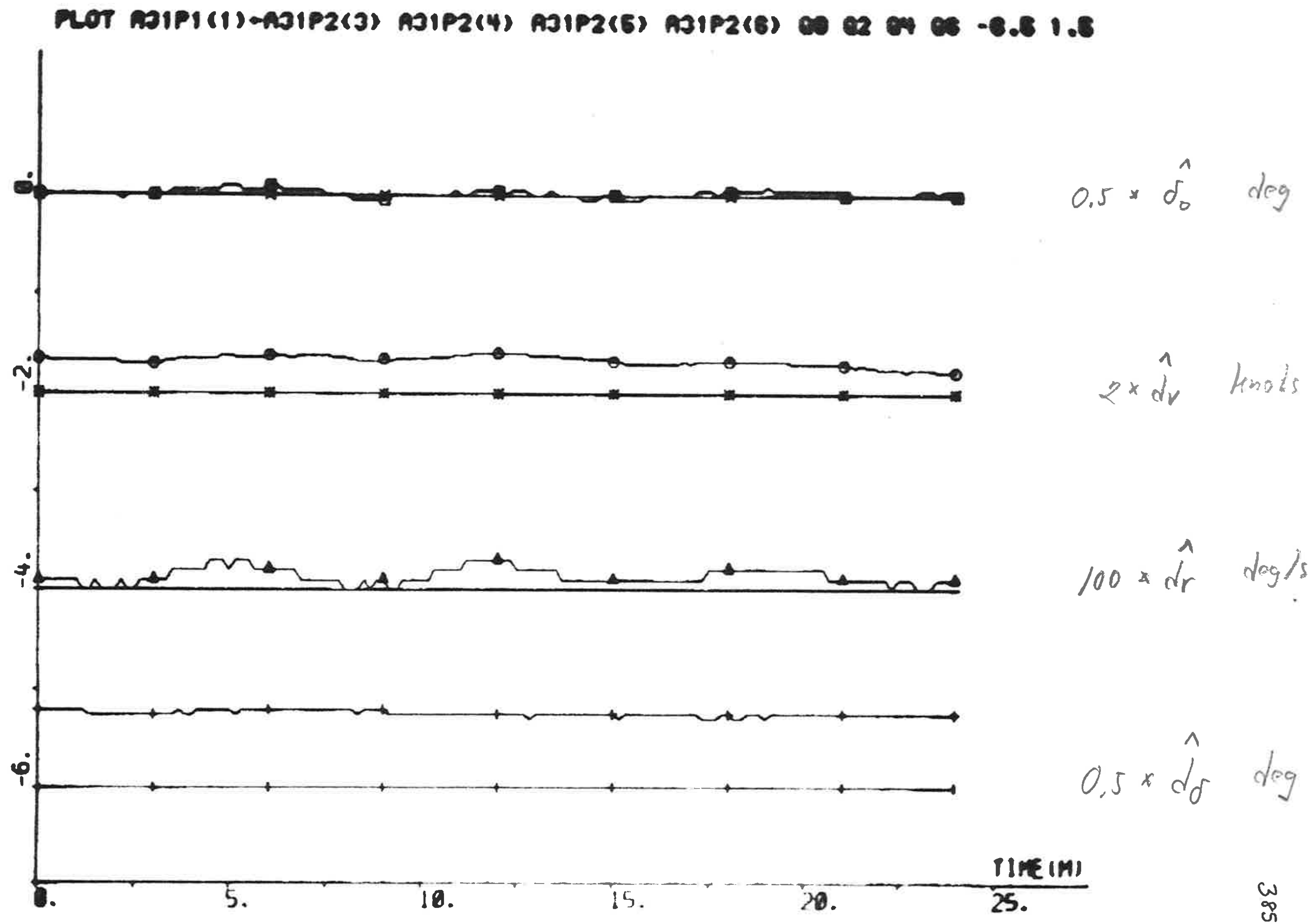
PLOT A31P1(1)-A31P1(4) A31P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 ° KNOTS




PLOT R31P1(1)-R31P1(6) R31P1(7) ERR3 EPS3
0.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂
εr


PLOT A31P1(A)-A31P1(B) A31P1(B) ERR4 EPS4 00 01 02 03 -3.4 0.0
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$\hat{\psi} - \psi_{ref}$
$\psi - \hat{\psi}$
ε_ψ


PLOT R31P1(1)-R31P1(2) R31P1(3) ERR1 EPS1 00 020 040 060 -05 15
0.
-20.
-40.
-60.
δ
δ̂
δ - δ̂
εδ
TIME(M)
0.
5.
10.
15.
20.
25.


PLOT A31P1(1)-A31P2(3) A31P2(4) A31P2(5) A31P2(6) 00 02 04 06 -8.8 1.8
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0,5 * $\hat{d}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0,5 * $\hat{d}_\delta$ deg

EXPERIMENT A32

Date	1976-04-26	Forward draught	10.9 m
Time	19.31	Aft draught	12.9 m
Duration	25 min	Wind direction	S (1; see App. A)
Position	S 07°20' W 05°38'	Wind velocity	9 m/s (fresh breeze)
ψ_{ref}	142 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 120 min.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -10.51 \\ 9.96 \\ 4.86 \\ -4.33 \\ 0.49 \\ 0.12 \\ -0.69 \\ 70.44 \end{bmatrix} \qquad P = \begin{bmatrix} 6.87 & & & & & & & \\ -13.89 & 43.74 & & & & & & \\ 8.32 & -44.87 & 64.19 & & & & & \\ -0.76 & 14.64 & -27.68 & 14.46 & & & & \\ 0.26 & -1.20 & 1.50 & -0.55 & 0.05 & & & \\ -0.03 & 0.26 & -0.52 & 0.31 & -0.01 & 0.02 & & \\ -0.82 & 1.24 & -0.28 & -0.19 & 0.00 & 0.01 & 0.85 & \\ 14.47 & -31.32 & 3.88 & 11.30 & 1.55 & 0.18 & 18.10 & 894.76 \end{bmatrix}$$

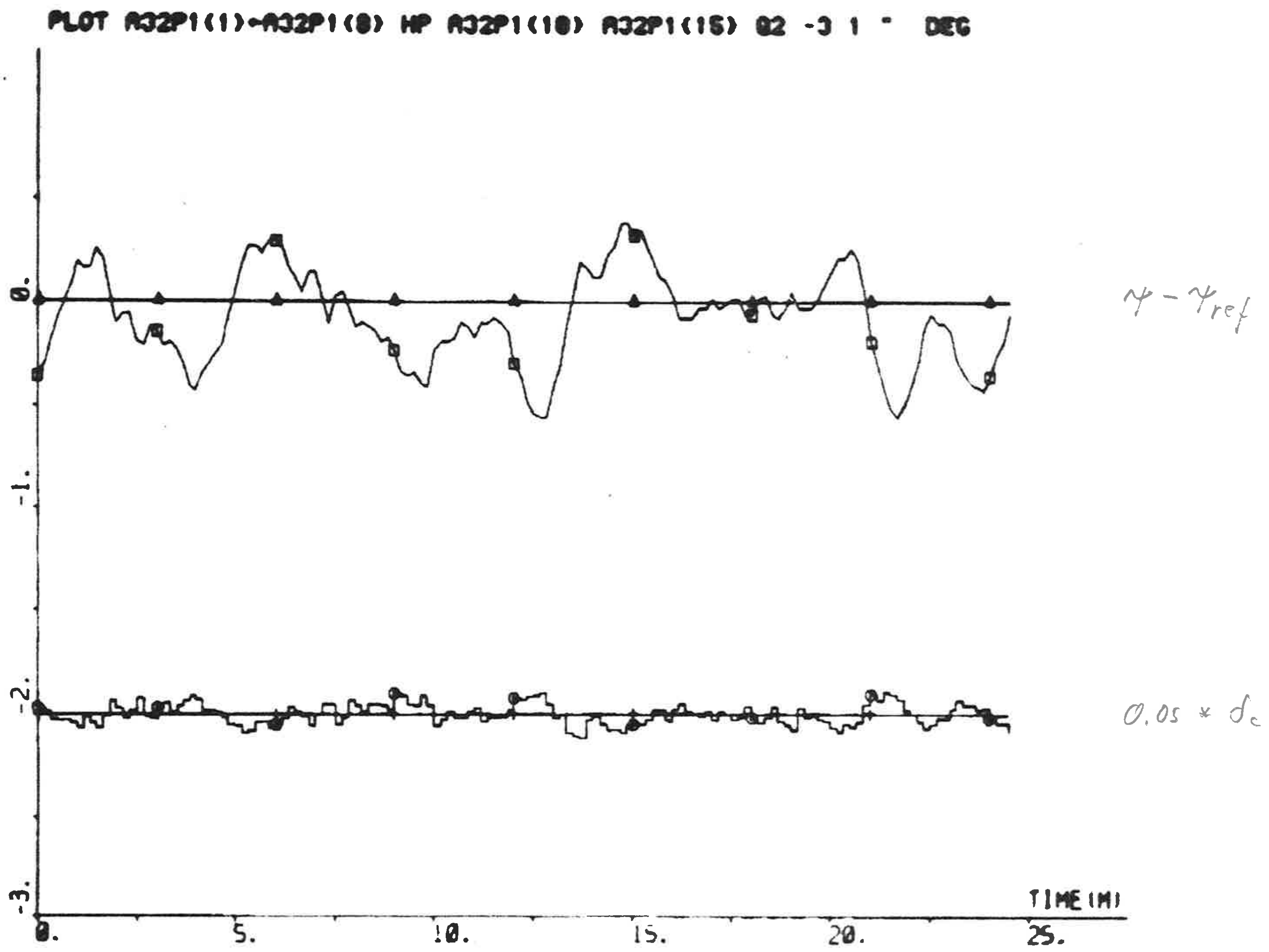
$a_1 + a_2 + a_3 + a_4 = -0.02$

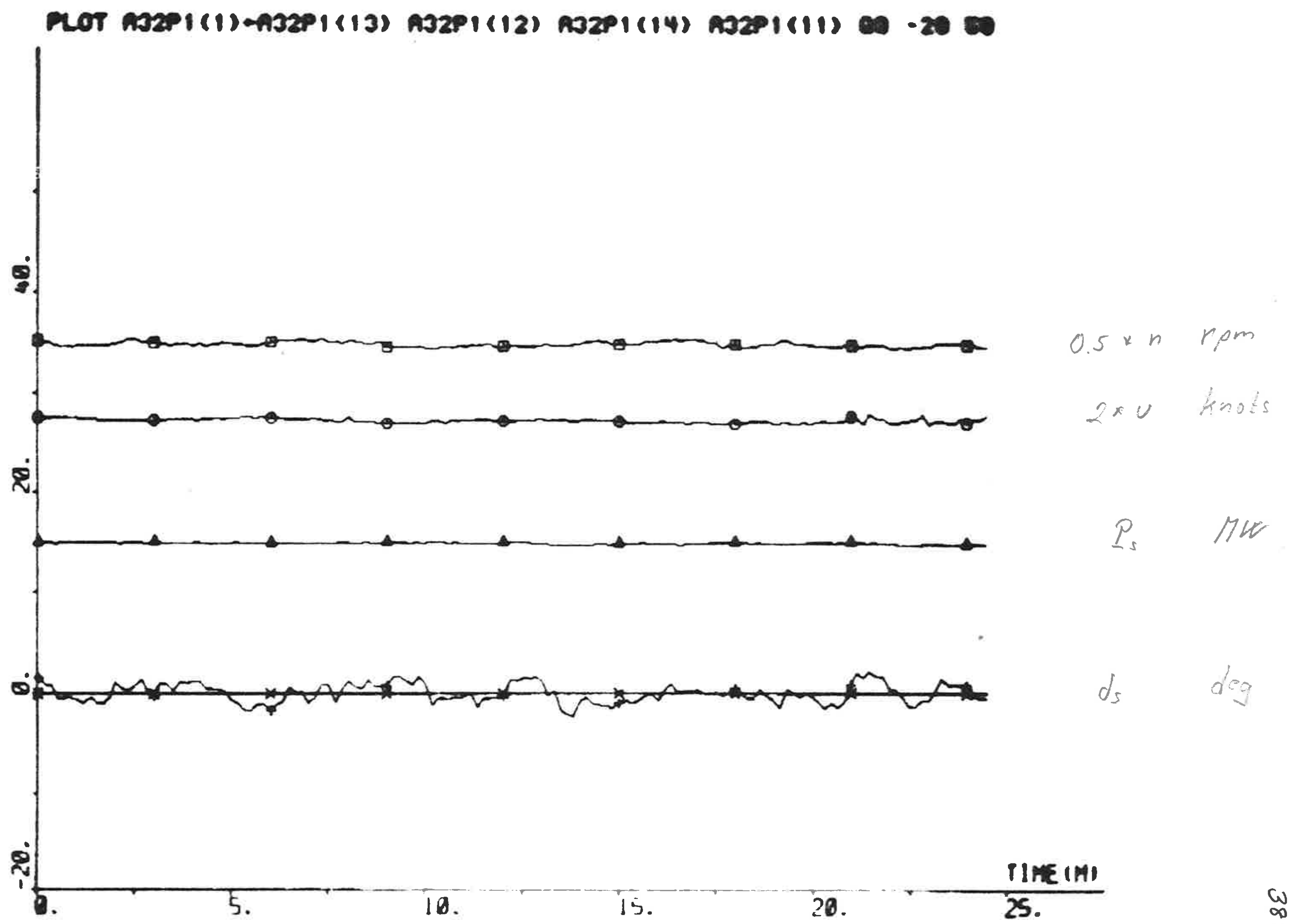
$\hat{\delta}_0 = 0.2$ deg $\hat{d}_v = 0.06$ knots $\hat{d}_r = 0.002$ deg/s $\hat{d}_\delta = 1.7$ deg

Statistics (mean value and standard deviation)

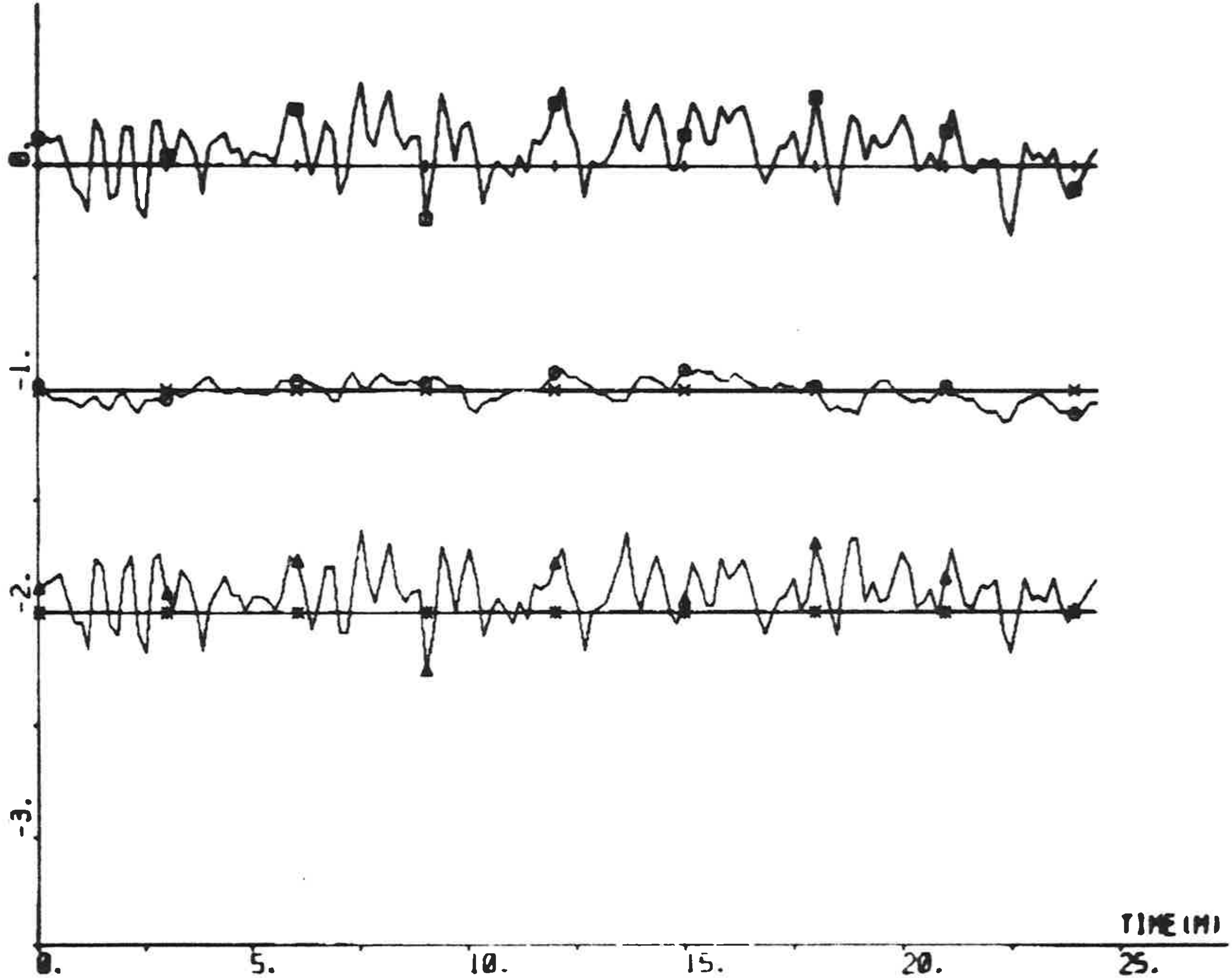
δ_c	-0.01 ± 0.98	deg		P_s	14.9 ± 0.1	MW
δ	1.65 ± 0.82	deg		ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	-0.082 ± 0.223	deg		ε_r	0.00 ± 0.02	deg/s
n	69.9 ± 0.5	rpm		ε_ψ	0.00 ± 0.03	deg
u	13.6 ± 0.1	knots		ε_δ	0.1 ± 0.5	deg

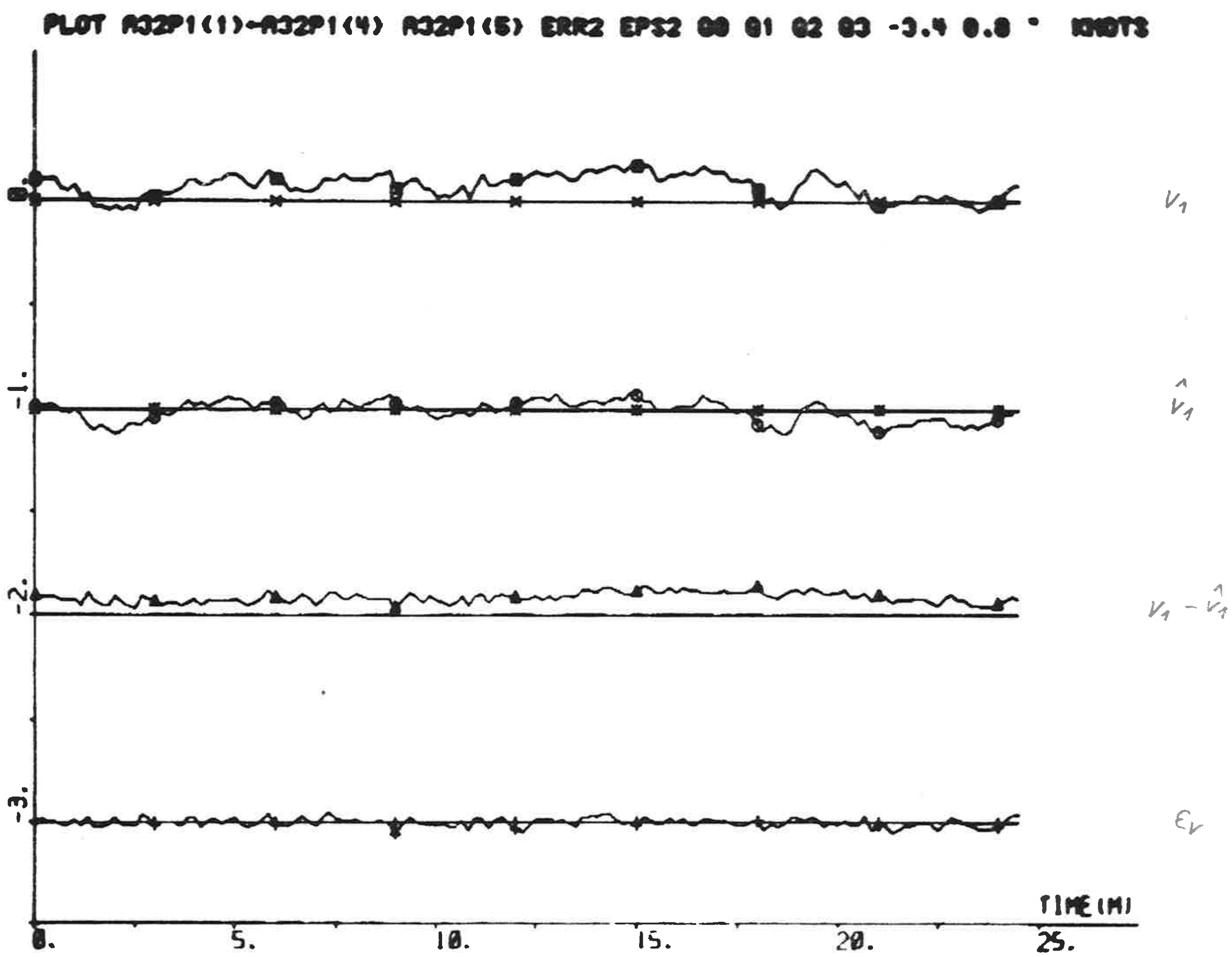
$V_1 = 0.136$

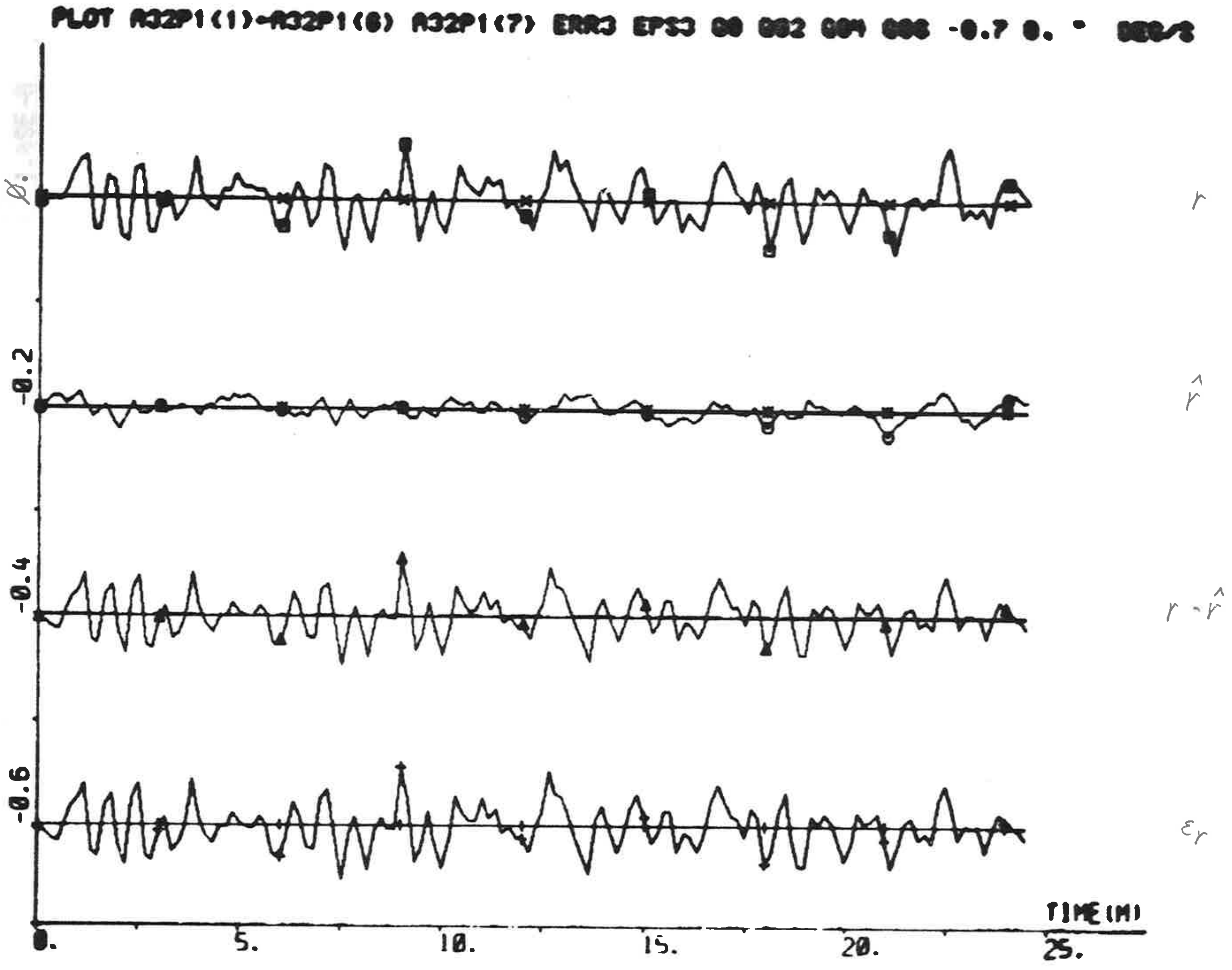

PLOT A32P1(1)-A32P1(8) HP A32P1(10) A32P1(15) 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$0.05 * \delta_c$

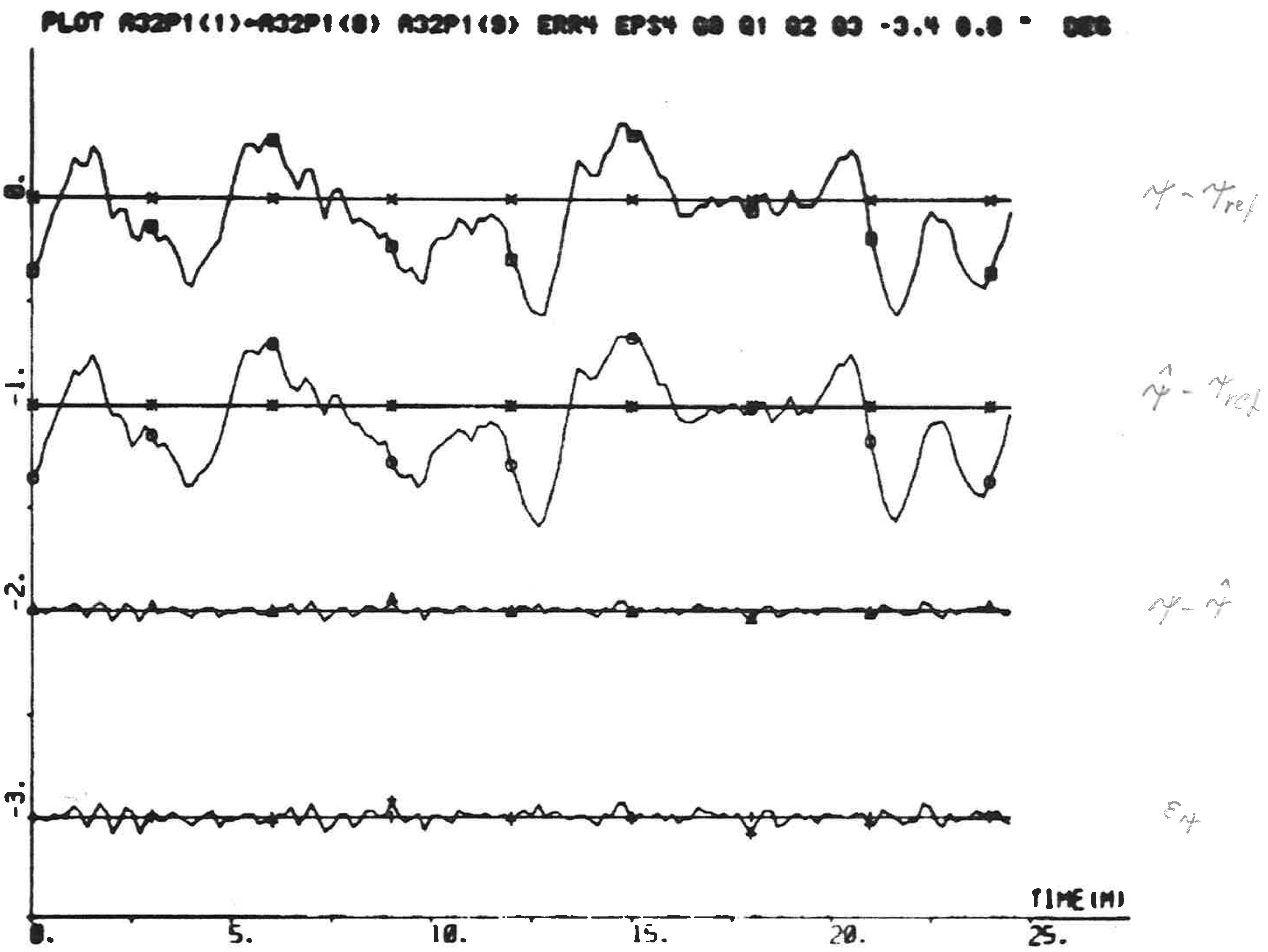

PLOT A32P1(1)-A32P1(13) A32P1(12) A32P1(14) A32P1(11) 00 -20 00
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 × n rpm
2 × v knots
P_s MW
d_s deg

PLOT A32P1(1)-A32P2(1) A32P2(2) ERRS 00 01 02 -3.4 0.0 " KNOTS

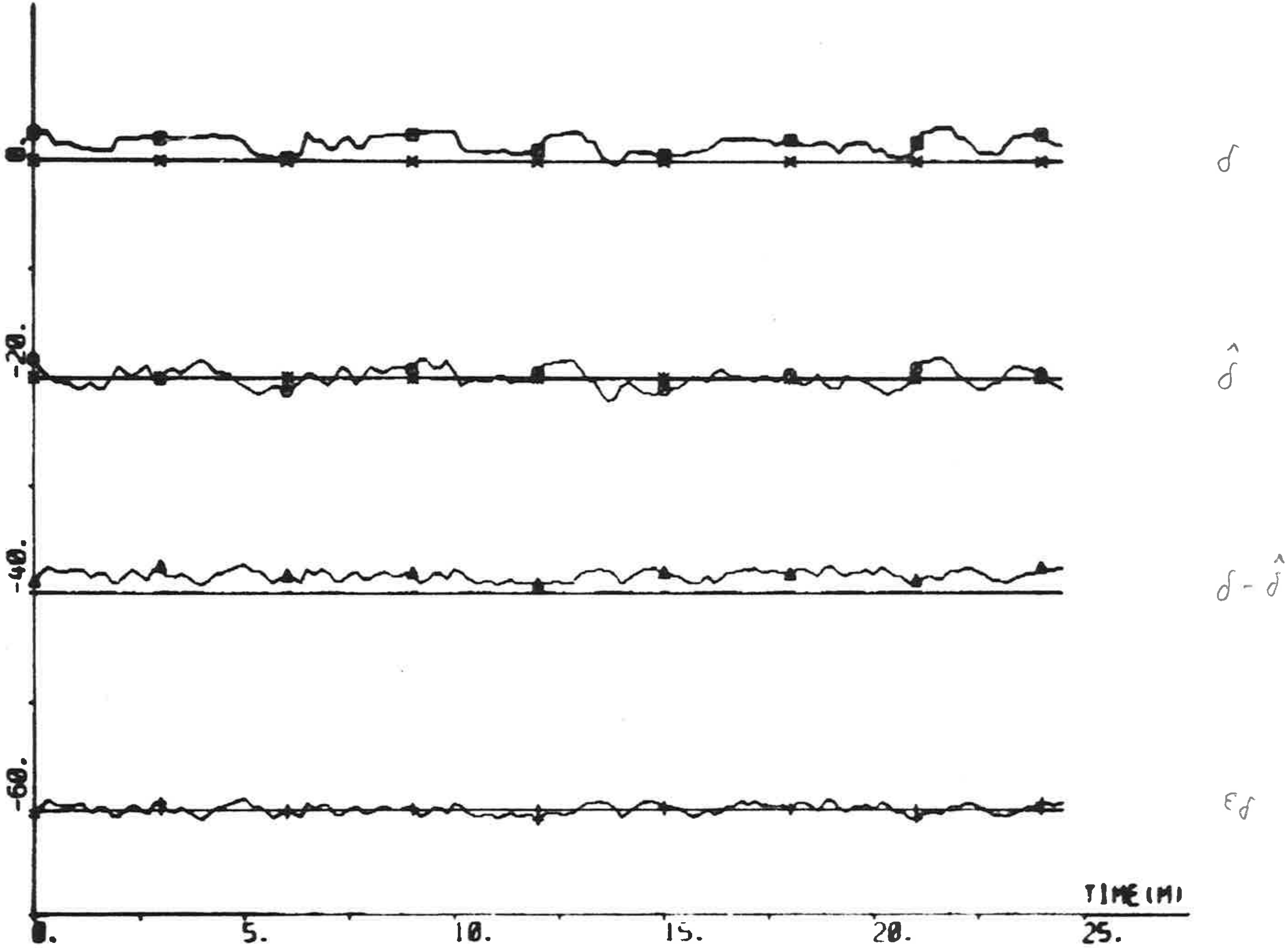



PLOT A32P1(1)-A32P1(4) A32P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 ° KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V1
V̂1
V1 - V̂1
εv

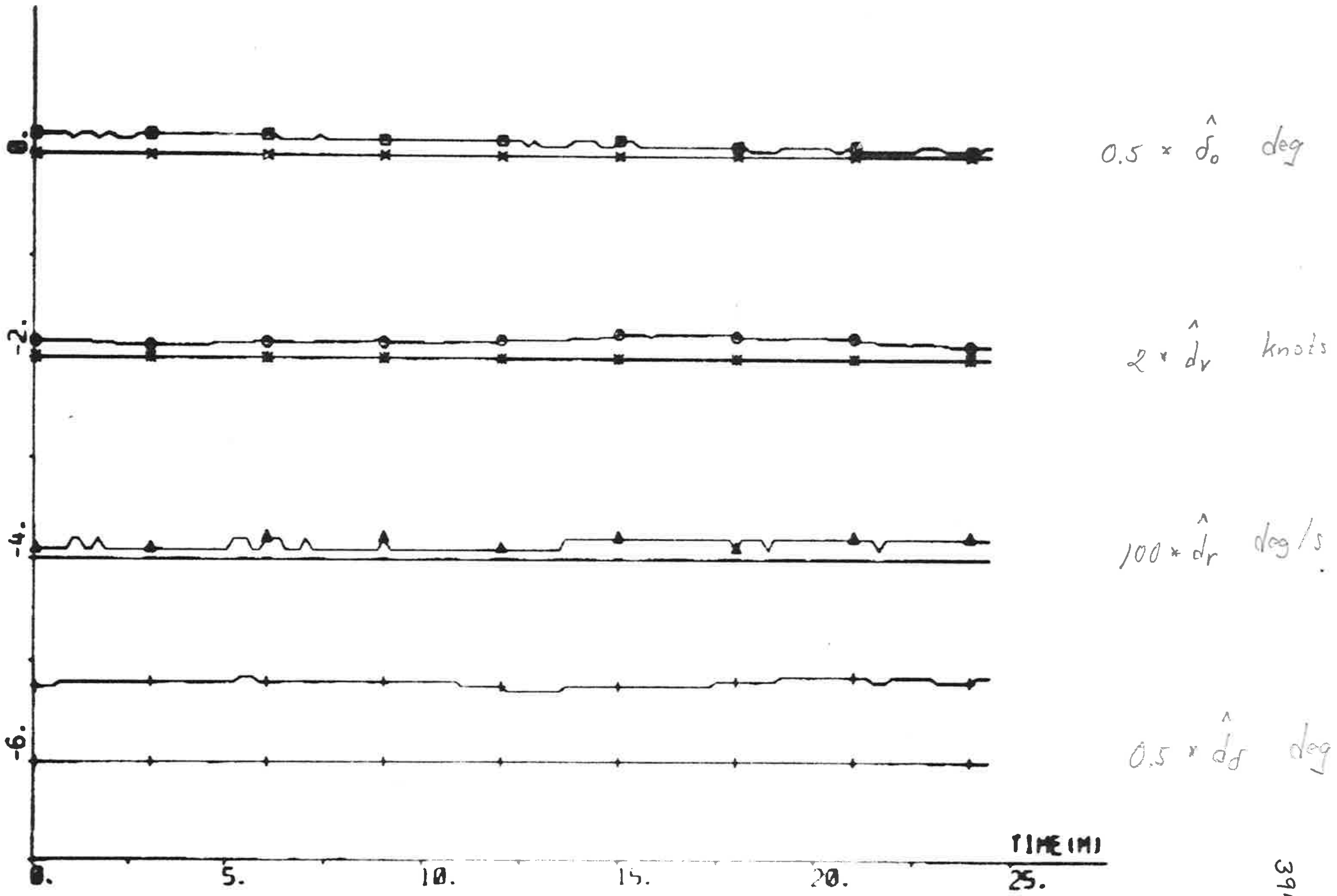

PLOT A32P1(1)-A32P1(6) A32P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. - DEG/S
Ø.
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂
εr


PLOT A32P1(1)-A32P1(8) A32P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

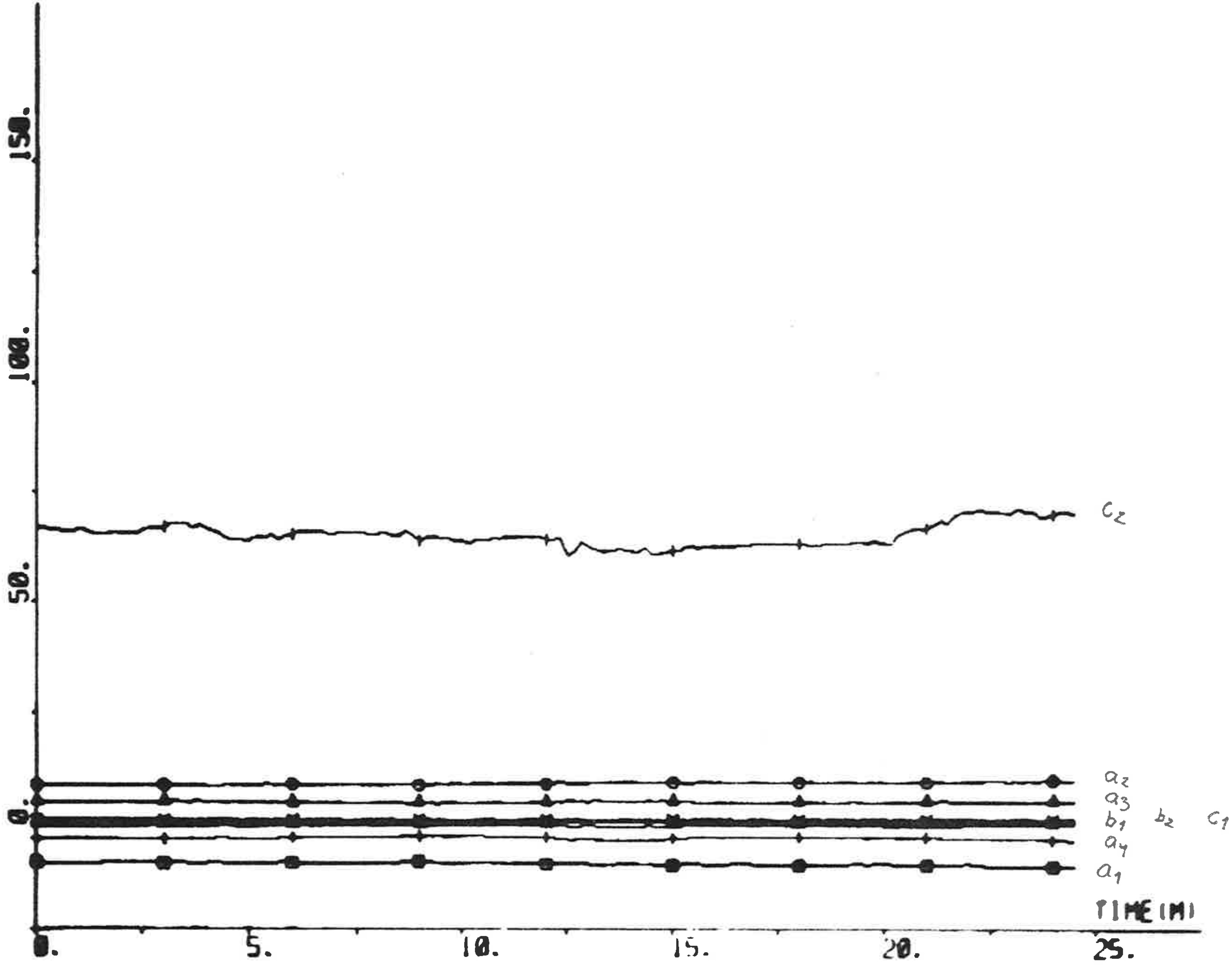
PLOT A32P1(1)-A32P1(2) A32P1(3) ERR1 EPS1 00 020 040 000 -65 15 " DEG



PLOT A32P1(1)-A32P2(3) A32P2(4) A32P2(5) A32P2(6) 00 02 04 06 -6.5 1.5



PLOT A32P1(1)-A32P2(7) A32P2(8) A32P2(9) A32P2(10) A32P2(11) A32P2(12) A3



EXPERIMENT A33

Date	1976-04-27	Forward draught	10.9 m
Time	09.34	Aft draught	12.9 m
Duration	51 min	Wind direction	SE (1; see App. A)
Position	S 09°39' W 03°51'	Wind velocity	10 m/s (fresh breeze)
ψ_{ref}	145 deg	Wave height	-

Self-tuning regulator using estimates from the Kalman filter

Tuning time before the experiment started: > 120 min

NC1 = 1 NC2 = 1 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -13.33 \\ 16.86 \\ -2.60 \\ -1.14 \\ 0.41 \\ 0.23 \\ -0.39 \\ 100.94 \end{bmatrix} \quad P = \begin{bmatrix} 8.89 & & & & & & & \\ -16.40 & 51.67 & & & & & & \\ 8.49 & -54.21 & 81.12 & & & & & \\ -0.17 & 18.64 & -36.86 & 19.72 & & & & \\ 0.22 & -1.14 & 1.51 & -0.59 & 0.04 & & & \\ 0.01 & 0.12 & -0.38 & 0.27 & 0.00 & 0.01 & & \\ -1.92 & 2.54 & 0.28 & -1.08 & -0.02 & -0.01 & 1.31 & \\ -1.67 & 4.54 & -13.71 & 11.25 & 0.63 & 0.25 & 21.26 & 887.07 \end{bmatrix}$$

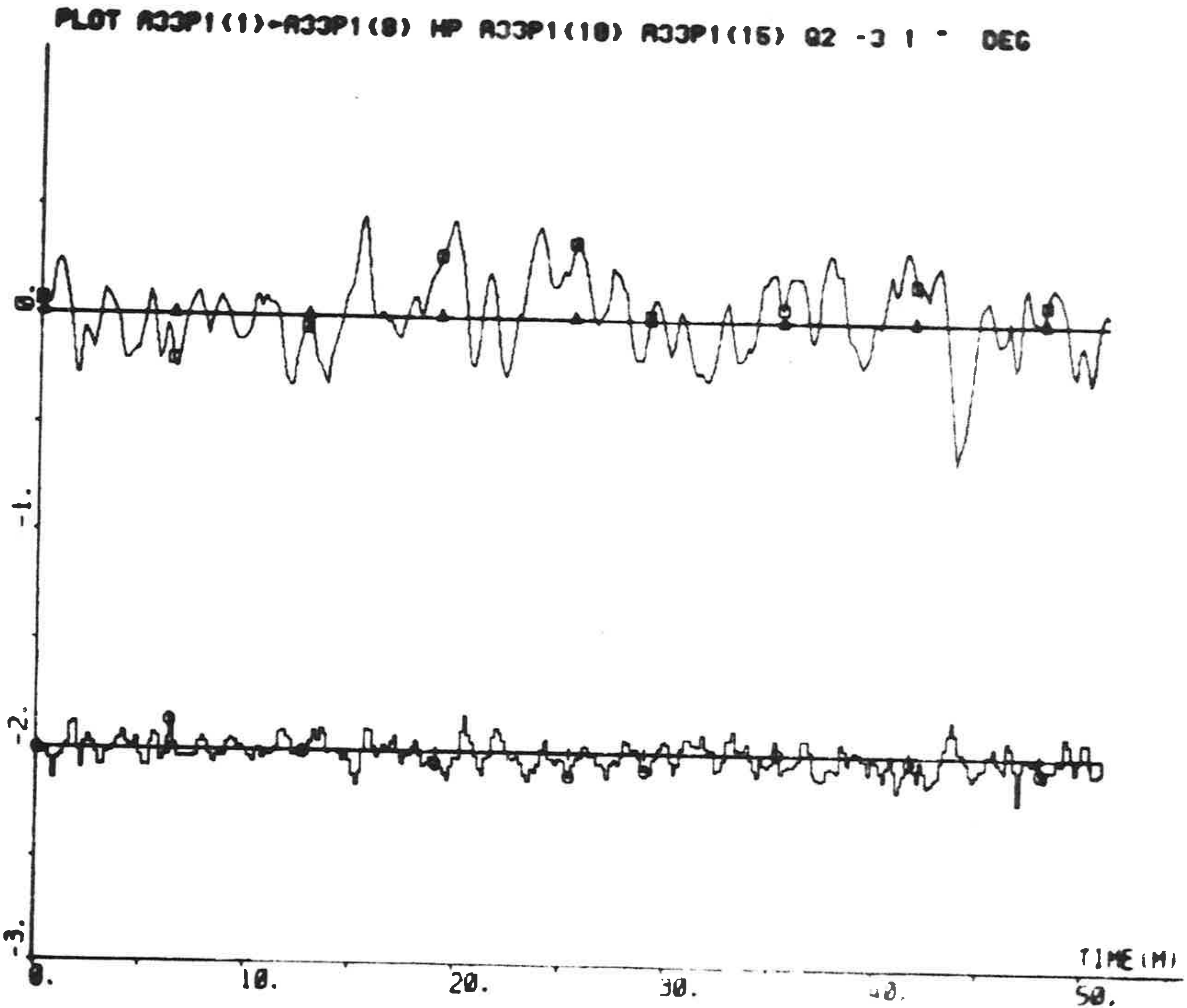
$a_1 + a_2 + a_3 + a_4 = -0.21$

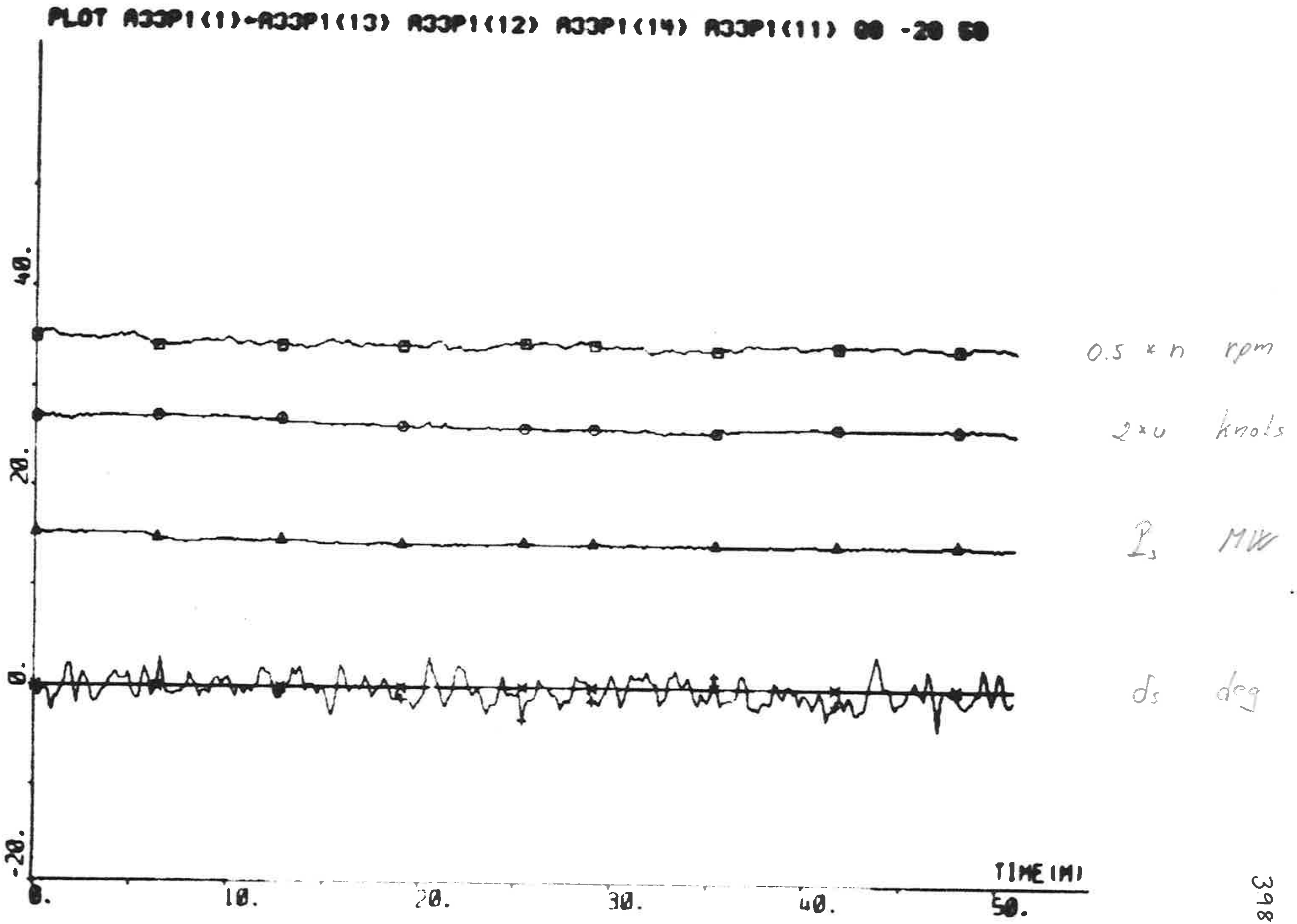
$\hat{\delta}_0 = -0.3$ deg $\hat{d}_v = 0.11$ knots $\hat{d}_r = 0.003$ deg/s $\hat{d}_\delta = 1.5$ deg

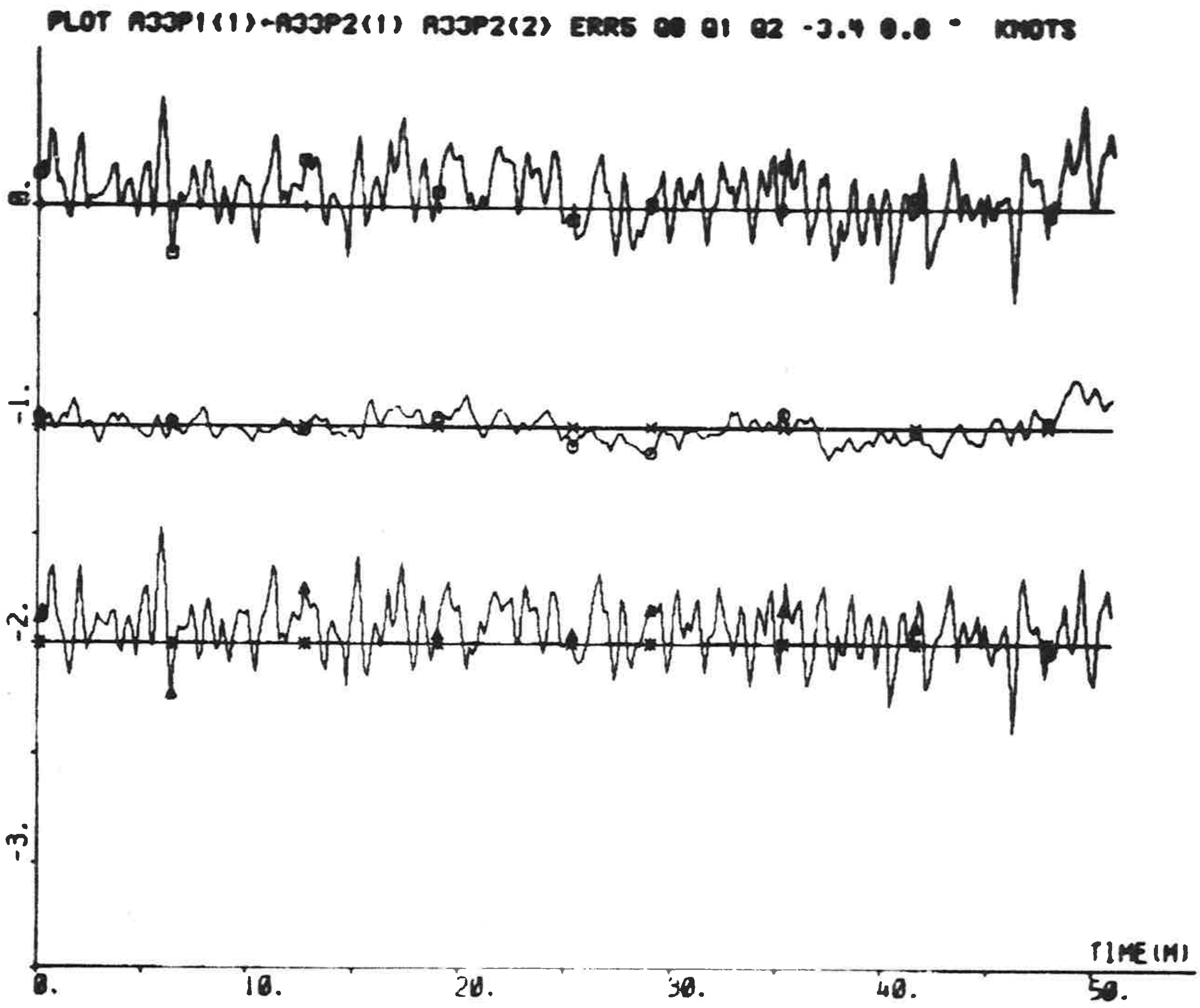
Statistics (mean value and standard deviation)

δ_c	-0.24 ± 1.18	deg		P_s	14.4 ± 0.3	MW
δ	1.28 ± 1.03	deg		ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.016 ± 0.181	deg		ε_r	0.00 ± 0.02	deg/s
n	69.0 ± 0.6	rpm		ε_ψ	0.00 ± 0.03	deg
u	13.2 ± 0.2	knots		ε_δ	0.0 ± 0.5	deg

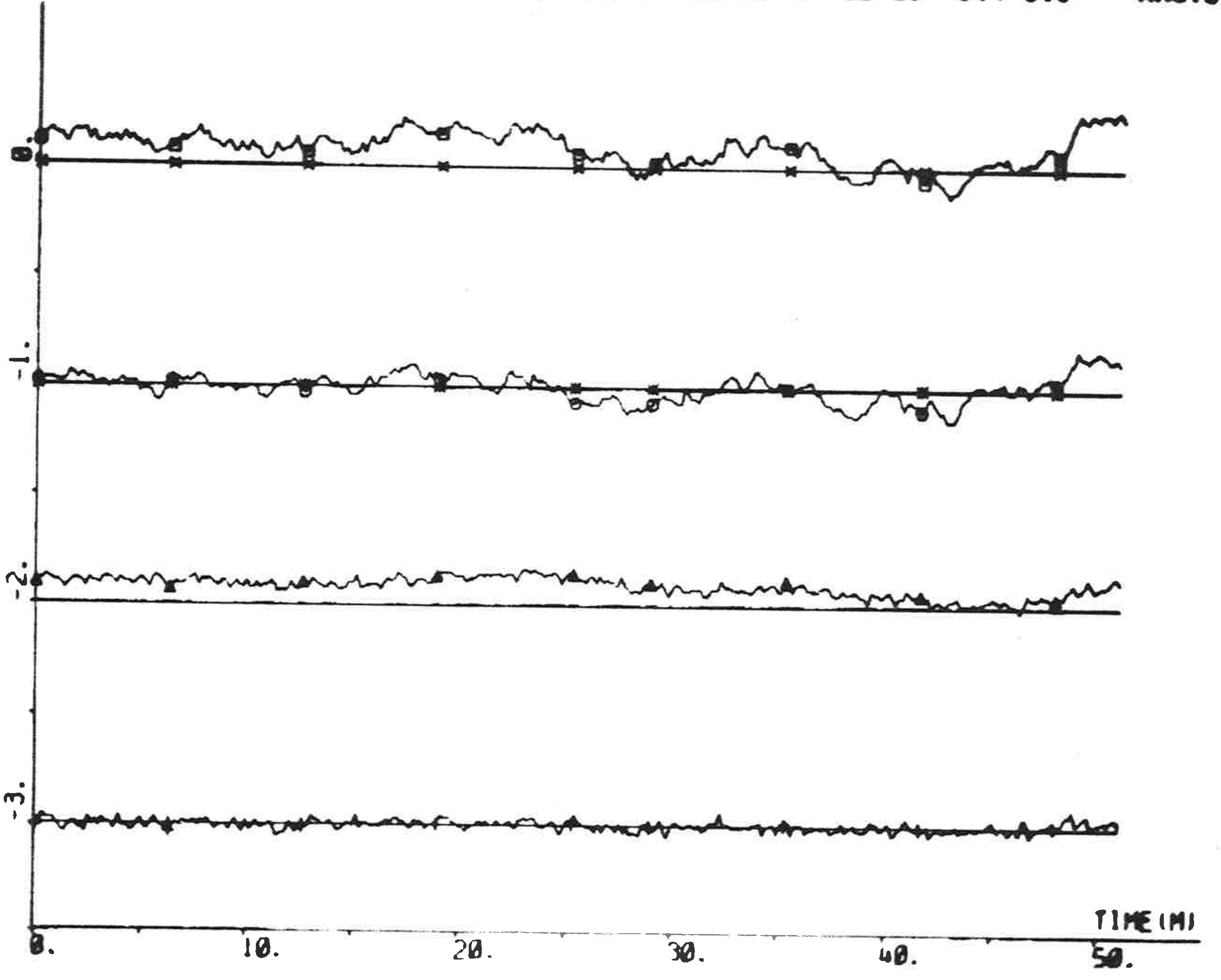
$V_1 = 0.149$


PLOT A33P1(1)-A33P1(8) HP A33P1(10) A33P1(15) Q2 -3 1 - DEG
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
ψ - ψref
0.05 × δc

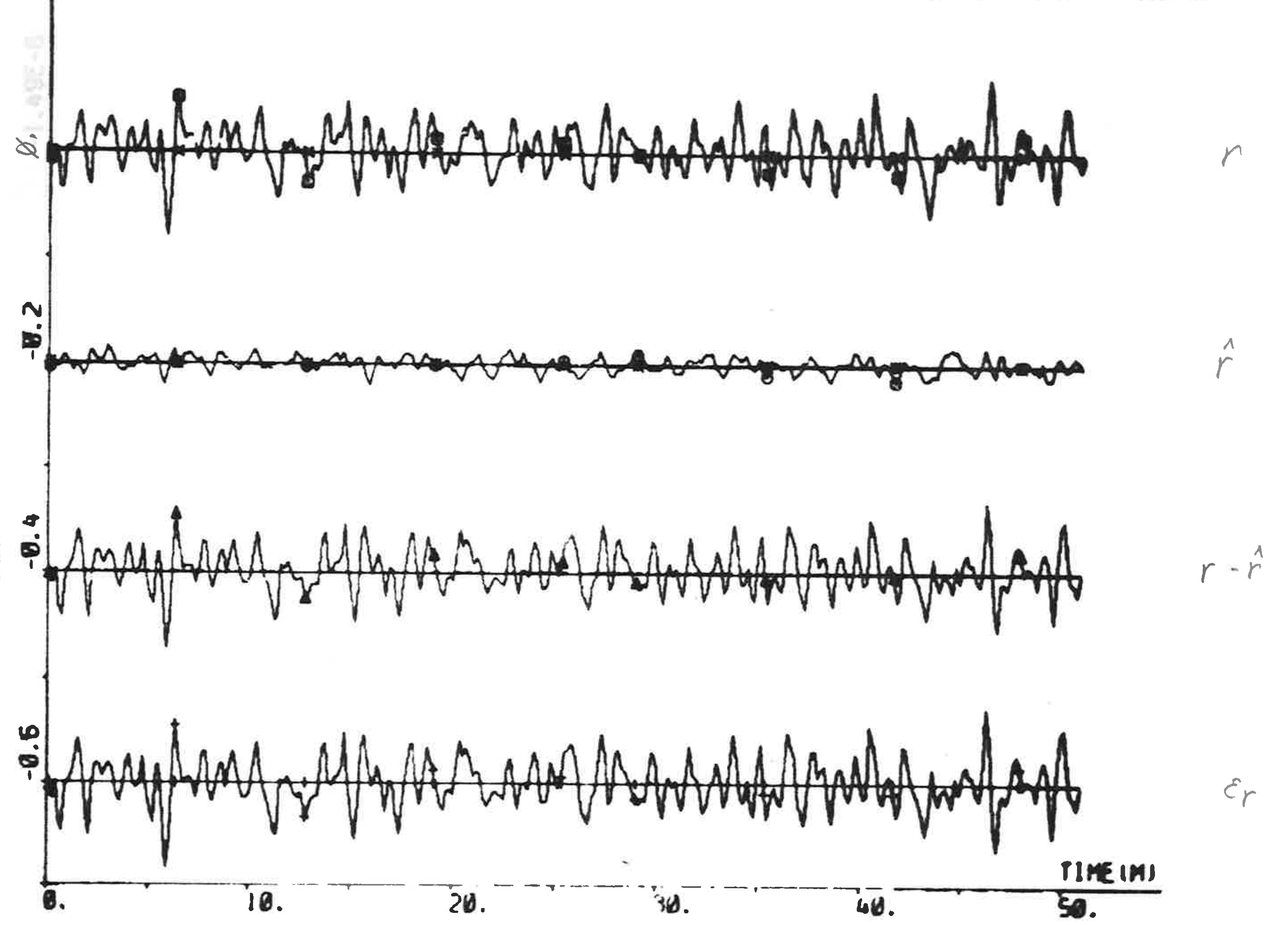

PLOT A33P1(1)-A33P1(13) A33P1(12) A33P1(14) A33P1(11) 00 -20 60
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME(M)
0.5 * n rpm
2 * u knots
P_s MW
δ_s deg


PLOT A33P1(1)-A33P2(1) A33P2(2) ERRS 00 01 02 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
10.
20.
30.
40.
50.

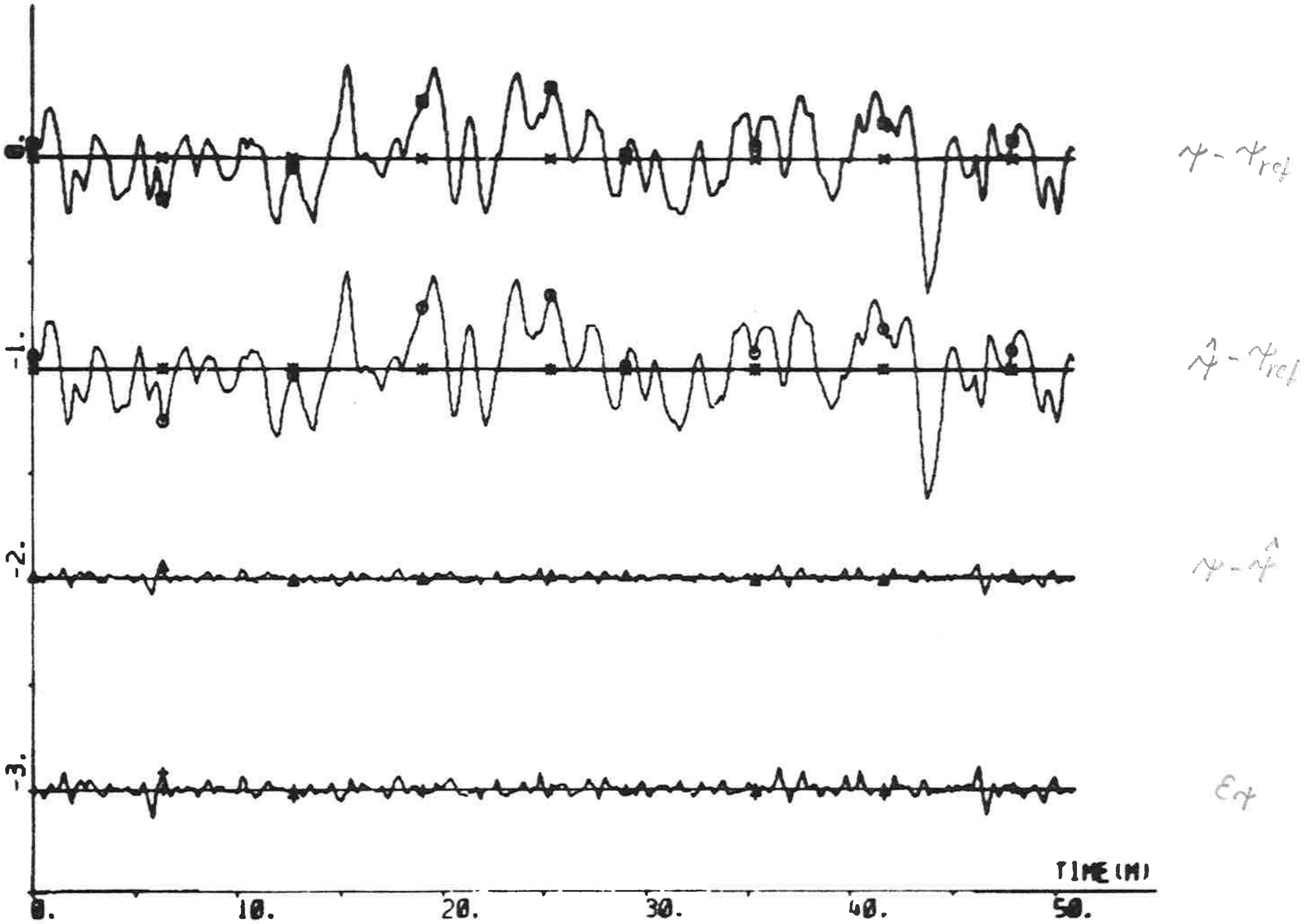
PLOT A33P1(1)-A33P1(4) A33P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 KNOTS



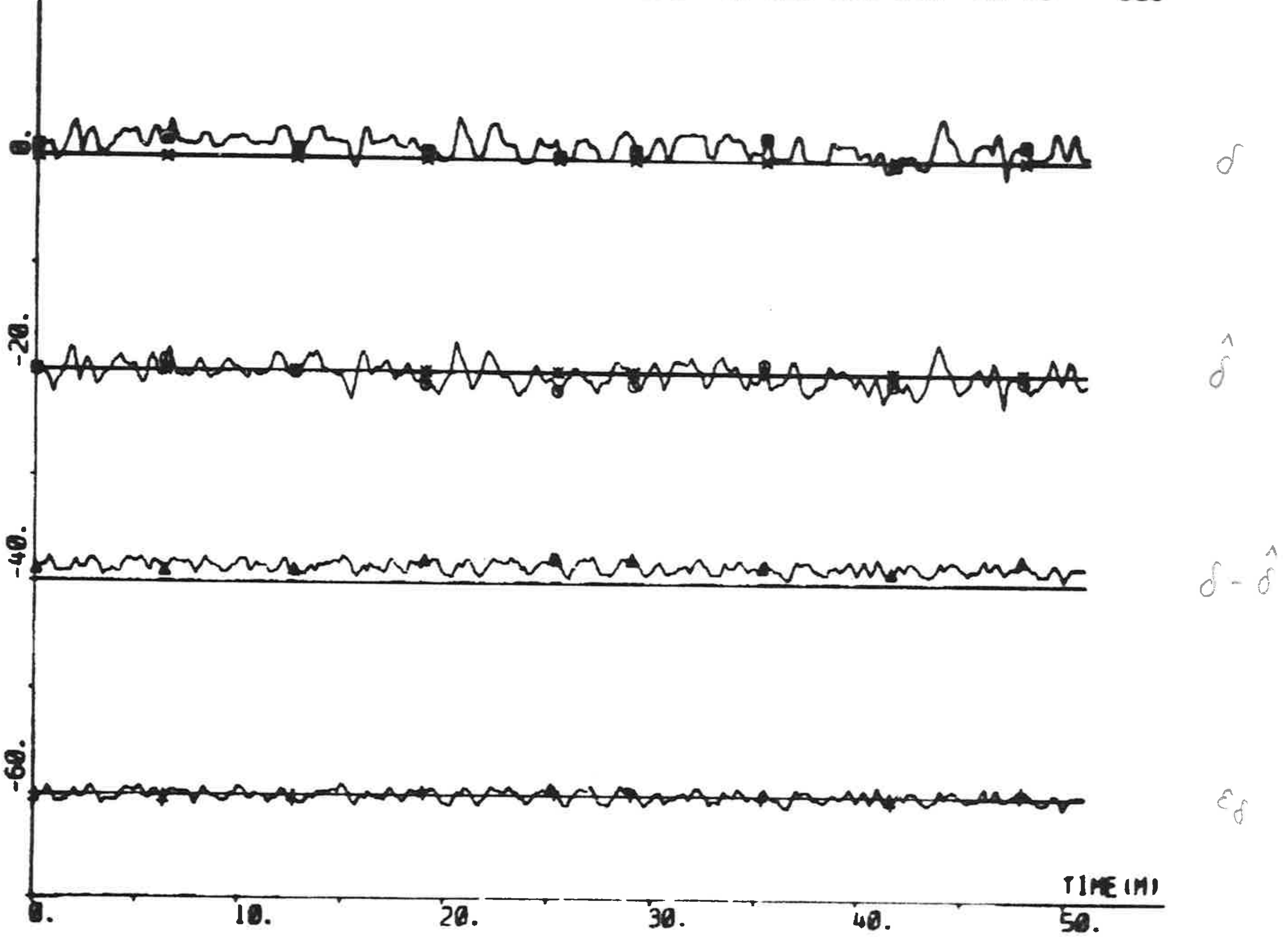
PLOT A33P1(1)-A33P1(6) A33P1(7) ERR3 EPS3 00 002 004 006 -0.7 0.

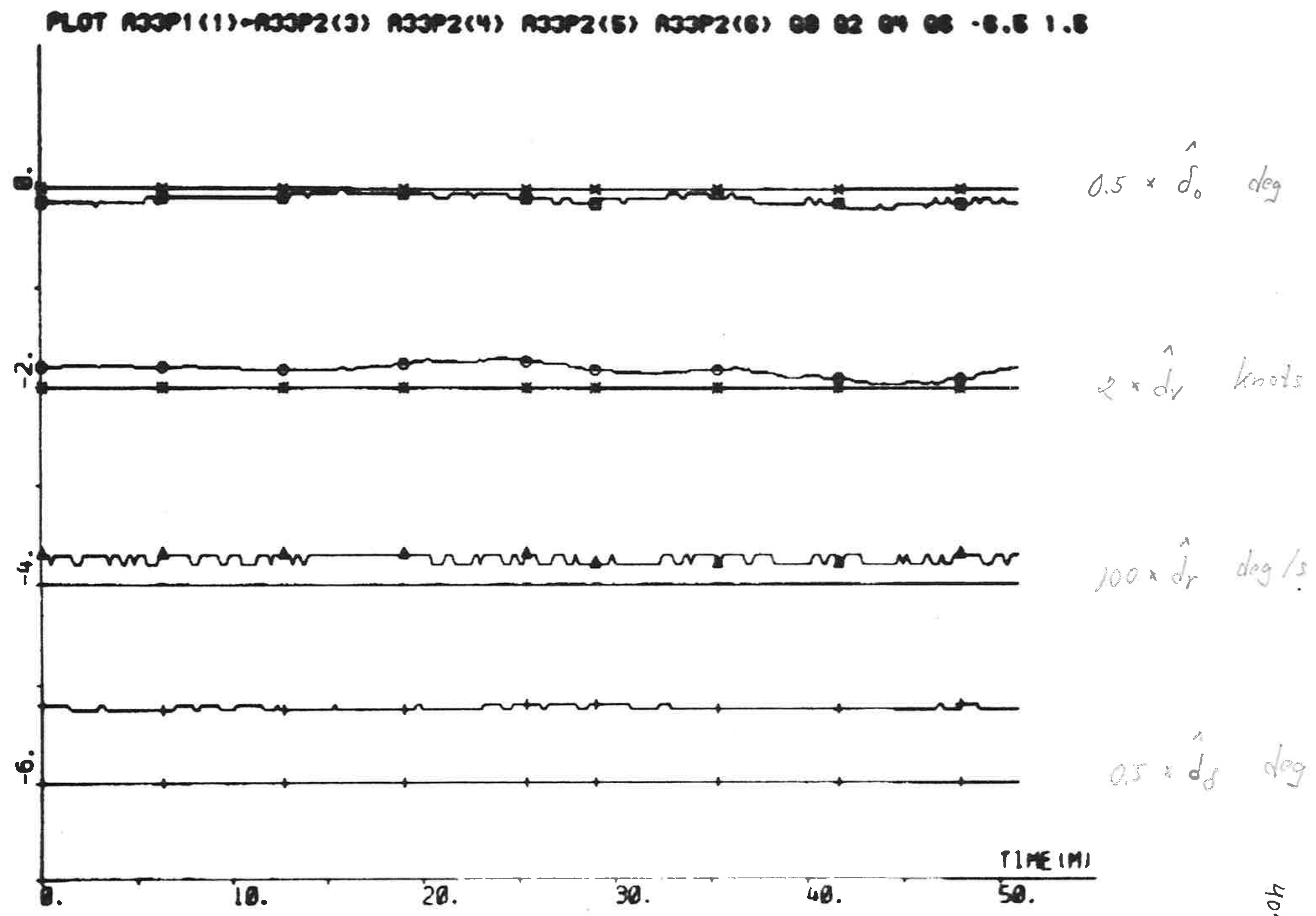


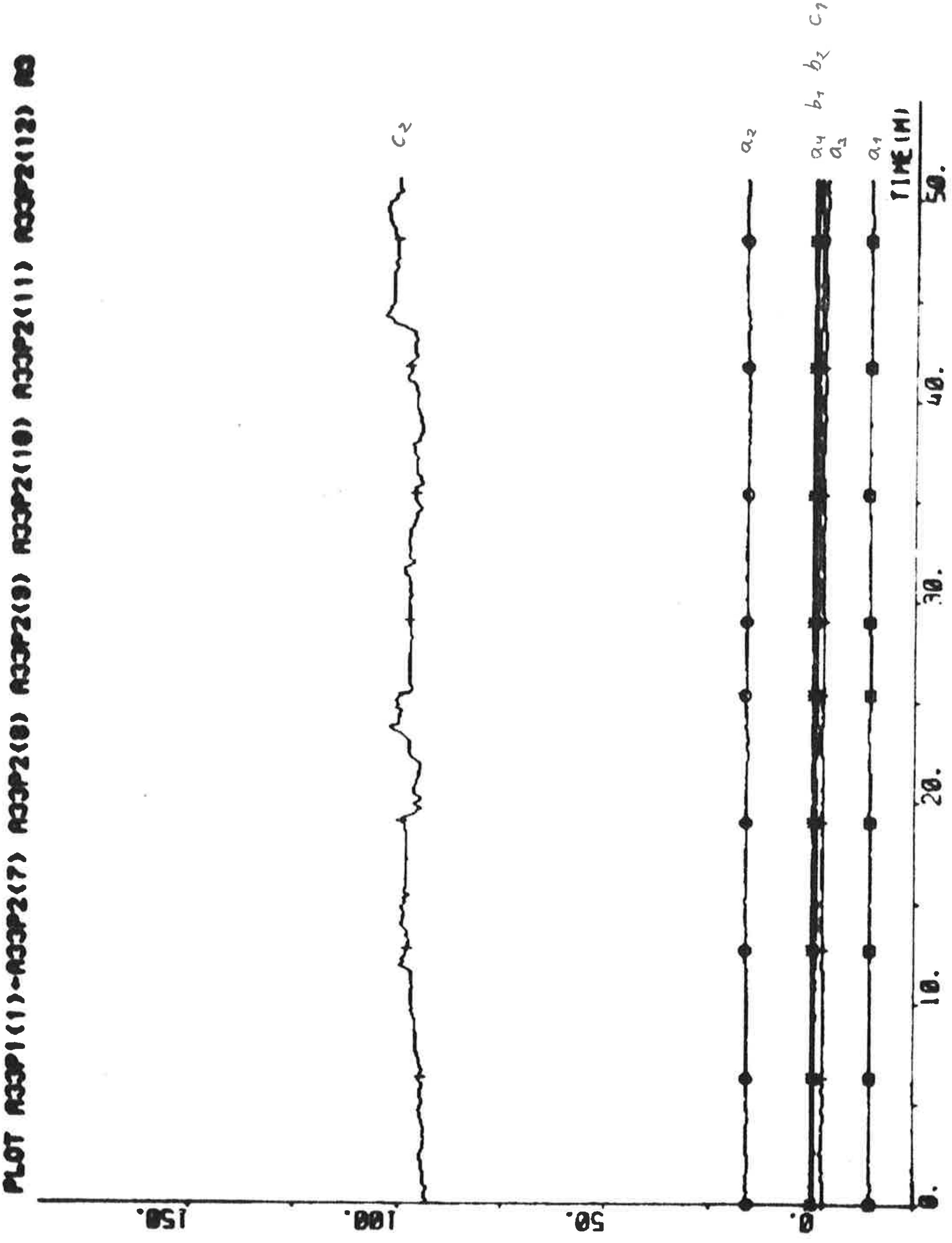
PLOT A33P1(1)-A33P1(8) A33P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 DEG



PLOT A33P1(1)-A33P1(2) A33P1(3) ERR1 EPS1 00 020 040 060 -05 16 * 086




PLOT R33P1(1)-R33P2(3) R33P2(4) R33P2(5) R33P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
10.
20.
30.
40.
50.
TIME (M)
0.5 × $\hat{\delta}_o$ deg
2 × $\hat{d}_v$ knots
100 × $\hat{d}_r$ deg/s
0.5 × $\hat{d}_\delta$ deg



PLOT
TIME (M)
0.
10.
20.
30.
40.
50.
0.
50.
100.
150.
c2
a2
a4
a3
b1
b2
c1
a1

EXPERIMENT A34

Date	1976-04-29	Forward draught	10.9 m
Time	11.04	Aft draught	12.9 m
Duration	48 min	Wind direction	SE (1; see App. A)
Position	S 17°41' E 04°42'	Wind velocity	10 m/s (fresh breeze)
ψ_{ref}	148 deg	Wave height	High sea from SE

Self-tuning regulator using estimates from the Kalman filter

Tuning time before the experiment started: ≥ 120 min

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -9.25 \\ 10.23 \\ -0.26 \\ -0.85 \\ 0.48 \\ 0.21 \\ -0.03 \\ 103.99 \end{bmatrix} \quad P = \begin{bmatrix} 4.73 & & & & & & & \\ -8.55 & 25.21 & & & & & & \\ 4.03 & -23.61 & 32.40 & & & & & \\ 0.20 & 6.87 & -13.42 & 6.92 & & & & \\ 0.03 & -0.49 & 0.74 & -0.30 & 0.02 & & & \\ 0.00 & -0.11 & 0.13 & -0.02 & 0.01 & 0.01 & & \\ -0.61 & 1.02 & -0.14 & -0.27 & -0.01 & 0.00 & 0.41 & \\ 10.91 & -15.66 & 2.62 & 3.53 & -0.02 & -0.15 & 7.18 & 447.56 \end{bmatrix}$$

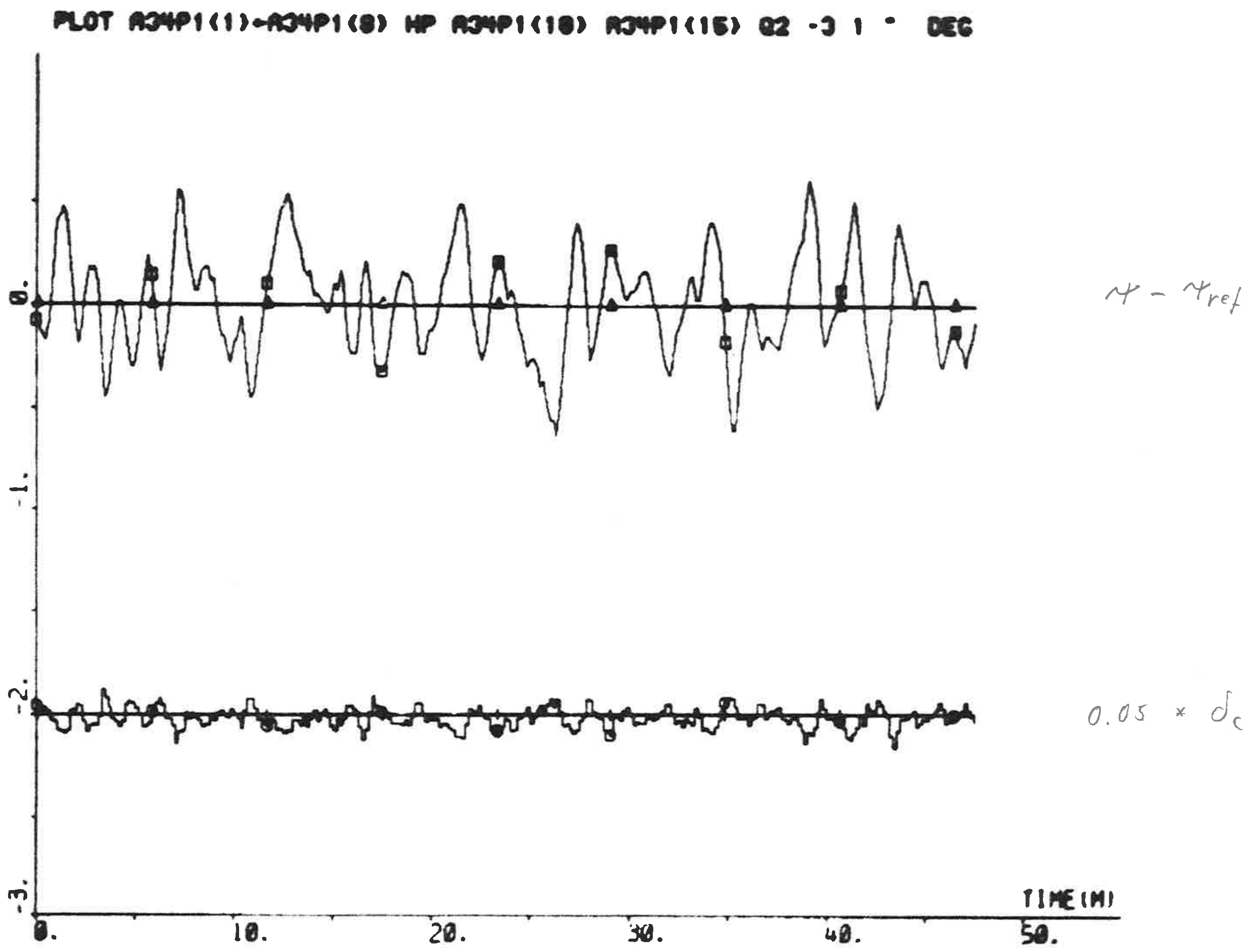
$a_1 + a_2 + a_3 + a_4 = -0.13$

$\hat{\delta}_0 = -0.3$ deg $\hat{d}_v = 0.17$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

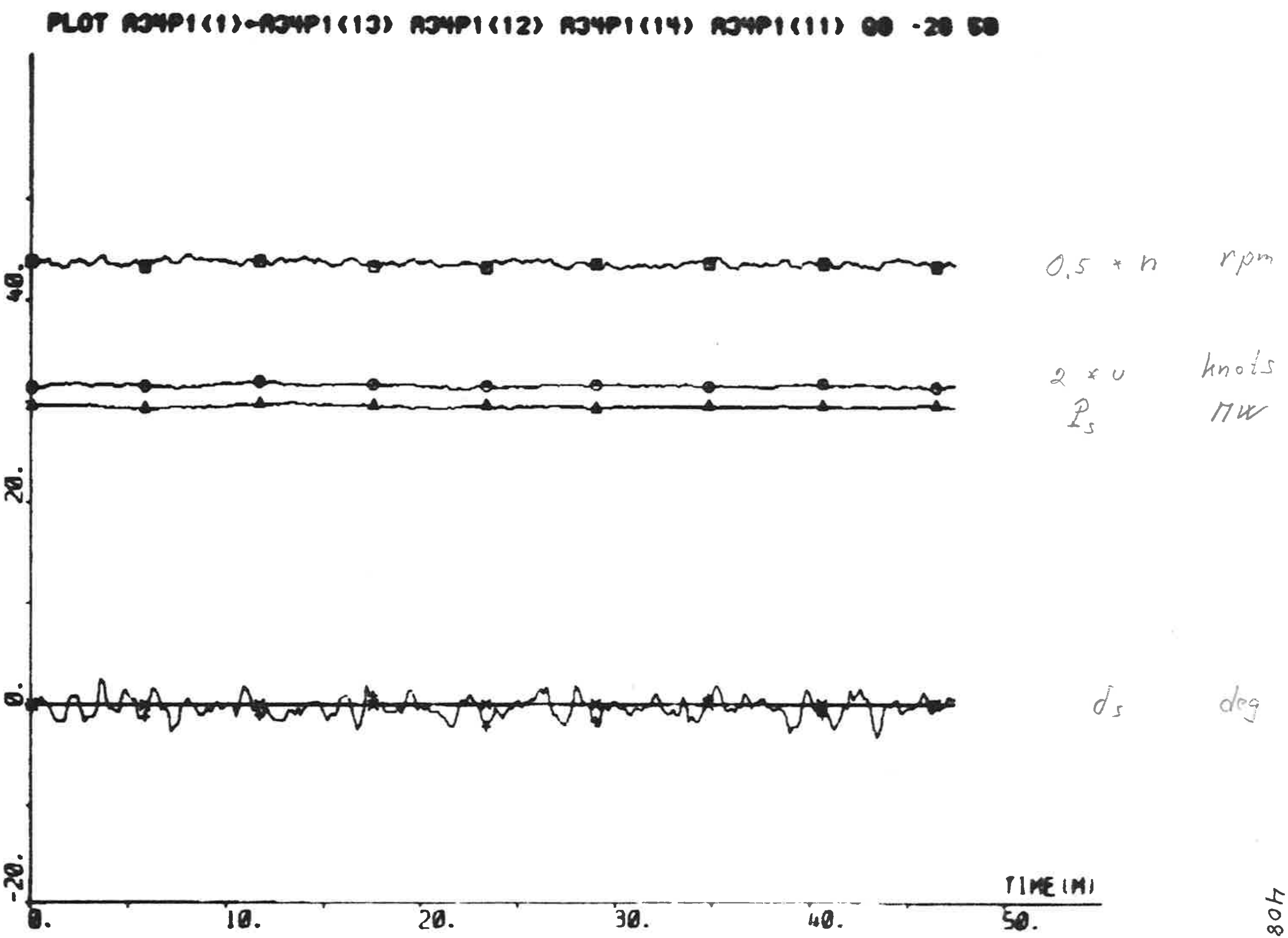
Statistics (mean value and standard deviation)

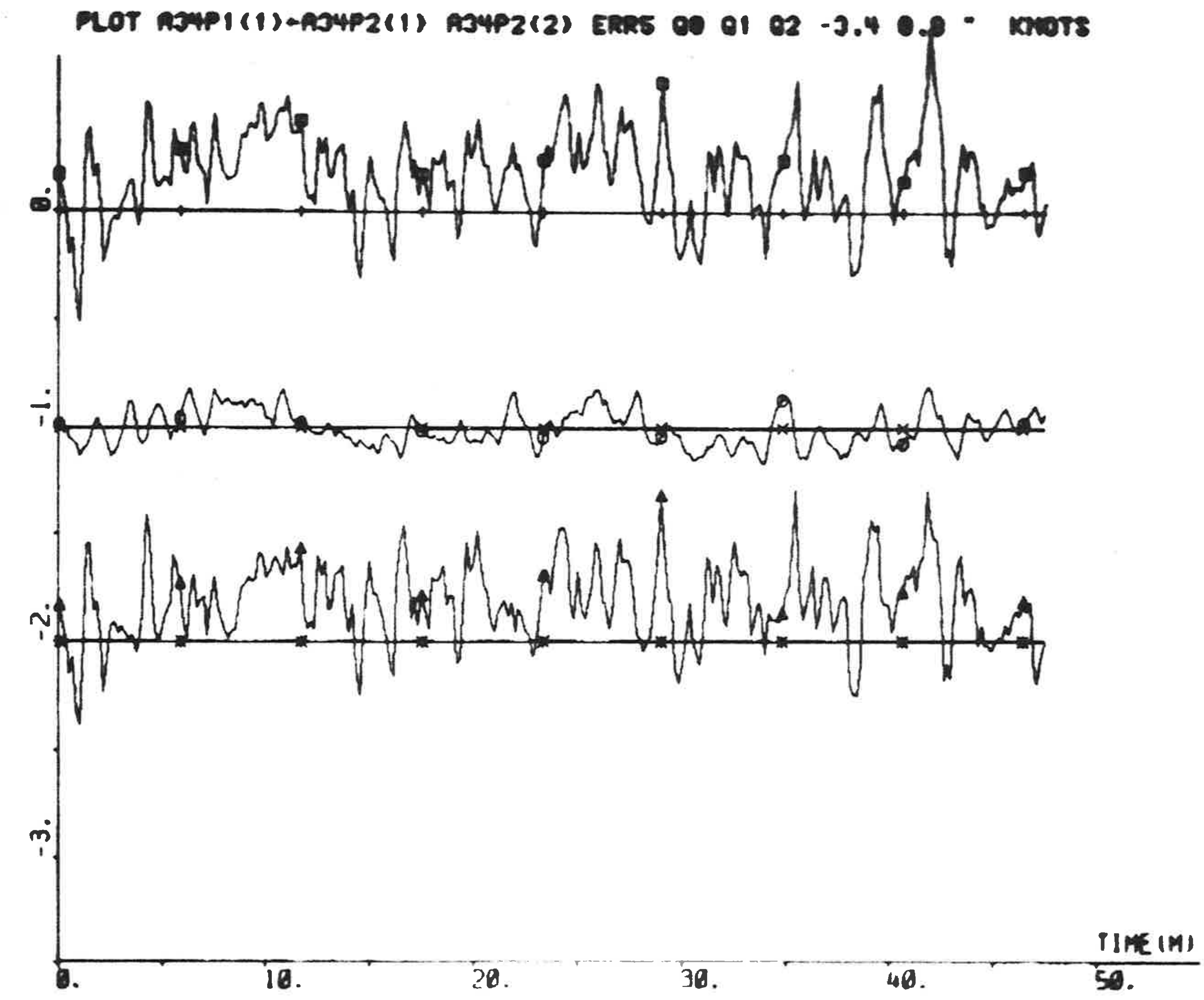
δ_c	-0.33 ± 0.95	deg		P_s	29.6 ± 0.1	MW
δ	1.18 ± 0.96	deg		ε_v	0.00 ± 0.03	knots
$\psi-\psi_{ref}$	0.001 ± 0.251	deg		ε_r	0.00 ± 0.03	deg/s
n	87.6 ± 0.5	rpm		ε_ψ	0.00 ± 0.06	deg
u	15.8 ± 0.1	knots		ε_δ	0.0 ± 0.4	deg

