Simulation of Ship Steering

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Claes Källström

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SIMULATION OF SHIP STEERING

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Abstract

Computer simulations of ship steering are presented. The ship model describes a tanker. An adaptive autopilot, consisting of a Kalman filter, a self-tuning regulator for steady state course keeping, and a turning regulator is tested in different load and speed conditions. Straight course keeping as well as turning is simulated. Comparisons to a conventional autopilot based on a PID-regulator is also performed.

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1. INTRODUCTION

Simulations of straight course keeping and yawing in different load and speed conditions with an autopilot consisting of a stationary Kalman filter, a self-tuning regulator and a yaw regulator are presented in this report. The simulations are performed on the computer UNIVAC 1108 by use of the interactive program SIMNON (see Elmqvist (1975)). The ship model used describes a 350 000 tdw tanker of Kockums' design.

The self-tuning regulator for straight course keeping is based on least squares identification and minimum variance control. A descrete, fixed gain PID-regulator is also used for comparison. The yaw regulator consists of different discrete fixed gain PID-regulators. The reference values used by the yaw regulator are the yaw rate and the heading angle. Either the non-filtered measurements or the Kalman filter estimates are used by the different regulators.

Simulation of ship steering is also discussed in Aspernäs and Foisack (1975), Aspernäs and Källström (1975), Källström (1976a) and (1976b). Full-scale experiments on 255 000 tdw tankers are described in Källström (1974) and (1975).

Listings of the programs used are given in the Appendix.

2. SHIP STEERING DYNAMICS

The following model, which describes a 350 000 tdw tanker of Kockums' design, is used in the simulations (cf. Norrbin (1970)):

$$\dot{\delta} = -\frac{1}{T_r}\,\delta + \frac{1}{T_r\cdot CRG}\,\delta_c$$

$$|\dot{\delta}| \leq \frac{1}{CRG}\,\delta_{lim}$$

$$\begin{aligned}\left(1 - X''_{\dot{u}}\right)\dot{u} = {} & \frac{1}{L}\,X''_{u|u|}\,u|u| + \frac{1}{L}\,X''_{uu}\,u^2 + \left(1 + X''_{vr}\right)vr + \\ & + L\left(X''_{rr} + x''_G\right)r^2 + \frac{1}{gL^2}\,X''_{uvv|v|}\,uv^2|v| + \frac{1}{L}\,X''_{u|u|\delta\delta}\,u|u|\delta^2 + \\ & + (1-t)(T/m) - F_w\cos\left(\frac{\alpha}{CRG} - \psi\right)\end{aligned}$$

$$\begin{aligned}\left(1 - Y''_{\dot{v}}\right)\dot{v} = {} & \left(Y''_{ru} - 1\right)ru + \frac{1}{\sqrt{gL}}\,Y''_{ru|u|}\,ru|u| + \frac{1}{L}\,Y''_{|u|v}\,|u|v + \\ & + \frac{1}{\sqrt{gL^3}}\,Y''_{u|u|v}\,u|u|v + \frac{1}{L}\,Y''_{v|v|}\,v|v| + Y''_{r|v|}\,r|v| + \\ & + Y''_{|r|v}\,|r|v + \frac{1}{L}\,Y''_{uu\delta}\,u^2\delta + \frac{1}{L}\,Y''_{u|u|\delta}\,u|u|\delta + \\ & + Y''_{T\delta}\,(T/m)\delta + k_{TY}(T/m) - F_w\sin\left(\frac{\alpha}{CRG} - \psi\right) + w_1\end{aligned}$$

$$\begin{aligned}\left(k''^2_{zz} - N''_{\dot{r}}\right)\dot{r} = {} & \frac{1}{L}\left(N''_{r|u|} - x''_G\right)r|u| + \frac{1}{\sqrt{gL^3}}\,N''_{ru|u|}\,ru|u| + \\ & + \frac{1}{L^2}\,N''_{uv}\,uv + \frac{1}{\sqrt{gL^5}}\,N''_{u|u|v}\,u|u|v + \frac{1}{L^2}\,N''_{v|v|}\,v|v| + \\ & + N''_{r|r|}\,r|r| + \frac{1}{L}\,N''_{r|v|}\,r|v| + \frac{1}{L}\,N''_{|r|v}\,|r|v + \\ & + \frac{1}{L^2}\,N''_{uu\delta}\,u^2\delta + \frac{1}{L^2}\,N''_{u|u|\delta}\,u|u|\delta + \frac{1}{L}\,N''_{T\delta}\,(T/m)\delta + \\ & + \frac{1}{L}\,k_{TN}\,(T/m) + \frac{1}{L^2}\,F_w\,\ell_w\sin\left(\frac{\alpha}{CRG} - \psi\right) + w_2\end{aligned}$$

$$\dot{\psi} = r \qquad (2.1)$$

It is assumed that the number of propeller revolutions n is kept constant to a specified value n_o by a regulator during all the simulations. The propeller thrust per mass unit (T/m) is computed as:

$$J = \frac{u\ (1-w) \cdot 60}{nD}$$

$$J' = \frac{J}{\sqrt{1 + J^2}}$$

$$K_T' = -0.33 \cdot J'^2 - 0.38 \cdot J' + 0.35 \qquad (2.2)$$

$$T = K_T' \left(\frac{J}{J'}\right)^2 \rho_s\ n^2\ D^4/3600$$

$$(T/m) = \frac{T}{\rho_s\ \nabla}$$

Notice that the terms $(T/m)\delta$ in (2.1) always are limited by the value $(T/m)_o\delta$, where $(T/m)_o$ is computed from (2.2) with the stationary forward speed corresponding to $n = n_o$ rpm.

Input signals:

rudder command (or rudder servo position)	δ_c	[deg]
number of propeller revolutions	n	[rpm]

States:

rudder angle	δ	[rad]
forward velocity	u	[m/s]
sway velocity	v	[m/s]
yaw rate	r	[rad/s]
heading angle	ψ	[rad]

Disturbances:

sway acceleration disturbance	w_1	[m/s^2]
disturbance of yaw angle acceleration	w_2	[rad/s^2]

Other notations:

time constant of rudder servo	T_r	[s]
limit of rudder turning rate	δ_{lim}	[deg/s]
length of ship	L	[m]
acceleration of gravity	g	[m/s^2]
propeller thrust per mass unit	T/m	[m/s^2]
wind force per mass unit	F_w	[m/s^2]
lever arm of wind force	ℓ_w	[m]
angle of wind direction	α	[deg]
conversion factor rad — deg	CRG	[deg]

The following parameter values are used:

$T_r = 5$ s

$\delta_{lim} = 2.32$ deg/s

L = 350 m

$g = 9.80665$ m/s^2

$F_w = 0.002$ m/s^2

$\ell_w = 25$ m

$\alpha = 90$ deg

CRG = 57.2958 deg

The values of the other parameters are given in Dyne and Trägårdh (1975). Two different load conditions are considered corresponding to the mean draught T = 22.3 m (full load, forward and aft draught equal to 22.3 m) and T = 10.5 m (ballast, forward and aft draught equal to

9.0 m and 12.0 m, resp.). The forward speed u which corresponds to n = 87.6 rpm is equal to 15.8 knots when T = 22.3 m and equal to 17.25 knots when T = 10.5 m. If the model (2.1) and (2.2) is linearized, the following transfer function relating the yaw rate r to the rudder angle δ is obtained:

$$G(s) = \frac{K(1+sT_3)}{(1+sT_1)(1+sT_2)} \tag{2.3}$$

If the forward speed u is assumed to be constant and equal to 15.8 knots, then the following parameter values of (2.3) are obtained when T = 22.3 m:

$$\begin{aligned} K &= -0.0161 \text{ 1/s} \\ T_1 &= -110.1 \text{ s} \\ T_2 &= 18.3 \text{ s} \\ T_3 &= 54.3 \text{ s} \end{aligned} \tag{2.4}$$

The corresponding values when u = 17.25 knots and T = 10.5 m are:

$$\begin{aligned} K &= -0.0707 \text{ 1/s} \\ T_1 &= -337.1 \text{ s} \\ T_2 &= 19.9 \text{ s} \\ T_3 &= 69.5 \text{ s} \end{aligned} \tag{2.5}$$

Notice that the sign of the rudder angle in the model is chosen in such a way that a positive rudder angle (starboard rudder) gives a positive yaw rate (starboard yaw). From (2.4) and (2.5) it can be concluded that the tanker is unstable in full load condition as well as in ballast condition.

The disturbance signals w_1 and w_2 are obtained as white, gaussian noise. The covariance matrix of the white noise vector, which generates w_1 and w_2, is

$$R_w = \begin{pmatrix} 0.8\cdot 10^{-4} & 0 \\ 0 & 0.53\cdot 10^{-10} \end{pmatrix} \tag{2.6}$$

The measured outputs from the model (2.1) and (2.2) are

$$\begin{aligned}
\delta_m &= CRG \cdot \delta + d_\delta + e_1 \\
v_1 &= \bar{v}_1 + d_v + e_2, \qquad \bar{v}_1 = CMK \cdot (v + \ell_1 r) \\
r_m &= CRG \cdot r + d_r + e_3 \\
\psi_m &= CRG \cdot \psi + e_4 \\
u_m &= CMK \cdot u \\
n_m &= n
\end{aligned}$$

where e_1, e_2, e_3 and e_4 are white, gaussian measurement noise with covariance matrix

$$R_e = \begin{pmatrix} 0.04 & 0 & 0 & 0 \\ 0 & 0.0025 & 0 & 0 \\ 0 & 0 & 0.0004 & 0 \\ 0 & 0 & 0 & 0.0025 \end{pmatrix} \tag{2.7}$$

The measured rudder angle δ_m [deg], sway velocity of bow v_1 [knots], yaw rate r_m [deg/s], heading angle ψ_m [deg], forward speed u_m [knots] and number of propeller revolutions n_m [rpm] are used by the autopilot. The conversion factor from m/s to knots CMK is equal to 1.943844 and the lever arm ℓ_1 is equal to 164.35 m. The measurement biases are assigned the following values:

$$\begin{aligned}
d_\delta &= 2 \text{ deg} \\
d_v &= 0.5 \text{ knots} \\
d_r &= 0.05 \text{ deg/s}
\end{aligned} \tag{2.8}$$

It should be pointed out that the model of the disturbances is extremely simplified. A more realistic approach is given in Berlekom, Trägårdh, and Dellhag (1975). Notice, however, that the disturbances applied in the simulations describe a rather rough weather condition.

The program of the ship model, TANK3, is given in the Appendix. Almost the same model was used in the simulations of Källström (1976b).

3. AUTOPILOT

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

$$V_s = 0.18 \cdot n_m / CMK \tag{3.1}$$

The signals δ_m, v_1, r_m, ψ_m, u_m and n_m are measured every second. The Kalman filtering as well as the computation of v_m [knots] according to

$$v_m = v_1 - CMK \cdot \ell_1 \cdot r_m / CRG \tag{3.2}$$

are performed every second. Either the estimates from the Kalman filter $\hat{v}$, $\hat{r}$ and $\hat{\psi}$ or the measurements v_m, r_m and ψ_m are used by the self-tuning regulator, the PID-regulator, and the yaw regulator. The rudder command δ_c is computed with sampling interval 10 s or 15 s. The PID-regulator for straight course keeping is only used for comparison. The reference course ψ_{ref} and the reference yaw rate r_{ref} for yawing as well as the rudder limit δ_ℓ are also used by the autopilot. The complete autopilot is implemented by the Fortran subroutines AUTP3 and STUR given in the Appendix.