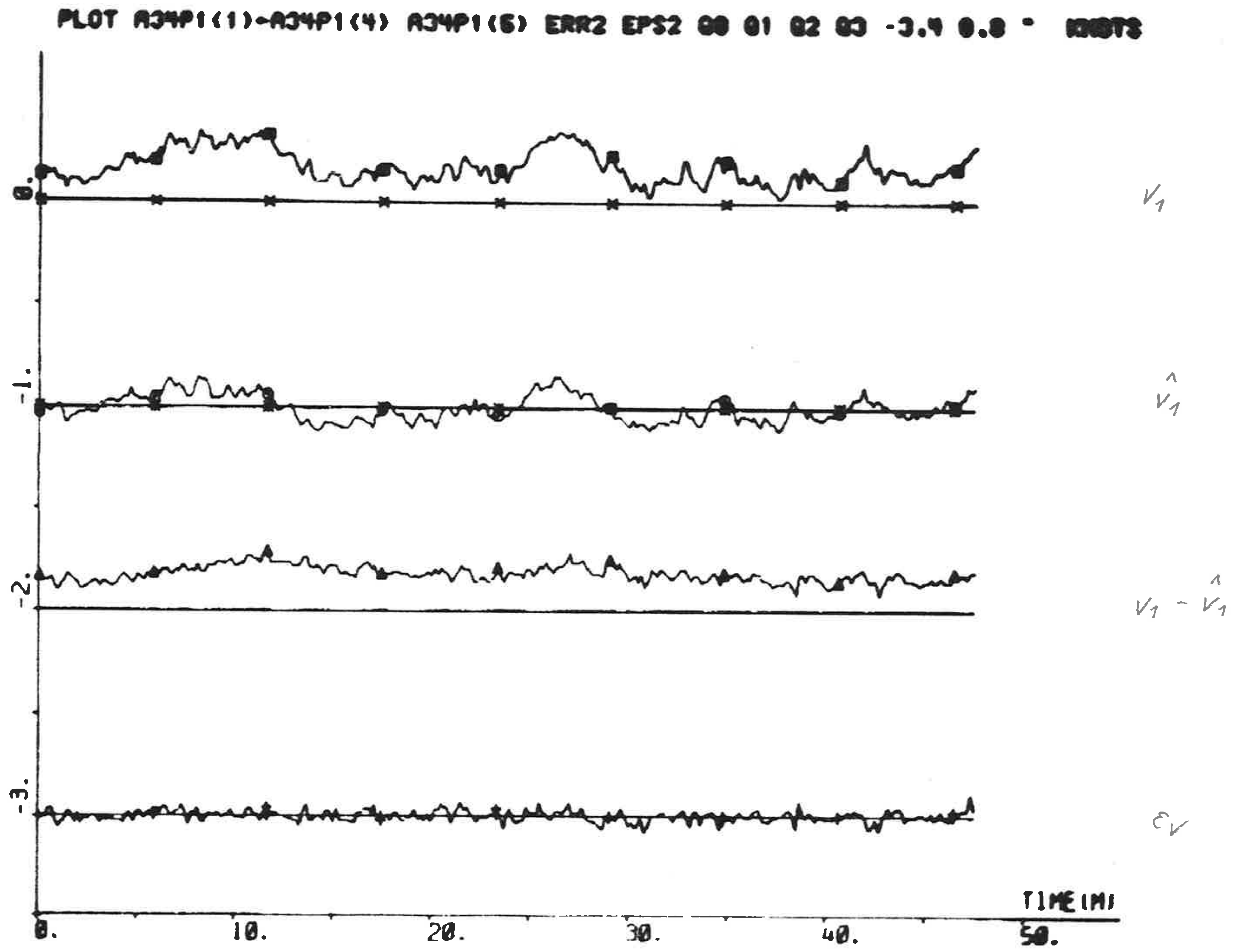
$V_1 = 0.138$

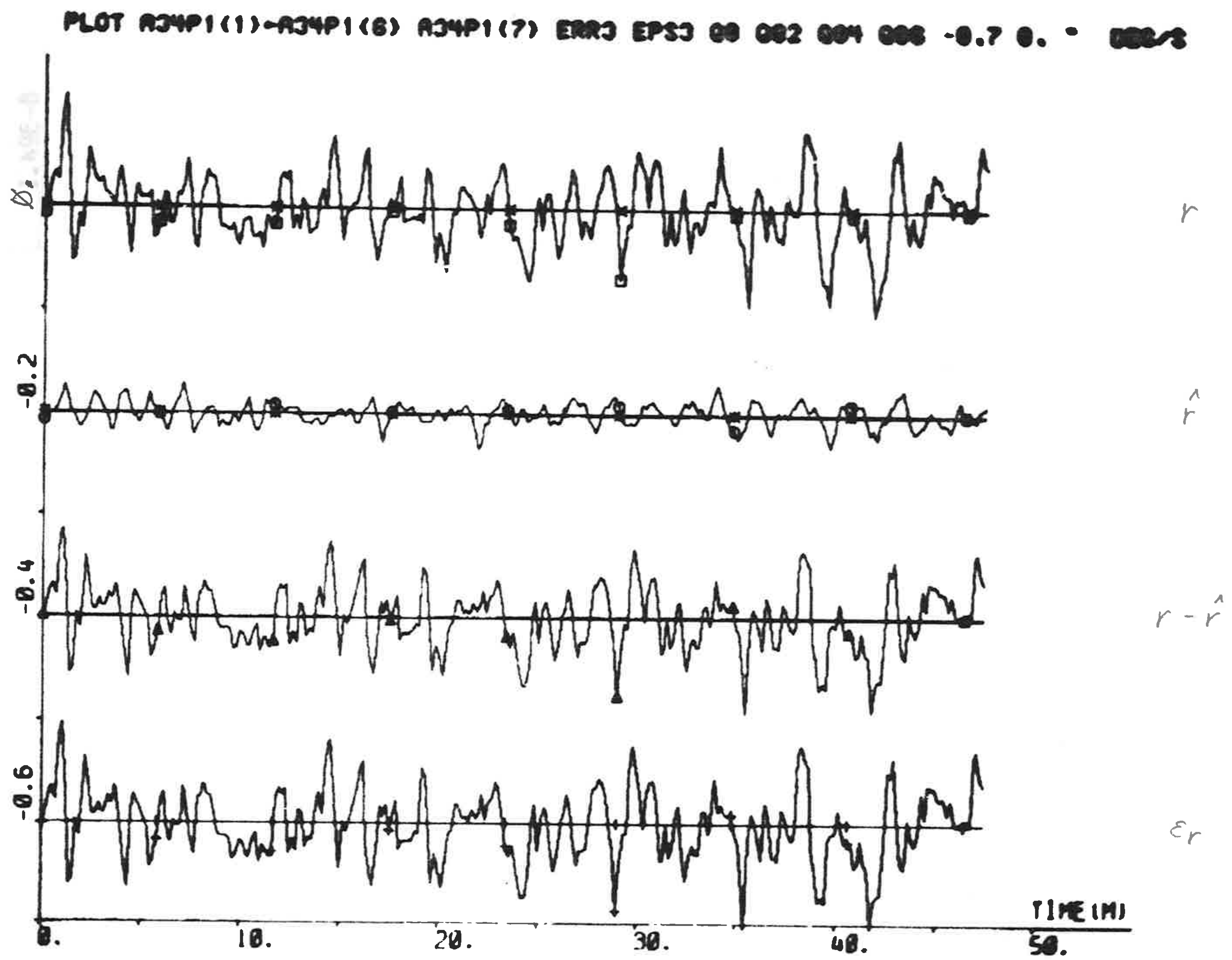


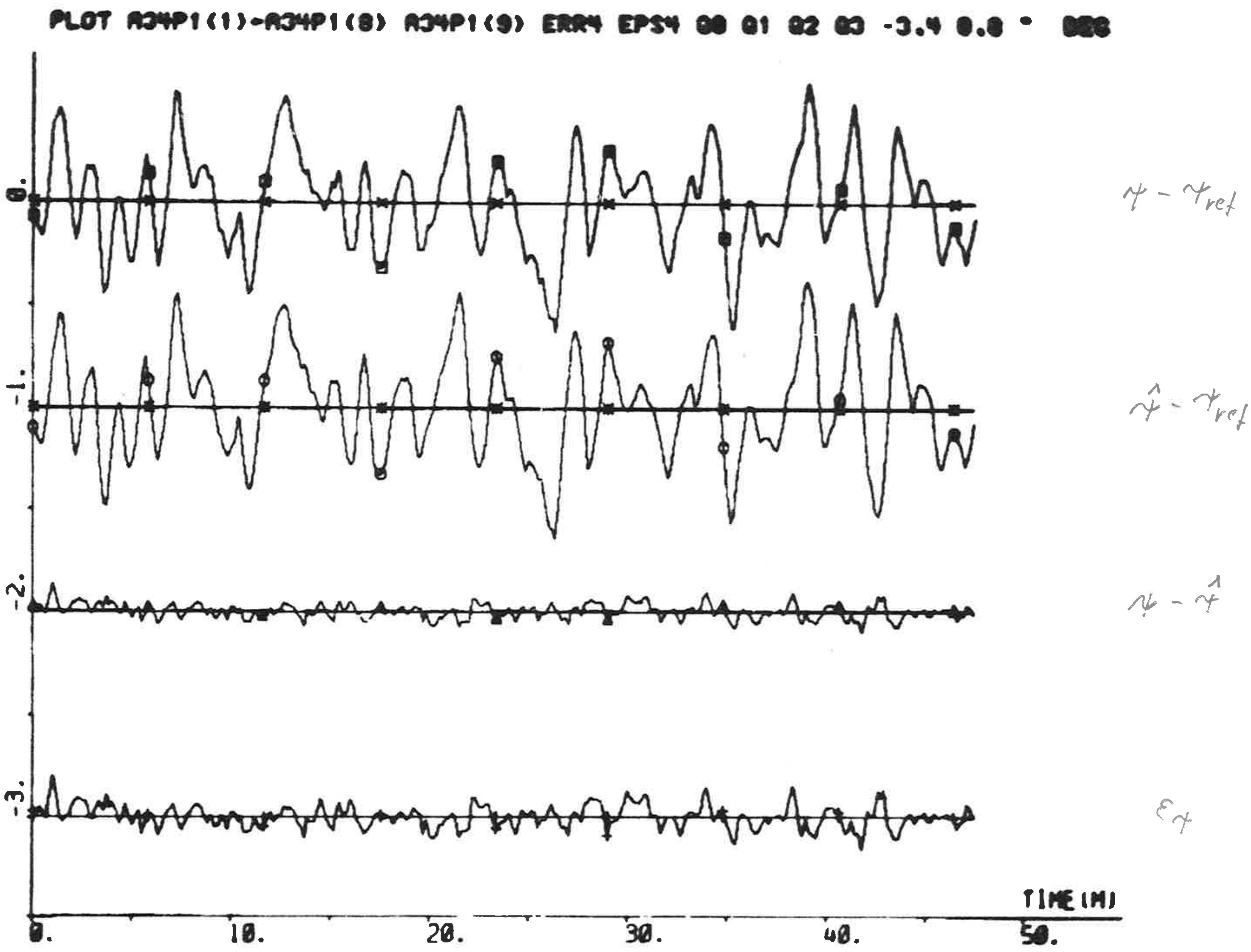
PLOT A34P1(1)-A34P1(8) HP A34P1(10) A34P1(15) Q2 -3 1 ° DEG
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
ψ - ψref
0.05 * δc

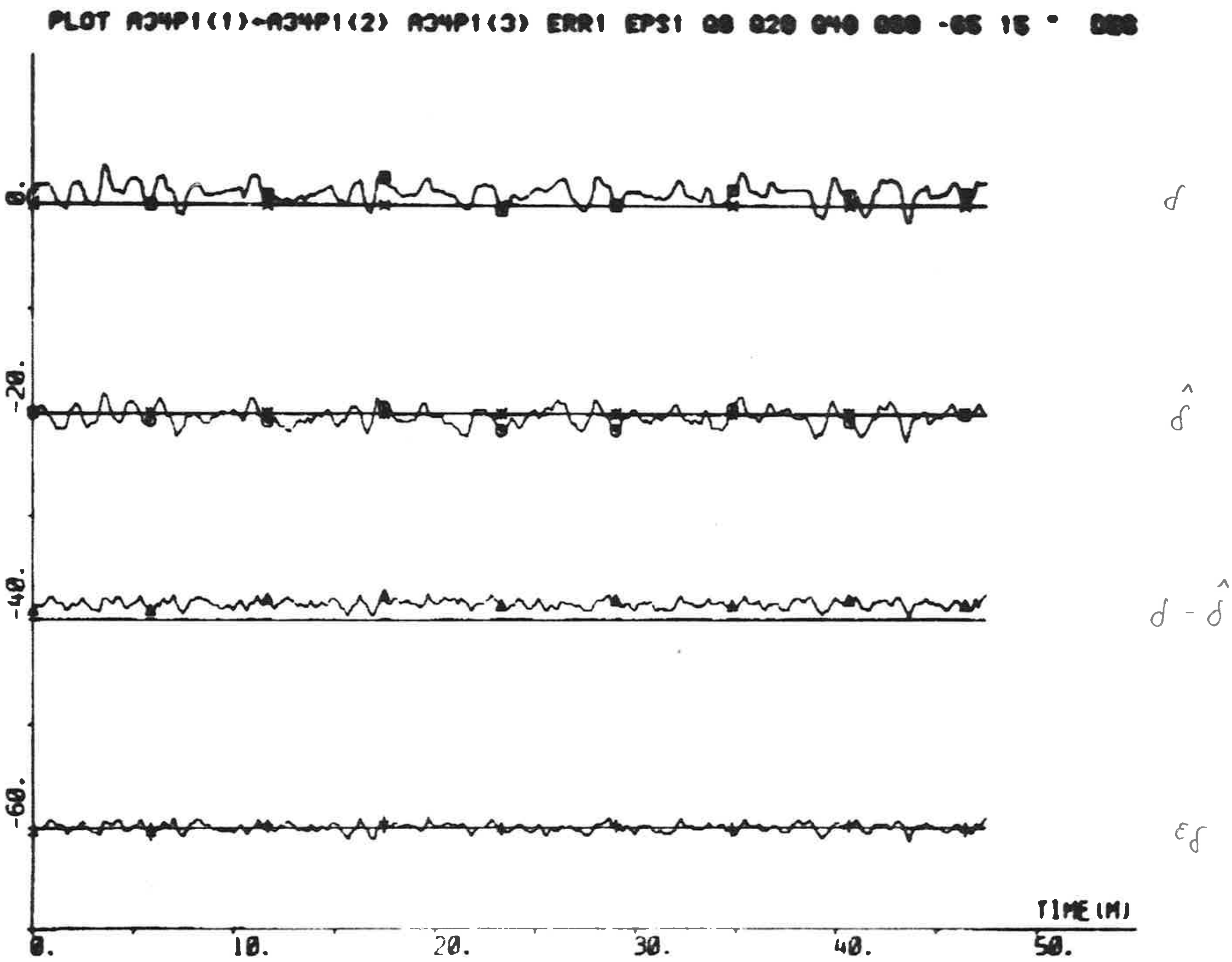

PLOT A34P1(1)-A34P1(13) A34P1(12) A34P1(14) A34P1(11) 00 -20 50
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME (M)
0.5 * n rpm
2 * u knots
P_s MW
d_s deg


PLOT A34P1(1)-A34P2(1) A34P2(2) ERRS 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)

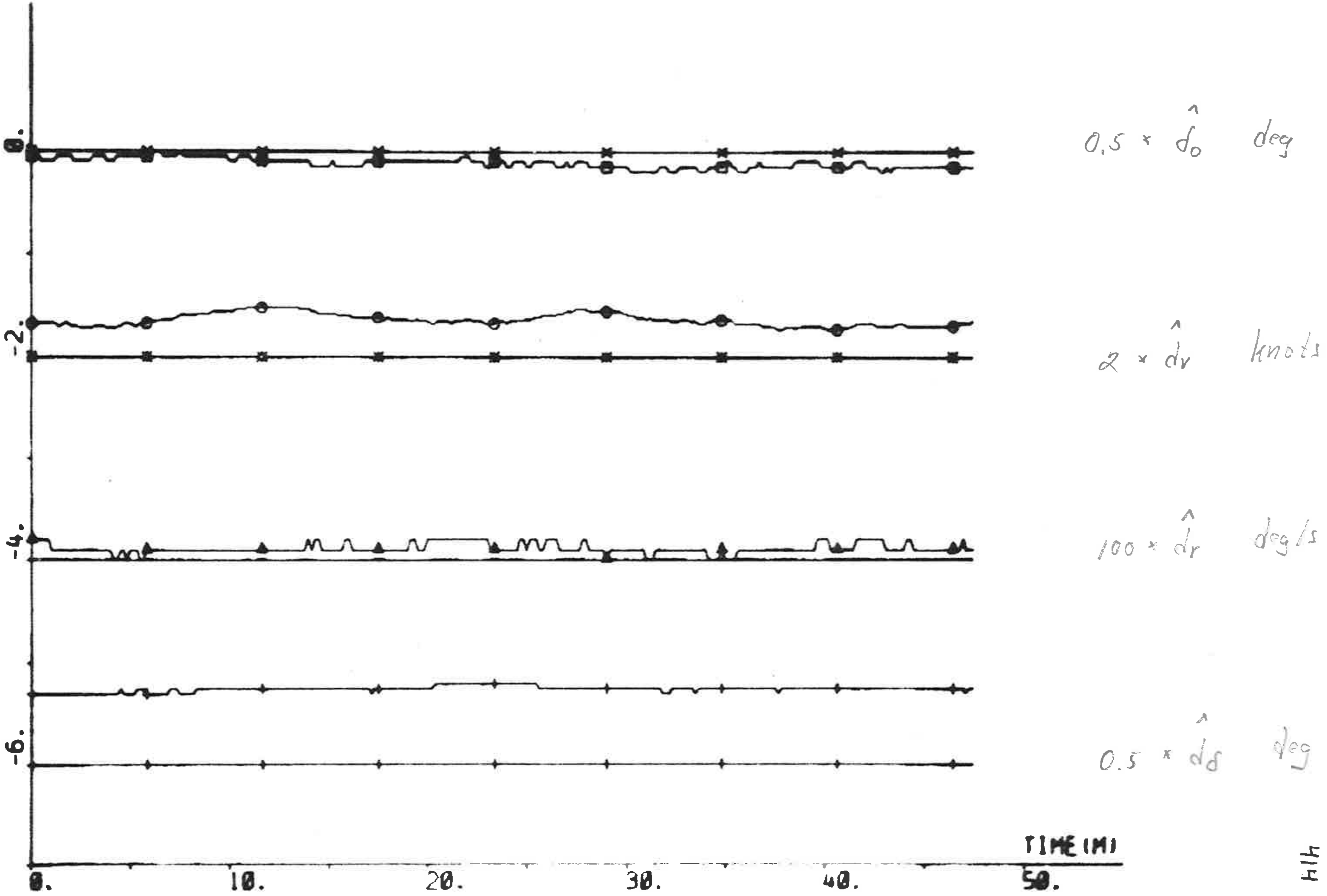

PLOT A34P1(1)-A34P1(4) A34P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.8
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V

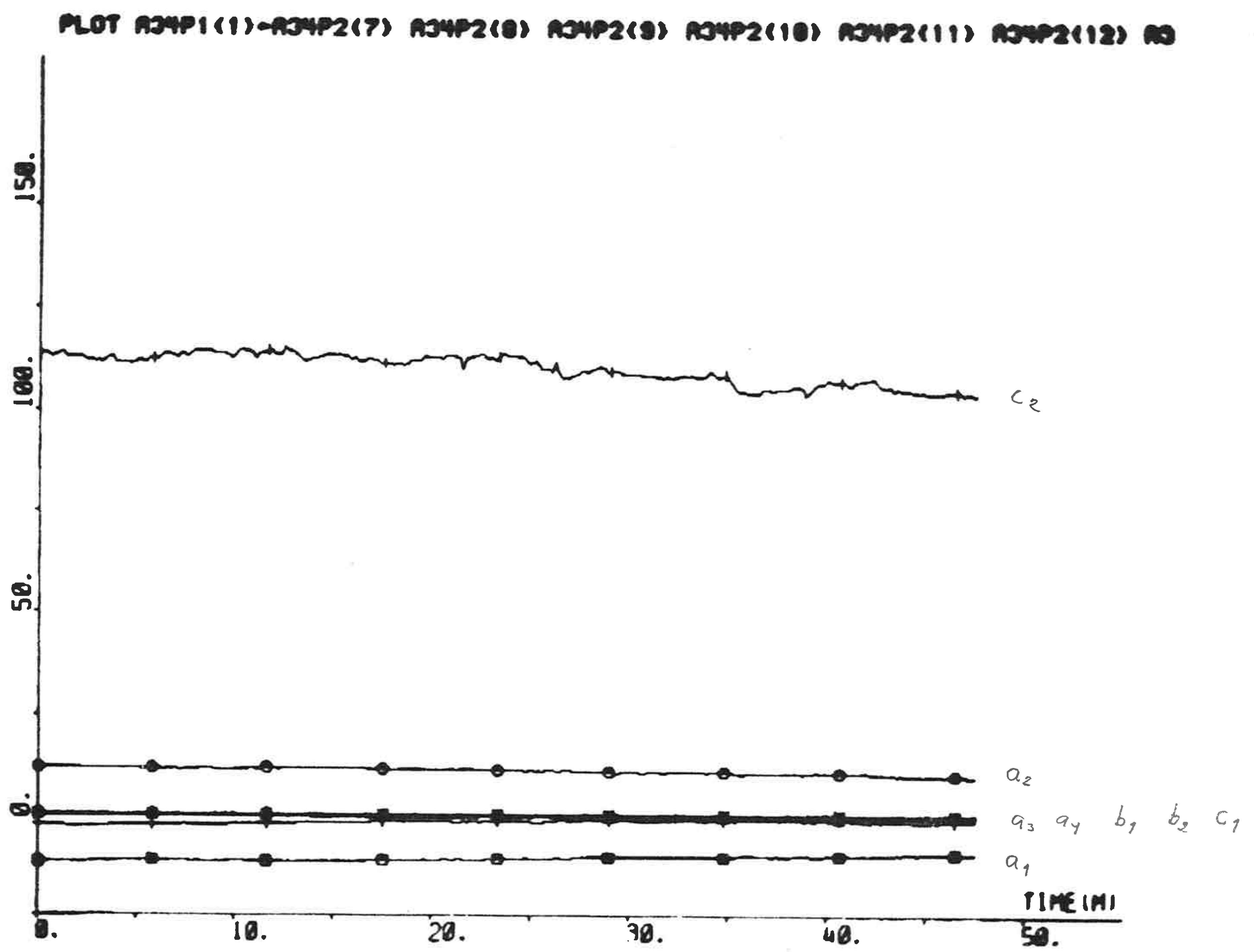

PLOT A34P1(1)-A34P1(6) A34P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. - DEG/S
0.
-0.2
-0.4
-0.6
0.
10.
20.
30.
40.
50.
TIME(M)
r
r̂
r - r̂
εr


PLOT A34P1(1)-A34P1(8) A34P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.8 ° DEG
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A34P1(1)-A34P1(2) A34P1(3) ERR1 EPS1
0.
-20.
-40.
-60.
0.
10.
20.
30.
40.
50.
TIME (M)

PLOT A34P1(1)-A34P2(3) A34P2(4) A34P2(5) A34P2(6) 00 02 04 06 -6.6 1.6




PLOT A34P1(1)-A34P2(7) A34P2(8) A34P2(9) A34P2(10) A34P2(11) A34P2(12) AS
150.
100.
50.
0.
0.
10.
20.
30.
40.
50.
TIME(M)
c2
a2
a3 a4 b1 b2 c1
a1

EXPERIMENT A35

Date	1976-04-29	Forward draught	10.9 m
Time	14.45	Aft draught	12.9 m
Duration	45 min	Wind direction	SE (1; see App. A)
Position	S 18°30' E 05°15'	Wind velocity	11 m/s (strong breeze)
ψ_{ref}	143 deg	Wave height	High sea from SE

PID-regulator using estimates from the Kalman filter

$k_P = 3$ $k_D = 140$ s $k_I = 0.02$ 1/s

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

The parameters were manually tuned before the experiment started.

Final values:

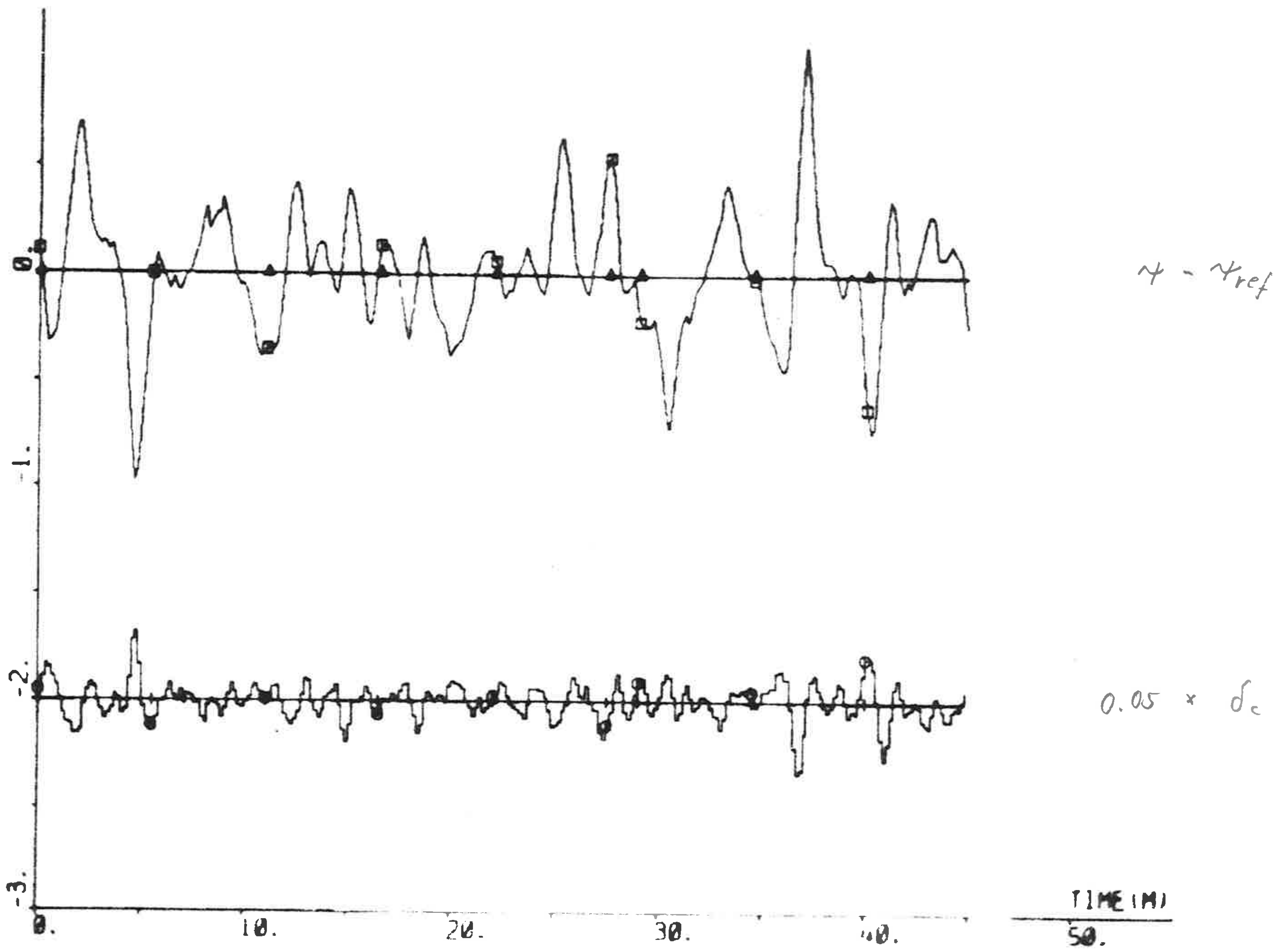
$\hat{\delta}_0 = 0.0$ deg $\hat{d}_v = 0.14$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.4$ deg

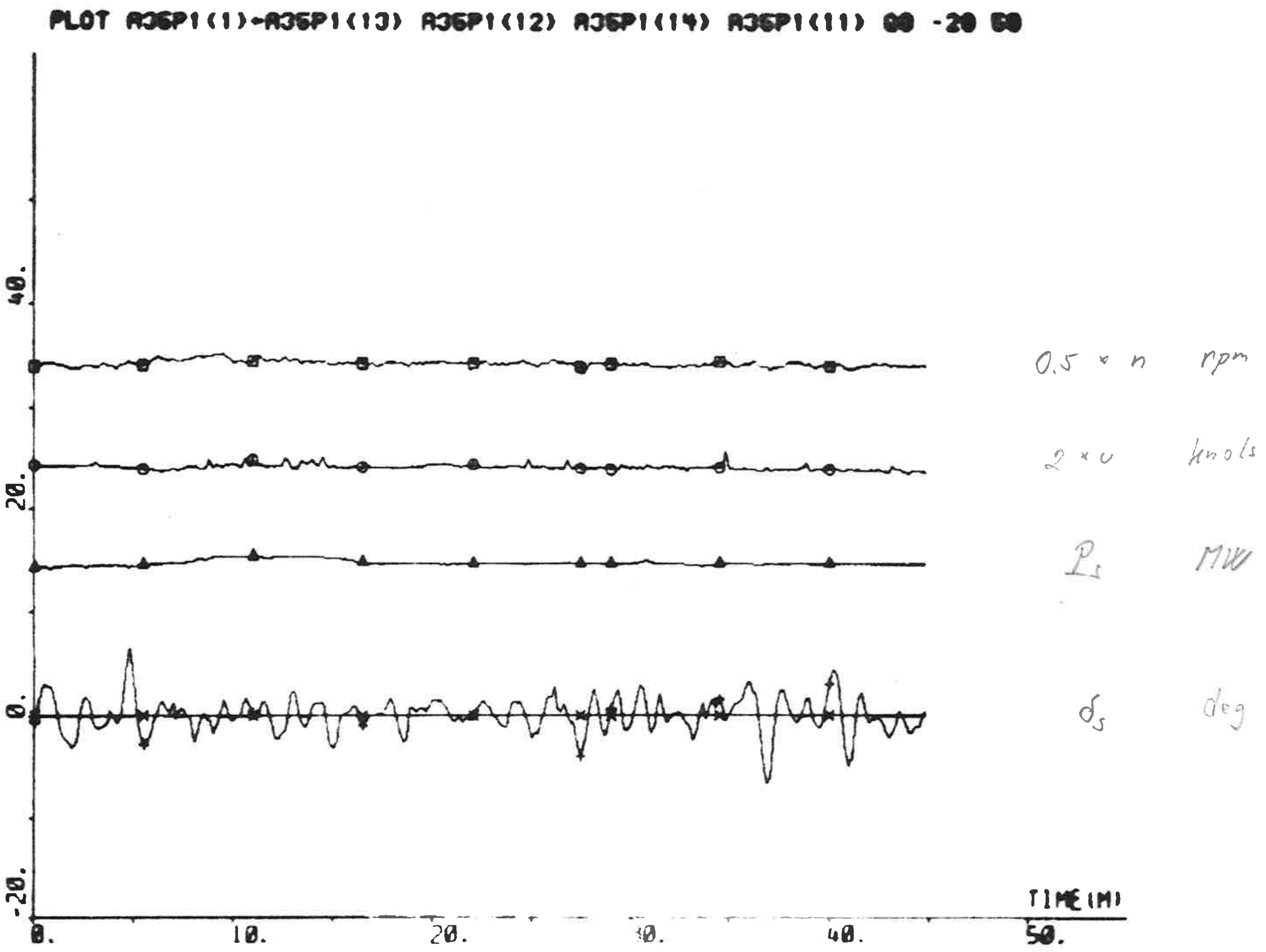
Statistics (mean value and standard deviation)

δ_c	0.01 ± 1.66 deg		P_s	14.7 ± 0.3 MW
δ	1.46 ± 1.55 deg		ε_v	0.00 ± 0.03 knots
$\psi-\psi_{ref}$	0.008 ± 0.295 deg		ε_r	0.00 ± 0.04 deg/s
n	68.6 ± 0.5 rpm		ε_ψ	0.00 ± 0.04 deg
u	12.1 ± 0.1 knots		ε_δ	0.0 ± 0.4 deg

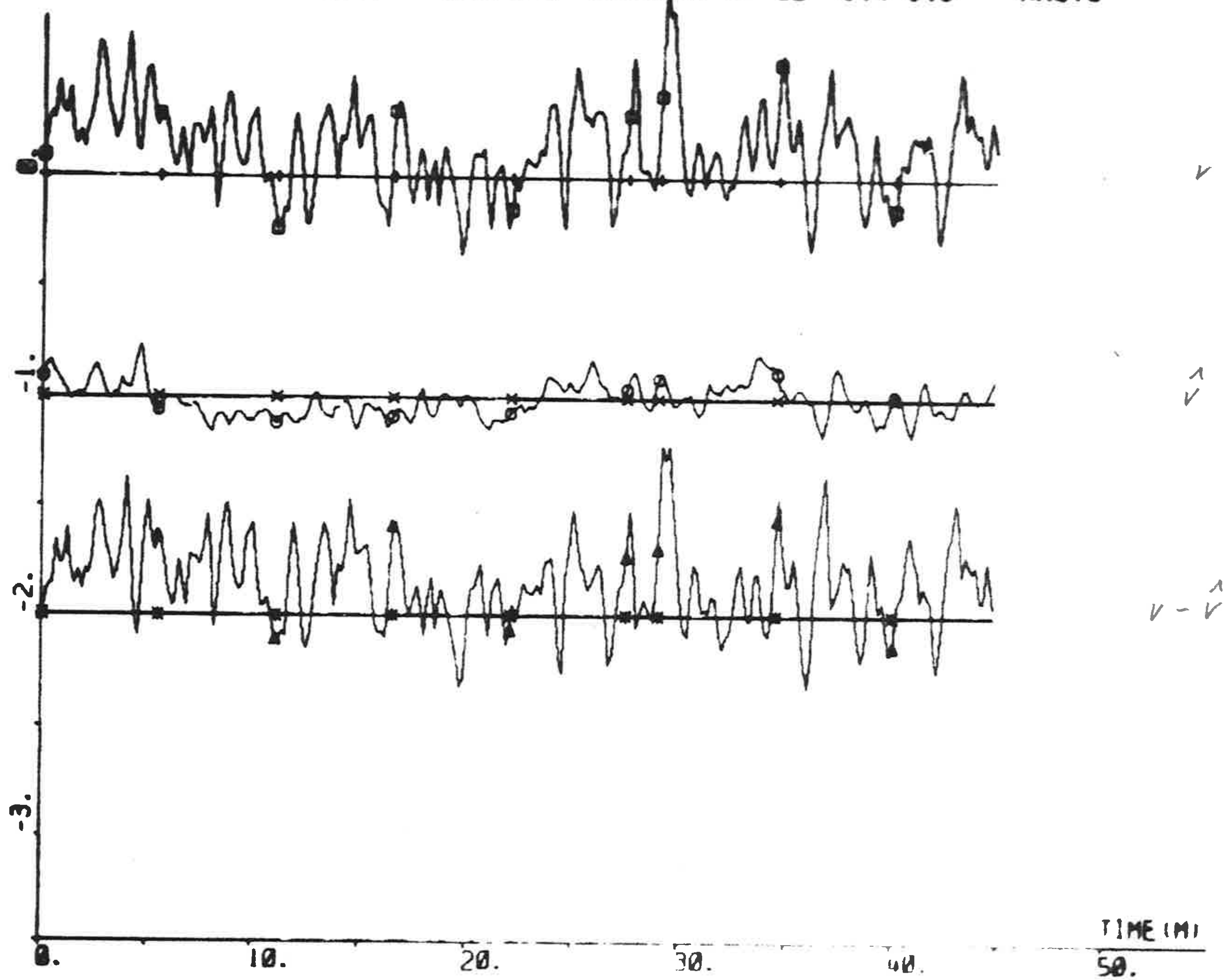
$V_1 = 0.317$

PLOT AJ6P1(1)-AJ6P1(8) HP AJ6P1(10) AJ6P1(15) Q2 -3 1 DEG

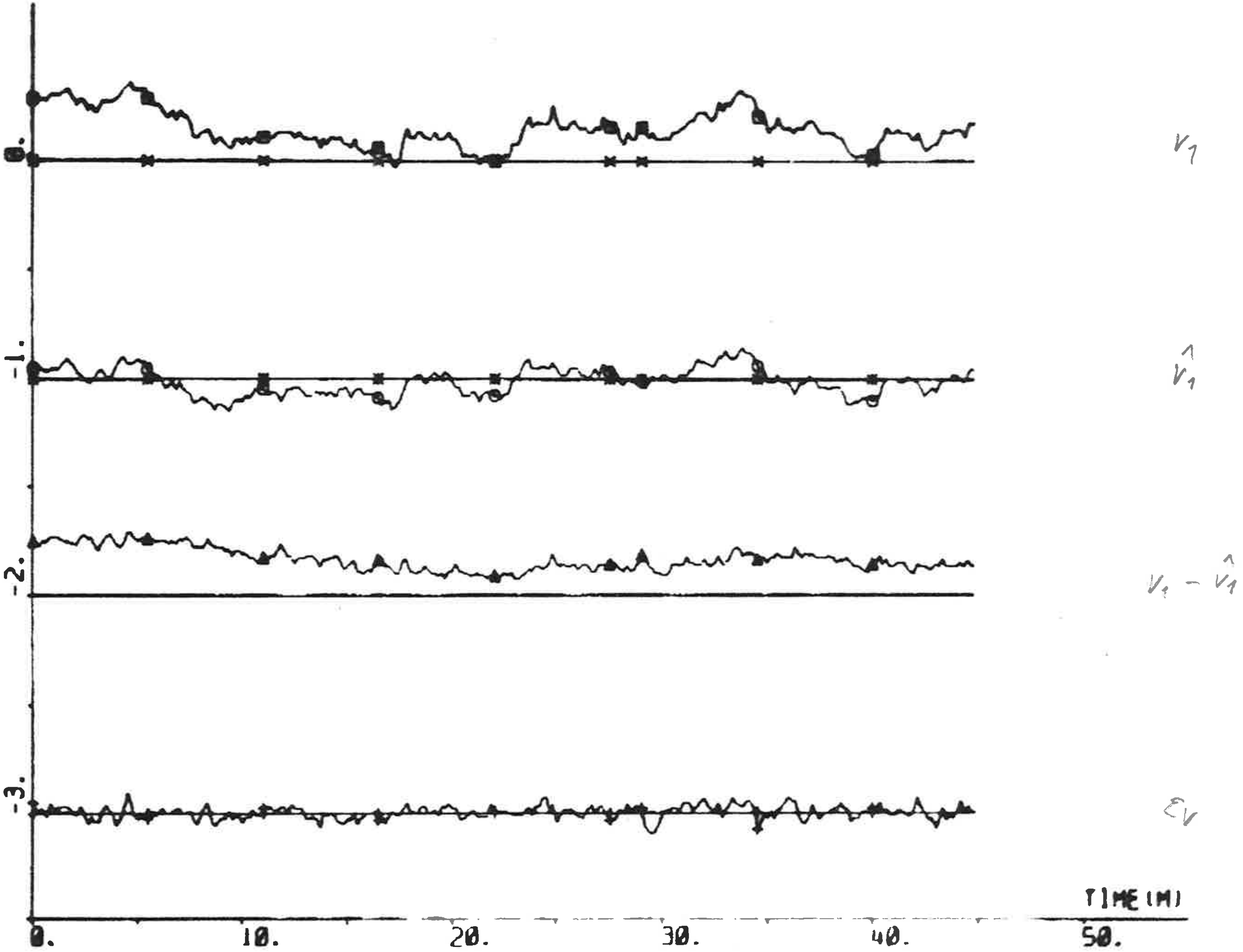



PLOT A36P1(1)-A36P1(13) A36P1(12) A36P1(14) A36P1(11) 60 -20 60
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME(M)
0.5 * n rpm
2 * v knots
P_s MW
δ_s deg

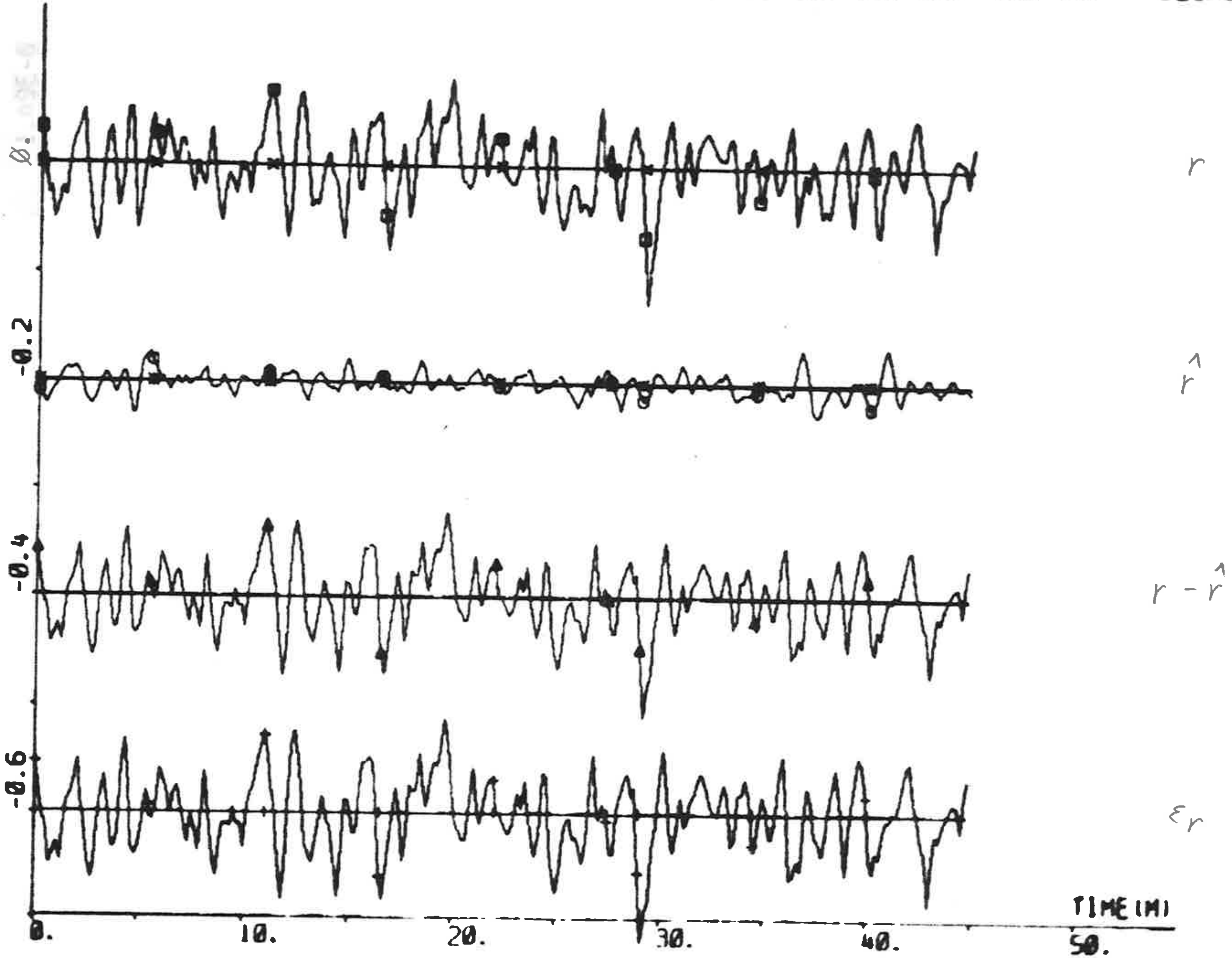
PLOT A36P1(1)-A36P2(1) A36P2(2) ERR6 Q0 Q1 Q2 -3.4 0.0 - KNOTS

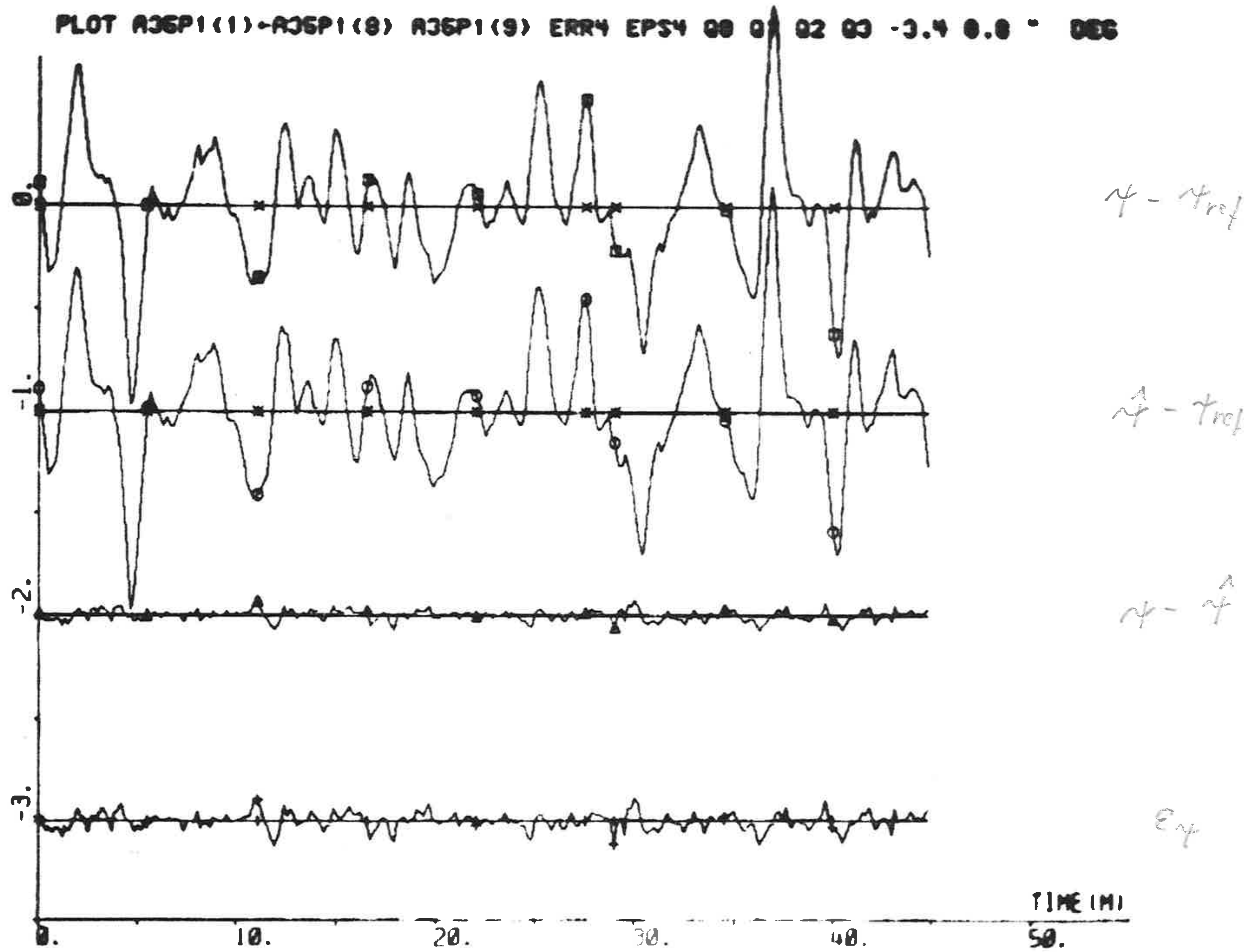


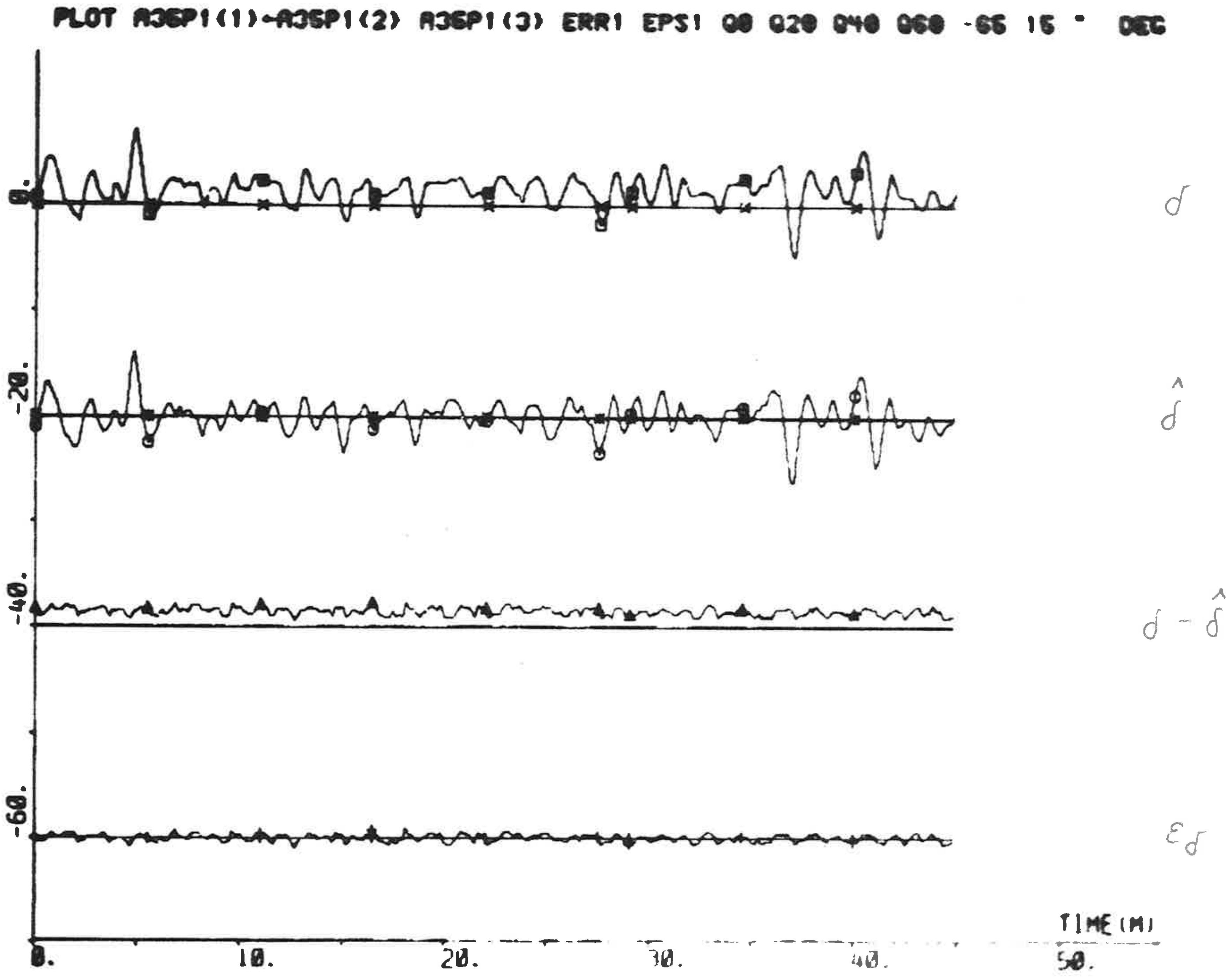
PLOT A36P1(1)-A36P1(4) A36P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 * KNOTS

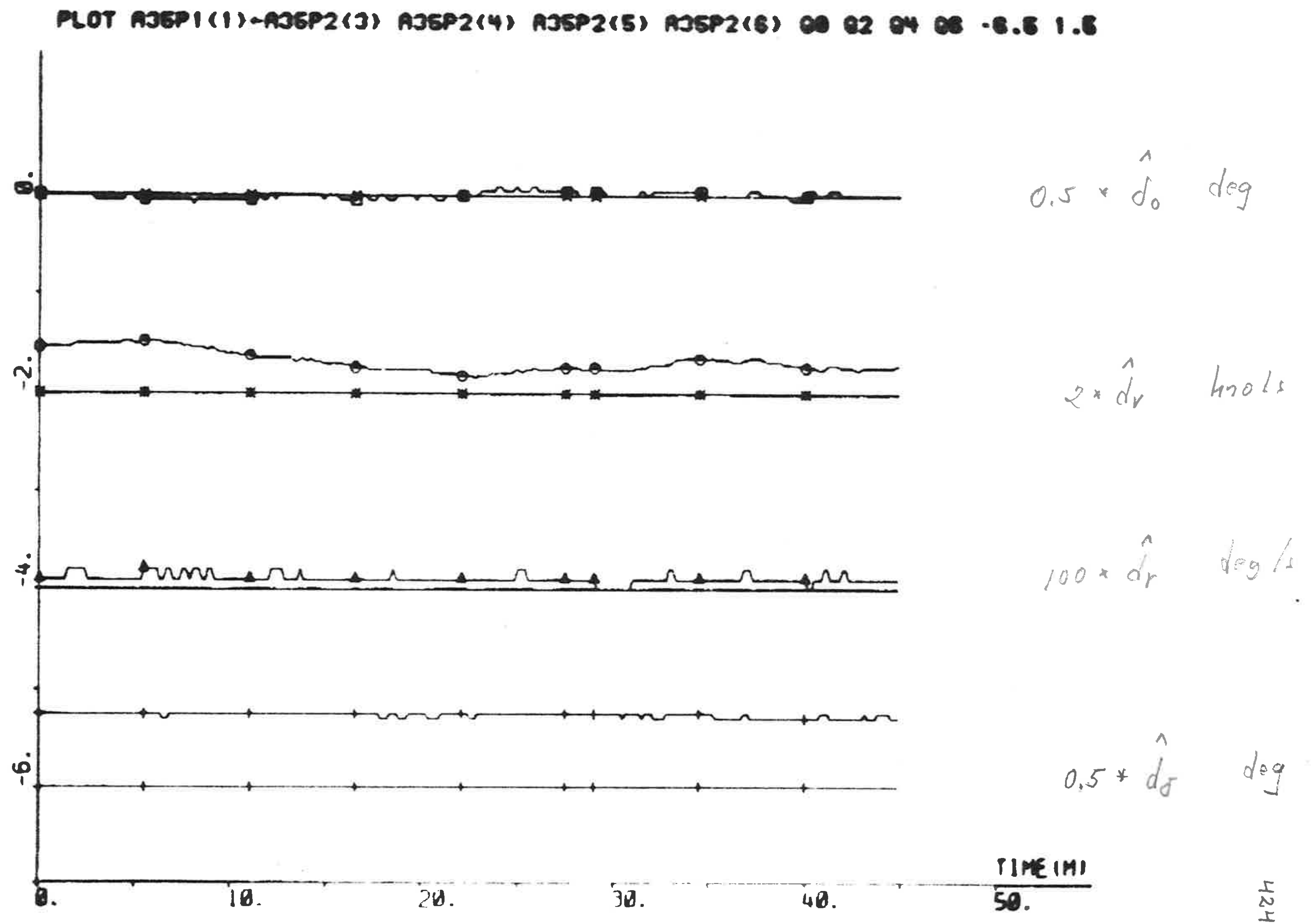


PLOT A3SP1(1)-A3SP1(6) A3SP1(7) ERR3 EPS3 00 002 004 006 -0.7 0. * DEG/S




PLOT A36P1(1)-A36P1(8) A36P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 - DEG
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT A3SP1(1)-A3SP1(2) A3SP1(3) ERR1 EPS1 Q0 Q20 Q40 Q60 -65 15 ° DEG
0.
-20.
-40.
-60.
0.
10.
20.
30.
40.
50.
TIME (M)
δ
$\hat{\delta}$
$\delta - \hat{\delta}$
ε_δ



PLOT A36P1(1)-A36P2(3) A36P2(4) A36P2(5) A36P2(6) Q0 Q2 Q4 Q6 -6.6 1.6
0.
-2.
-4.
-6.
0.5 * $\hat{d}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0.5 * $\hat{d}_\delta$ deg
0.
10.
20.
30.
40.
50.
TIME(M)

EXPERIMENT A36

Date	1976-04-29	Forward draught	10.9 m
Time	15.54	Aft draught	12.9 m
Duration	47 min	Wind direction	SE (1; see App. A)
Position	S 18°40' E 05°23'	Wind velocity	11 m/s (strong breeze)
ψ_{ref}	143 deg	Wave height	High sea from SE

An incorrect measurement of the yaw rate r was obtained after about 36 min. This measurement was skipped by the Kalman filter.

Self-tuning regulator using estimates from the Kalman filter

Tuning time before the experiment started: > 120 min

NC1 = 1   NC2 = 1   k = 7   q = 0

T_s = 10 s V_0 = 6 m/s   IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -11.12 \\ 12.52 \\ 1.53 \\ -3.00 \\ 0.59 \\ 0.29 \\ 0.45 \\ 89.21 \end{bmatrix} \quad P = \begin{bmatrix} 6.28 & & & & & & & \\ -10.88 & 36.77 & & & & & & \\ 5.02 & -38.68 & 57.22 & & & & & \\ 0.02 & 12.66 & -23.82 & 11.65 & & & & \\ 0.00 & -0.88 & 1.50 & -0.63 & 0.05 & & & \\ 0.01 & -0.28 & 0.37 & -0.09 & 0.01 & 0.02 & & \\ -0.89 & 1.07 & 0.71 & -0.92 & 0.01 & 0.00 & 1.14 & \\ 17.26 & -39.46 & 31.87 & -10.04 & 0.56 & 0.04 & 17.74 & 774.32 \end{bmatrix}$$

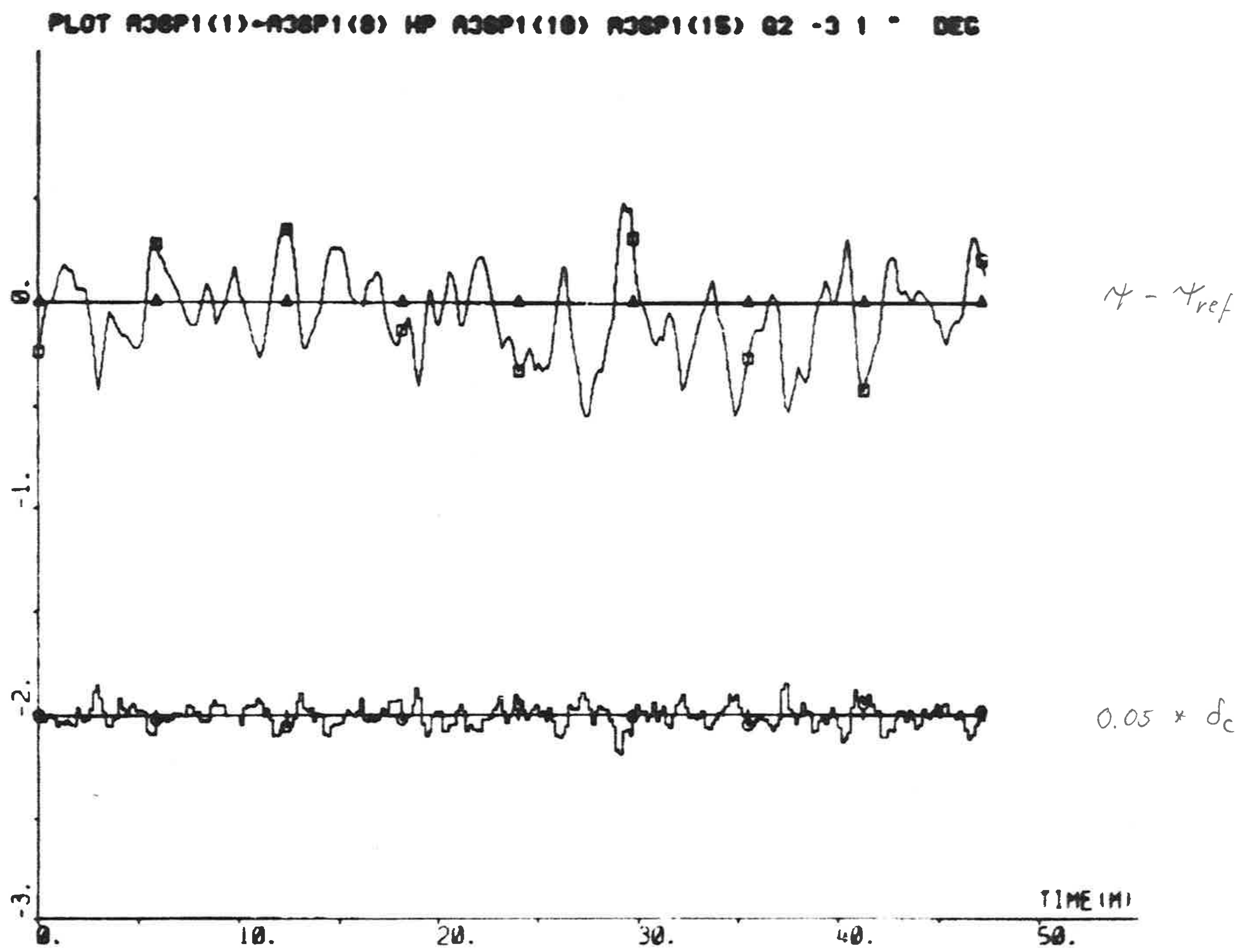
$a_1 + a_2 + a_3 + a_4 = -0.07$

$\hat{\delta}_0 = 0.1$ deg $\hat{d}_v = 0.08$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

Statistics (mean value and standard deviation)

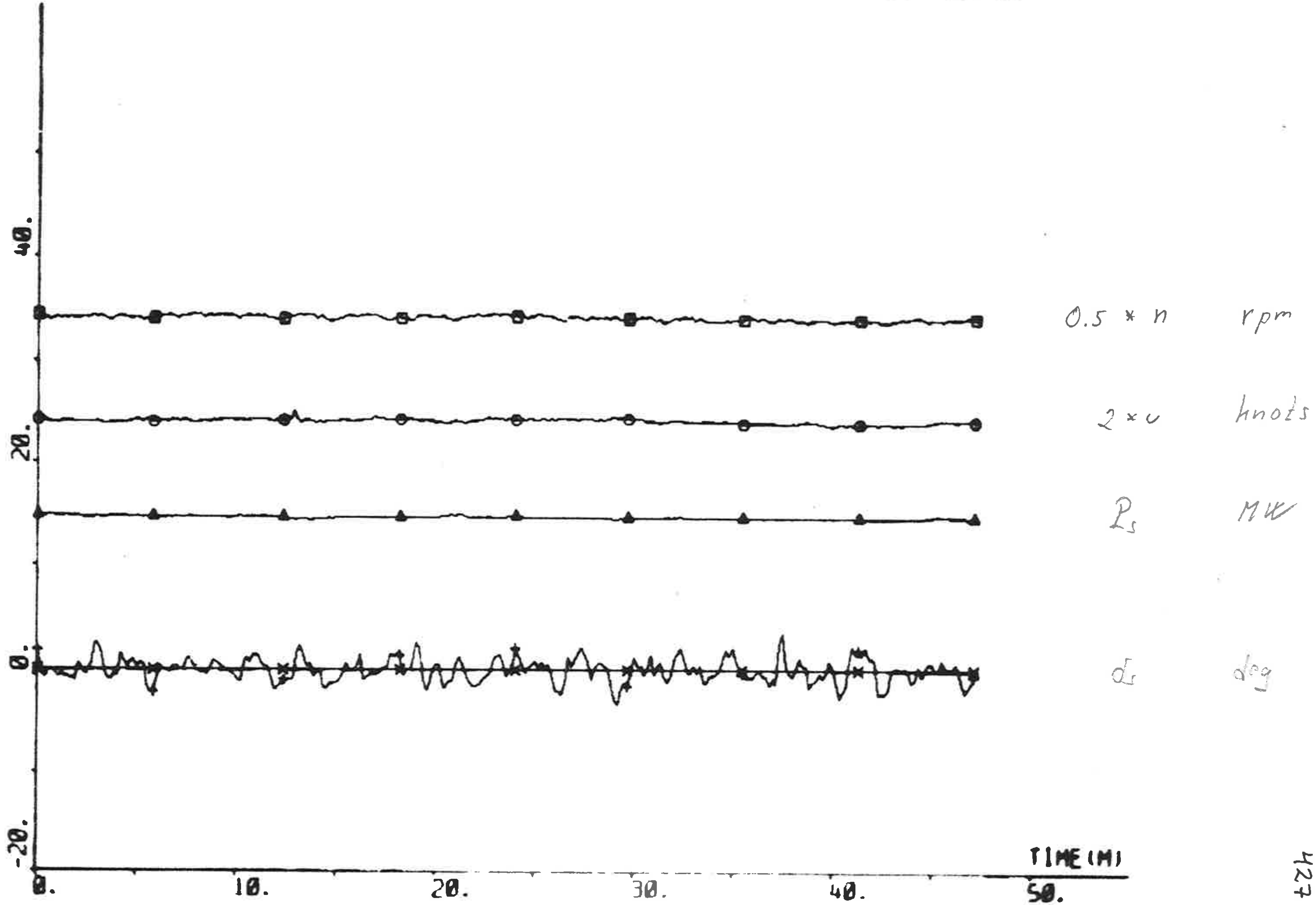
δ_c	-0.05 ± 1.08	deg		P_s	14.7 ± 0.1	MW
δ	1.48 ± 1.01	deg		ε_v	-0.01 ± 0.02	knots
$\psi-\psi_{ref}$	-0.058 ± 0.206	deg		ε_r	0.09 ± 1.49	deg/s
n	68.5 ± 0.3	rpm		ε_ψ	0.01 ± 0.05	deg
u	12.1 ± 0.1	knots		ε_δ	0.0 ± 0.4	deg

$V_1 = 0.143$

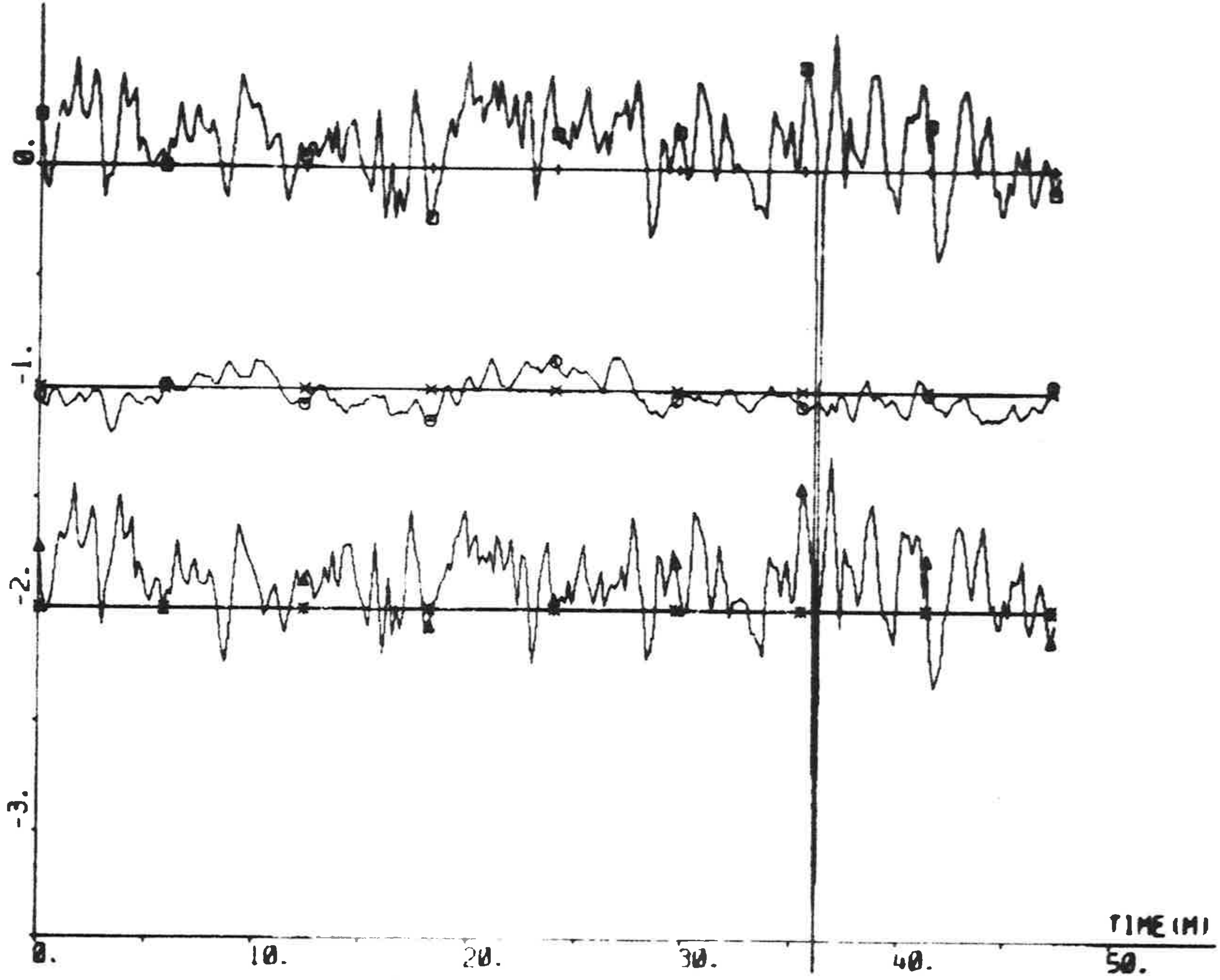


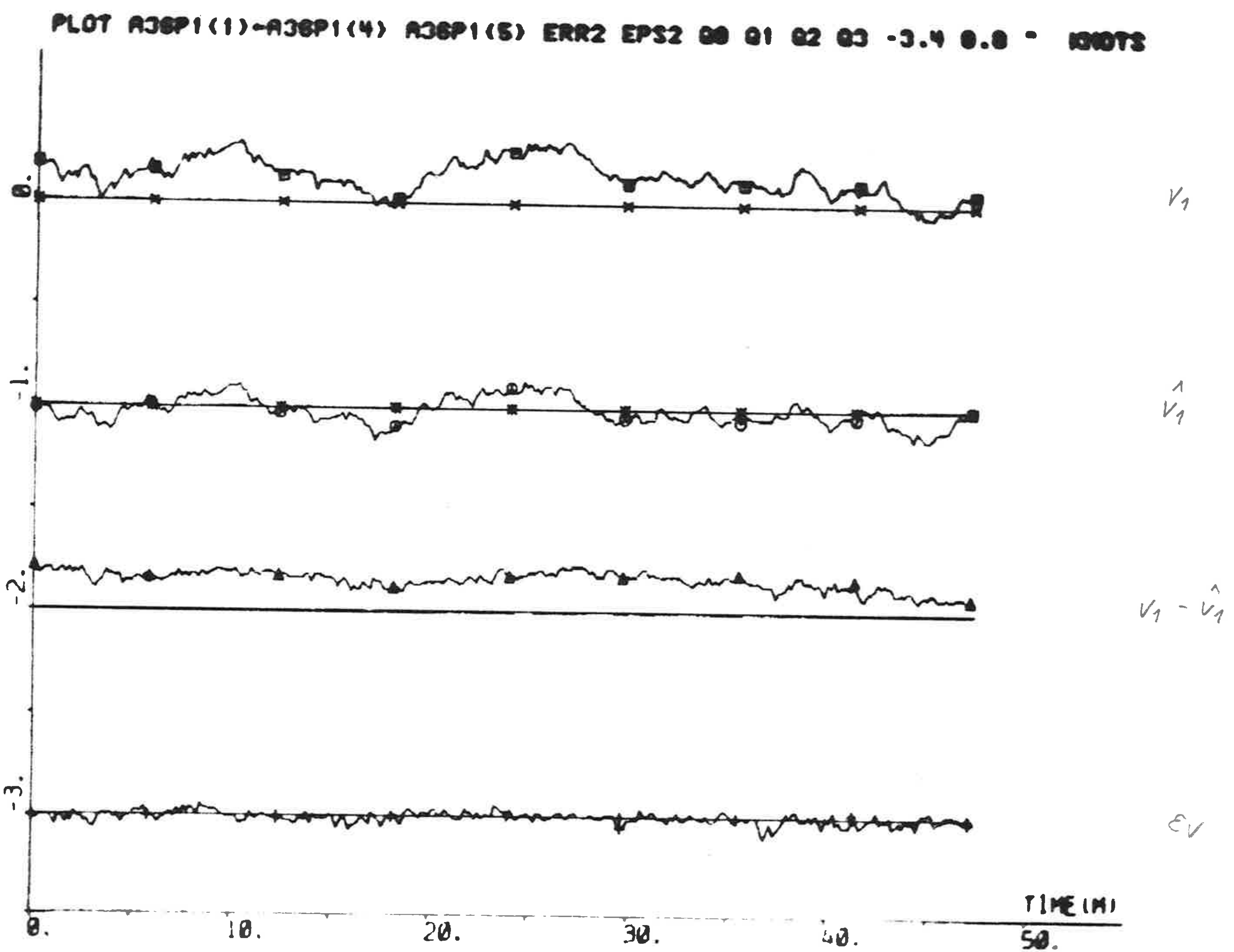
PLOT A38P1(1)-A38P1(8) HP A38P1(10) A38P1(15) 02 -3 1 ° DEG
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
$\psi - \psi_{ref}$
$0.05 * \delta_c$

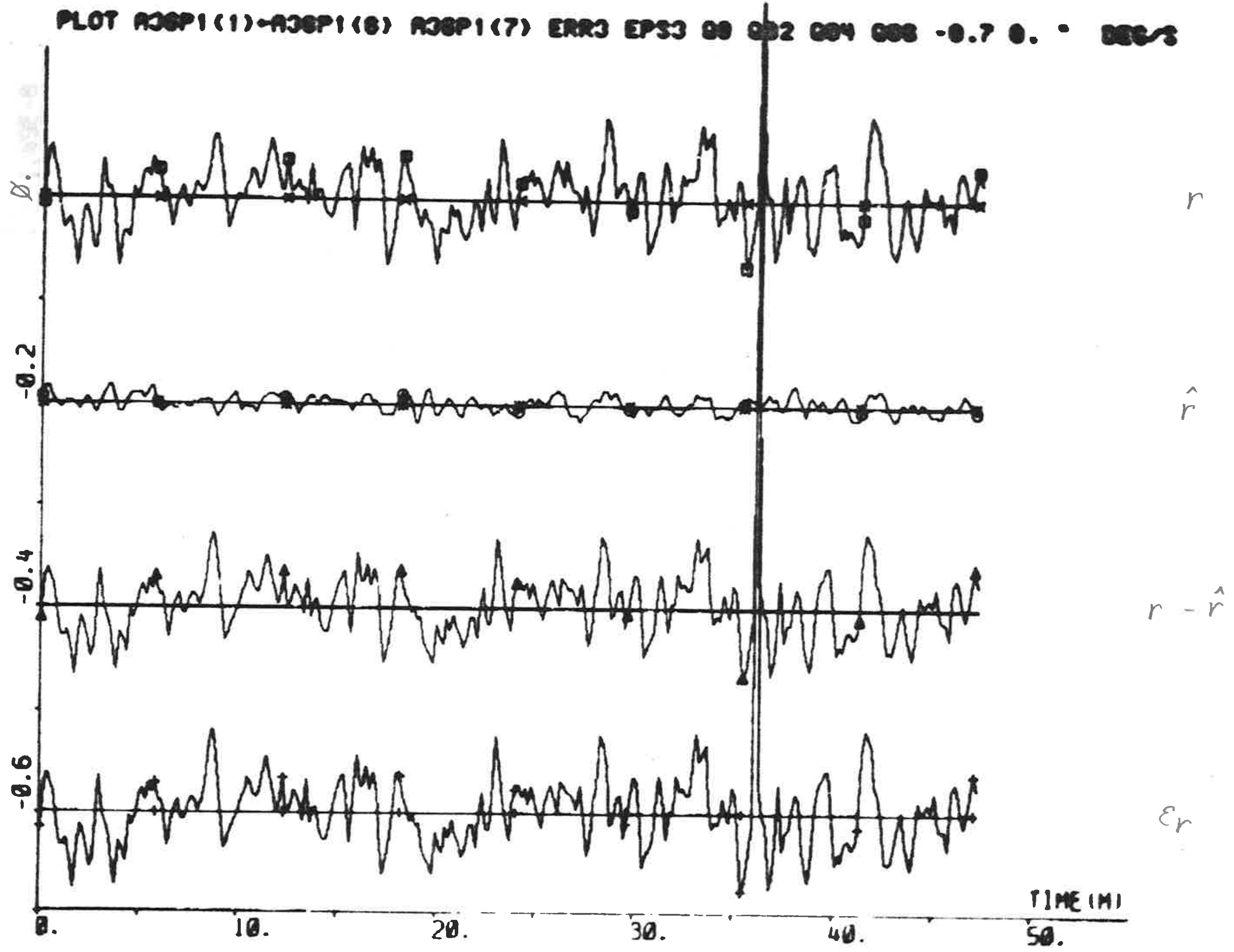
PLOT A38P1(1)-A38P1(13) A38P1(12) A38P1(14) A38P1(11) 60 -20 50

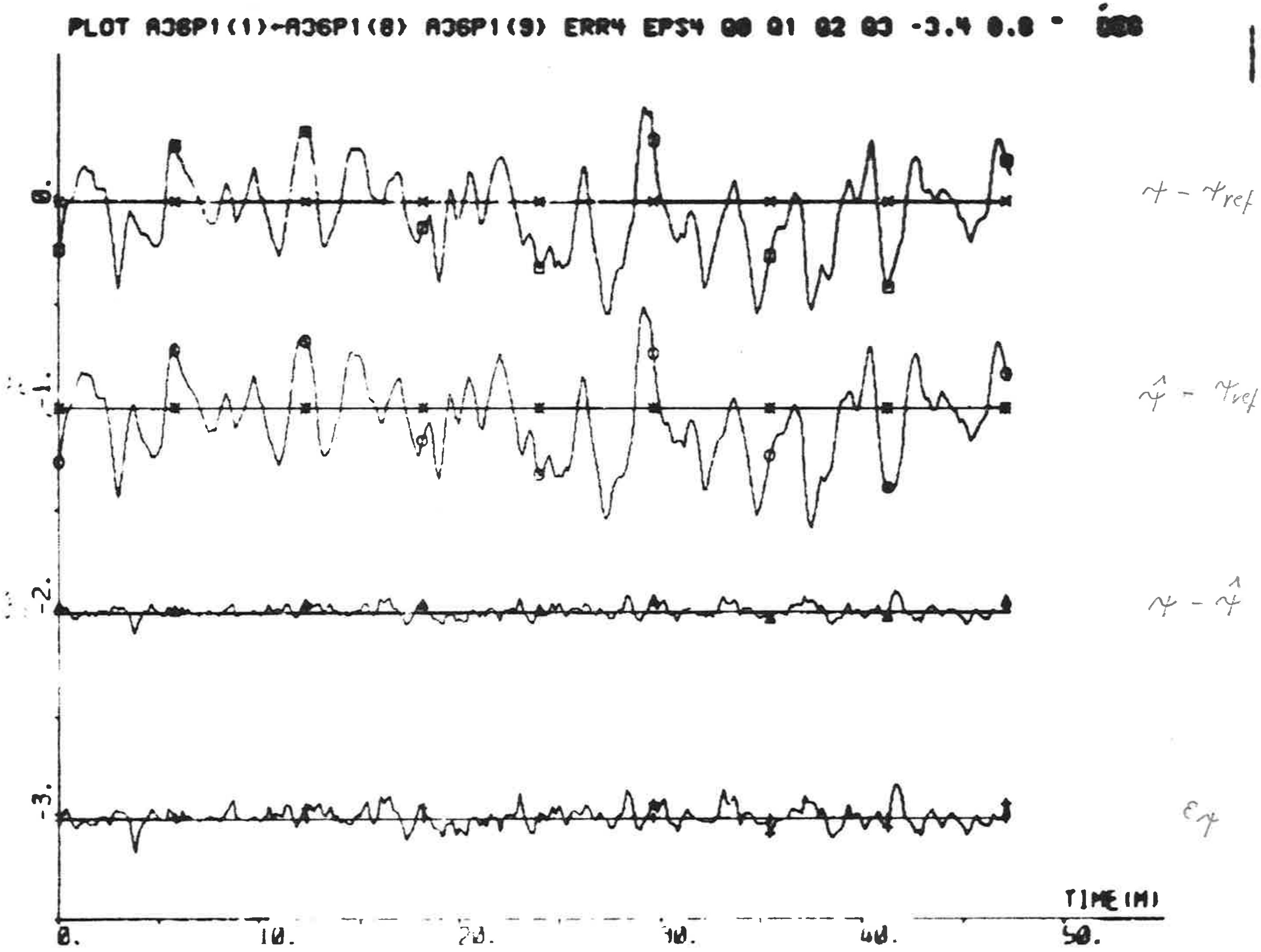


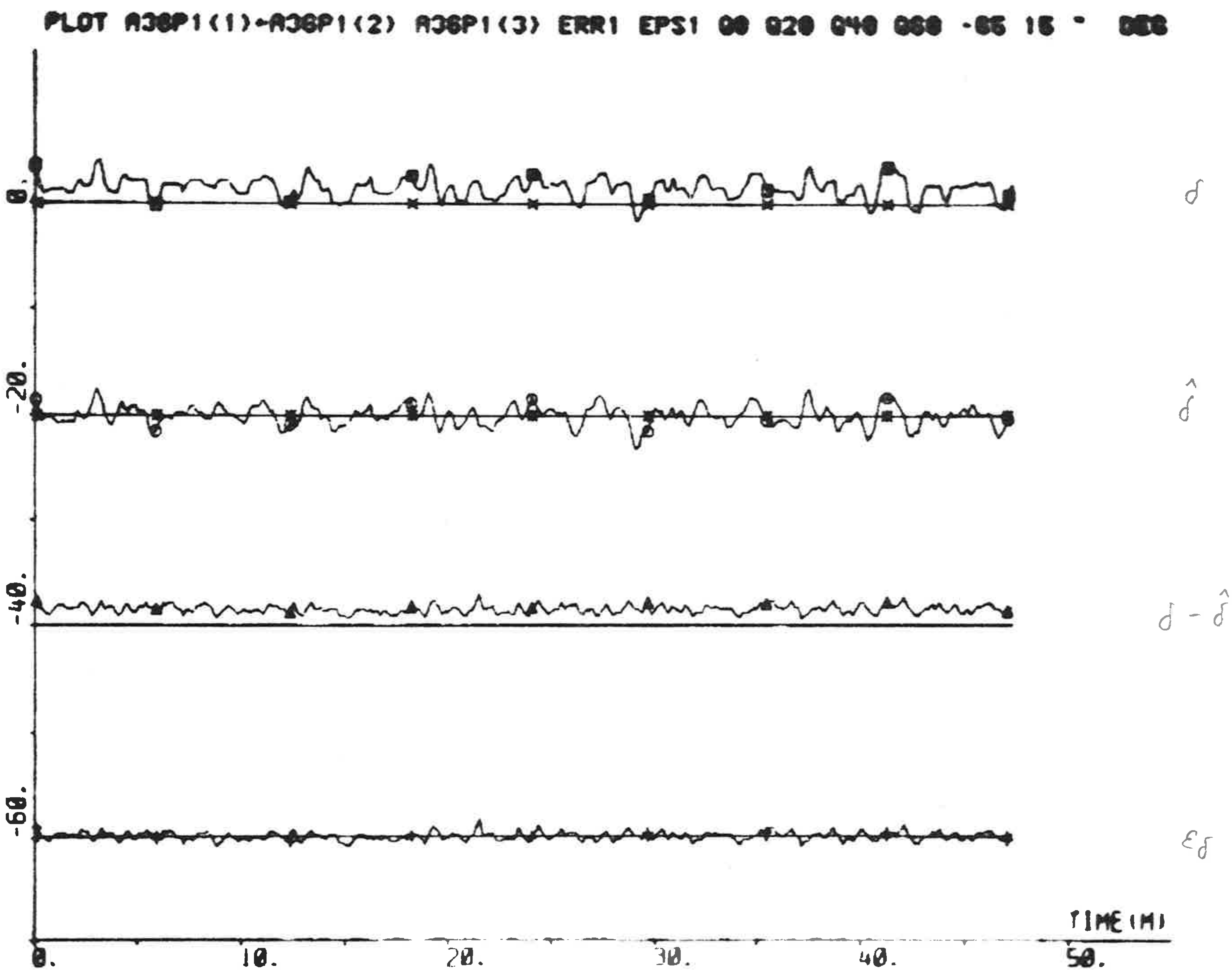
PLOT A38P1(1)-A38P2(1) A38P2(2) ERRS Q0 Q1 Q2 -3.4 0.0 - KNOTS

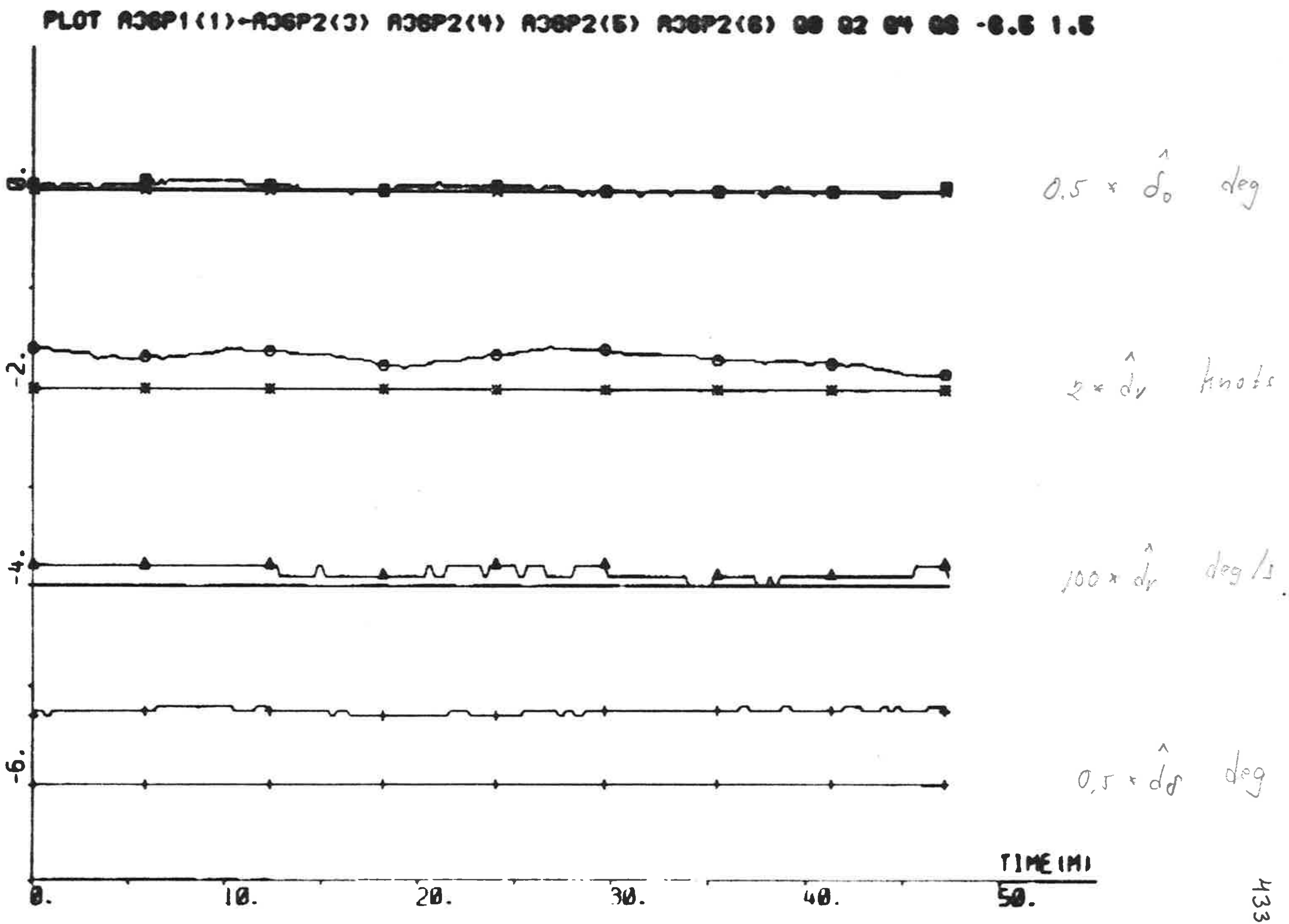



PLOT A3BP1(1)-A3BP1(4) A3BP1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.8 - KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
εV

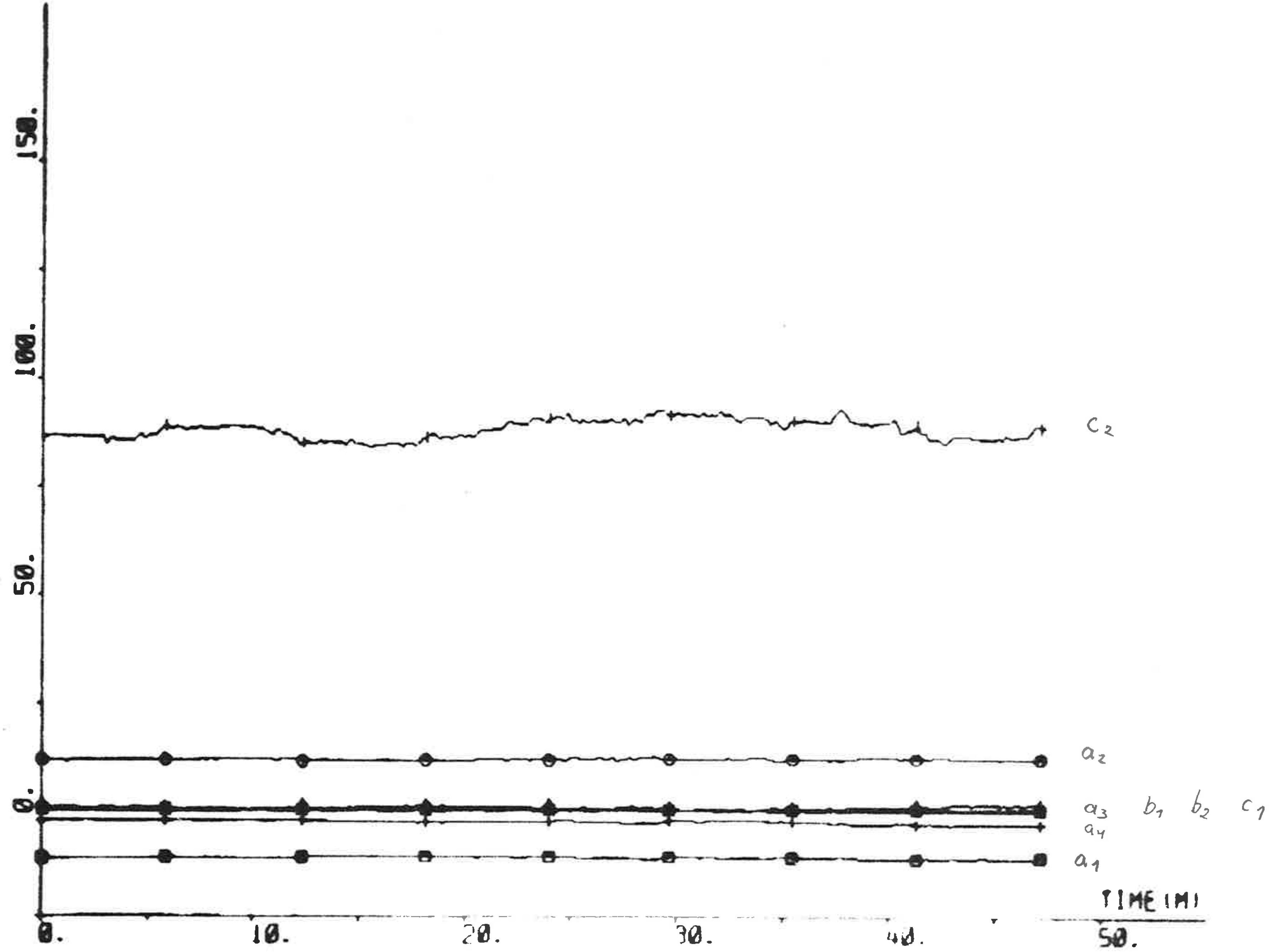

PLOT A36P1(1)-A36P1(6) A36P1(7) ERR3 EPS3 G0 G02 G04 G08 -0.7 0. * DEG/S
0.
-0.2
-0.4
-0.6
0.
10.
20.
30.
40.
50.
TIME(M)
r
r̂
r - r̂
εr


PLOT A36P1(1)-A36P1(8) A36P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.8
0.
-1.
-2.
-3.
TIME(M)
0.
10.
20.
30.
40.
50.
ψ - ψref
ψ̂ - ψref
ψ - ψ̂
εψ


PLOT A36P1(1)-A36P1(2) A36P1(3) ERR1 EPS1 00 020 040 060 -05 15 " 008
0.
-20.
-40.
-60.
0.
10.
20.
30.
40.
50.
TIME(M)
δ
δ̂
δ - δ̂
εδ


PLOT A36P1(1)-A36P2(3) A36P2(4) A36P2(5) A36P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)
0.5 * $\hat{\delta}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0,5 * $\hat{d}_\delta$ deg

PLOT A38P1(1)-A38P2(7) A38P2(8) A38P2(9) A38P2(10) A38P2(11) A38P2(12) A3



EXPERIMENT B1

Date	1976-04-26	Forward draught	10.9 m
Time	20.13	Aft draught	12.9 m
Duration	26 min	Wind direction	SE (1; see App. A)
Position	S 07°28' W 05°32'	Wind velocity	6 m/s (moderate breeze)
ψ_{ref}	142, 143, 142 deg	Wave height	-

The data were punched on paper tape every second. A yaw rate estimate is computed every second by the difference approximation

$$\hat{r}_d(t) = \frac{\psi(t) - \psi(t-5)}{5}$$

Final values:

$\hat{\delta}_0 = -0.1$ deg $\quad \hat{d}_v = 0.12$ knots $\quad \hat{d}_r = 0.002$ deg/s $\quad \hat{d}_\delta = 1.7$ deg

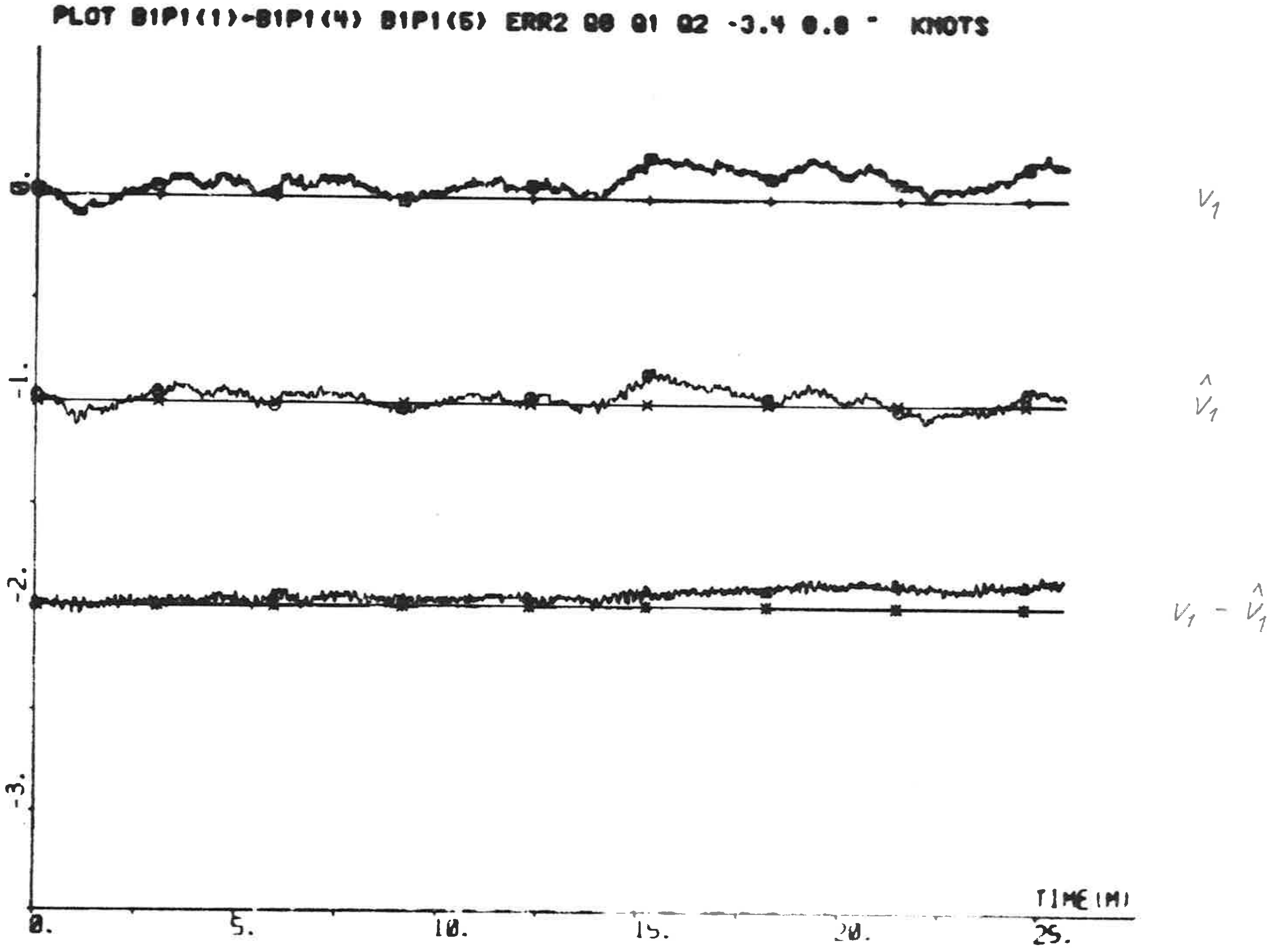
Statistics (mean value and standard deviation)

r	0.002 ± 0.022 deg/s
$\hat{r}$	0.000 ± 0.009 deg/s
$\hat{r}_d$	0.000 ± 0.014 deg/s

$n \approx 69.2$ rpm

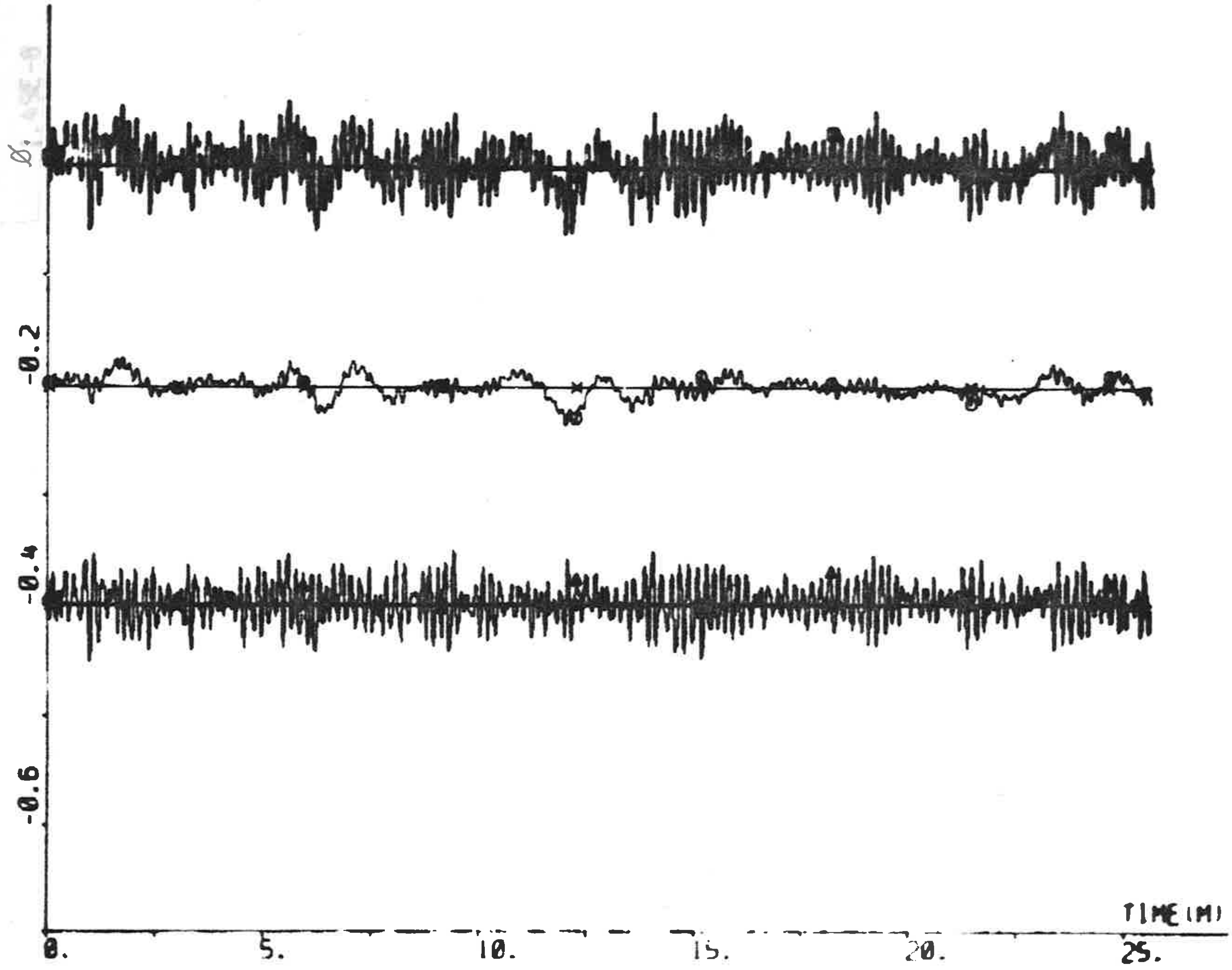
$u \approx 13.7$ knots

$P_s \approx 14.9$ MW

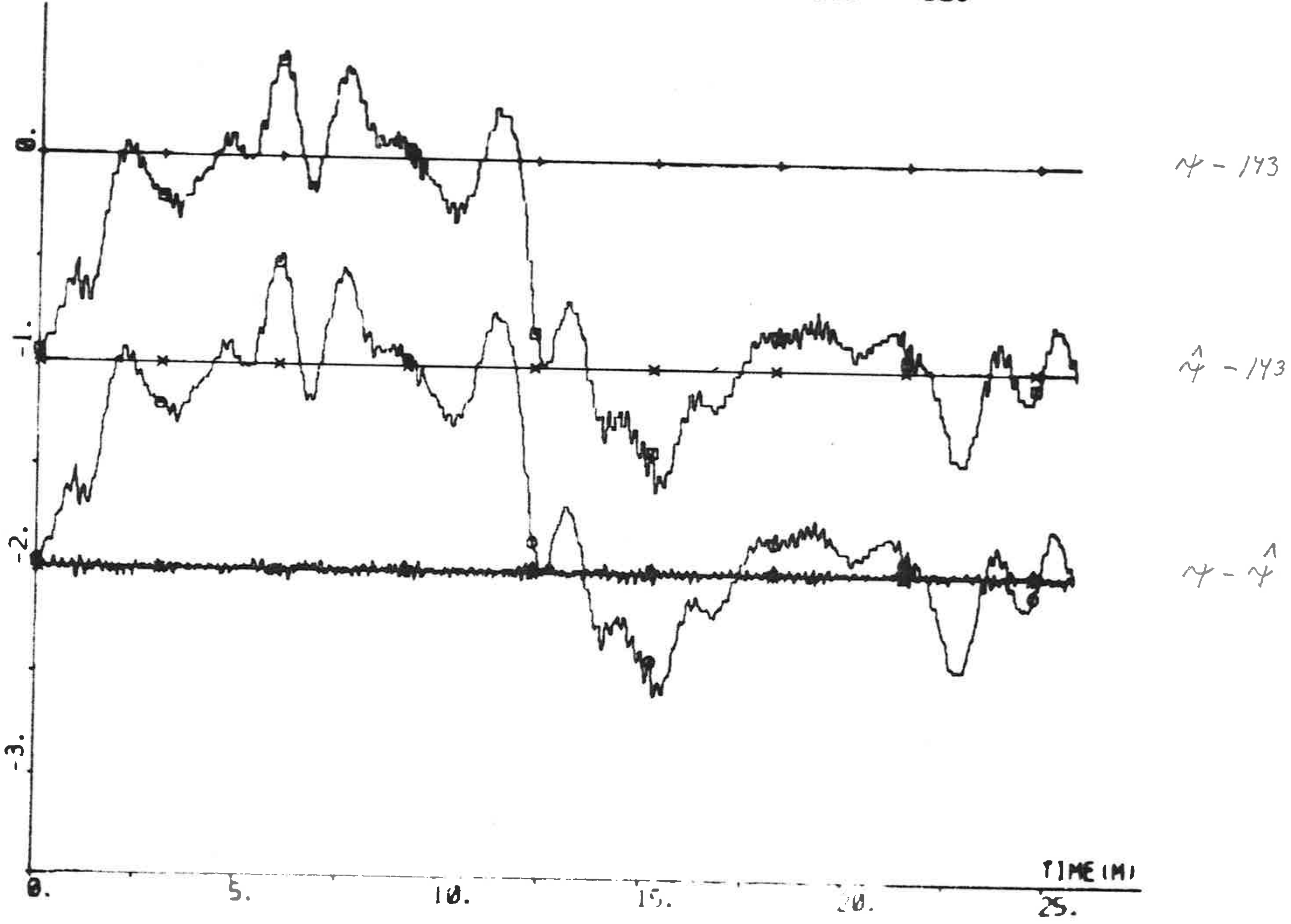


PLOT B1P1(1)-B1P1(4) B1P1(5) ERR2 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$

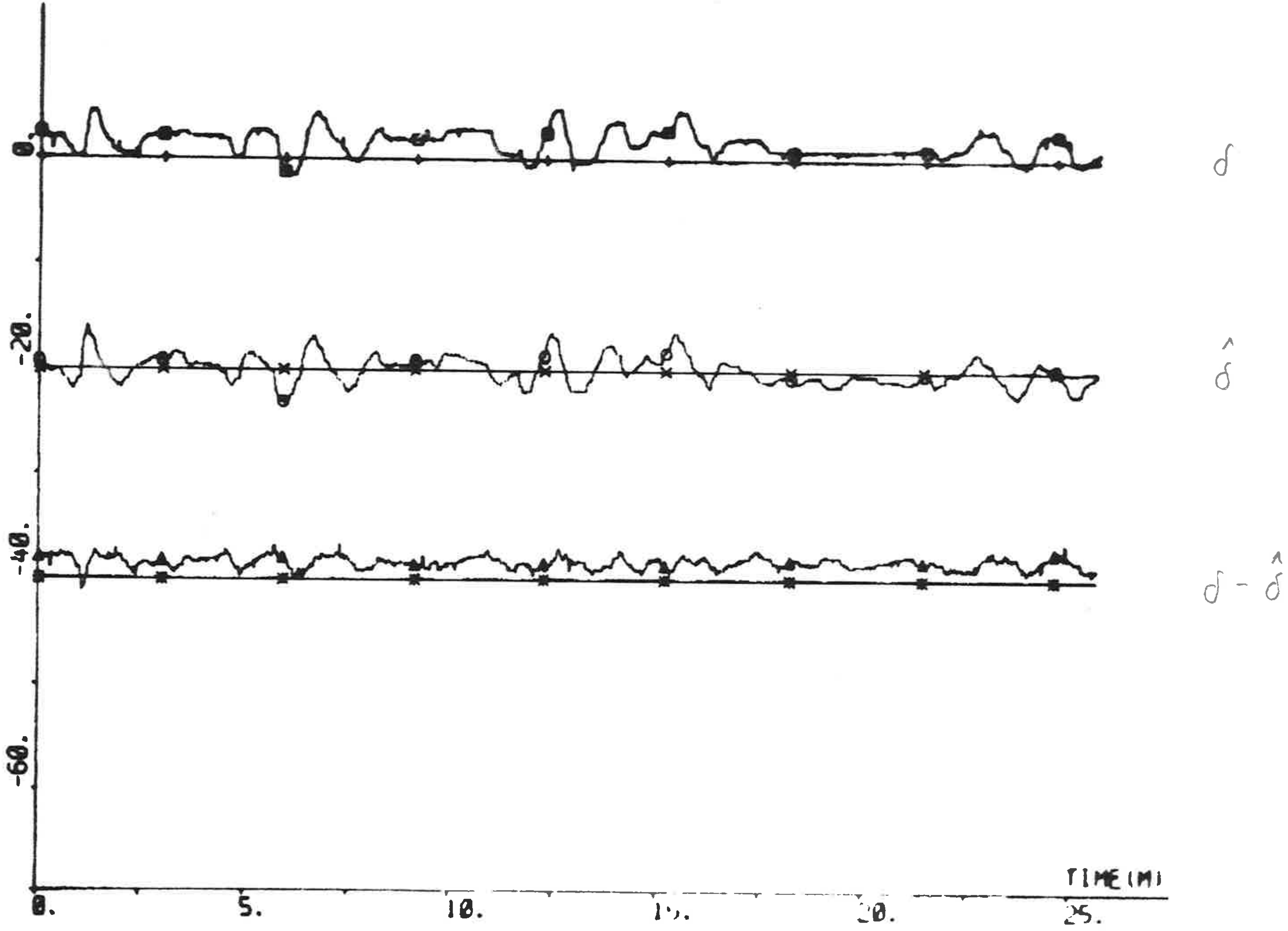
PLOT B1P1(1)-B1P1(6) B1P1(7) ERR3 00 002 004 -0.7 0. DEG/S



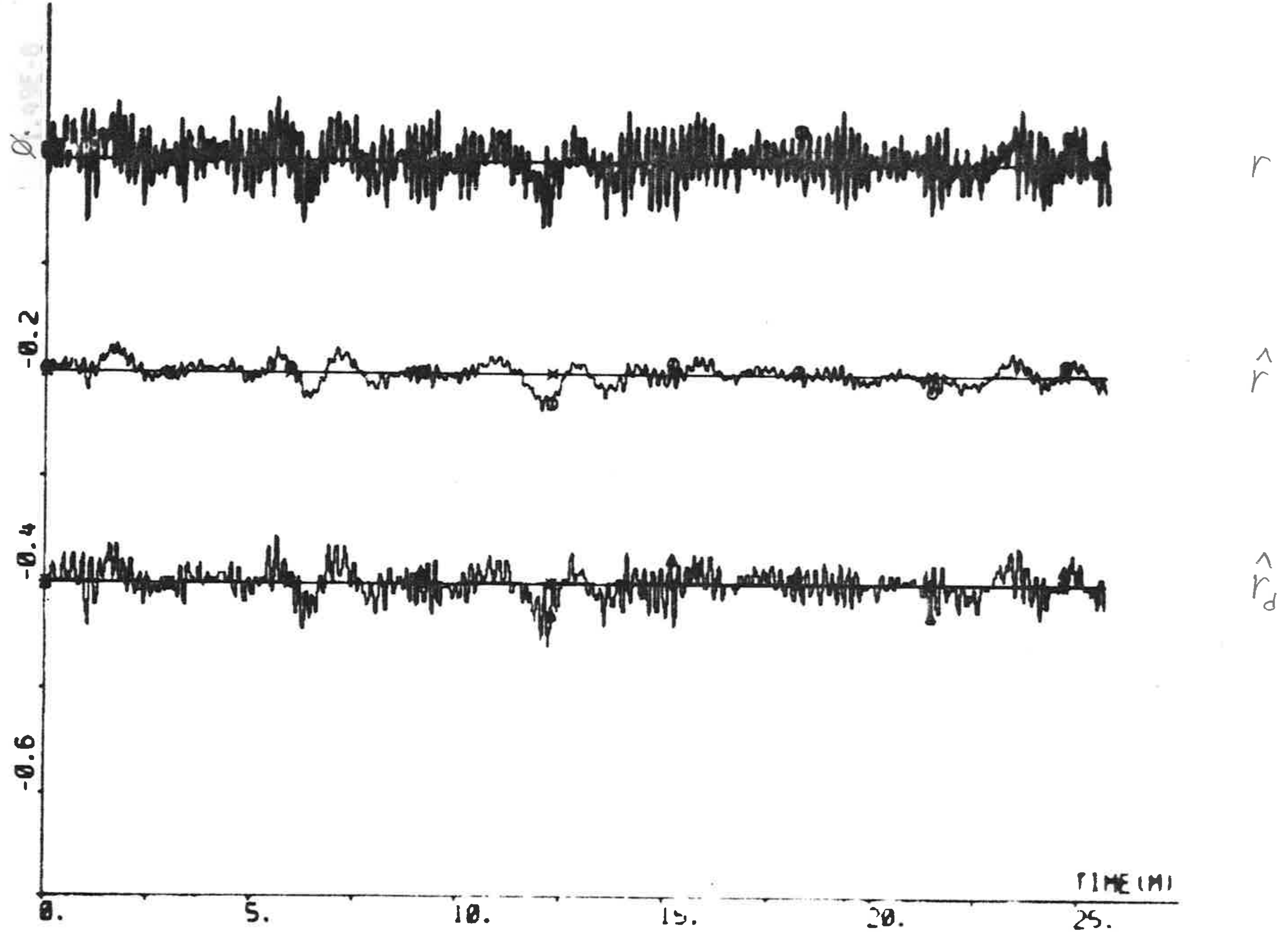
PLOT B1P1(1)-B1P1(8) B1P1(9) ERR4 00 01 02 -3.4 0.0 - DEG



PLOT B1P1(1)-B1P1(2) B1P1(3) ERR1 Q0 Q20 Q40 -65 15 - DEG



PLOT B1P1(1)-B1P1(6) B1P1(7) DPSI 00 002 004 -0.7 0. - DEG/S



EXPERIMENT B2

Date	1976-04-27	Forward draught	10.9 m
Time	08.48	Aft draught	12.9 m
Duration	25 min	Wind direction	SE (1; see App. A)
Position	S 09°31' W 03°57'	Wind velocity	8 m/s (moderate breeze)
ψ_{ref}	145 deg	Wave height	-

The data were punched on paper tape every second. A yaw rate estimate is computed every second by the difference approximation

$$\hat{r}_d(t) = \frac{\psi(t) - \psi(t-5)}{5}$$

Final values:

$\hat{\delta}_0 = -0.4$ deg $\hat{d}_v = 0.06$ knots $\hat{d}_r = 0.002$ deg/s $\hat{d}_\delta = 1.6$ deg

Statistics (mean value and standard deviation)

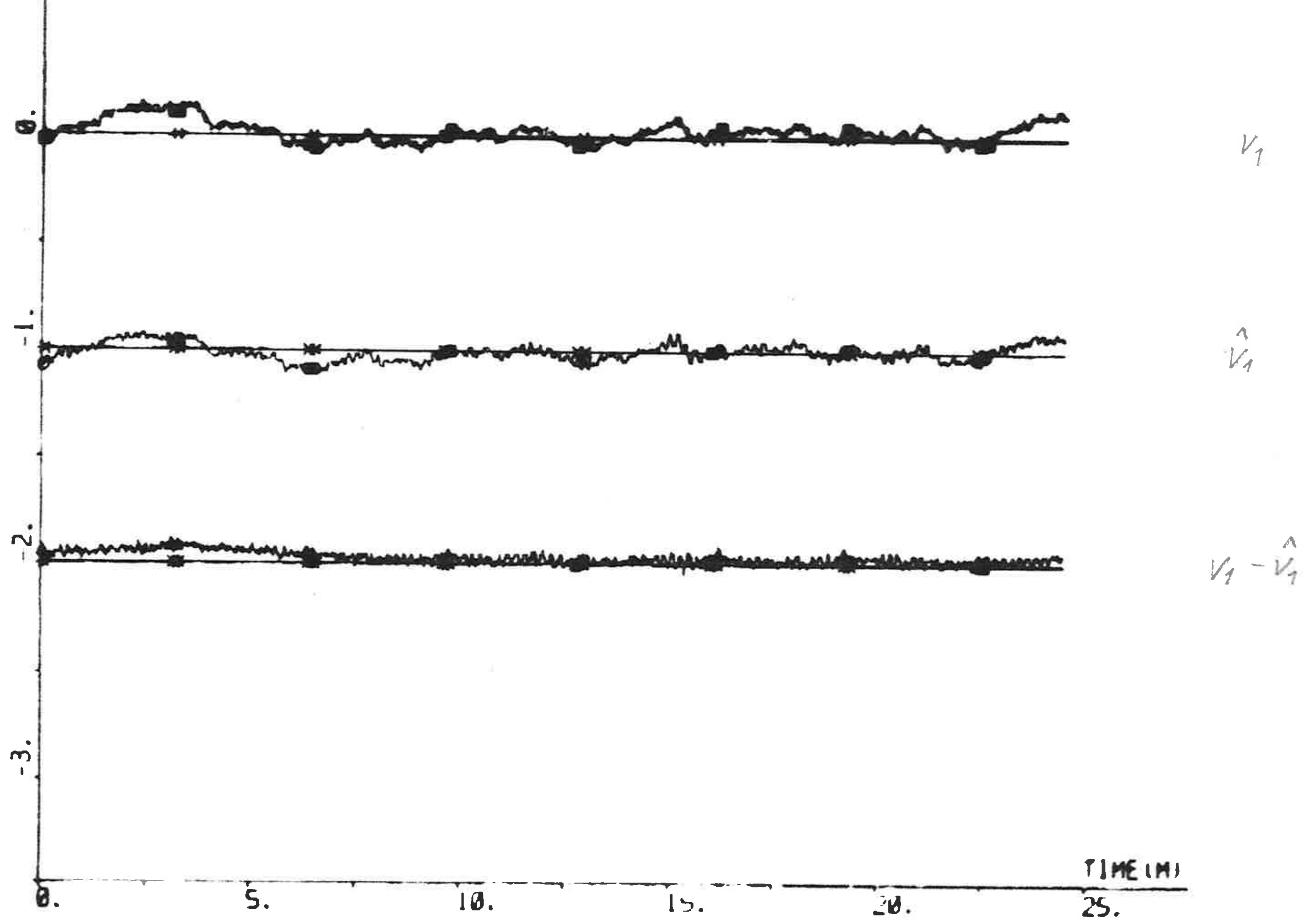
r	0.003 ± 0.023 deg/s
$\hat{r}$	0.000 ± 0.007 deg/s
$\hat{r}_d$	0.000 ± 0.014 deg/s

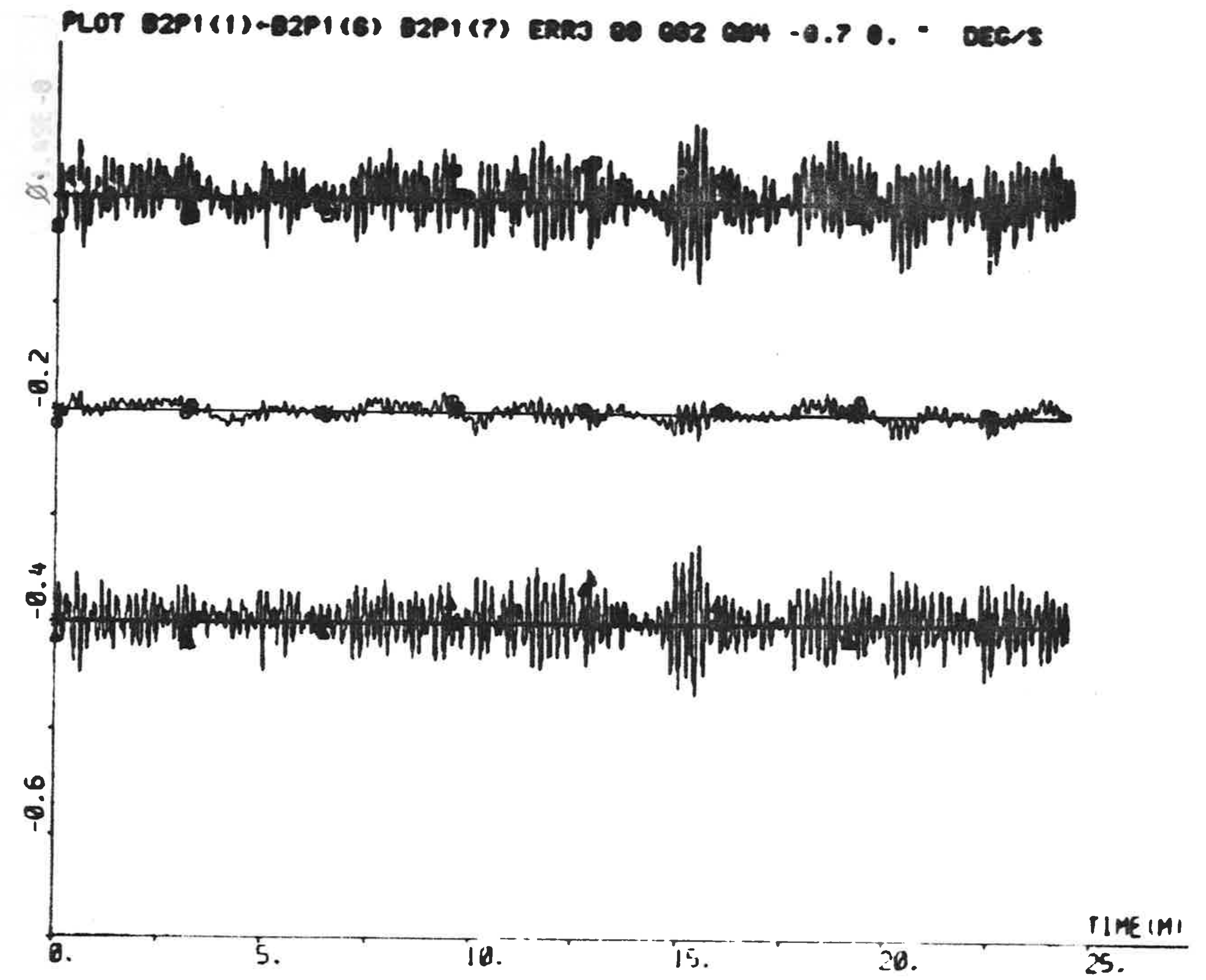
$n \approx 70.1$ rpm

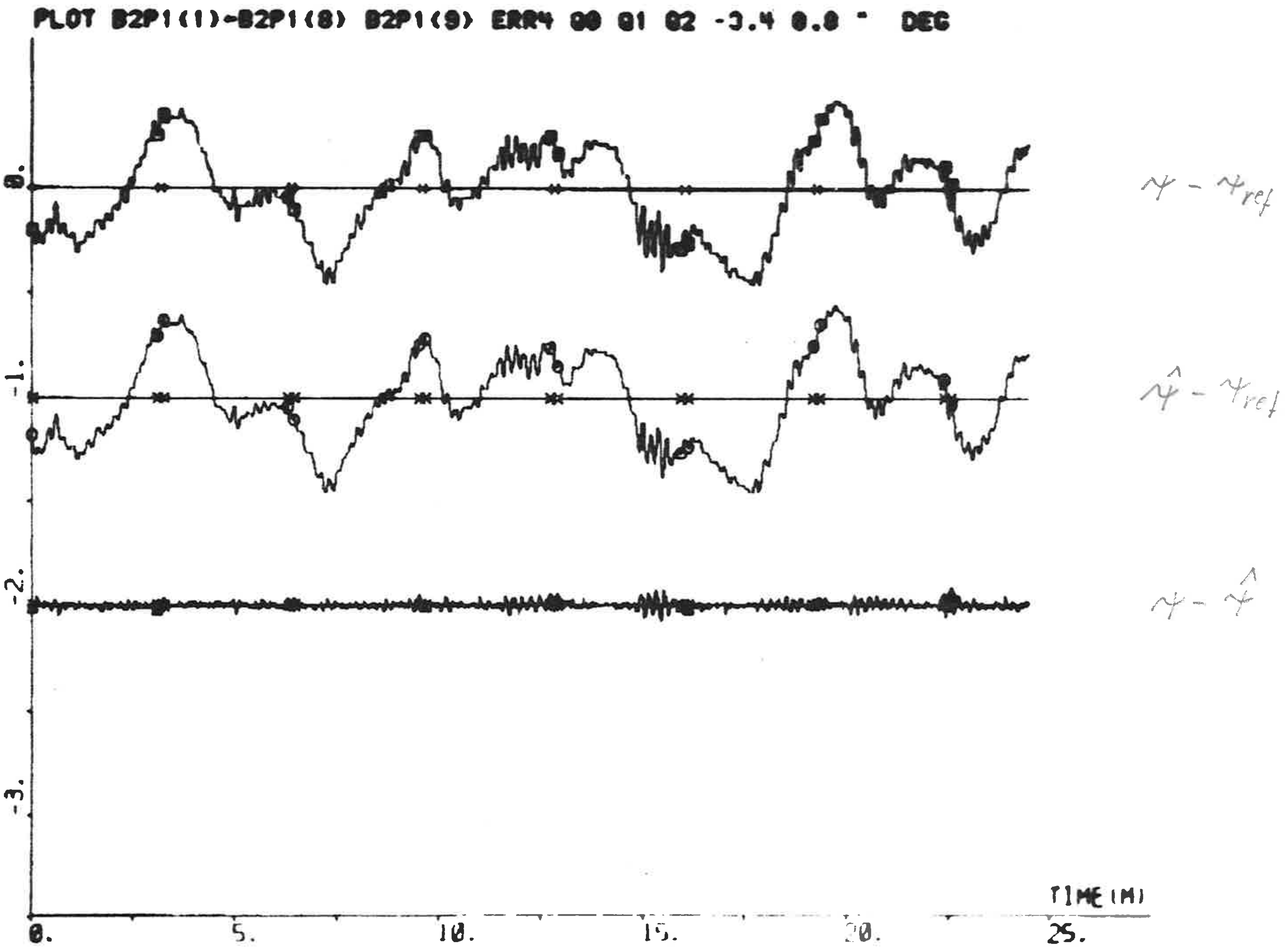
$u \approx 13.3$ knots

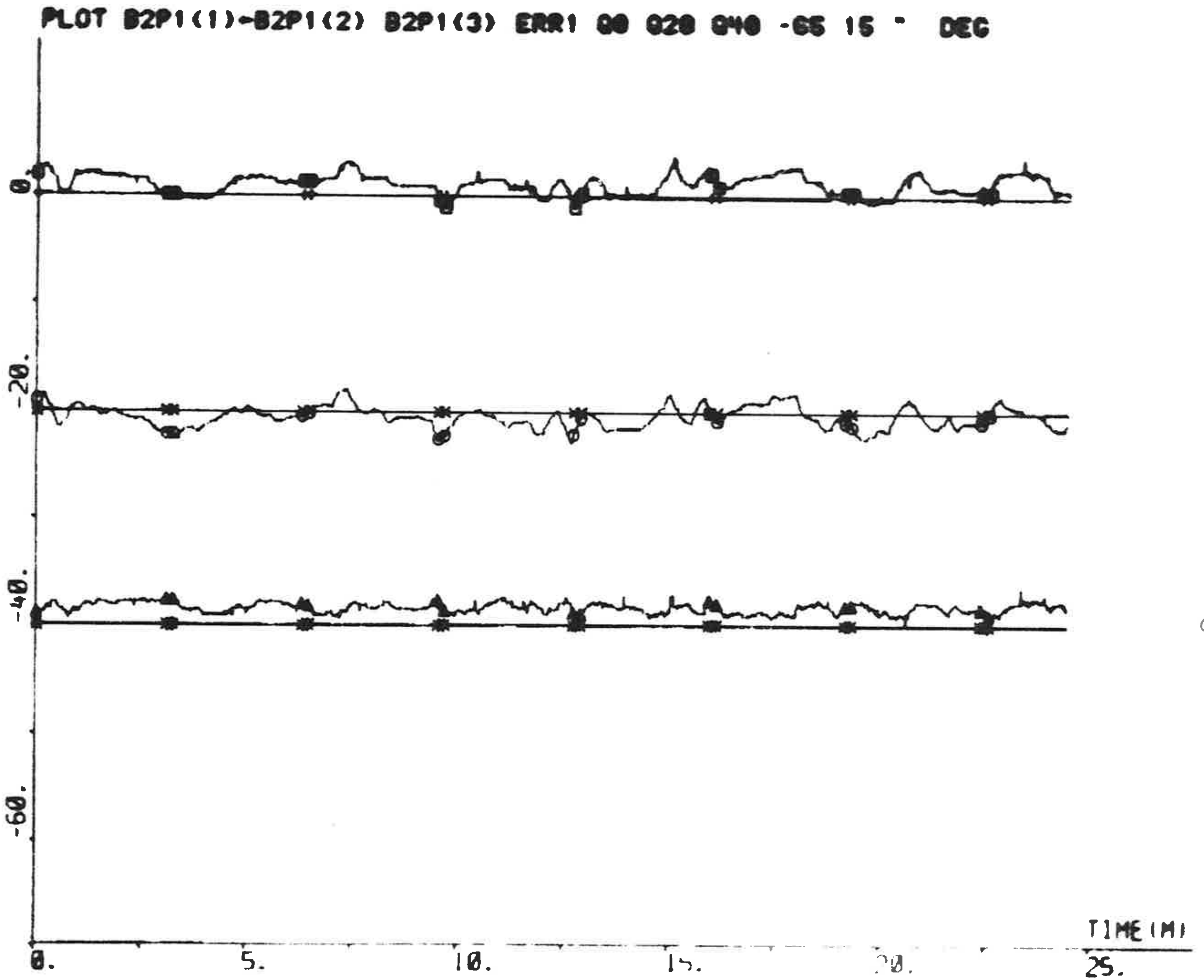
$P_s \approx 15.2$ MW

PLOT B2P1(1)-B2P1(4) B2P1(5) ERR2 00 01 02 -3.4 0.0 - KNOTS



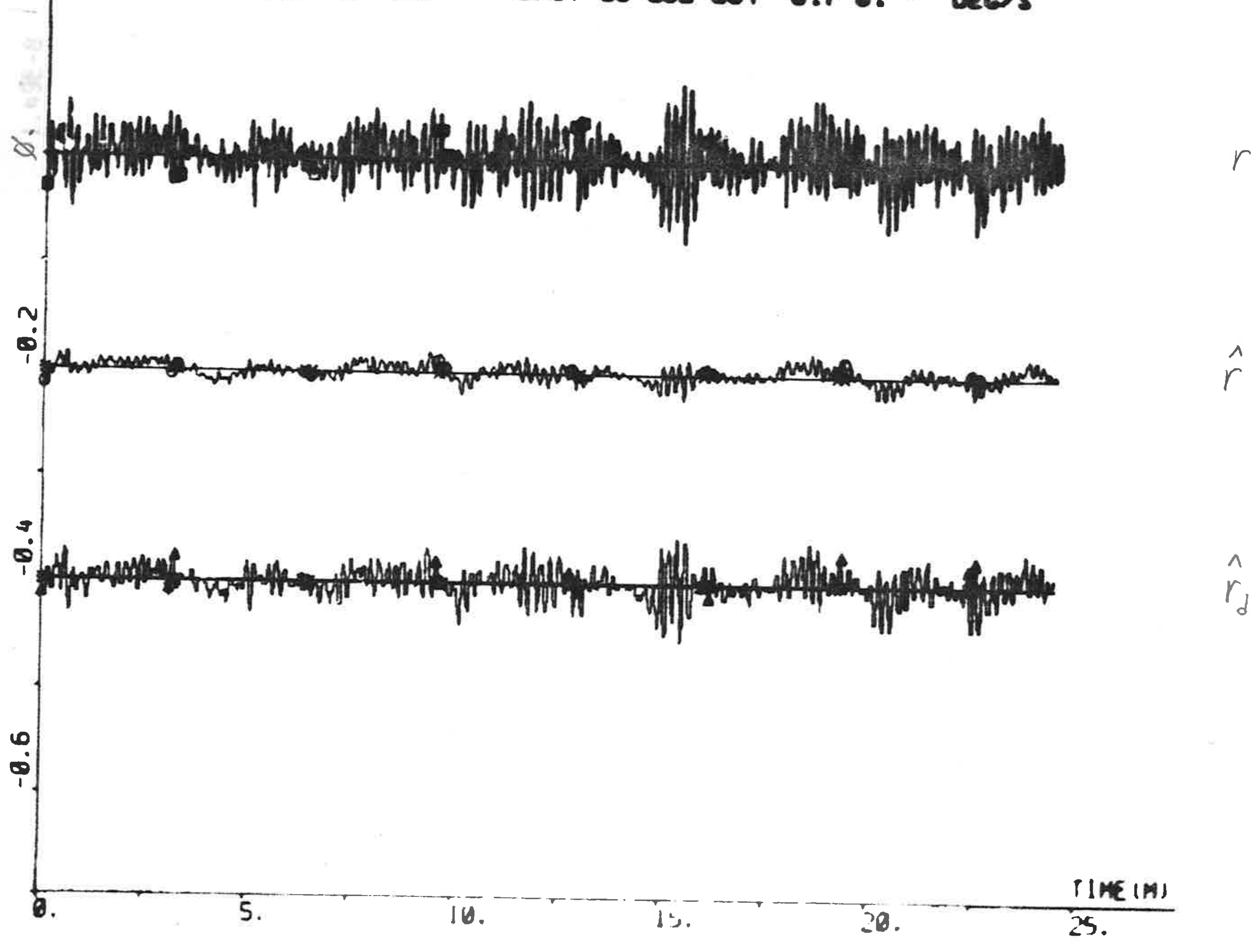

PLOT B2P1(1)-B2P1(6) B2P1(7) ERR3 00 002 004 -0.7 0. - DEG/S
Ø
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂


PLOT B2P1(1)-B2P1(8) B2P1(9) ERR4 00 01 02 -3.4 0.0 " DEG
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.
$\psi - \psi_{ref}$
$\hat{\psi} - \psi_{ref}$
$\psi - \hat{\psi}$



PLOT B2P1(1)-B2P1(2) B2P1(3) ERR1 00 020 040 -65 15 " DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
$\hat{\delta}$
$\delta - \hat{\delta}$

PLOT B2P1(1)-B2P1(8) B2P1(7) DPSI 00 002 004 -0.7 0. " DEG/S



EXPERIMENT B3

Date	1976-04-29	Forward draught	10.9 m
Time	12.59	Aft draught	12.9 m
Duration	26 min	Wind direction	SE (1; see App. A)
Position	S 18°07' E 04°58'	Wind velocity	15 m/s (moderate gale)
ψ_{ref}	145 deg	Wave height	High sea from SE

The data were punched on paper tape every second. A yaw rate estimate is computed every second by the difference approximation

$$\hat{r}_d(t) = \frac{\psi(t) - \psi(t-5)}{5}$$

Final values:

$\hat{\delta}_0 = -0.3$ deg $\hat{d}_v = 0.15$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.4$ deg

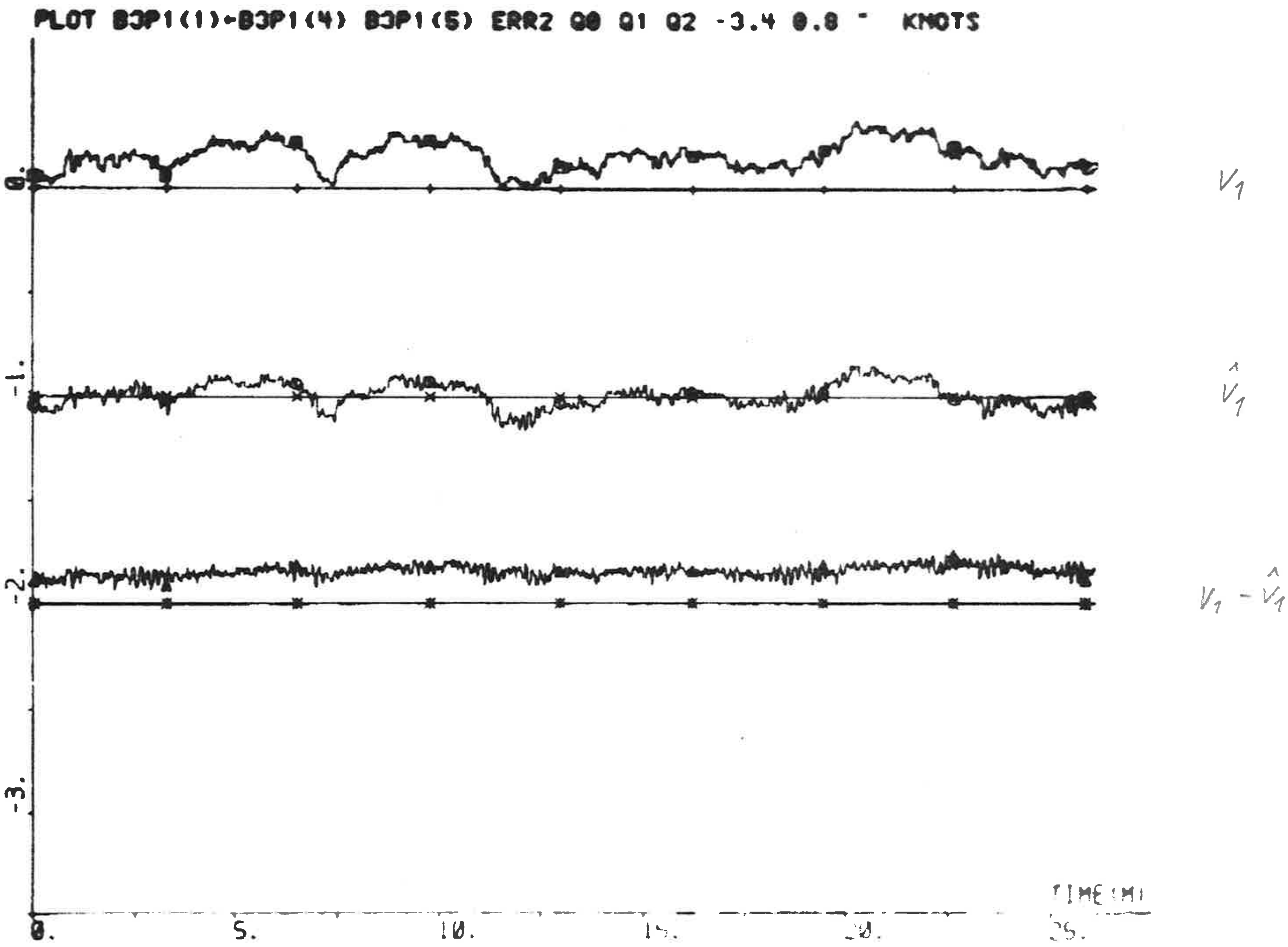
Statistics (mean value and standard deviation)

r	0.001 ± 0.034 deg/s
$\hat{r}$	0.000 ± 0.011 deg/s
$\hat{r}_d$	0.000 ± 0.021 deg/s

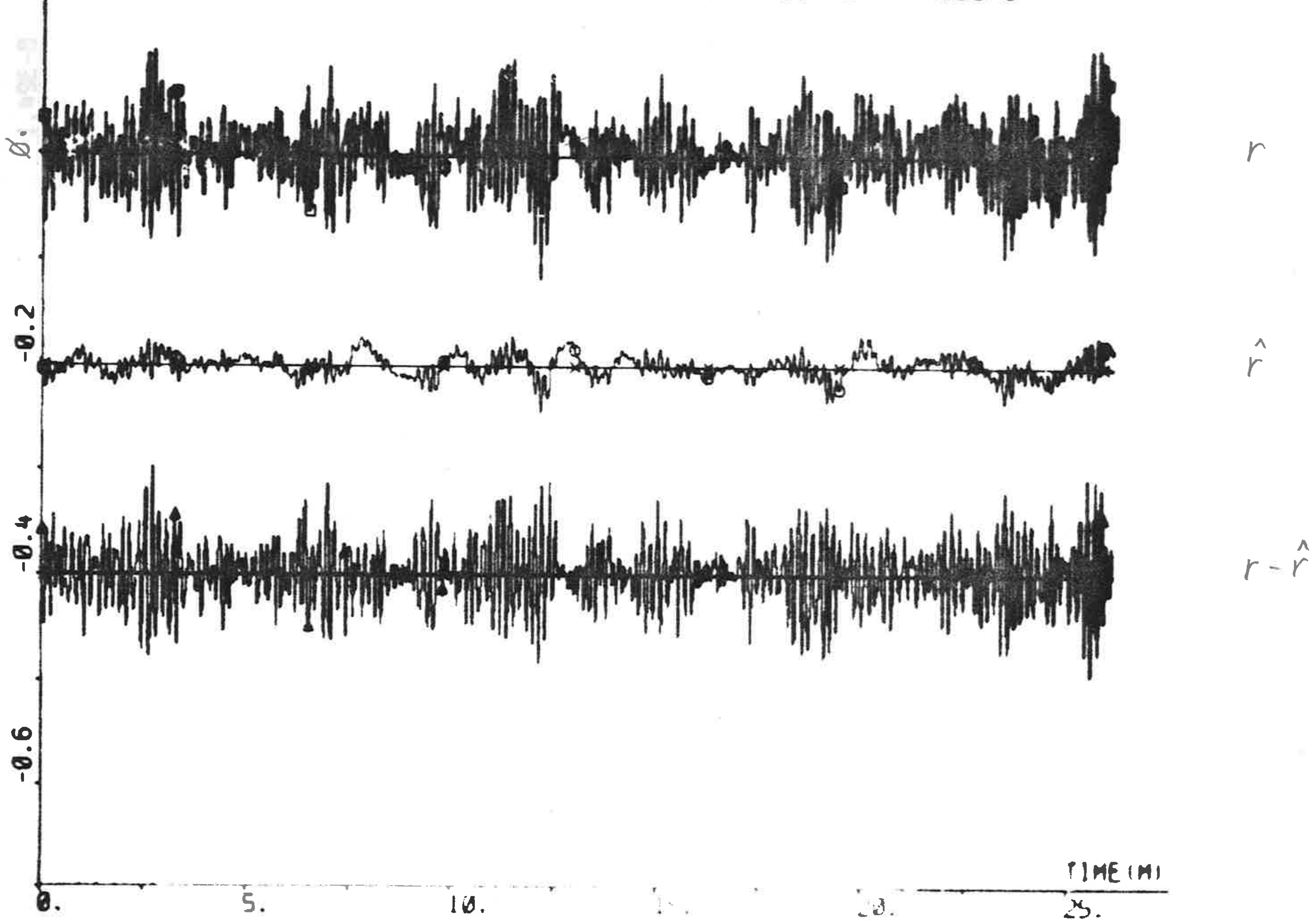
$n \approx 87.4$ rpm

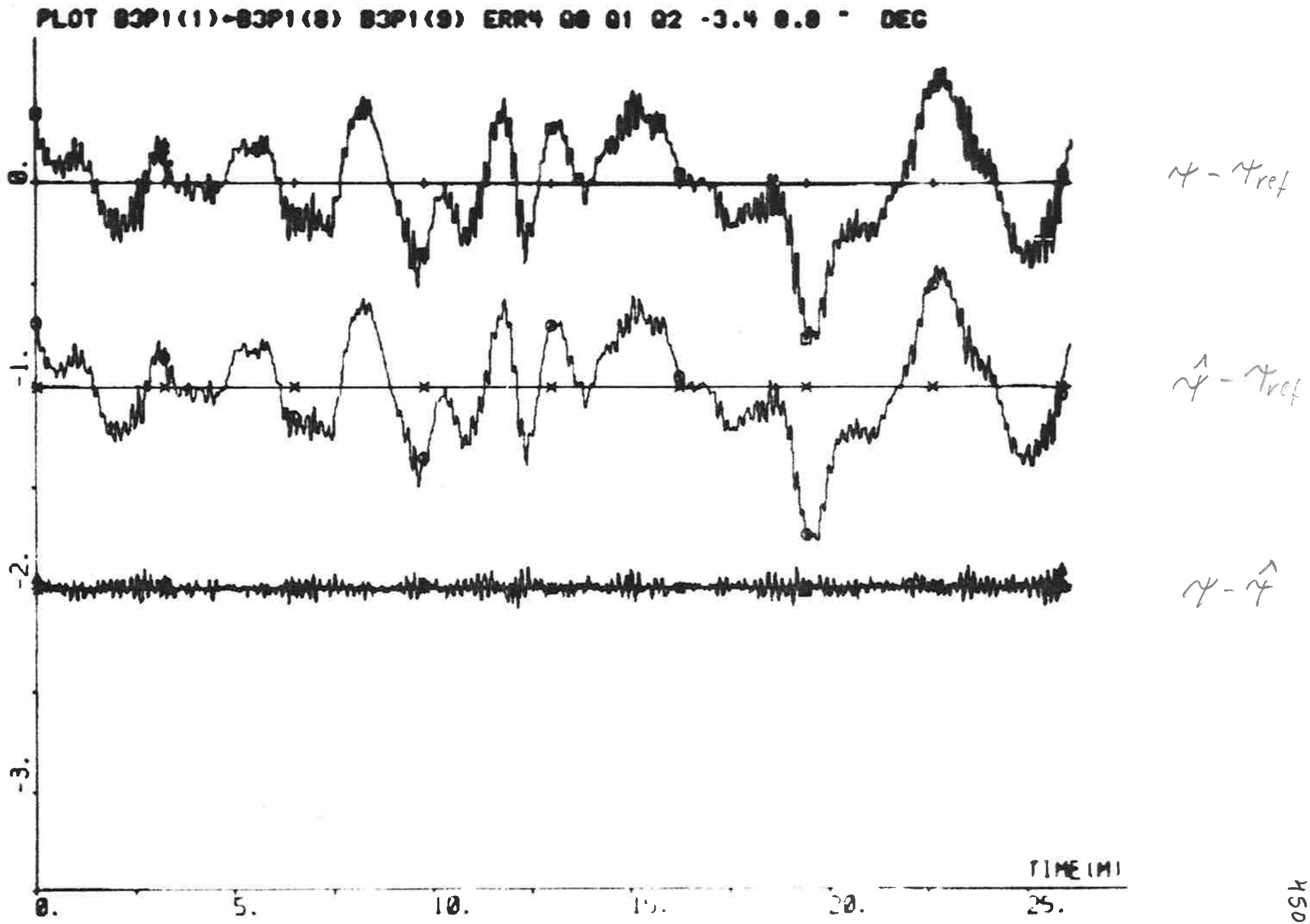
$u \approx 15.9$ knots

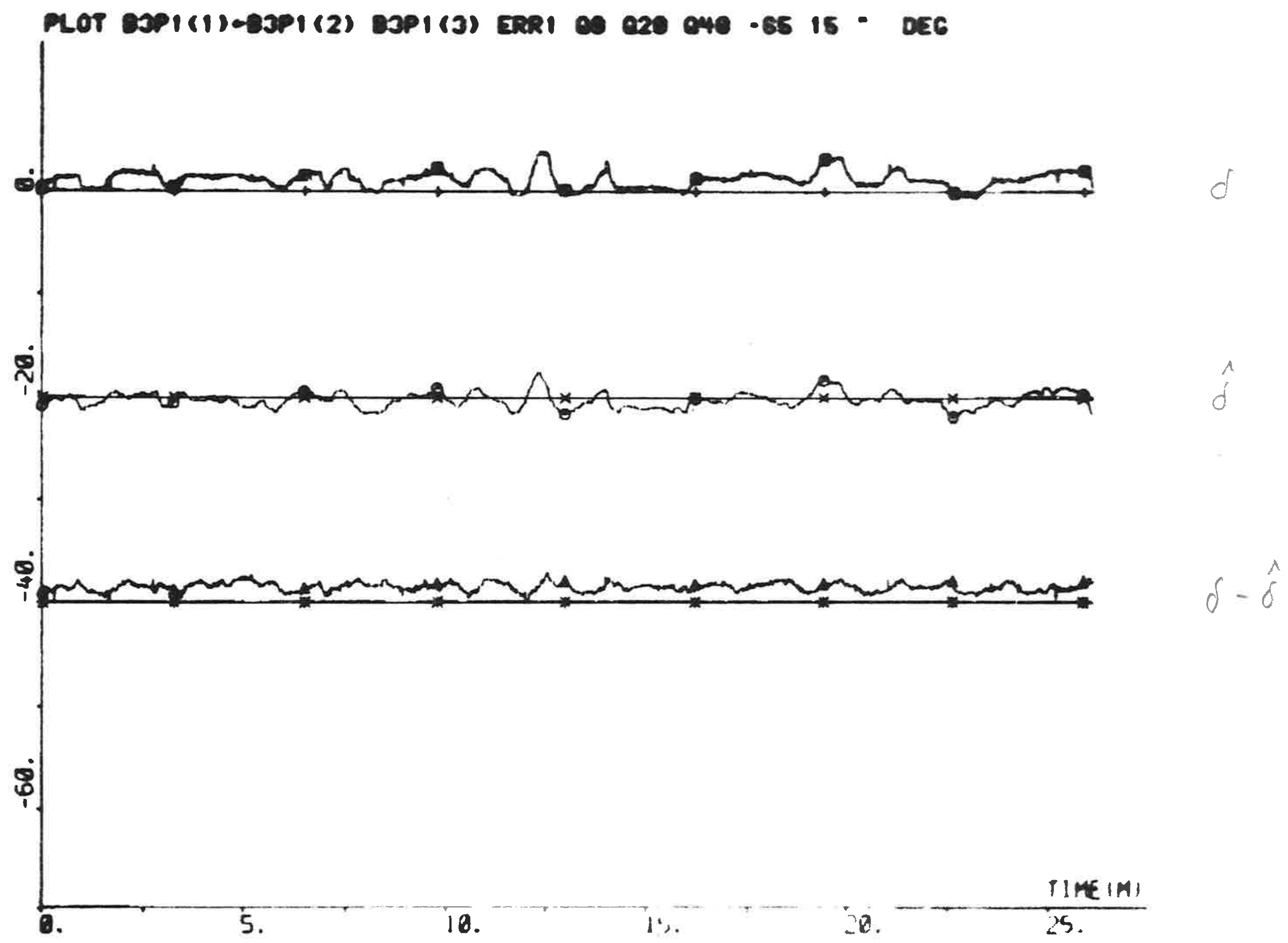
$P_s \approx 29.5$ MW

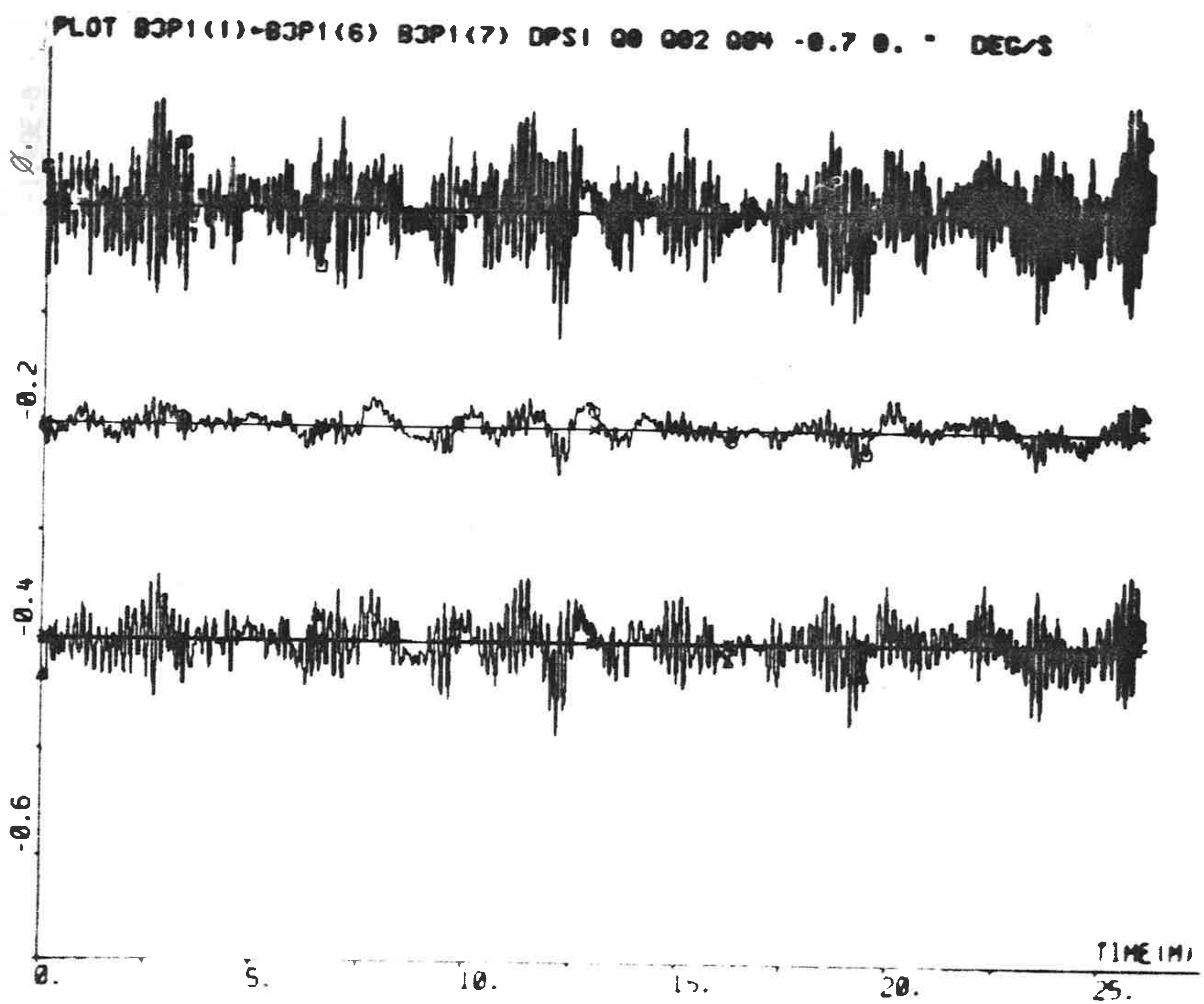

PLOT B3P1(1)-B3P1(4) B3P1(5) ERR2 Q0 Q1 Q2 -3.4 0.8 - KNOTS
0.
-1.
-2.
-3.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
TIME(M)
0.
5.
10.
20.

PLOT B3P1(1)-B3P1(6) B3P1(7) ERR3 00 002 004 -0.7 0. - DEG/S




PLOT B3P1(1)-B3P1(8) B3P1(9) ERR4 Q0 Q1 Q2 -3.4 0.0 " DEG
0.
-1.
-2.
-3.
0.
5.
10.
20.
25.
TIME(M)
$\psi - \psi_{ref}$
$\hat{\psi} - \psi_{ref}$
$\psi - \hat{\psi}$


PLOT B3P1(1)-B3P1(2) B3P1(3) ERR1 Q0 Q20 Q40 -65 15 - DEC
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂


PLOT B3P1(1)-B3P1(6) B3P1(7) DPSI 00 002 004 -0.7 0. " DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r̂d
0.
5.
10.
15.
20.
25.
TIME(M)

EXPERIMENT C1

Date	1976-04-20	Forward draught	9.0 m
Time	22.11	Aft draught	12.0 m
Duration	41 min	Wind direction	N (5; see App. A)
Position	N 20°22' W 18°31'	Wind velocity	9 m/s (fresh breeze)
ψ_{ref}	180, (184), 195, 175, 180 deg	Wave height	-
r_{ref}	0.05, 0.1 deg/s		

The sign of the sway velocity v_1 was incorrect during the experiment.

Self-tuning regulator and yaw regulator using estimates from the Kalman filter.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 7 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.27 \\ 6.10 \\ 2.67 \\ -2.07 \\ 0.48 \\ 0.08 \\ -0.09 \\ 95.45 \end{bmatrix} \qquad P = \begin{bmatrix} 8.21 &&&&&&& \\ -8.63 & 16.92 &&&&&& \\ -4.06 & -8.26 & 27.23 &&&&& \\ 4.71 & -0.08 & -14.92 & 10.58 &&&& \\ -0.26 & -0.15 & 0.81 & -0.39 & 0.06 &&& \\ -0.17 & 0.12 & 0.00 & 0.06 & 0.02 & 0.03 && \\ -1.04 & 1.14 & 0.61 & -0.57 & 0.06 & 0.02 & 0.92 & \\ 29.03 & -5.28 & -71.52 & 49.66 & -2.97 & -0.80 & 15.36 & 1100.32 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.57$

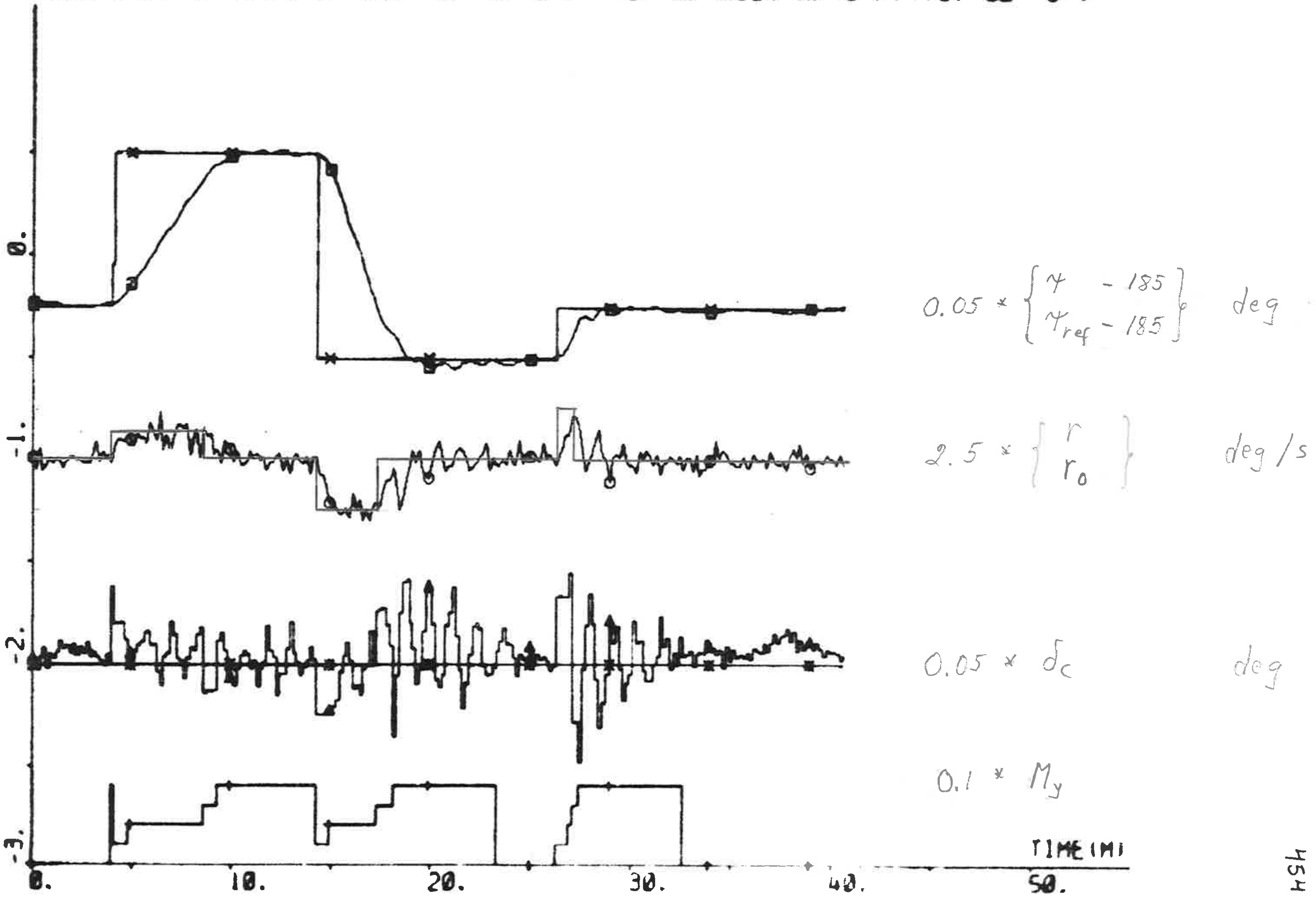
$\hat{\delta}_0 = 1.0$ deg $\hat{d}_v = -0.18$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.4$ deg

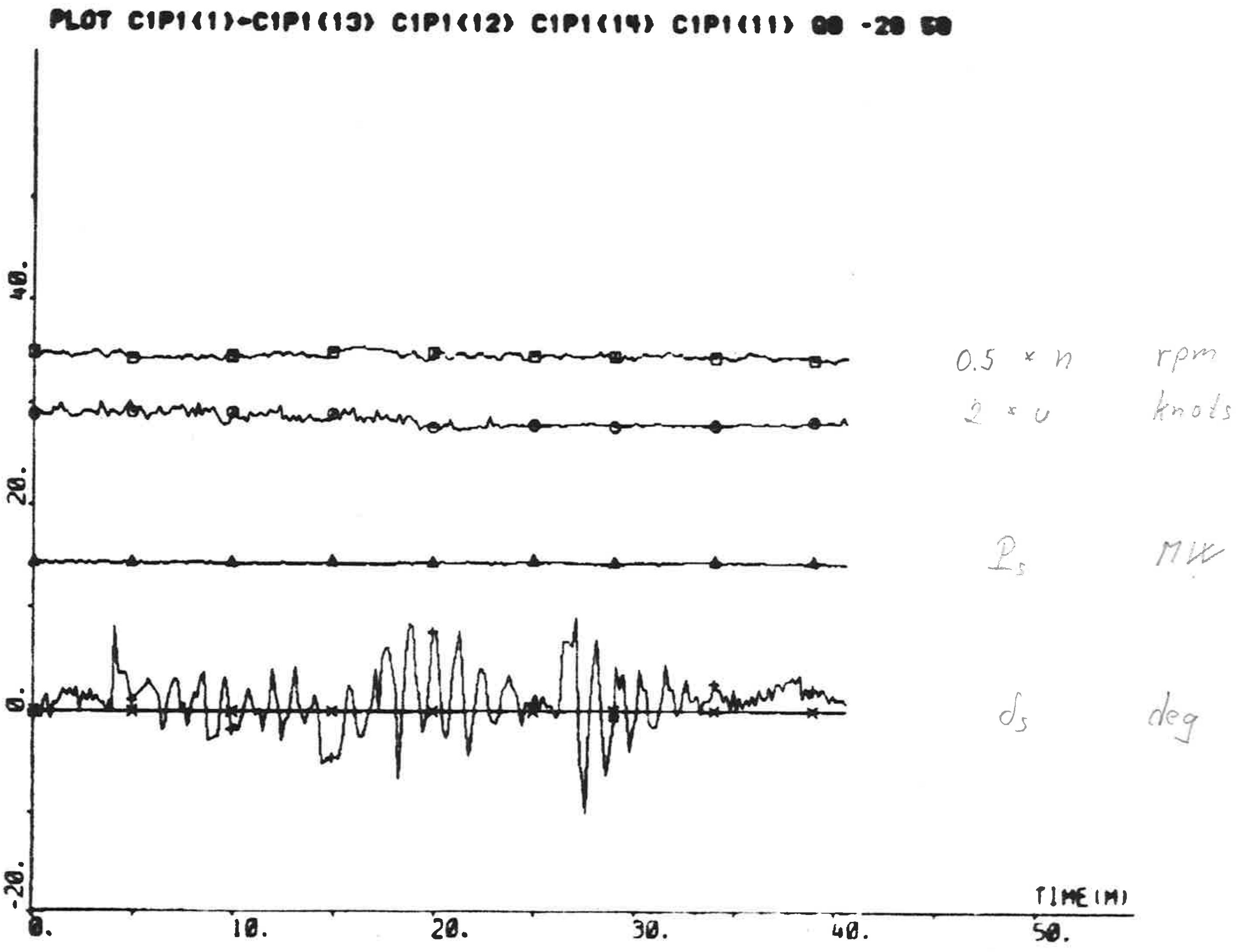
$\bar{\delta}_c = 0.7$ deg (Initial value: 1.1 deg)

Statistics (mean value and standard deviation)

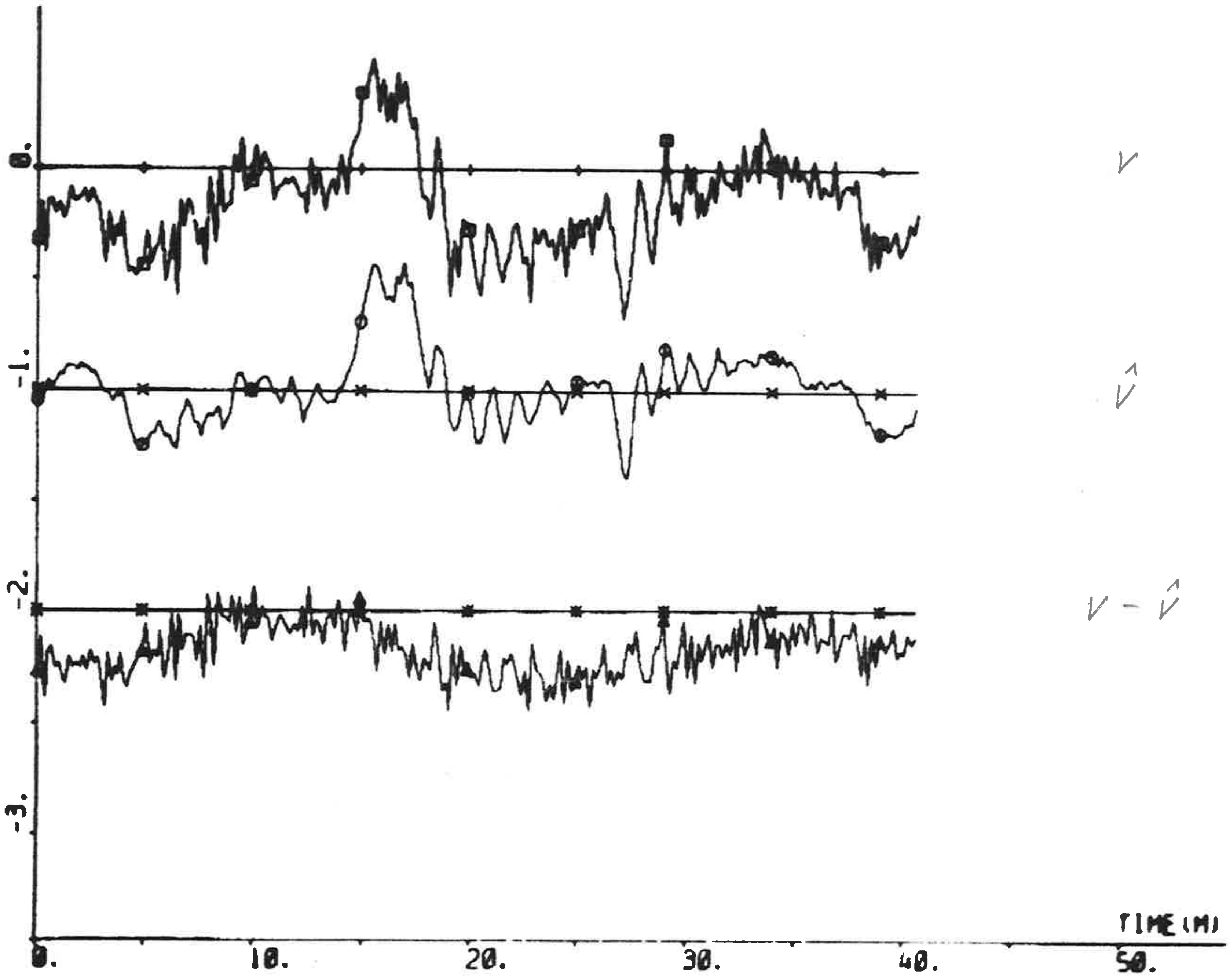
n	69.5 ± 0.5 rpm	ε_v	0.00 ± 0.03 knots
u	14.2 ± 0.3 knots	ε_r	0.00 ± 0.01 deg/s
P_s	14.4 ± 0.1 MW	ε_ψ	0.00 ± 0.03 deg
		ε_δ	0.0 ± 0.4 deg

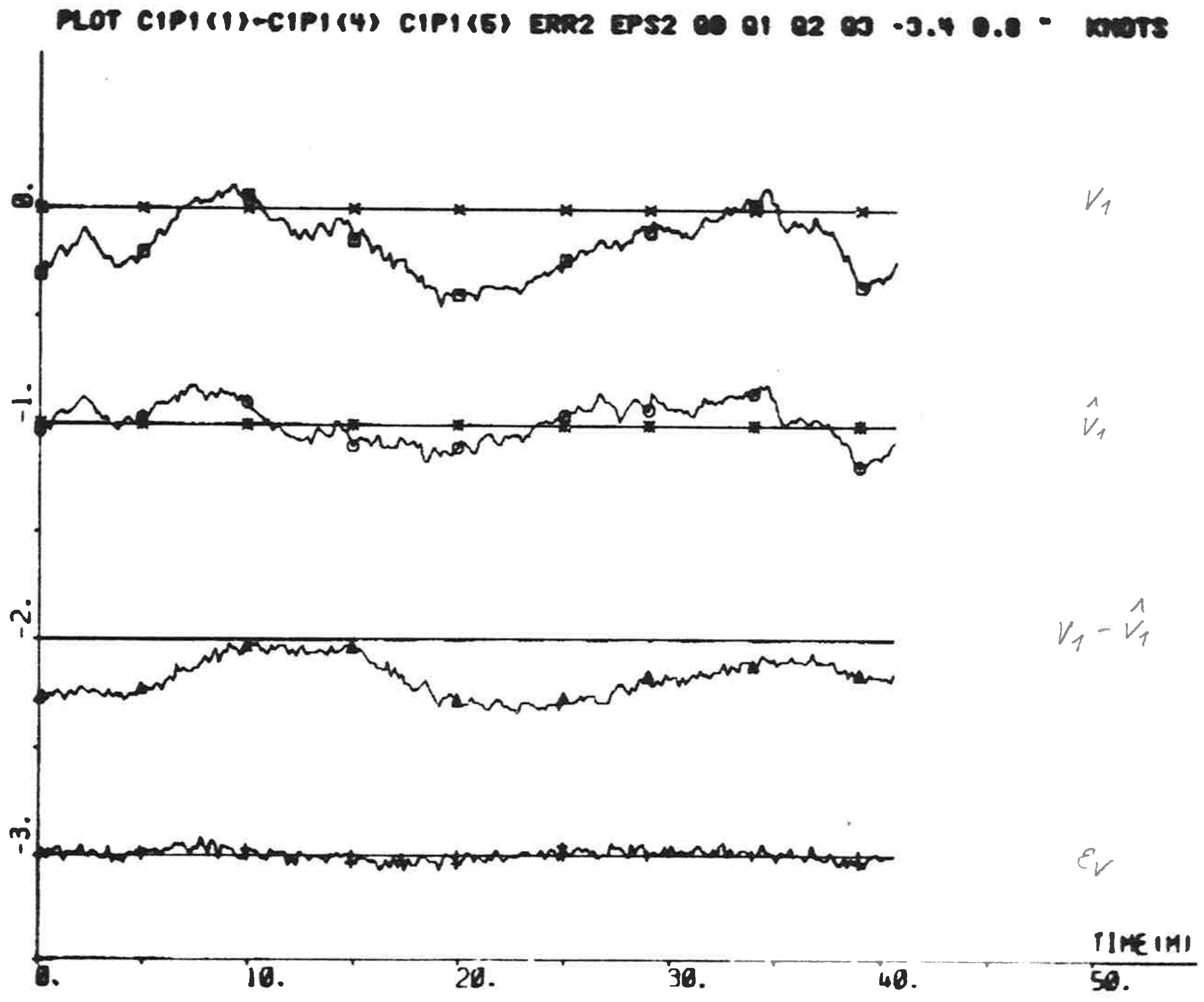
PLOT C1P1(1)-C1P1(8) C1P1(6) HP C1P1(10) HP MODY HP C1P1(15) 02 -3 1

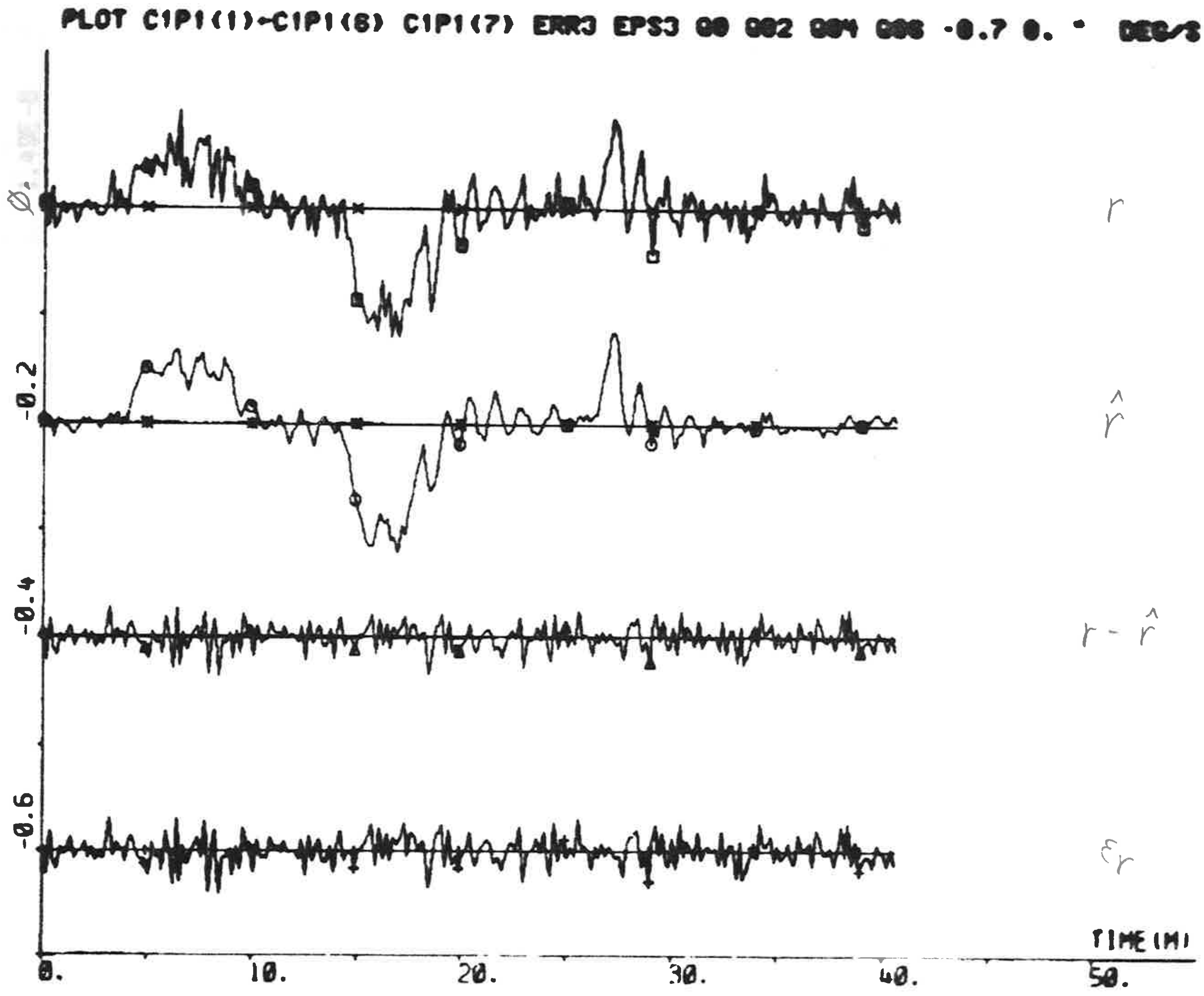


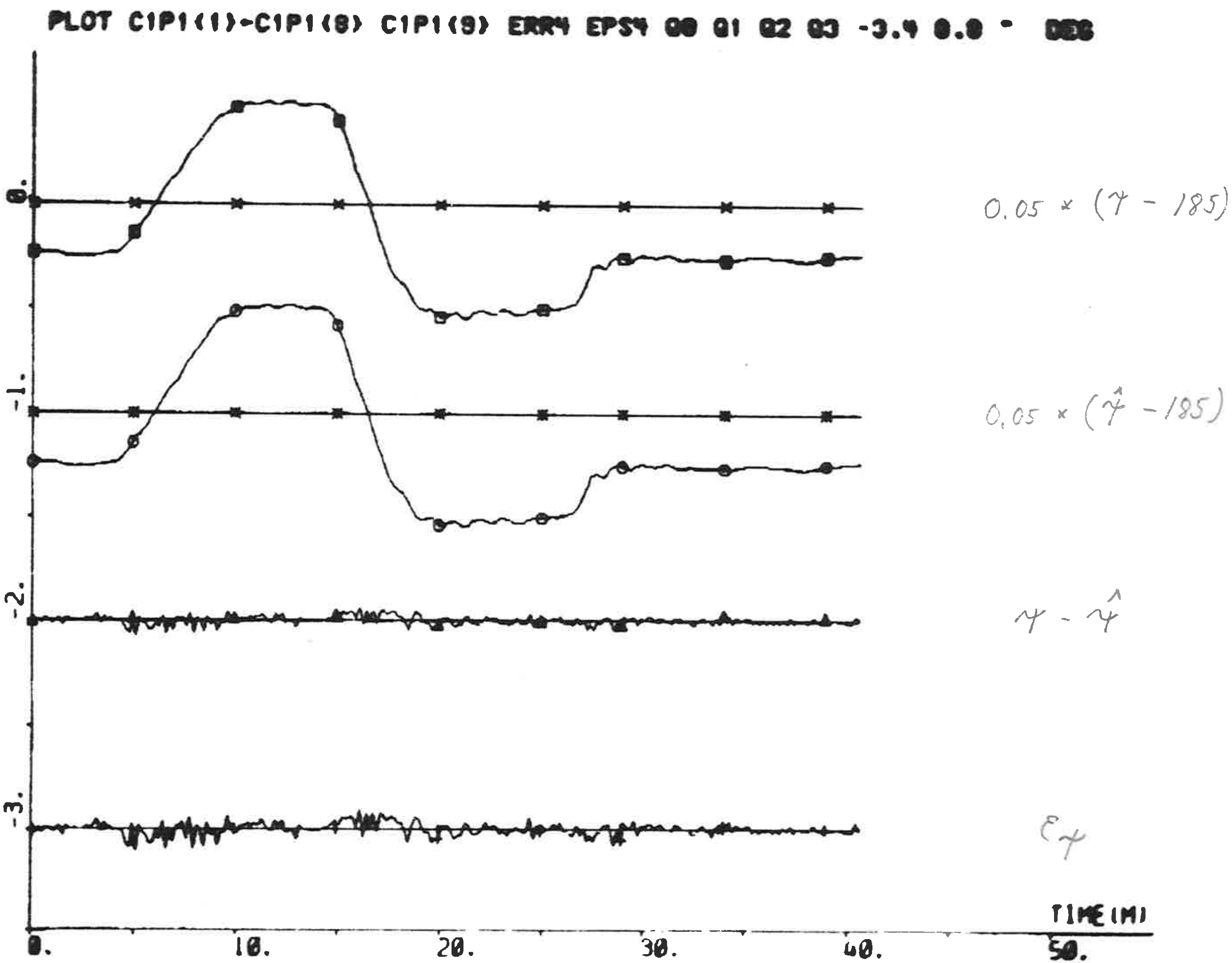

PLOT C1P1(1)-C1P1(13) C1P1(12) C1P1(14) C1P1(11) 00 -20 50
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME(M)
0.5 × n rpm
2 × v knots
P_s MW
δ_s deg

PLOT C1P1(1)-C1P2(1) C1P2(2) ERRS Q0 Q1 Q2 -3.4 0.8 - KNOTS

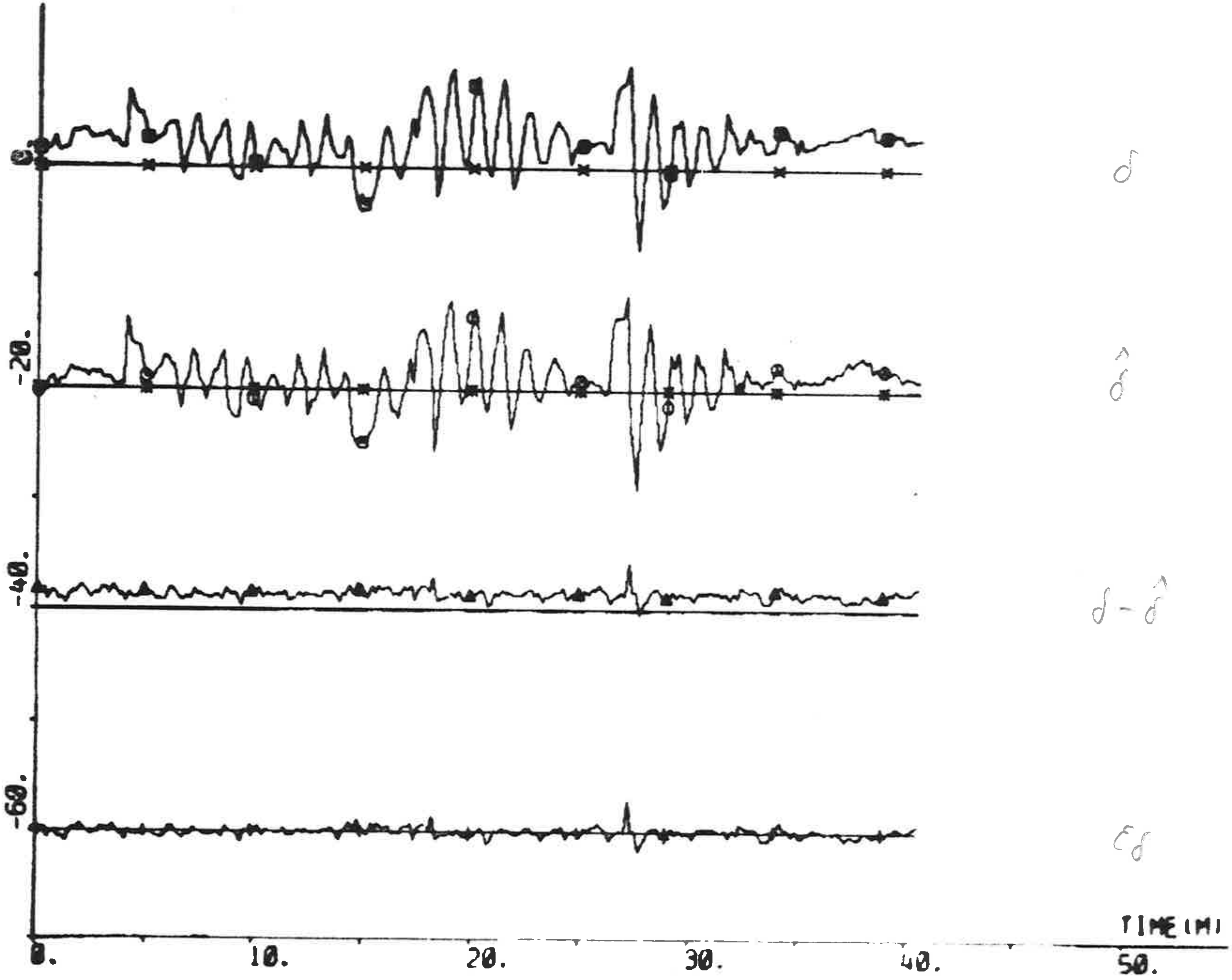



PLOT C1P1(1)-C1P1(4) C1P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
10.
20.
30.
40.
50.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V

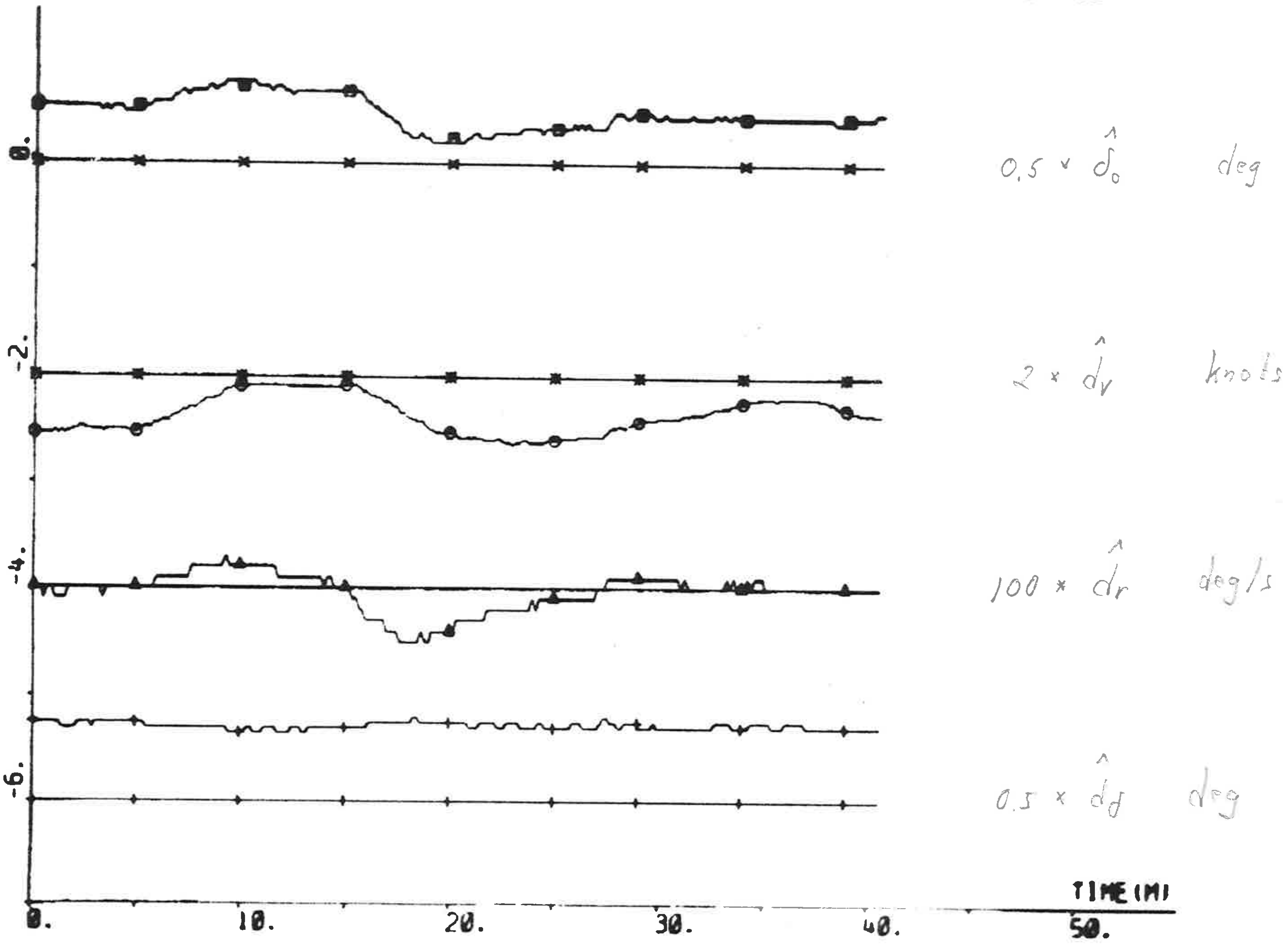

PLOT C1P1(1)-C1P1(6) C1P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. * DEG/S
Ø.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
TIME(M)
0.
10.
20.
30.
40.
50.