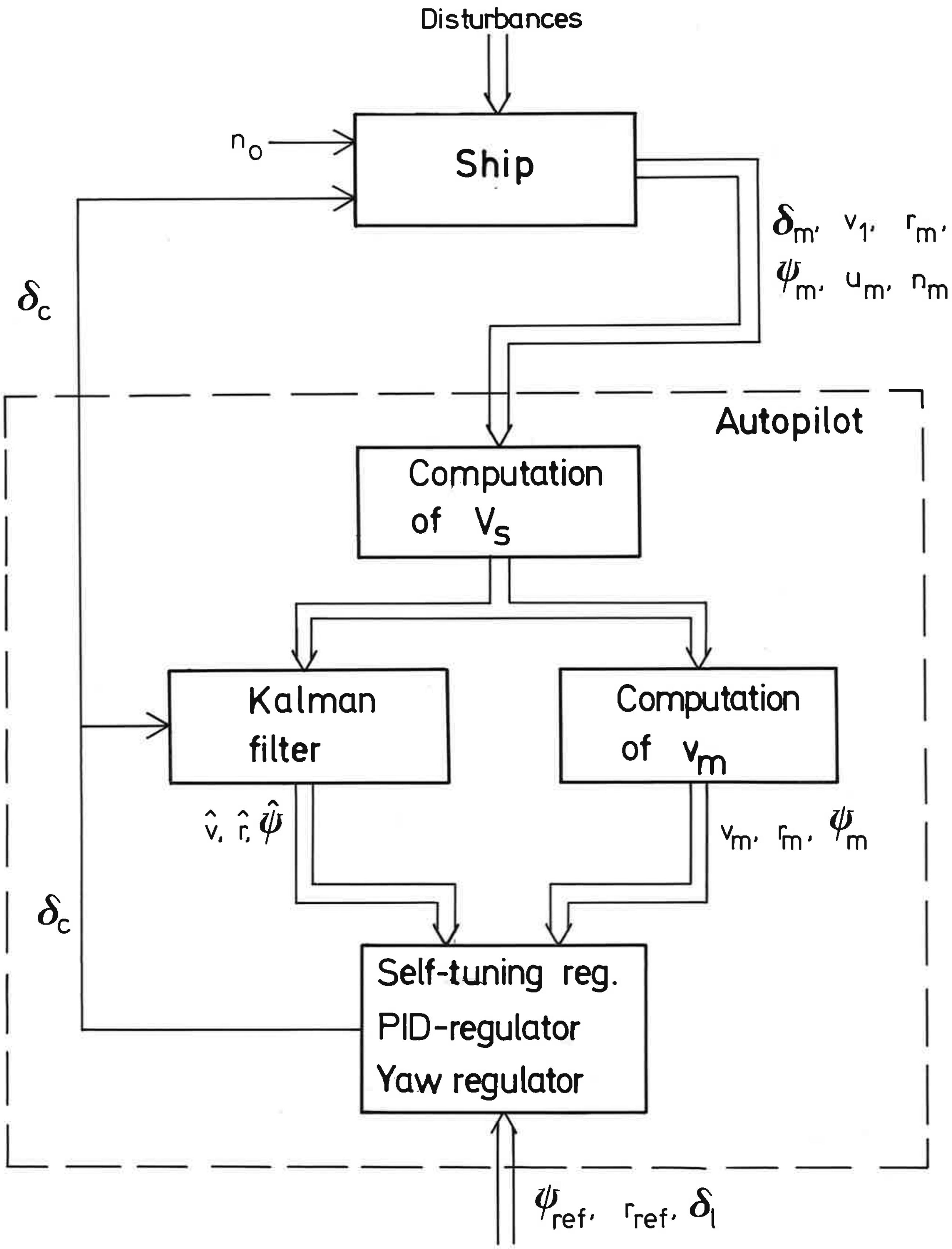


Fig. 3.1 - Structure of the autopilot.

3.1 Kalman Filter

The following linear model is used when designing the Kalman filter:

$$\begin{cases} dx = Ax\,dt + Bu\,dt + dw \\ y(t_k) = \theta x(t_k) + \tilde{e}(t_k), \quad k = 0,\ 1,\ 2,\ldots \end{cases} \tag{3.3}$$

where $\{ w(t),\ t_0 \leq t \leq \infty \}$ is assumed to be a wiener process with incremental covariance $R_1 dt$ and the measurement errors $\{ \tilde{e}(t_k) \}$ are assumed to be independent and gaussian with zero mean and covariance $\tilde{R}_2$. It is furthermore assumed that the measurement errors are independent of $\{ w(t),\ t_0 \leq t \leq \infty \}$. The vectors and matrices of (3.3) are explained by:

$$x^T = \begin{bmatrix} v & r & \psi & \delta_d & \delta_0 & d_v / CMK & d_r / CRG & d_\delta / CRG \end{bmatrix}$$

$$u = \delta_c / CRG$$

$$y^T = \begin{bmatrix} \delta_m / CRG & v_1 / CMK & r_m / CRG & \psi_m / CRG \end{bmatrix}$$

$$A = \begin{bmatrix} a_{11}\frac{V}{L} & a_{12}V & 0 & b_{11}\frac{V^2}{L} & 0 & 0 & 0 & 0 \\ a_{21}\frac{V}{L^2} & a_{22}\frac{V}{L} & 0 & b_{21}\frac{V^2}{L^2} & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_r} & -\frac{1}{T_r} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B^T = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{T_r} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\theta = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & \ell_1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\text{diag}\ (R_1) = \begin{bmatrix} r_1 & r_2 & r_3 & r_4 & r_5 & r_6 & r_7 & r_8 \end{bmatrix}$$

$$\text{diag}\ (\tilde{R}_2) = \begin{bmatrix} (\sigma_\delta / CRG)^2 & (\sigma_v / CMK)^2 & (\sigma_r / CRG)^2 & (\sigma_\psi / CRG)^2 \end{bmatrix}$$

where δ_0 [rad] is the rudder bias due to disturbances, δ_d [rad] is equal to $\delta - \delta_0$ and d_v [knots], d_r [deg/s] and d_δ [deg] are measurement biases (cf (2.8)). The total speed is denoted V [m/s]. The parameters are assigned the following values (cf Chapter 2):

$CRG = 57.2958$ deg

$CMK = 1.943844$ knots $*$ s/m

$L = 350$ m

$\ell_1 = 164.35$ m

$T_r = 5$ s

$a_{11} = Y''_{|u|v} / (1 - Y''_{\dot{v}}) = -0.385$

$a_{12} = (Y''_{ru} - 1) / (1 - Y''_{\dot{v}}) = -0.451$

$a_{21} = N''_{uv} / (k''^2_{zz} - N''_{\dot{r}}) = -3.398$

$a_{22} = (N''_{r|u|} - x''_G) / (k''^2_{zz} - N''_{\dot{r}}) = -1.583$

$b_{11} = (Y''_{uu\delta} + Y''_{u|u|\delta}) / (1 - Y''_{\dot{v}}) = -0.0967$

$b_{21} = (N''_{uu\delta} + N''_{u|u|\delta}) / (k''^2_{zz} - N''_{\dot{r}}) = 0.806$

$r_1 = 2.5 \cdot 10^{-5}$ m^2/s^3

$r_2 = 5 \cdot 10^{-9}$ $1/s^3$

$r_3 = 8 \cdot 10^{-8}$ $1/s$

$$
\left.\begin{aligned}
r_4 &= 8 \cdot 10^{-8} \quad 1/s \\
r_5 &= 3 \cdot 10^{-9} \quad 1/s \\
r_6 &= 9 \cdot 10^{-8} \quad m^2/s^3 \\
r_7 &= 3 \cdot 10^{-12} \quad 1/s^3 \\
r_8 &= 8 \cdot 10^{-11} \quad 1/s
\end{aligned}\right.
$$

$$
\left.\begin{aligned}
\sigma_\delta &= 0.2 \text{ deg} \\
\sigma_v &= 0.05 \text{ knots} \\
\sigma_r &= 0.02 \text{ deg/s} \\
\sigma_\psi &= 0.05 \text{ deg}
\end{aligned}\right\} \text{cf. (2.7)}
$$

The dynamics of (3.3) is equivalent to the linearization of the model (2.1) when parameter values for full load condition are used. By performing some calculations it can be concluded that the model (3.3) is observable, if the heading measurement ψ_m is one of the outputs. This means that one or more of the measurement signals δ_m, v_1 and r_m can be rejected and still it is possible to obtain good state estimates, at least if the dynamics and the disturbances are modelled reasonably well.

The model (3.3) is now normalized using the length of the ship L as unit of length and the time to cover the length L, i.e. L/V, as unit of time:

$$
\begin{cases}
dx' = A'x'dt' + B'u'dt' + dw' \\
y'(t_k') = \theta'x'(t_k') + \tilde{e}'(t_k'), \quad k = 0, 1, 2, \ldots
\end{cases} \tag{3.4}
$$

where

$$(x')^T = \begin{bmatrix} v' & r' & \psi' & \delta_d' & \delta_0' & d_v' & d_r' & d_\delta' \end{bmatrix}$$

$$u' = \delta_c'$$

$$(y')^T = \begin{bmatrix} \delta'_m & v'_1 & r'_m & \psi'_m \end{bmatrix}$$

$$A' = \begin{bmatrix} a_{11} & a_{12} & 0 & b_{11} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & b_{21} & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{L}{V}\cdot\frac{1}{T_r} & -\frac{L}{V}\cdot\frac{1}{T_r} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$(B')^T = \begin{bmatrix} 0 & 0 & 0 & \frac{L}{V}\cdot\frac{1}{T_r} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\theta' = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & \ell_1/L & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\text{diag } (R'_1) = \begin{bmatrix} \frac{L}{V^3}r_1 & \frac{L^3}{V^3}r_2 & \frac{L}{V}r_3 & \frac{L}{V}r_4 & \frac{L}{V}r_5 & \frac{L}{V^3}r_6 & \frac{L^3}{V^3}r_7 & \frac{L}{V}r_8 \end{bmatrix}$$

$$\text{diag } (\tilde{R}'_2) = \begin{bmatrix} (\sigma_\delta/CRG)^2 & (\sigma_v/(CMK\cdot V))^2 & (\sigma_r\cdot L/(CRG\cdot V))^2 & (\sigma_\psi/CRG)^2 \end{bmatrix}$$

The normalized variables are obtained as

$$
\begin{aligned}
t' &= \frac{V}{L} \cdot t \\
t_k' &= \frac{V}{L} \cdot t_k \\
v' &= \frac{1}{V} v \\
r' &= \frac{L}{V} r \\
\psi' &= \psi \\
\delta_d' &= \delta_d \\
\delta_0' &= \delta_0 \\
d_v' &= \frac{1}{CMK \cdot V} d_v \\
d_r' &= \frac{L}{CRG \cdot V} d_r \\
d_\delta' &= d_\delta / CRG \\
\delta_c' &= \delta_c / CRG \\
\delta_m' & \quad \delta_m / CRG \\
v_1' &= \frac{1}{CMK \cdot V} v_1 \\
r_m' &= \frac{L}{CRG \cdot V} r_m \\
\psi_m' &= \psi_m / CRG
\end{aligned}
\tag{3.5}
$$

The normalized model (3.4) is now transformed to a discrete model with sampling interval $h' = \frac{V}{L} h$, where $h = 1$ s:

$$
\begin{cases}
x'(t'+h') = \Phi' x'(t') + \Gamma' u'(t') + \tilde{w}'(t') \\
y'(t') = \theta' x'(t') + \tilde{e}'(t')
\end{cases}
\tag{3.6}
$$

Since the value of h' is rather small (e.g. $h' = 0.023$ if $V = 8$ m/s), the following approximations are not too bad:

$$
\begin{aligned}
\Phi' &\approx I + A'h' \\
\Gamma' &\approx B'h' \\
\tilde{R}_1 &\approx R_1'h'
\end{aligned}
\tag{3.7}
$$

It can be concluded using (3.7) that the speed dependence of Φ', Γ' and θ' in (3.6) is rather insignificant. Some elements of the covariance matrices $\tilde{R}_1'$ and $\tilde{R}_2'$, however, are dependent on the speed V.

If it is assumed that V = 8 m/s, the following matrices are obtained (no approximations):

$$\Phi' = \begin{bmatrix} 0.99163 & -1.00810\cdot10^{-2} & 0 & -2.08207\cdot10^{-3} & 2.12358\cdot10^{-4} & 0 & 0 & 0 \\ -7.59537\cdot10^{-2} & 0.96485 & 0 & 1.64706\cdot10^{-2} & -1.70991\cdot10^{-3} & 0 & 0 & 0 \\ -8.74514\cdot10^{-4} & 2.24515\cdot10^{-2} & 1 & 1.95418\cdot10^{-4} & -1.32723\cdot10^{-5} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.81873 & -0.18127 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$(\Gamma')^T = \begin{bmatrix} -2.12358\cdot10^{-4} & 1.70991\cdot10^{-3} & 1.32723\cdot10^{-5} & 0.18127 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\theta' = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0.46957 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$\tilde{R}_1'$ = (see page 16)

$$\text{diag}\,(\tilde{R}_2') = \begin{bmatrix} 1.21847\cdot10^{-5} & 1.03380\cdot10^{-5} & 2.33223\cdot10^{-4} & 7.61544\cdot10^{-7} \end{bmatrix}$$

$$\tilde{R}_1' = \begin{bmatrix} 3.87637\cdot10^{-7} & -6.23157\cdot10^{-8} & -8.42885\cdot10^{-10} & -7.45031\cdot10^{-11} & 2.14470\cdot10^{-13} & 0 & 0 & 0 \\ -6.23157\cdot10^{-8} & 9.23544\cdot10^{-6} & 1.05534\cdot10^{-7} & 6.00259\cdot10^{-10} & -1.74199\cdot10^{-12} & 0 & 0 & 0 \\ -8.42885\cdot10^{-10} & 1.05534\cdot10^{-7} & 8.16225\cdot10^{-8} & 4.57698\cdot10^{-12} & -1.00657\cdot10^{-14} & 0 & 0 & 0 \\ -7.45031\cdot10^{-11} & 6.00259\cdot10^{-10} & 4.57698\cdot10^{-12} & 6.59705\cdot10^{-8} & -2.80961\cdot10^{-10} & 0 & 0 & 0 \\ 2.14470\cdot10^{-13} & -1.74199\cdot10^{-12} & -1.00657\cdot10^{-14} & -2.80961\cdot10^{-10} & 3.00000\cdot10^{-9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.40625\cdot10^{-9} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 5.74218\cdot10^{-9} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8.00000\cdot10^{-11} \end{bmatrix}$$