PLOT C1P1(1)-C1P1(8) C1P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 - DEG
0.
-1.
-2.
-3.
0.05 × (ψ - 185)
0.05 × (ψ̂ - 185)
ψ - ψ̂
ε_ψ
TIME(M)
0.
10.
20.
30.
40.
50.

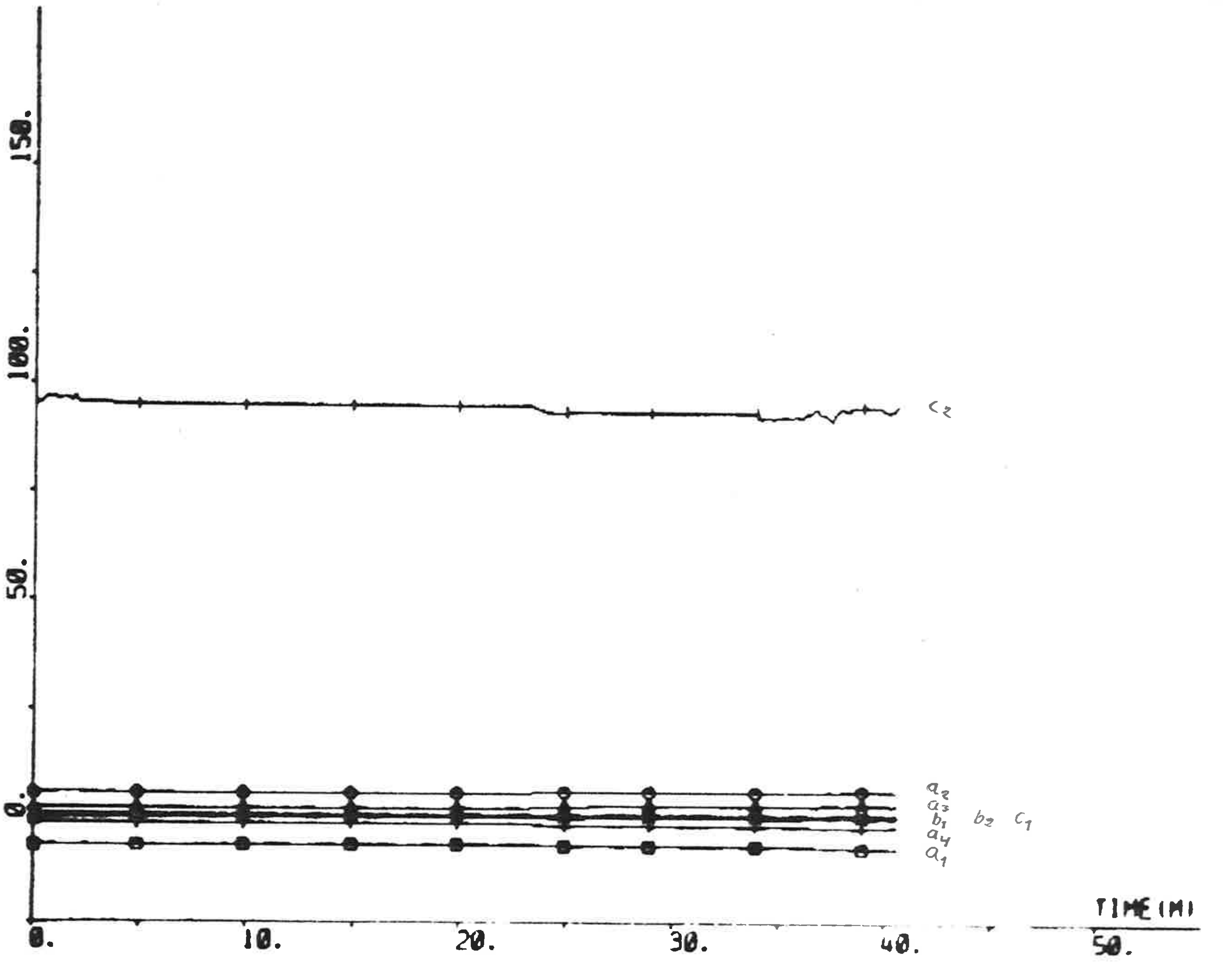
PLOT C1P1(1)-C1P1(2) C1P1(3) ERR1 EPS1 Q0 Q20 Q40 Q60 -65 15 - DEG



PLOT C1P1(1)-C1P2(3) C1P2(4) C1P2(5) C1P2(6) 00 02 04 06 -6.5 1.5



PLOT C1P1(1)-C1P2(7) C1P2(8) C1P2(9) C1P2(10) C1P2(11) C1P2(12) C1P2(13)



EXPERIMENT C2

Date	1976-04-22	Forward draught	8.5 m
Time	18.25	Aft draught	12.5 m
Duration	33 min	Wind direction	NW (4,5; see App. A)
Position	N 10°16' W 18°29'	Wind velocity	6 m/s (moderate breeze)
ψ_{ref}	180, (176), (147), 143 deg	Wave height	Moderate swell from N
r_{ref}	0.1 deg/s		

Self-tuning regulator and yaw regulator using estimates from the Kalman filter.

NCl = 1　　NC2 = 1　　k = 8　　q = 0

T_s = 10 s　　V_0 = 6 m/s　　IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -10.20 \\ 11.11 \\ 2.38 \\ -3.34 \\ 0.54 \\ 0.26 \\ -0.71 \\ 65.62 \end{bmatrix} \qquad P = \begin{bmatrix} 12.68 &&&&&&& \\ -15.73 & 39.39 &&&&&& \\ -3.62 & -32.48 & 73.15 &&&&& \\ 6.95 & 9.07 & -37.59 & 22.09 &&&& \\ -0.35 & -0.60 & 2.11 & -1.14 & 0.08 &&& \\ -0.19 & 0.16 & 0.04 & -0.03 & 0.01 & 0.02 && \\ -2.11 & 2.63 & 0.97 & -1.48 & 0.05 & 0.01 & 1.21 & \\ 50.22 & -17.07 & -114.61 & 81.47 & -4.60 & -0.60 & 11.50 & 1304.89 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.05$

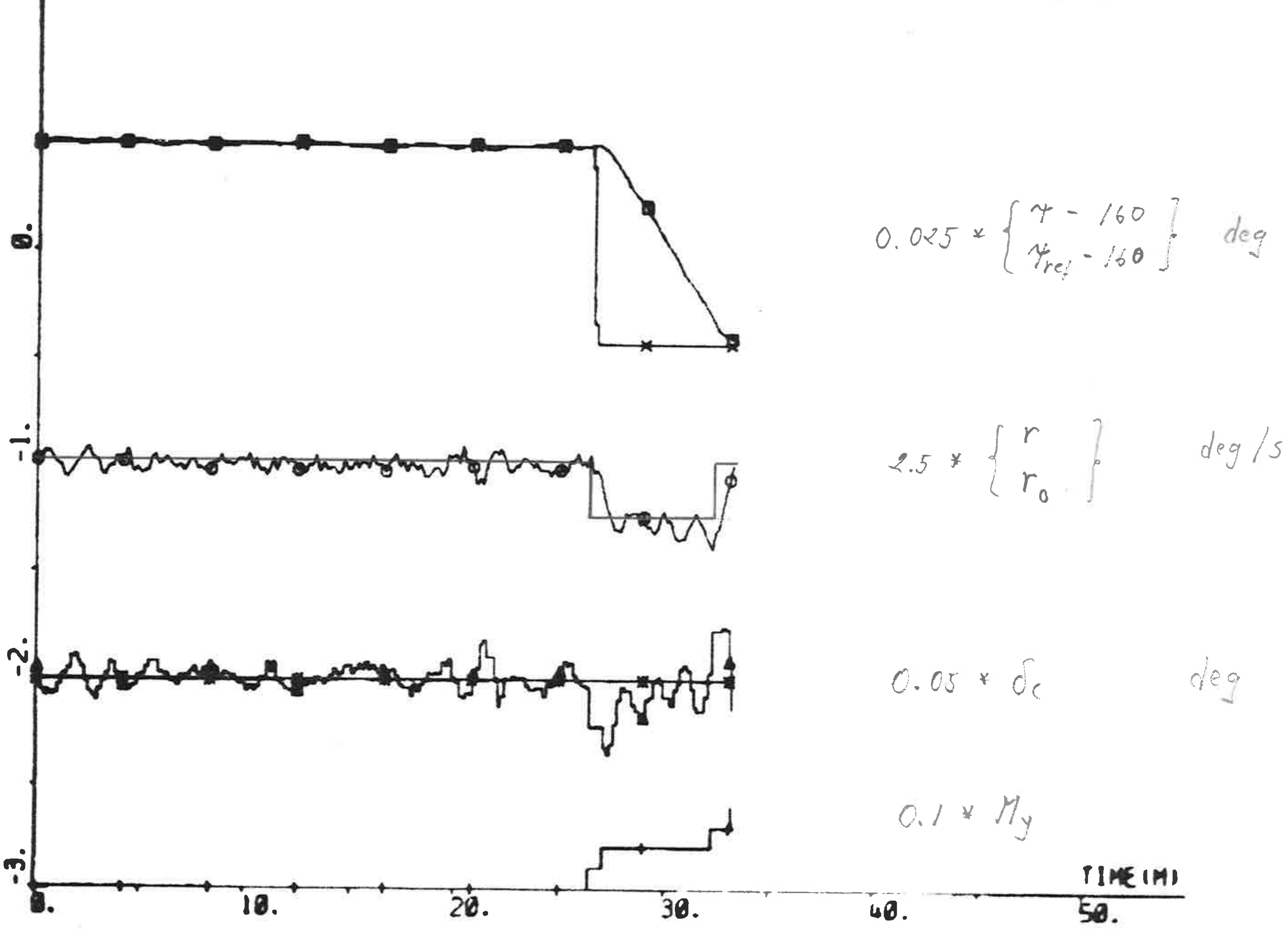
$\hat{\delta}_0 = -1.2$ deg　　$\hat{d}_v = 0.04$ knots　　$\hat{d}_r = -0.011$ deg/s　　$\hat{d}_\delta = 1.7$ deg

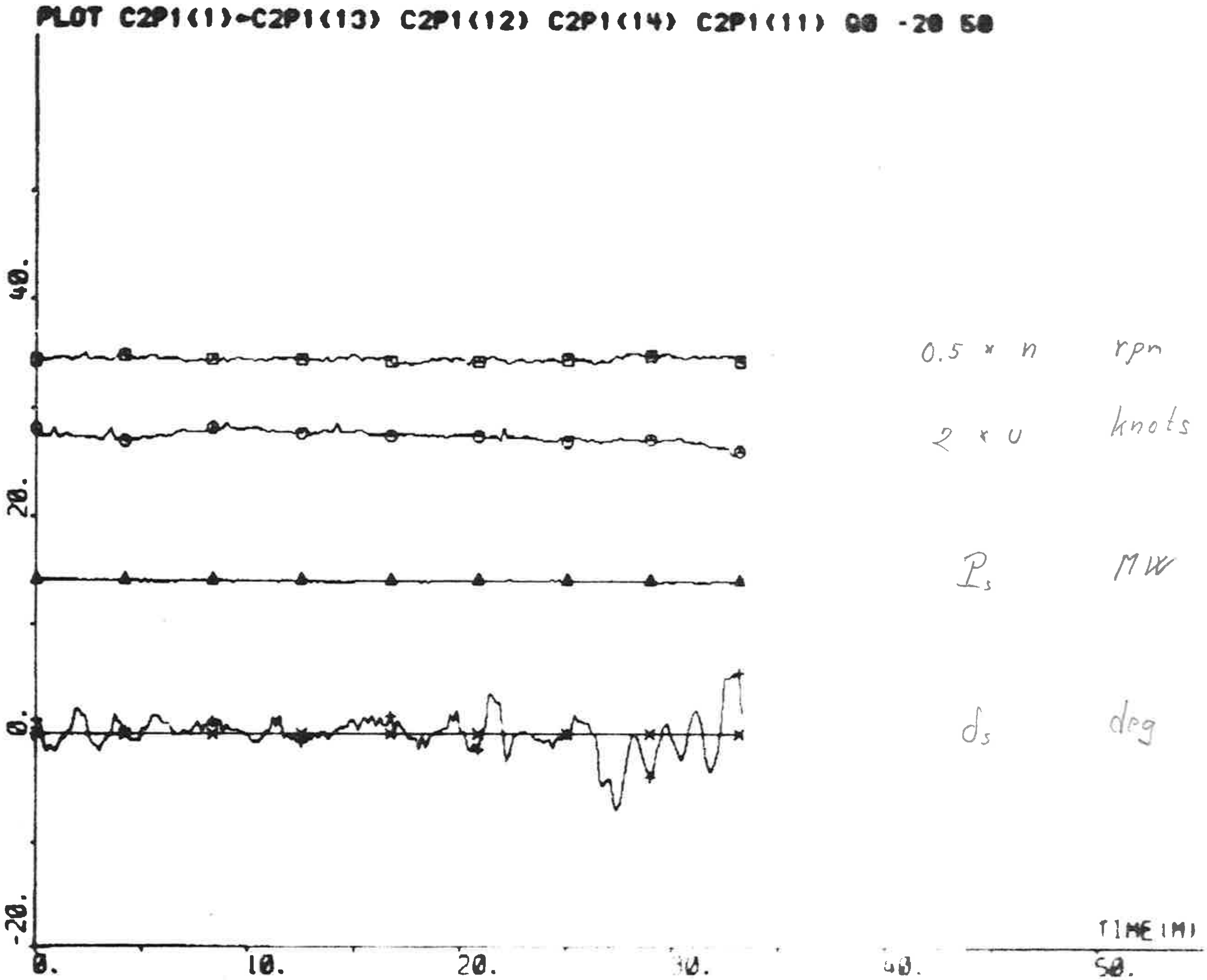
$\bar{\delta}_c = 1.2$ deg　　(Initial value: 0.3 deg)

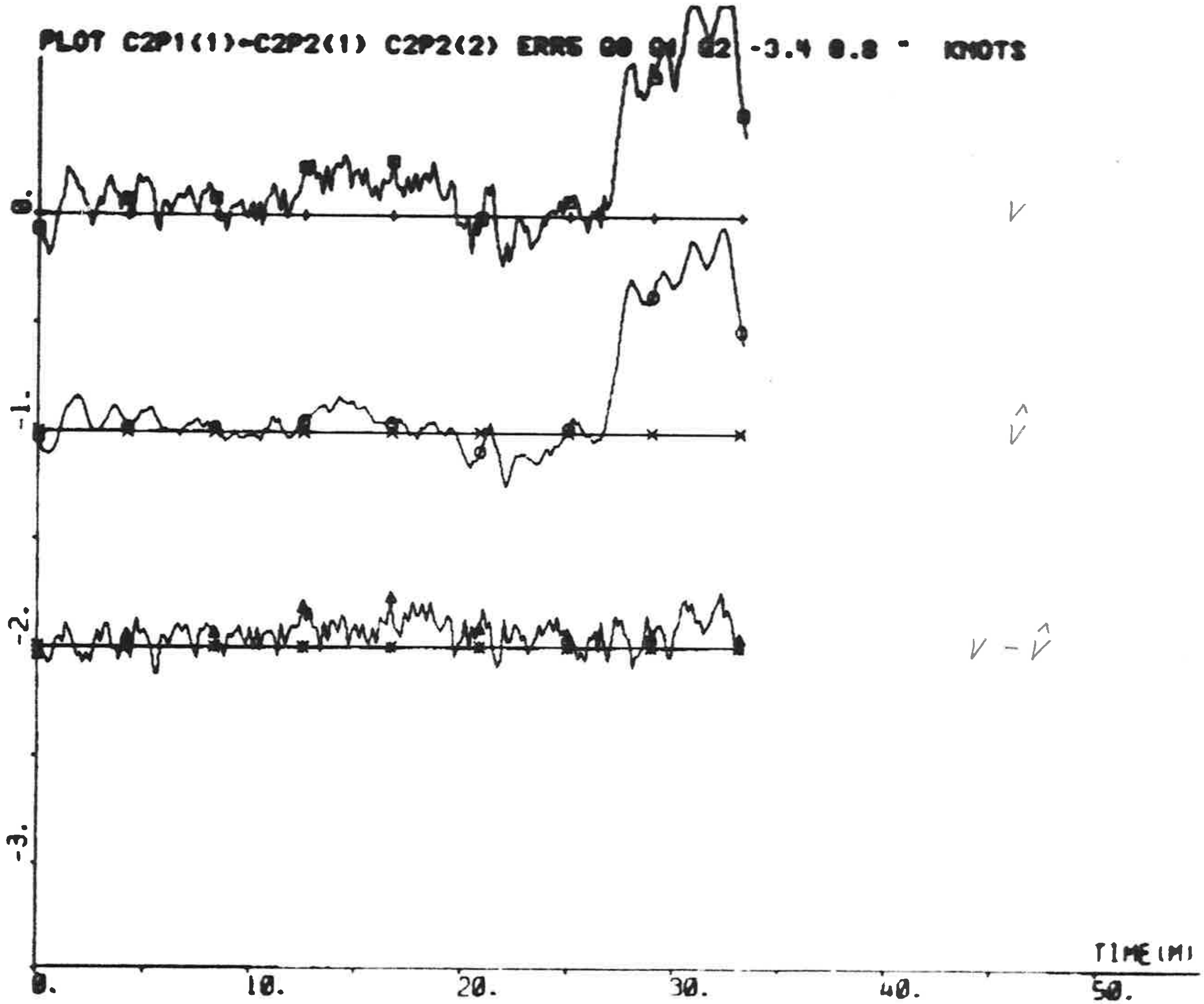
Statistics (mean value and standard deviation)

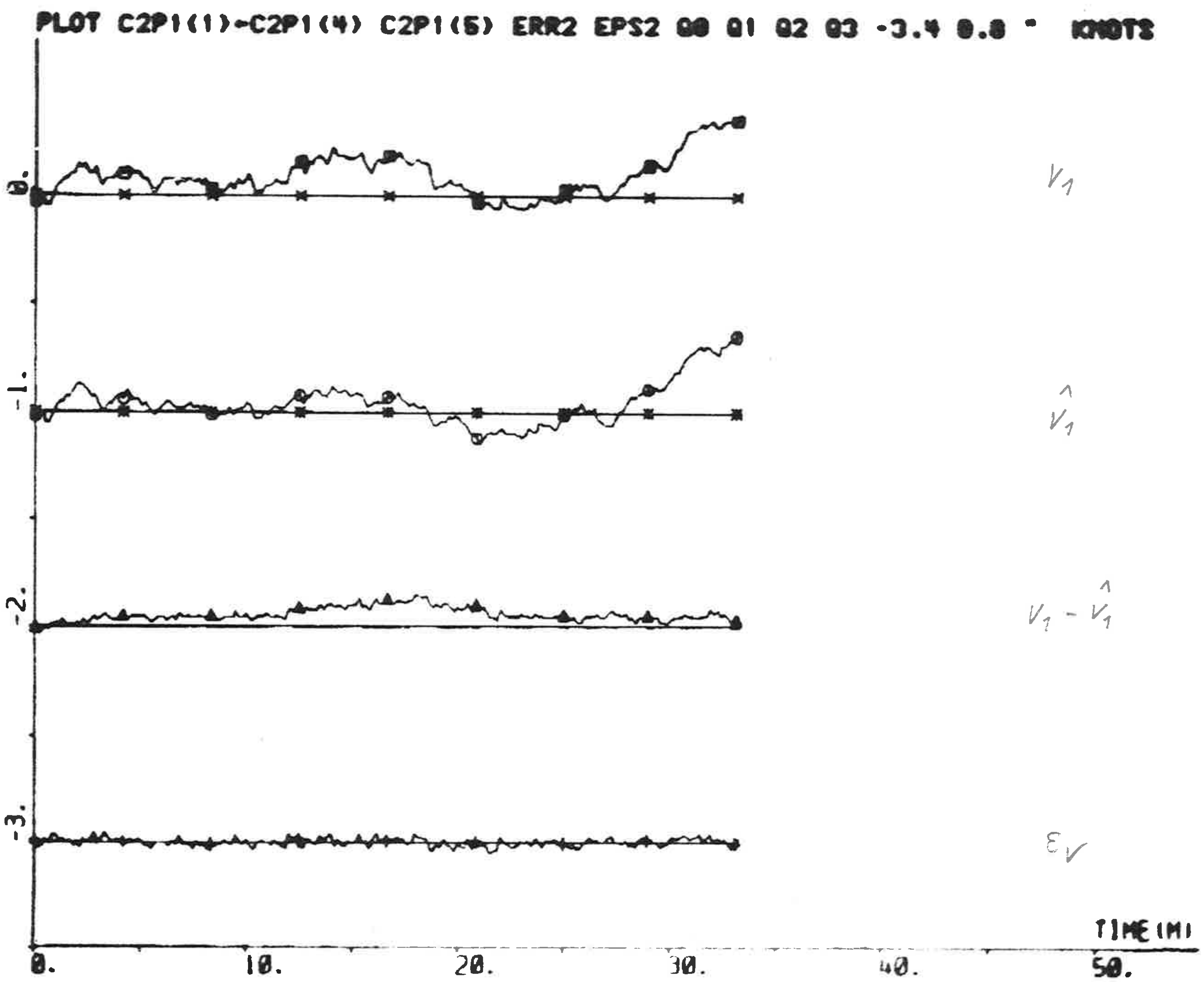
n	69.3 ± 0.5 rpm	ε_v	0.00 ± 0.02 knots
u	13.7 ± 0.2 knots	ε_r	0.00 ± 0.01 deg/s
P_s	14.0 ± 0.1 MW	ε_ψ	0.01 ± 0.02 deg
		ε_δ	0.1 ± 0.6 deg

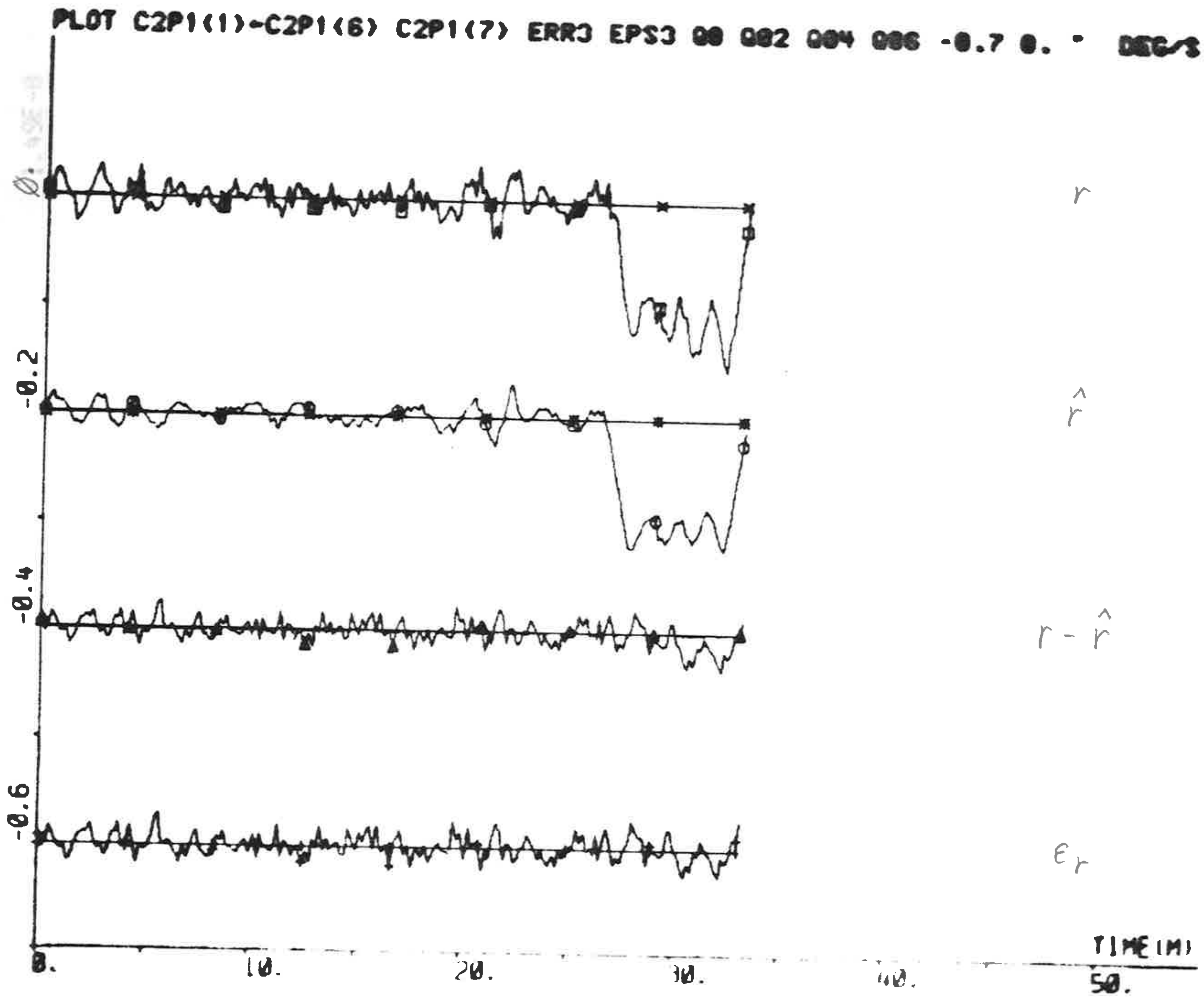
PLOT C2P1(1)-C2P1(8) C2P1(6) HP C2P1(10) HP MODY HP C2P1(15) 02 -3 1

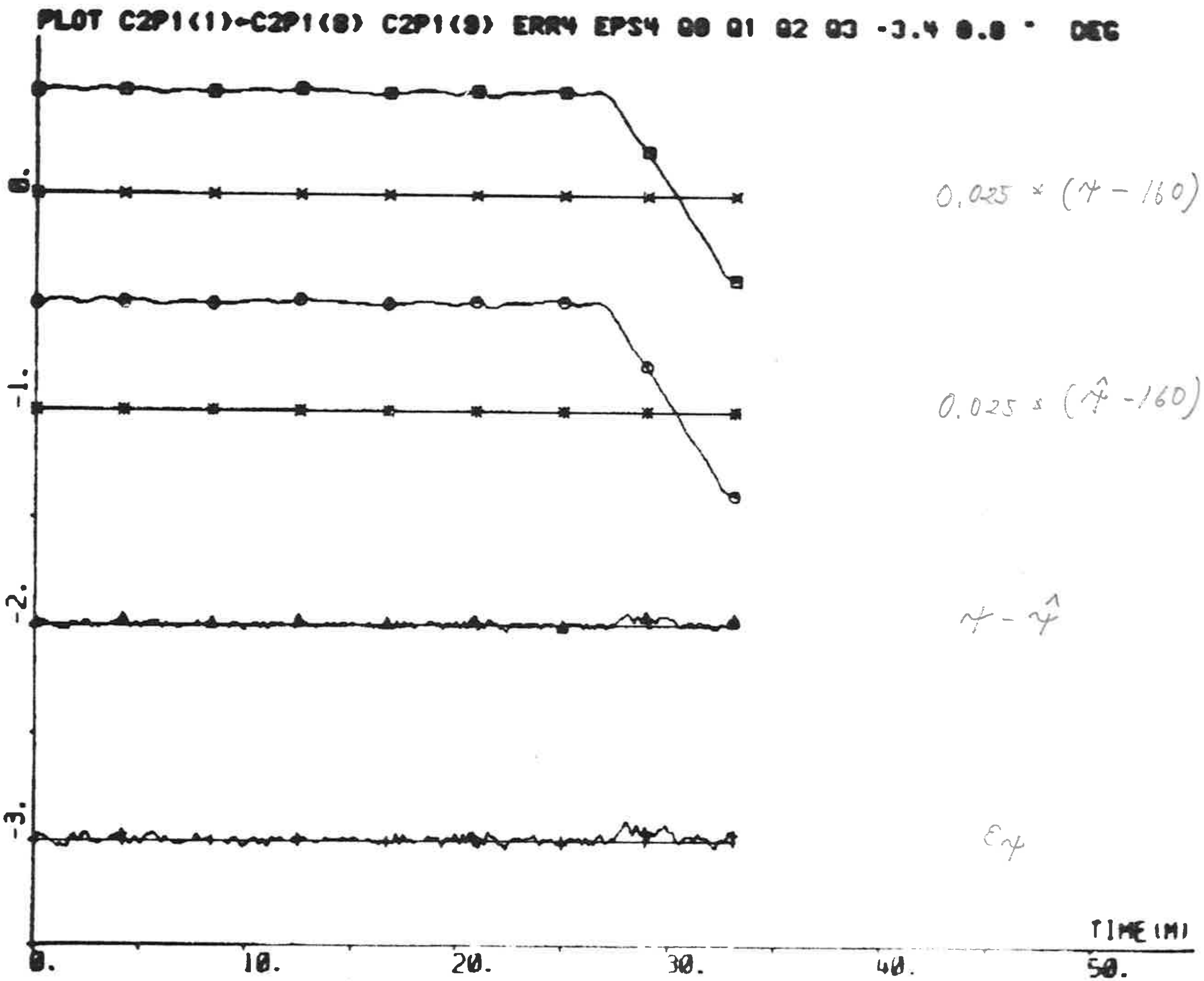


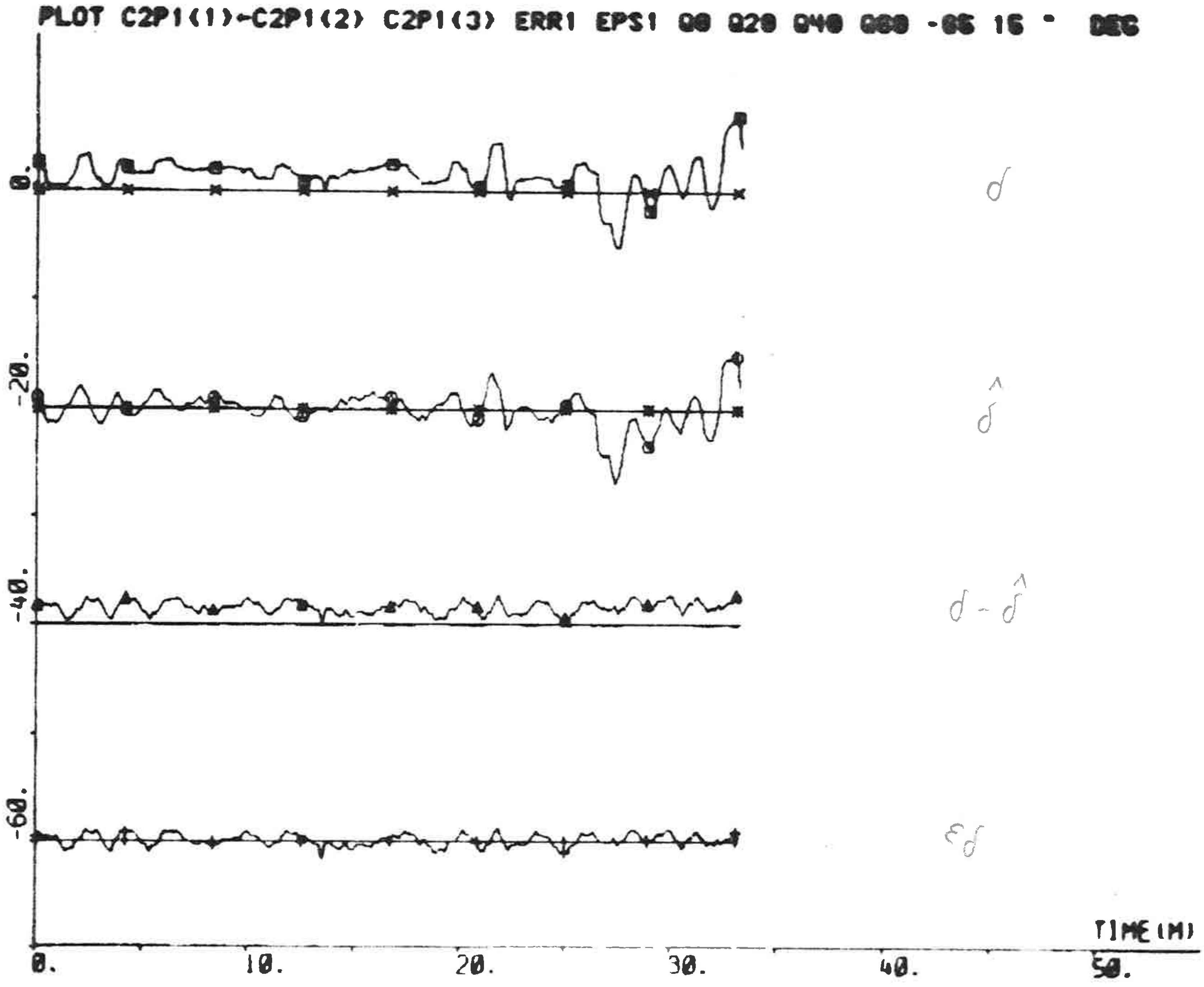

PLOT C2P1(1)-C2P1(13) C2P1(12) C2P1(14) C2P1(11) 00 -20 50
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME(M)
0.5 * n rpm
2 * u knots
P_s MW
δ_s deg

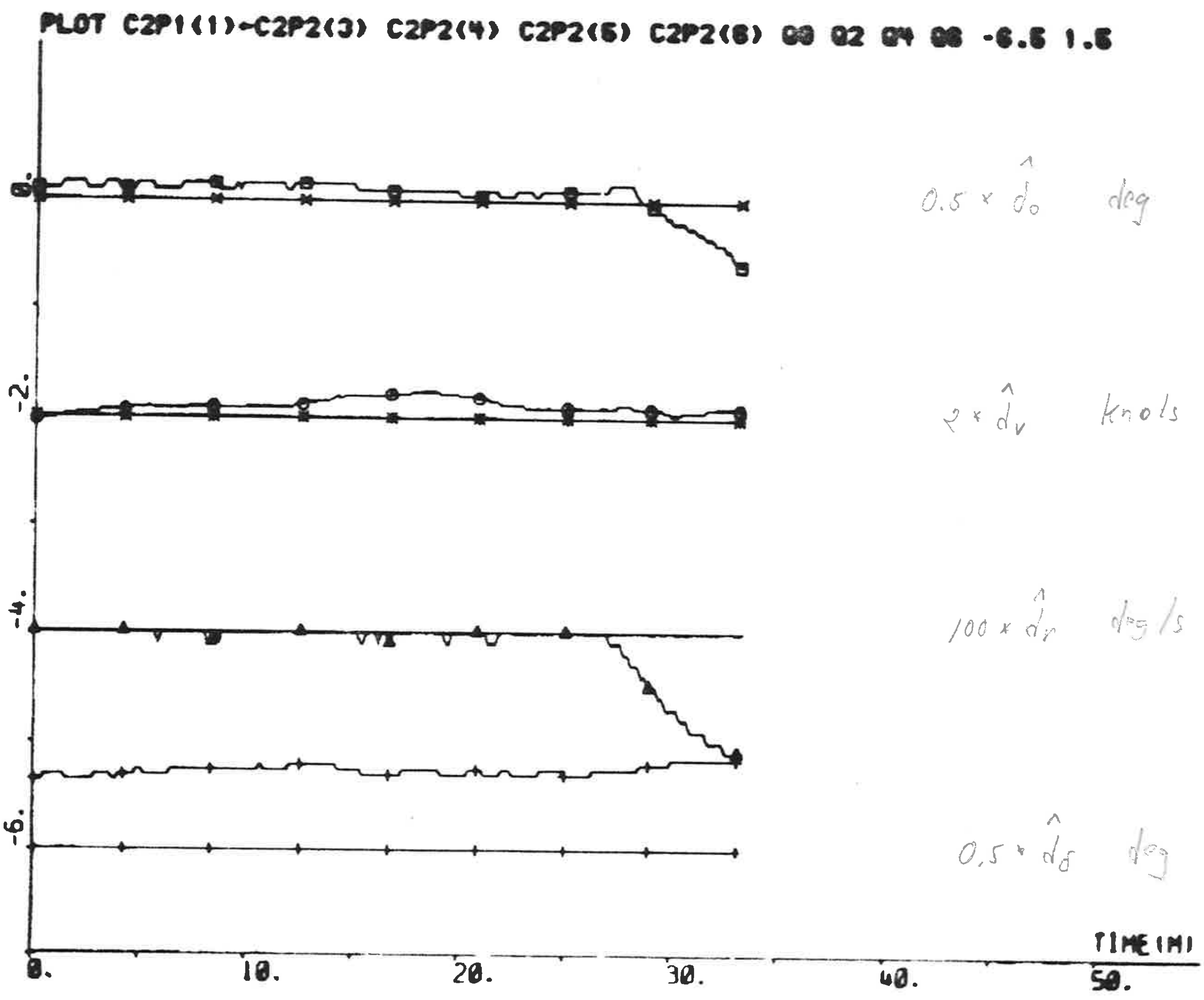

PLOT C2P1(1)-C2P2(1) C2P2(2) ERRS 00 01 02 -3.4 0.8 - KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
V
V̂
V - V̂

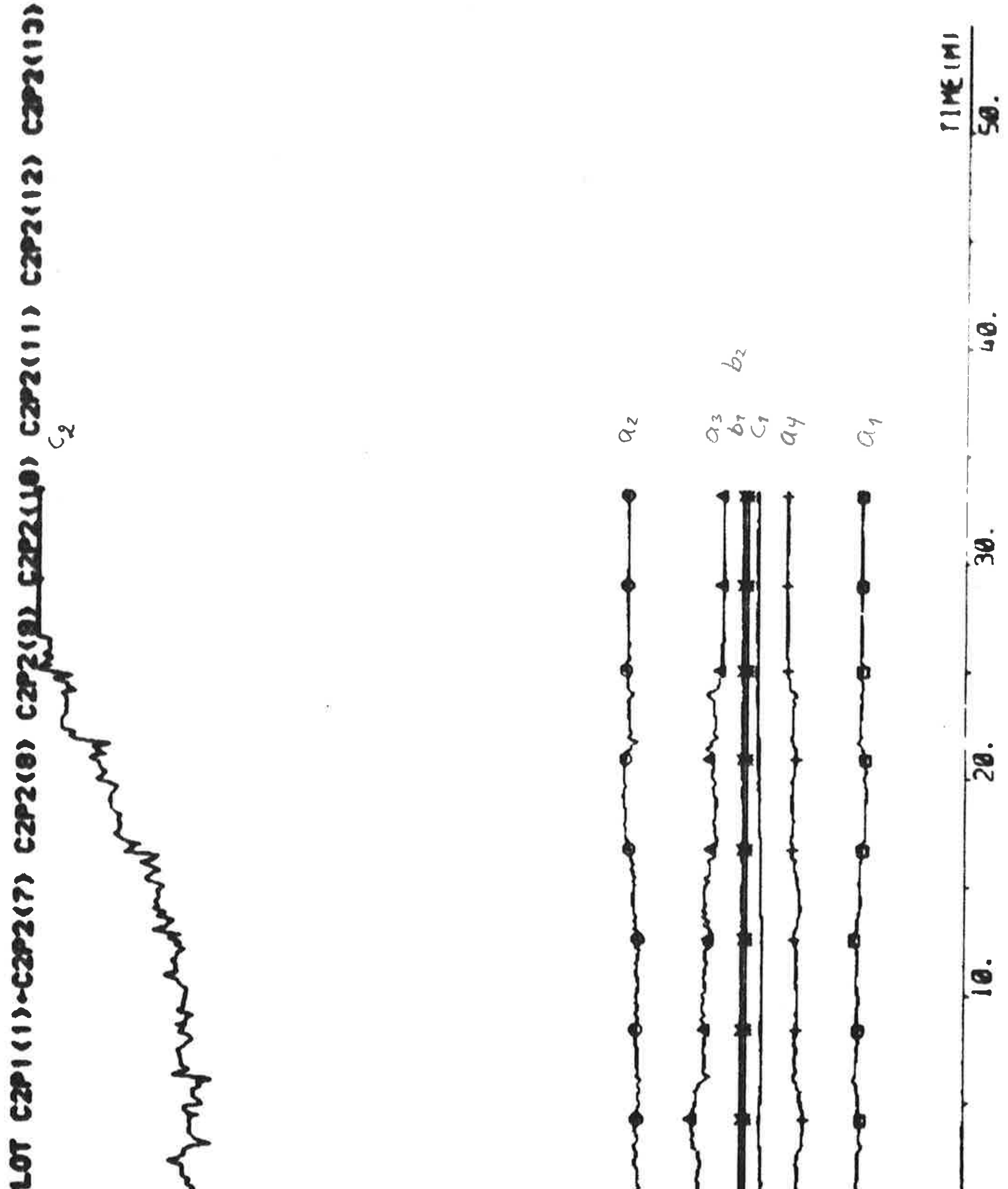

PLOT C2P1(1)-C2P1(4) C2P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.8 " KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT C2P1(1)-C2P1(6) C2P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. DEG/S
-0.2
-0.4
-0.6
0.
10.
20.
30.
40.
50.
TIME(M)
r
r̂
r - r̂
εr


PLOT C2P1(1)-C2P1(8) C2P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.8 ° DEG
0.
-1.
-2.
-3.
0.025 * (ψ - 160)
0.025 * (ψ̂ - 160)
ψ - ψ̂
εψ
TIME (M)
0.
10.
20.
30.
40.
50.


PLOT C2P1(1)-C2P1(2) C2P1(3) ERR1 EPS1 00 020 040 060 -06 16 ° DEG
0.
-20.
-40.
-60.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT C2P1(1)-C2P2(3) C2P2(4) C2P2(5) C2P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.5 × $\hat{d}_o$ deg
2 × $\hat{d}_v$ knots
100 × $\hat{d}_r$ deg/s
0.5 × $\hat{d}_\delta$ deg
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT C2P1(1)-C2P2(7) C2P2(8) C2P2(9) C2P2(10) C2P2(11) C2P2(12) C2P2(13)
TIME(M)
0.
10.
20.
30.
40.
50.
40.
20.
0.
-20.
c2
a2
a3
b1
c1
a4
a1
b2

EXPERIMENT C3

Date	1976-04-26	Forward draught	10.9 m
Time	21.16	Aft draught	12.9 m
Duration	63 min	Wind direction	SE (1; see App. A)
Position	S 07°39' W 05°24'	Wind velocity	7 m/s (moderate breeze)
ψ_{ref}	142, (148), 162, (159), (131), 122, (134), 142 deg	Wave height	–
r_{ref}	0.05, 0.1 deg/s		

Self-tuning regulator and yaw regulator using estimates from the Kalman filter

The estimates $\hat{\delta}'_0$, $\hat{d}'_v$, $\hat{d}'_r$ and $\hat{d}'_\delta$ were not updated during the experiment.

NC1 = 1   NC2 = 1   k = 7   q = 0

T_s = 10 s V_0 = 6 m/s   IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -10.55 \\ 12.90 \\ -0.97 \\ -1.57 \\ 0.38 \\ 0.17 \\ -0.54 \\ 89.70 \end{bmatrix} \qquad P = \begin{bmatrix} 8.37 & & & & & & & \\ -15.05 & 45.05 & & & & & & \\ 6.78 & -44.53 & 67.66 & & & & & \\ 0.16 & 14.52 & -30.18 & 16.19 & & & & \\ 0.23 & -1.19 & 1.57 & -0.60 & 0.05 & & & \\ -0.04 & 0.24 & -0.47 & 0.30 & -0.01 & 0.02 & & \\ -1.78 & 2.64 & 0.15 & -1.09 & -0.03 & -0.01 & 1.26 & \\ 1.83 & -4.92 & 5.09 & -1.17 & 0.59 & 0.04 & 22.65 & 961.96 \end{bmatrix}$$

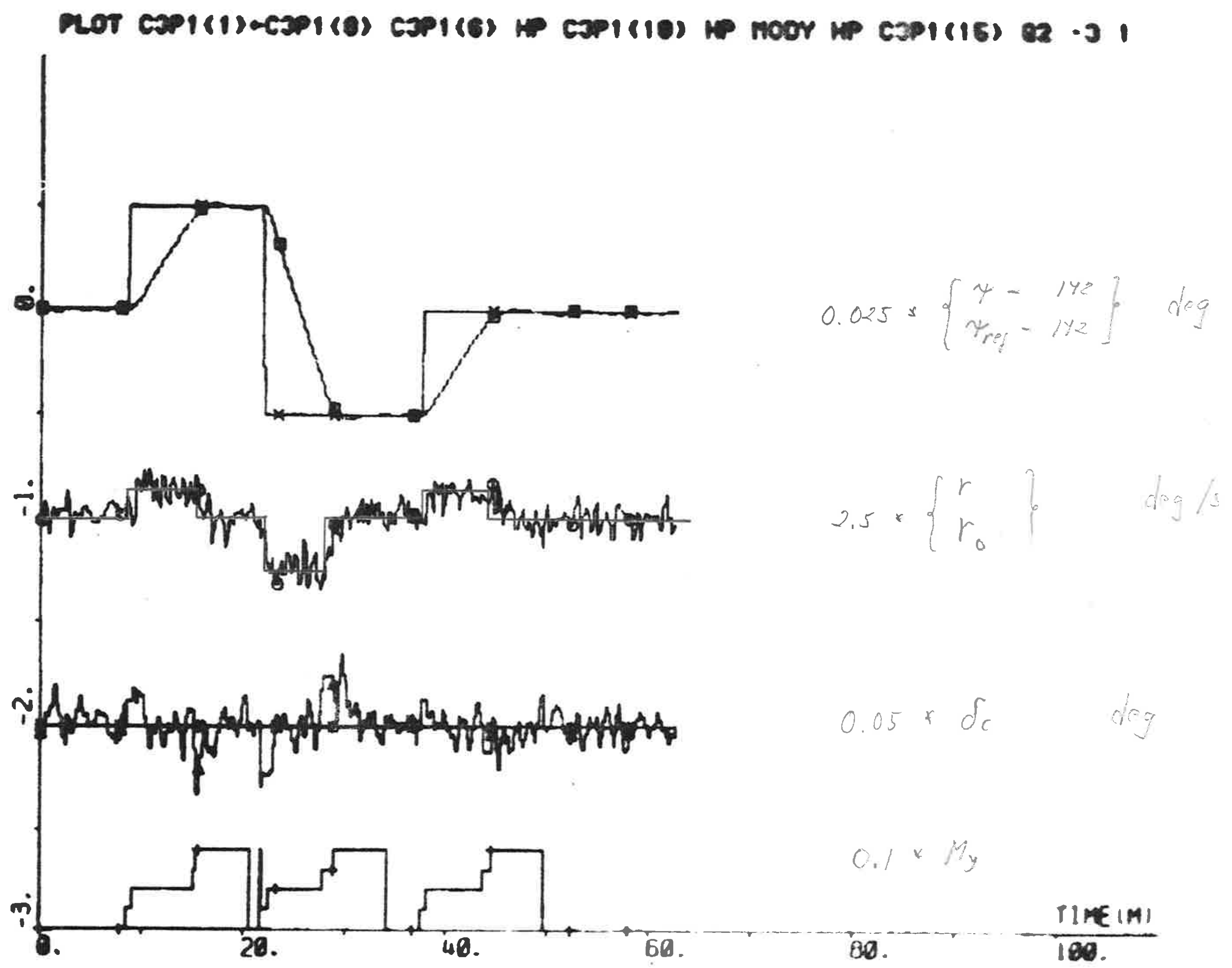
$a_1 + a_2 + a_3 + a_4 = -0.19$

$\hat{\delta}_0 = 0.0$ deg $\hat{d}_r = 0.21$ knots $\hat{d}_r = 0.002$ deg/s $\hat{d}_\delta = 1.7$ deg

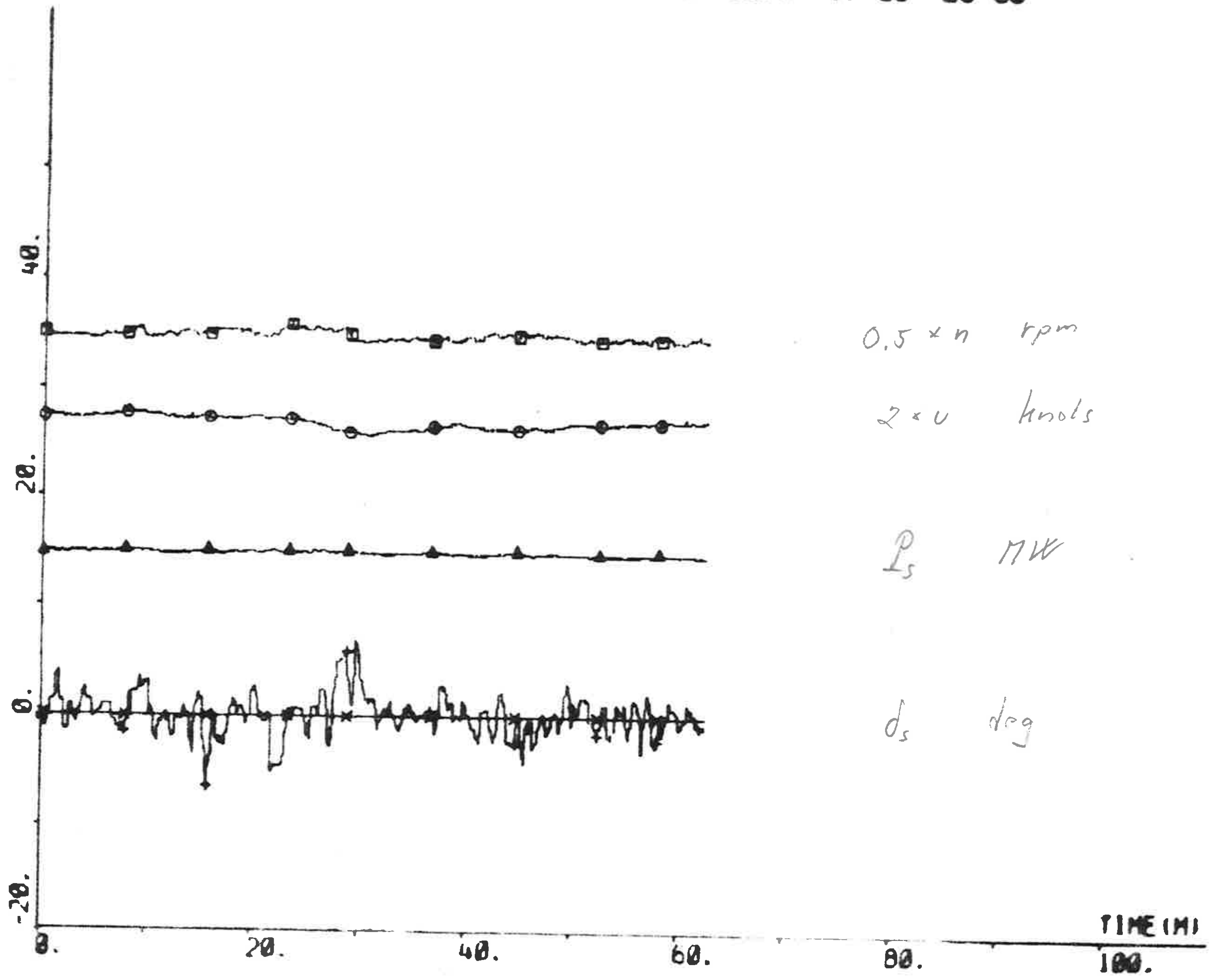
$\bar{\delta}_c = 0.8$ deg   (Initial value: 0.0 deg)

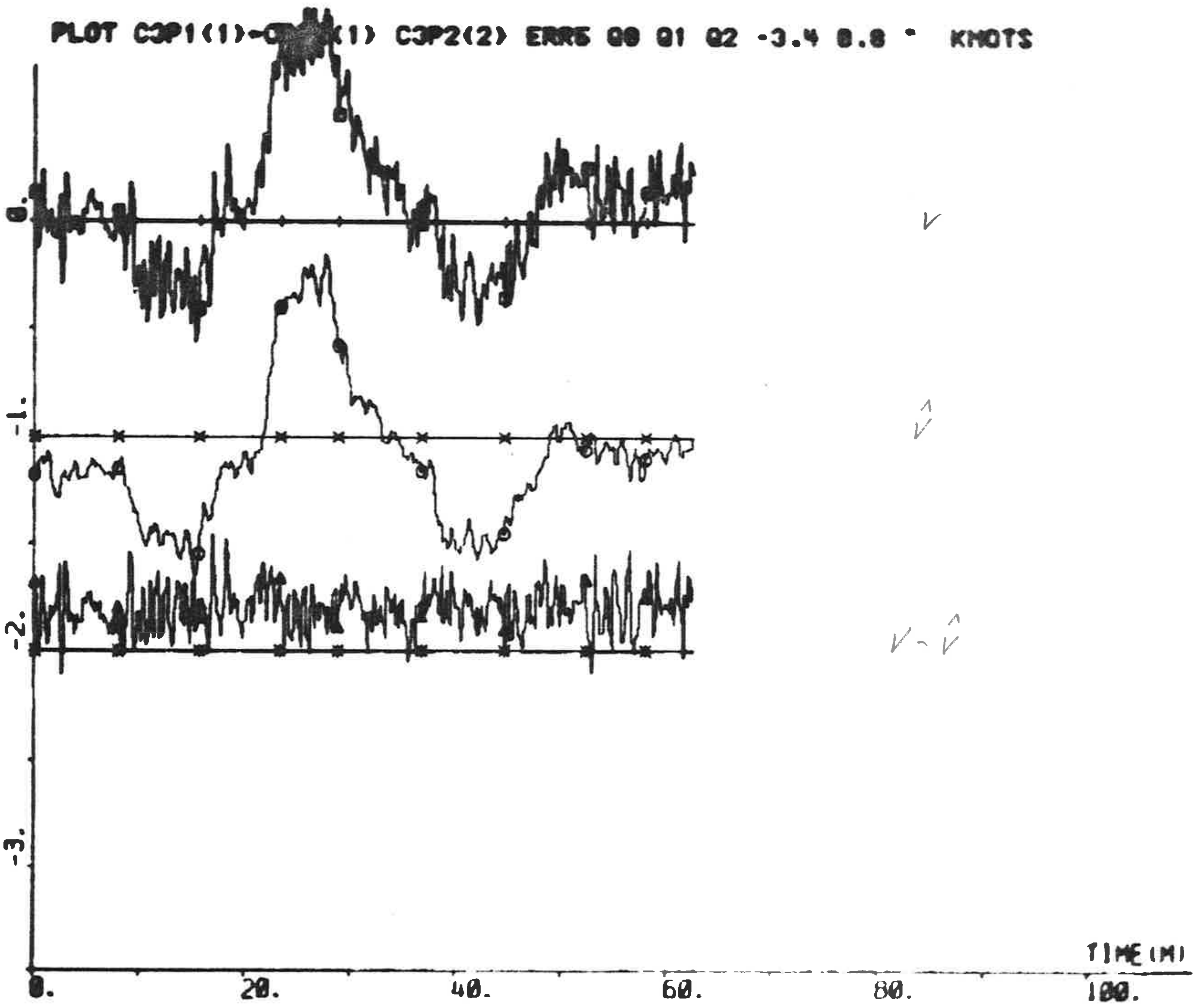
Statistics (mean value and standard deviation)

n	69.8 ± 0.7 rpm	ε_v	-0.01 ± 0.02 knots
u	13.4 ± 0.2 knots	ε_r	0.00 ± 0.02 deg/s
P_s	14.9 ± 0.1 MW	ε_ψ	0.01 ± 0.06 deg
		ε_δ	-0.1 ± 0.5 deg


PLOT C3P1(1)-C3P1(8) C3P1(6) HP C3P1(10) HP MODY HP C3P1(15) 02 -3 1
0.
-1.
-2.
-3.
0.025 × { ψ - 142 ; ψ_ref - 142 } deg
2.5 × { r ; r_0 } deg/s
0.05 × δ_c deg
0.1 × M_y
0.
20.
40.
60.
80.
100.
TIME(M)

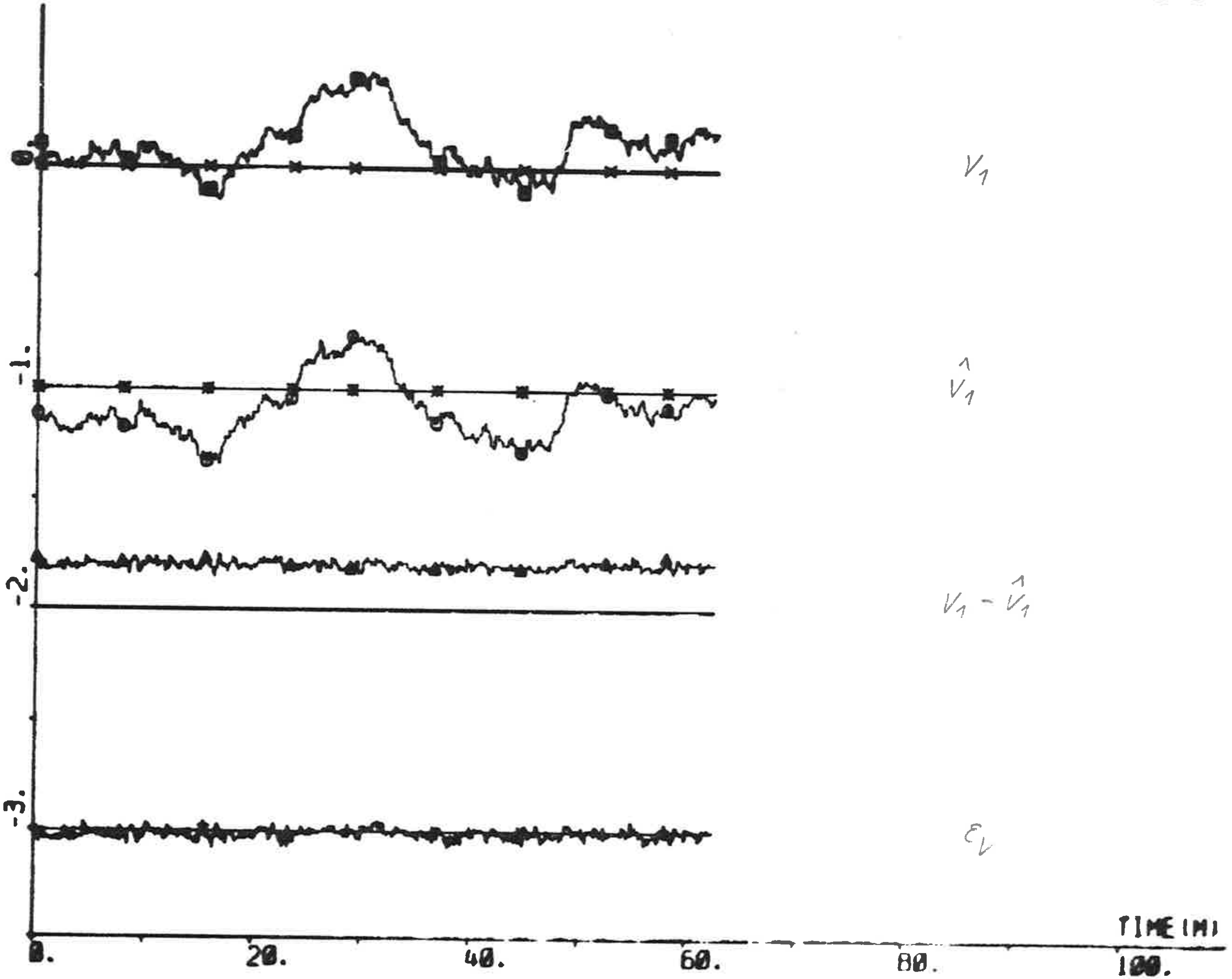
PLOT C3P1(1)-C3P1(13) C3P1(12) C3P1(14) C3P1(11) 00 -20 50



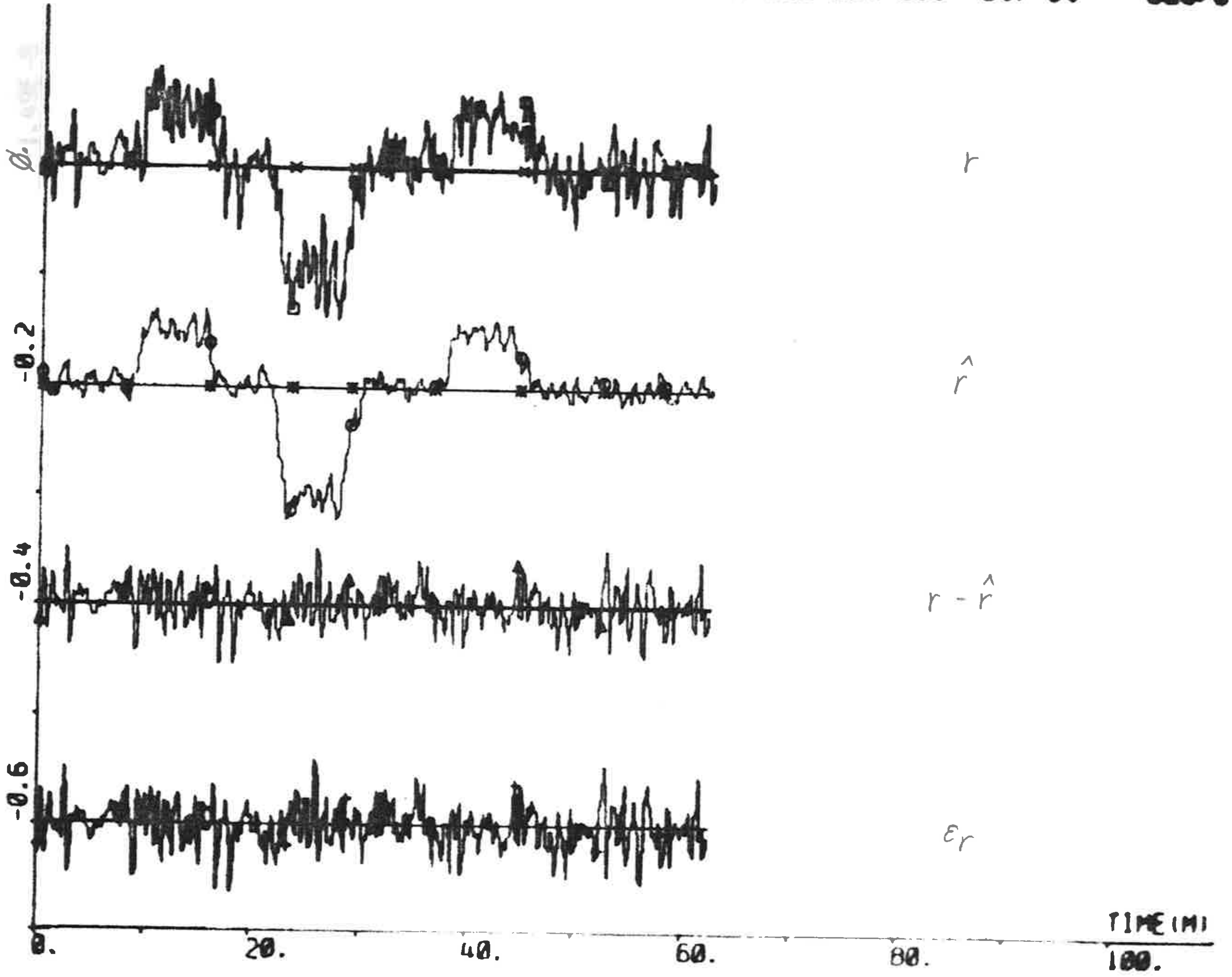


PLOT C3P1(1)- (1) C3P2(2) ERRS Q0 Q1 Q2 -3.4 0.8 KNOTS
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)

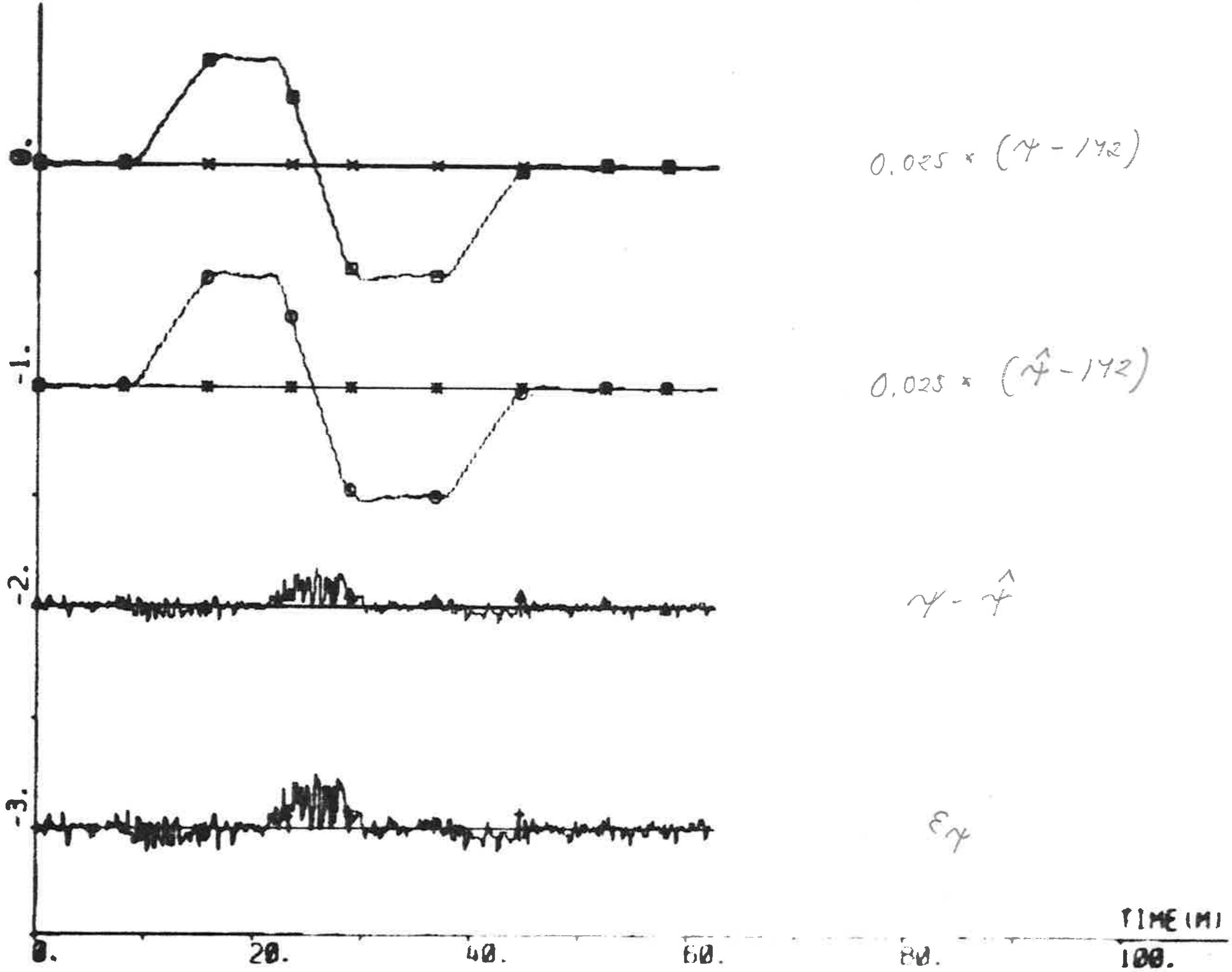
PLOT C3P1(1)-C3P1(4) C3P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 - KNOTS

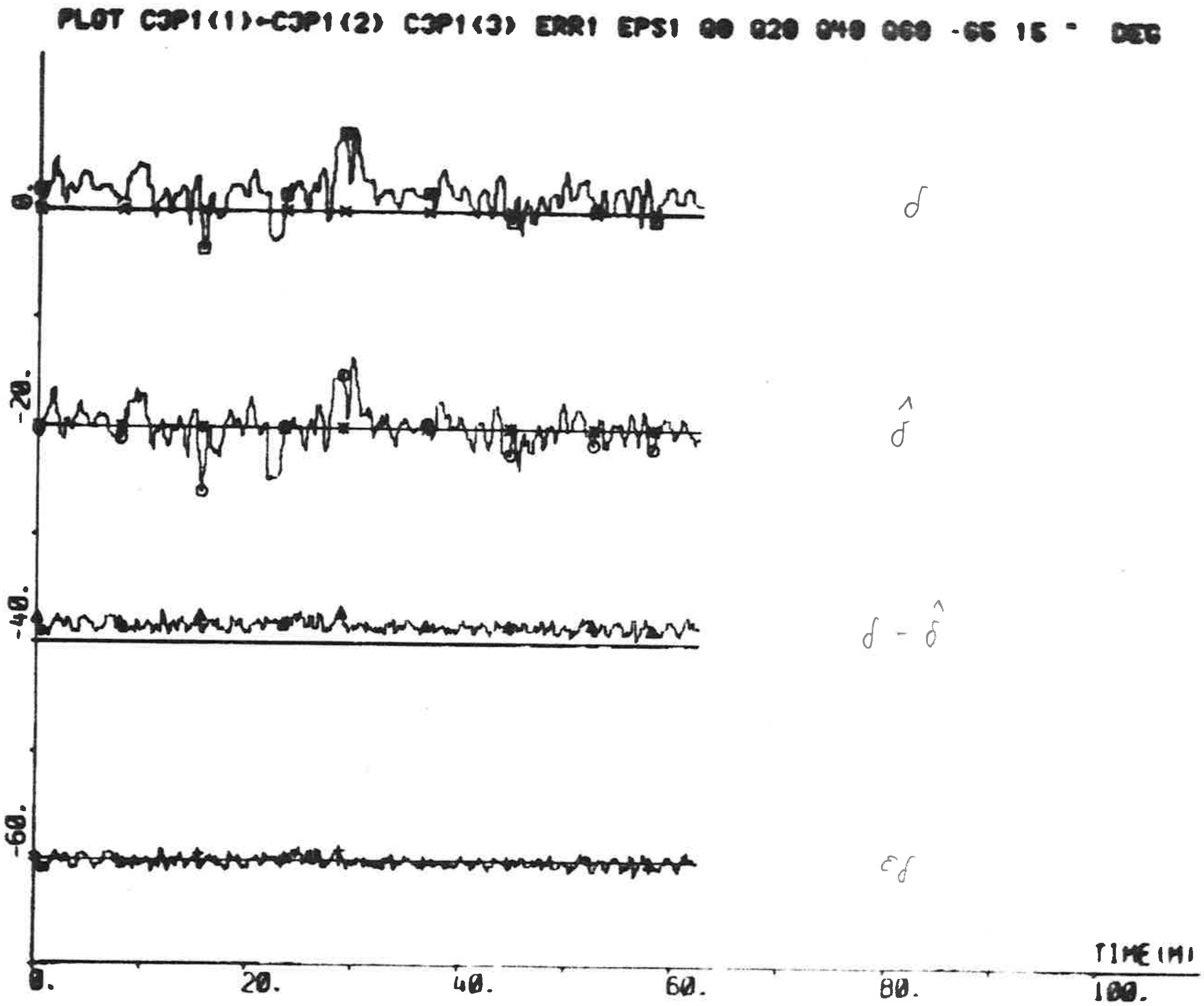


PLOT C3P1(1)-C3P1(6) C3P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. - DEG/S

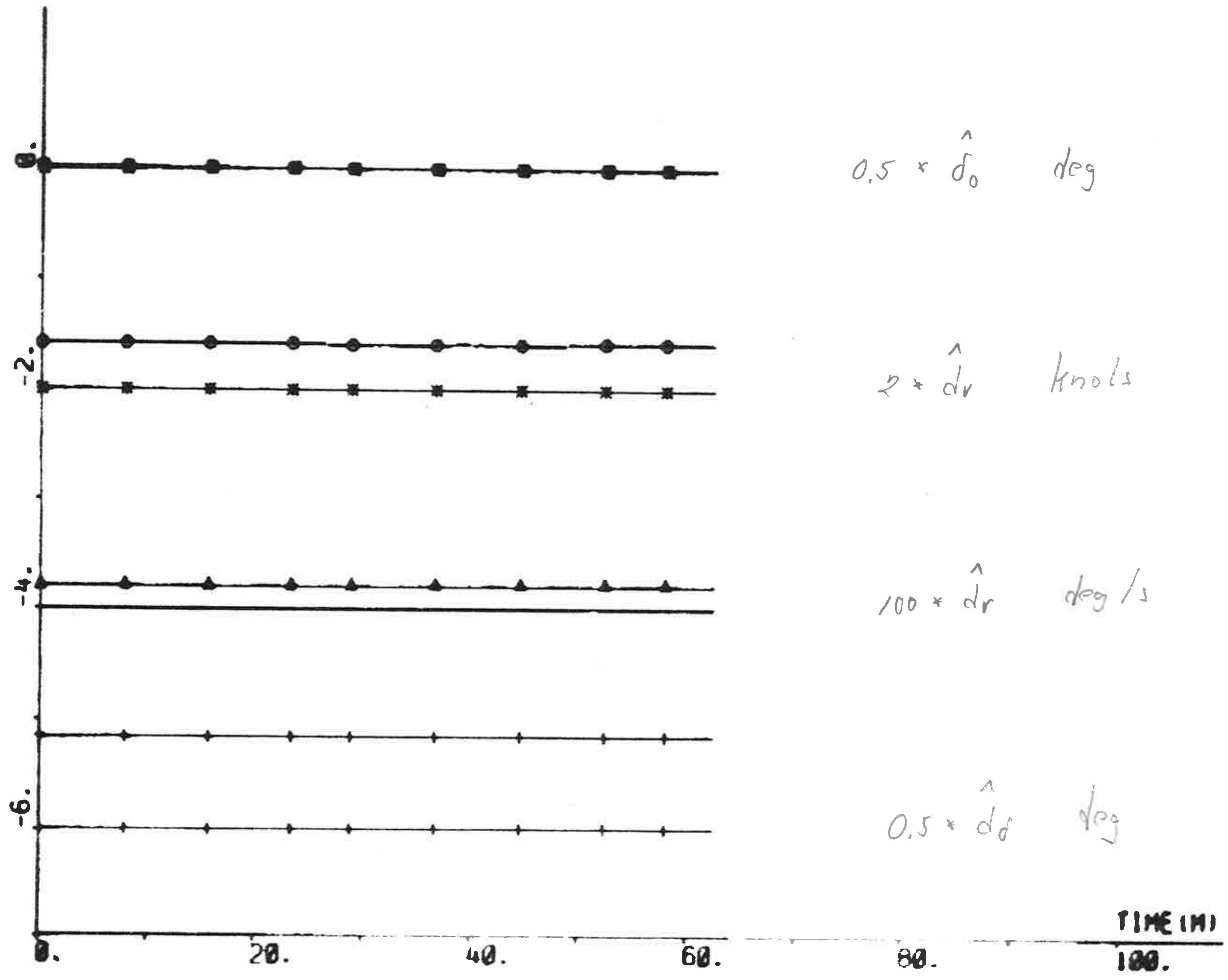


PLOT C3P1(1)-C3P1(8) C3P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 - DEG

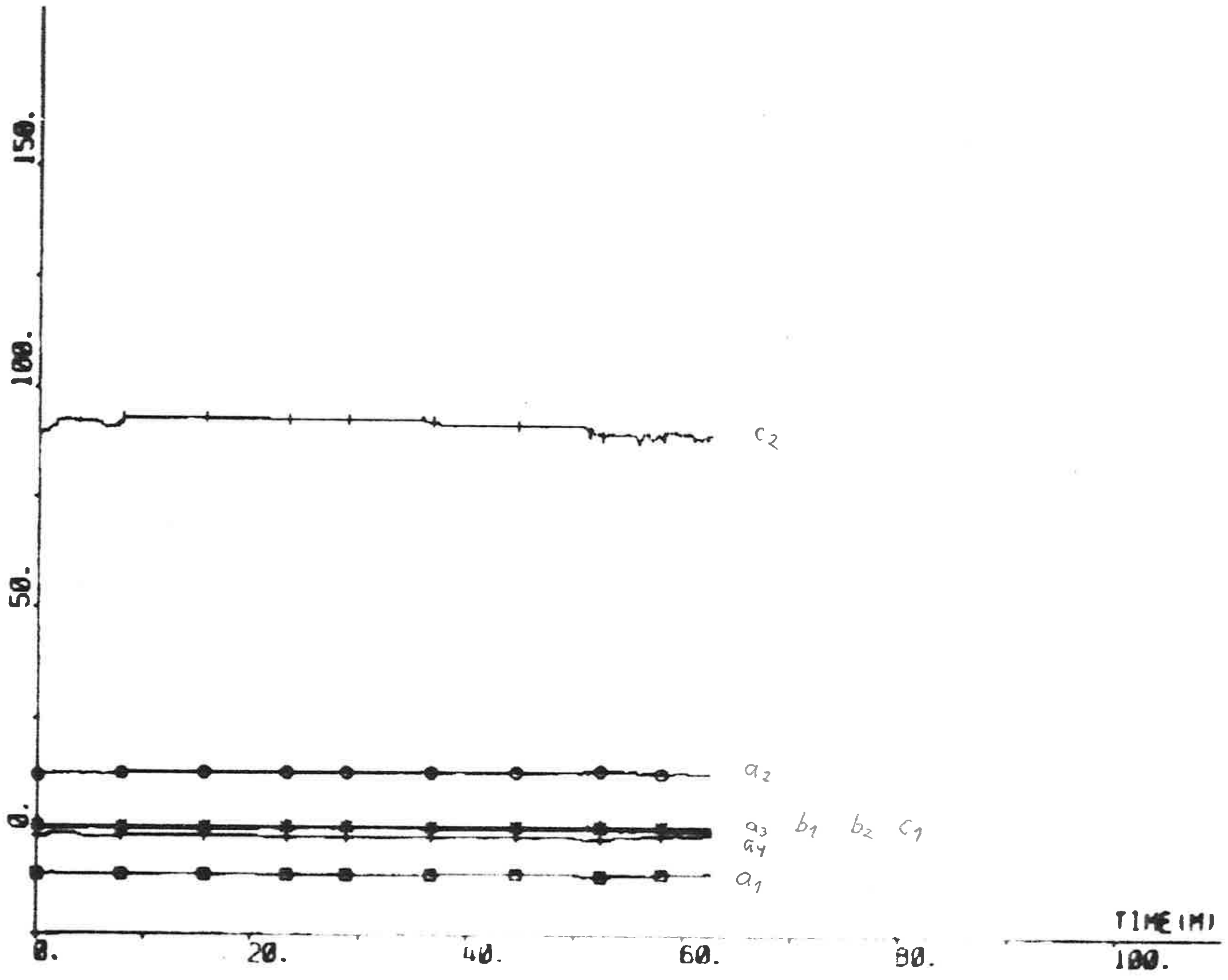



PLOT C3P1(1)-C3P1(2) C3P1(3) ERR1 EPS1 00 020 040 060 -65 15 " DEG
0.
-20.
-40.
-60.
0.
20.
40.
60.
80.
100.
TIME(M)
δ
$\hat{\delta}$
$\delta - \hat{\delta}$
ε_δ

PLOT C3P1(1)-C3P2(3) C3P2(4) C3P2(5) C3P2(6) 00 02 04 06 -6.5 1.5



PLOT C3P1(1)-C3P2(7) C3P2(8) C3P2(9) C3P2(10) C3P2(11) C3P2(12) C3P2(13)



EXPERIMENT C4

Date	1976-04-27	Forward draught	10.9 m
Time	10.53	Aft draught	12.9 m
Duration	49 min	Wind direction	SE (1; see App. A)
Position	S 09°53' W 03°40'	Wind velocity	11 m/s (strong breeze)
ψ_{ref}	145, (147), 165, (159), (129), 125, (126), (131), 145 deg	Wave height	-
r_{ref}	0.1, 0.2 deg/s		

Self-tuning regulator and yaw regulator using estimates from the Kalman filter.