Using (3.6) the Kalman filter equations are obtained as (cf. Åström (1970)):

$$\hat{x}'(t'|t'-h') = \Phi'\hat{x}'(t'-h'|t'-h') + \Gamma'u'(t'-h')$$
$$\hat{x}'(t'|t') = \hat{x}'(t'|t'-h') + K\,\varepsilon'(t') \qquad (3.8)$$
$$y'(t') = \theta'\hat{x}'(t'|t'-h') + \varepsilon'(t')$$

where

$$(\varepsilon')^T = \begin{bmatrix} \varepsilon'_\delta & \varepsilon'_v & \varepsilon'_r & \varepsilon'_\psi \end{bmatrix} \qquad (3.9)$$

and

$$K = \begin{bmatrix} -1.29\cdot10^{-4} & 9.73\cdot10^{-2} & -2.40\cdot10^{-2} & -0.369 \\ 5.31\cdot10^{-4} & 0.481 & 9.61\cdot10^{-2} & 1.01 \\ 1.22\cdot10^{-5} & 7.90\cdot10^{-3} & 3.12\cdot10^{-3} & 0.326 \\ 1.60\cdot10^{-2} & -2.13\cdot10^{-4} & 1.65\cdot10^{-3} & 1.89\cdot10^{-2} \\ -5.82\cdot10^{-12} & 3.08\cdot10^{-4} & -1.63\cdot10^{-3} & -1.88\cdot10^{-2} \\ -3.69\cdot10^{-5} & 9.39\cdot10^{-3} & 1.61\cdot10^{-4} & 8.17\cdot10^{-5} \\ -1.40\cdot10^{-6} & -1.56\cdot10^{-3} & 3.01\cdot10^{-3} & -5.78\cdot10^{-2} \\ 2.54\cdot10^{-3} & 2.57\cdot10^{-6} & 3.31\cdot10^{-6} & 3.66\cdot10^{-5} \end{bmatrix} \qquad (3.10)$$

The speed V_s (cf. (3.1)) is used to normalize the measurement vector, i.e.

$$(y')^T = \begin{bmatrix} \delta_m/CRG & \frac{1}{CMK\cdot V_s} v_1 & \frac{L}{CRG\cdot V_s} r_m & \psi_m/CRG \end{bmatrix} \qquad (3.11)$$

The state estimate vector

$$(\hat{x}')^T = \begin{bmatrix} \hat{v}' & \hat{r}' & \hat{\psi}' & \hat{\delta}'_d & \hat{\delta}'_0 & \hat{d}'_v & \hat{d}'_r & \hat{d}'_\delta \end{bmatrix} \qquad (3.12)$$

is updated every second. The initial state estimate vector is equal to

$$(\hat{x}'(t_0))^T = \left[\frac{1}{CMK \cdot V_s} v_m \quad \frac{L}{CRG \cdot V_s} r_m \quad \psi_m/CRG \quad \delta_m/CRG \quad 0 \quad 0 \quad 0 \quad 0 \right]$$

where v_m is obtained from (3.2) and all the measurements are from the time t_0.

If

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

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

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

or

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

where

$$\begin{aligned} t'_\delta &= 0.75 \\ t'_v &= 0.06 \\ t'_r &= 0.25 \\ t'_\psi &= 0.015, \end{aligned} \tag{3.13}$$

then the corresponding measurement or measurements are rejected, when the state estimate vector is updated. A measurement signal is definitively rejected when 10 consecutive measurements are rejected. However, during the first 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 (see (3.10)) equal to zero. Notice that the values of (3.13) are chosen very large to avoid rejectings when the Kalman filter is tested.

The non-normalized state estimate vector is obtained as (cf. (3.12)):

$$(\hat{x})^T = \begin{bmatrix} \hat{v} & \hat{r} & \hat{\psi} & \hat{\delta}_d & \hat{\delta}_0 & \hat{d}_v & \hat{d}_r & \hat{d}_\delta \end{bmatrix} \qquad (3.14)$$

where

$$\hat{v} = CMK \cdot V_s \cdot \hat{v}' \qquad [\text{knots}]$$

$$\hat{r} = \frac{CRG \cdot V_s}{L} \hat{r}' \qquad [\text{deg/s}]$$

$$\hat{\psi} = CRG \cdot \hat{\psi}' \qquad [\text{deg}]$$

$$\hat{\delta}_d = CRG \cdot \hat{\delta}_d' \qquad [\text{deg}]$$

$$\hat{\delta}_0 = CRG \cdot \hat{\delta}_0' \qquad [\text{deg}]$$

$$\hat{d}_v = CMK \cdot V_s \cdot \hat{d}_v' \qquad [\text{knots}]$$

$$\hat{d}_r = \frac{CRG \cdot V_s}{L} \hat{d}_r' \qquad [\text{deg/s}]$$

$$\hat{d}_\delta = CRG \cdot \hat{d}_\delta' \qquad [\text{deg}]$$

Notice the following expressions, too:

$$\hat{v}_1 = \hat{v} + CMK \cdot \ell_1 \cdot \hat{r}/CRG \qquad [\text{knots}]$$

$$\hat{\delta} = \hat{\delta}_d + \hat{\delta}_0 \qquad [\text{deg}]$$

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:

$$\begin{aligned}
&\left(\hat{\psi}(t) - \psi_{ref}\right) + a_1\left(\hat{\psi}(t-k-1) - \psi_{ref}\right) + \ldots + \\
&+ a_{NA}\left(\hat{\psi}(t-k-NA) - \psi_{ref}\right) = \qquad (3.15)\\
&= \left(V_s(t-k-1)/V_0\right)^2 b_0 \nabla\delta_c(t-k-1) + \\
&+ \left(V_s(t-k-2)/V_0\right)^2 b_0 b_1 \nabla\delta_c(t-k-2) + \ldots + \\
&+ \left(V_s(t-k-NB-1)/V_0\right)^2 b_0 b_{NB} \nabla\delta_c(t-k-NB-1) + \\
&+ V_s(t-k-1) c_1 \nabla\hat{v}(t-k-1) + c_2 \nabla\hat{r}(t-k-1) + \varepsilon(t)
\end{aligned}$$

where the design speed is denoted V_0 [m/s] and the speed V_s [m/s] is defined by (3.1). The minimum variance control is given by

$$\begin{aligned}
\nabla\delta_c(t) = &\left(\frac{V_0}{V_s(t)}\right)^2 \frac{1}{b_0} \Big[a_1\left(\hat{\psi}(t) - \psi_{ref}\right) + \ldots + \\
&+ a_{NA}\left(\hat{\psi}(t-NA+1) - \psi_{ref}\right) - \\
&- \left(V_s(t-1)/V_0\right)^2 b_0 b_1 \nabla\delta_c(t-1) - \ldots - \\
&- \left(V_s(t-NB)/V_0\right)^2 b_0 b_{NB} \nabla\delta_c(t-NB) - \\
&- V_s(t) c_1 \nabla\hat{v}(t) - c_2 \nabla\hat{r}(t)\Big] \qquad (3.16)
\end{aligned}$$

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 (3.15) and (3.16) 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

$\lambda_f = 0.99$

$b_0 = 1$

$V_0 = 8$ m/s

where T_s is the sampling interval and λ_f the exponential forgetting factor. Other values of k and T_s are sometimes used. The following initial values of the parameters and of the covariance matrix P are used when the Kalman filter estimates are fed into the self-tuning regulator:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \\ c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} -6.91 \\ 5.95 \\ 3.88 \\ -3.57 \\ 0.48 \\ 0.11 \\ -2.10 \\ 34.73 \end{bmatrix} \qquad P = \begin{bmatrix} 1 & & & & & & & \\ & 1 & & & & & 0 & \\ & & 1 & & & & & \\ & & & 1 & & & & \\ & & & & 0.01 & & & \\ & & & & & 0.01 & & \\ & 0 & & & & & 1 & \\ & & & & & & & 100 \end{bmatrix} \tag{3.17}$$

When non-filtered measurements are used instead of Kalman filter estimates, then $c_1 = c_2 = 0$, i.e. no feedforward signals. The following initial values are then used:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -7.64 \\ 8.44 \\ 1.74 \\ -3.15 \\ 0.00834 \\ 0.195 \end{bmatrix} \qquad P = \begin{bmatrix} 1 & & & & & \\ & 1 & & & 0 & \\ & & 1 & & & \\ & & & 1 & & \\ & 0 & & & 0.01 & \\ & & & & & 0.01 \end{bmatrix} \tag{3.18}$$

By use of the minimum variance control (3.16) the following criterion is minimized:

$$J_1 = \sum_{n=k+1}^{N} \left(\hat{\psi}(nT_s) - \psi_{ref}\right)^2 \tag{3.19}$$

If the criterion

$$J_2 = \sum_{n=k+1}^{N} \left[\left(\hat{\psi}(nT_s) - \psi_{ref}\right)^2 + q_2\left(\nabla\delta_c\left((n-k-1)T_s\right)\right)^2\right] \tag{3.20}$$

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 (3.20) is modified to read

$$J_3(n) = \left(\hat{\psi}\left((n+k+1)T_s\right) - \psi_{ref}\right)^2 + q_2\left(\nabla\delta_c(nT_s)\right)^2 \qquad (3.21)$$

$$n = 0, 1, \ldots, N-k-1$$

and if (3.21) is minimized at every sample event, then a simpler regulator is obtained. By inserting (3.15) into (3.21) and then performing the minimization, the following control is obtained:

$$\overline{\nabla\delta_c(t)} = \frac{\left(V_s(t)/V_0\right)^4 b_0^2}{\left(V_s(t)/V_0\right)^4 b_0^2 + q_2} \nabla\delta_c(t) \qquad (3.22)$$

where $\nabla\delta_c(t)$ is the minimum variance control given by (3.16). If $q_2 = 0$, then minimization of (3.21) gives the same result as minimization of (3.19) and consequently the controls (3.22) and (3.16) are equivalent. Notice that (3.22) only is a very small modification of (3.16) and that the identification part of the self-tuning regulator is unchanged. However, the control (3.22) has the serious disadvantage that no guarantee of closed loop stability is obtained in the general case.

The minimum variance control (3.16) is approximately scaled by $\left(V_0/V_s(t)\right)^2$ when the speed changes, i.e. (3.22) may be re-written

$$\overline{\nabla\delta_c(t)} = \frac{b_0^2}{b_0^2 + \left(\frac{V_0}{V_s(t)}\right)^4 q_2} \left(\frac{V_0}{V_s(t)}\right)^2 \left[\nabla\delta_c(t)\right]_{V_0} \qquad (3.23)$$

where $[\nabla\delta_c(t)]_{V_0}$ denotes the minimum variance control when $V_s = V_0$. By introducing $q_2^* = \left(V_0/V_s(t)\right)^4 q_2$ we obtain

$$\overline{\nabla\delta_c(t)} = \frac{b_0^2}{b_0^2 + q_2^*}\left(\frac{V_0}{V_s(t)}\right)^2 [\nabla\delta_c(t)]_{V_0} =$$

$$= \frac{b_0^2}{b_0^2 + q_2^*} \nabla\delta_c(t) \qquad (3.24)$$

which is the actual control used in the autopilot. The standard value of q_2^* 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:

$$\delta_c(nT_s) = -\left(\frac{V_0}{V_s(nT_s)}\right)^2 \left[k_P\left(\hat{\psi}(nT_s) - \psi_{ref}\right) + k_D\,\hat{r}(nT_s) + \right.$$

$$\left. + k_I\, T_s \sum_{i=0}^{n-1} \left(\hat{\psi}(iT_s) - \psi_{ref}\right)\right] \qquad (3.25)$$

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

The following standard values are used:

$$\begin{aligned} k_P &= 3 \\ k_D &= 75 \text{ s} \\ k_I &= 0.02 \text{ 1/s} \\ T_s &= 10 \text{ s} \\ V_0 &= 8 \text{ m/s} \end{aligned} \qquad (3.26)$$

The scaling speed V_s is obtained from (3.1). Notice that it is possible to use the non-filtered measurements instead of the Kalman filter estimates in (3.25). The special speed scaling used in (3.25) will approximately give the same course keeping performance independent of the forward speed. The rudder deviations, however, are increased proportional to $(V_0/V_s)^2$ 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:

$$\delta_c(nT_s) = -\left(\frac{V_0}{V_s(nT_s)}\right)^2 k_4 \left[\hat{r}(nT_s) - r_0\right] + \bar{\delta}_c$$

$$\left| k_4 \left[\hat{r}(nT_s) - r_0\right] \right| \leq \left| \bar{c}_1 r_0 \right|$$