The estimates $\hat{\delta}_0'$, $\hat{d}_v'$, $\hat{d}_r'$ and $\hat{d}_\delta'$ were not updated during the experiment.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -15.46 \\ 18.76 \\ -1.80 \\ -2.39 \\ 0.40 \\ 0.19 \\ 0.29 \\ 108.85 \end{bmatrix} \quad P = \begin{bmatrix} 8.33 & & & & & & & \\ -15.68 & 51.68 & & & & & & \\ 9.50 & -57.08 & 84.40 & & & & & \\ -1.80 & 20.73 & -37.65 & 19.44 & & & & \\ 0.18 & -1.20 & 1.69 & -0.69 & 0.04 & & & \\ -0.06 & 0.17 & -0.36 & 0.26 & 0.00 & 0.01 & & \\ -1.67 & 2.09 & 0.81 & -1.35 & 0.00 & -0.02 & 1.46 & \\ 6.98 & -15.94 & 16.67 & -9.62 & 0.67 & -0.57 & 22.66 & 971.56 \end{bmatrix}$$

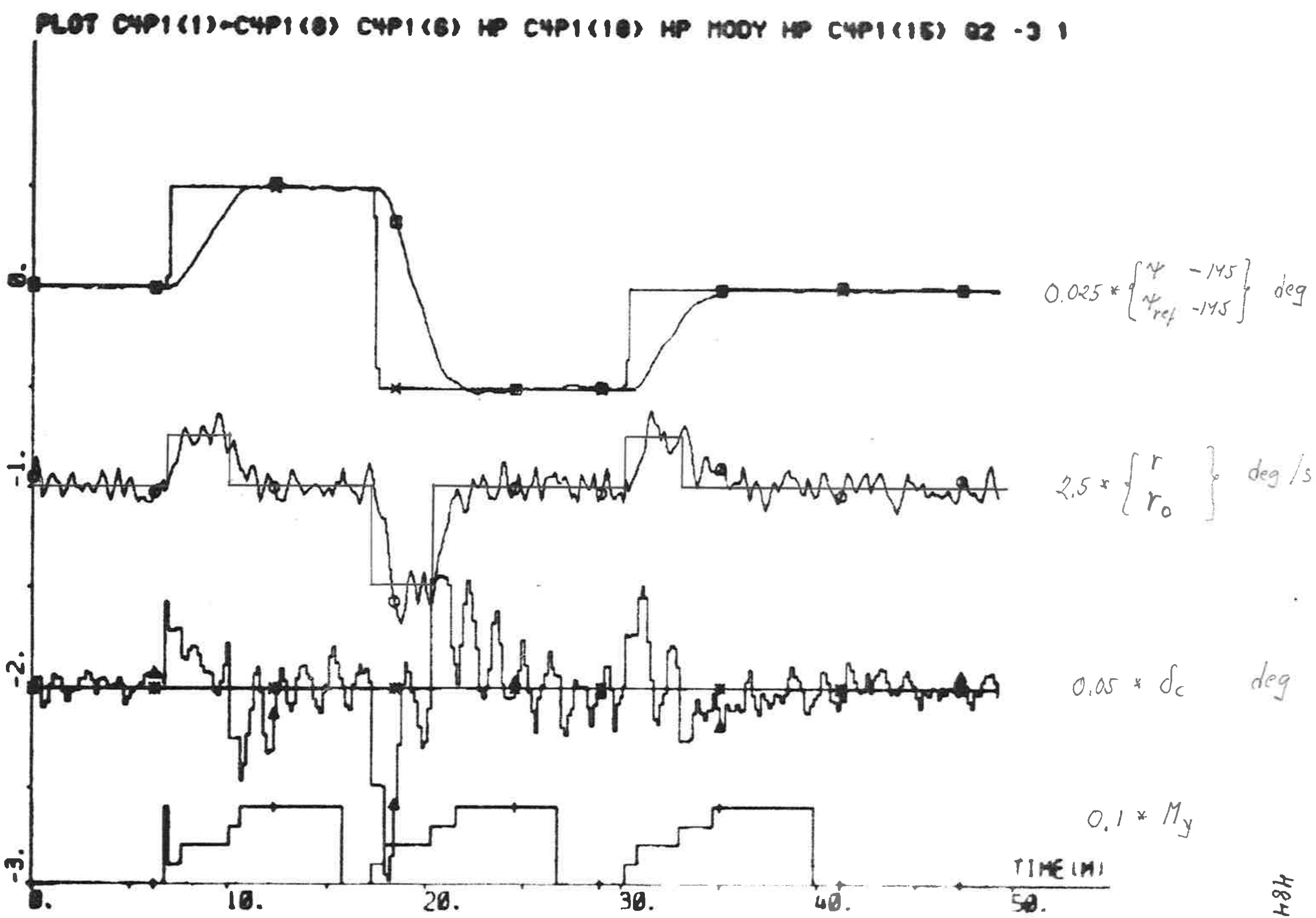
$a_1 + a_2 + a_3 + a_4 = -0.89$

$\hat{\delta}_0 = -0.4$ deg $\hat{d}_v = 0.10$ knots $\hat{d}_r = 0.003$ deg/s $\hat{d}_\delta = 1.5$ deg

$\bar{\delta}_c = -0.5$ deg (Initial value: -0.1 deg)

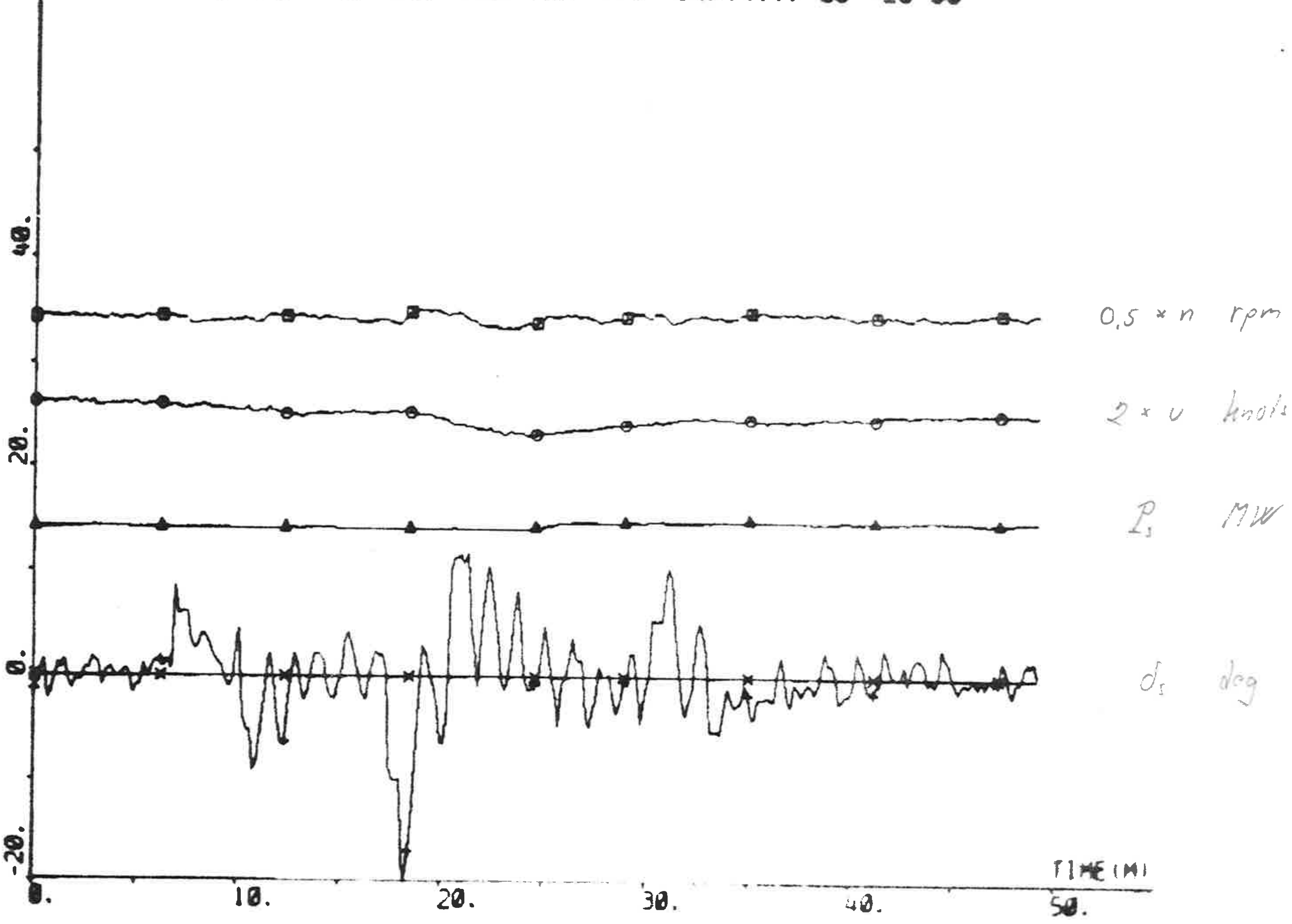
Statistics (mean value and standard deviation)

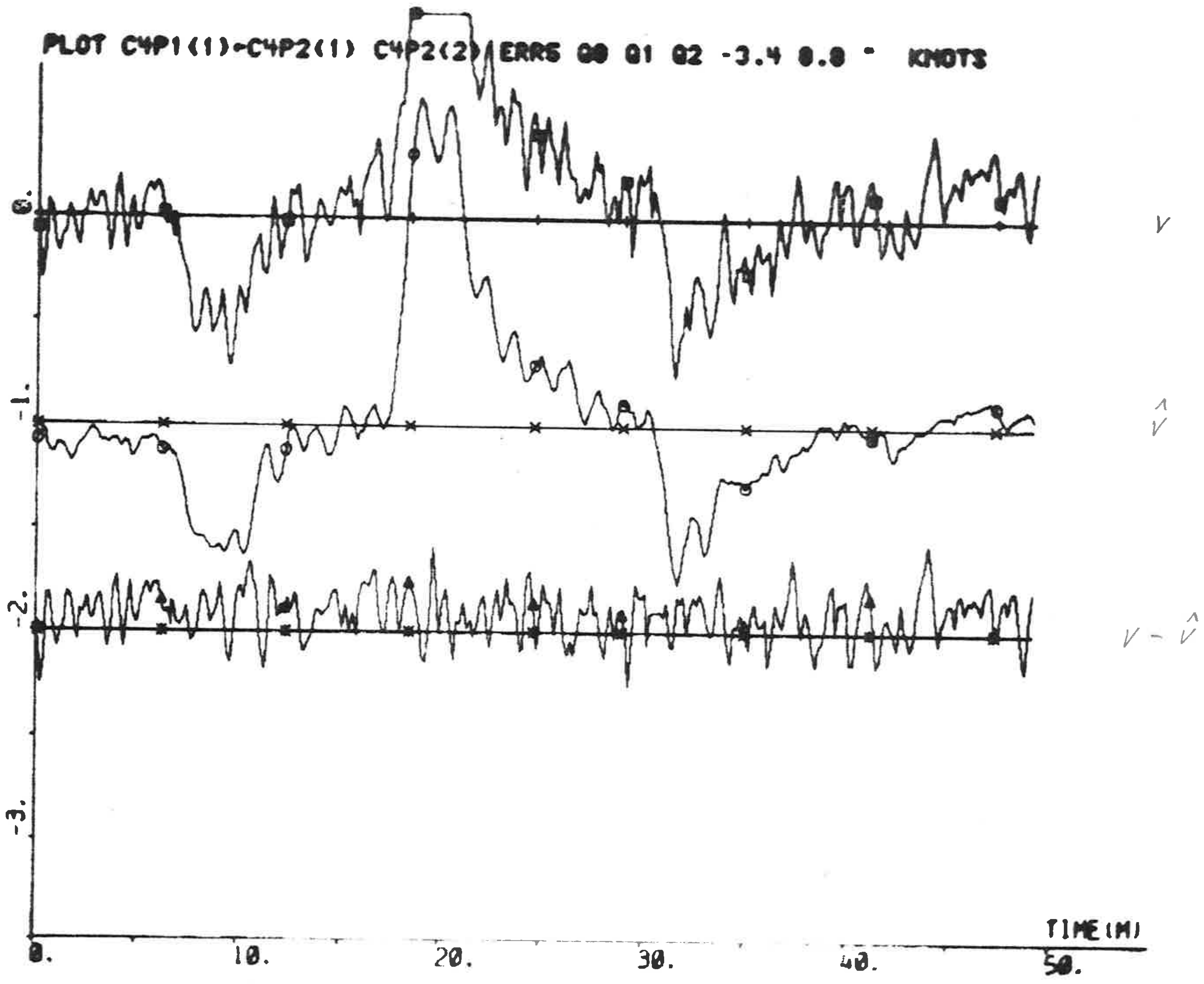
n	69.1 ± 0.8 rpm	ε_v	0.00 ± 0.03 knots
u	12.5 ± 0.4 knots	ε_r	0.00 ± 0.02 deg/s
P_s	14.5 ± 0.4 MW	ε_ψ	0.00 ± 0.06 deg
		ε_δ	0.0 ± 0.6 deg

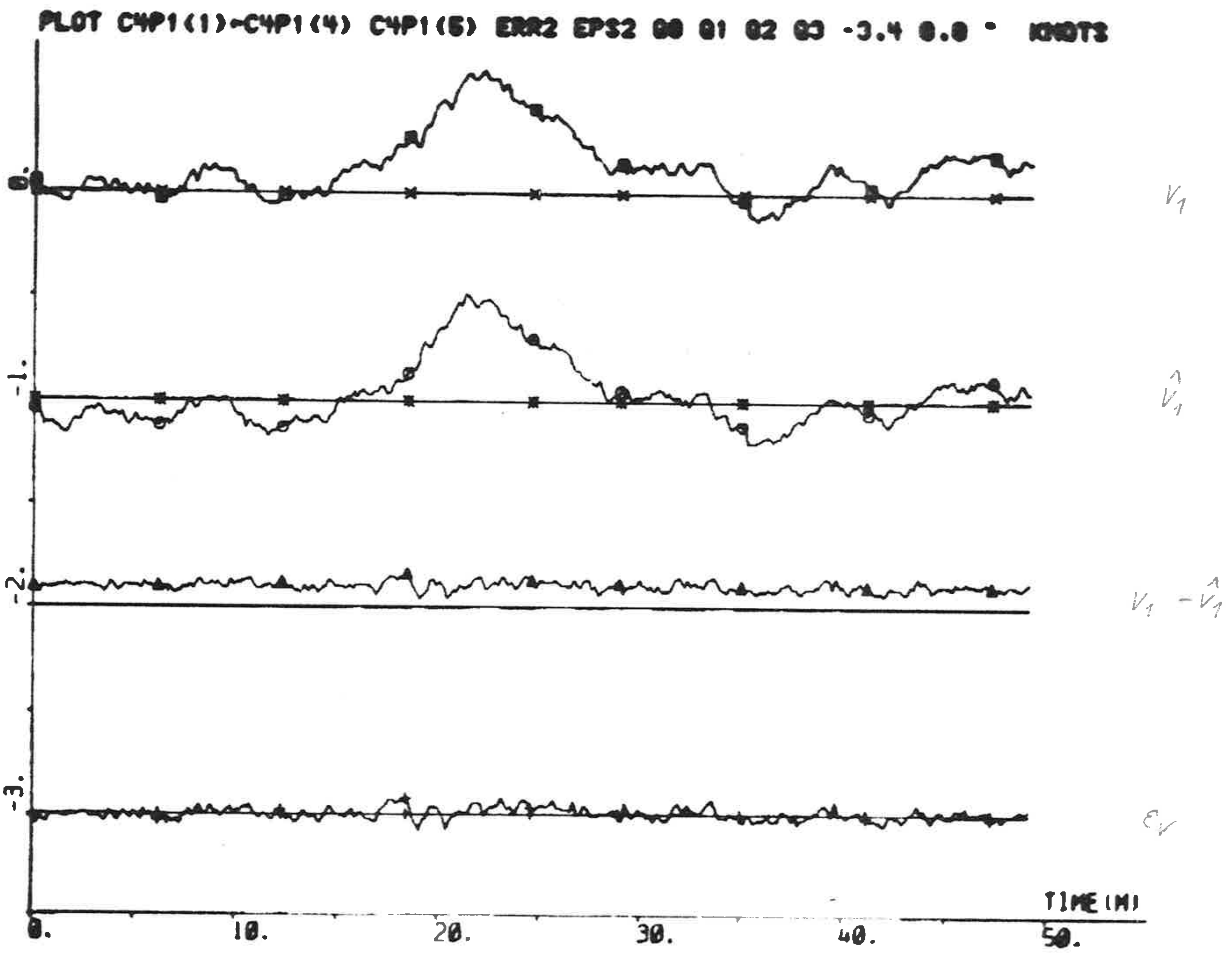


PLOT C4P1(1)-C4P1(8) C4P1(6) HP C4P1(10) HP MODY HP C4P1(15) 02 -3 1
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)
0.025 * {Ψ -145; Ψref -145} deg
2.5 * {r; r0} deg/s
0.05 * δc deg
0.1 * My

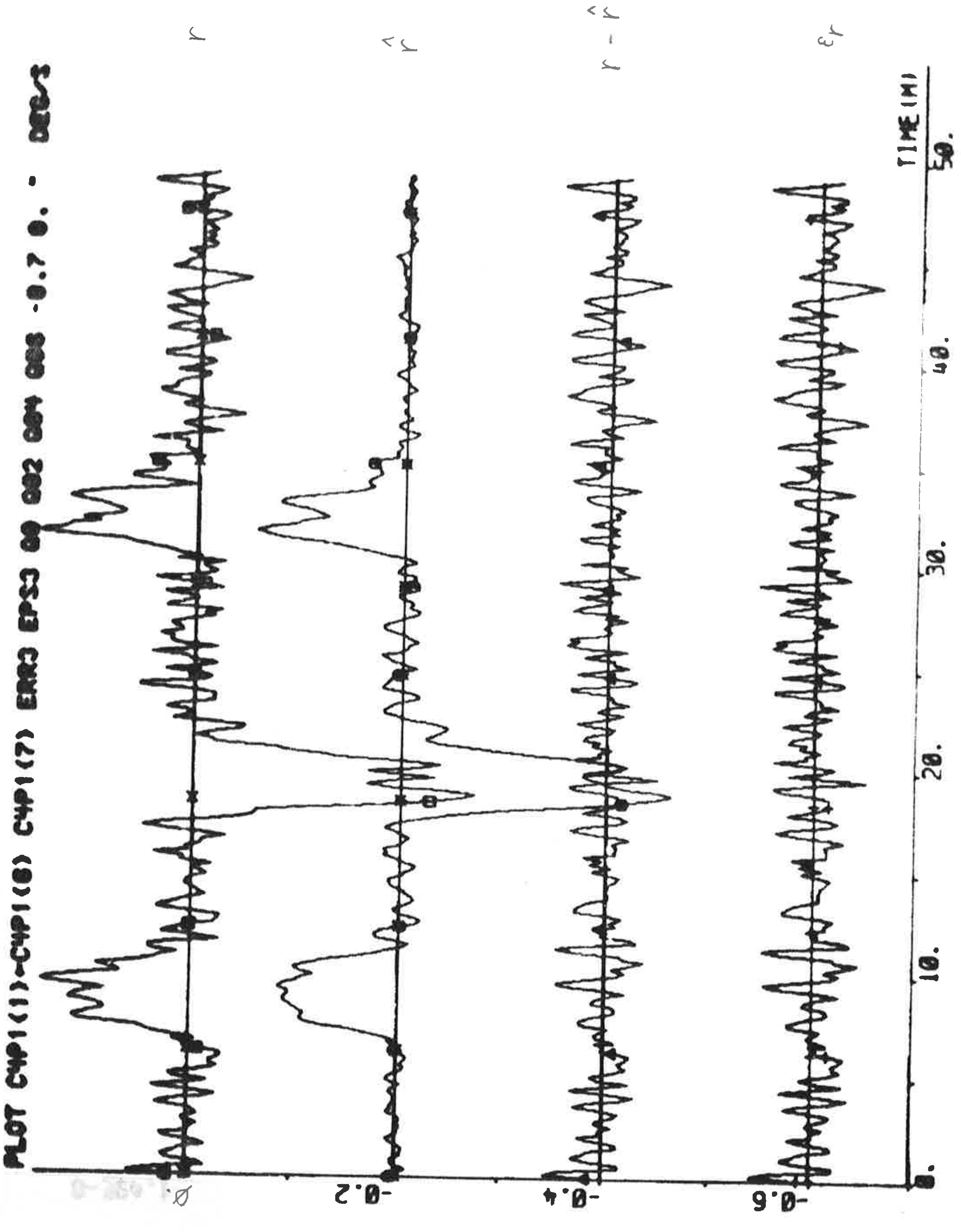
PLOT C4P1(1)-C4P1(13) C4P1(12) C4P1(14) C4P1(11) 00 -20 50

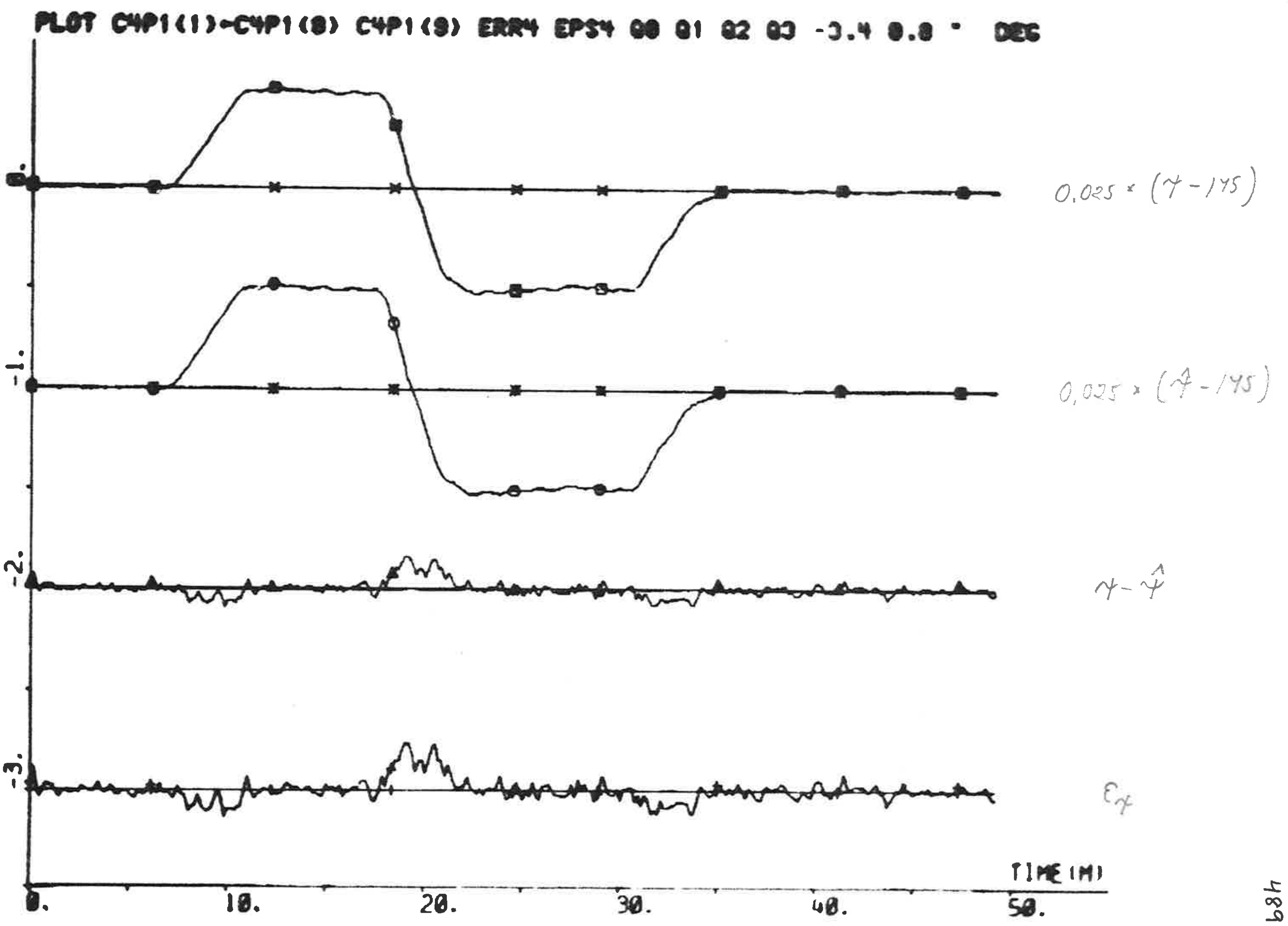


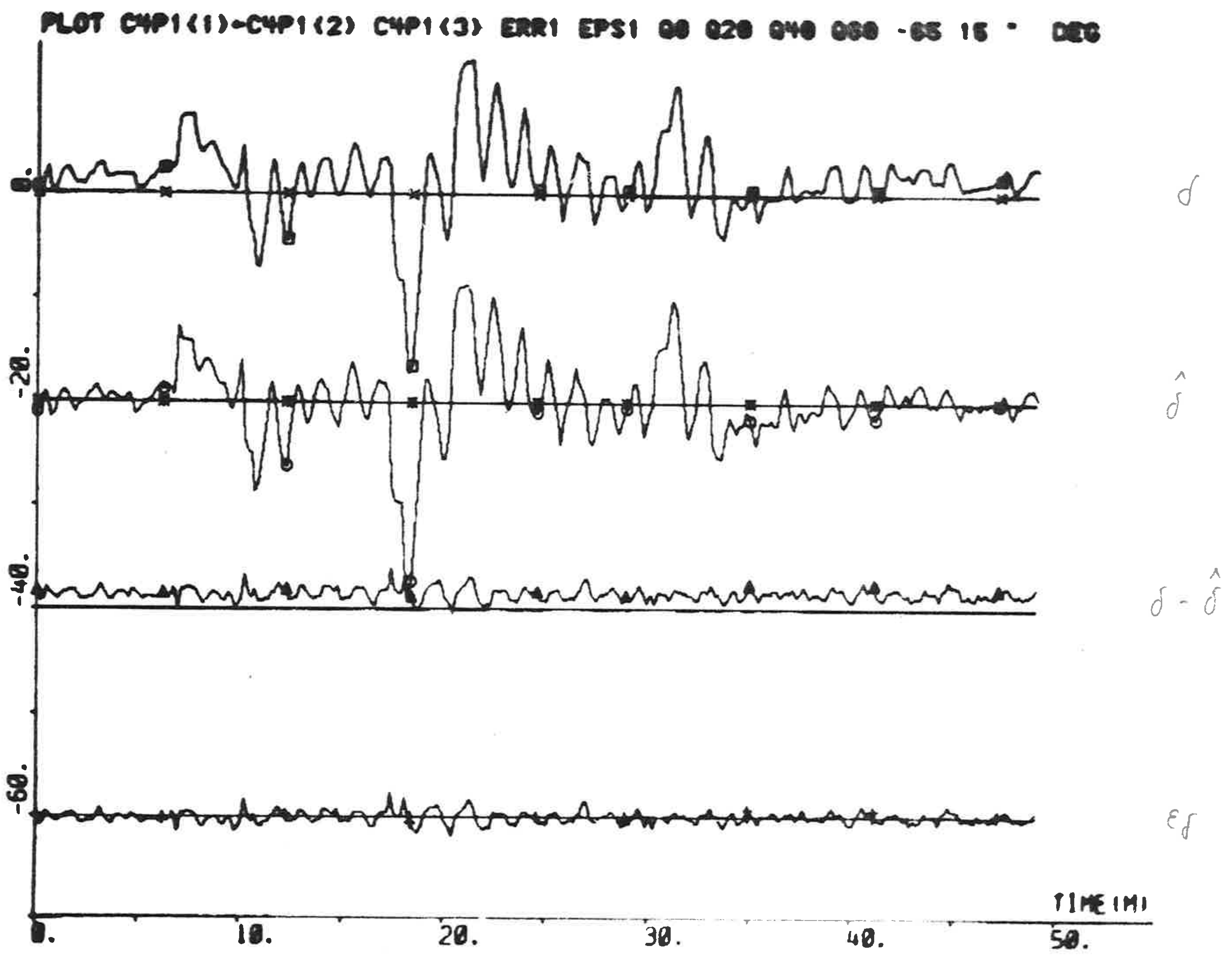

PLOT C4P1(1)-C4P2(1) C4P2(2) ERRS 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)

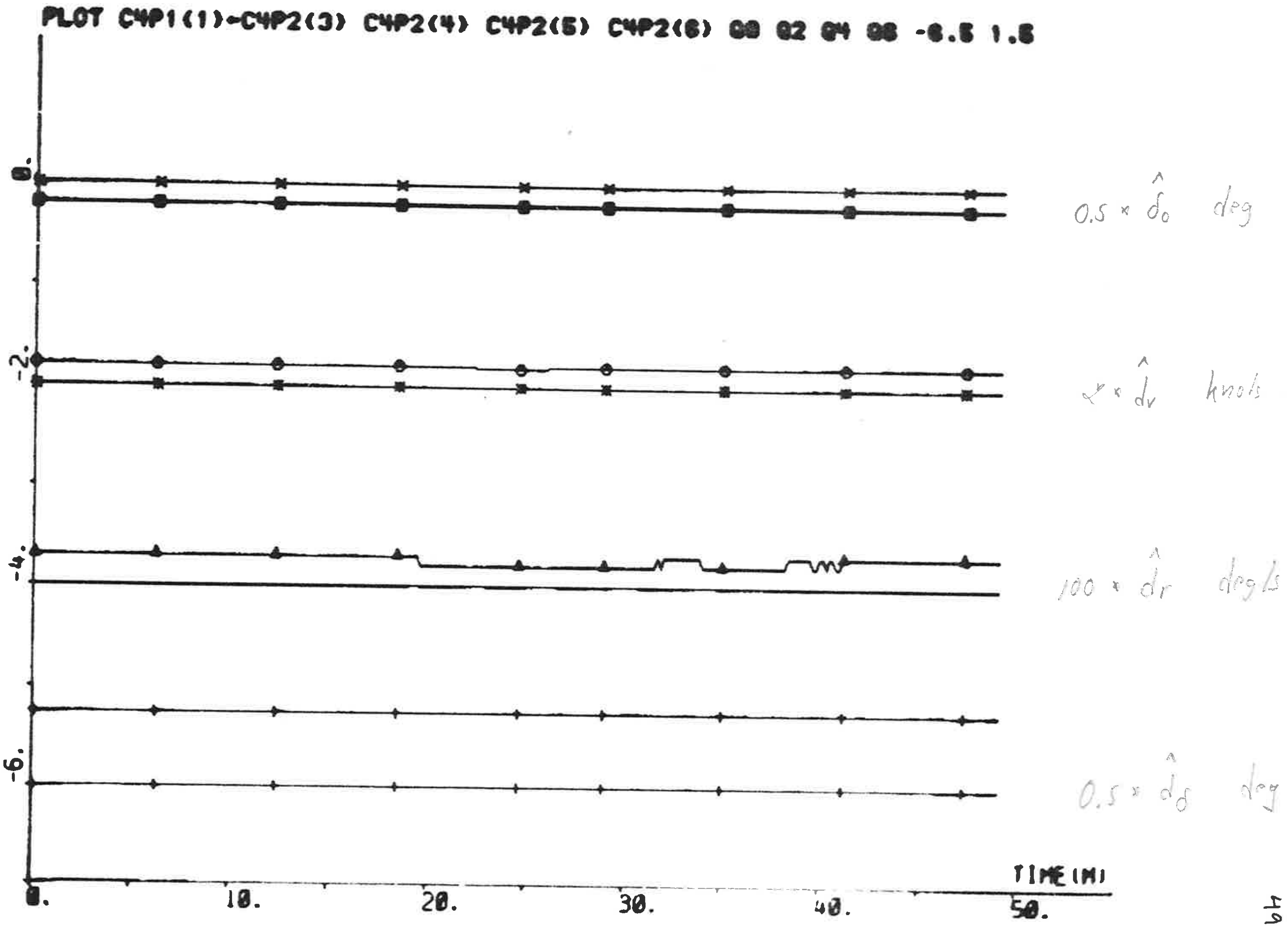


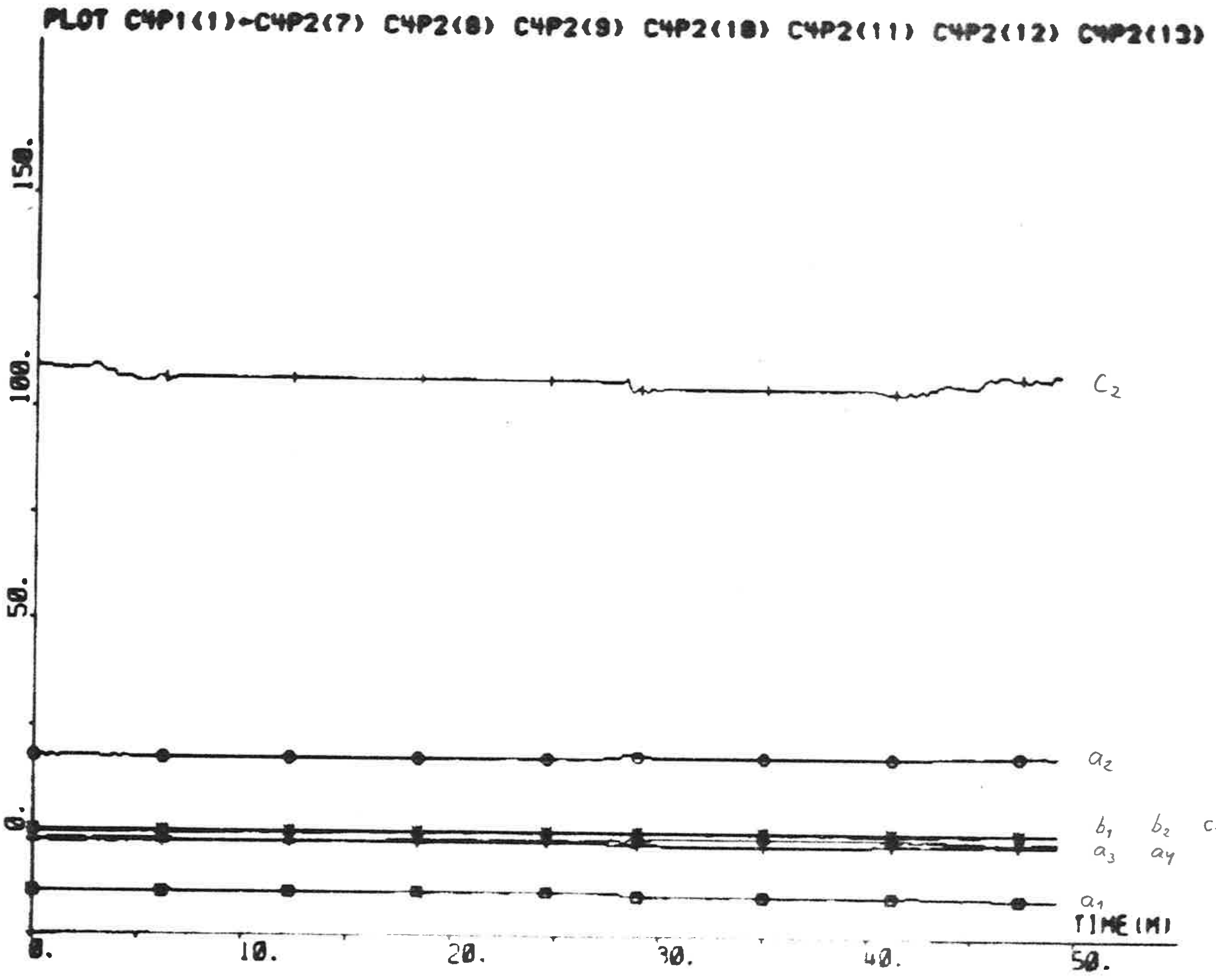
PLOT C4P1(1)-C4P1(4) C4P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 • KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT C4P1(1)-C4P1(6) C4P1(7) ERR3 EPS3 00 0S2 0S4 0S5 -0.7 0. DEG/S
TIME (M)
0.
10.
20.
30.
40.
50.
-0.2
-0.4
-0.6


PLOT C4P1(1)-C4P1(8) C4P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.8 ' DEG
0.
-1.
-2.
-3.
0.025 * (ψ - 145)
0,025 * (ψ - 145)
ψ - ψ̂
ε_ψ
TIME (M)
0.
10.
20.
30.
40.
50.


PLOT C4P1(1)-C4P1(2) C4P1(3) ERR1 EPS1 Q0 Q20 Q40 Q60 -05 15 " DEG
0.
-20.
-40.
-60.
0.
10.
20.
30.
40.
50.
TIME(M)
δ
δ̂
δ - δ̂
εδ


PLOT C4P1(1)-C4P2(3) C4P2(4) C4P2(5) C4P2(6) 00 02 04 08 -6.5 1.5
0.
-2.
-4.
-6.
0.
10.
20.
30.
40.
50.
TIME(M)
0.5 × $\hat{\delta}_o$ deg
knots
100 × $\hat{d}_r$ deg/s
0.5 × $\hat{d}_\delta$ deg


PLOT C4P1(1)-C4P2(7) C4P2(8) C4P2(9) C4P2(10) C4P2(11) C4P2(12) C4P2(13)
150.
100.
50.
0.
C2
a2
b1 b2 c1
a3 a4
a1
TIME(M)
0.
10.
20.
30.
40.
50.

EXPERIMENT C5

Date	1976-04-27	Forward draught	10.9 m
Time	14.10	Aft draught	12.9 m
Duration	27 min	Wind direction	SE (1; see App. A)
Position	S 10°27' W 03°14'	Wind velocity	8 m/s (moderate breeze)
ψ_{ref}	144, (150), 149, (147), 139, 144 deg	Wave height	-
r_{ref}	0.1 deg/s		

Self-tuning regulator and yaw regulator using estimates from the Kalman filter.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -10.07 \\ 8.90 \\ 5.69 \\ -4.90 \\ 0.41 \\ 0.05 \\ -1.54 \\ 48.49 \end{bmatrix} \quad P = \begin{bmatrix} 8.31 & & & & & & & \\ -13.48 & 35.98 & & & & & & \\ 3.24 & -29.55 & 47.87 & & & & & \\ 2.41 & 6.81 & -21.85 & 13.31 & & & & \\ 0.13 & -0.89 & 1.18 & -0.41 & 0.05 & & & \\ 0.00 & 0.14 & -0.44 & 0.33 & -0.01 & 0.03 & & \\ -1.08 & 1.49 & 0.26 & -0.68 & -0.01 & -0.01 & 1.09 & \\ 23.69 & -42.91 & 0.47 & 18.03 & 1.56 & -0.45 & 17.22 & 1078.29 \end{bmatrix}$$

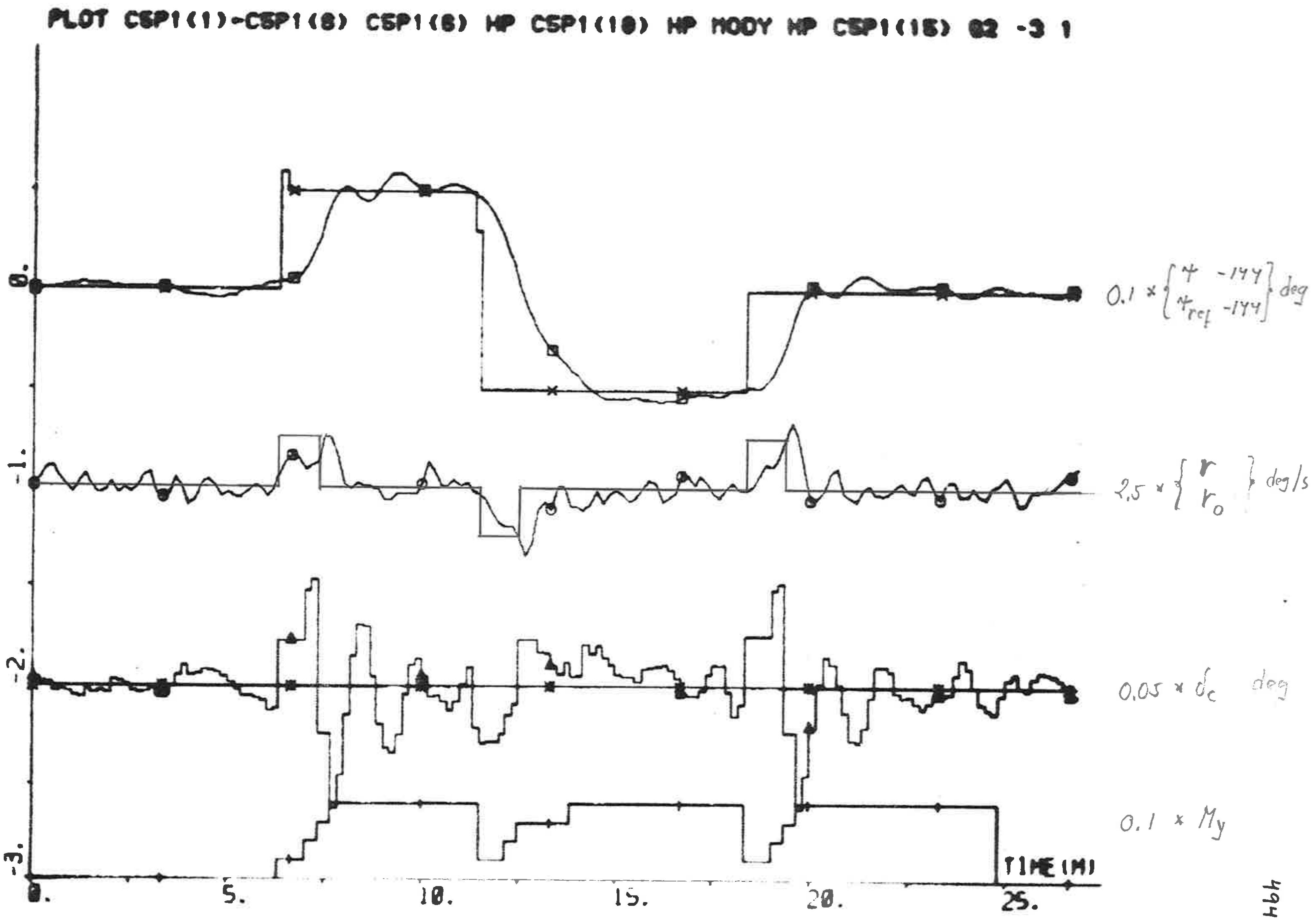
$a_1 + a_2 + a_3 + a_4 = -0.38$

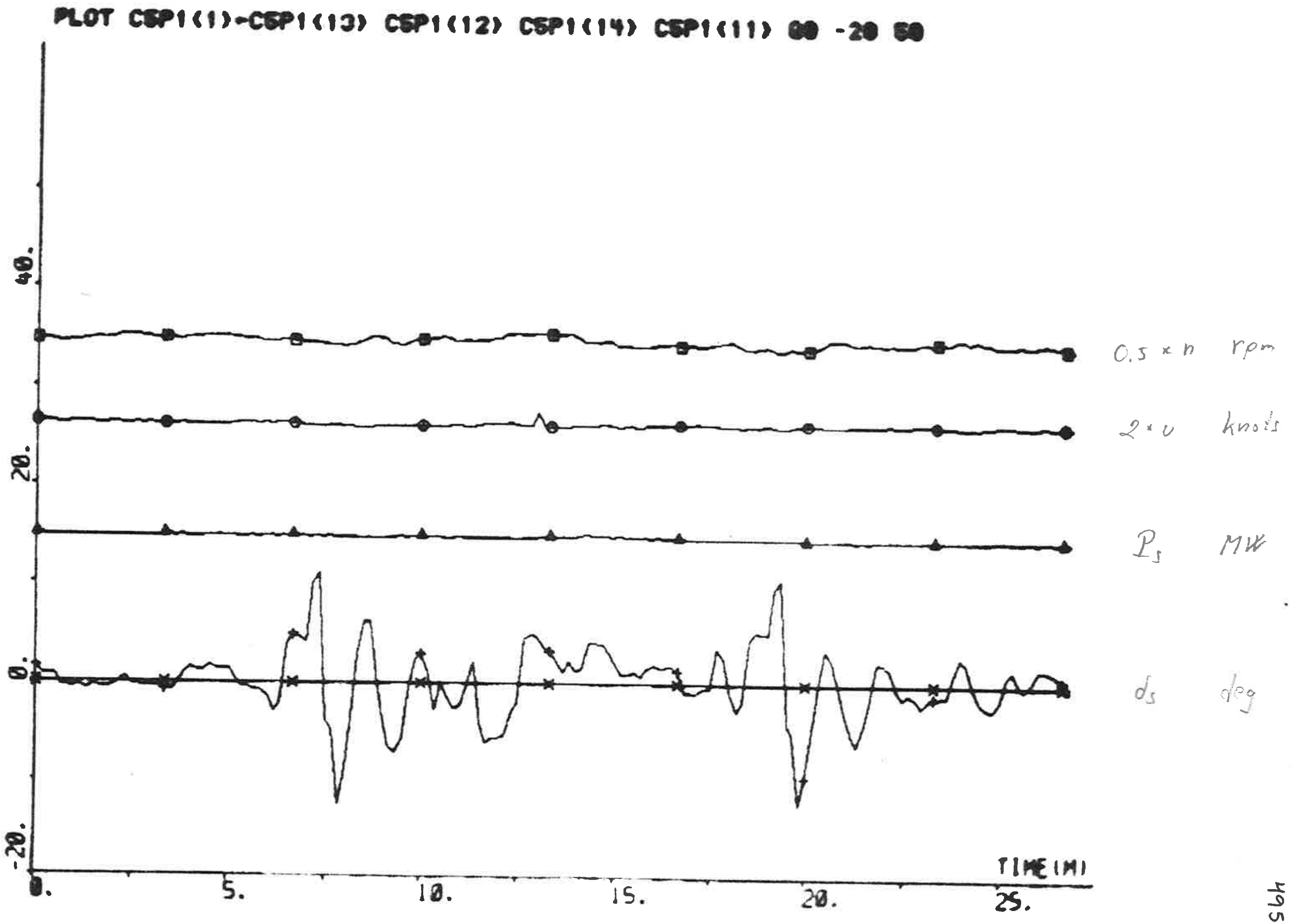
$\hat{\delta}_0 = 0.1$ deg $\hat{d}_v = 0.13$ knots $\hat{d}_r = 0.002$ deg/s $\hat{d}_\delta = 1.5$ deg

$\bar{\delta}_c = 0.4$ deg (Initial value: 0.3 deg)

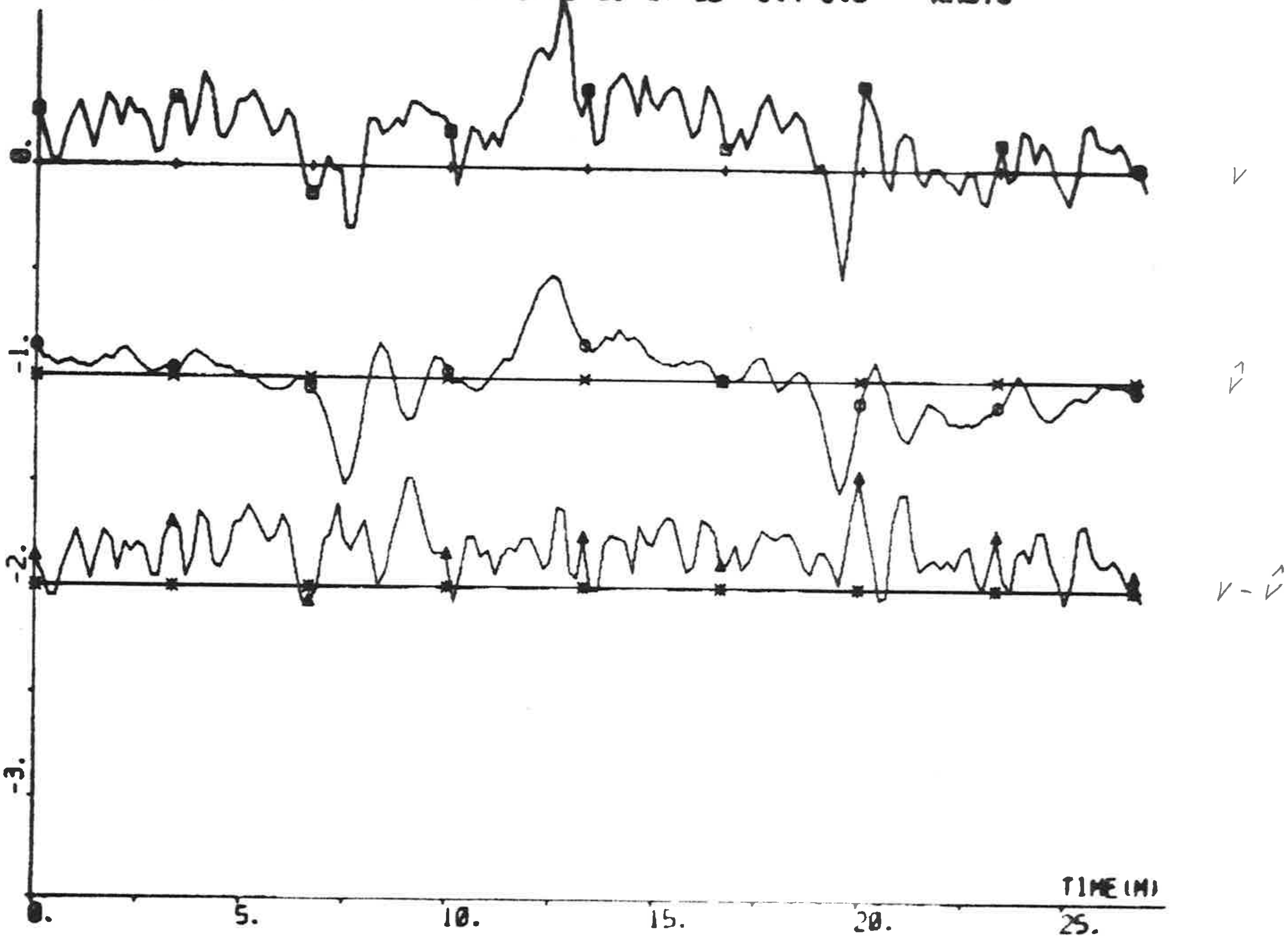
Statistics (mean value and standard deviation)

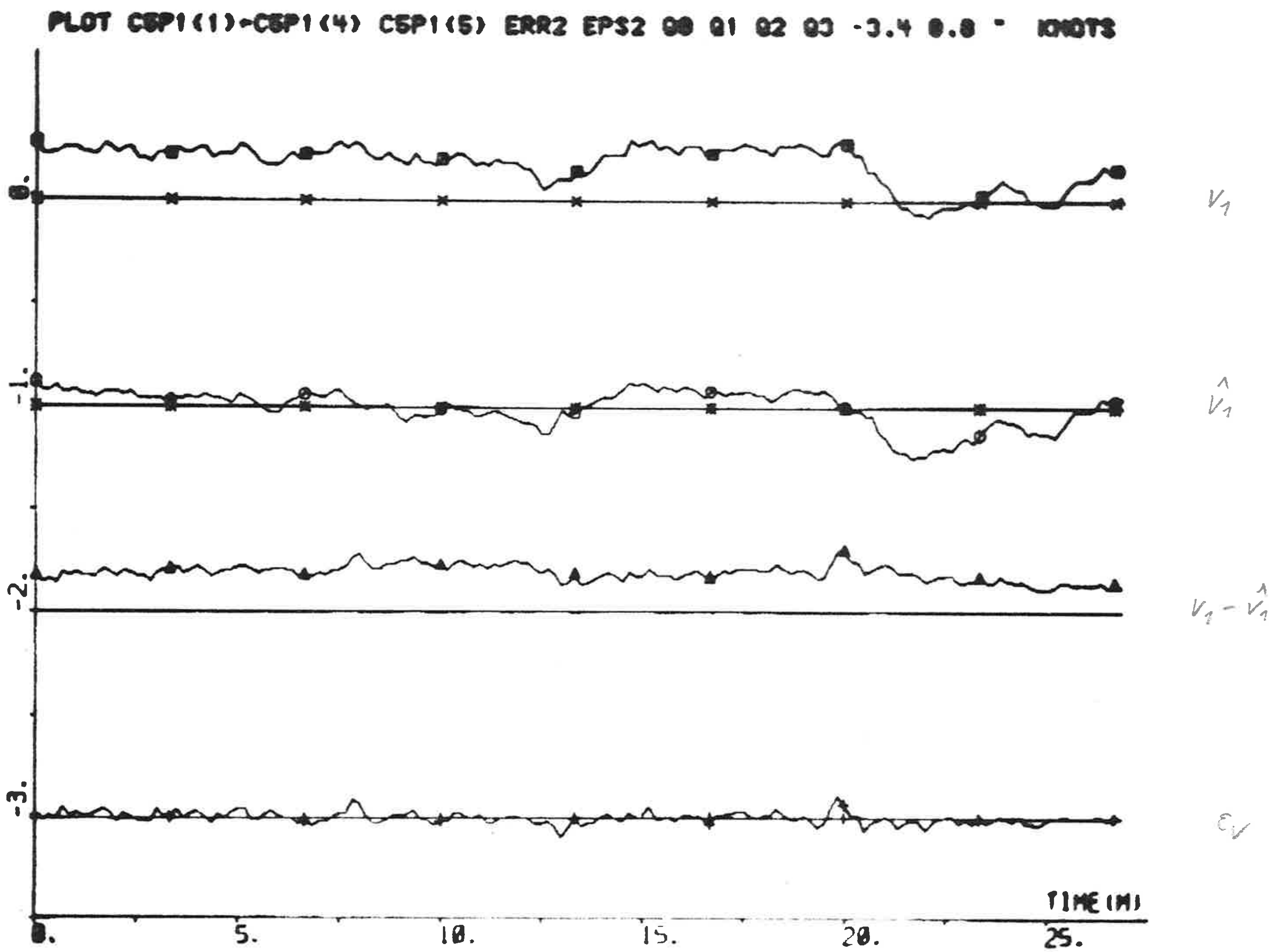
n	69.7 ± 0.7 rpm	ε_v	0.00 ± 0.03 knots
u	13.2 ± 0.1 knots	ε_r	0.00 ± 0.02 deg/s
P_s	14.7 ± 0.2 MW	ε_ψ	0.00 ± 0.03 deg
		ε_δ	0.0 ± 0.6 deg


PLOT CSP1(1)-CSP1(8) CSP1(6) HP CSP1(10) HP MODY HP CSP1(15) 02 -3 1
0.
-1.
-2.
-3.
0.1 × {ψ -144, ψref -144} deg
2.5 × {r, r0} deg/s
0.05 × δc deg
0.1 × My
TIME(M)
0.
5.
10.
15.
20.
25.

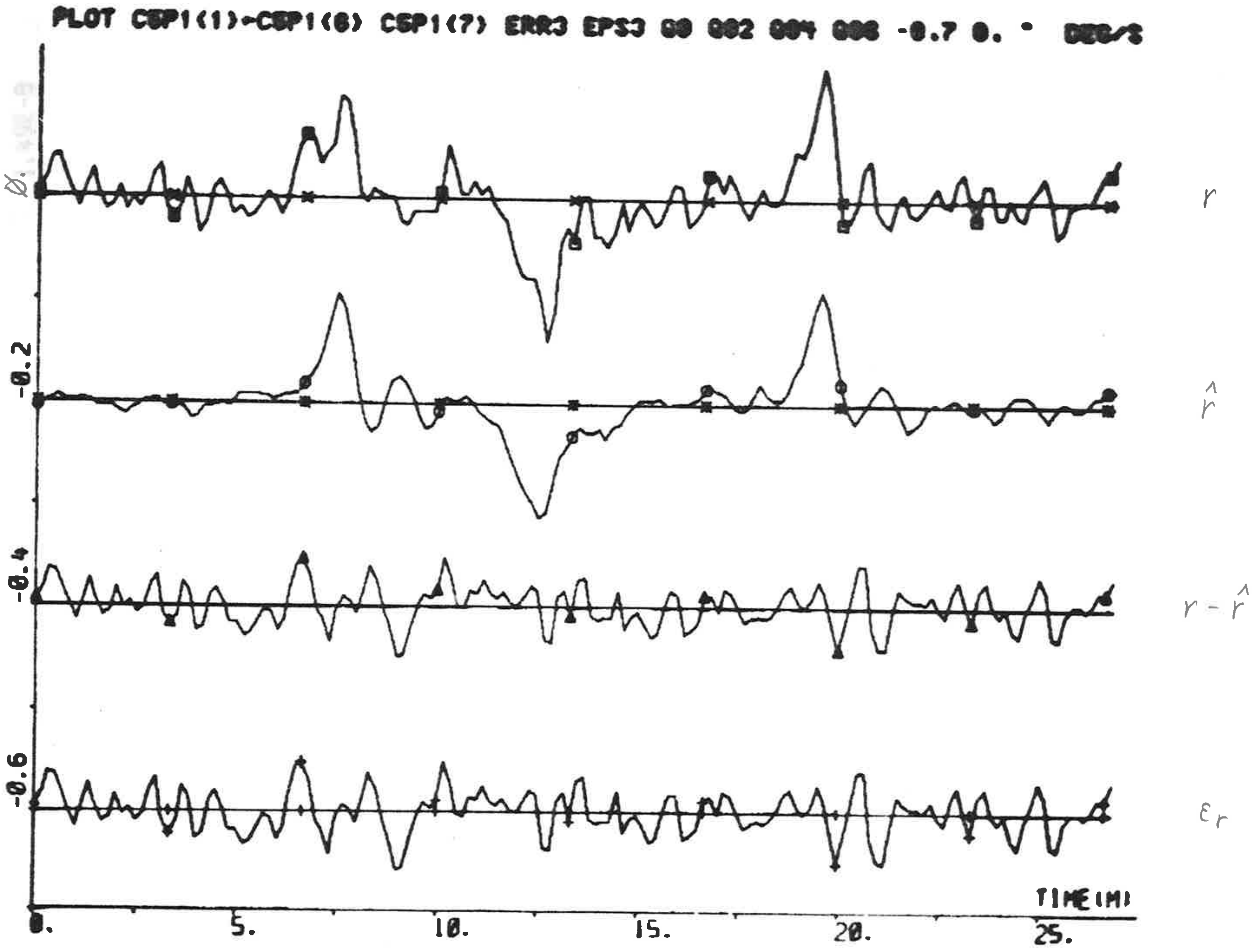

PLOT CSP1(1)-CSP1(13) CSP1(12) CSP1(14) CSP1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 × n rpm
2 × v knots
P_s MW
d_s deg

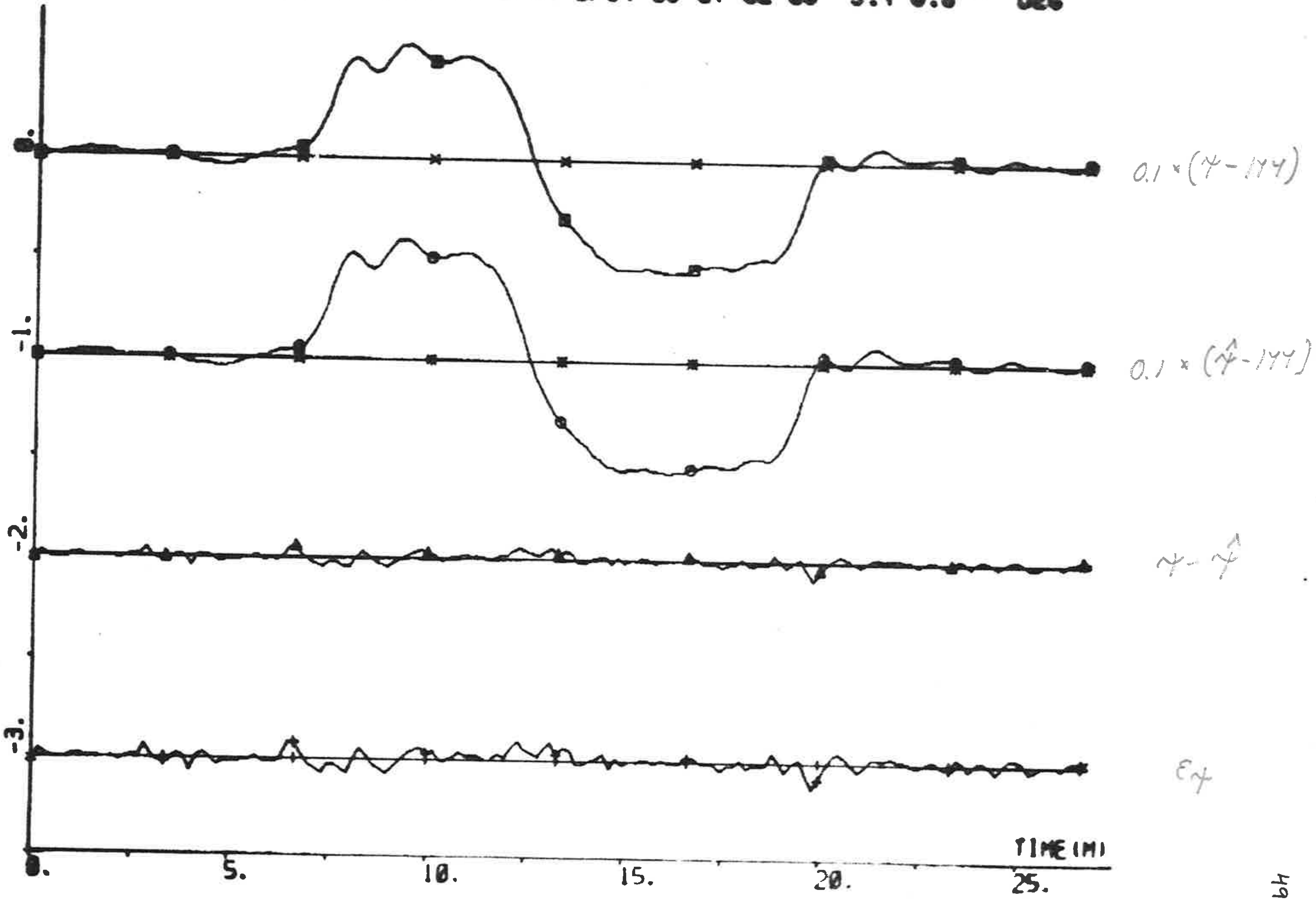
PLOT CSP1(1)-CSP2(1) CSP2(2) ERRS Q0 Q1 Q2 -3.4 0.0 * KNOTS

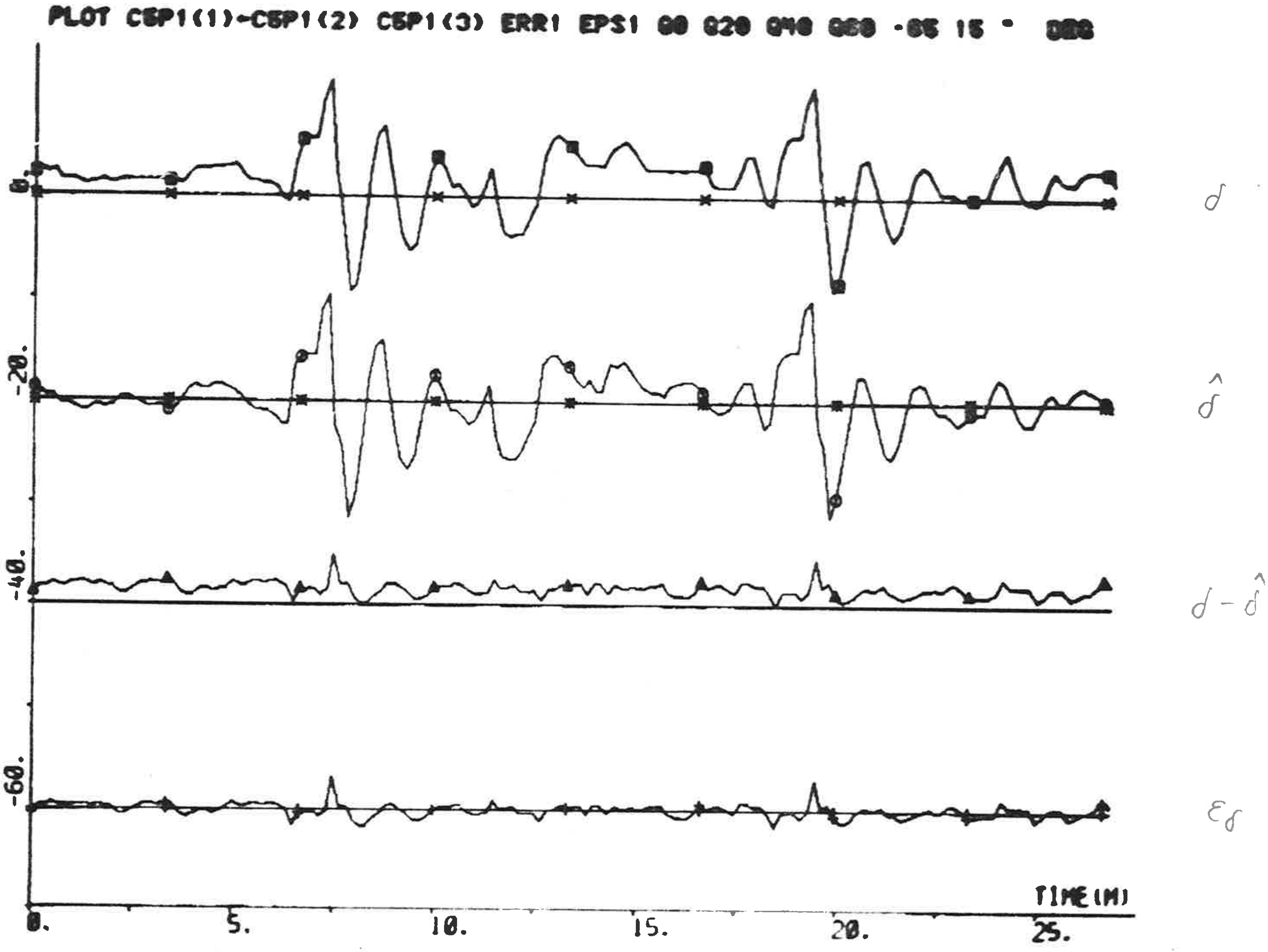




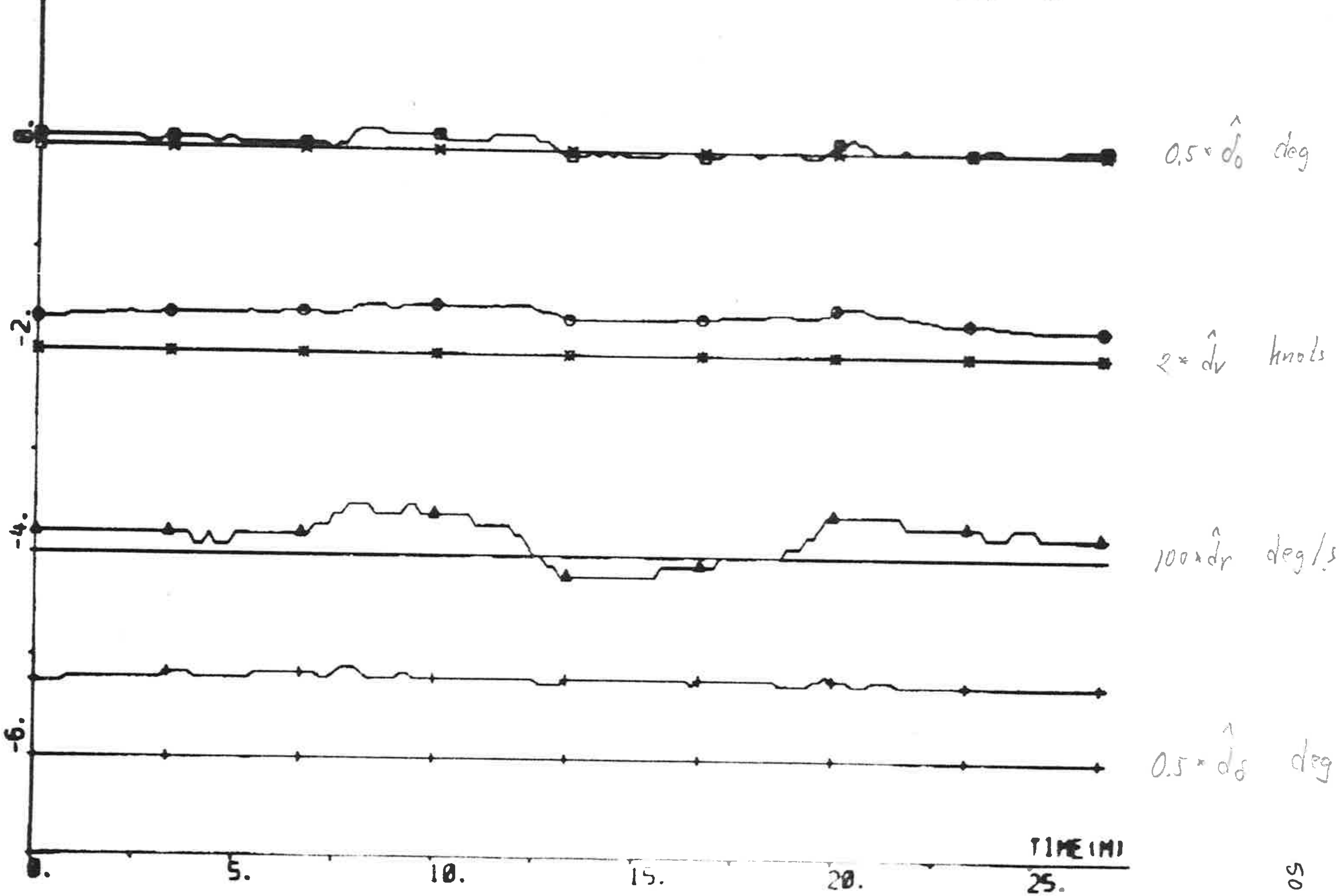
PLOT CSP1(1)-CSP1(4) CSP1(5) ERR2 EPS2 00 01 02 03 -3.4 0.8 - KNOTS
0.
-1.
-2.
-3.
TIME(H)
0.
5.
10.
15.
20.
25.

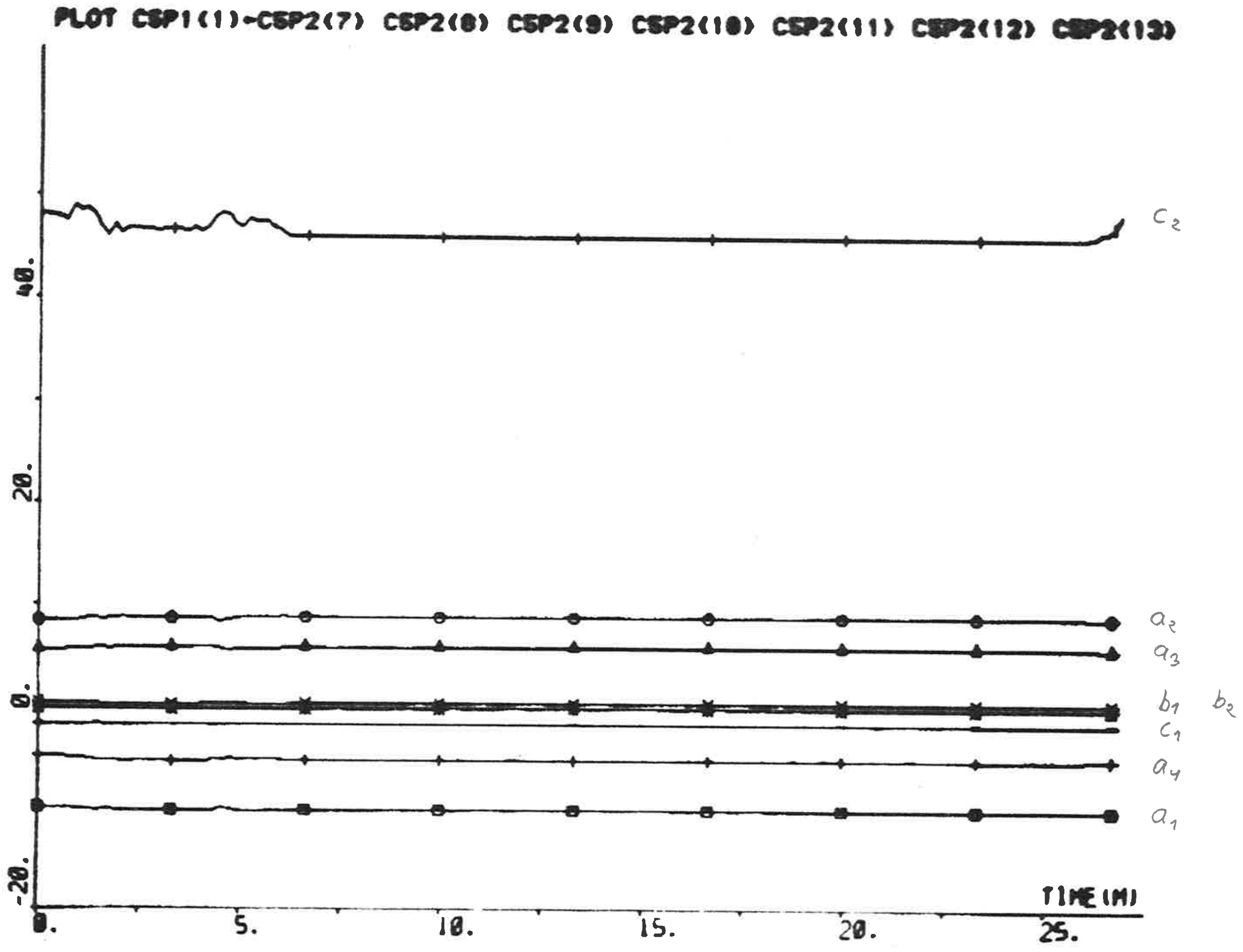

PLOT CSP1(1)-CSP1(6) CSP1(7) ERR3 EPS3 00 002 004 006 -0.7 0. DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT CSP1(1)-CSP1(8) CSP1(9) ERR4 EPS4 00 01 02 03 -3.4 0.0 - DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT CBP1(1)-CBP1(2) CBP1(3) ERR1 EPS1
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)
δ
δ̂
δ - δ̂
εδ

PLOT CSP1(1)-CSP2(3) CSP2(4) CSP2(5) CSP2(6) 00 02 04 06 -8.5 1.5




PLOT CSP1(1)-CSP2(7) CSP2(8) CSP2(9) CSP2(10) CSP2(11) CSP2(12) CSP2(13)
c2
a2
a3
b1
b2
c1
a4
a1
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME (H)

EXPERIMENT C6

Date	1976-04-27	Forward draught	10.9 m
Time	14.51	Aft draught	12.9 m
Duration	72 min	Wind direction	S (1; see App. A)
Position	S 10°34' W 03°09'	Wind velocity	12 m/s (strong breeze)
ψ_{ref}	144, (145), 146, 142, 144, 145, 143, 144 deg	Wave height	-
r_{ref}	0.1 deg/s		

Self-tuning regulator and yaw regulator using estimates from the Kalman filter

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 6 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -11.31 \\ 11.45 \\ 4.34 \\ -4.95 \\ 0.37 \\ 0.08 \\ -0.96 \\ 61.38 \end{bmatrix} \qquad P = \begin{bmatrix} 9.13 & & & & & & & \\ -19.56 & 63.44 & & & & & & \\ 12.93 & -67.50 & 95.10 & & & & & \\ -2.45 & 23.89 & -41.28 & 20.14 & & & & \\ 0.33 & -1.71 & 2.28 & -0.91 & 0.07 & & & \\ -0.11 & 0.49 & -0.78 & 0.40 & -0.02 & 0.02 & & \\ -1.62 & 2.83 & -0.97 & -0.24 & -0.03 & 0.00 & 1.16 & \\ 12.86 & -22.71 & -4.52 & 13.10 & 1.31 & -0.45 & 17.41 & 984.28 \end{bmatrix}$$

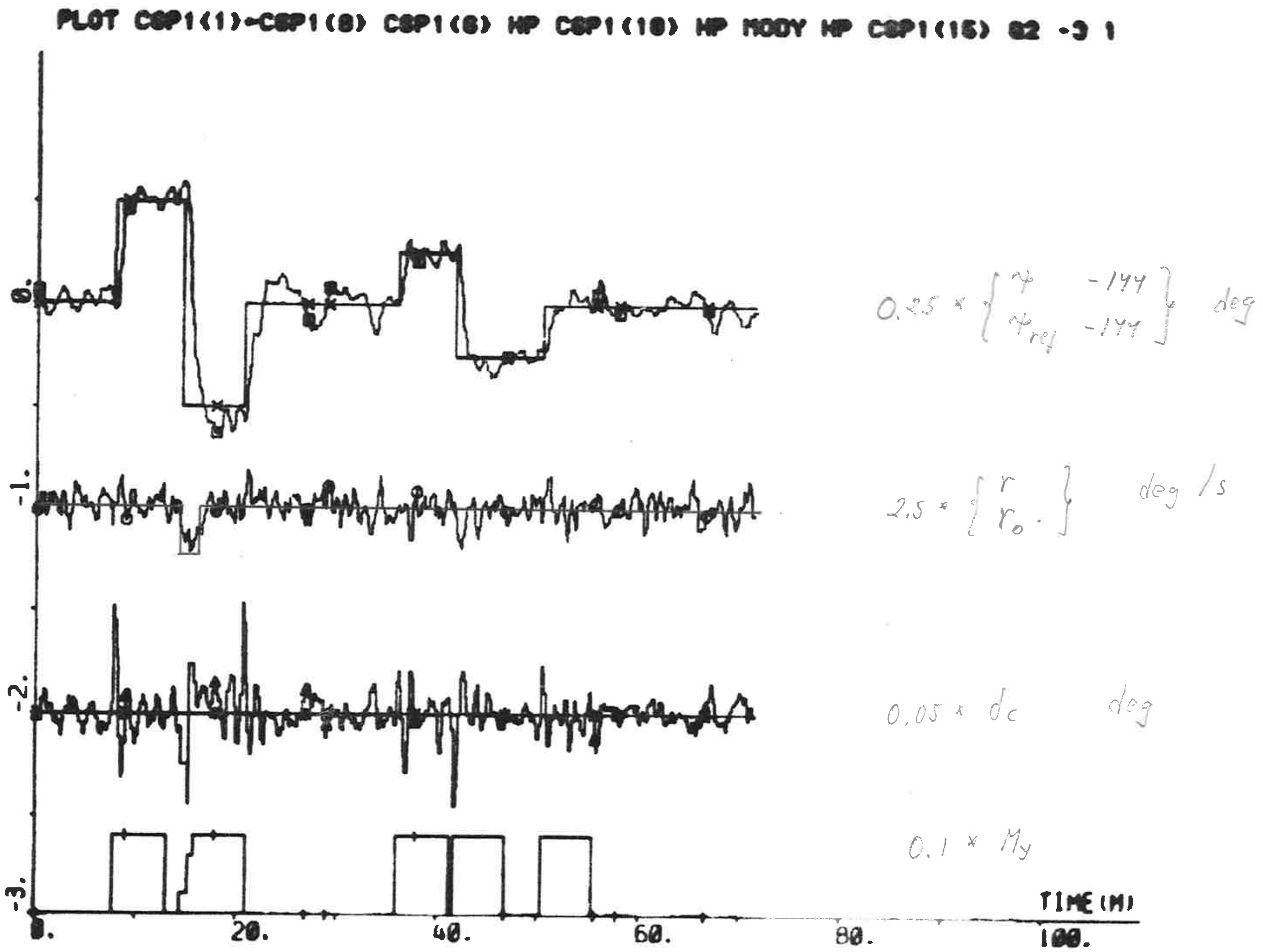
$a_1 + a_2 + a_3 + a_4 = -0.47$

$\hat{\delta}_0 = -0.1$ deg $\hat{d}_v = 0.19$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.5$ deg

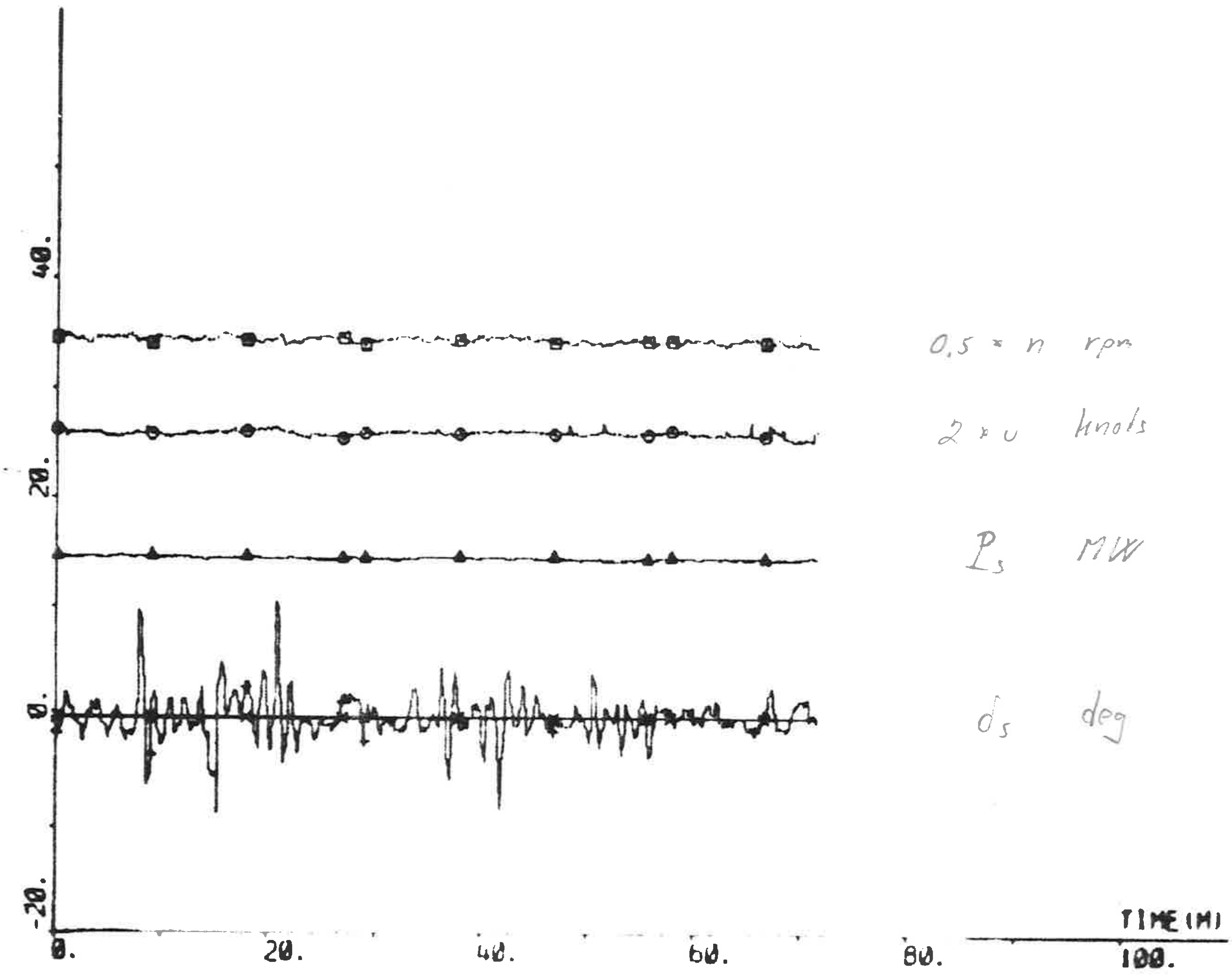
$\bar{\delta}_c = -0.2$ deg (Initial value: 0.2 deg)

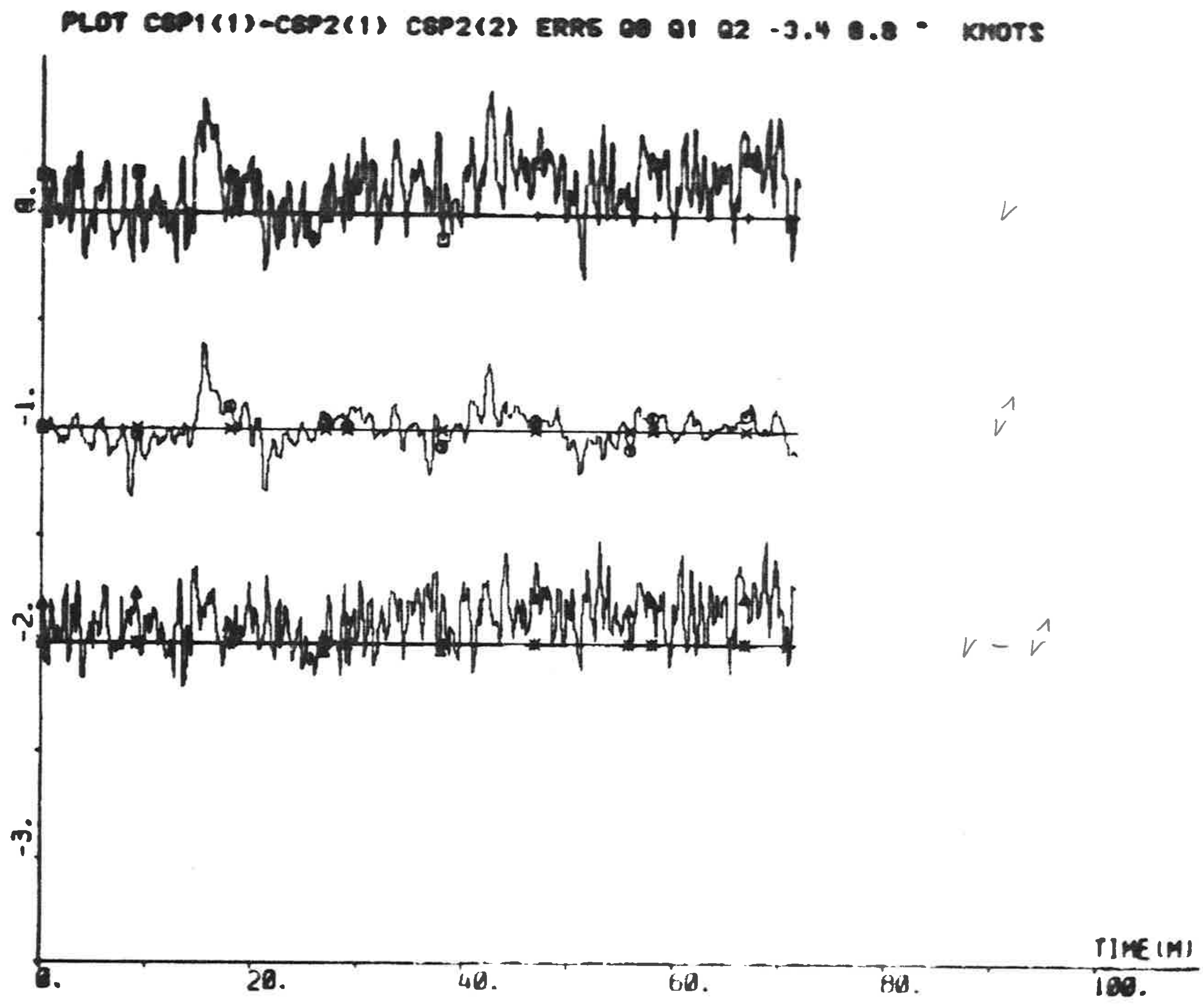
Statistics (mean value and standard deviation)

n	69.0 ± 0.4 rpm	ε_v	0.00 ± 0.02 knots
u	13.0 ± 0.1 knots	ε_r	0.00 ± 0.02 deg/s
P_s	14.4 ± 0.1 MW	ε_ψ	0.00 ± 0.03 deg
		ε_δ	0.0 ± 0.6 deg

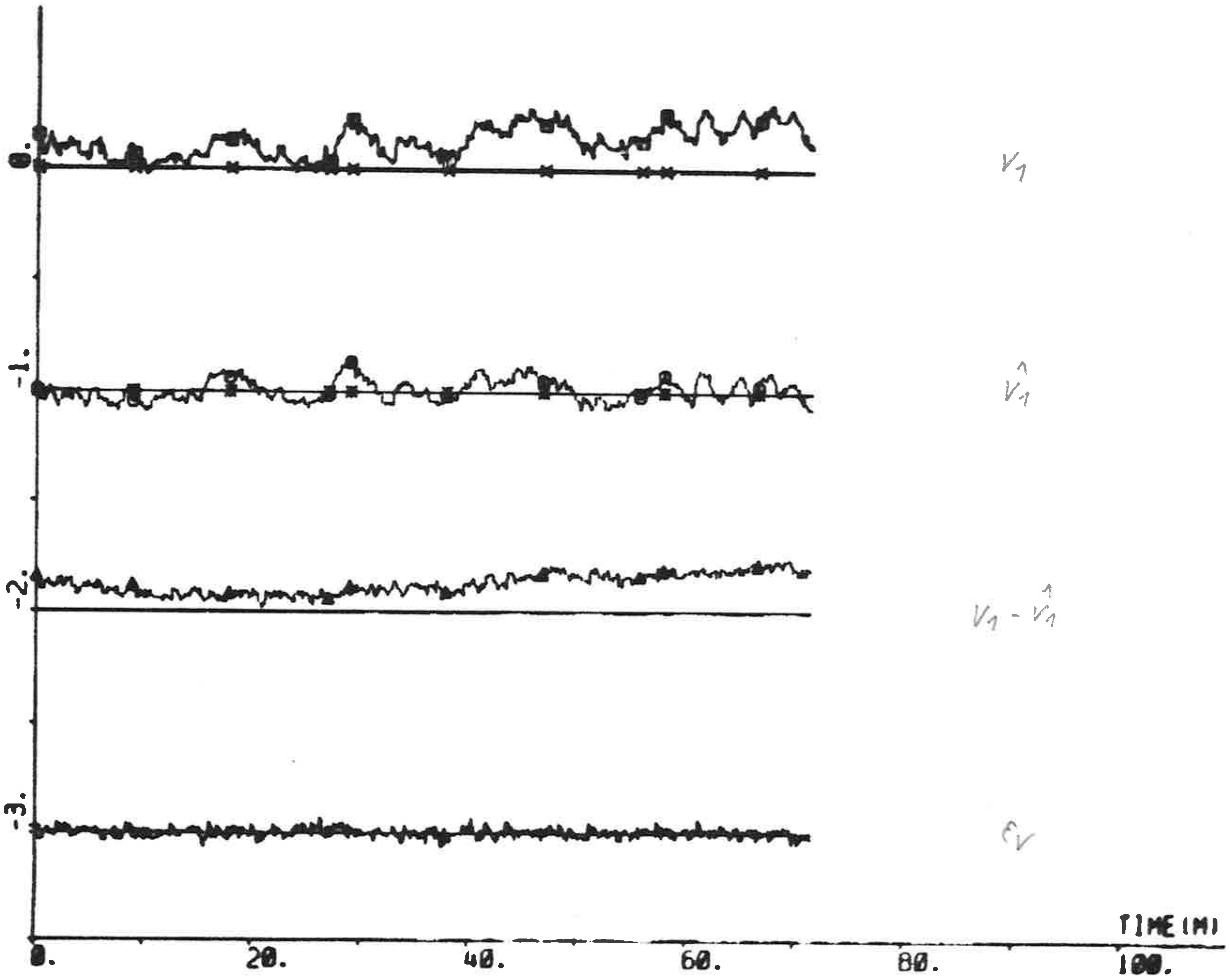

PLOT CSP1(1)-CSP1(8) CSP1(6) HP CSP1(10) HP MODY HP CSP1(15) 02 -3 1
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)
0.25 * {ψ -144, ψ_ref -144} deg
2.5 * {r, r_o} deg/s
0.05 * d_c deg
0.1 * M_y

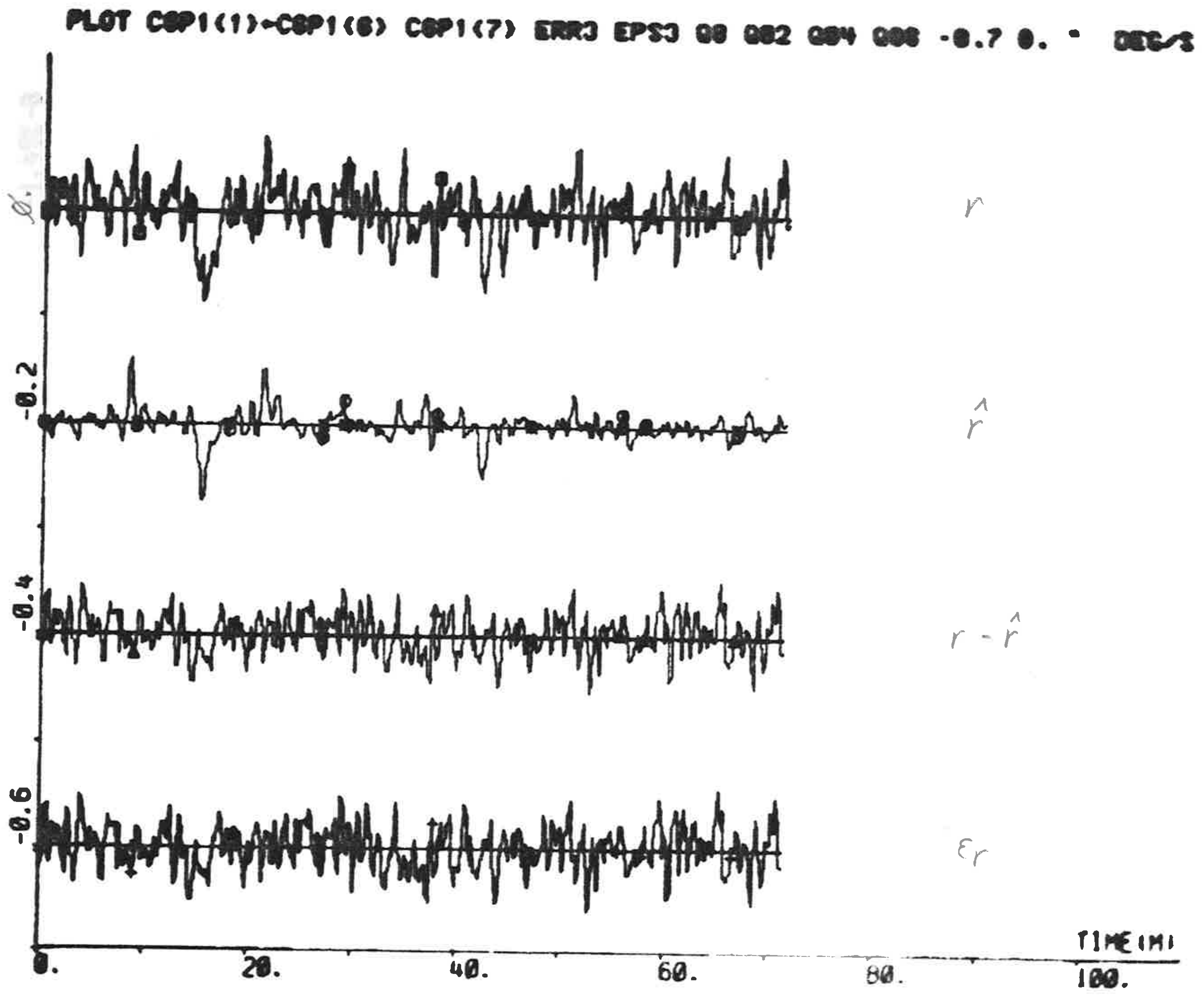
PLOT CSP1(1)-CSP1(13) CSP1(12) CSP1(14) CSP1(11) 00 -20 50

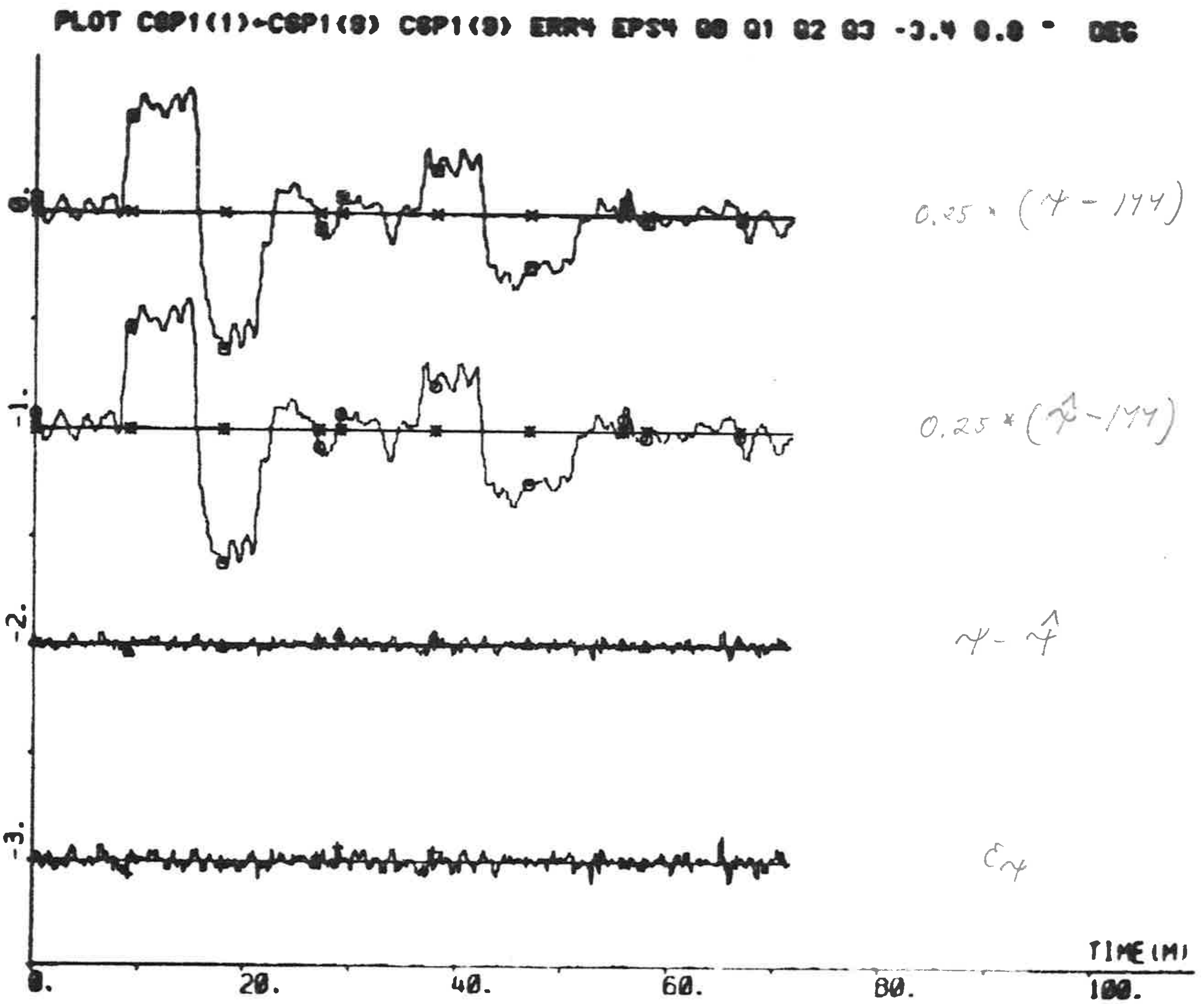



PLOT CSP1(1)-CSP2(1) CSP2(2) ERRS Q0 Q1 Q2 -3.4 0.8 KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
20.
40.
60.
80.
100.

PLOT CSP1(1)-CSP1(4) CSP1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 * KNOTS

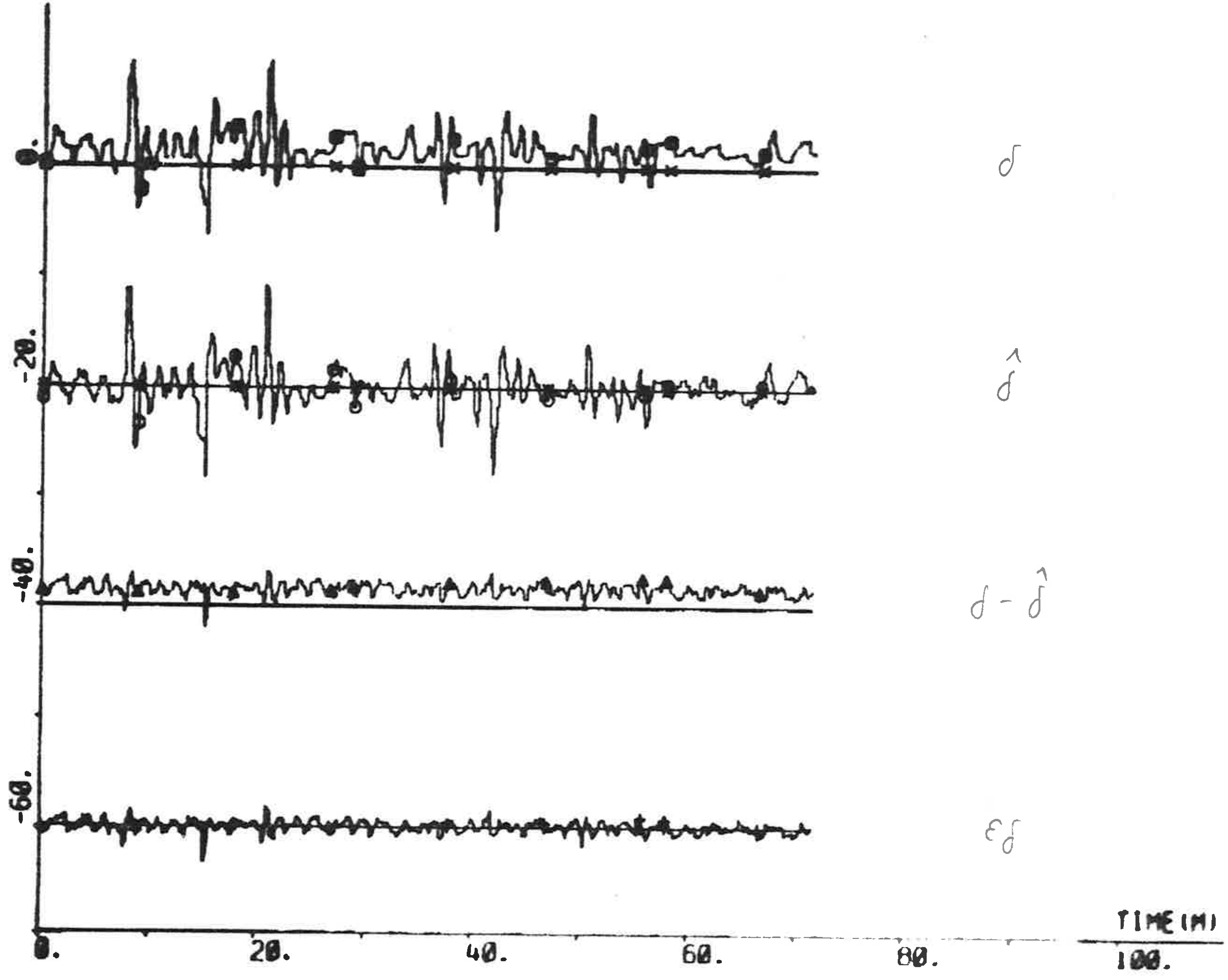


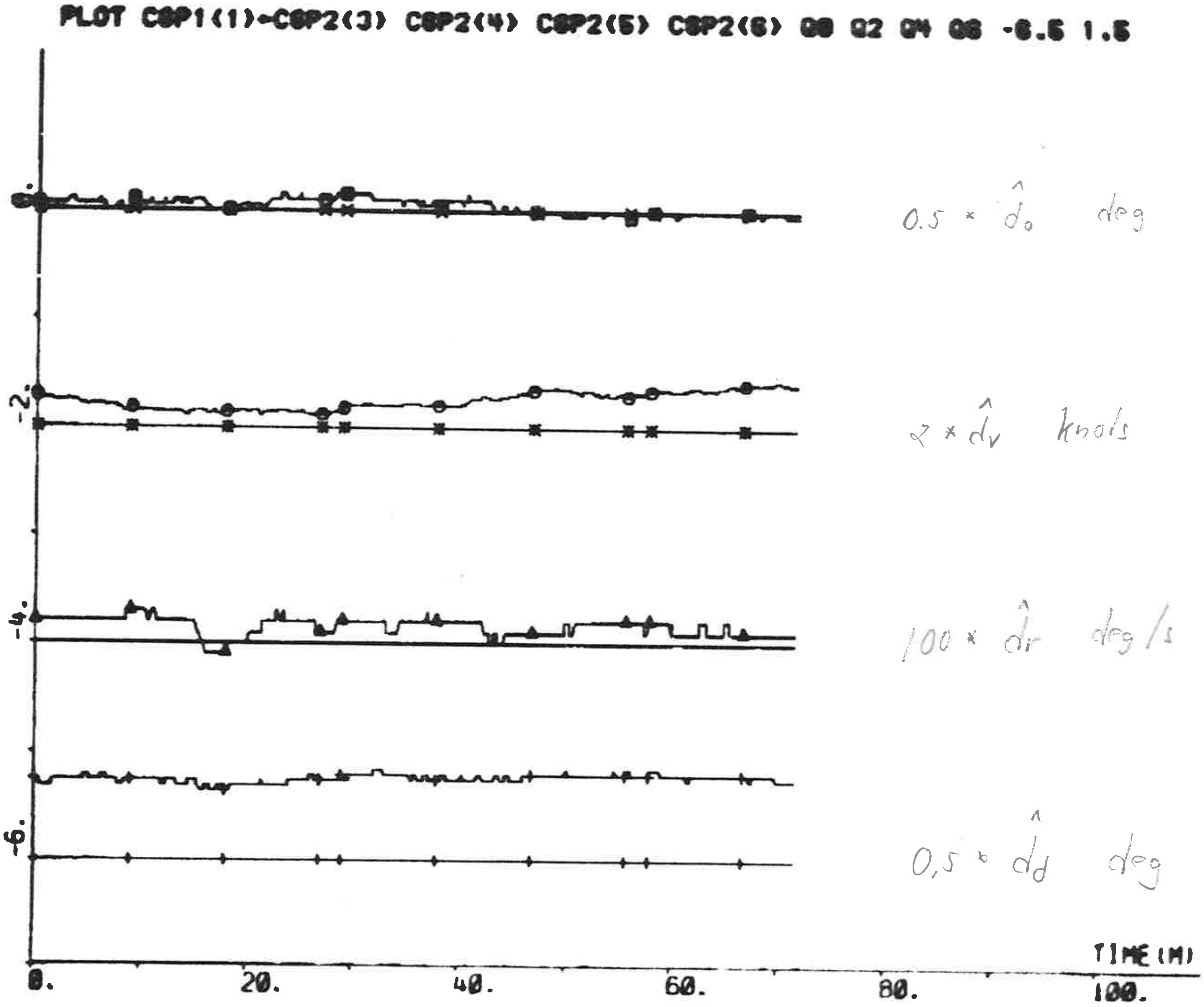

PLOT CSP1(1)-CSP1(6) CSP1(7) ERR3 EPS3 Q8 Q82 Q84 Q86 -0.7 0. " DEG/S
Ø
-0.2
-0.4
-0.6
0.
20.
40.
60.
80.
100.
TIME(M)
r
r̂
r - r̂
εr

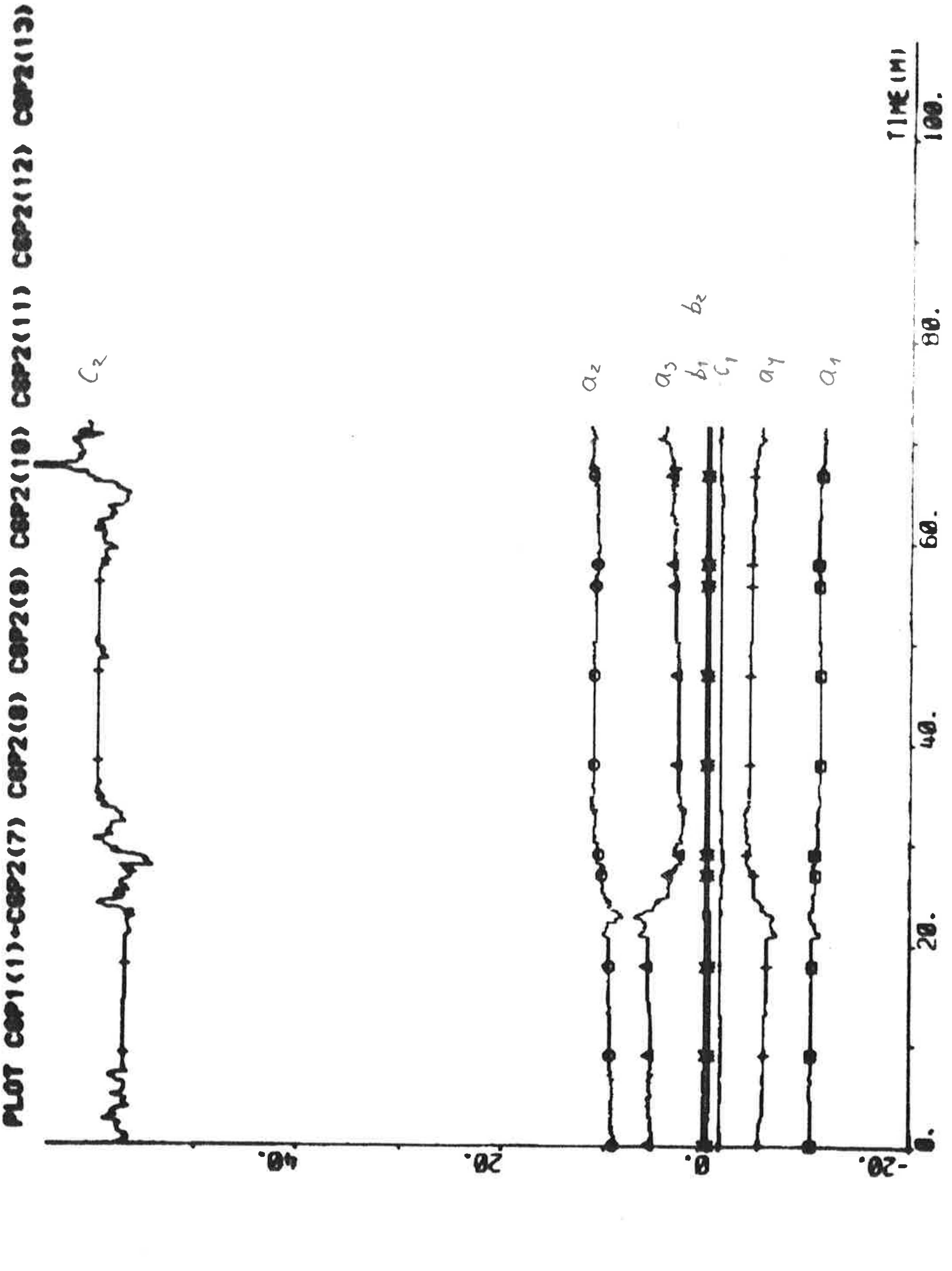

PLOT CSP1(1)-CSP1(9) CSP1(9) ERR4 EPS4 G0 G1 G2 G3 -3.4 0.0 - DEG
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)

509

PLOT CGP1(1)-CGP1(2) CGP1(3) ERR1 EPS1 G0 G20 G40 G60 -05 15 - DEG




PLOT CSP1(1)-CSP2(3) CSP2(4) CSP2(5) CSP2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.5 * $\hat{d}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0,5 * $\hat{d}_d$ deg
0.
20.
40.
60.
80.
100.
TIME (M)


PLOT CSP1(1)-CSP2(7) CSP2(8) CSP2(9) CSP2(10) CSP2(11) CSP2(12) CSP2(13)
TIME (M)
0.
20.
40.
60.
80.
100.
40.
20.
0
-20.
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT D1

Date	1976-04-19	Forward draught	8.5 m
Time	13.38	Aft draught	12.5 m
Duration	83 min	Wind direction	E (7; see App. A)
Position	N 28°09' W 15°17'	Wind velocity	5 m/s (gentle breeze)
ψ_{ref}	205, (201), 200, (183), 180, (184), 204, (202), 200 deg	Wave height	Low swell from ESE
r_{ref}	0.1 deg/s		

The forward speed u was measured by Sperry's log. The sway velocity v_1 was not measured during the experiment. The water depth was about 100 m during the last 15 min of the experiment. The rudder limit was 15 deg during the experiment.

Self-tuning regulator and yaw regulator using estimates from the Kalman filter.

The sway velocity v_1 was not used by the Kalman filter.

Tuning time before the experiment started: > 120 min.

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 8 m/s IVVC = 3 V_c = 7 m/s

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.32 \\ 6.37 \\ 3.37 \\ -2.70 \\ 0.38 \\ 0.02 \\ 1.41 \\ 112.69 \end{bmatrix} \qquad P = \begin{bmatrix} 105.55 & & & & & & & \\ -109.01 & 130.35 & & & & & & \\ -21.87 & -8.40 & 68.77 & & & & & \\ 23.83 & -10.89 & -38.41 & 25.71 & & & & \\ 0.50 & -1.62 & 2.56 & -1.48 & 0.26 & & & \\ 1.22 & -1.26 & -0.17 & 0.16 & 0.12 & 0.15 & & \\ -112.05 & 111.66 & 22.33 & -19.14 & -2.19 & -2.54 & 135.86 & \\ 1859.95 & 1907.60 & 198.28 & -179.47 & -55.06 & -51.19 & 2527.61 & 48427.16 \end{bmatrix}$$

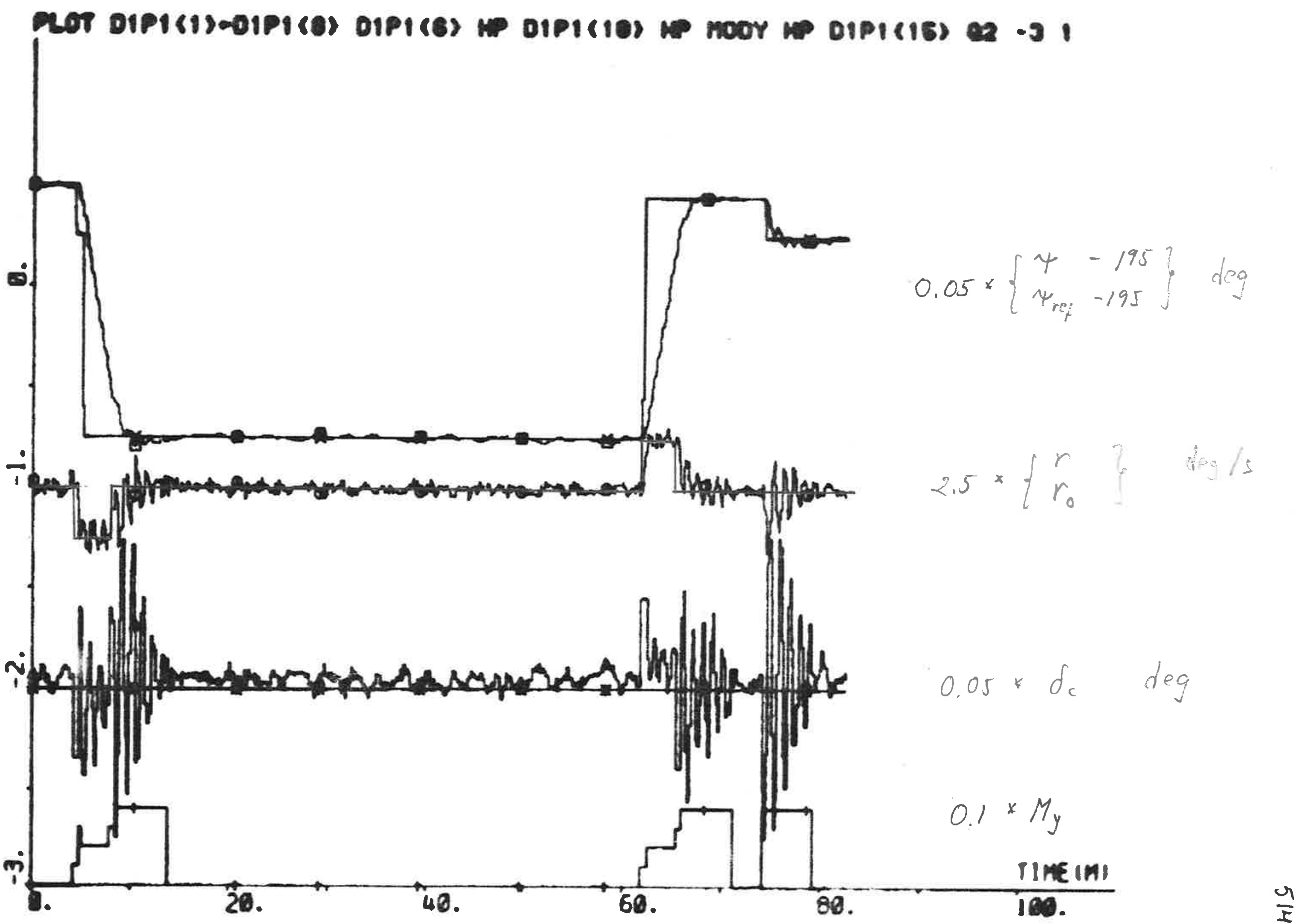
$a_1 + a_2 + a_3 + a_4 = -0.28$

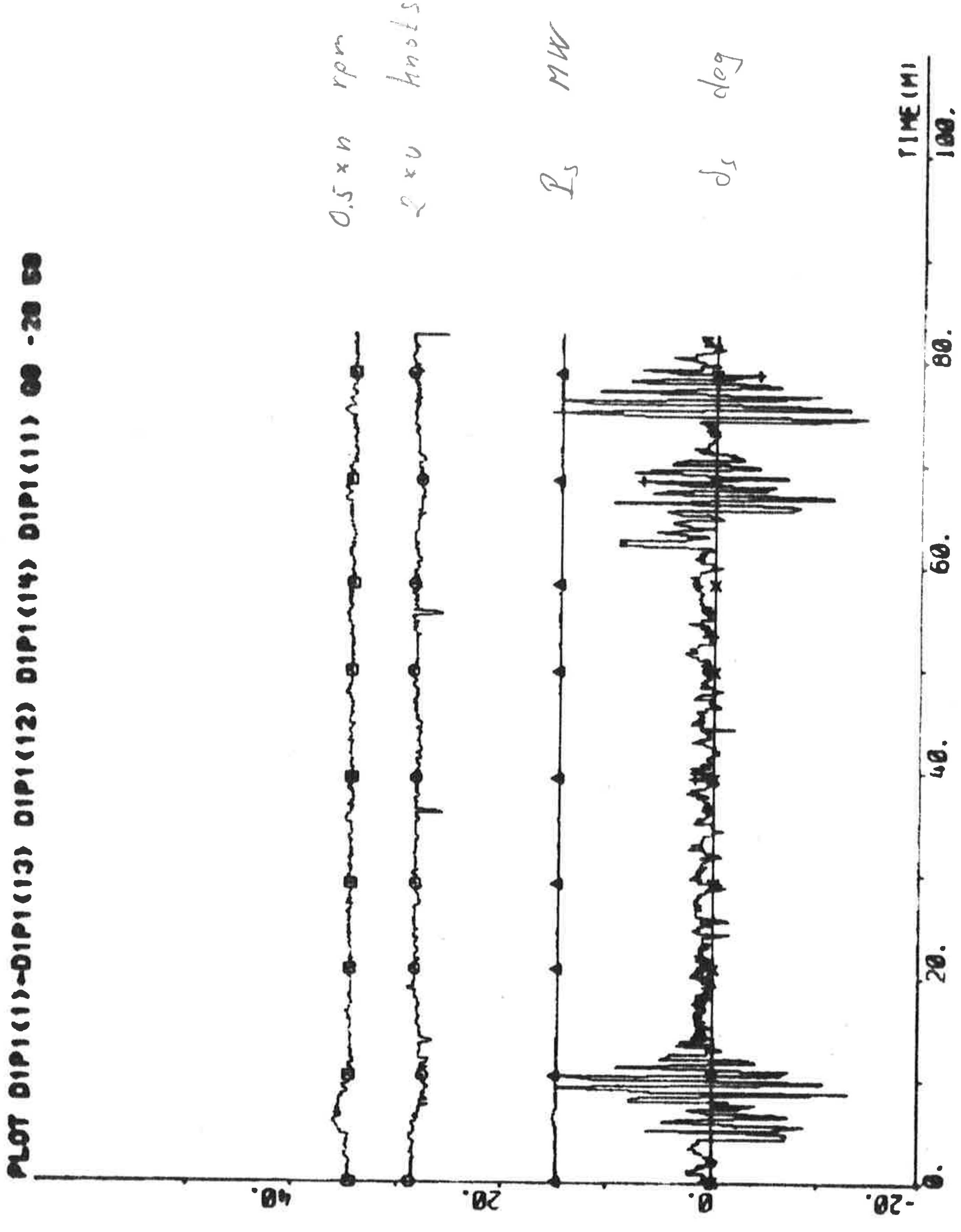
$\hat{\delta}_0 = 1.3$ deg $\hat{d}_v = -$ $\hat{d}_r = -0.002$ deg/s $\hat{d}_\delta = 0.9$ deg

$\bar{\delta}_c = 1.5$ deg (Initial value: 0.6 deg)

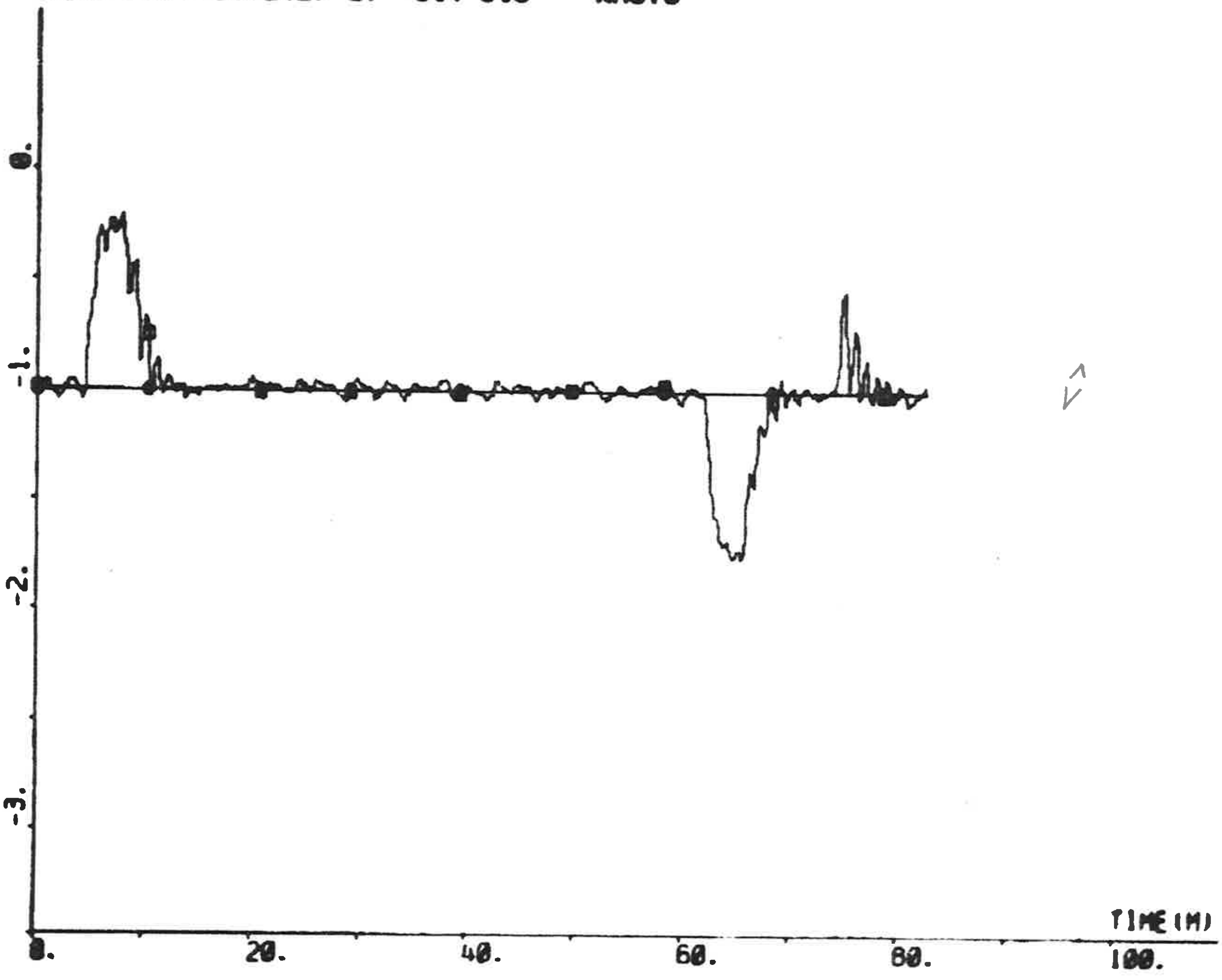
Statistics (mean value and standard deviation)

n	69.6 ± 0.6 rpm	ε_v	-
u	14.2 ± 0.2 knots	ε_r	0.00 ± 0.01 deg/s
P_s	14.7 ± 0.1 MW	ε_ψ	0.00 ± 0.02 deg
		ε_δ	0.0 ± 0.9 deg

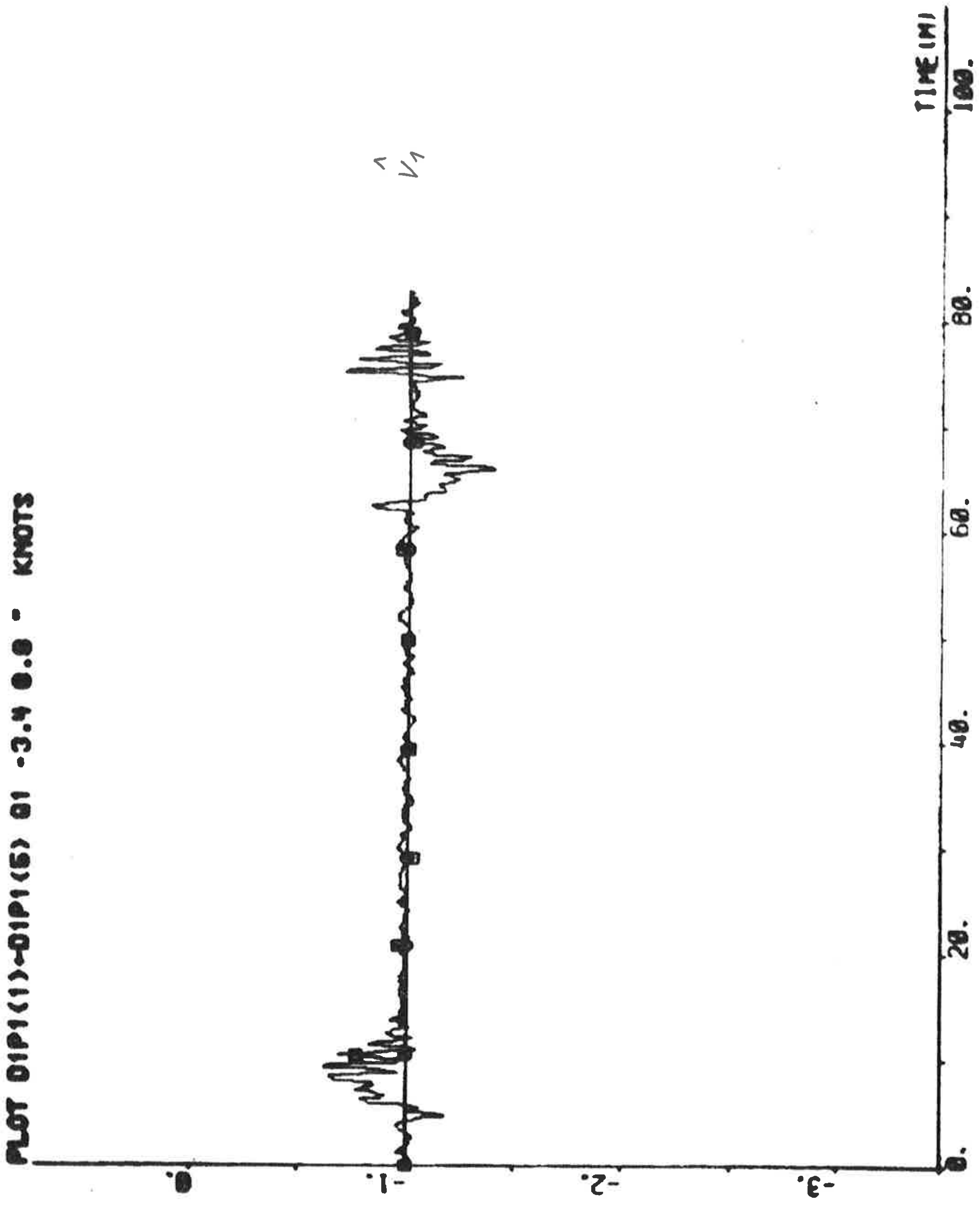

PLOT D1P1(1)-D1P1(8) D1P1(6) HP D1P1(10) HP MODY HP D1P1(15) 02 -3 1
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)
0.05 × { ψ - 195 ; ψref -195 } deg
2.5 × { r ; r0 } deg/s
0.05 × δc deg
0.1 × My

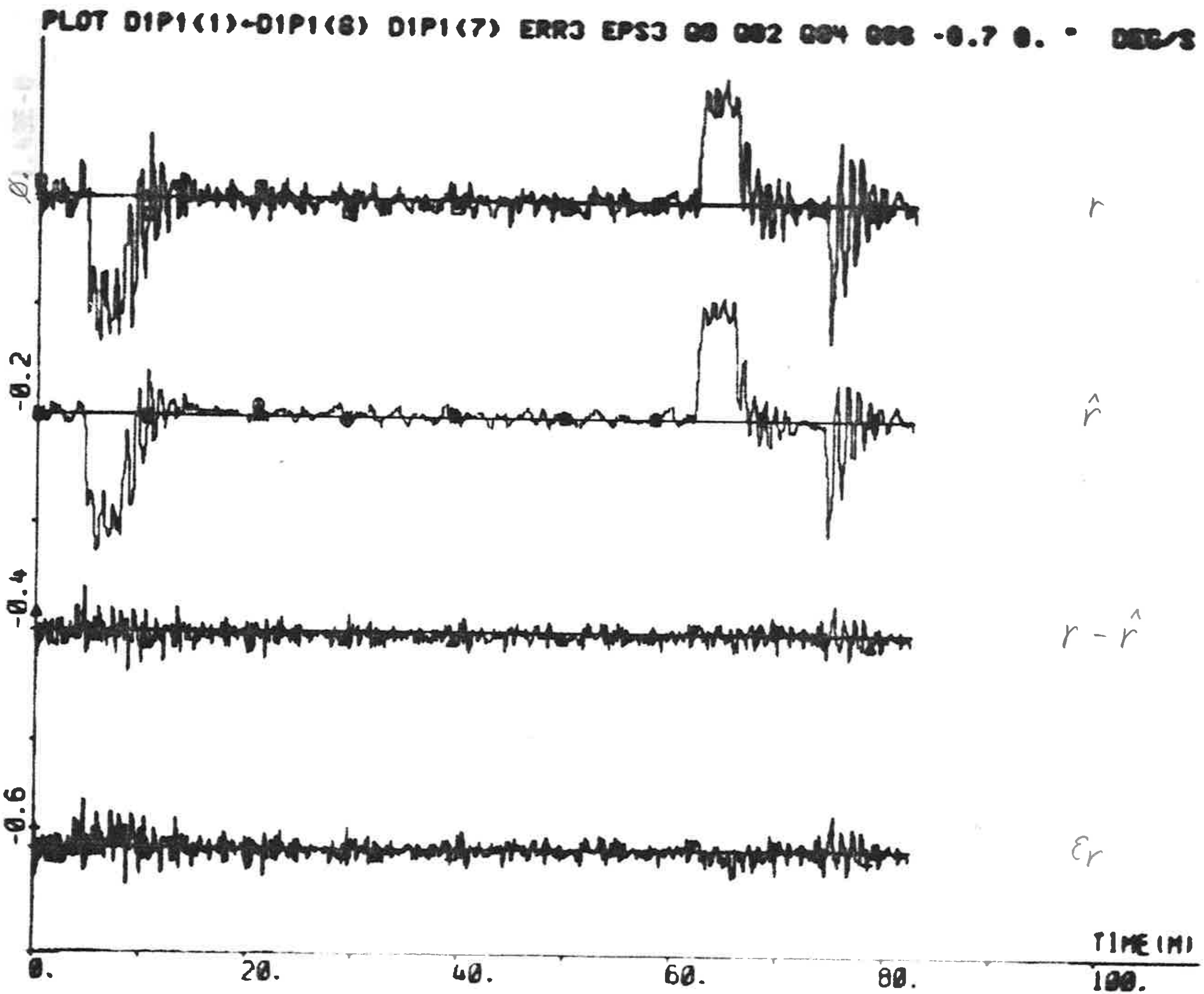

PLOT DIPI(1)-DIPI(13) DIPI(12) DIPI(14) DIPI(11)
0.5×n rpm
2×v knots
Ps MW
deg
40.
20.
0.
-20.
TIME(M)
0.
20.
40.
60.
80.
100.

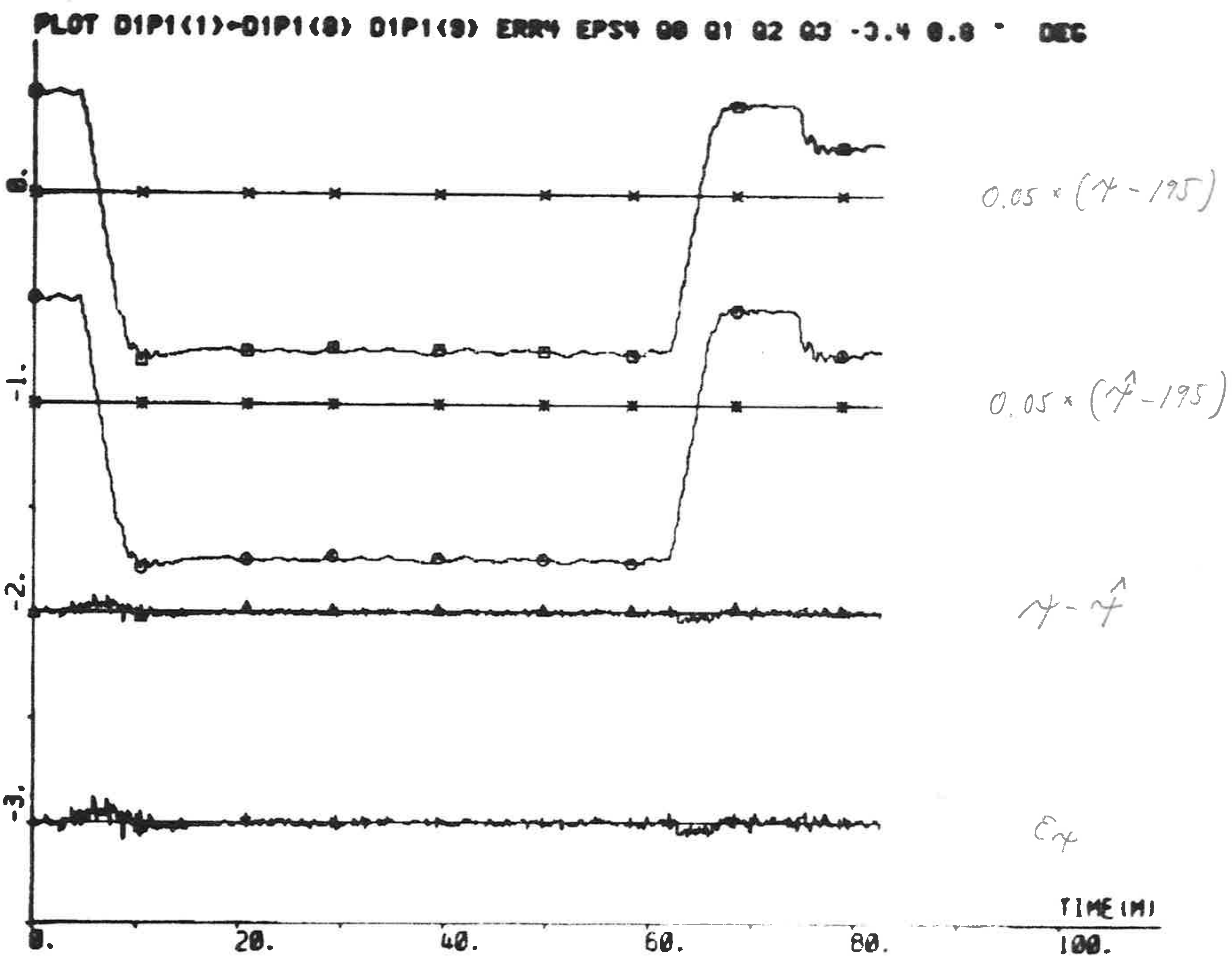
PLOT D1P1-D1P2(2) 81 -3.4 0.8 * KNOTS

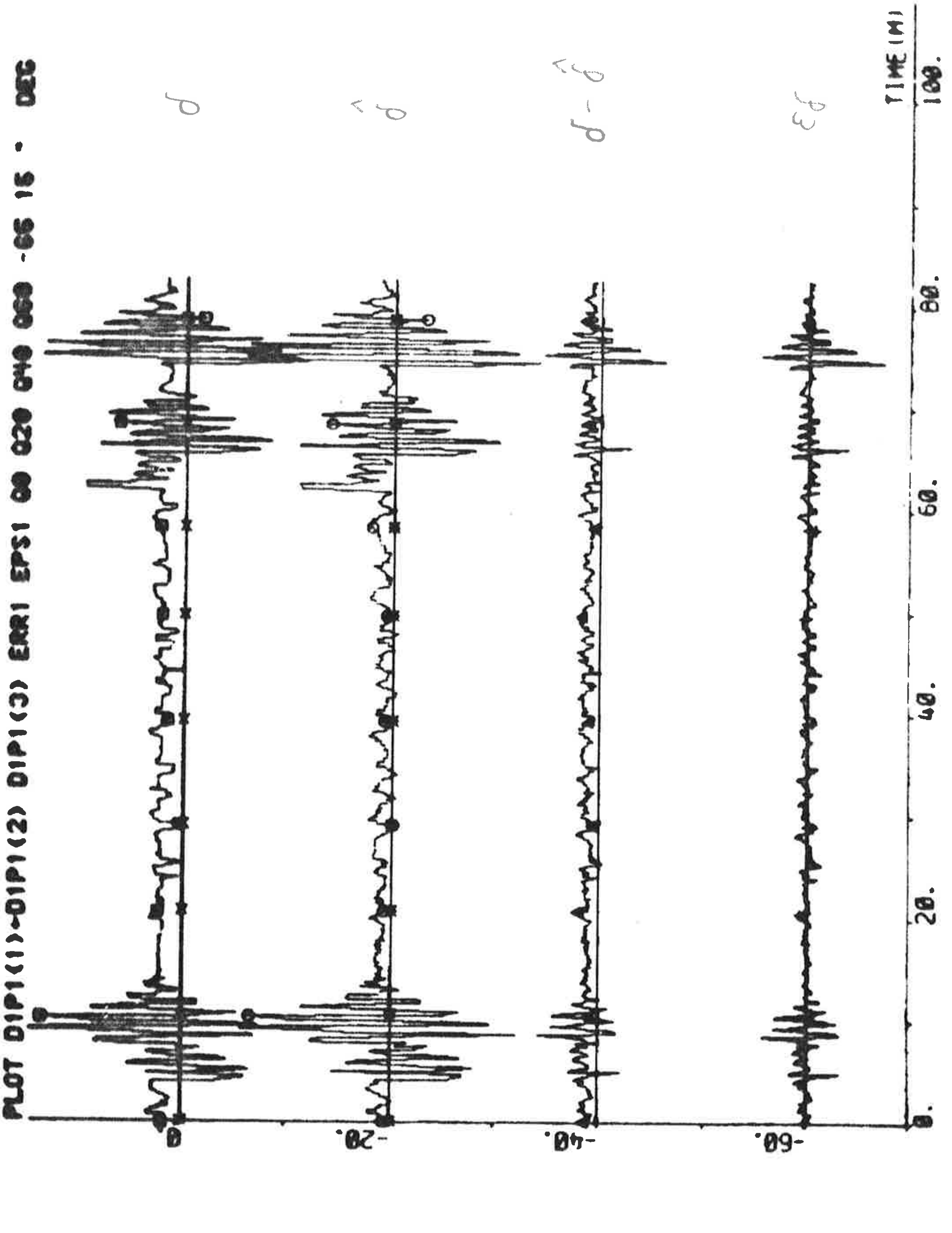


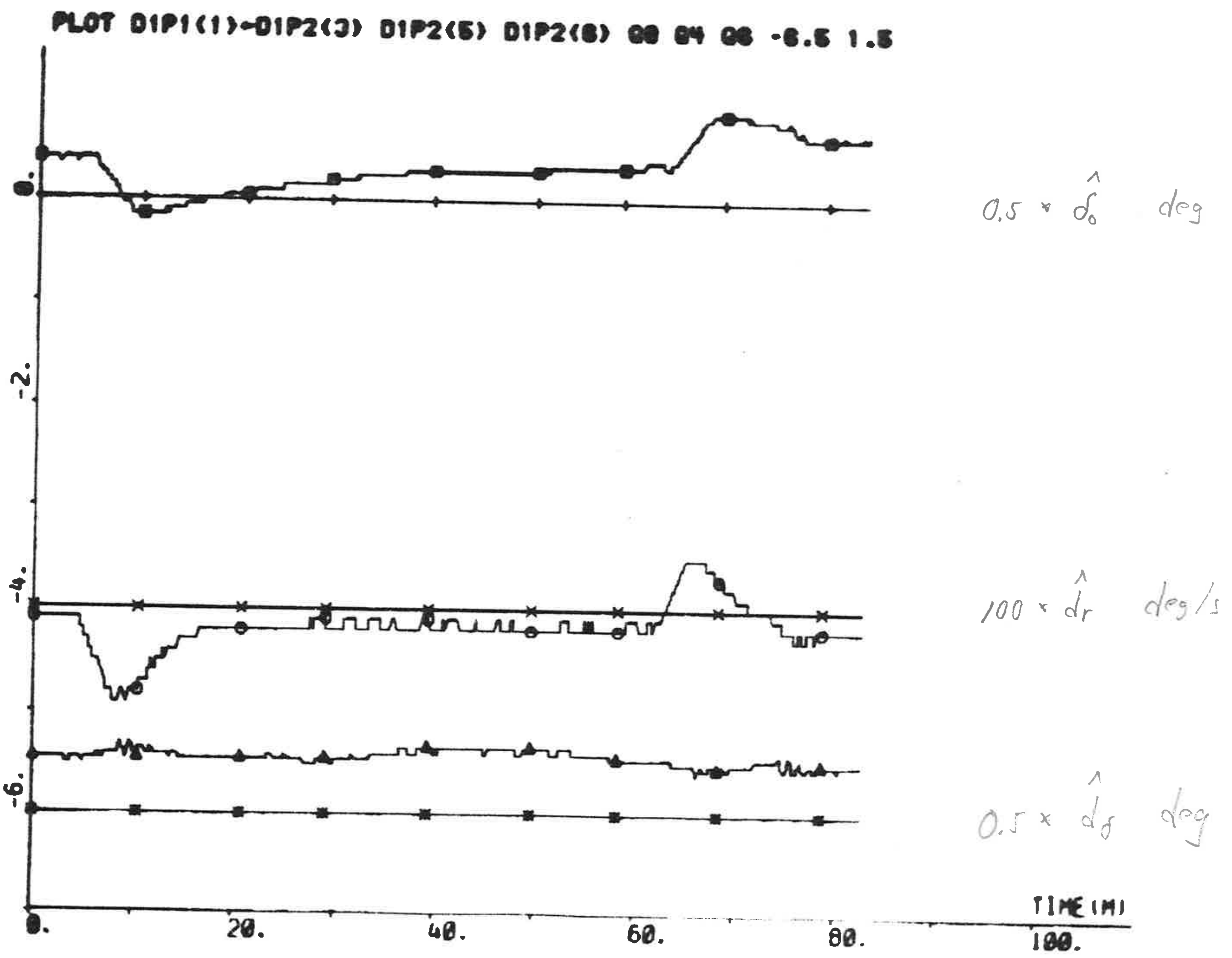
516

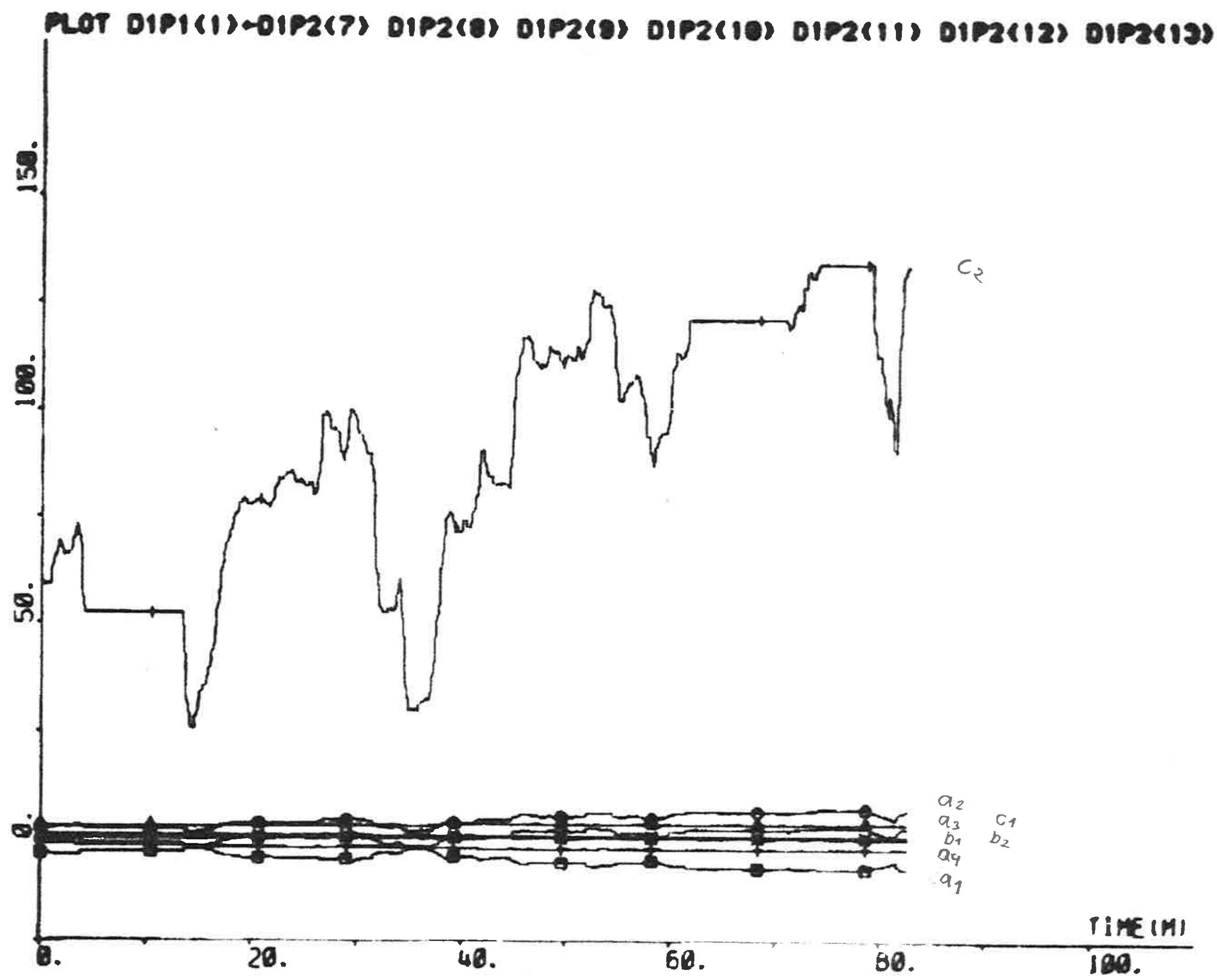

PLOT D1P1(1)-D1P1(5) @1 -3.4 0.0 * KNOTS
TIME (M)
0.
20.
40.
60.
80.
100.
0.
-1.
-2.
-3.


PLOT D1P1(1)-D1P1(8) D1P1(7) ERR3 EPS3 G0 G02 G04 G06 -0.7 0. DEG/S
0.
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
0.
20.
40.
60.
80.
100.
TIME(M)


PLOT D1P1(1)-D1P1(8) D1P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.8 - DEG
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)
0.05 * (ψ - 195)
0.05 * (ψ̂ - 195)
ψ - ψ̂
Eψ


PLOT DIP1(1)-DIP1(2) DIP1(3) ERR1 EPS1 00 020 040 060 -66 16 • DEG
0
-20.
-40.
-60.
TIME (M)
0.
20.
40.
60.
80.
100.


PLOT D1P1(1)-D1P2(3) D1P2(5) D1P2(8) 00 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.
20.
40.
60.
80.
100.
TIME (M)
0.5 × $\hat{\delta}_o$ deg
100 × $\hat{d}_r$ deg/s
0.5 × $\hat{d}_\delta$ deg


PLOT D1P1(1)-D1P2(7) D1P2(8) D1P2(9) D1P2(10) D1P2(11) D1P2(12) D1P2(13)
150.
100.
50.
0.
0.
20.
40.
60.
80.
100.
TIME(M)
c2
a2
a3
b1
a4
a1
c1
b2

EXPERIMENT D2

Date	1976-04-21	Forward draught	8.5 m
Time	14.21	Aft draught	12.5 m
Duration	40 min	Wind direction	N (5; see App. A)
Position	N 16°54' W 18°30'	Wind velocity	10 m/s (fresh breeze)
ψ_{ref}	180 deg	Wave height	2 m
r_{ref}	0.1 deg/s		

Self-tuning regulator and yaw regulator using estimates from the Kalman filter

Tuning time before the experiment started: 0 min

NC1 = 1 NC2 = 1 k = 7 q = 0

T_s = 10 s V_0 = 7 m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.57 \\ 5.86 \\ 4.14 \\ -2.95 \\ 0.51 \\ 0.12 \\ -1.69 \\ 39.59 \end{bmatrix} \qquad P = \begin{bmatrix} 3.34 \\ -3.76 & 7.08 \\ -0.75 & -2.95 & 7.69 \\ 1.44 & -0.47 & -4.09 & 3.41 \\ -0.10 & -0.04 & 0.24 & -0.09 & 0.02 \\ -0.09 & 0.04 & -0.01 & 0.07 & 0.01 & 0.02 \\ -0.56 & 0.81 & 0.38 & -0.62 & 0.00 & -0.02 & 0.74 \\ 7.71 & -10.70 & -6.14 & 7.67 & -0.33 & -0.27 & 10.77 & 636.32 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.52$

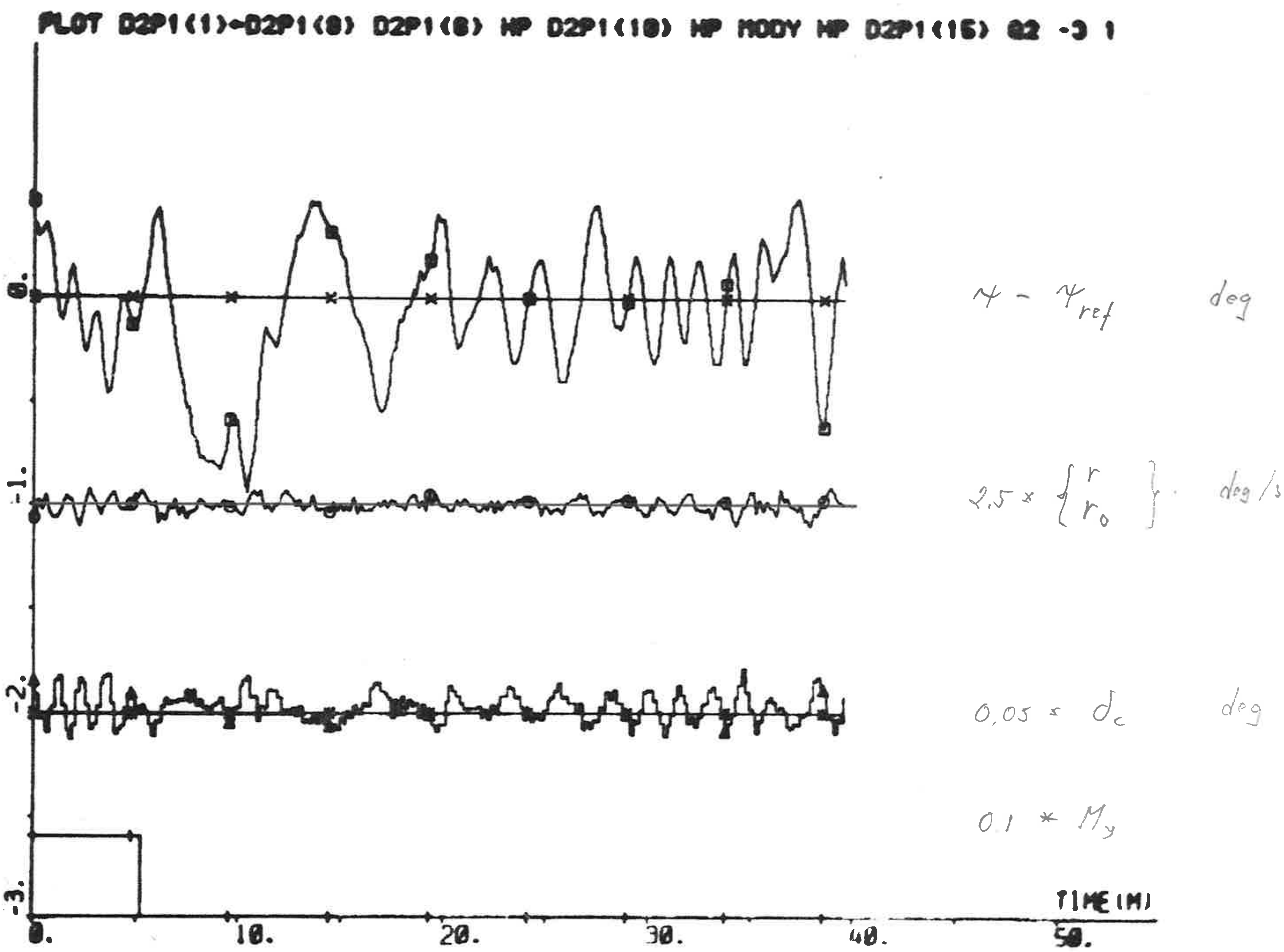
$\hat{\delta}_0 = 0.5$ deg $\hat{d}_v = 0.18$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.4$ deg

$\bar{\delta}_c = 0.4$ deg (Initial value: 0.0 deg)

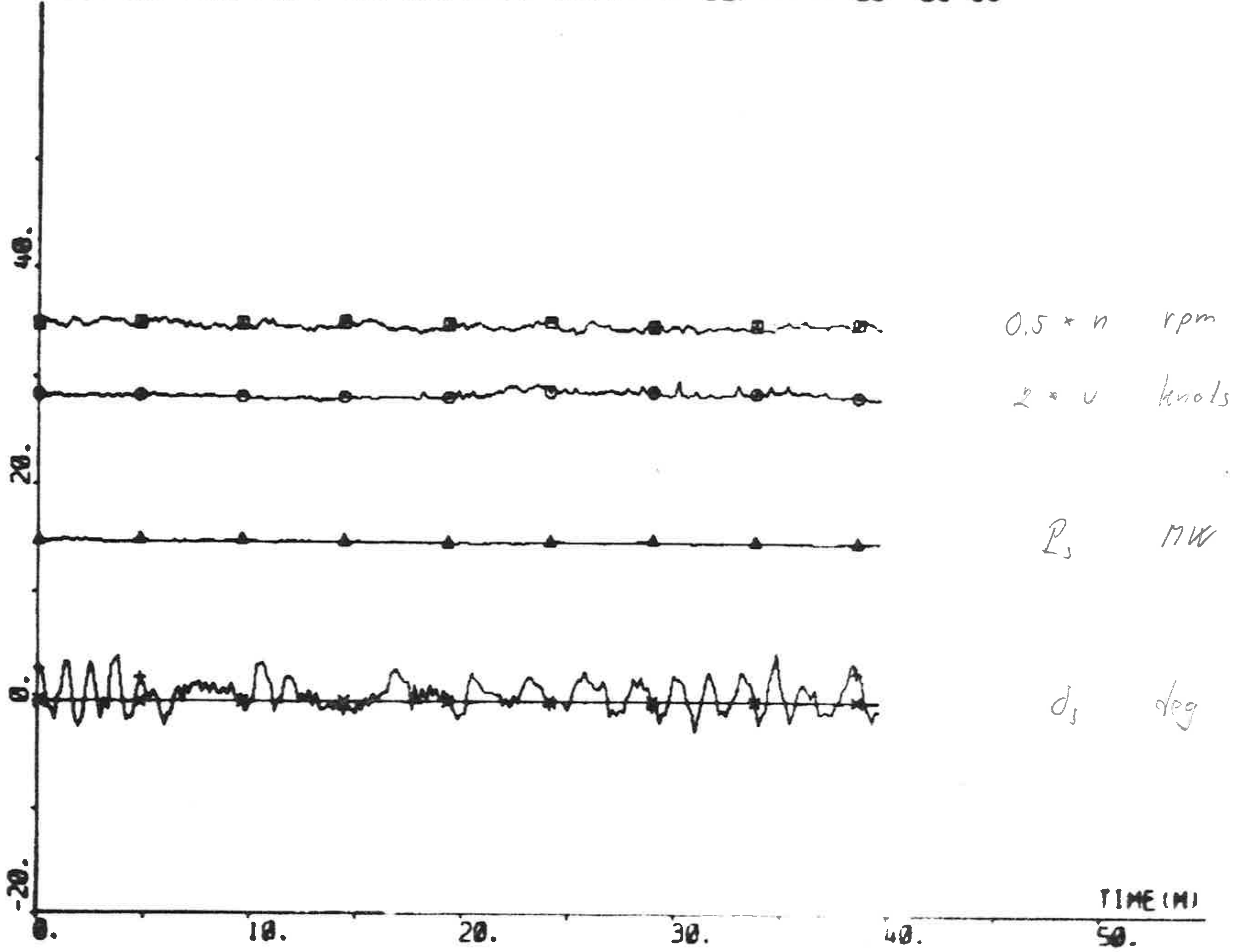
Statistics (mean value and standard deviation)

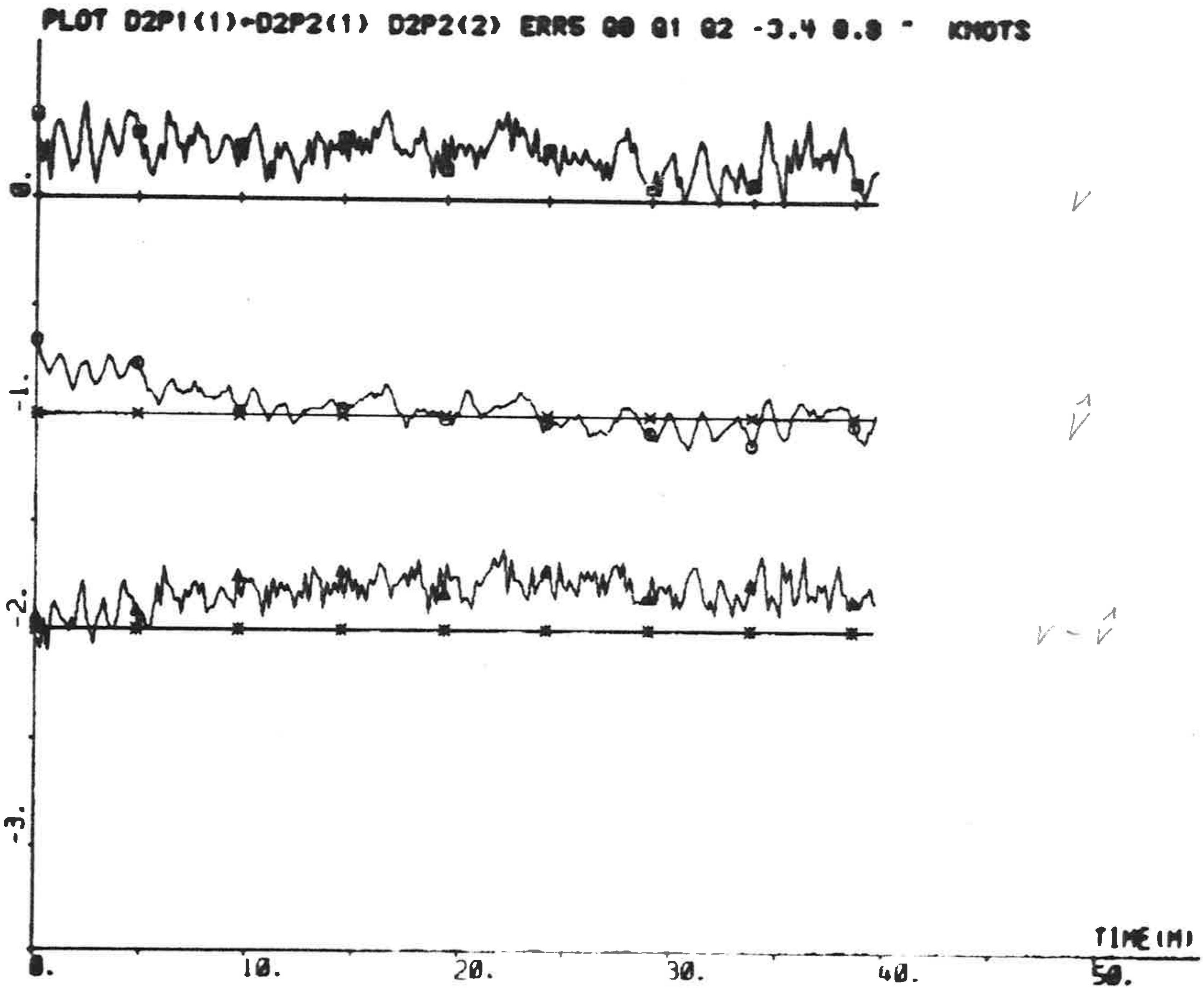
δ_c	0.56 ± 1.34	deg	P_s	14.7 ± 0.1	MW
δ	1.96 ± 1.25	deg	ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	-0.063 ± 0.319	deg	ε_r	0.00 ± 0.01	deg/s
n	69.7 ± 0.5	rpm	ε_ψ	0.00 ± 0.02	deg
u	14.2 ± 0.2	knots	ε_δ	0.2 ± 0.6	deg

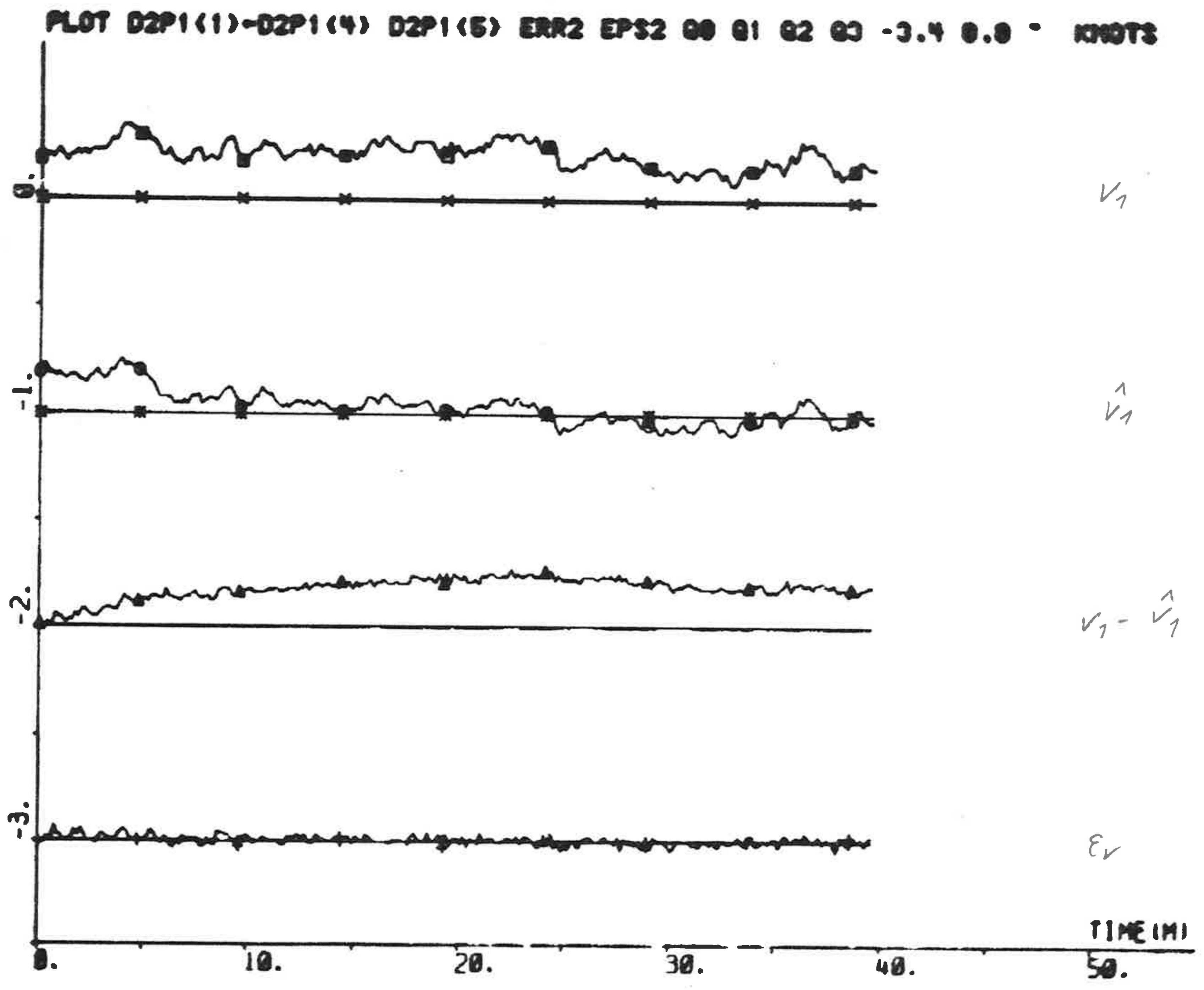
$V_1 = 0.255$

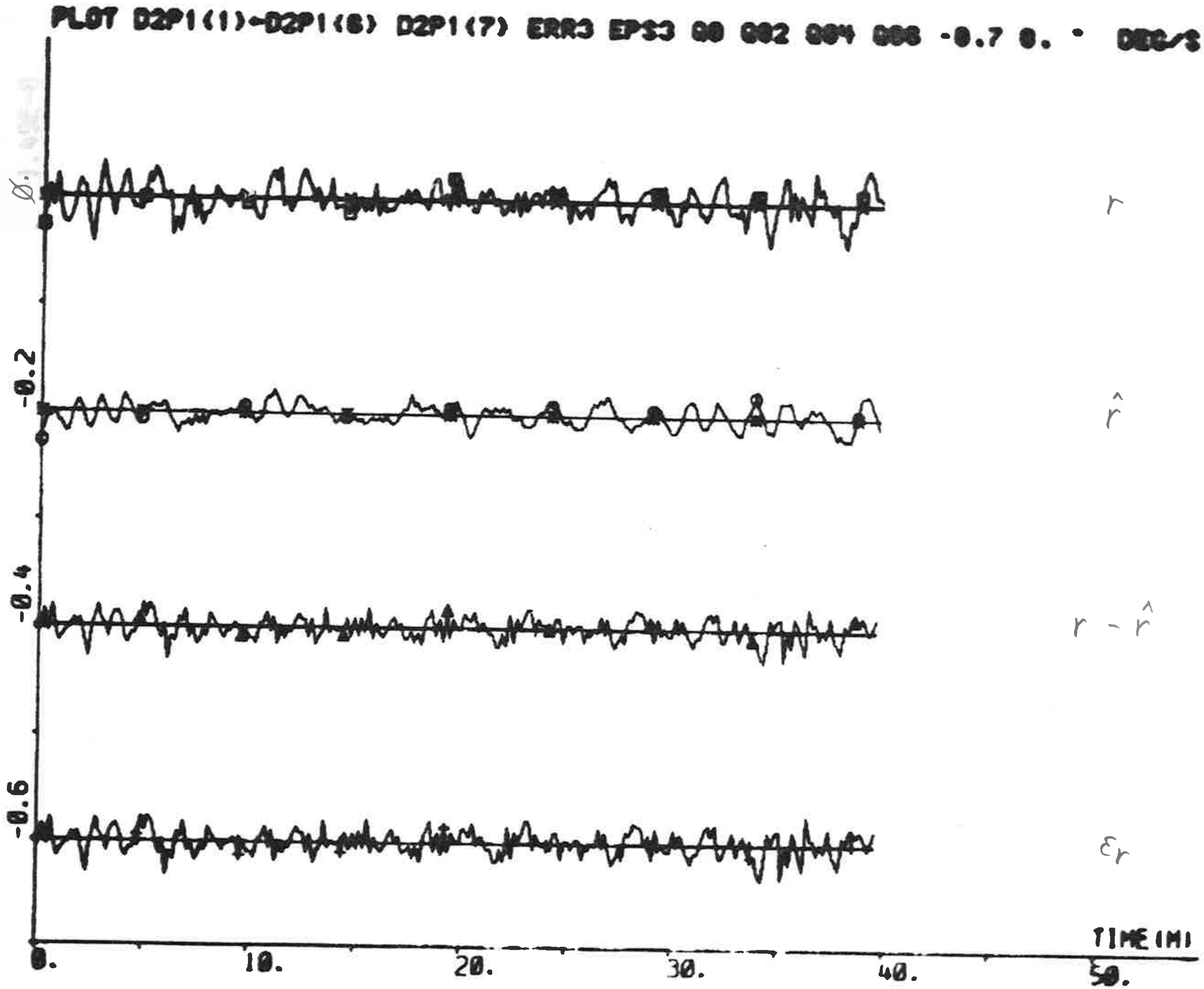

PLOT D2P1(1)-D2P1(8) D2P1(8) HP D2P1(10) HP MODY HP D2P1(15) 02 -3 1
0.
-1.
-2.
-3.
TIME(M)
0.
10.
20.
30.
40.
50.
ψ - ψ_ref deg
2,5 * {r, r_0} deg/s
0,05 * δ_c deg
0.1 * M_y

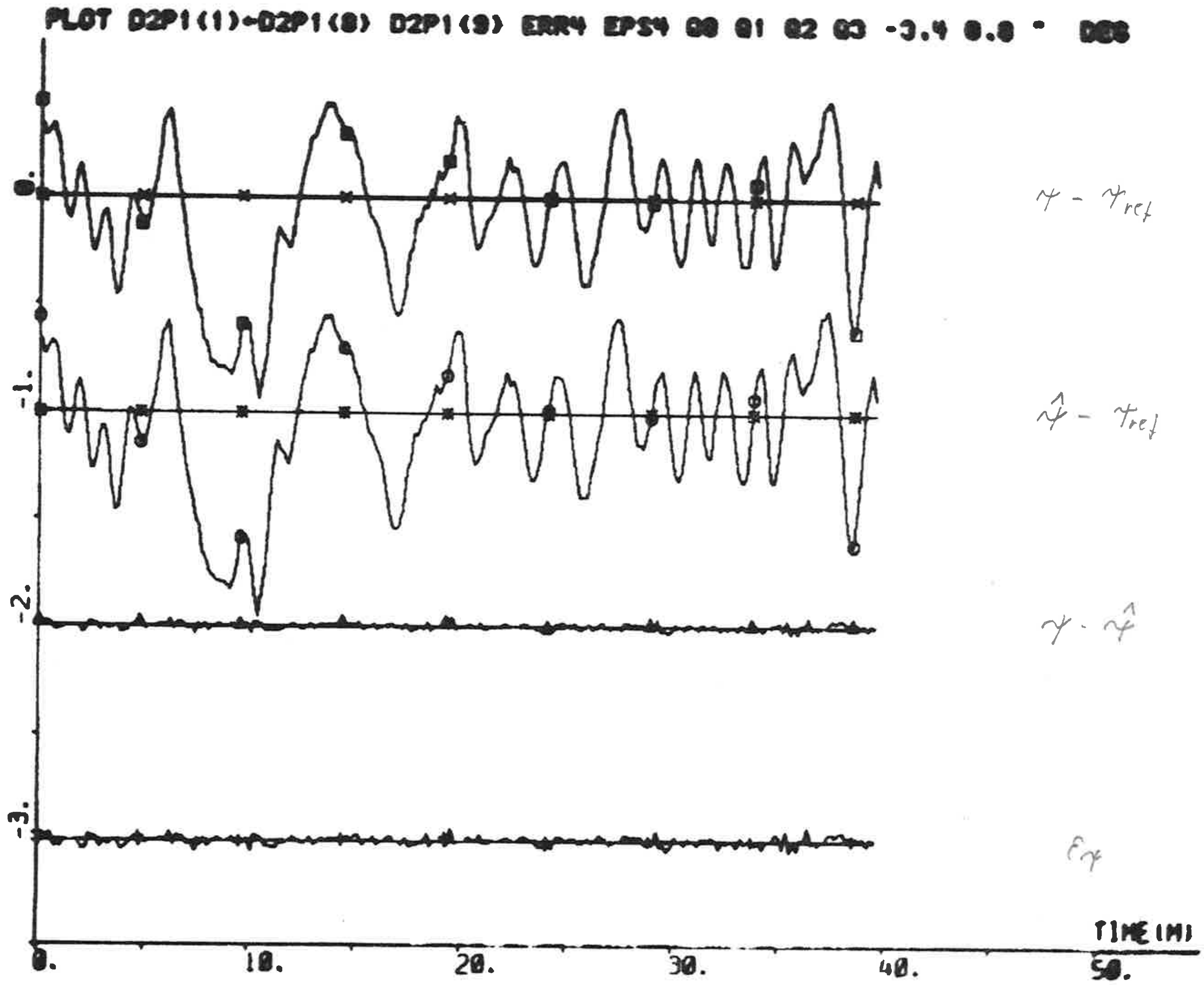
PLOT D2P1(1)-D2P1(13) D2P1(12) D2P1(14) D2P1(11) 00 -20 50

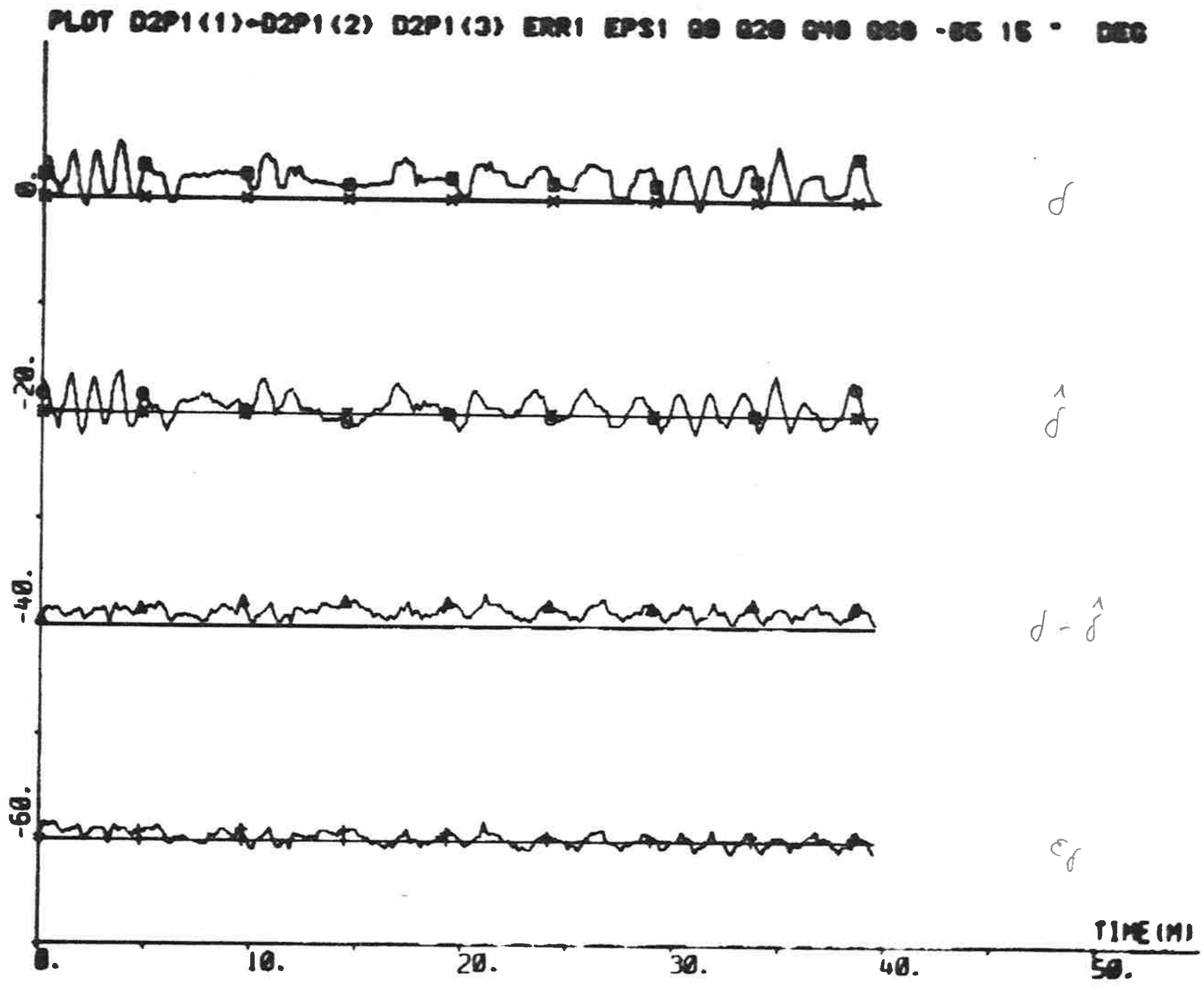



PLOT D2P1(1)-D2P2(1) D2P2(2) ERRS 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)


PLOT D2P1(1)-D2P1(4) D2P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
10.
20.
30.
40.
50.

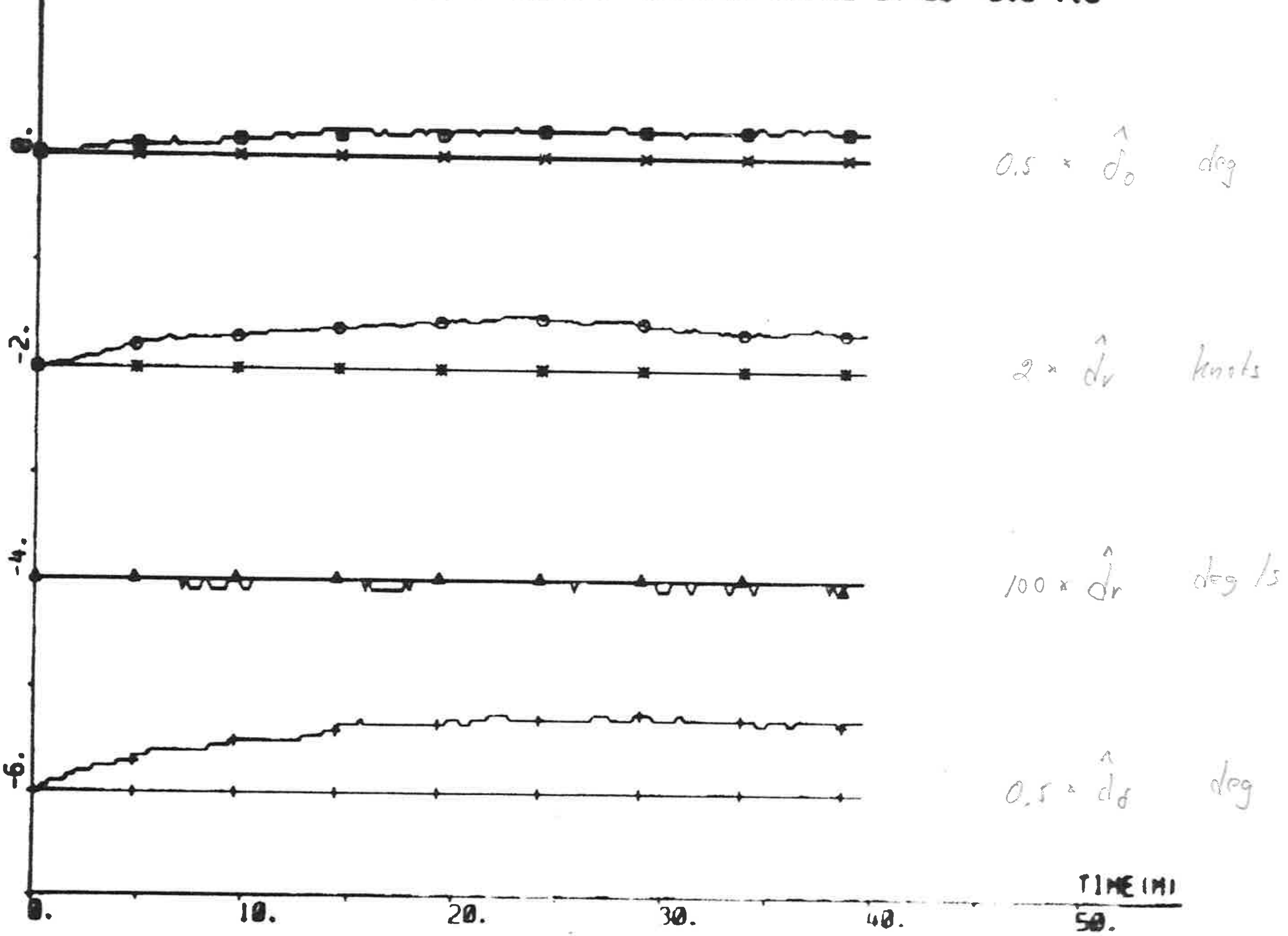

PLOT D2P1(1)-D2P1(6) D2P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. • DEG/S
0.
-0.2
-0.4
-0.6
0.
10.
20.
30.
40.
50.
TIME(M)
r
r̂
r - r̂
εr

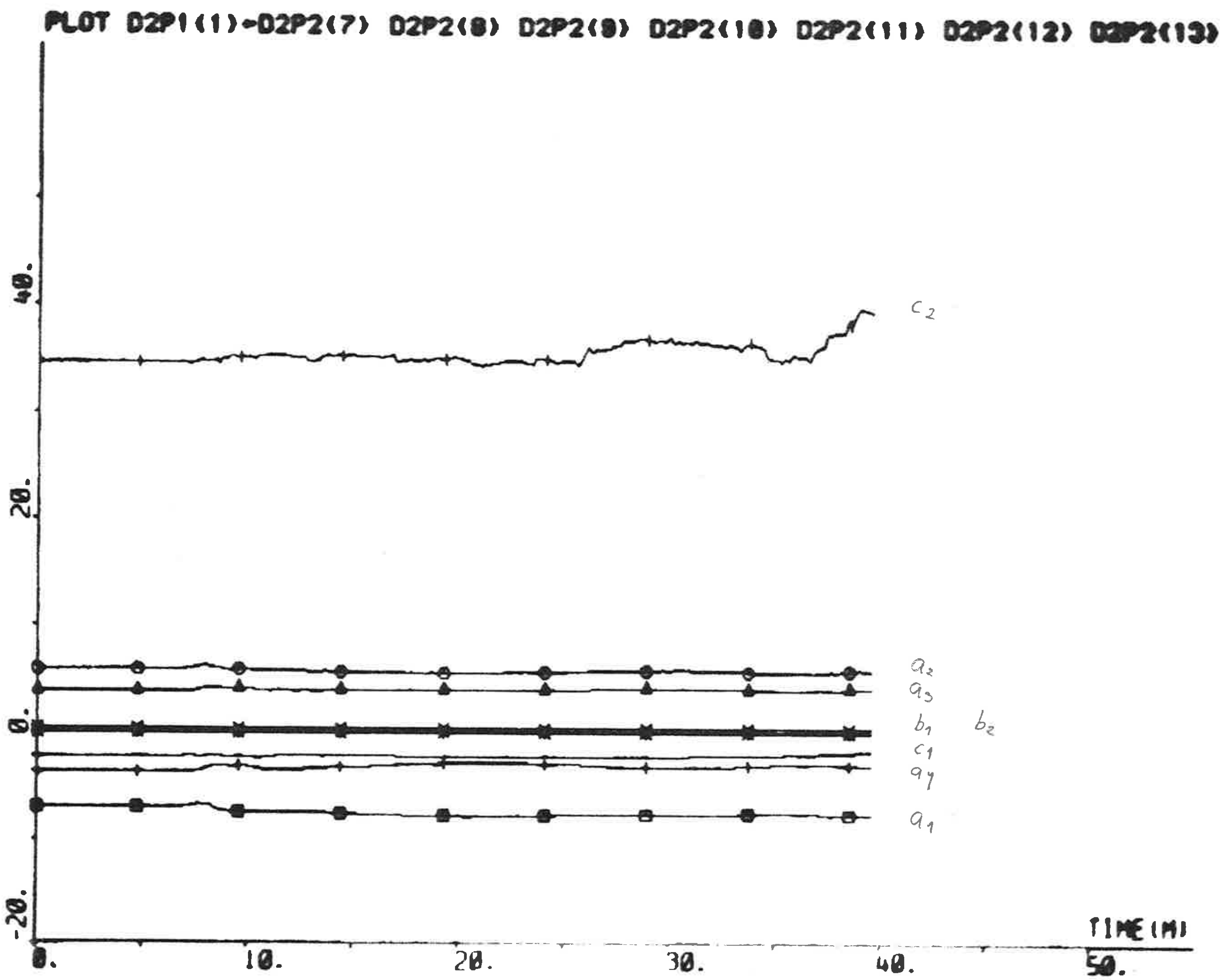

PLOT D2P1(1)-D2P1(8) D2P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.0 - DGS
0.
-1.
-2.
-3.
0.
10.
20.
30.
40.
50.
TIME(M)



PLOT D2P1(1)-D2P1(2) D2P1(3) ERR1 EPS1 00 020 040 060 -05 15 - DEG
0.
-20.
-40.
-60.
0.
10.
20.
30.
40.
50.
TIME(M)

PLOT D2P1(1)-D2P2(3) D2P2(4) D2P2(5) D2P2(8) 00 02 04 06 -6.6 1.6




PLOT D2P1(1)-D2P2(7) D2P2(8) D2P2(9) D2P2(10) D2P2(11) D2P2(12) D2P2(13)
40.
20.
0.
-20.
0.
10.
20.
30.
40.
50.
TIME(M)
c2
a2
a3
b1
b2
c1
a4
a1

EXPERIMENT D3

Date	1976-04-30	Forward draught	10.9 m
Time	15.35	Aft draught	12.9 m
Duration	68 min	Wind direction	S (1; see App. A)
Position	S 22°43' E 08°25'	Wind velocity	9 m/s (fresh breeze)
ψ_{ref}	144.3-147.0 deg (Sailmaster, Course Correction)	Wave height	-
r_{ref}	0.1 deg/s		

Self-tuning regulator and yaw regulator using estimates from the Kalman filter.