Phase 2:

$$\delta_c(nT_s) = -\left(\frac{V_0}{V_s(nT_s)}\right)^2 k_5 \left[\hat{r}(nT_s) - r_0\right] -$$

$$- \left(\frac{V_0}{V_s(nT_s)}\right)^2 k_6 T_s \sum_{i=0}^{n-1} \left[\hat{r}(iT_s) - r_0\right] + \bar{\delta}_c$$

Phase 3:

$$\delta_c(nT_s) = -\left(\frac{V_0}{V_s(nT_s)}\right)^2 k_7 \left[\hat{\psi}(nT_s) - \psi_{ref}\right] -$$

$$- \left(\frac{V_0}{V_s(nT_s)}\right)^2 k_8 \hat{r}(nT_s)$$

$$\left| k_7 \left[\hat{\psi}(nT_s) - \psi_{ref}\right] + k_8 \hat{r}(nT_s) \right| \leq \left| \bar{c}_3 r_0 \right|$$

Phase 4:

$$\delta_c(nT_s) = -\left(\frac{V_0}{V_s(nT_s)}\right)^2 k_1 \left[\hat{\psi}(nT_s) - \psi_{ref}\right] -$$

$$- \left(\frac{V_0}{V_s(nT_s)}\right)^2 k_2 \hat{r}(nT_s) -$$

$$- \left(\frac{V_0}{V_s(nT_s)}\right)^2 k_3 T_s \sum_{i=0}^{n-1} \left[\hat{\psi}(iT_s) - \psi_{ref}\right]$$

The scaling speed V_s is obtained from (3.1). The moving average $\bar{\delta}_c$ of the rudder commands δ_c is only updated during phase 0 and phase 4:

$$\bar{\delta}_c\left((k+1)T_s\right) = \bar{\delta}_c(kT_s) + \left(\frac{1-\gamma}{k+1} + \gamma\right)\left(\delta_c(kT_s) - \bar{\delta}_c(kT_s)\right), \quad k = 0, 1, 2, \ldots$$

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

The reference yaw rate r_0 including sign is computed once, when the yaw is initiated, as

$$r_0 = r_{ref} \quad \text{if} \quad \hat{\psi} - \psi_{ref} \leq 0$$

or as

$$r_0 = -r_{ref} \quad \text{if} \quad \hat{\psi} - \psi_{ref} > 0$$

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:

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

Phase 1 → phase 2:

$$r_0 \geq 0 \quad \text{and} \quad \hat{r} - r_0 > -\varepsilon_1$$

or

$$r_0 < 0 \quad \text{and} \quad \hat{r} - r_0 < \varepsilon_1$$

or

$$(\text{time in phase 1}) > T_1$$

Phase 1 or 2 → phase 3:

$$r_0 \geq 0 \quad \text{and} \quad -\bar{c}_2\,\hat{r} < \hat{\psi} - \psi_{ref}$$

or

$$r_0 < 0 \quad \text{and} \quad -\bar{c}_2\,\hat{r} > \hat{\psi} - \psi_{ref}$$

Phase 3 → phase 4:

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

or

$$r_0 \geq 0 \quad \text{and} \quad \hat{\psi} - \psi_{ref} > -\varepsilon_3$$

or

$$r_0 < 0 \quad \text{and} \quad \hat{\psi} - \psi_{ref} < \varepsilon_3$$

or

$$(\text{time in phase 3}) > T_3$$

Phase 4 → phase 0:

(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 (3.27)

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 (3.28)

$r_0 > 0, \quad \hat{\psi} - \psi_{ref} > 0$

and

$r_0 < 0, \quad \hat{\psi} - \psi_{ref} < 0$

is satisfied.

If neither condition (3.27) nor condition (3.28) is fulfilled, the new value of ψ_{ref} is used, but no other changes.

The following parameter values of the yaw regulator are used:

$k_1 = 5$	$\bar{c}_1 = 60$ s
$k_2 = 200$ s	$\bar{c}_2 = 50$ s
$k_3 = 0.005$ 1/s	$\bar{c}_3 = 60$ s
$k_4 = 200$ s	$T_1 = 30$ s
$k_5 = 200$ s	$T_3 = 100$ s
$k_6 = 8$	$T_4 = 300$ s
$k_7 = 2$	$\psi_1 = 0.35$ deg
$k_8 = 200$ s	$\psi_2 = 2.5$ deg
$\varepsilon_1 = 0$ deg/s	$\psi_3 = 2.5$ deg
$\varepsilon_2 = 0.02$ deg/s	$V_0 = 8$ m/s
$\varepsilon_3 = 1$ deg	$T_s = 10$ s
	$\gamma = 0.05$

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 respectively. 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 $(V_0/V_s)^2$ when the speed is decreased.

4. SIMULATIONS

To make it possible to compare the steering quality of different autopilot structures, a loss function is now introduced:

$$V_{\ell} = \frac{1}{\tau} \int_0^{\tau} \left[\left(\psi(t) - \psi_{ref}\right)^2 + \lambda\left(\delta(t) - m_{\delta}\right)^2 \right] dt \qquad (4.1)$$

where m_{δ} is the mean value of the rudder angle δ and the weighting factor λ is equal to 1/12 or 0. The duration of a simulation is denoted τ. The loss function is approximated by:

$$V_{\ell} = \frac{1}{N} \sum_{n=0}^{N-1} \left[\left(\psi(nh) - \psi_{ref}\right)^2 + \lambda\left(\delta(nh) - m_{\delta}\right)^2 \right] \qquad (4.2)$$

where $Nh = \tau$ and the sampling interval h always is equal to 1 s.

In the sequel the mean values m_{δ} and m_{ψ}, and the standard deviations σ_{δ} and σ_{ψ}, of the rudder angle δ and the course error $\psi - \psi_{ref}$, resp, will be presented as well as the loss function V_{ℓ}. Notice that the rudder angle δ and the heading angel ψ without measurement noise and without measurement bias are used. If nothing else is remarked, the standard values given in Chapters 2 and 3 are used in the simulations. 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. Notice that the initial forward speed is denoted u_0.

4.1 Kalman Filter Testing

Simulations of straight course keeping (ψ_{ref} = 0 deg) with the self-tuning regulator using estimates from the Kalman filter are presented in this section. The performance of the Kalman filter and the self-tuning regulator for different load conditions and different speeds are shown in Figs 4.1 - 4.6.

In Fig. 4.7 the initial covariance matrix of the self-tuning regulator is given as (cf. (3.17)):

$$\text{diag } (P) = [\ 10 \quad 10 \quad 10 \quad 10 \quad 0.1 \quad 0.1 \quad 10 \quad 500\ ] \tag{4.3}$$

The only measurement signal used by the Kalman filter in Figs. 4.8 and 4.9 is the heading angle. The first three columns of the filter gain K (cf. (3.10)) are cancelled in Fig. 4.8, while the following filter gain, designed correctly for the case of heading measurements only, is used in Fig. 4.9:

$$K^T = [\ -0.481 \quad 2.4 \quad 0.39 \quad 0.072 \quad -0.0716 \quad 0 \quad 0 \quad 0\ ] \tag{4.4}$$

The process noise is increased in Fig. 4.10 by use of the following covariance matrix (cf. (2.6)):

$$R_w = \begin{bmatrix} 3.2 \cdot 10^{-4} & 0 \\ 0 & 2.12 \cdot 10^{-10} \end{bmatrix} \tag{4.5}$$

A modified filter gain is used in Fig. 4.11. The tuning rate of the state estimates $\hat{\delta}_0$ and $\hat{d}_v$ is increased by changing two elements of R_1:

$$r_5 = 1.2 \cdot 10^{-8} \quad 1/s$$

$$r_6 = 4 \cdot 10^{-7} \quad m^2/s^3$$

The corresponding filter gain is (cf.(3.10)):

$$K = \begin{bmatrix} -9.27\cdot10^{-5} & 8.82\cdot10^{-2} & -2.40\cdot10^{-2} & -0.367 \\ 6.30\cdot10^{-4} & 0.481 & 9.65\cdot10^{-2} & 1.02 \\ 1.69\cdot10^{-5} & 7.86\cdot10^{-3} & 3.14\cdot10^{-3} & 0.326 \\ 1.66\cdot10^{-2} & -2.90\cdot10^{-3} & 5.65\cdot10^{-3} & 6.51\cdot10^{-2} \\ 1.03\cdot10^{-3} & 2.98\cdot10^{-3} & -5.63\cdot10^{-3} & -6.49\cdot10^{-2} \\ -1.26\cdot10^{-4} & 2.00\cdot10^{-2} & -6.69\cdot10^{-5} & -5.06\cdot10^{-3} \\ 1.63\cdot10^{-6} & -1.68\cdot10^{-3} & 3.02\cdot10^{-3} & -5.77\cdot10^{-2} \\ 2.54\cdot10^{-3} & 7.61\cdot10^{-6} & 1.24\cdot10^{-5} & 1.41\cdot10^{-4} \end{bmatrix} \tag{4.6}$$

All the simulations are summarized in Table 4.1. The reason why $\lambda = 0$ (cf.(4.1)) when the initial speed u_0 is equal to 4 knots is that the course keeping is much more important than the rudder deviations at such a low speed.

From the simulations it can be concluded that the performance of the Kalman filter is very good for the initial speeds 15.8 knots and 10 knots in full load condition as well as in ballast condition (cf. Figs 4.1 - 4.4). Notice, however, that the tuning rate of the state estimates $\hat{\delta}_0$ and $\hat{d}_v$ is rather small. The performance of the Kalman filter for the initial speed u_0 = 4 knots (Figs 4.5 - 4.7) is not as good as for larger speeds, but quite acceptable. The small tuning rate of $\hat{d}_v$, however, is emphasized. Another difficulty is that the limited rudder turning rate has not been considered in the Kalman filter. This means large values of the residuals ε_δ' (see Figs 4.6j and 4.7j) when large rudder changes are requested, which is the case quite often when the speed is low. To avoid incorrect rejectings of the rudder angle measurements, the test value t_δ' (cf.(3.13)) must be chosen that large, that the checking is quite meaningless.

T [m]	n_0 [rpm]	u_0 [knots]	δ_ℓ [deg]	m_δ [deg]	σ_δ [deg]	m_ψ [deg]	σ_ψ [deg]	V_ℓ [deg^2]	λ	Fig.	Remarks
22.3	87.6	15.8	10	- 1.28	2.04	-0.09	0.47	0.55	1/12	4.1	
10.5	87.6	15.8	10	- 0.15	1.55	-0.01	0.29	0.29	1/12	4.2	
22.3	55.443	10	35	- 3.71	4.61	-0.16	0.51	2.05	1/12	4.3	
10.5	55.443	10	35	- 1.18	3.36	-0.01	0.35	1.06	1/12	4.4	
22.3	22.1772	4	45	-21.62	19.96	0.66	1.01	1.46	0	4.5	
10.5	22.1772	4	45	- 8.93	19.24	0.30	0.61	0.46	0	4.6	
22.3	22.1772	4	45	-22.29	22.53	0.90	1.14	2.11	0	4.7	Initial P given by (4.3).
22.3	87.6	15.8	10	- 1.30	2.58	0.03	0.48	0.79	1/12	4.8	Only ψ_m used by Kalman filter.
22.3	87.6	15.8	10	- 1.30	2.52	0.03	0.46	0.74	1/12	4.9	Only ψ_m used by Kalman filter. Correct K (4.4).
22.3	87.6	15.8	10	- 1.38	3.83	-0.14	0.82	1.91	1/12	4.10	R_w given by (4.5).
22.3	87.6	15.8	10	- 1.28	2.04	-0.06	0.44	0.54	1/12	4.11	K given by (4.6).

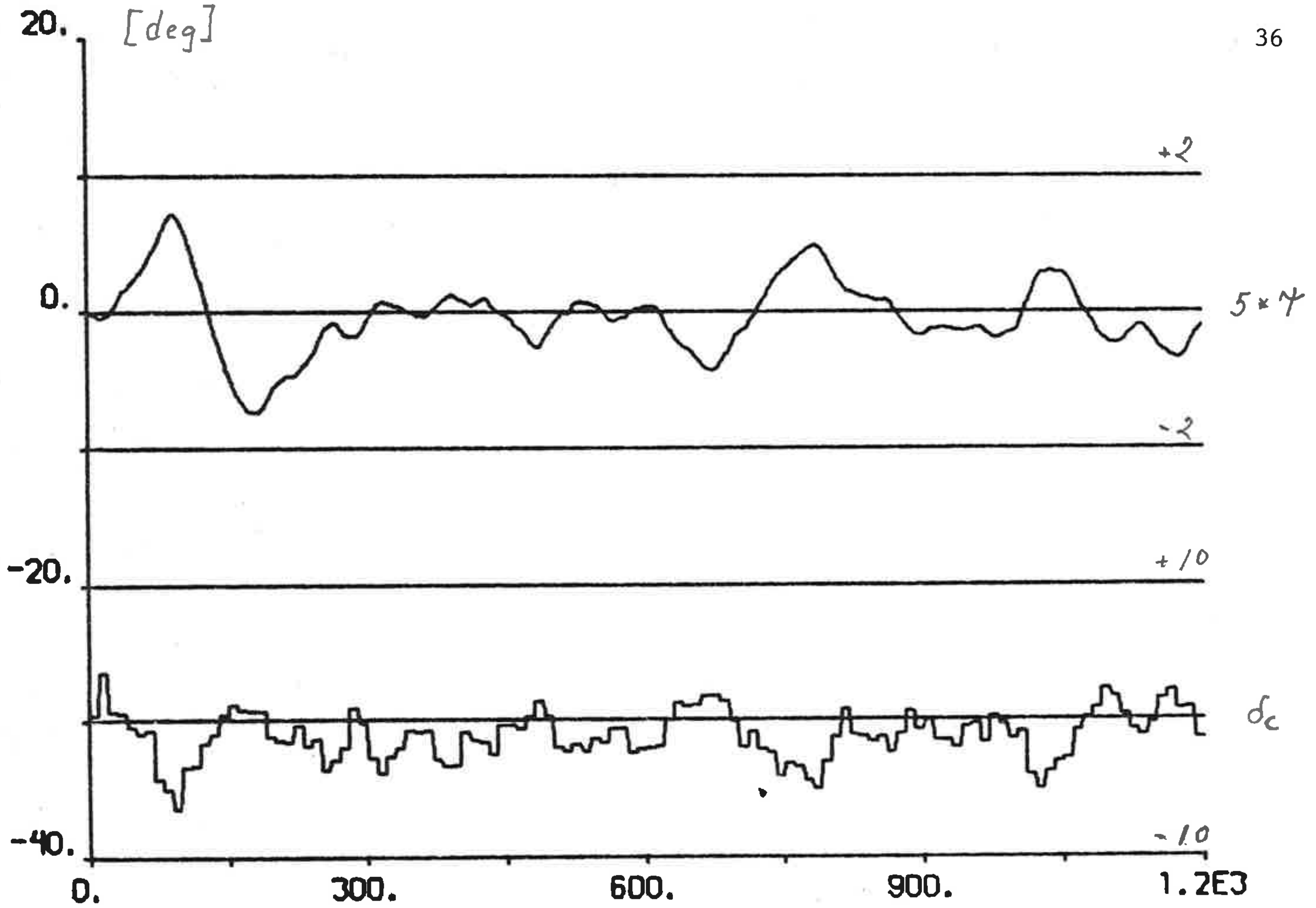
Table 4.1 - Summary of simulations for Kalman filter testing. The duration of each simulation is 2400 s, but the values of m_δ, σ_δ, m_ψ, σ_ψ, and V_ℓ are computed for the part 1200 - 2400 s. The straight course keeping (ψ_{ref} = 0 deg) is performed by the self-tuning regulator using estimates from the Kalman filter.

If the only measurement signal used by the Kalman filter is the heading angle, the state estimates $\hat{v}$, $\hat{r}$, $\hat{\psi}$, $\hat{\delta}$ and $\hat{\delta}_0$ are nevertheless good, which can be concluded from Figs 4.8 and 4.9. The difference between cancelling the corresponding columns of K (Fig. 4.8) and designing a correct K (Fig. 4.9) is very small.

The quality of the Kalman filter estimates is only decreased very little, when the standard deviations of the process disturbances are doubled (see Fig. 4.10).

Finally a filter gain designed for increased tuning rate of $\hat{\delta}_0$ and $\hat{d}_v$ is tested in the simulation of Fig. 4.11. It can be concluded that the tuning rate of $\hat{d}_v$ still is small, although an improvement is obtained compared to Fig. 4.1.

The final parameter values of the self-tuning regulator are summarized in Table 4.7 of the next section. Some examples of the performance of the Kalman filter during yaws are shown in Section 4.3.



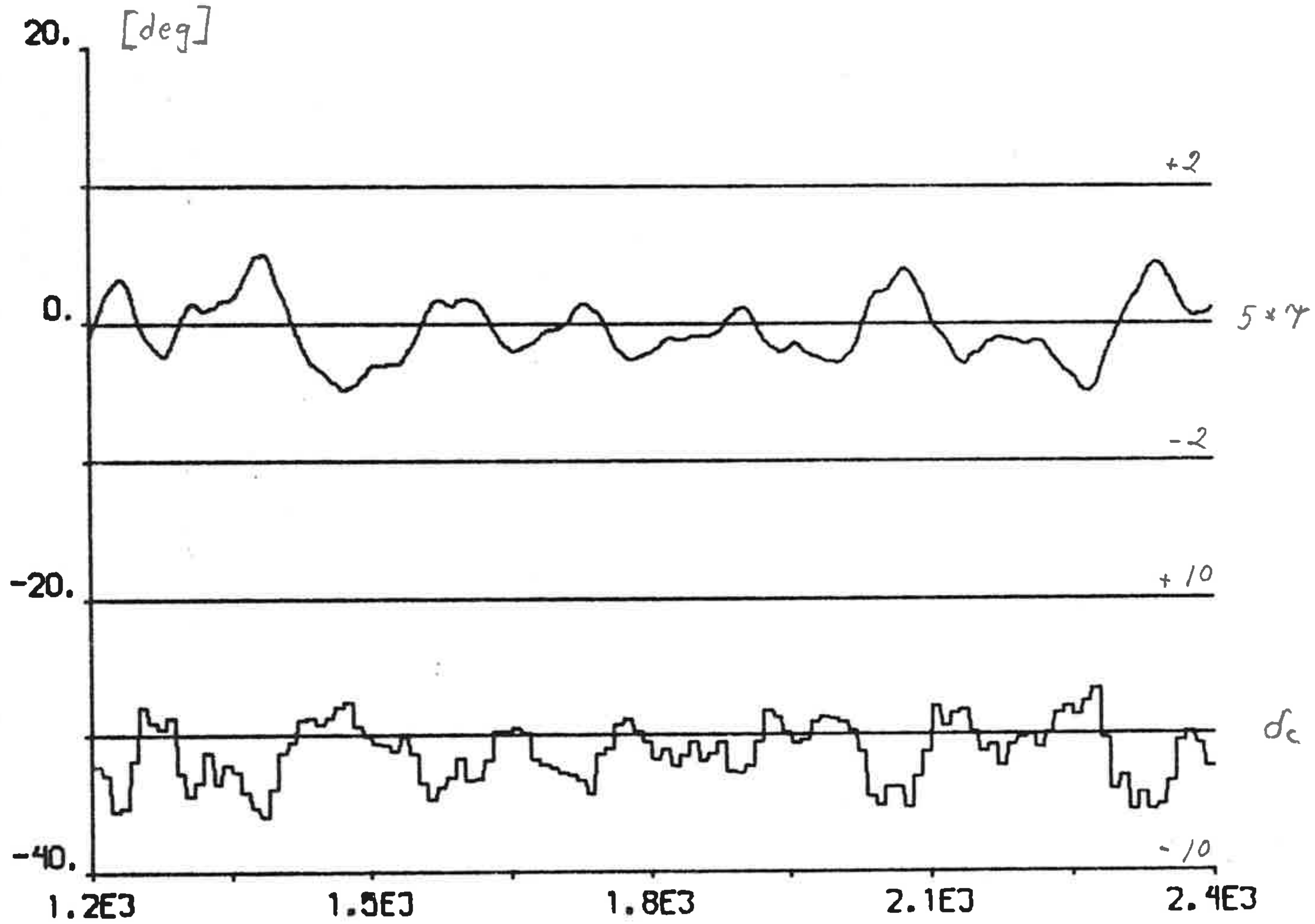


Fig. 4.1a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using estimates from the Kalman filter.

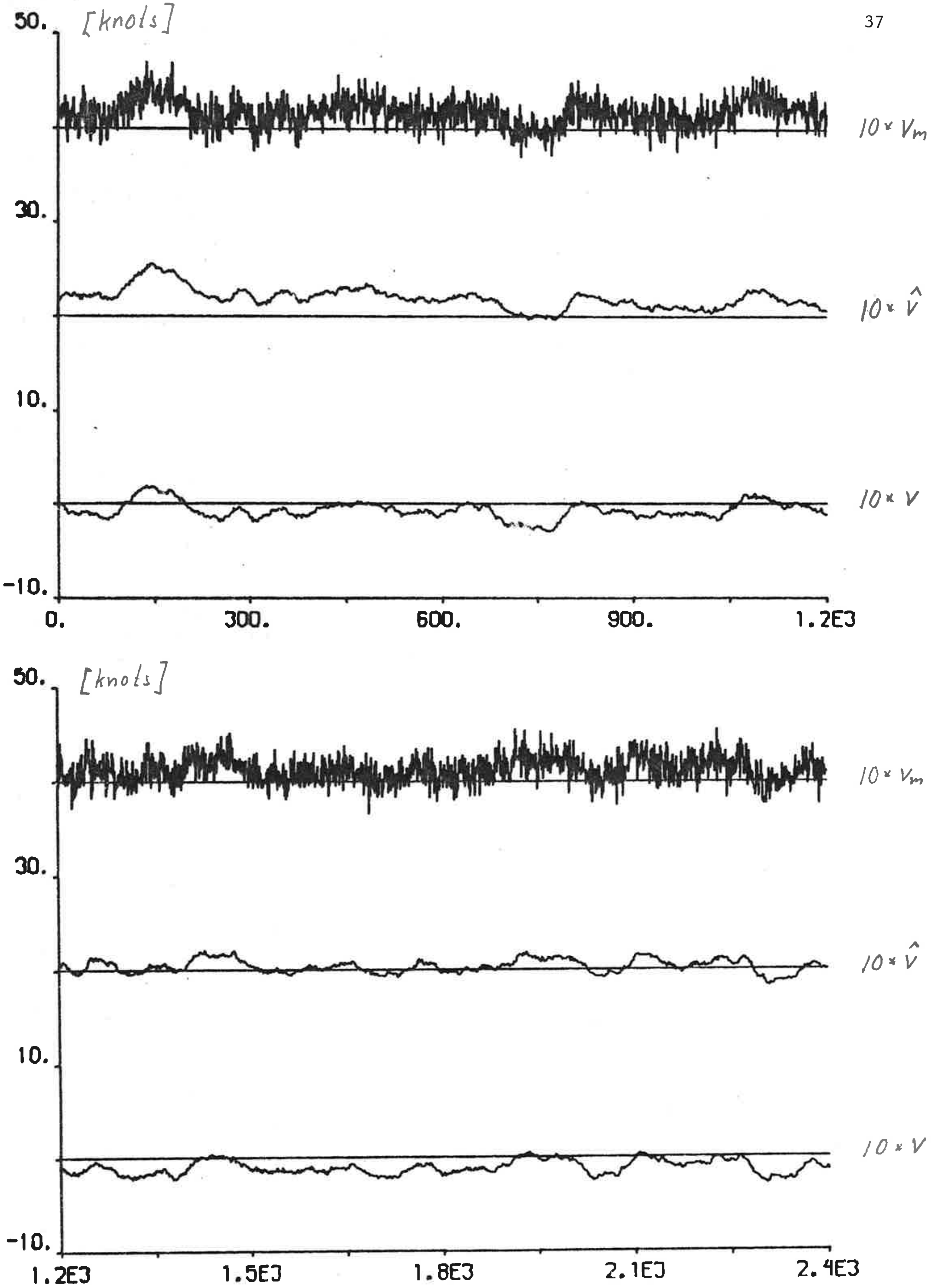
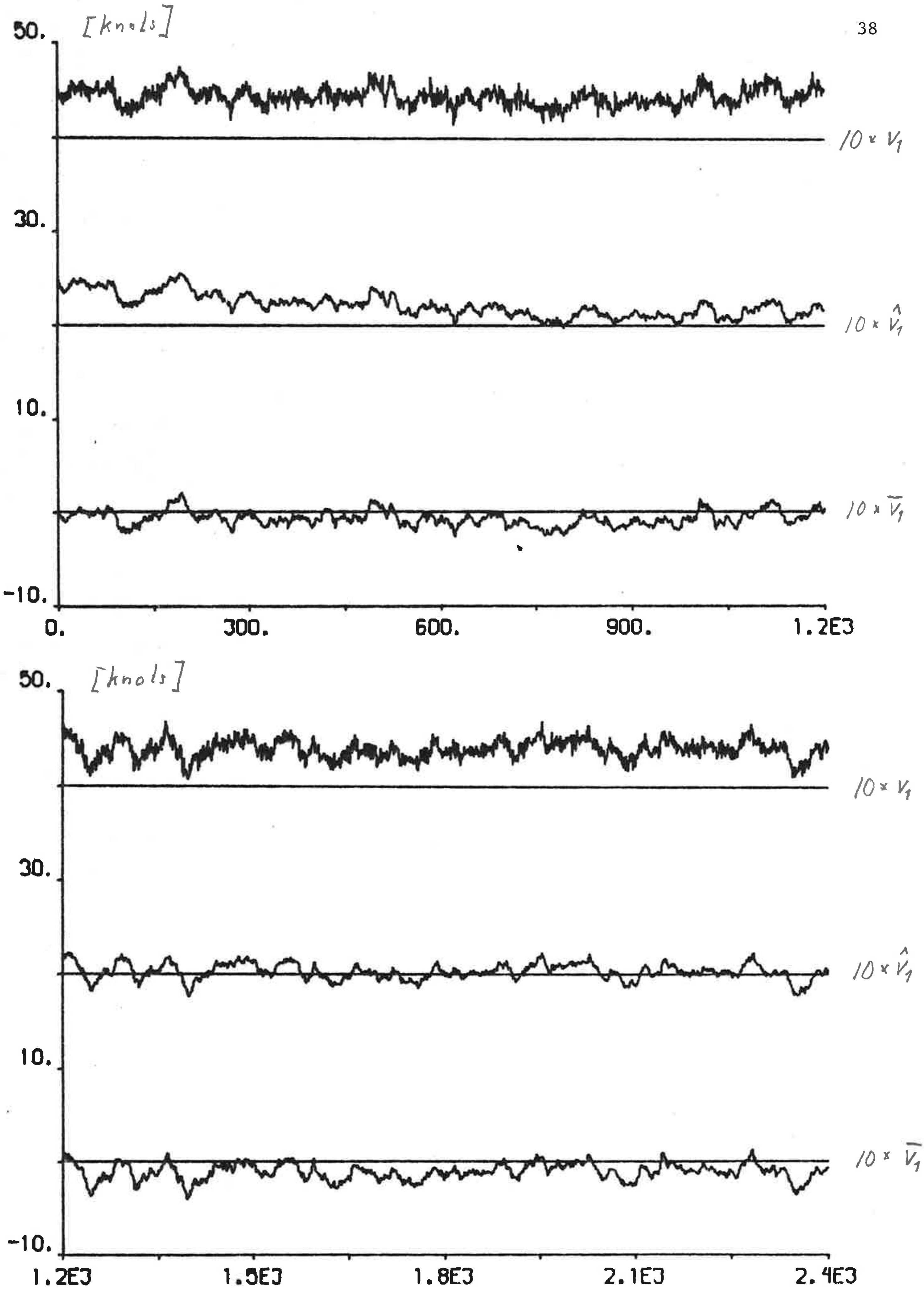