Tuning time before the experiment started: 0 min

NC1 = 1 NC2 = 1 $k = 7$ $q = 0$

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -8.24 \\ 6.08 \\ 4.67 \\ -2.61 \\ 0.52 \\ 0.16 \\ -1.30 \\ 46.13 \end{bmatrix} \qquad P = \begin{bmatrix} 2.47 & & & & & & & \\ -2.79 & 7.74 & & & & & & \\ -0.60 & -5.55 & 11.39 & & & & & \\ 1.15 & 0.41 & -5.33 & 4.13 & & & & \\ -0.06 & -0.24 & 0.46 & -0.15 & 0.04 & & & \\ 0.01 & -0.07 & -0.08 & 0.16 & 0.00 & 0.02 & & \\ -0.04 & 0.34 & -0.25 & -0.09 & -0.03 & -0.02 & 0.60 & \\ 13.22 & -18.44 & -6.72 & 10.98 & -0.76 & 0.32 & 13.50 & 701.56 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.10$

$\hat{\delta}_0 = -0.5$ deg $\hat{d}_v = 0.13$ knots $\hat{d}_r = 0.001$ deg/s $\hat{d}_\delta = 1.6$ deg

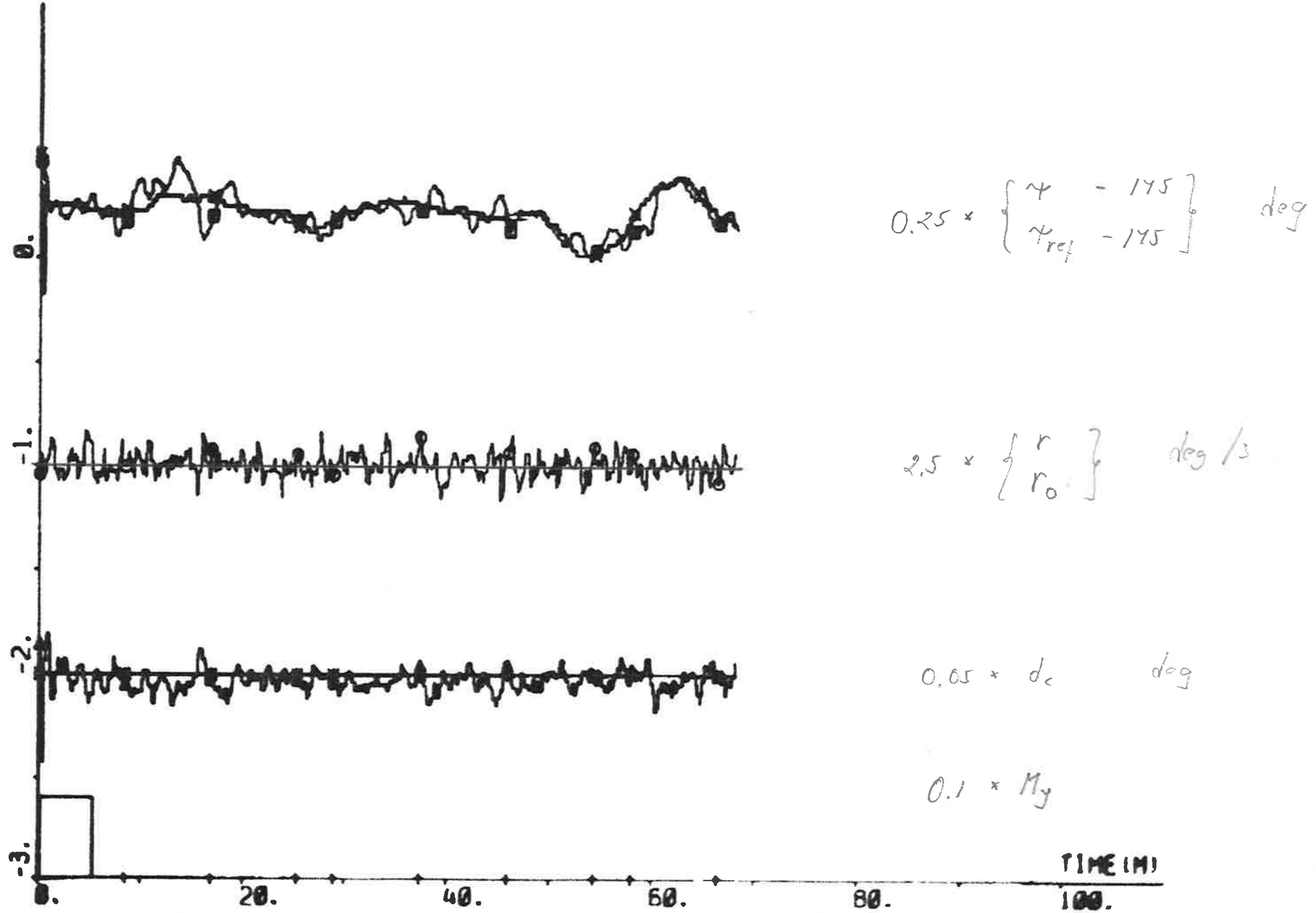
$\bar{\delta}_c = -0.4$ deg (Initial value: 0.0 deg)

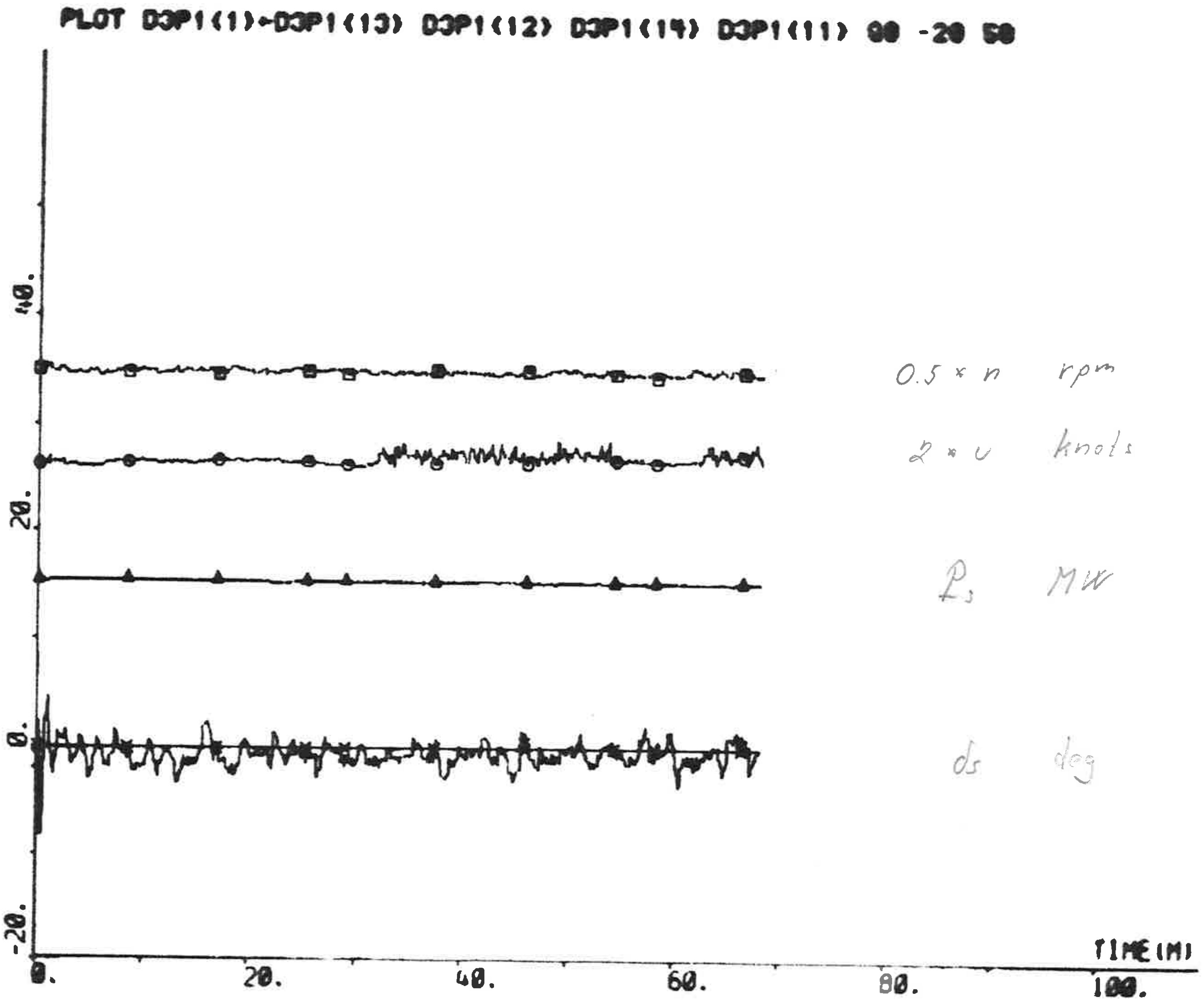
Statistics (mean value and standard deviation)

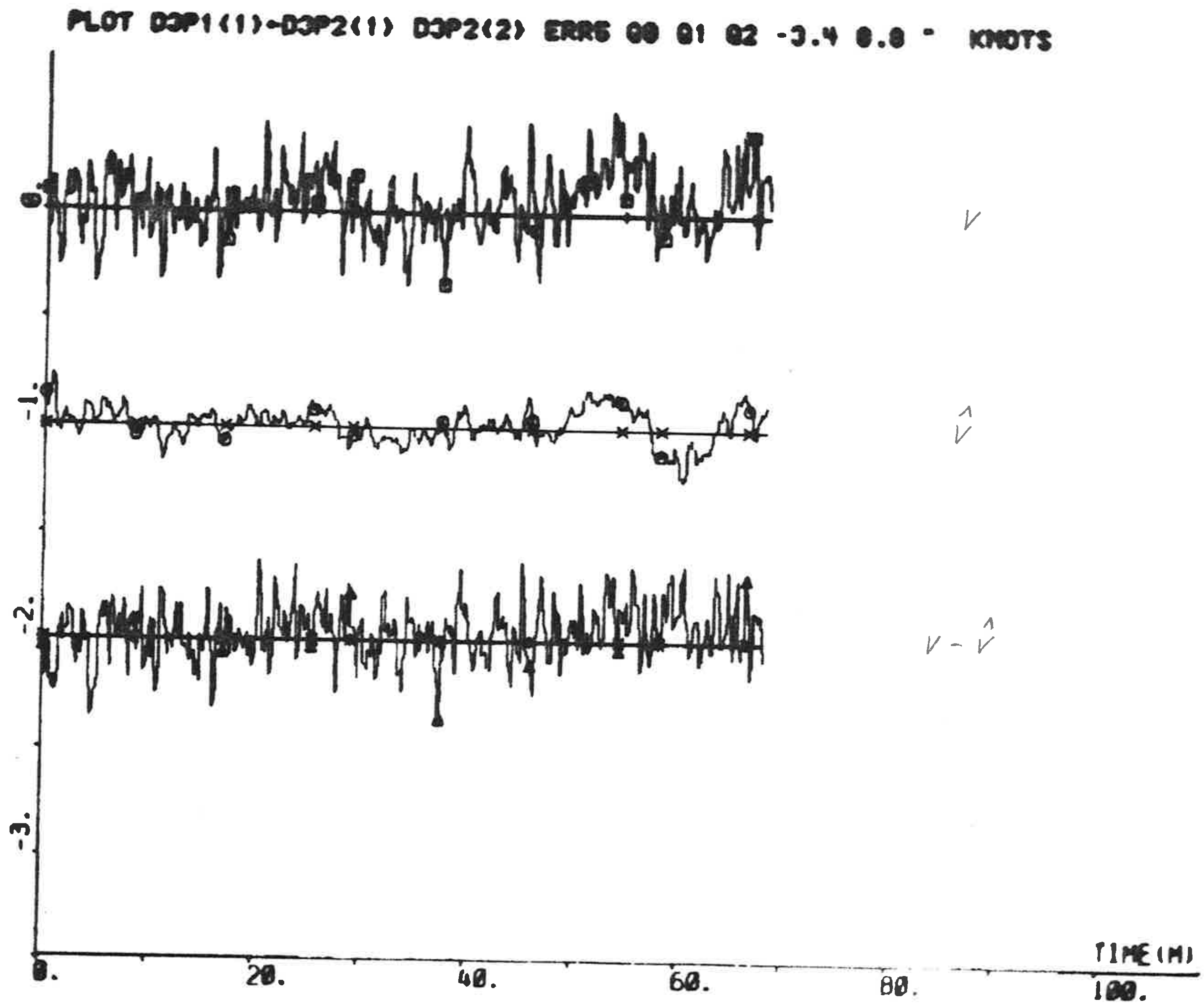
δ_c	-0.60 ± 1.08	deg	P_s	15.4 ± 0.1	MW
δ	1.09 ± 0.97	deg	ε_v	0.00 ± 0.02	knots
$\psi-\psi_{ref}$	0.005 ± 0.284	deg	ε_r	0.00 ± 0.02	deg/s
n	69.9 ± 0.4	rpm	ε_ψ	0.00 ± 0.03	deg
u	13.4 ± 0.3	knots	ε_δ	0.2 ± 0.5	deg

$V_1 = 0.178$

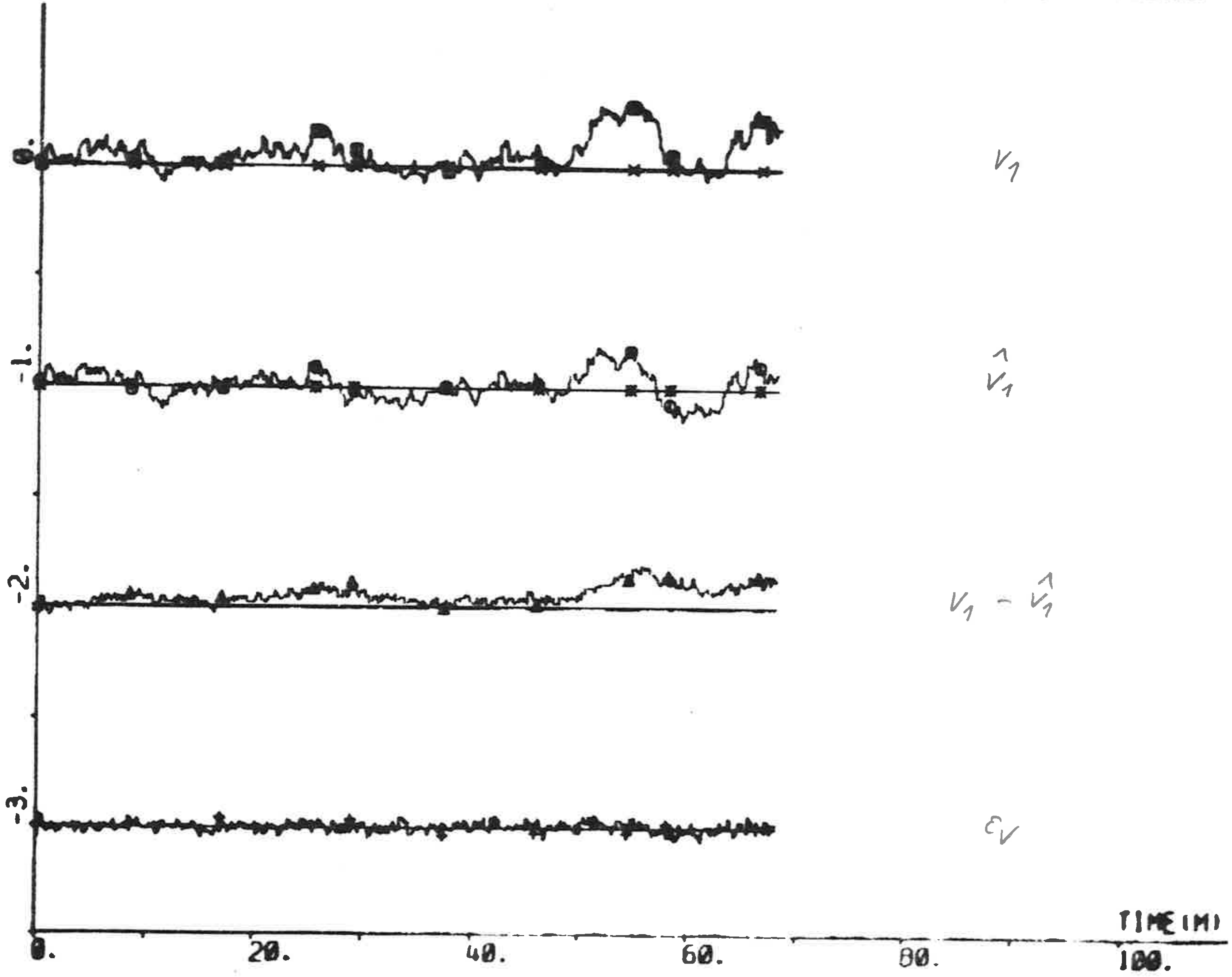
PLOT D3P1(1)-D3P1(6) D3P1(6) HP D3P1(10) HP MODY HP D3P1(15) 02 -3 1



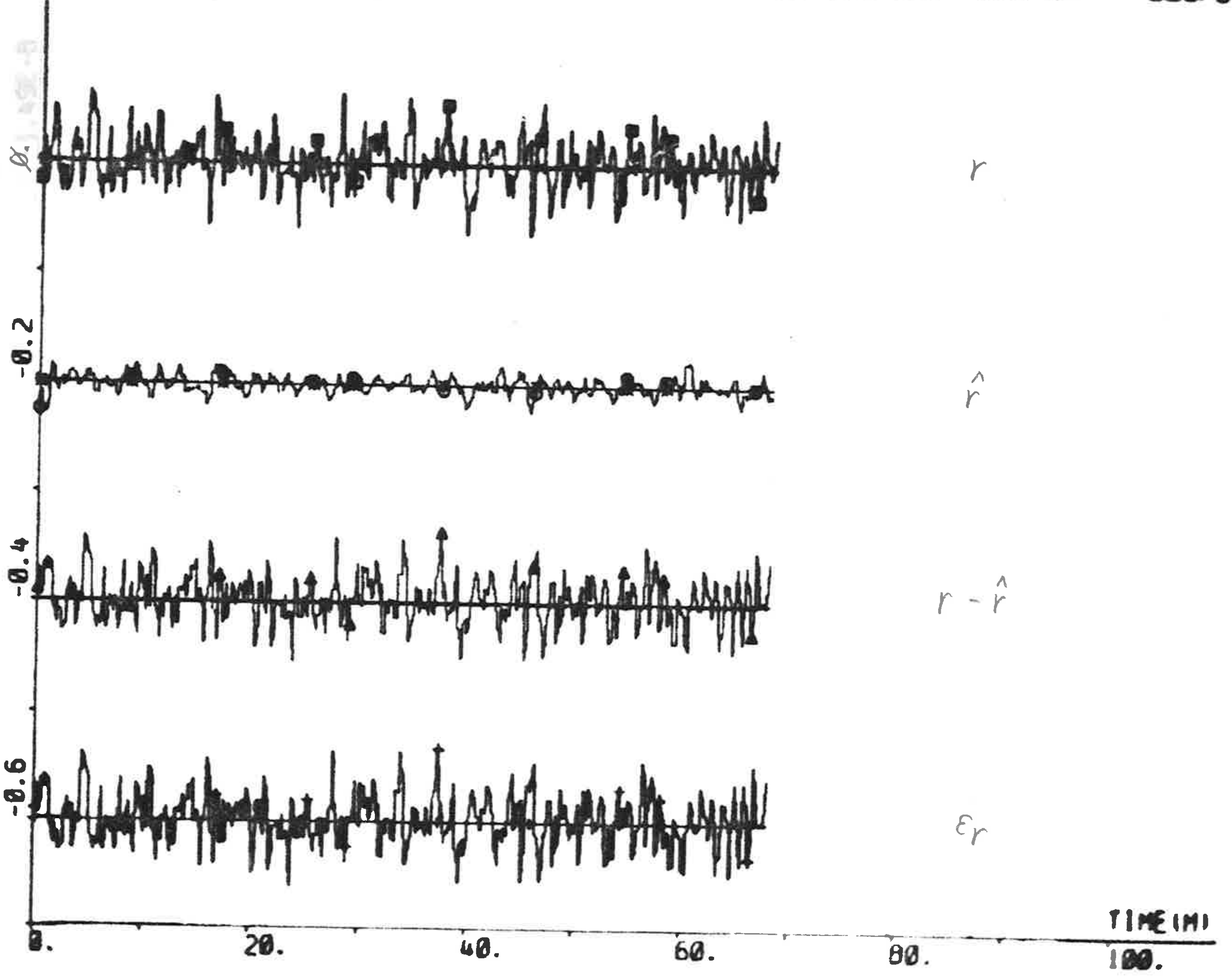

PLOT D3P1(1)-D3P1(13) D3P1(12) D3P1(14) D3P1(11) 90 -20 50
40.
20.
0.
-20.
0.
20.
40.
60.
80.
100.
TIME(M)
0.5 * n rpm
2 * v knots
P_s MW
δ_s deg

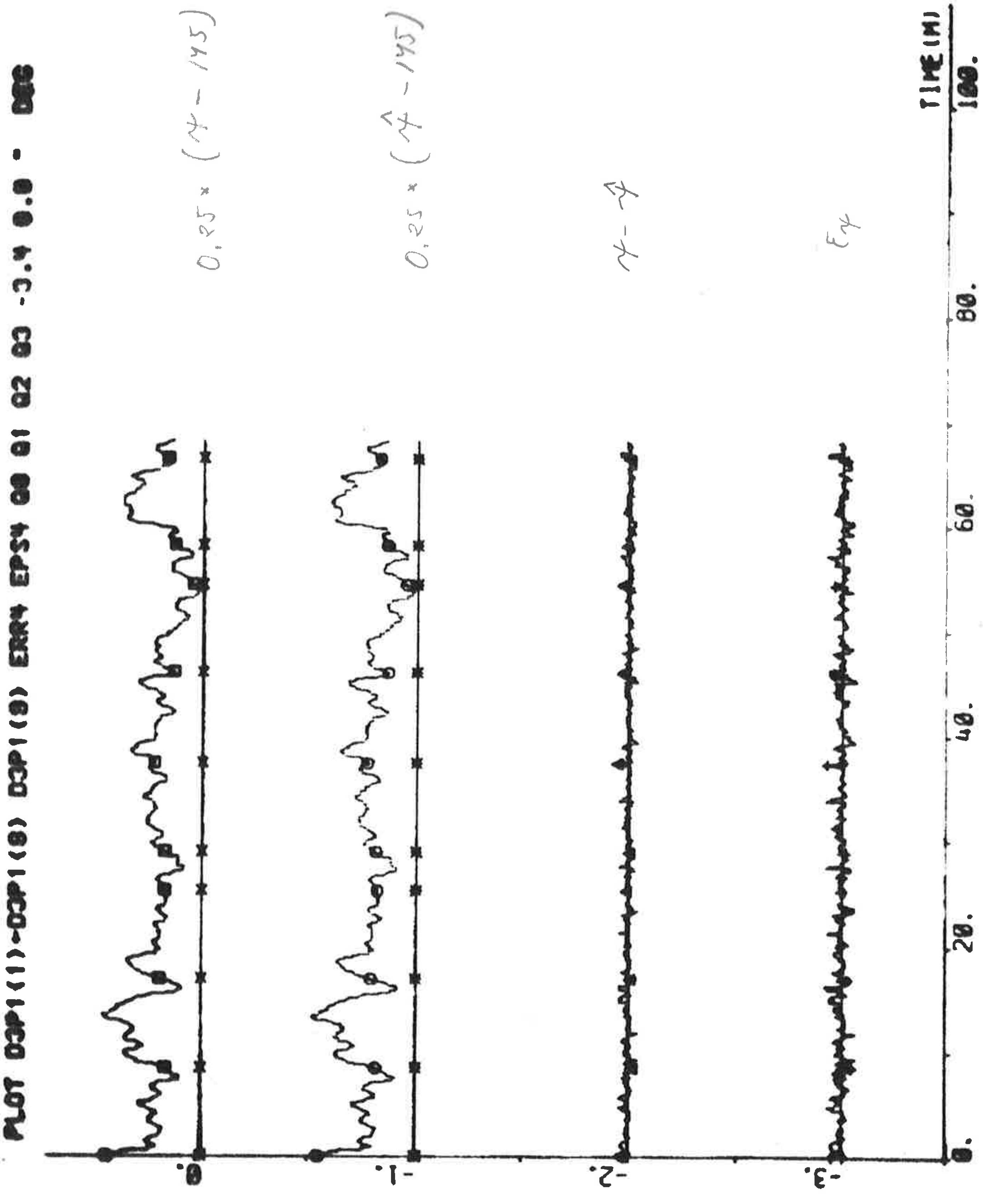

PLOT D3P1(1)-D3P2(1) D3P2(2) ERRS 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)

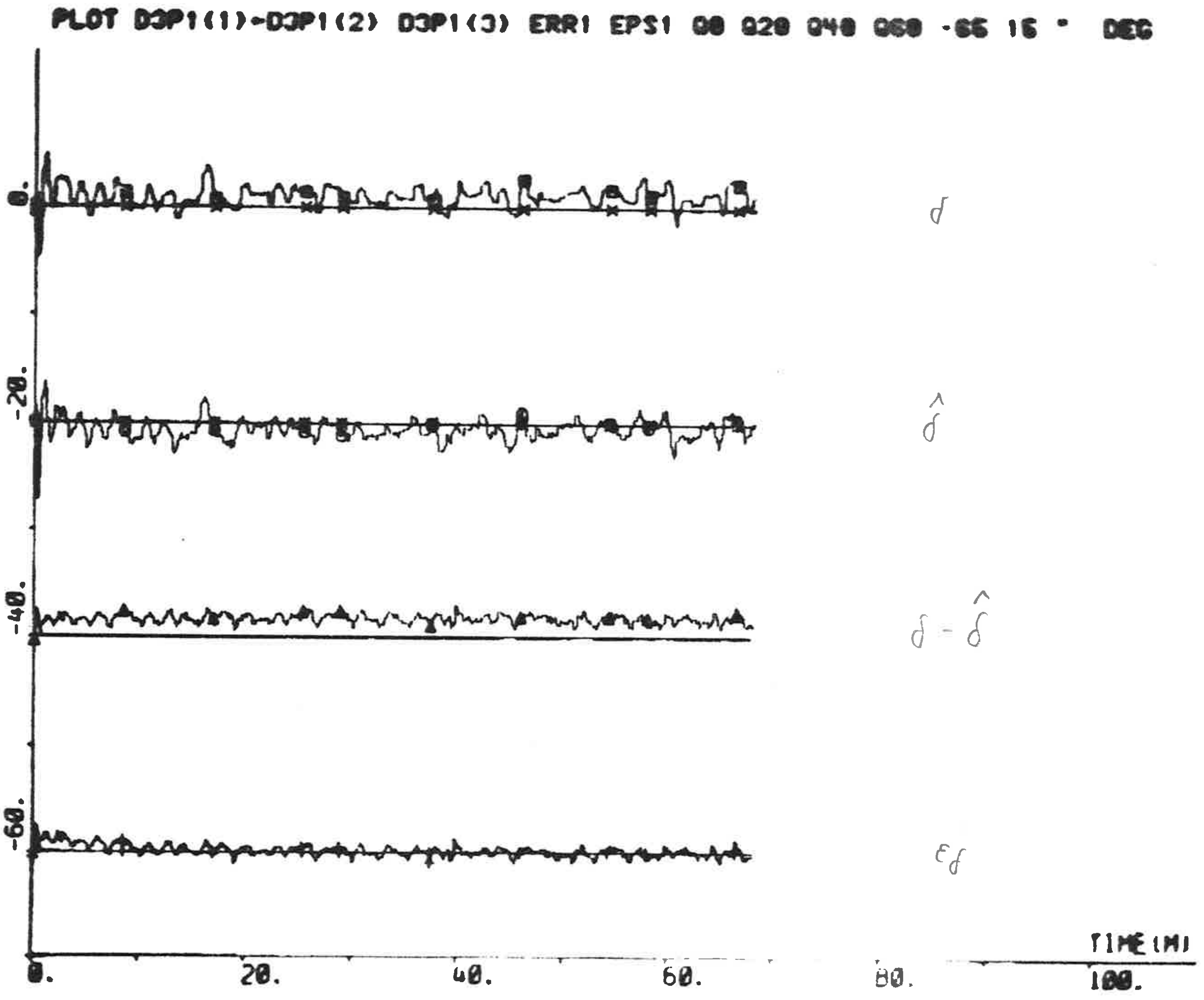
PLOT D3P1(1)-D3P1(4) D3P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 • KNOTS



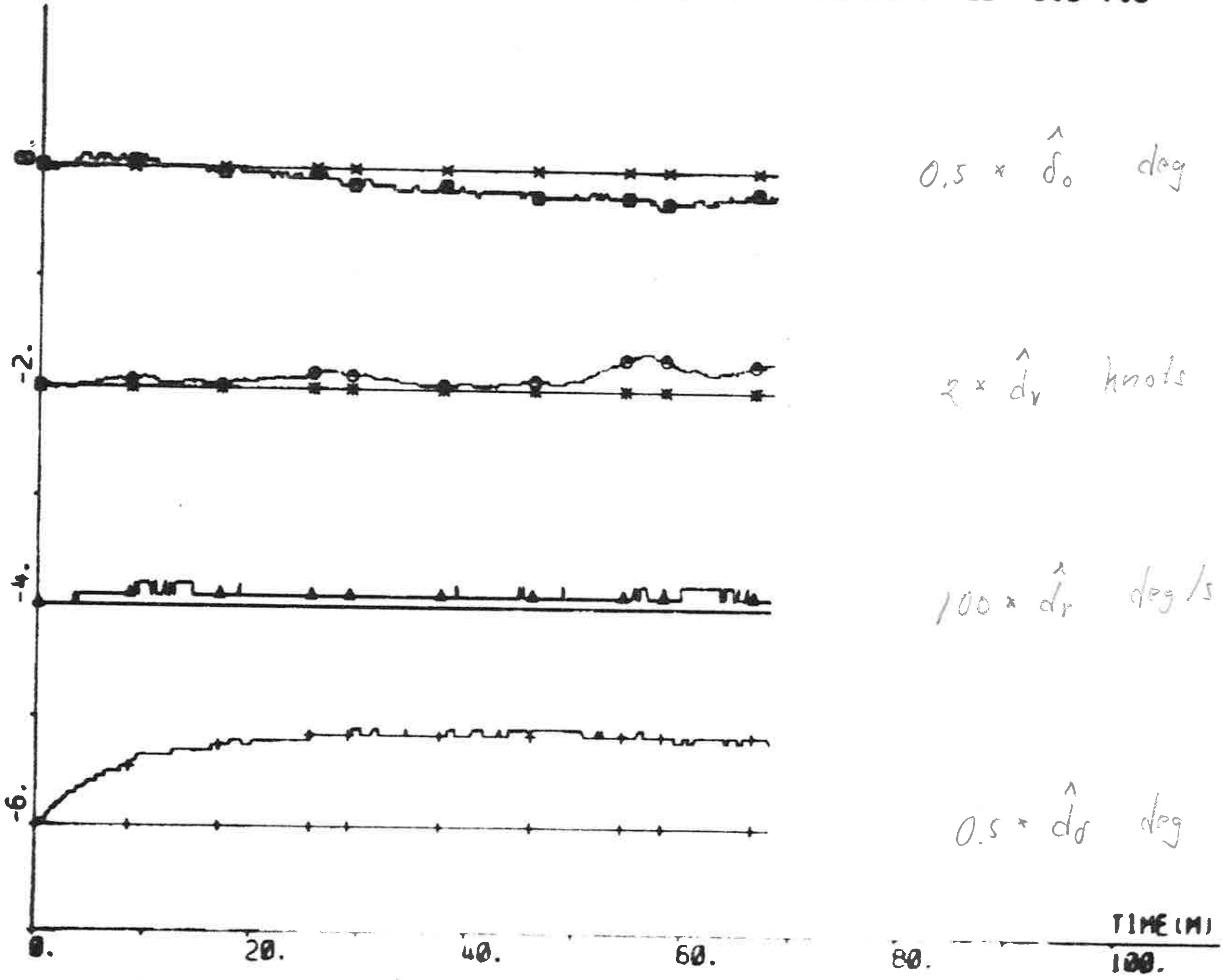
PLOT D3P1(1)-D3P1(6) D3P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. * DEG/S



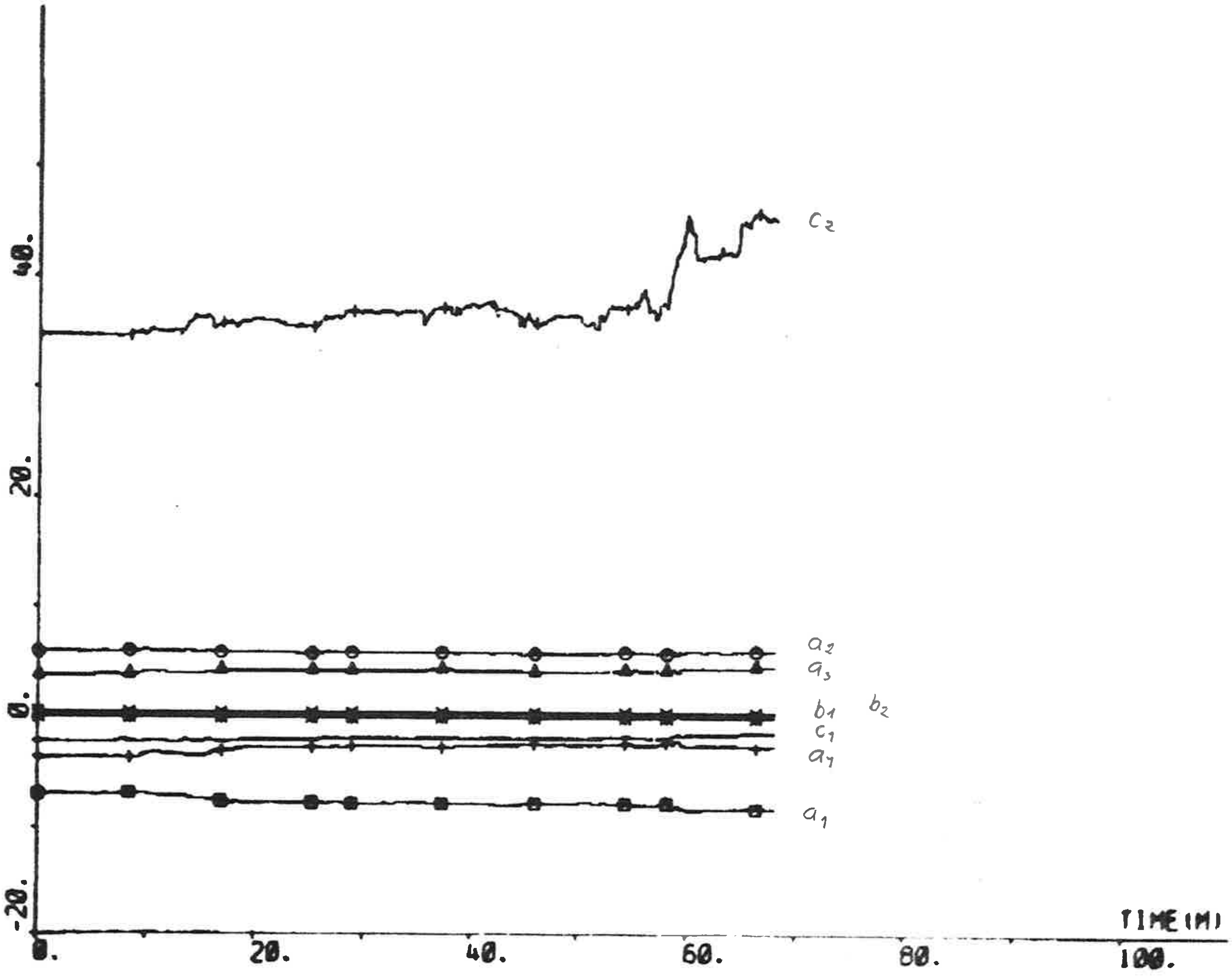

PLOT DCP1(1)-DCP1(8) DCP1(9) ERR4 EPS4 G0 G1 G2 G3 -3.4 0.0 - DEG
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)


PLOT D3P1(1)-D3P1(2) D3P1(3) ERR1 EPS1 00 020 040 060 -66 16 * DEG
0.
-20.
-40.
-60.
δ
δ̂
δ - δ̂
εδ
TIME (M)
0.
20.
40.
60.
80.
100.

PLOT D3P1(1)-D3P2(3) D3P2(4) D3P2(5) D3P2(6) 00 02 04 08 -6.5 1.5



PLOT D3P1(1)-D3P2(7) D3P2(8) D3P2(9) D3P2(10) D3P2(11) D3P2(12) D3P2(13)



EXPERIMENT E1

Date	1976-04-30	Forward draught	10.9 m
Time	09.00	Aft draught	12.9 m
Duration	89 min	Wind direction	SE (1; see App. A)
Position	S 21°35' E 07°34'	Wind velocity	11 m/s (strong breeze)
ψref	146 deg	Wave height	-

Open loop experiment for identification

Tuning time for the Kalman filter before the experiment started: 0 min.

δ_{amp} = 3, 5 deg k_{id} = 0

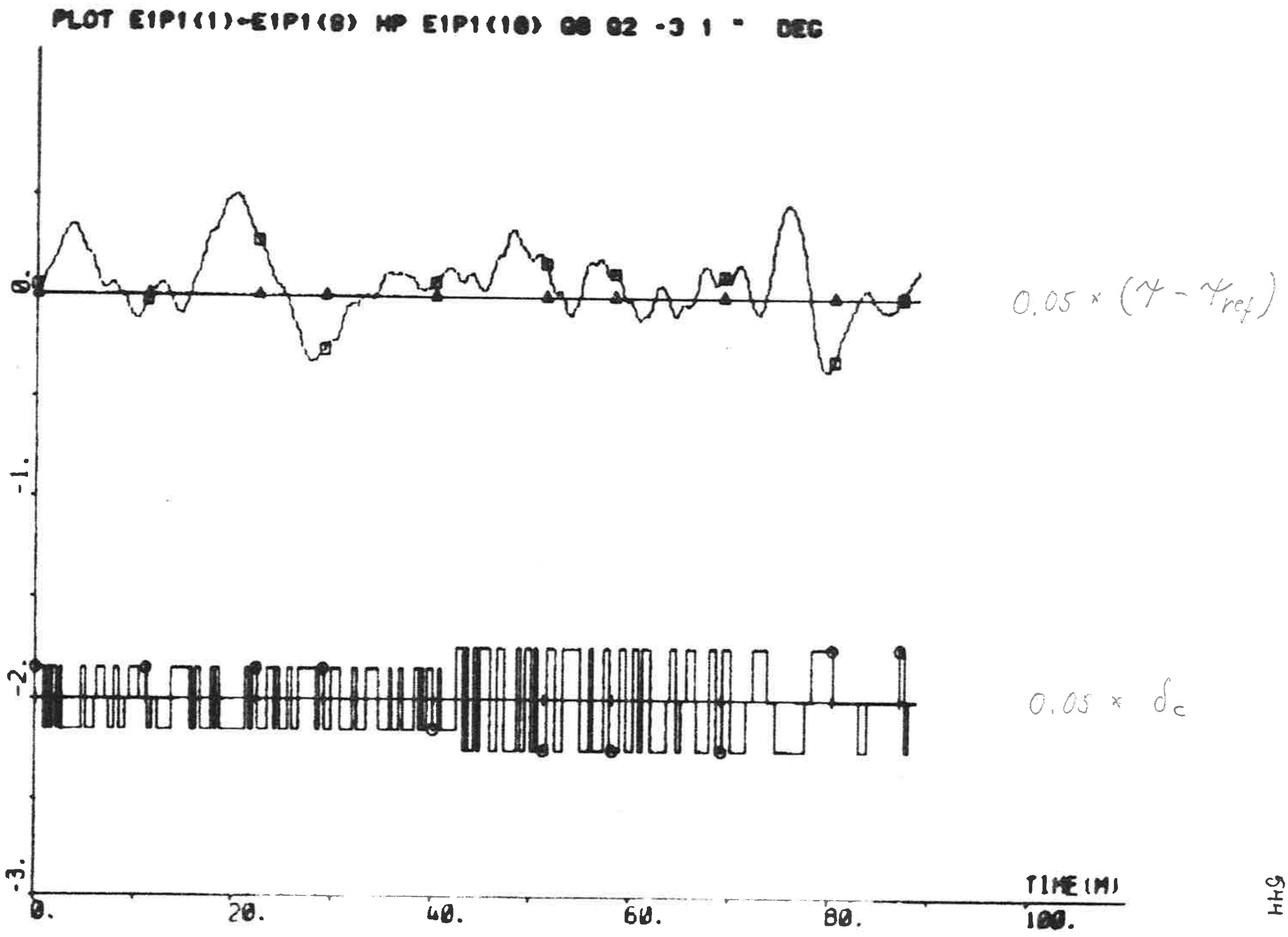
T_s = 10 s   IVVC = 1

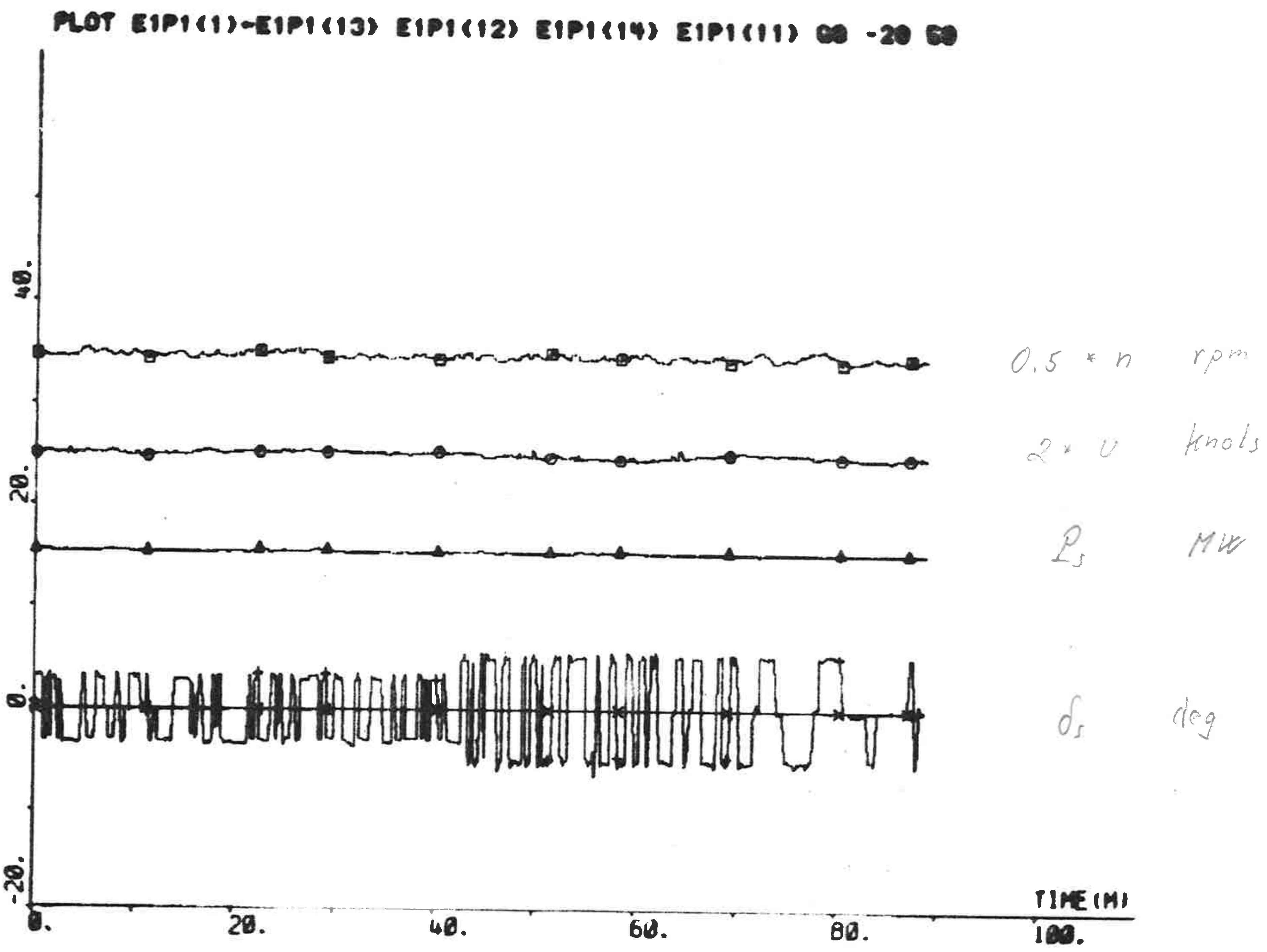
Final values:

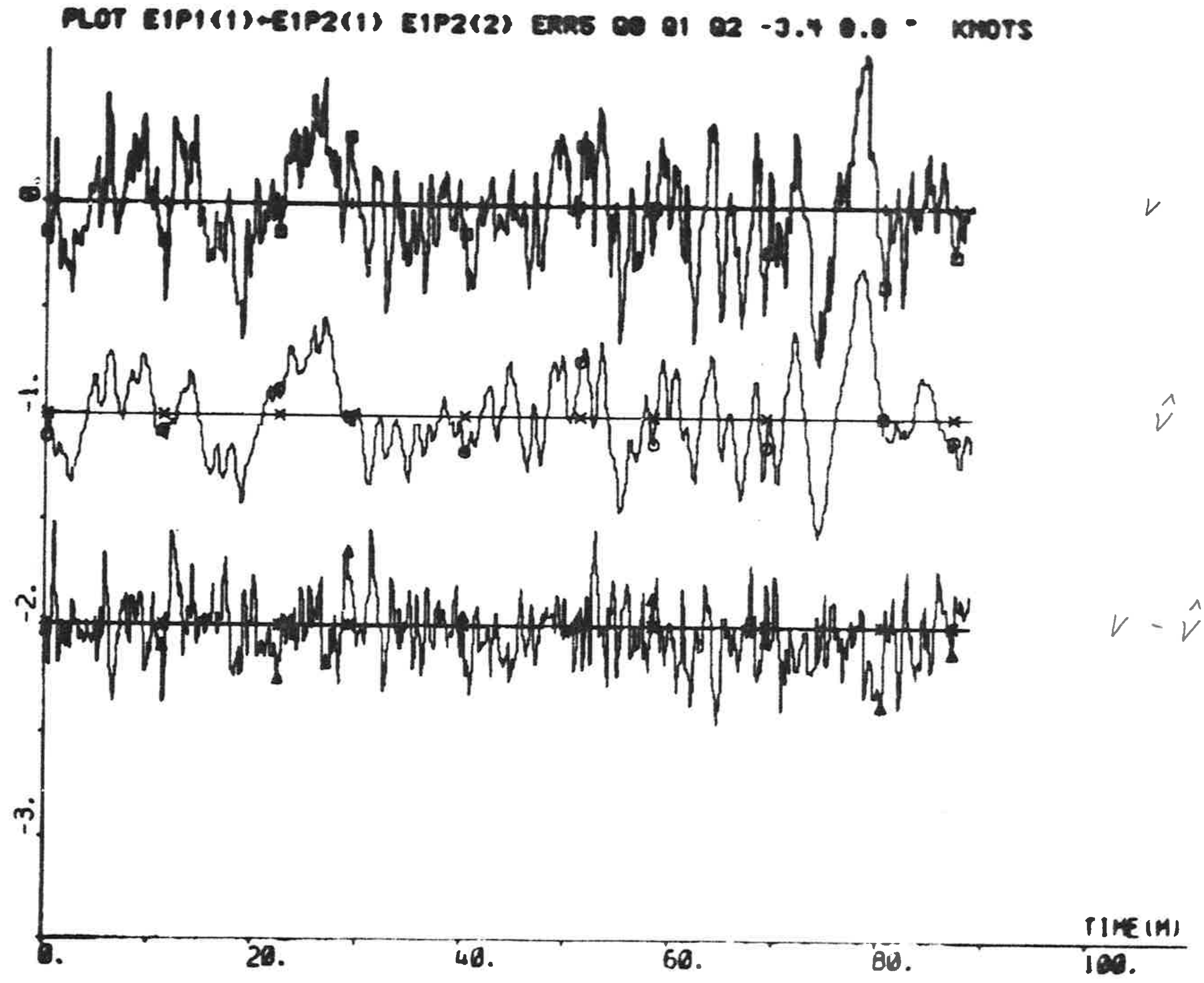
$\hat{\delta}_0$ = -0.3 deg $\hat{d}_v$ = 0.07 knots $\hat{d}_r$ = 0.005 deg/s $\hat{d}_\delta$ = 1.5 deg

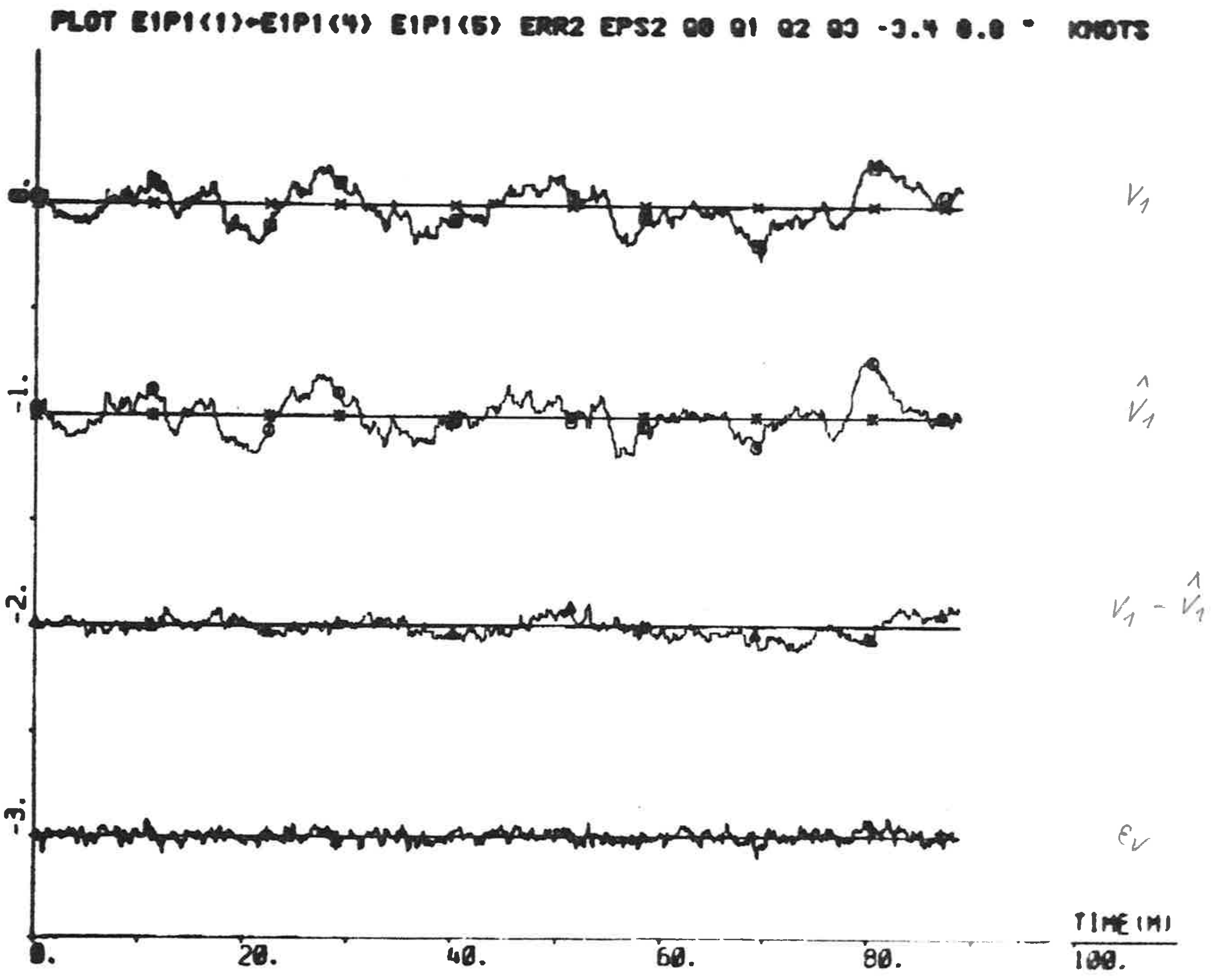
Statistics

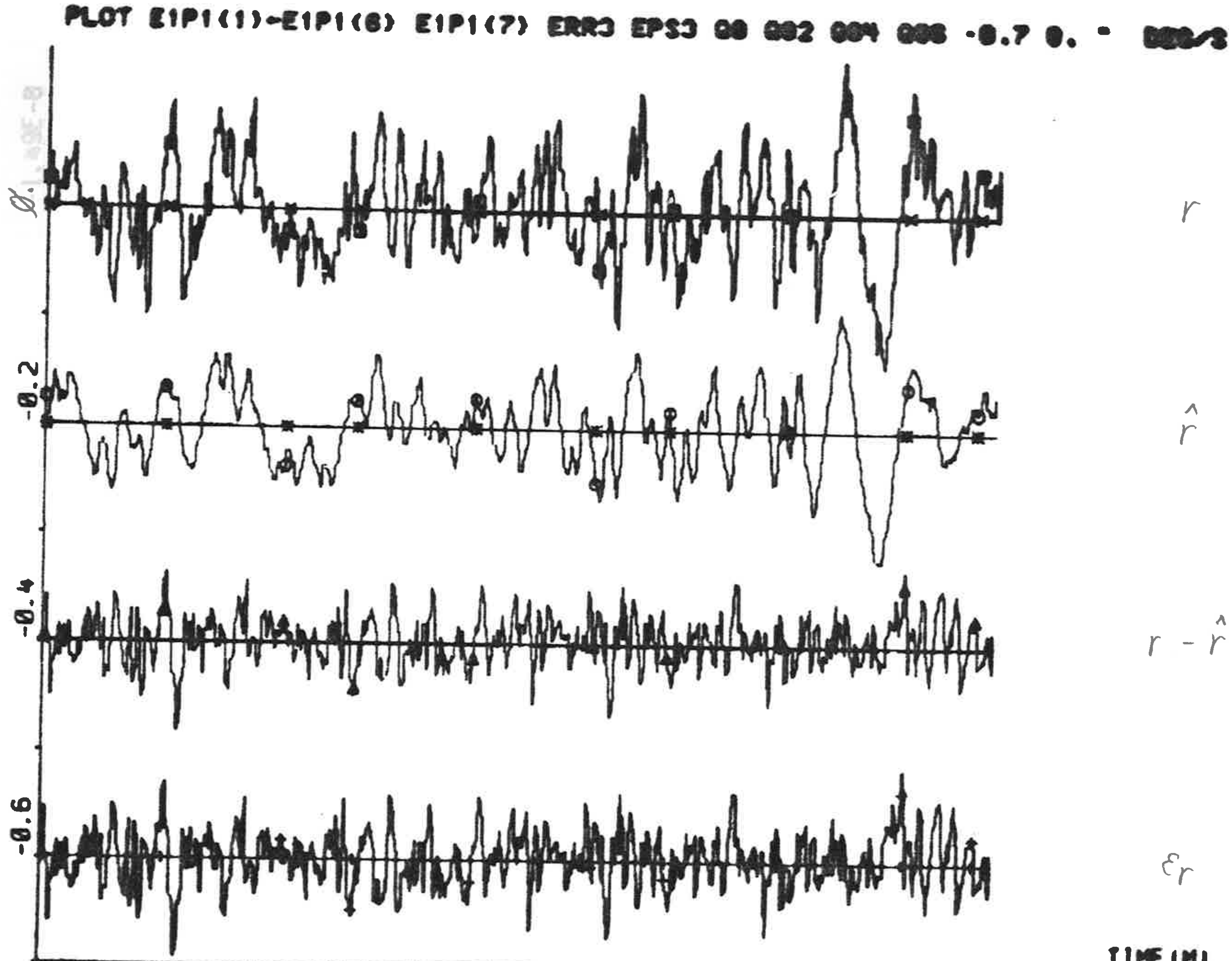
		Mean value	Stand. dev.			Mean value	Stand. dev.
δ_c	deg	-0.28	3.77	r	deg/s	0.003	0.047
δ_s	deg	-0.30	3.80	$\hat{r}$	deg/s	0.000	0.037
n	rpm	69.65	0.55	$r-\hat{r}$	deg/s	0.003	0.023
u	knots	12.54	0.10	ε_r	deg/s	0.001	0.027
P_s	MW	15.42	0.08	$\psi-\psi_{ref}$	deg	1.369	3.432
v	knots	-0.026	0.253	$\hat{\psi}-\psi_{ref}$	deg	1.370	3.432
$\hat{v}$	knots	0.001	0.211	$\psi-\hat{\psi}$	deg	0.000	0.027
$v-\hat{v}$	knots	-0.026	0.148	ε_ψ	deg	0.000	0.043
v_1	knots	-0.007	0.096	δ	deg	1.12	3.52
$\hat{v}_1$	knots	0.001	0.088	$\hat{\delta}$	deg	-0.27	3.54
$v_1-\hat{v}_1$	knots	-0.009	0.042	$\delta-\hat{\delta}$	deg	1.38	0.64
ε_v	knots	0.001	0.029	ε_δ	deg	0.11	0.68


PLOT E1P1(1)-E1P1(8) HP E1P1(10) 08 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)
0.05 × (ψ - ψref)
0.05 × δc

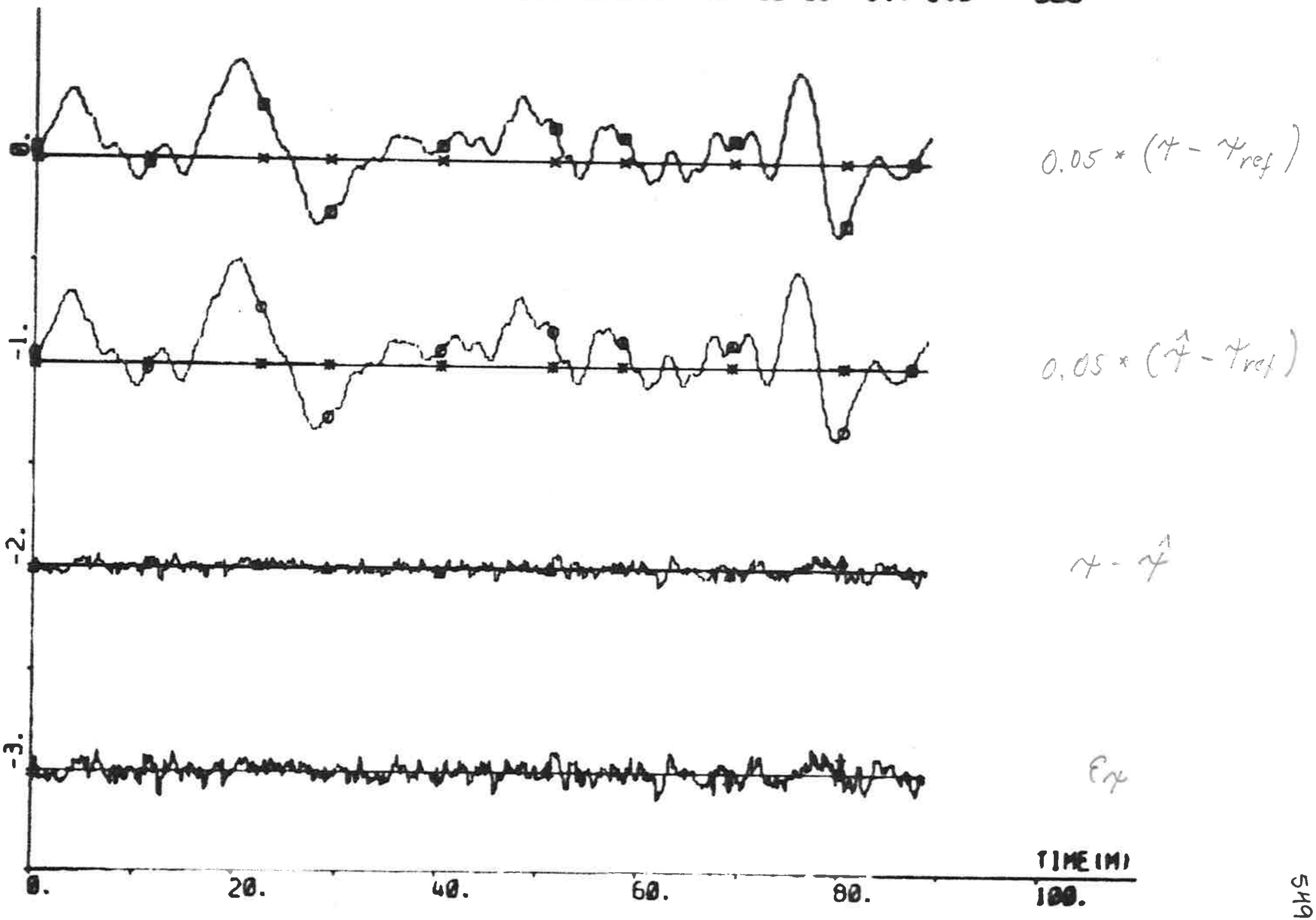

PLOT E1P1(1)-E1P1(13) E1P1(12) E1P1(14) E1P1(11) 00 -20 60
40.
20.
0.
-20.
0.
20.
40.
60.
80.
100.
TIME(M)
0.5 * n rpm
2 * v knots
P_s MW
δ_s deg


PLOT E1P1(1)-E1P2(1) E1P2(2) ERRS Q0 Q1 Q2 -3.4 0.0 ° KNOTS
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)

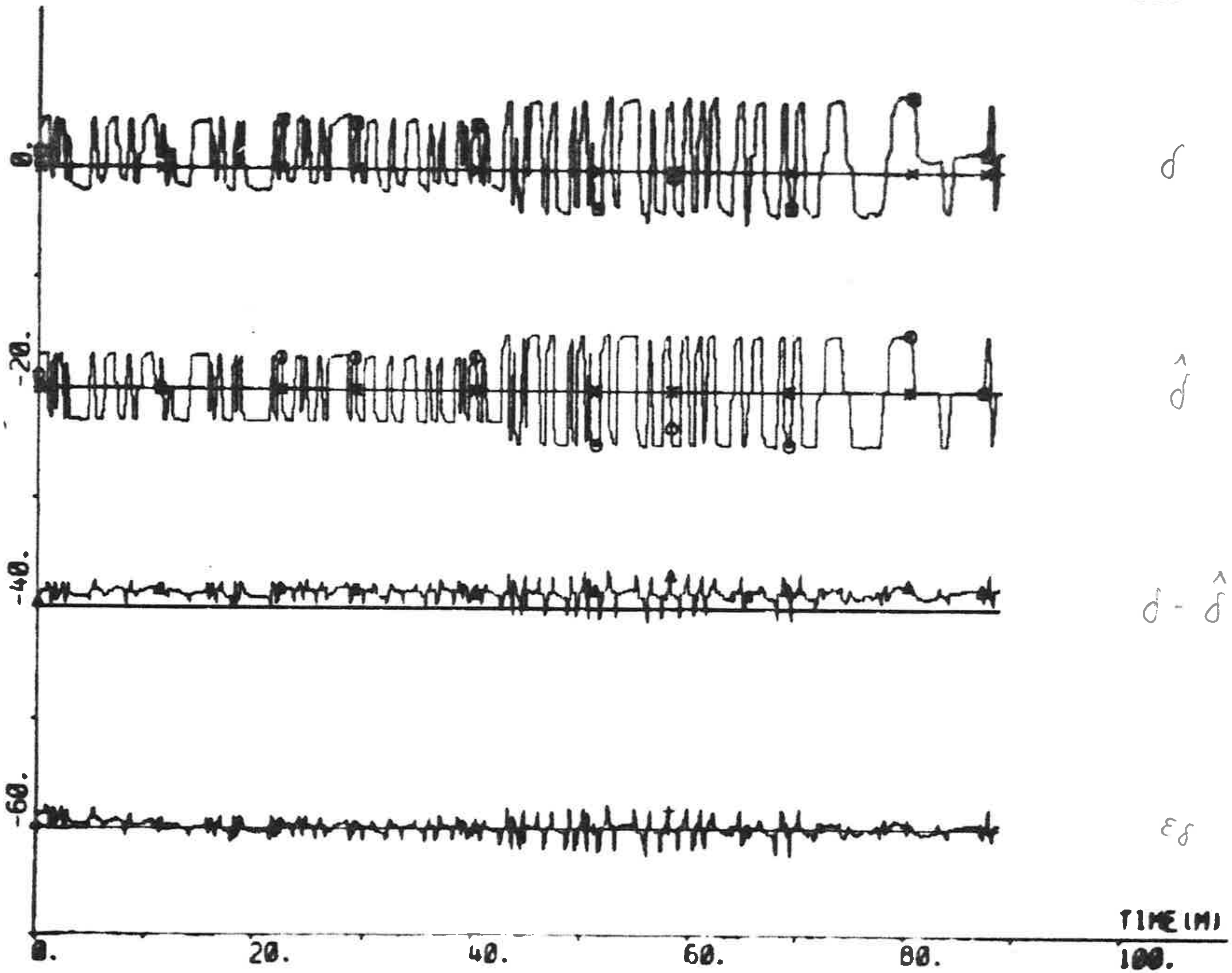

PLOT E1P1(1)-E1P1(4) E1P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 KNOTS
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
TIME(M)
100.
V_1
$\hat{V}_1$
$V_1 - \hat{V}_1$
ε_V


PLOT E1P1(1)-E1P1(6) E1P1(7) ERR3 EPS3 G0 G02 G04 G06 -0.7 0. - D00/S
Ø
-0.2
-0.4
-0.6
r
r̂
r - r̂
εr
0.
20.
40.
60.
80.
100.
TIME(M)

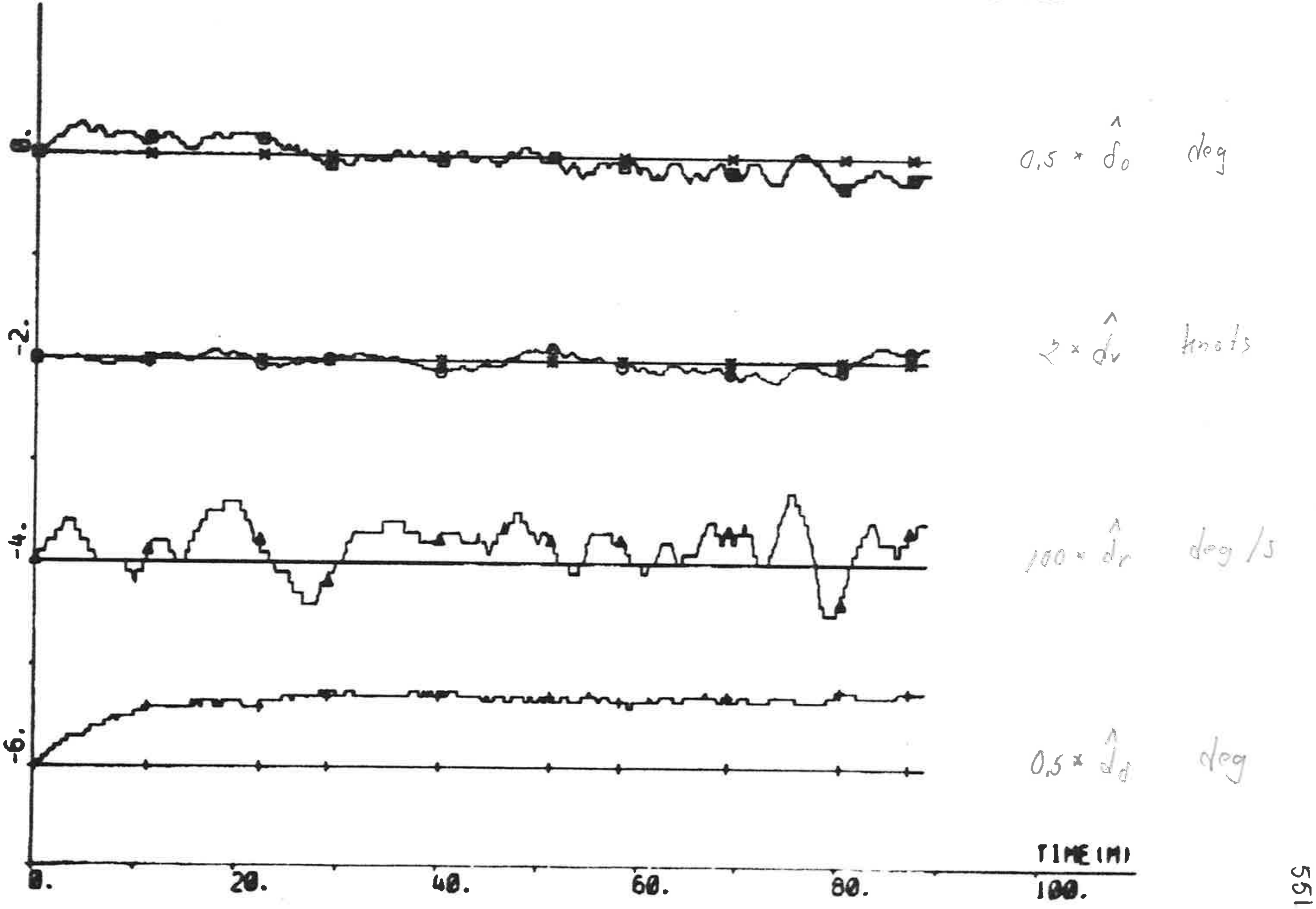
PLOT E1P1(1)-E1P1(8) E1P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.8 * 008



PLOT E1P1(1)-E1P1(2) E1P1(3) ERR1 EPS1 00 020 040 060 -85 15 - DEG



PLOT E1P1(1)-E1P2(3) E1P2(4) E1P2(5) E1P2(6) 00 02 04 06 -6.5 1.5



EXPERIMENT E2

Date	1976-04-30	Forward draught	10.9 m
Time	11.03	Aft draught	12.9 m
Duration	19 min	Wind direction	SE (1; see App. A)
Position	S 21°56' E 07°49'	Wind velocity	14 m/s (mod. gale)
ψ_{ref}	143 deg	Wave height	-

Open loop experiment for identification (5°/5° zig-zag test)

Tuning time for the Kalman filter before the experiment started: 0 min.

δ_{amp} = 5 deg k_{id} = 0

T_s = 10 s   IVVC = 1

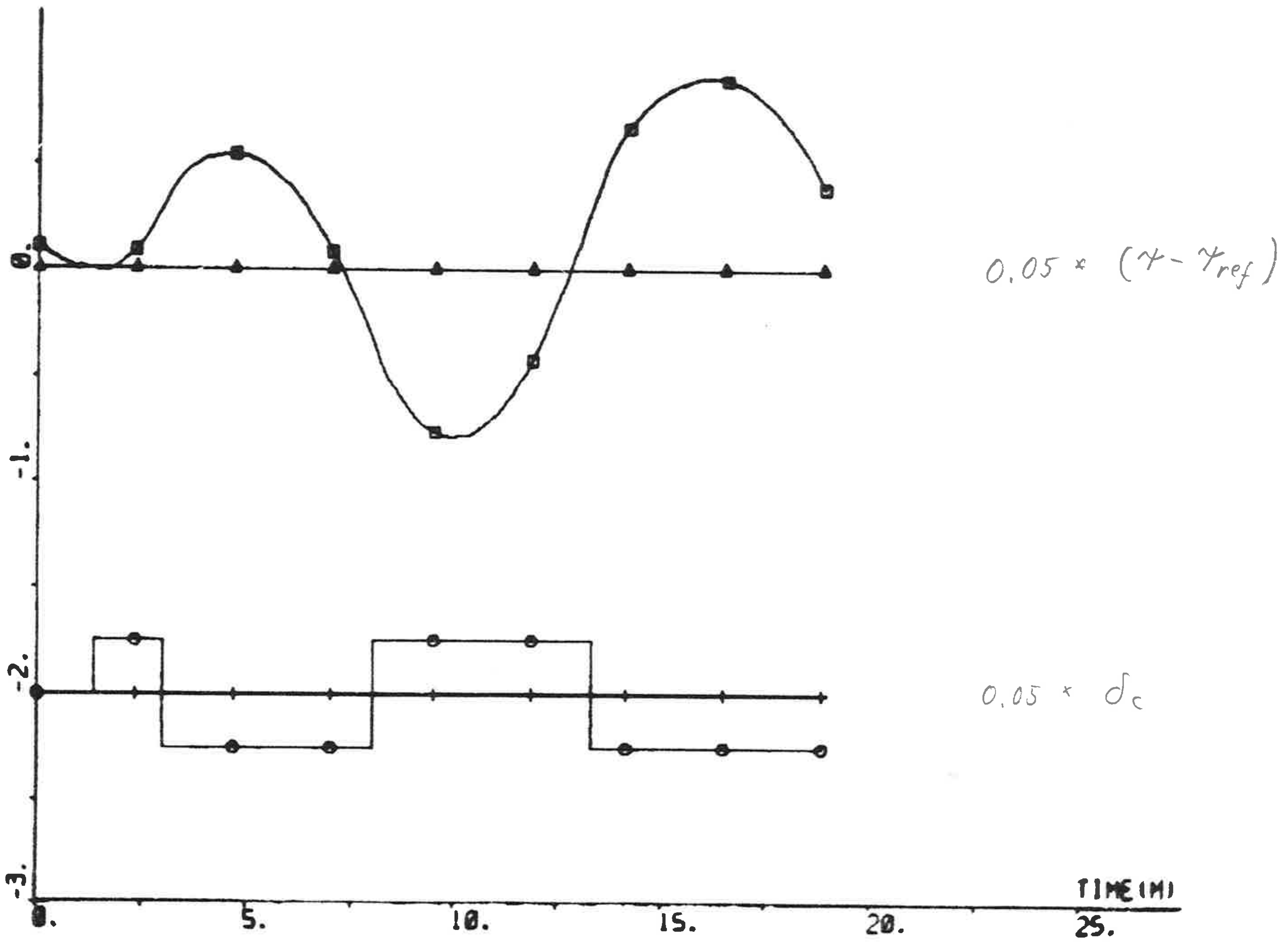
Final values:

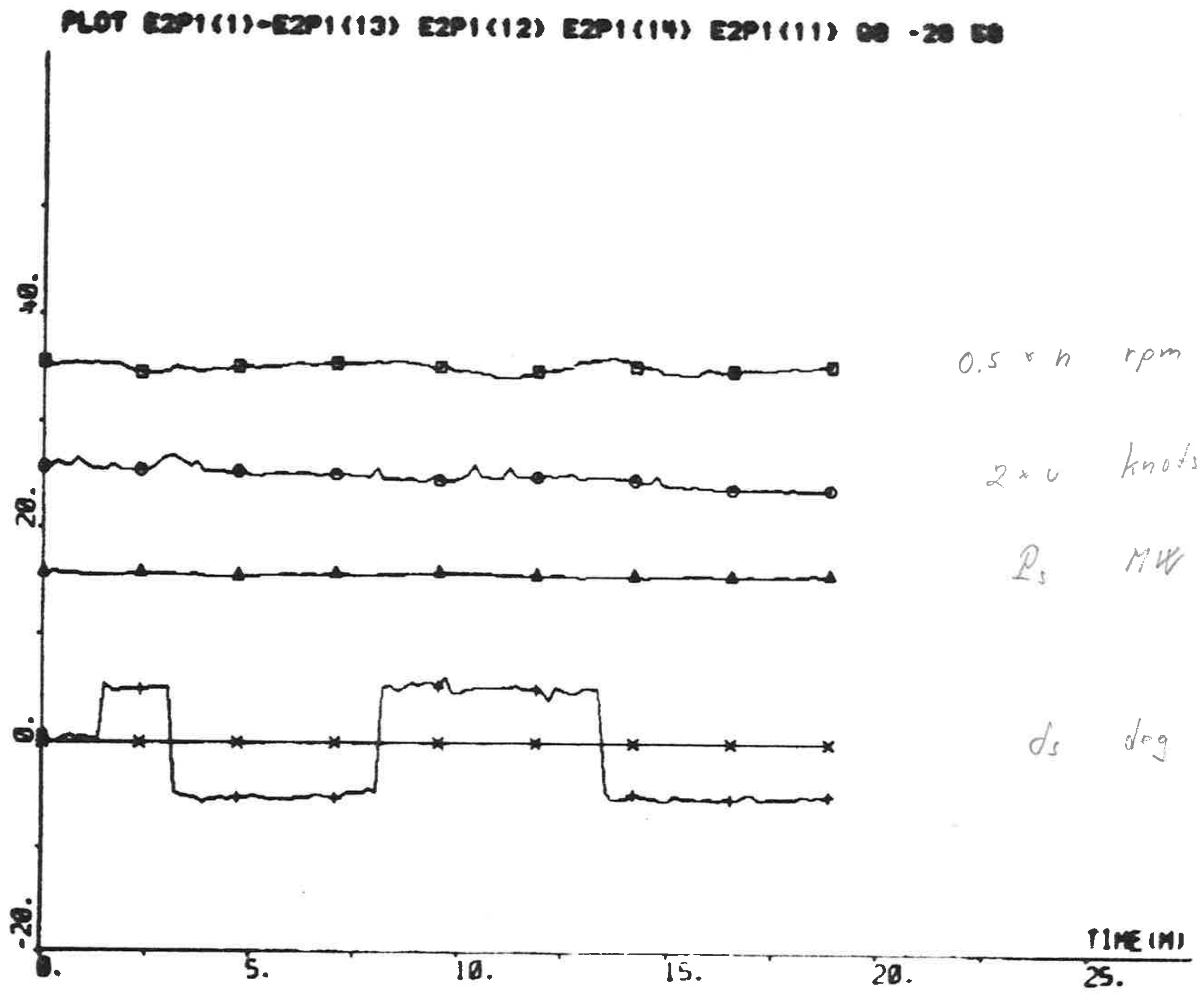
$\hat{\delta}_0$ = 0.4 deg $\hat{d}_v$ = 0.00 knots $\hat{d}_r$ = -0.001 deg/s $\hat{d}_\delta$ = 1.3 deg

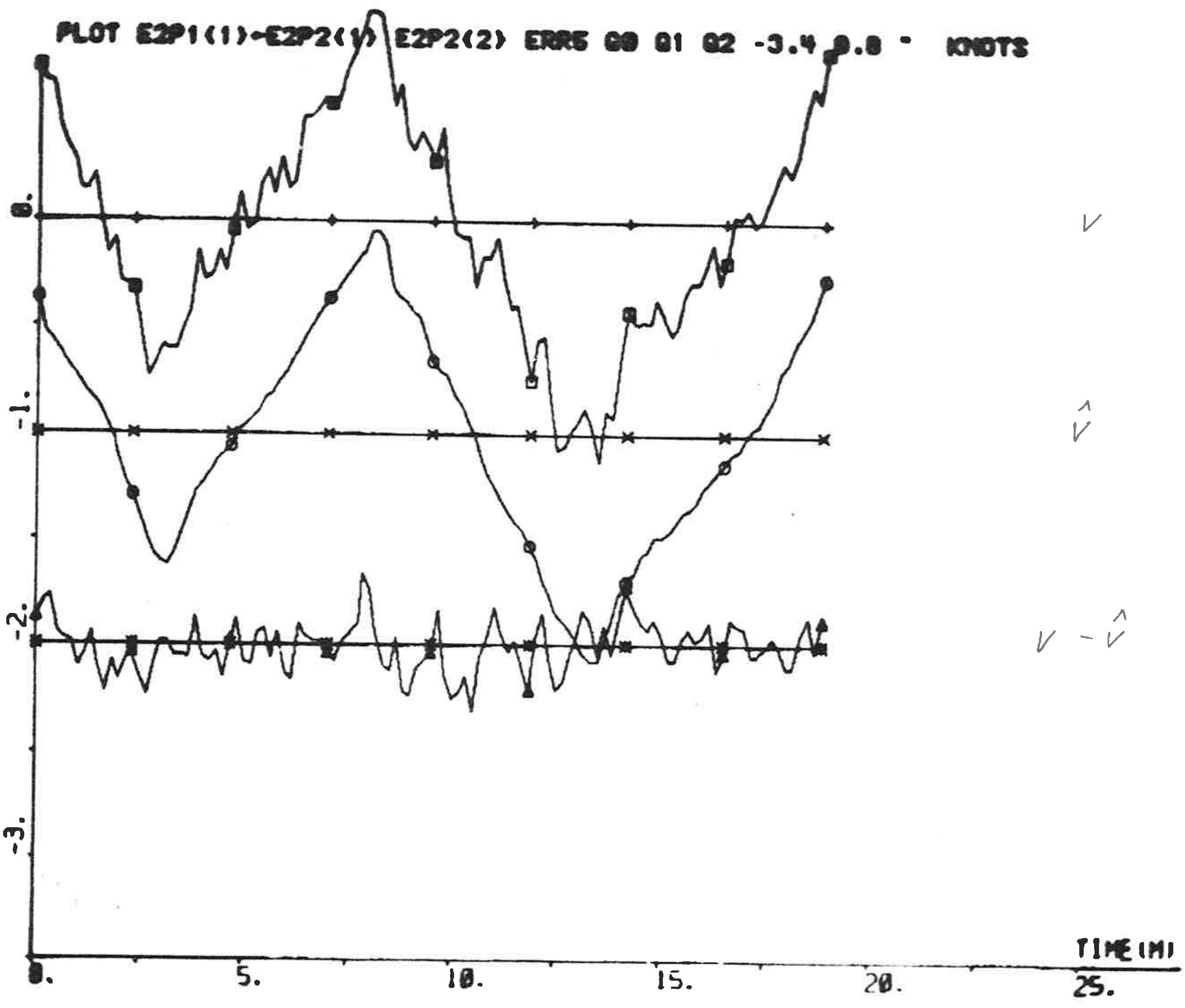
Statistics

		Mean value	Stand. dev.			Mean value	Stand. dev.
δ_c	deg	-0.93	4.73	r	deg/s	0.005	0.093
δ_s	deg	-0.87	4.77	$\hat{r}$	deg/s	0.004	0.088
n	rpm	70.53	0.79	$r-\hat{r}$	deg/s	0.002	0.018
u	knots	12.48	0.35	ε_r	deg/s	0.001	0.023
P_s	MW	15.66	0.08	$\psi-\psi_{ref}$	deg	3.545	10.617
v	knots	-0.047	0.526	$\hat{\psi}-\psi_{ref}$	deg	3.546	10.611
$\hat{v}$	knots	-0.038	0.509	$\psi-\hat{\psi}$	deg	-0.001	0.051
$v-\hat{v}$	knots	-0.009	0.120	ε_ψ	deg	-0.002	0.076
v_1	knots	-0.012	0.127	δ	deg	0.60	4.74
$\hat{v}_1$	knots	-0.017	0.155	$\hat{\delta}$	deg	-0.83	4.68
$v_1-\hat{v}_1$	knots	0.005	0.040	$\delta-\hat{\delta}$	deg	1.43	0.49
ε_v	knots	0.005	0.028	ε_δ	deg	0.45	0.64

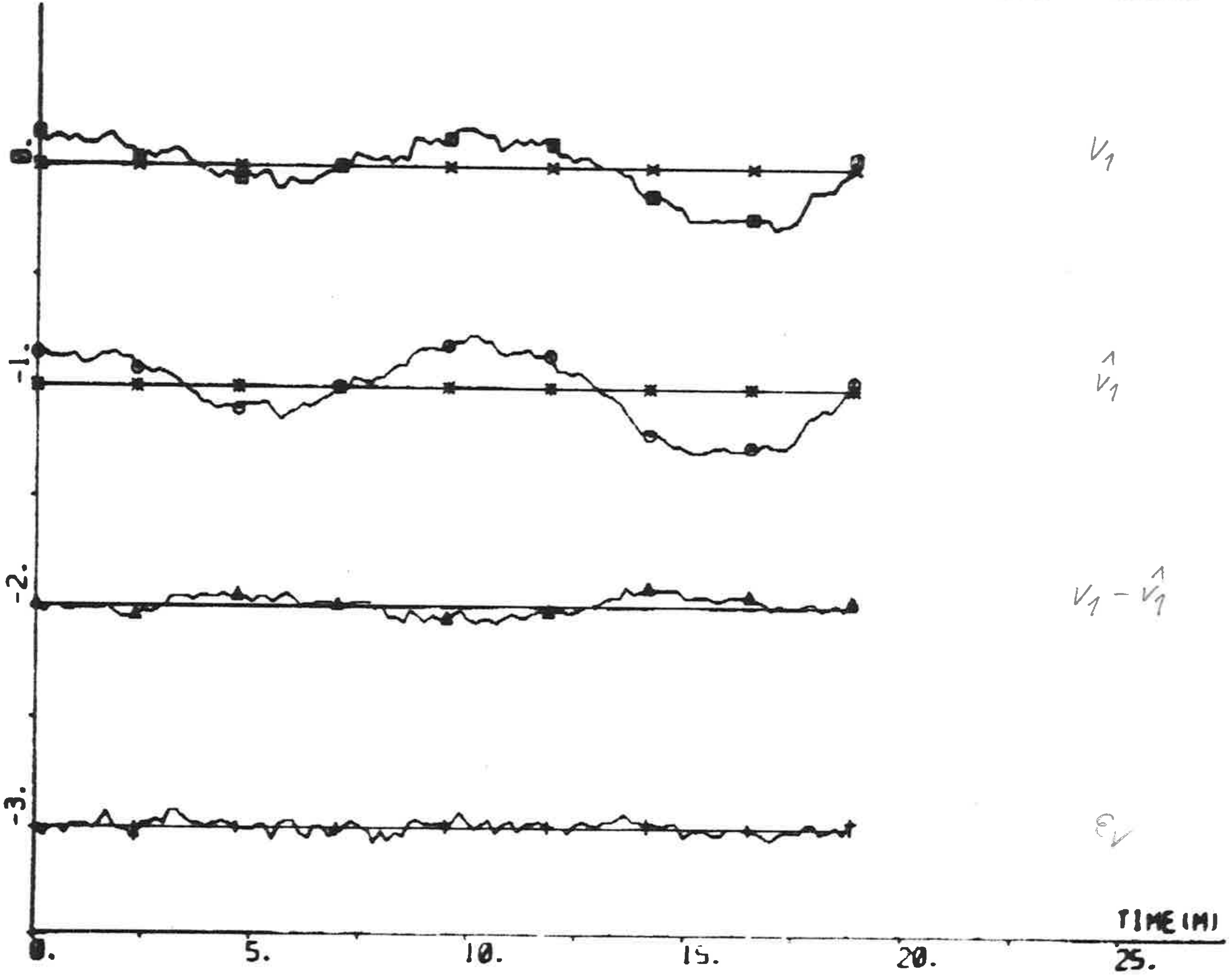
PLOT E2P1(1)-E2P1(8) HP E2P1(10) 00 02 -3 1 ° DEG

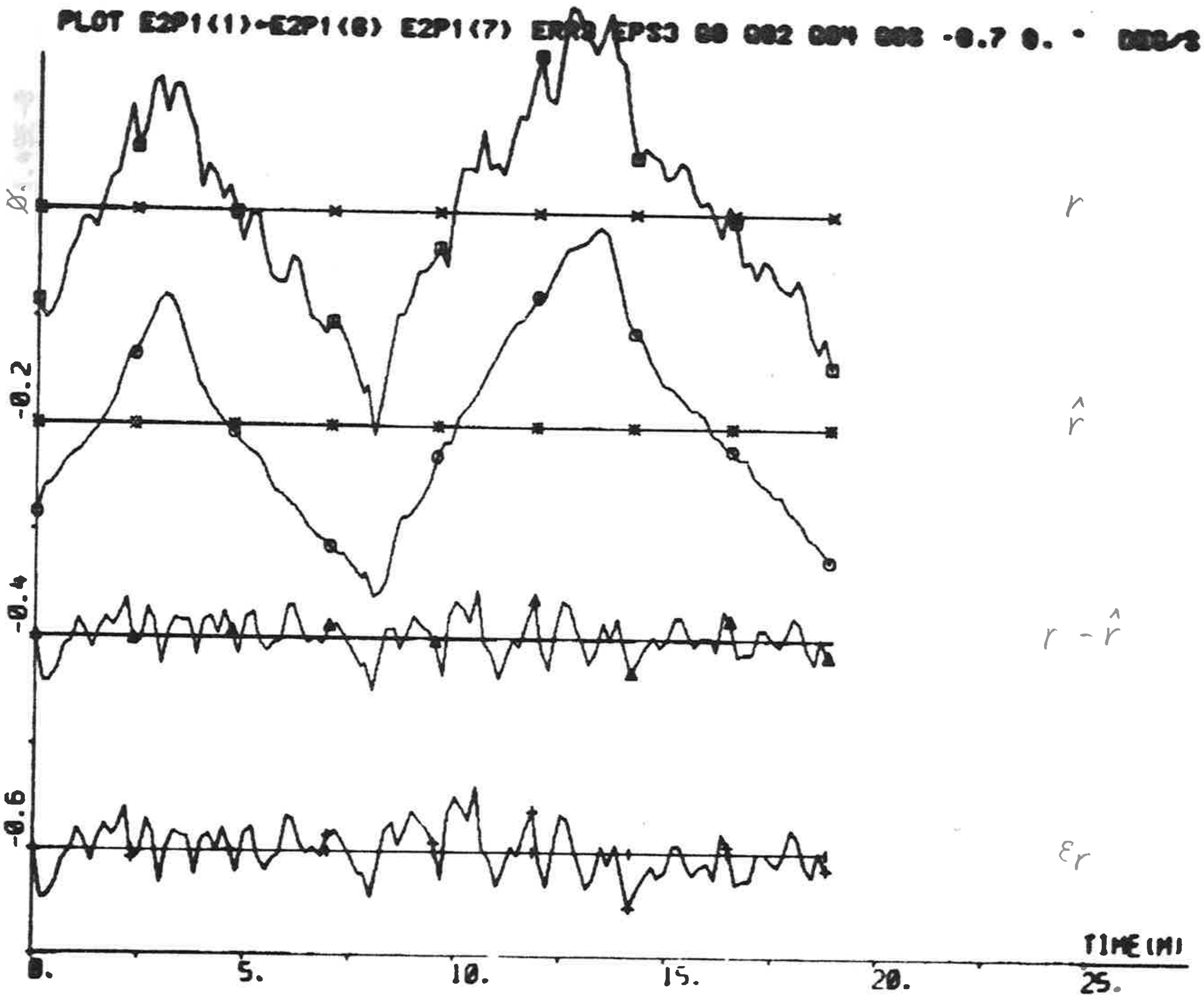


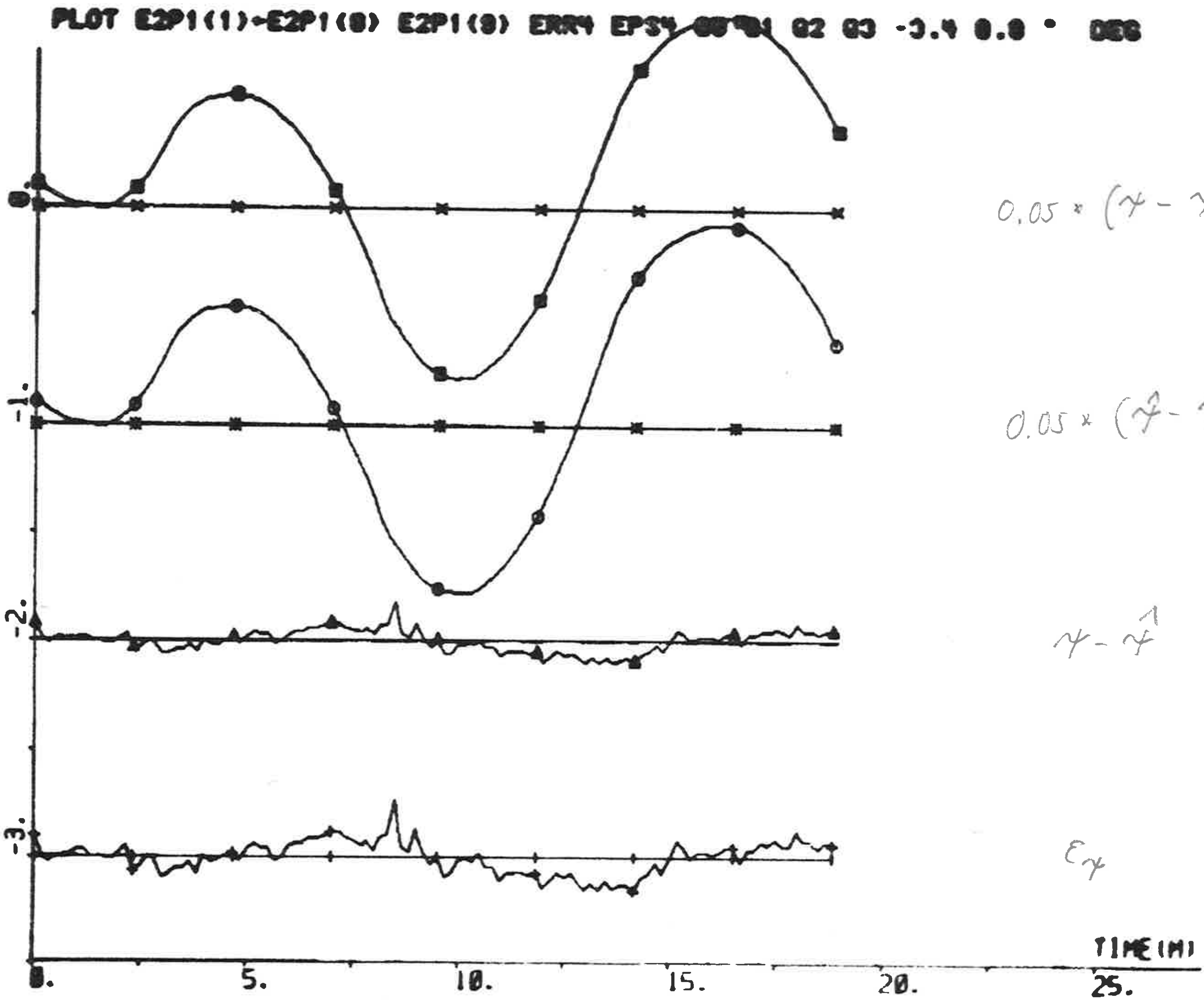

PLOT E2P1(1)-E2P1(13) E2P1(12) E2P1(14) E2P1(11) 00 -20 50
40.
20.
0.
-20.
0.
5.
10.
15.
20.
25.
TIME(M)
0.5 * n rpm
2 * v knots
P_s MW
d_s deg

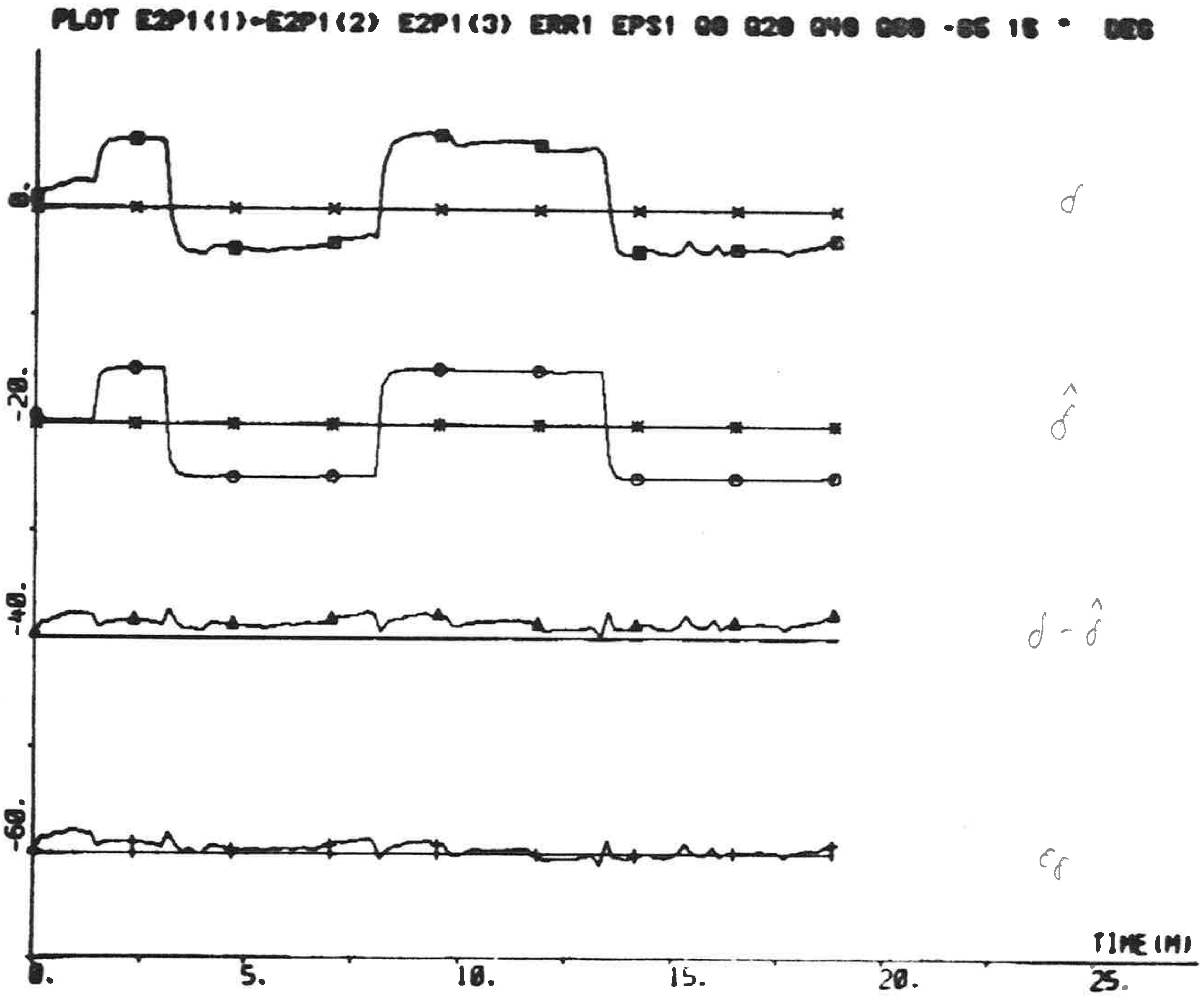

PLOT E2P1(1)-E2P2(1) E2P2(2) ERRS 00 01 02 -3.4 0.0 - KNOTS
0.
-1.
-2.
-3.
TIME(M)
0.
5.
10.
15.
20.
25.