50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × Vm
10 × V̂
10 × V
50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × Vm
10 × V̂
10 × V

Fig. 4.1b



[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × V1
10 × V̂1
10 × V̄1
[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × V1
10 × V̂1
10 × V̄1

Fig. 4.1c

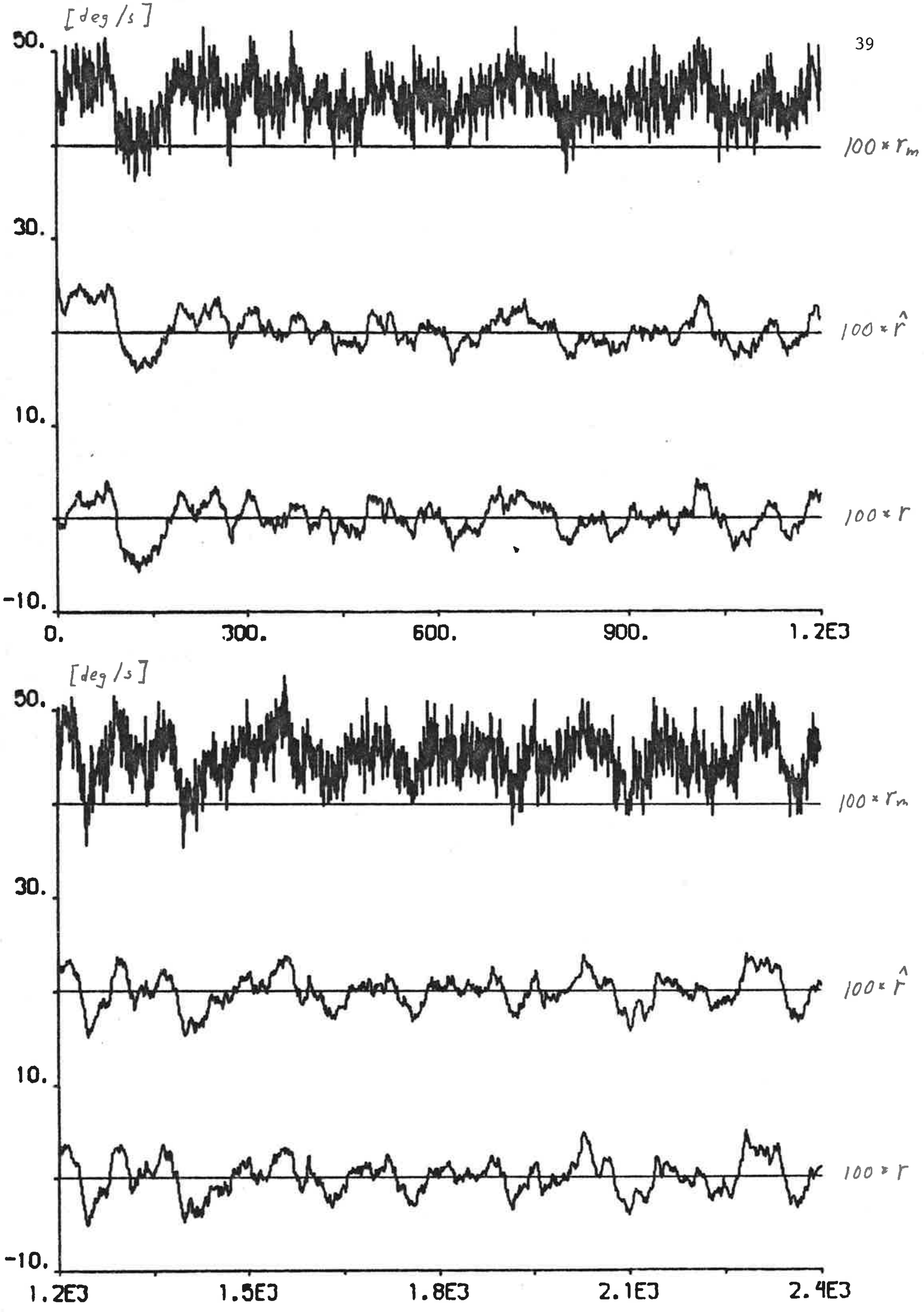
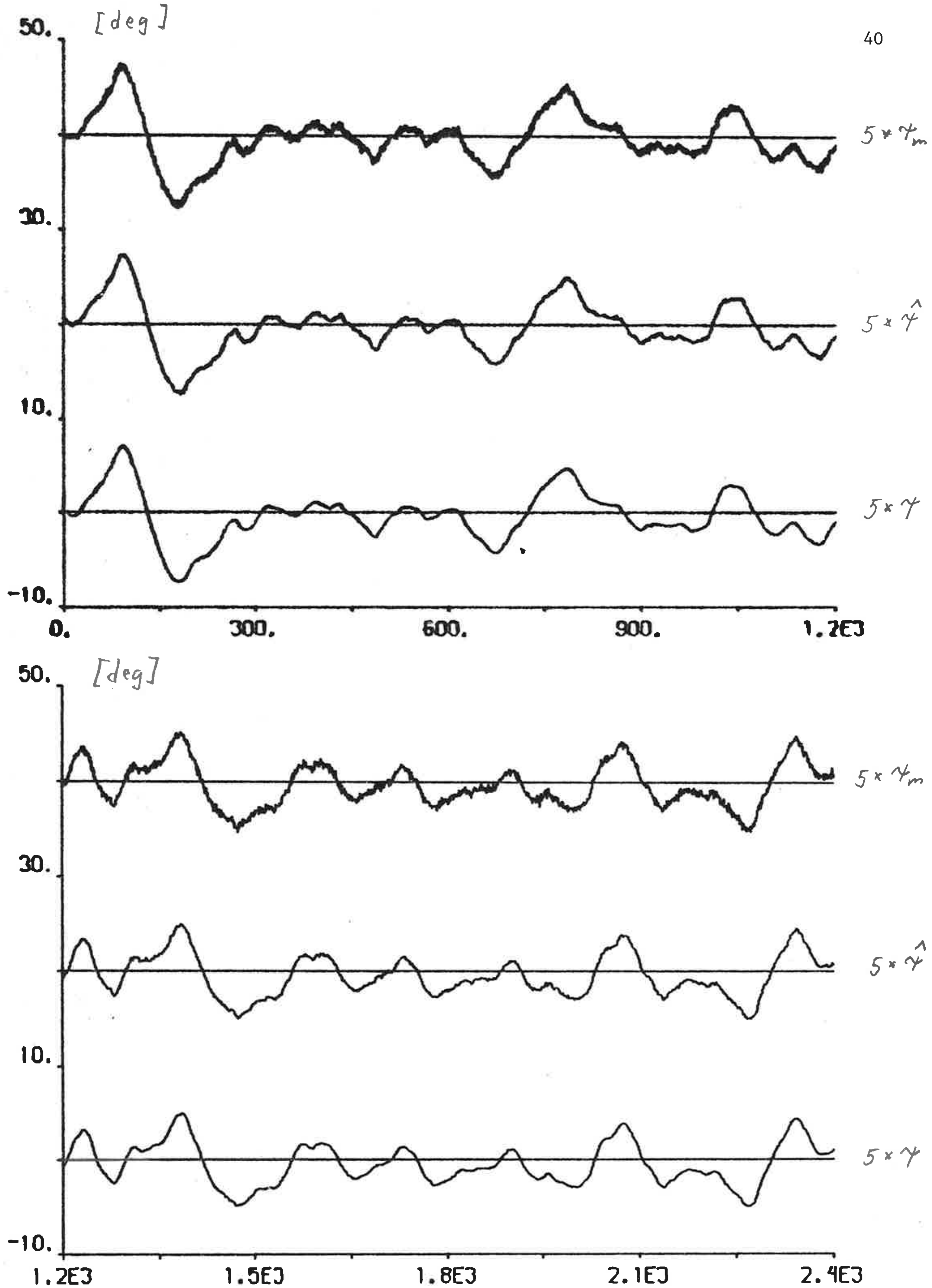
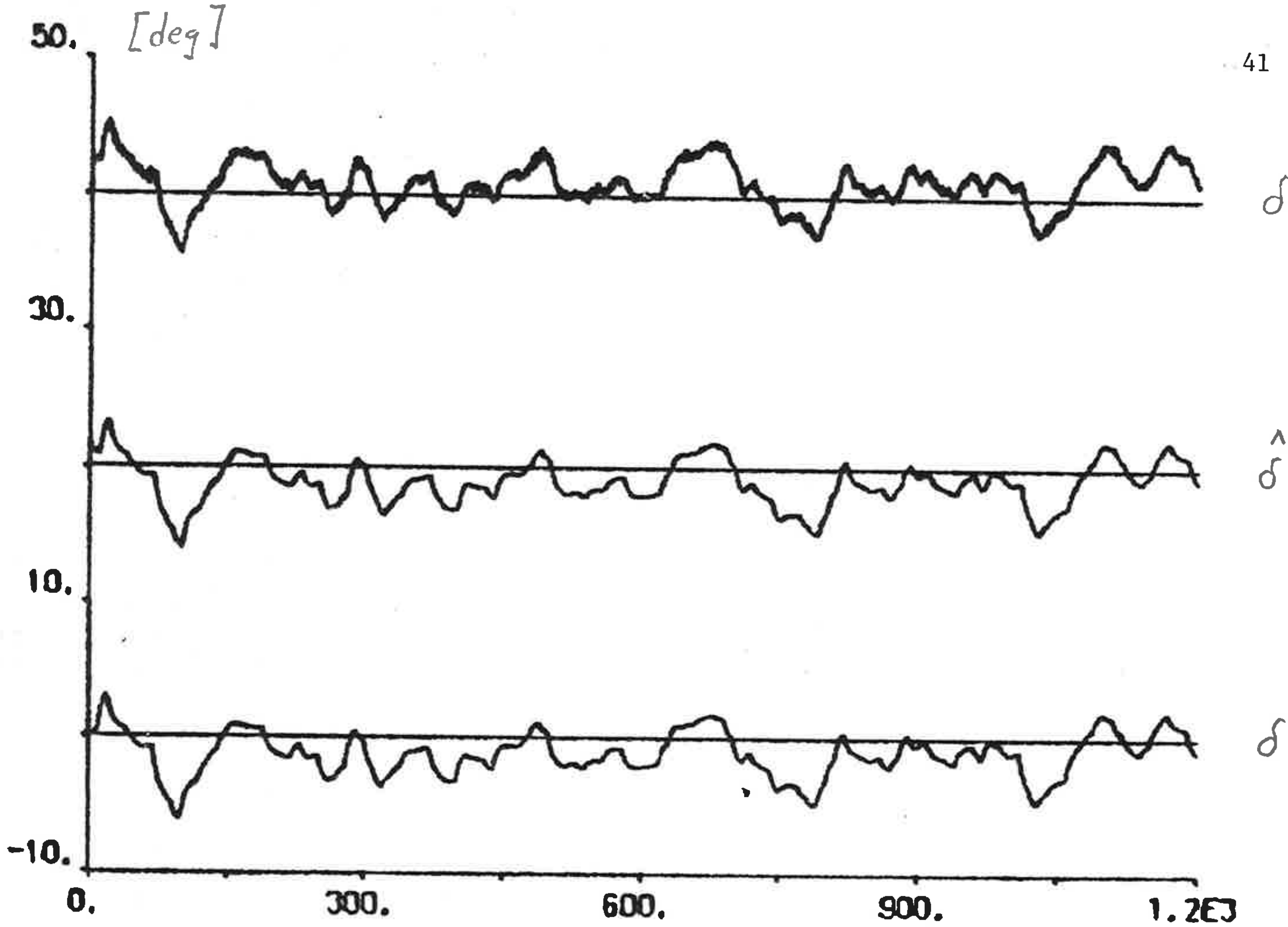

[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 * r_m
100 * $\hat{r}$
100 * r
[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 * r_m
100 * $\hat{r}$
100 * r

Fig. 4.1d

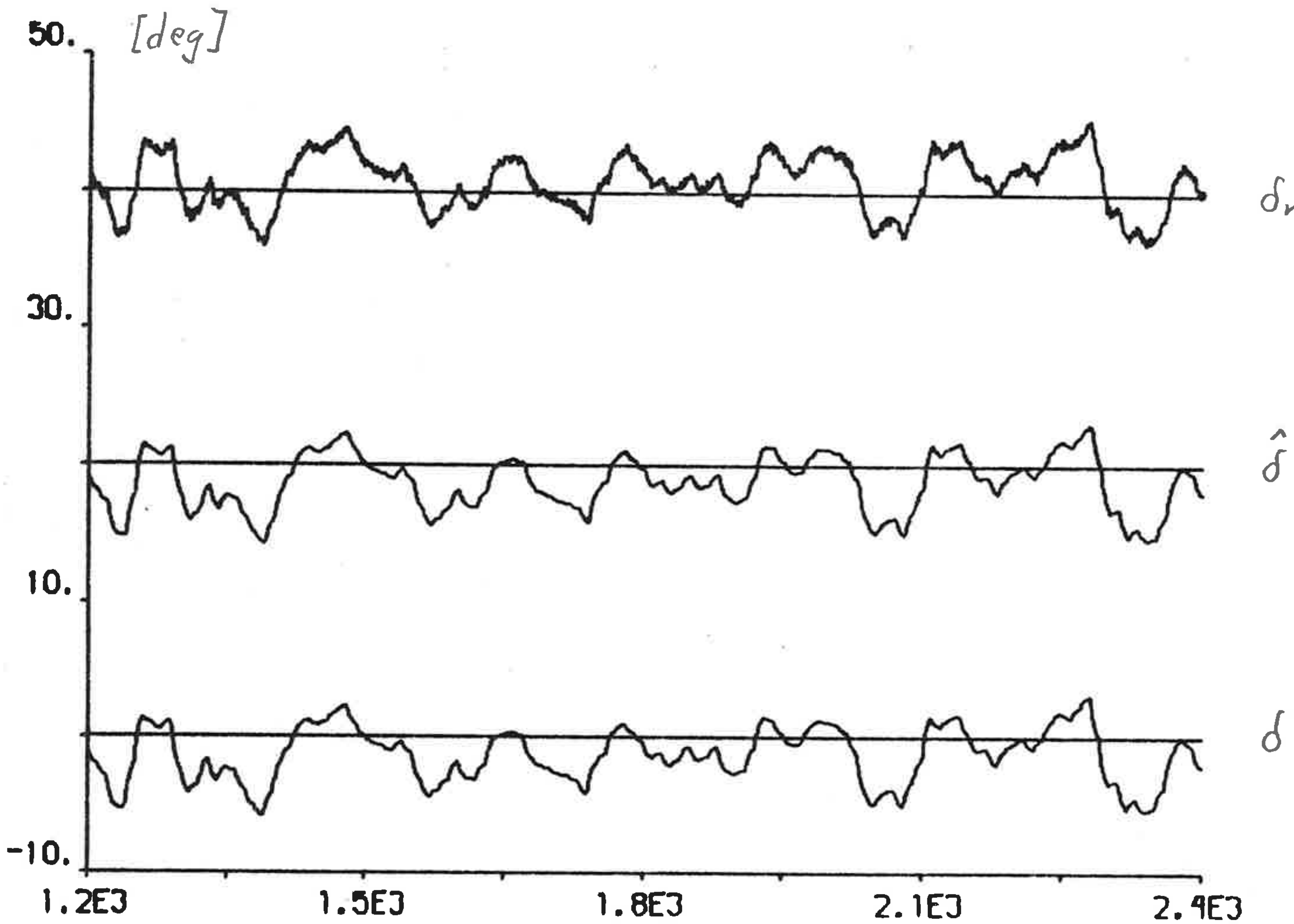


[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5 * ψm
5 * ψ̂
5 * ψ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5 * ψm
5 * ψ̂
5 * ψ

Fig. 4.1e

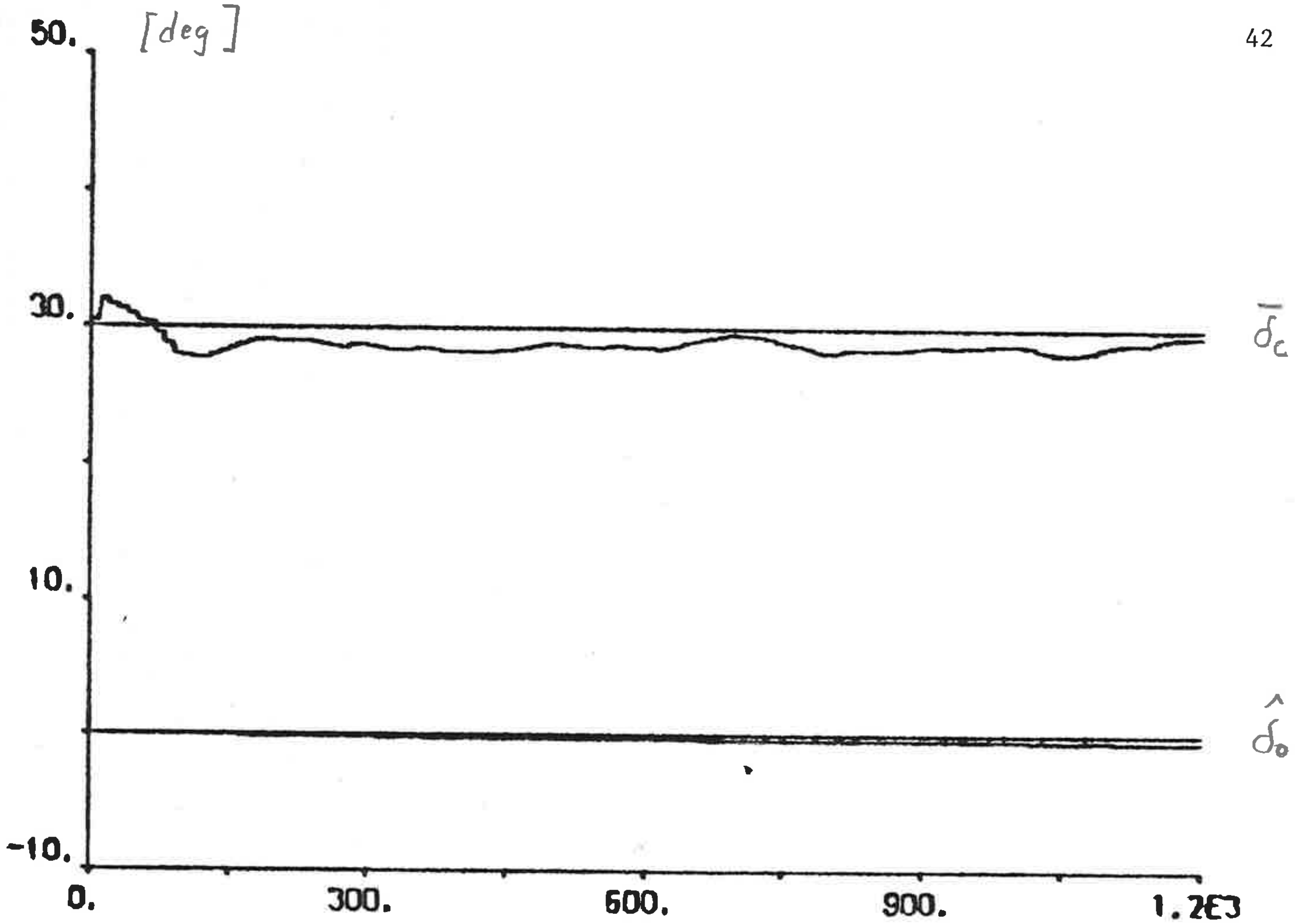


50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
δ
δ̂
δ



50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
δ̂
δ

Fig. 4.1f


50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$\bar{\delta}_c$
$\hat{\delta}_o$