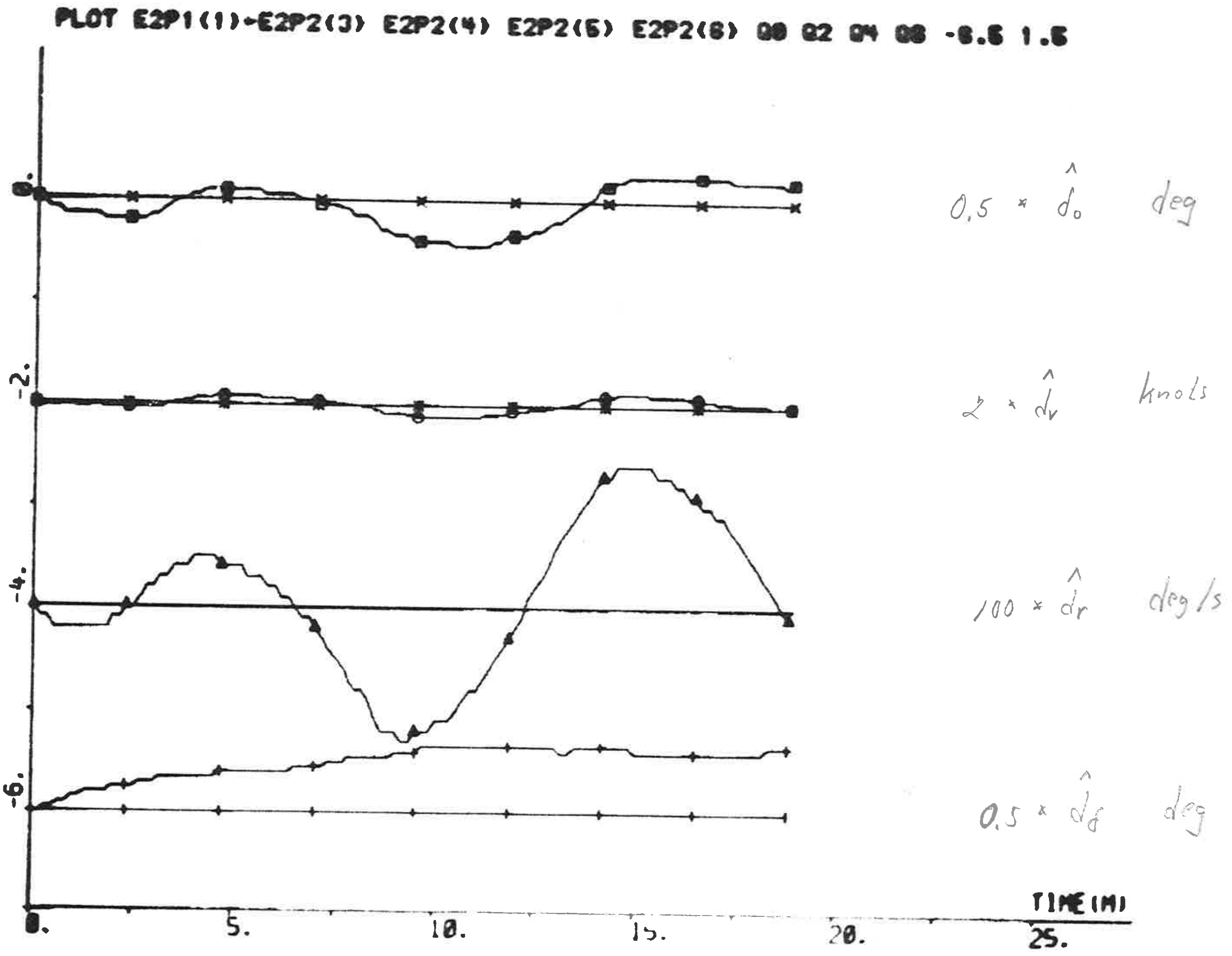
PLOT E2P1(1)-E2P1(4) E2P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 - KNOTS




PLOT E2P1(1)-E2P1(8) E2P1(7) ERR3 EPS3
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT E2P1(1)-E2P1(8) E2P1(8) ERR4 EPS4 ... 02 03 -3.4 0.0 DEG
0.05 * (ψ - ψ_ref)
0.05 * (ψ̂ - ψ_ref)
ψ - ψ̂
ε_ψ
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)


PLOT E2P1(1)-E2P1(2) E2P1(3) ERR1 EPS1 Q0 Q20 Q40 Q60 -65 15 DEG
0.
-20.
-40.
-60.
TIME (M)
0.
5.
10.
15.
20.
25.
δ
$\hat{\delta}$
$\delta - \hat{\delta}$
ε_δ


PLOT E2P1(1)-E2P2(3) E2P2(4) E2P2(5) E2P2(8) 00 02 04 08 -6.5 1.5
0.
-2.
-4.
-6.
0.
5.
10.
15.
20.
25.
TIME(M)
0,5 * $\hat{d}_o$ deg
2 * $\hat{d}_v$ knots
100 * $\hat{d}_r$ deg/s
0,5 * $\hat{d}_\delta$ deg

EXPERIMENT E3

Date	1976-04-30	Forward draught	10.9 m
Time	13.00	Aft draught	12.9 m
Duration	90 min	Wind direction	S (2; see App. A)
Position	S 22°18' E 08°05'	Wind velocity	9 m/s (fresh breeze)
ψ_{ref}	146 deg	Wave height	-

The rudder limit was 15 deg during the experiment.

Closed loop experiment for identification using additive rudder disturbances.

Tuning time for the Kalman filter before the experiment started: 1 min.

$\delta_{amp} = 5$ deg $k_{id} = 2$

$T_s = 10$ s IVVC = 1

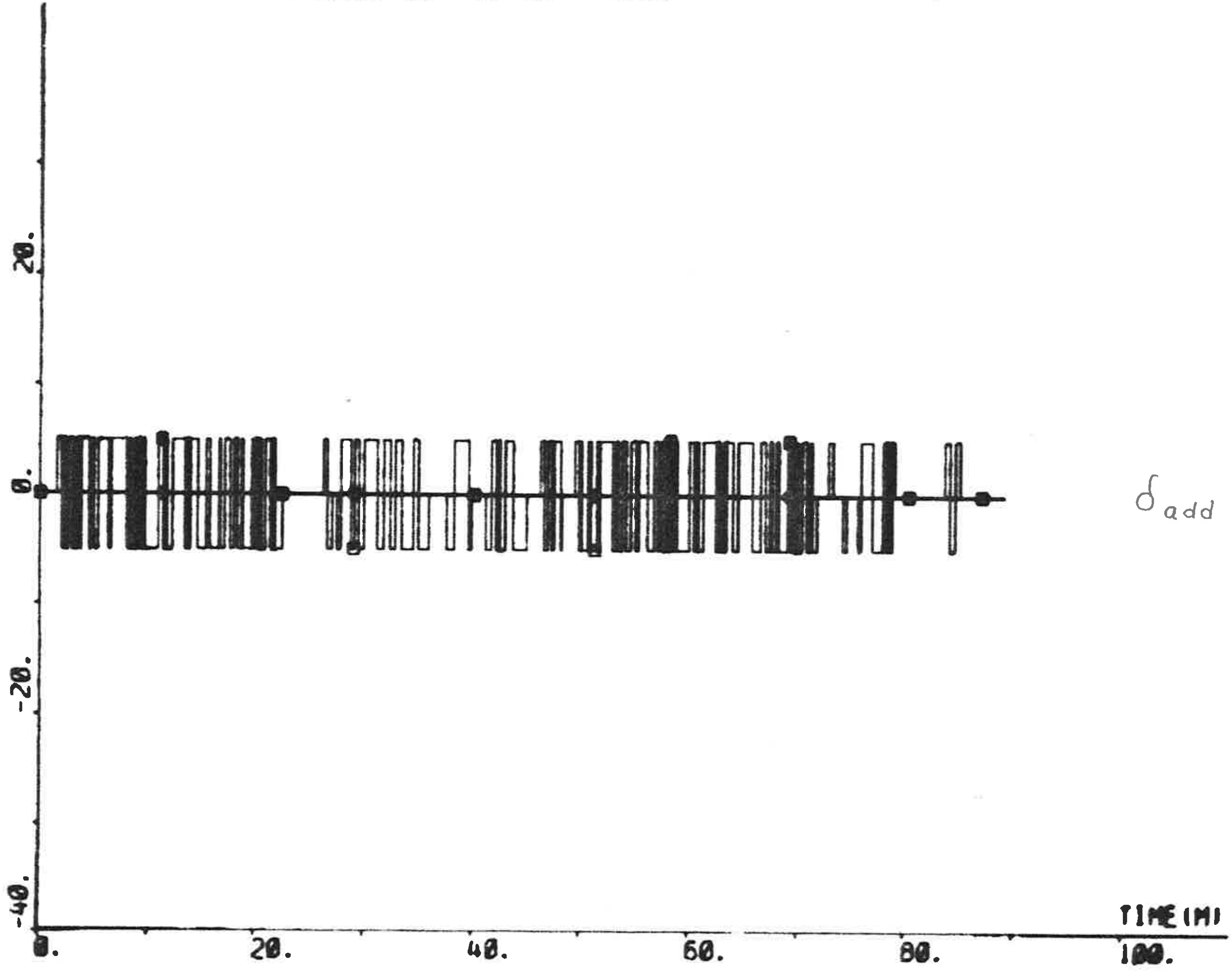
Final values:

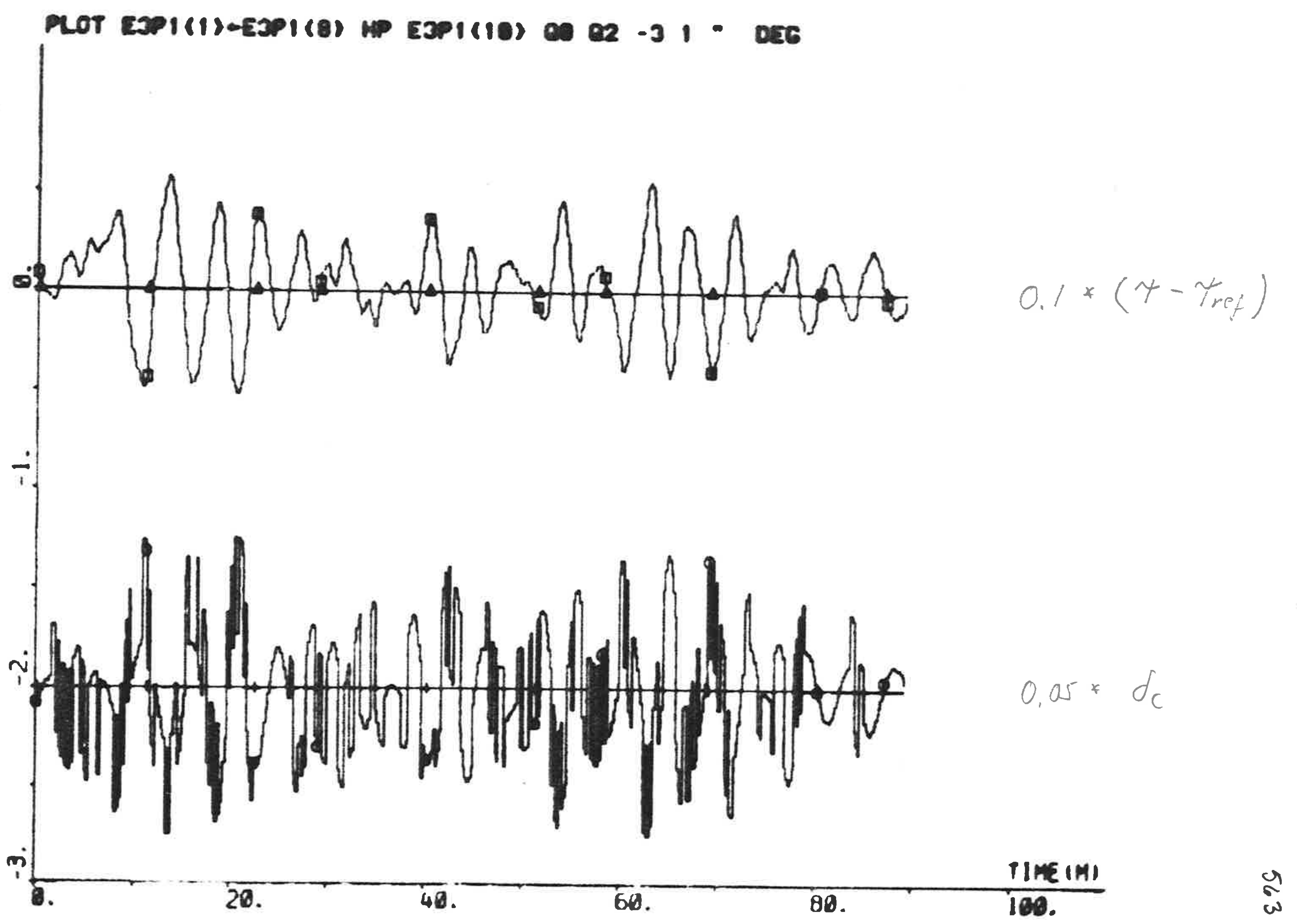
$\hat{\delta}_0 = -0.3$ deg $\hat{d}_v = -0.03$ knots $\hat{d}_r = 0.002$ deg/s $\hat{d}_\delta = 1.5$ deg

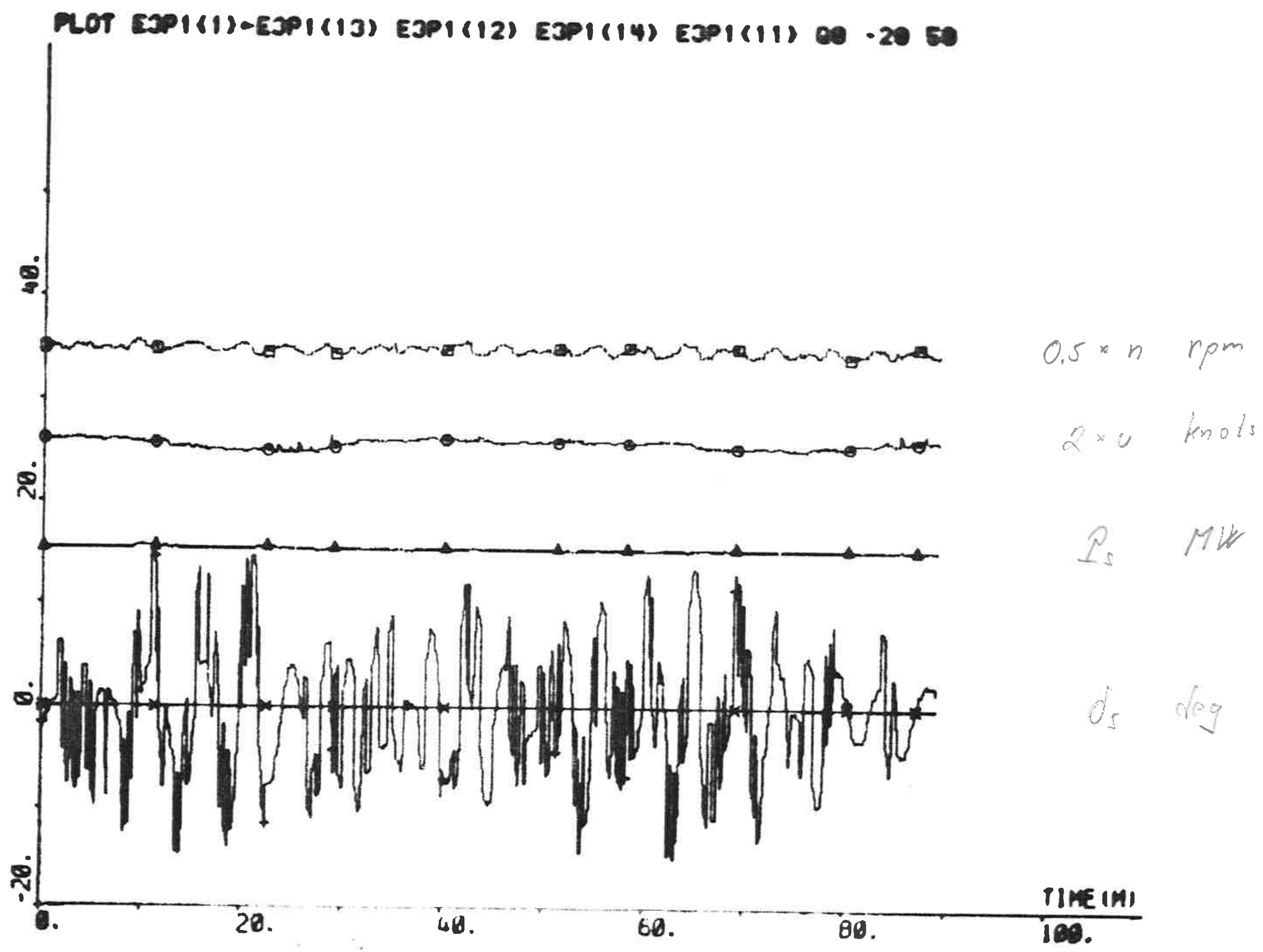
Statistics

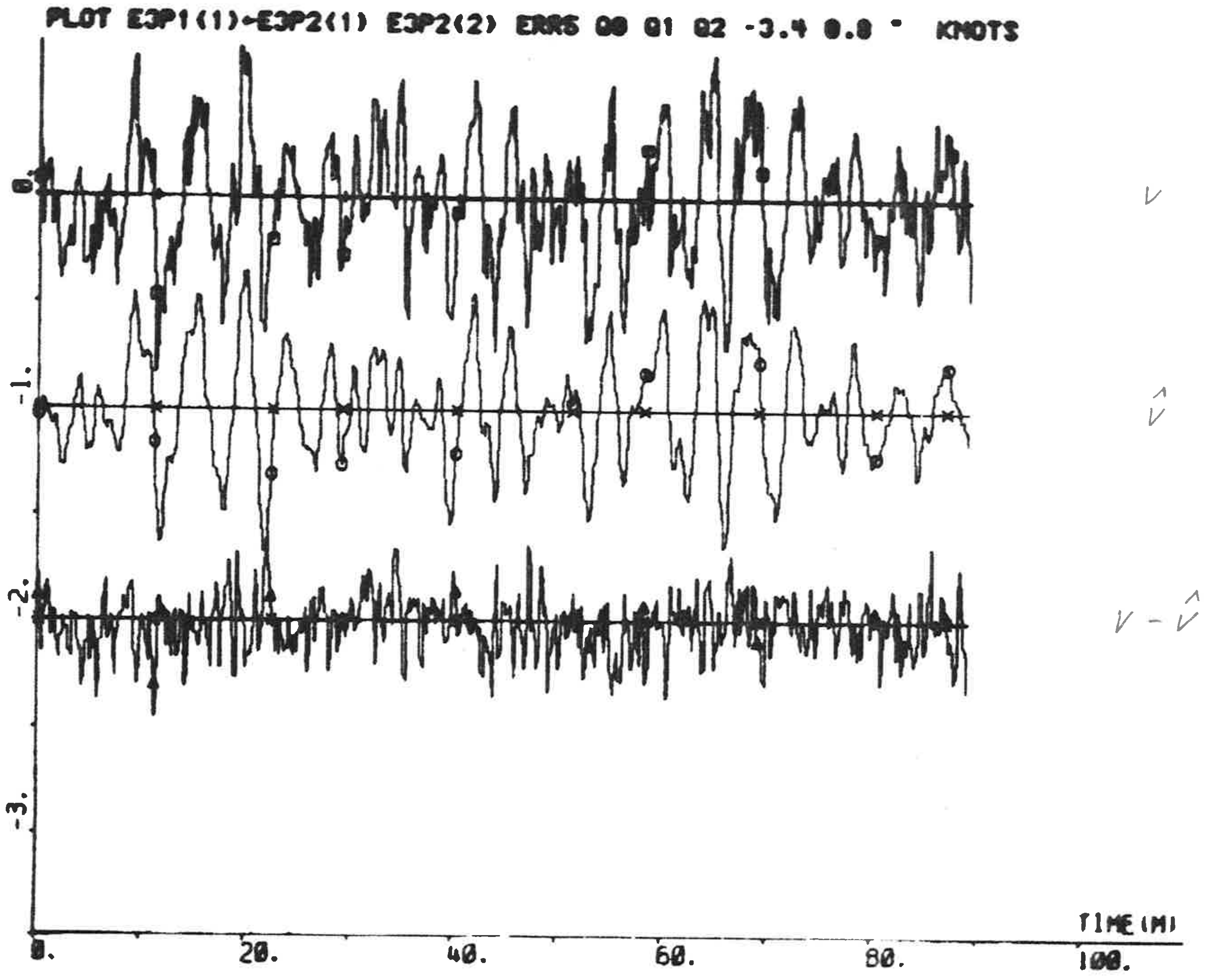
		Mean value	Stand. dev.			Mean value	Stand. dev.
δ_{add}	deg	0.12	4.29	r	deg/s	0.001	0.057
δ_c	deg	-0.42	6.21	$\hat{r}$	deg/s	0.000	0.053
δ_s	deg	-0.43	6.17	$r-\hat{r}$	deg/s	0.002	0.021
n	rpm	70.03	0.68	ε_r	deg/s	0.000	0.024
u	knots	12.89	0.21	$\psi-\psi_{ref}$	deg	0.273	2.211
P_s	MW	15.37	0.08	$\hat{\psi}-\psi_{ref}$	deg	0.272	2.220
v	knots	-0.021	0.290	$\psi-\hat{\psi}$	deg	0.001	0.034
$\hat{v}$	knots	-0.002	0.253	ε_ψ	deg	0.001	0.053
$v-\hat{v}$	knots	-0.019	0.136	δ	deg	1.09	5.59
v_1	knots	-0.014	0.076	$\hat{\delta}$	deg	-0.41	5.85
$\hat{v}_1$	knots	-0.004	0.076	$\delta-\hat{\delta}$	deg	1.50	0.95
$v_1-\hat{v}_1$	knots	-0.010	0.040	ε_δ	deg	0.10	0.98
ε_v	knots	0.002	0.032				

PLOT E3P1(1)+HP DEL0 00 -40 40 - DEG

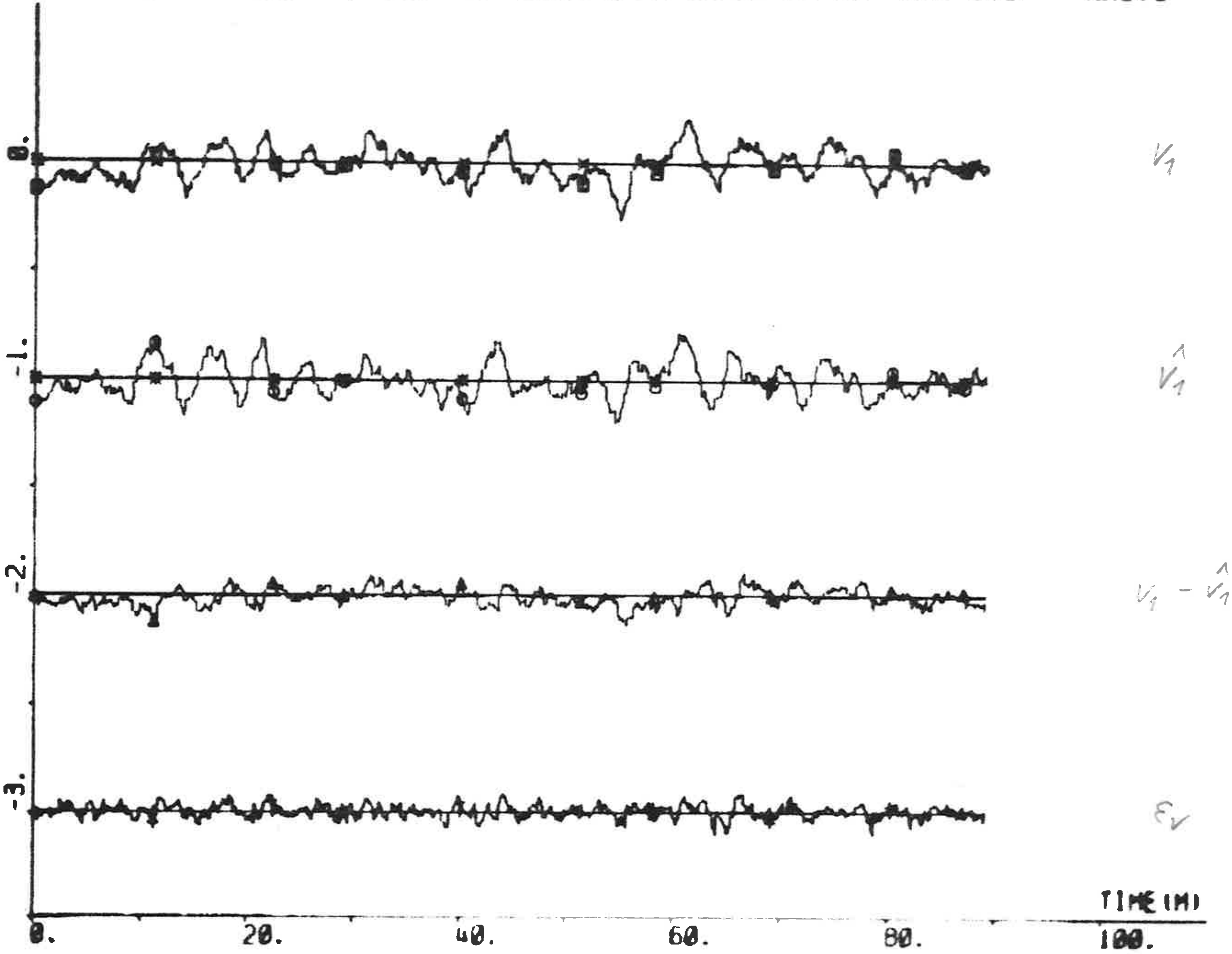


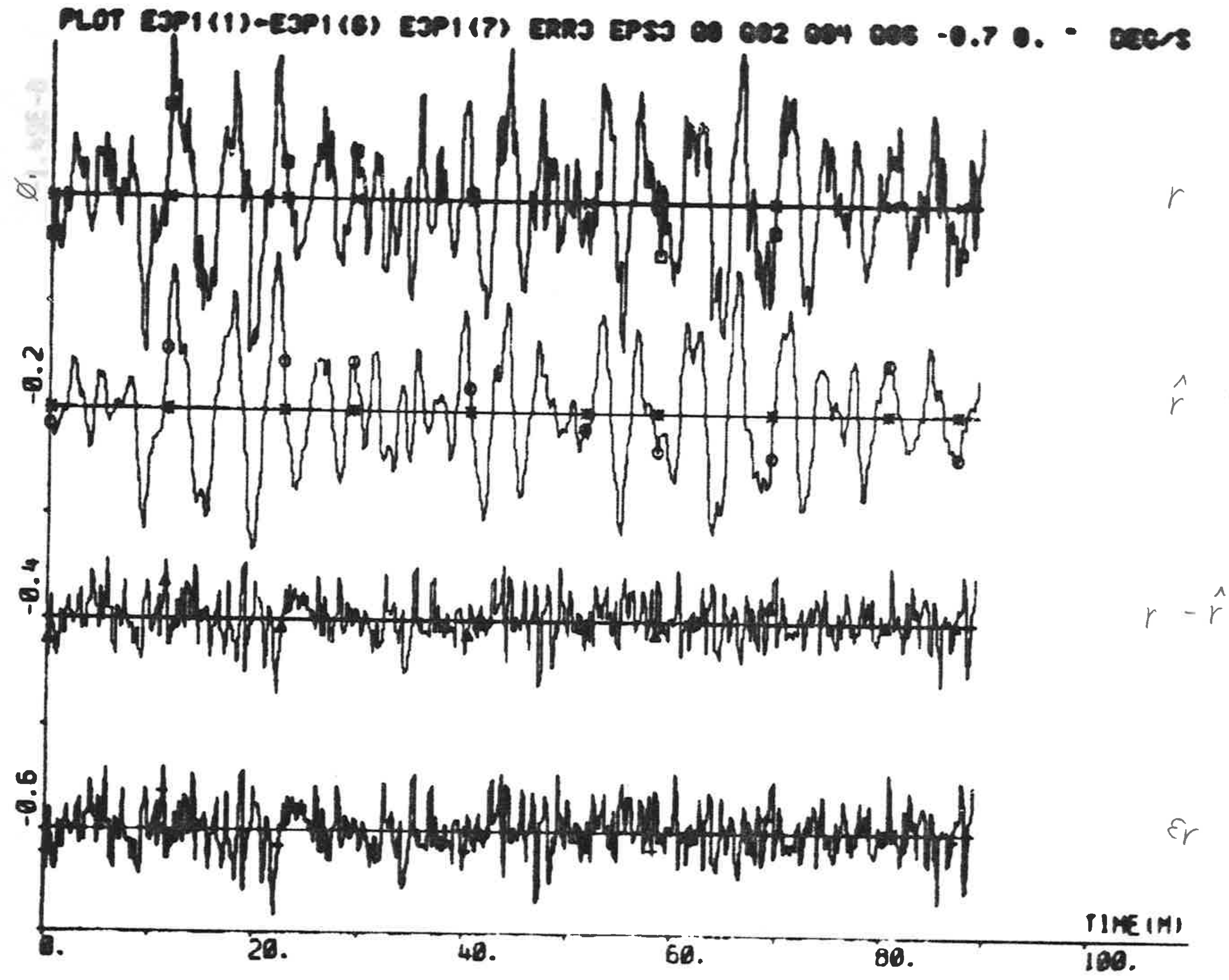

PLOT E3P1(1)-E3P1(8) HP E3P1(10) 00 02 -3 1 " DEG
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME(M)
0.1 * (ψ - ψref)
0.05 * δc

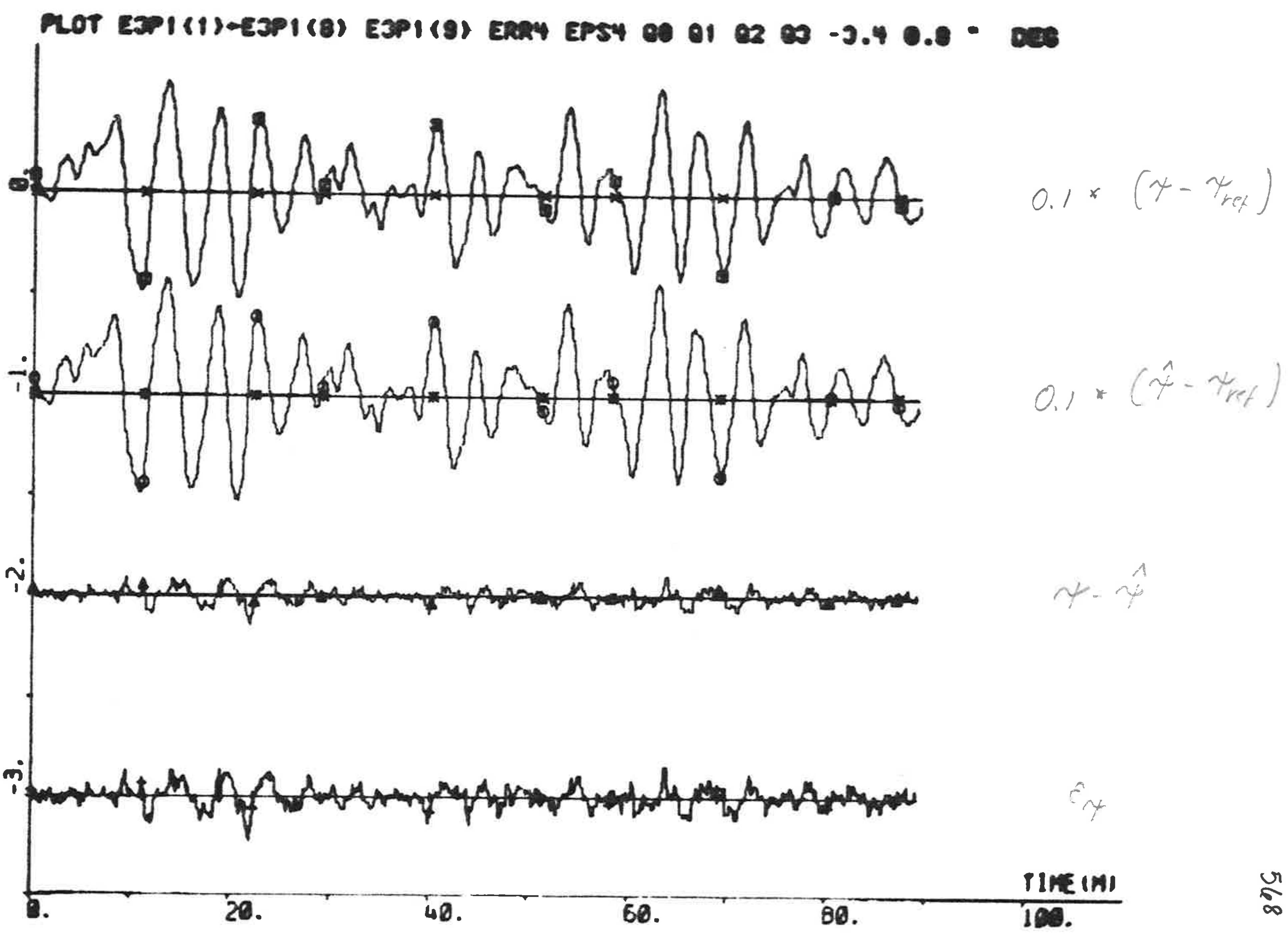

PLOT E3P1(1)-E3P1(13) E3P1(12) E3P1(14) E3P1(11) 00 -20 50
40.
20.
0.
-20.
0.
20.
40.
60.
80.
100.
TIME(M)
0.5 × n rpm
2 × v knots
P_s MW
δ_s deg

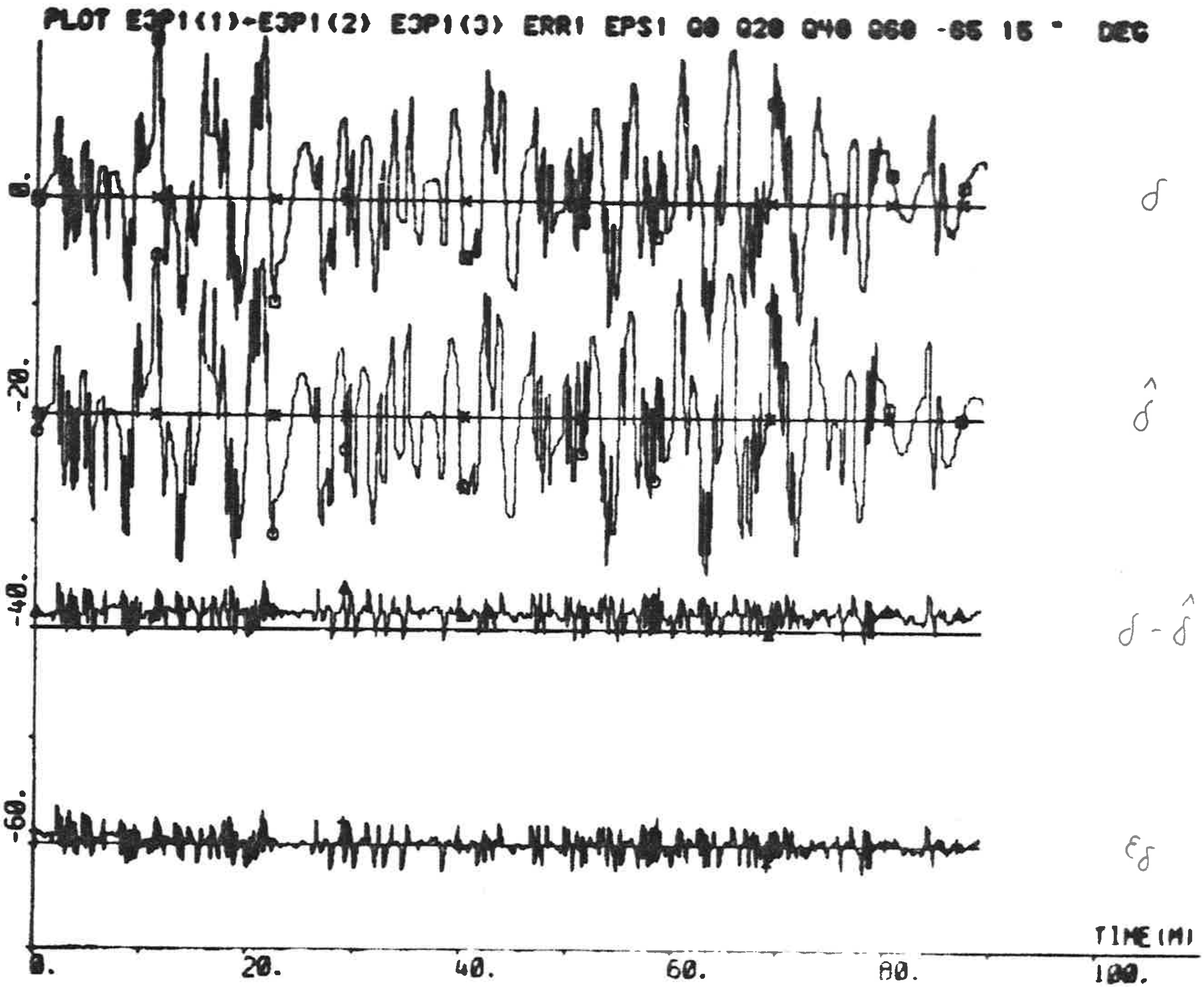

PLOT E3P1(1)-E3P2(1) E3P2(2) ERRS 00 01 02 -3.4 0.8 KNOTS
0.
-1.
-2.
-3.
0.
20.
40.
60.
80.
100.
TIME (M)

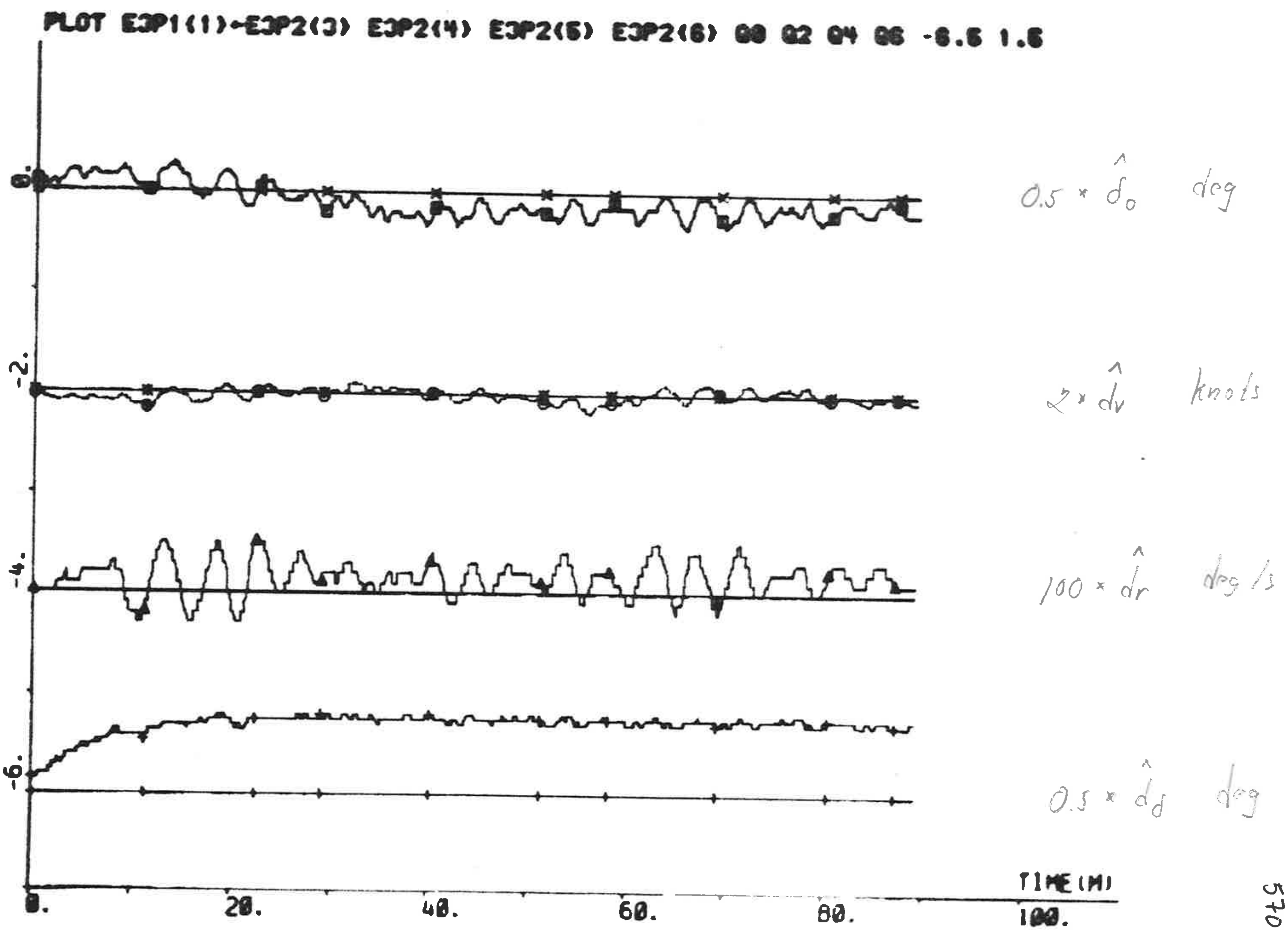
PLOT E3P1(1)-E3P1(4) E3P1(5) ERR2 EPS2 00 01 02 03 -3.4 0.0 - KNOTS




PLOT E3P1(1)-E3P1(6) E3P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. - DEG/S
Ø
-0.2
-0.4
-0.6
0.
20.
40.
60.
80.
100.
TIME(M)
r
r̂
r - r̂
εr


PLOT E3P1(1)-E3P1(8) E3P1(9) ERR4 EPS4 00 01 02 03 -3.4 0.8 - DEG
0.1 * ($\psi - \psi_{ref}$)
0.1 * ($\hat{\psi} - \psi_{ref}$)
$\psi - \hat{\psi}$
ε_ψ
0.
-1.
-2.
-3.
TIME(M)
0.
20.
40.
60.
80.
100.


PLOT E3P1(1)-E3P1(2) E3P1(3) ERR1 EPS1 00 020 040 060 -65 15 - DEG
0.
-20.
-40.
-60.
0.
20.
40.
60.
80.
100.
TIME(M)
δ
δ̂
δ - δ̂
εδ


PLOT E3P1(1)-E3P2(3) E3P2(4) E3P2(5) E3P2(6) 00 02 04 06 -6.5 1.5
0.
-2.
-4.
-6.
0.5 * d̂o deg
2 * d̂v knots
100 * d̂r deg/s
0.5 * d̂d deg
TIME(M)
0.
20.
40.
60.
80.
100.

EXPERIMENT E4

Date	1976-04-30	Forward draught	10.9 m
Time	14.43	Aft draught	12.9 m
Duration	26 min	Wind direction	S (1; see App. A)
Position	S 22°36' E 08°18'	Wind velocity	11 m/s (strong breeze)
ψ_{ref}	146 deg	Wave height	-

Open loop experiment for identification

Tuning time for the Kalman filter before the experiment started: 0 min.

δ_{amp} = 10 deg k_{id} = 0

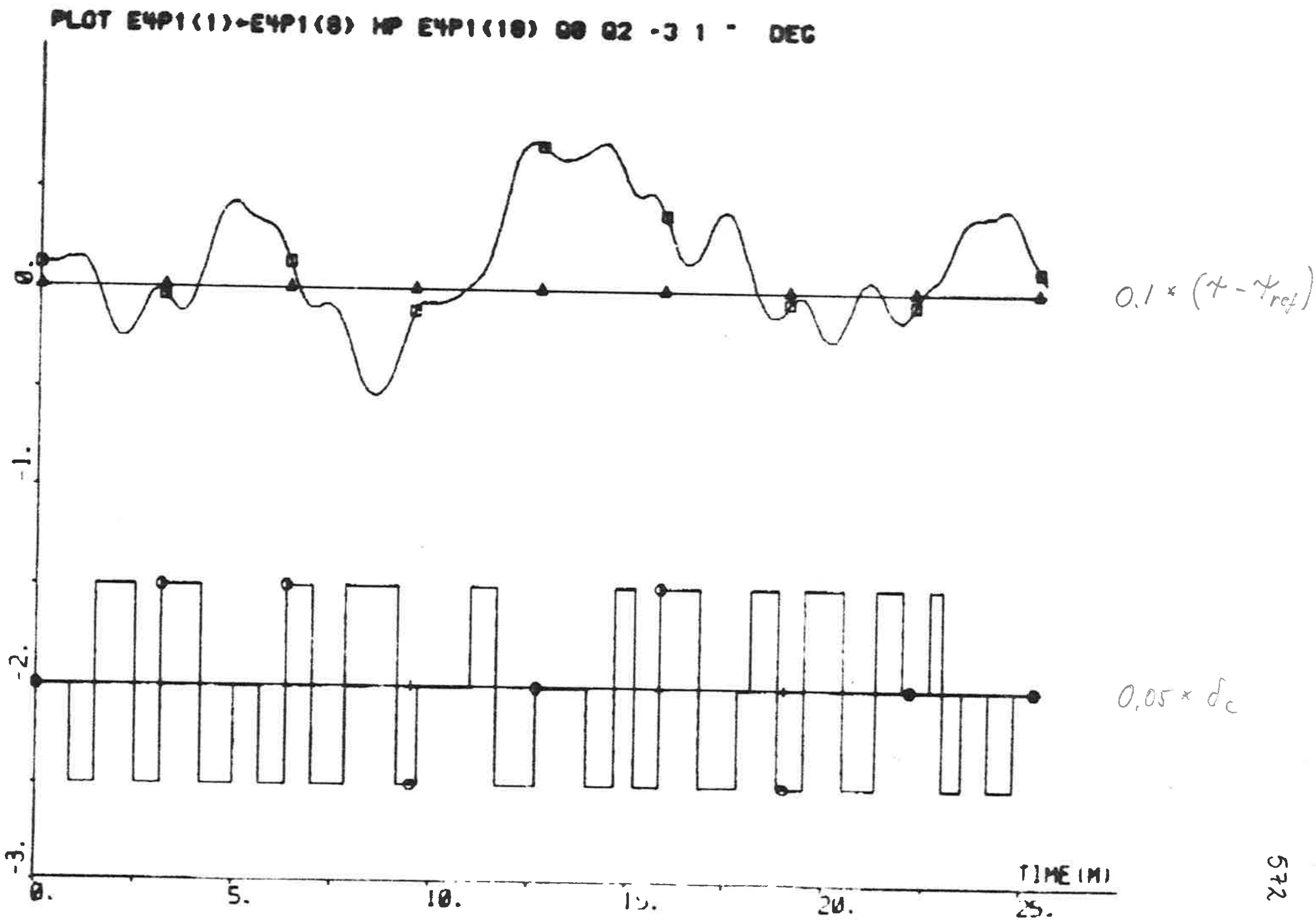
T_s = 10 s IVVC = 1

Final values:

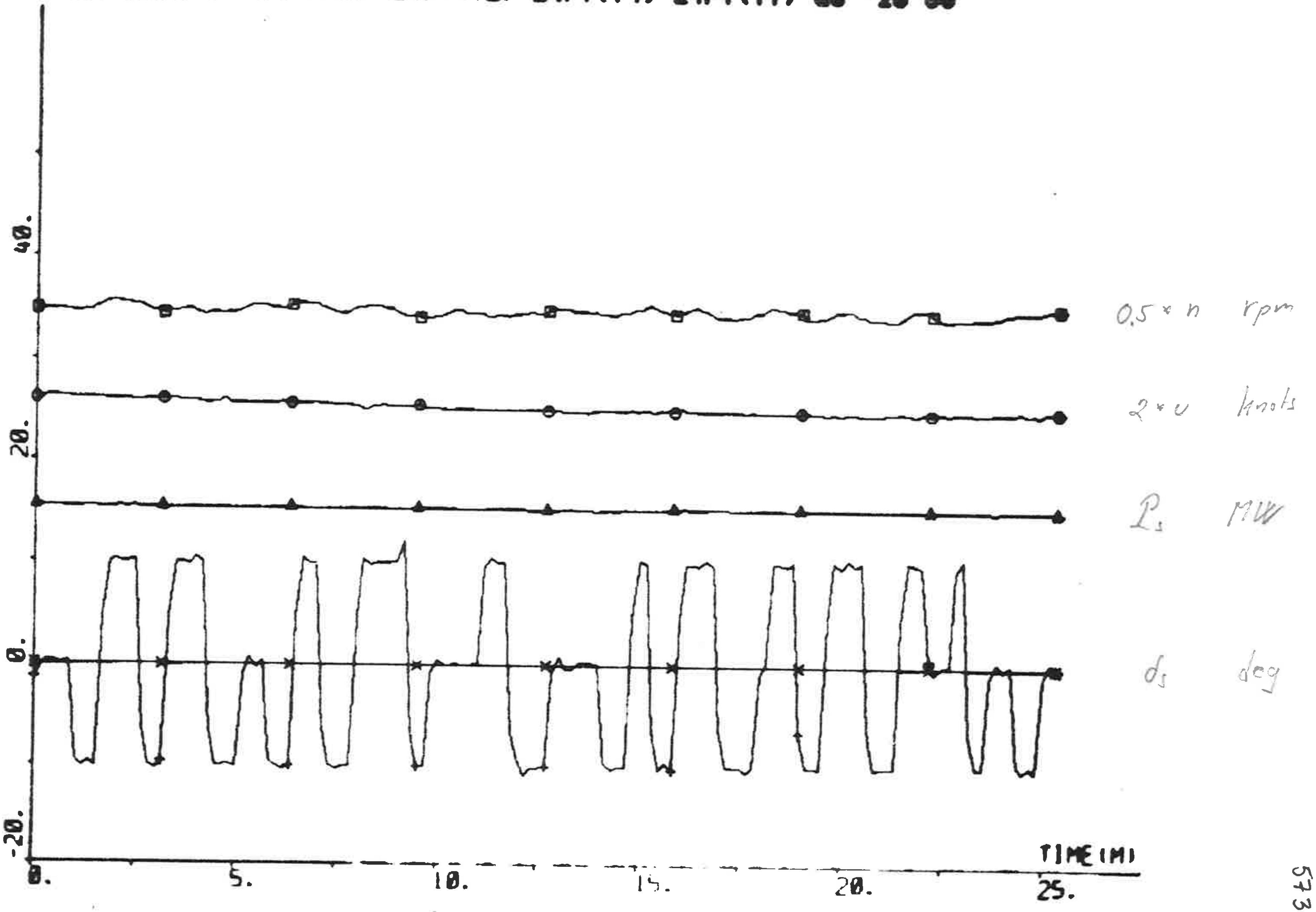
$\hat{\delta}_0$ = 0.1 deg $\hat{d}_v$ = 0.01 knots $\hat{d}_r$ = 0.001 deg/s $\hat{d}_\delta$ = 1.4 deg

Statistics

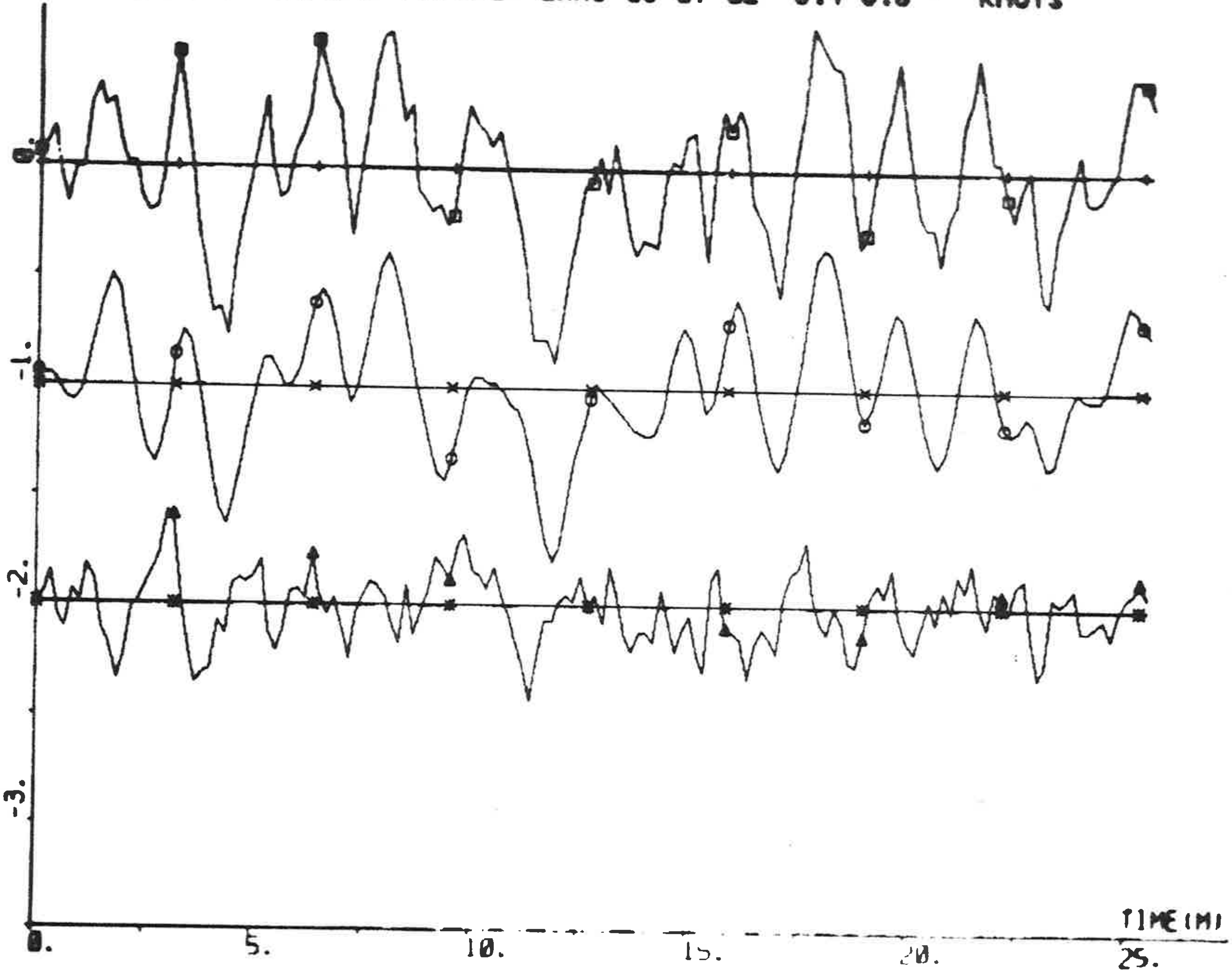
		Mean value	Stand. dev.			Mean value	Stand. dev.
δ_c	deg	-0.52	8.59	r	deg/s	-0.001	0.061
δ_s	deg	-0.57	8.17	$\hat{r}$	deg/s	-0.002	0.054
n	rpm	69.81	0.70	$r-\hat{r}$	deg/s	0.001	0.024
u	knots	12.69	0.20	ε_r	deg/s	0.000	0.026
P_s	MW	15.34	0.08	$\psi-\psi_{ref}$	deg	1.393	3.058
v	knots	-0.013	0.332	$\hat{\psi}-\psi_{ref}$	deg	1.395	3.061
$\hat{v}$	knots	0.003	0.285	$\psi-\hat{\psi}$	deg	-0.001	0.040
$v-\hat{v}$	knots	-0.016	0.155	ε_ψ	deg	-0.002	0.063
v_1	knots	-0.017	0.073	δ	deg	0.92	7.35
$\hat{v}_1$	knots	-0.006	0.080	$\hat{\delta}$	deg	-0.48	8.00
$v_1-\hat{v}_1$	knots	-0.010	0.040	$\delta-\hat{\delta}$	deg	1.40	2.45
ε_v	knots	0.002	0.043	ε_δ	deg	0.36	2.49

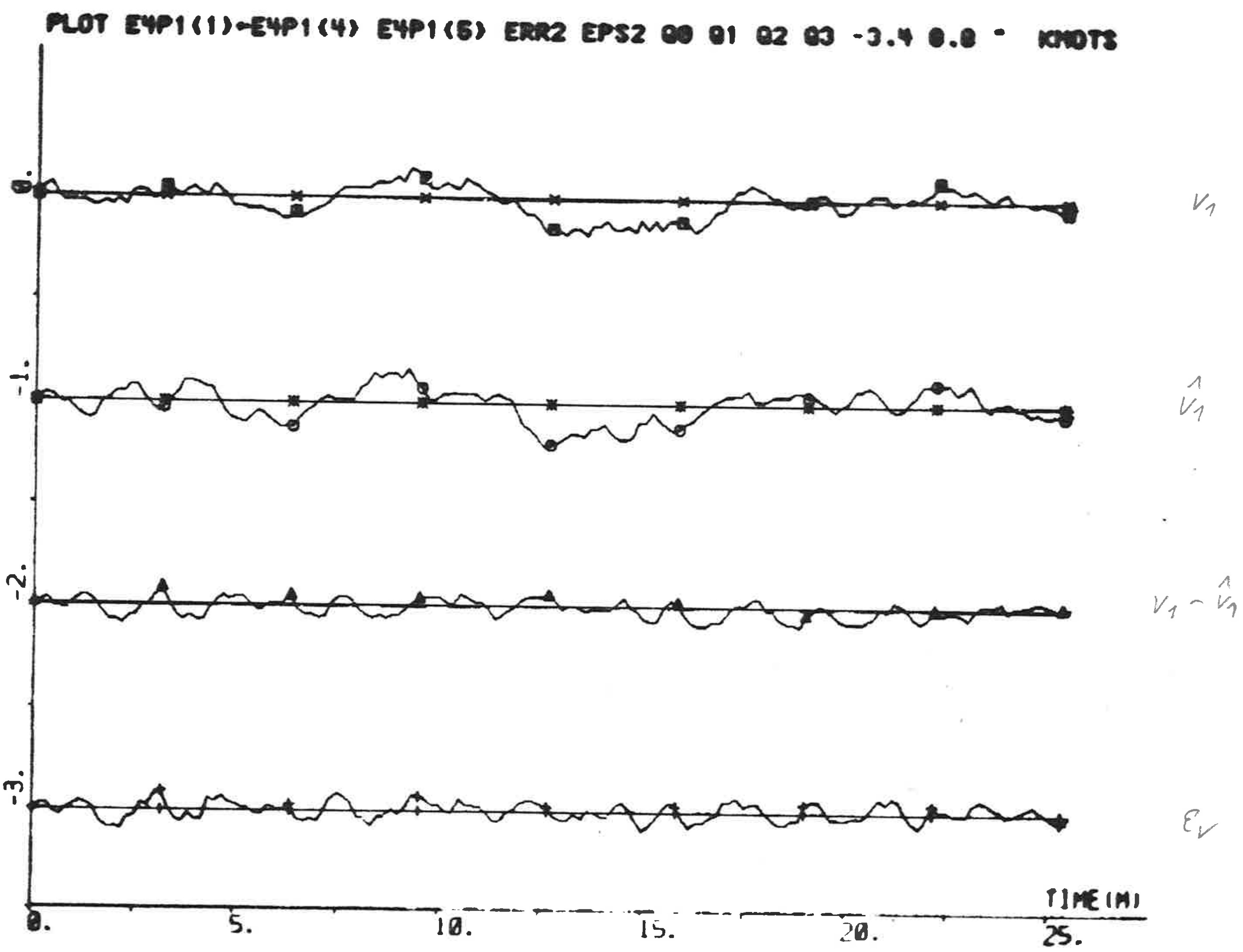

PLOT E4P1(1)-E4P1(8) MP E4P1(10) 00 02 -3 1 - DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
0.1 * (ψ - ψref)
0.05 * δc

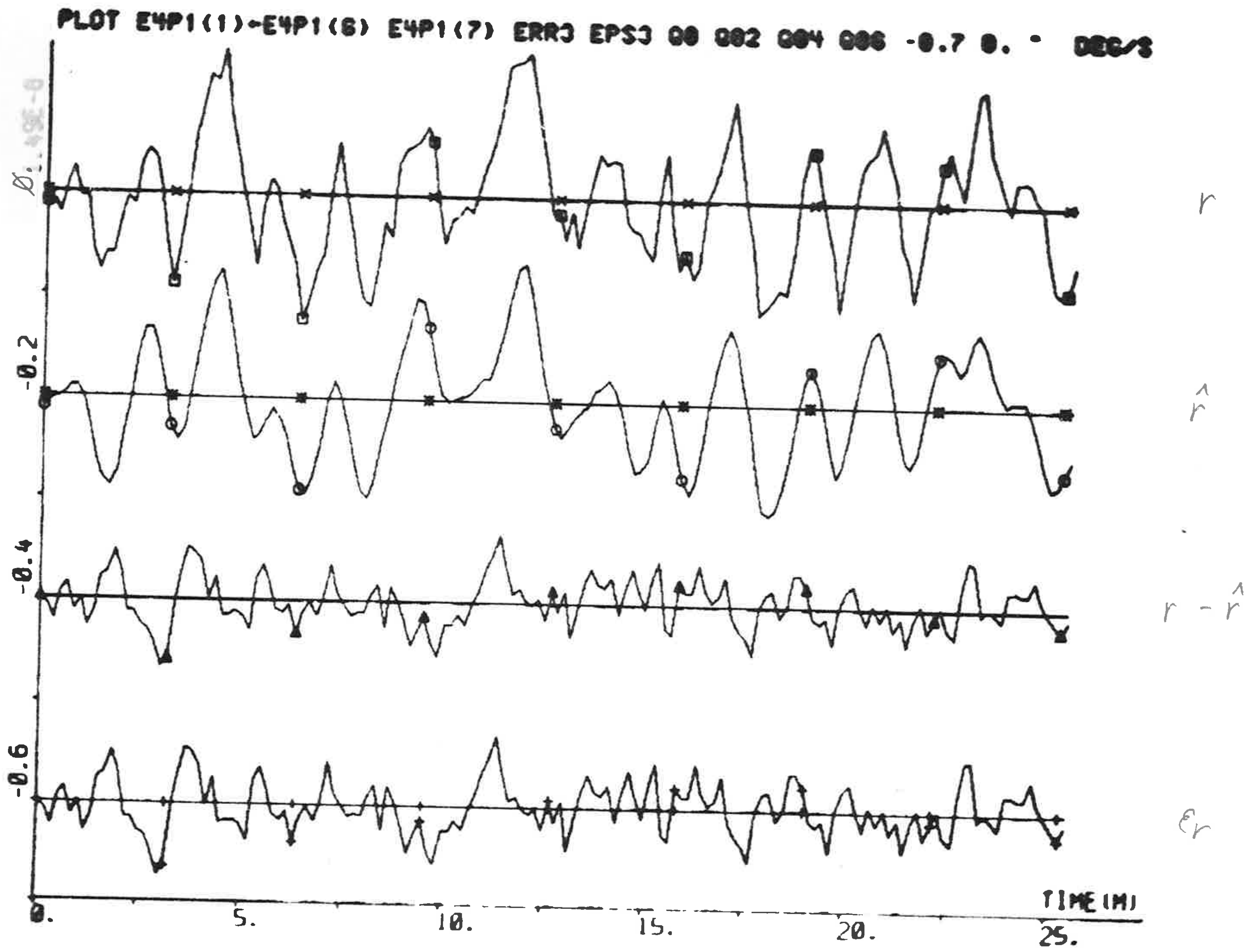
PLOT E4P1(1)-E4P1(13) E4P1(12) E4P1(14) E4P1(11) 00 -20 50

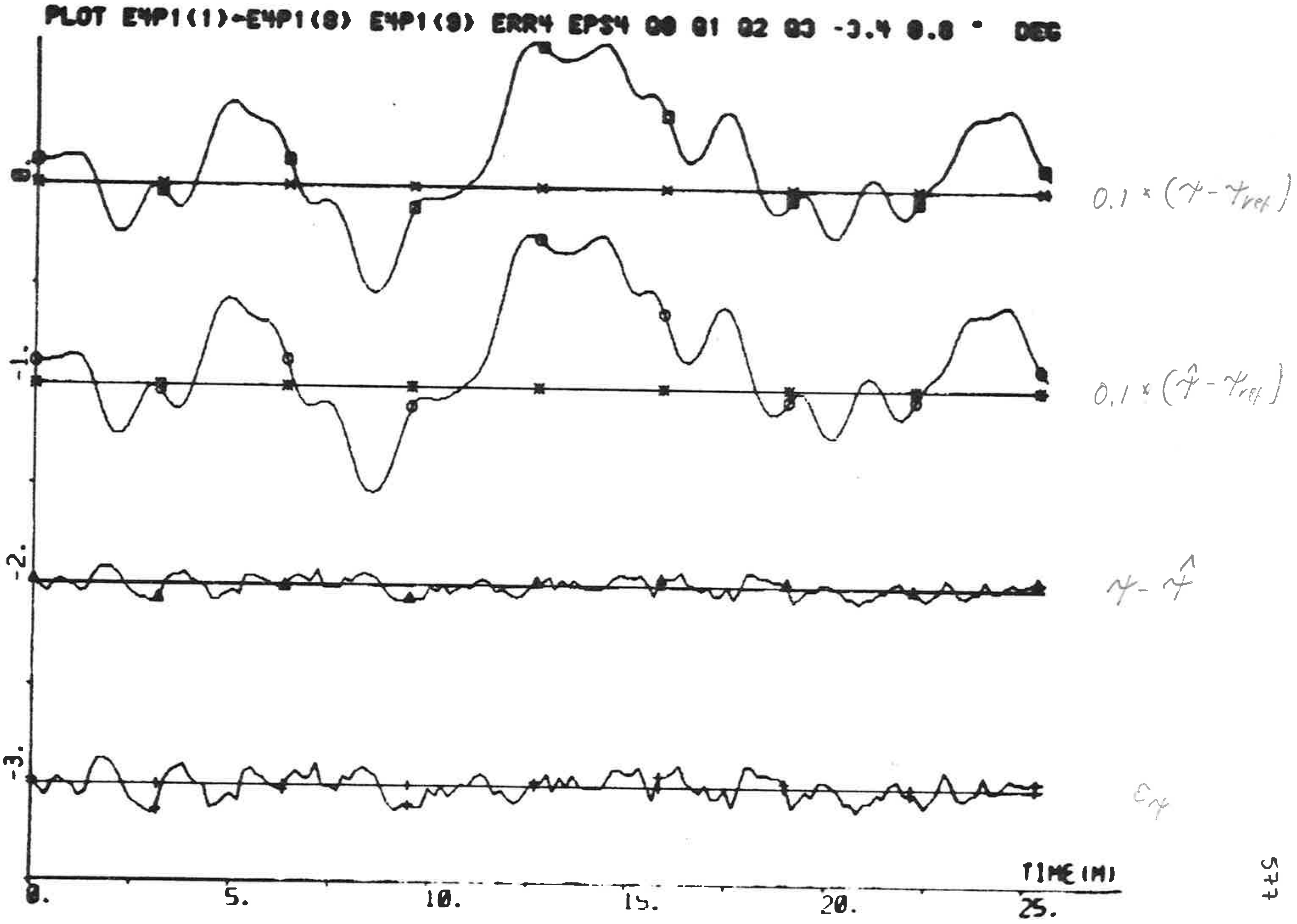


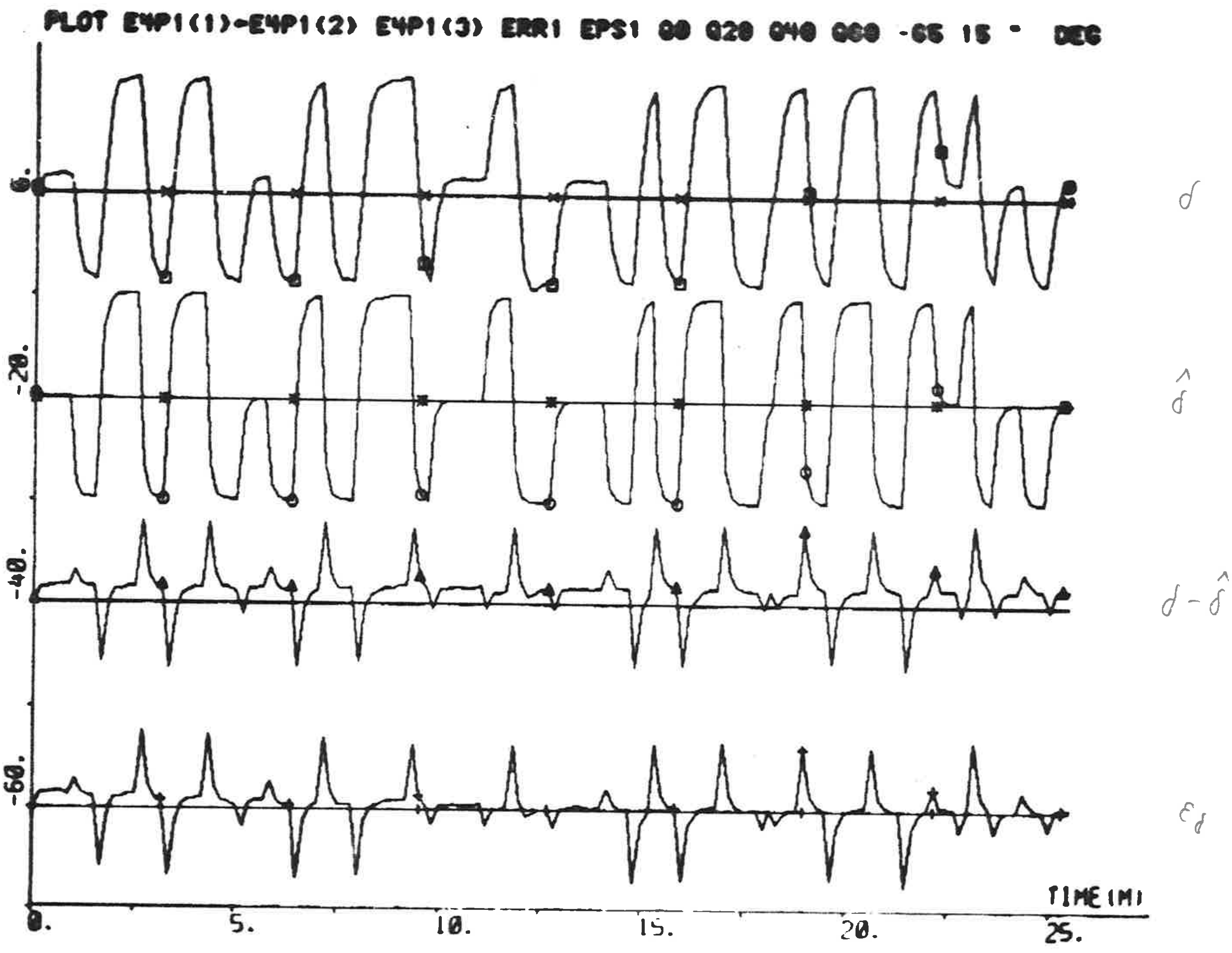
PLOT E4P1(1)-E4P2(1) E4P2(2) ERR6 Q0 Q1 Q2 -3.4 0.8 · KNOTS




PLOT E4P1(1)-E4P1(4) E4P1(5) ERR2 EPS2 Q0 Q1 Q2 Q3 -3.4 0.0 - KMDTS
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)

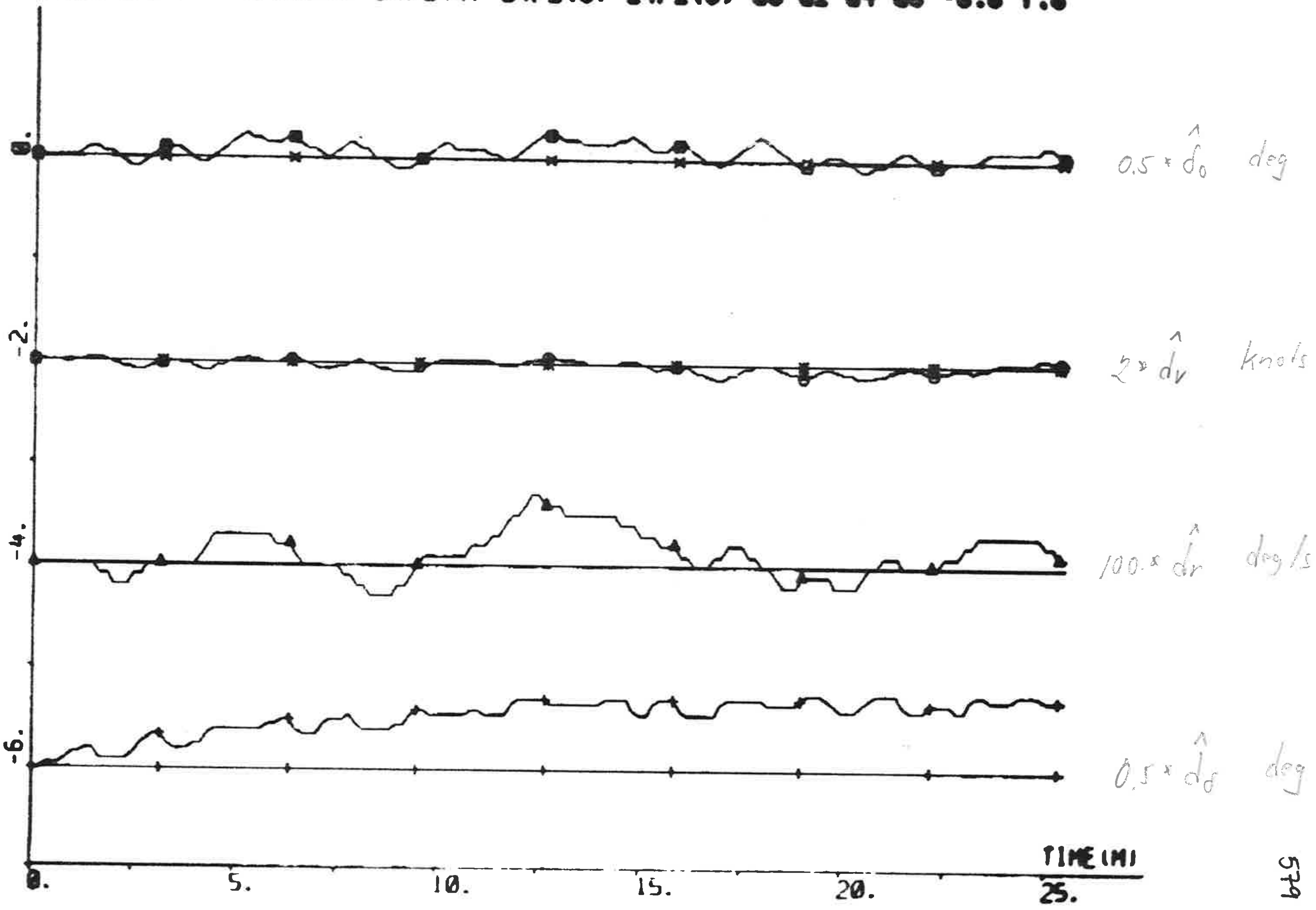

PLOT E4P1(1)-E4P1(6) E4P1(7) ERR3 EPS3 00 002 004 006 -0.7 0. DEG/S
Ø
-0.2
-0.4
-0.6
0.
5.
10.
15.
20.
25.
TIME(M)
r
r̂
r - r̂
εr


PLOT E4P1(1)-E4P1(8) E4P1(9) ERR4 EPS4 Q0 Q1 Q2 Q3 -3.4 0.8 · DEG
0.
-1.
-2.
-3.
0.
5.
10.
15.
20.
25.
TIME(M)
0.1 * (ψ - ψ_ref)
0.1 * (ψ̂ - ψ_ref)
ψ - ψ̂
ε_ψ



PLOT E4P1(1)-E4P1(2) E4P1(3) ERR1 EPS1 00 020 040 060 -65 15 - DEG
0.
-20.
-40.
-60.
0.
5.
10.
15.
20.
25.
TIME(M)

PLOT E4P1(1)-E4P2(3) E4P2(4) E4P2(5) E4P2(6) 00 02 04 06 -6.5 1.5



EXPERIMENT F1

Date	1976-04-19	Forward draught	8.5 m
Time	09.03	Aft draught	12.5 m
Duration	60 min	Wind direction	E (6; see App. A)
Position	N 29°11' W 14°46'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	204.4 - 204.5 deg (Sailmaster)	Wave height	-

The rudder limit was 15 deg during the experiment.

<u>Self-tuning regulator using estimates from the Kalman filter</u>

The sway velocity v_1 was not used by the Kalman filter.

NC1 = 1	NC2 = 1	k = 7	q = 0
T_s = 10 s	V_0 = 8 m/s	IVVC = 3	V_c = 7 m/s

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -7.05 \\ 5.88 \\ 3.03 \\ -1.67 \\ 0.46 \\ 0.06 \\ 3.88 \\ 152.75 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = 0.19$

$\hat{\delta}_0 = 0.4$ deg $\hat{d}_v = -$ $\hat{d}_r = -0.001$ deg/s $\hat{d}_\delta = 1.3$ deg

<u>Statistics</u>

Mean value of δ	= 1.71 deg	$n \approx 69.8$ rpm
Mean value of $\psi - \psi_{ref}$	= -0.002 deg	$u \approx 14.4$ knots
V_2	= 0.038	$P_s \approx 14.7$ MW

EXPERIMENT F2

Date	1976-04-19	Forward draught	8.5 m
Time	10.20	Aft draught	12.5 m
Duration	49 min	Wind direction	E (7; see App. A)
Position	N 28°54' W 14°55'	Wind velocity	3 m/s (light breeze)
ψ_{ref}	204.1 - 204.3 deg (Sailmaster)	Wave height	-

The rudder limit was 15 deg during the experiment.

PID-regulator using non-filtered measurements

$k_P = 3$ $k_D = 75$ s $k_I = 0.02$ 1/s

$T_s = 10$ s $V_0 = 8$ m/s IVVC = 3 $V_c = 7$ m/s

Standard parameter values were used.

Statistics

Mean value of δ	= 1.86 deg	$n \approx 69.6$ rpm
Mean value of $\psi-\psi_{ref}$	= -0.016 deg	$u \approx 14.4$ knots
V_2	= 0.259	$P_s \approx 14.7$ MW

EXPERIMENT F3

Date	1976-04-29	Forward draught	10.9 m
Time	17.00	Aft draught	12.9 m
Duration	57 min	Wind direction	SE (1; see App. A)
Position	S 18°49' E 05°31'	Wind velocity	11 m/s (strong breeze)
ψ_{ref}	147 deg	Wave height	High sea from SE

The rudder limit was 15 deg during the experiment.

Self-tuning regulator using estimates from the Kalman filter.

NC1 = 1　　NC2 = 1　　k = 7　　q = 0

T_s = 10 s　　V_0 = 6 m/s　　IVVC = 1

Final values:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -11.47 \\ 13.11 \\ 0.48 \\ -2.31 \\ 0.58 \\ 0.31 \\ -0.07 \\ 79.27 \end{bmatrix}$$

$a_1 + a_2 + a_3 + a_4 = -0.19$

$\hat{\delta}_0 = 0.2$ deg　　$\hat{d}_v = 0.13$ knots　　$\hat{d}_r = 0.001$ deg/s　　$\hat{d}_\delta = 1.5$ deg

Statistics

Mean value of δ	= 1.67 deg	$n \approx 69.1$ rpm
Mean value of $\psi-\psi_{ref}$	= -0.073 deg	$u \approx 12.1$ knots
V_2	= 0.160	$P_s \approx 15.1$ MW

EXPERIMENT F4

Date	1976-04-29	Forward draught	10.9 m
Time	18.04	Aft draught	12.9 m
Duration	54 min	Wind direction	SE (1; see App. A)
Position	S 18°49' E 05°31'	Wind velocity	11 m/s (strong breeze)
ψ_{ref}	147 deg	Wave height	High sea from SE

The rudder limit was 15 deg during the experiment.

PID-regulator using estimates from the Kalman filter

$k_P = 3$ $k_D = 140$ s $k_I = 0.02$ 1/s

$T_s = 10$ s $V_0 = 6$ m/s IVVC = 1

The parameters were manually tuned before the experiment started.

Final values:

$\hat{\delta}_0 = 0.0$ deg $\hat{d}_v = 0.14$ knots $\hat{d}_r = 0.000$ deg/s $\hat{d}_\delta = 1.5$ deg

Statistics

Mean value of δ	= 1.54 deg	n	≈ 69.7 rpm
Mean value of $\psi-\psi_{ref}$	= -0.009 deg	u	≈ 12.2 knots
V_2	= 0.304	P_s	≈ 15.5 MW