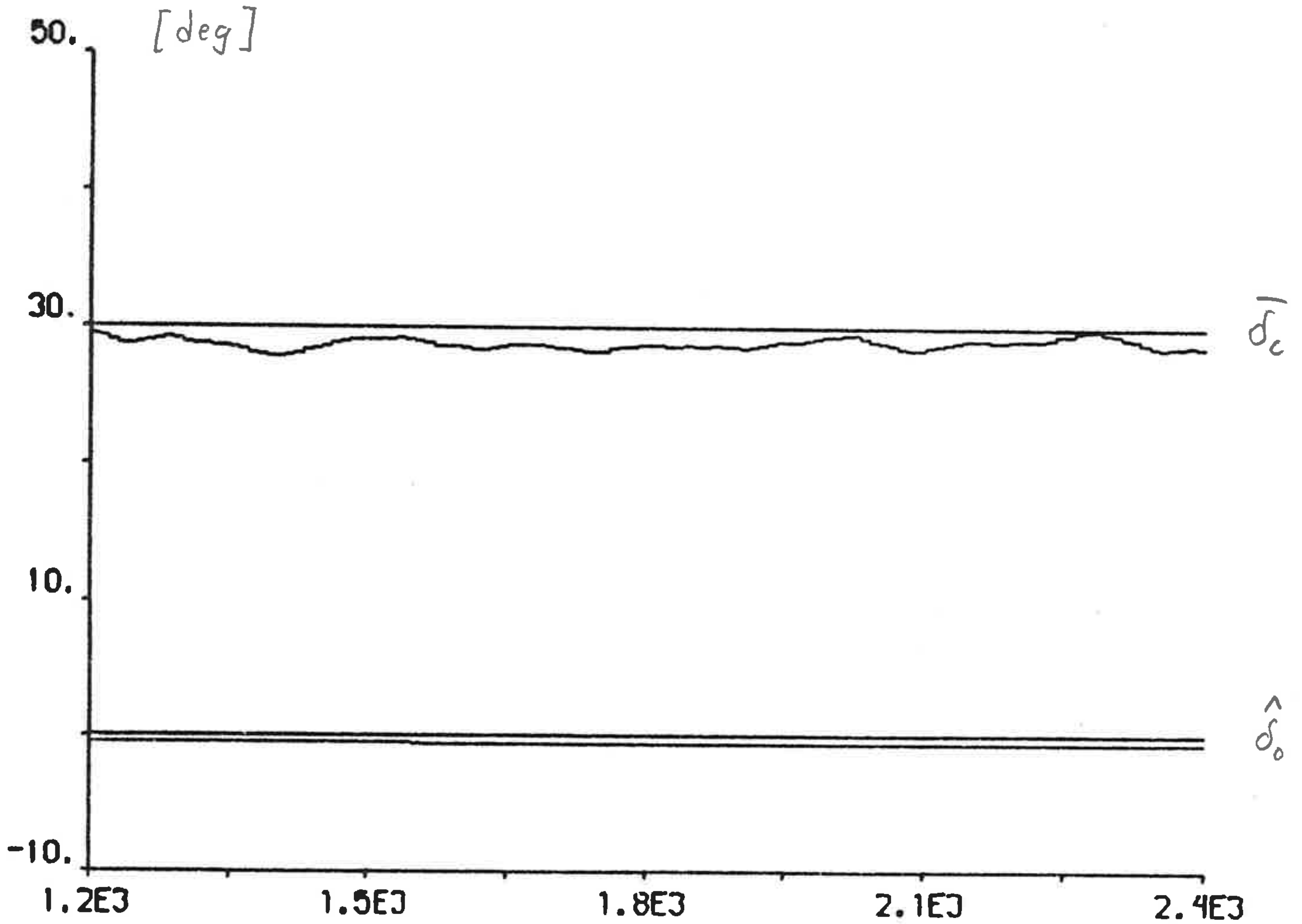
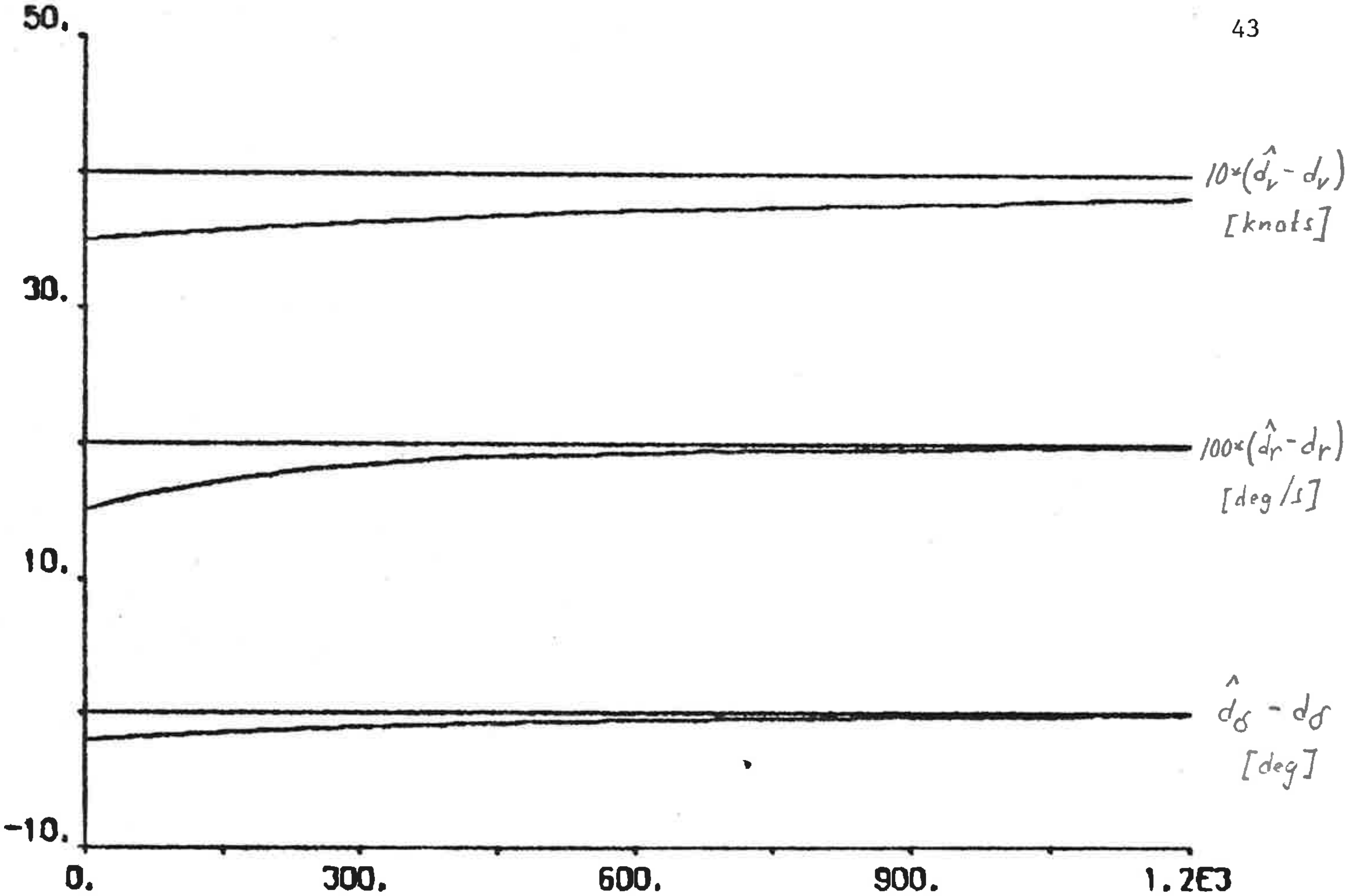

50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
$\bar{\delta}_c$
$\hat{\delta}_o$

Fig. 4.1g


50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10*(d̂v - dv)
[knots]
100*(d̂r - dr)
[deg/s]
d̂δ - dδ
[deg]

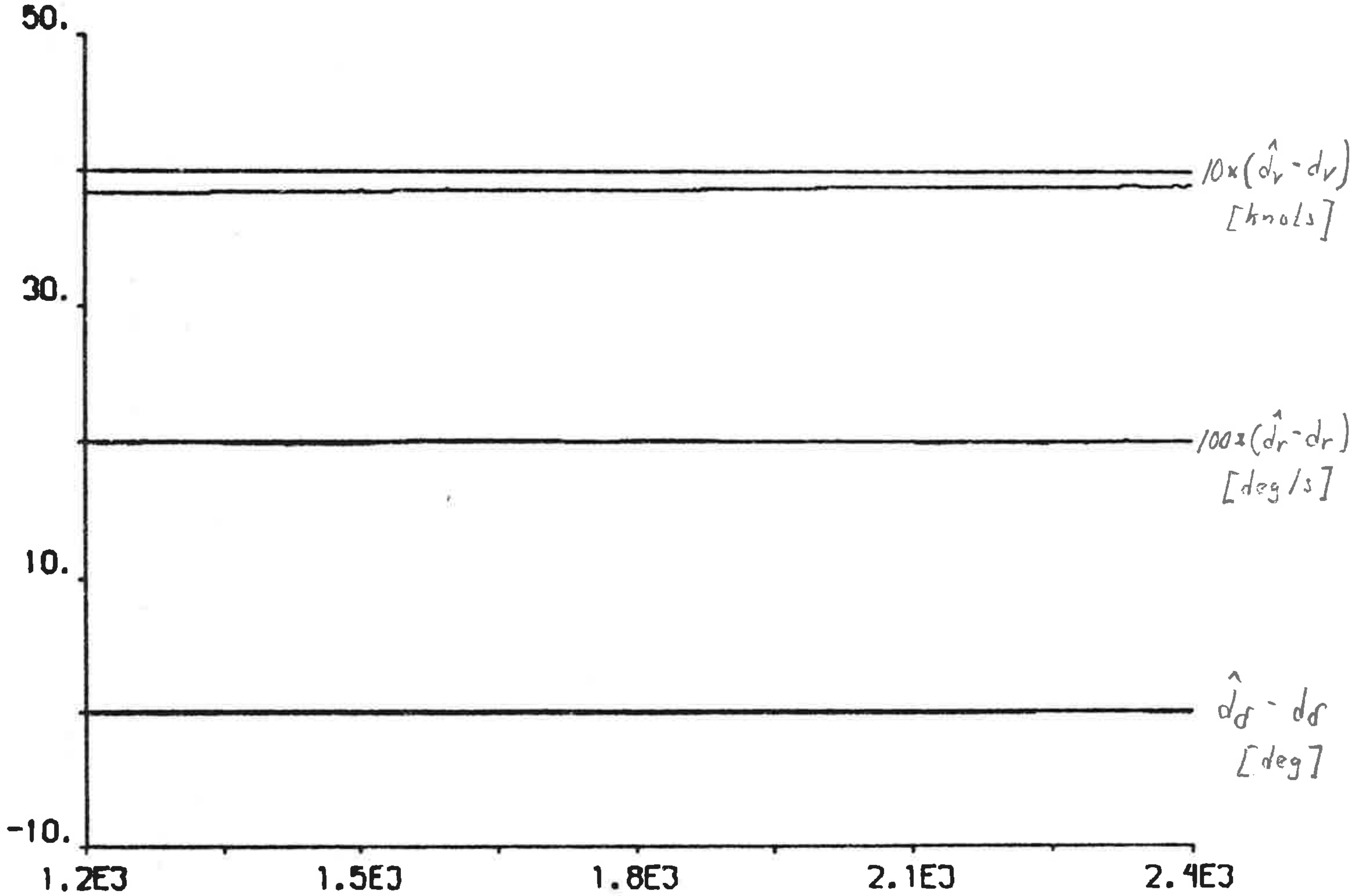
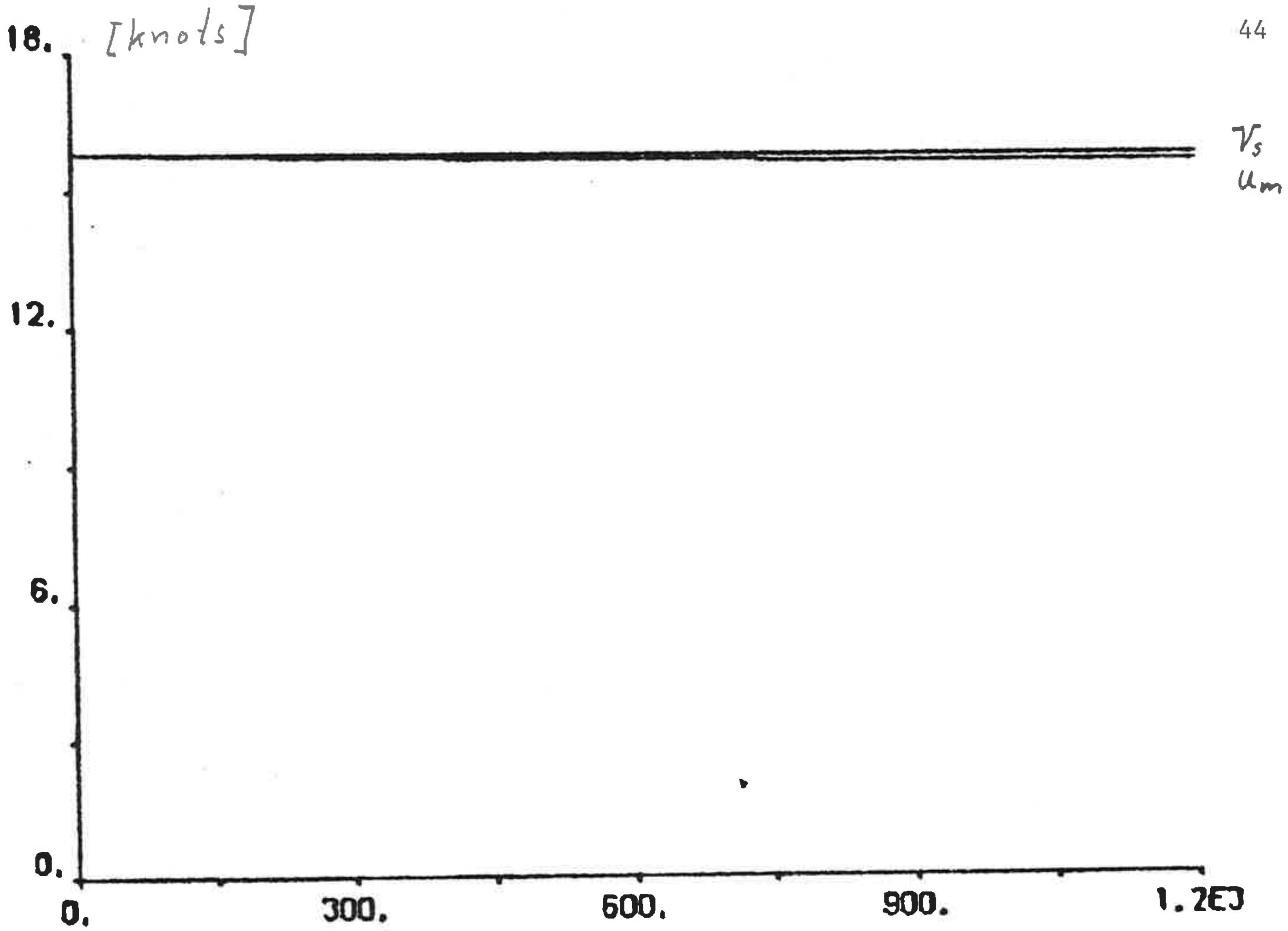

50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10x(d̂v - dv)
[knots]
100x(d̂r - dr)
[deg/s]
d̂δ - dδ
[deg]

Fig. 4.1h


18.
[knots]
Vs
um
12.
6.
0.
0.
300.
600.
900.
1.2E3

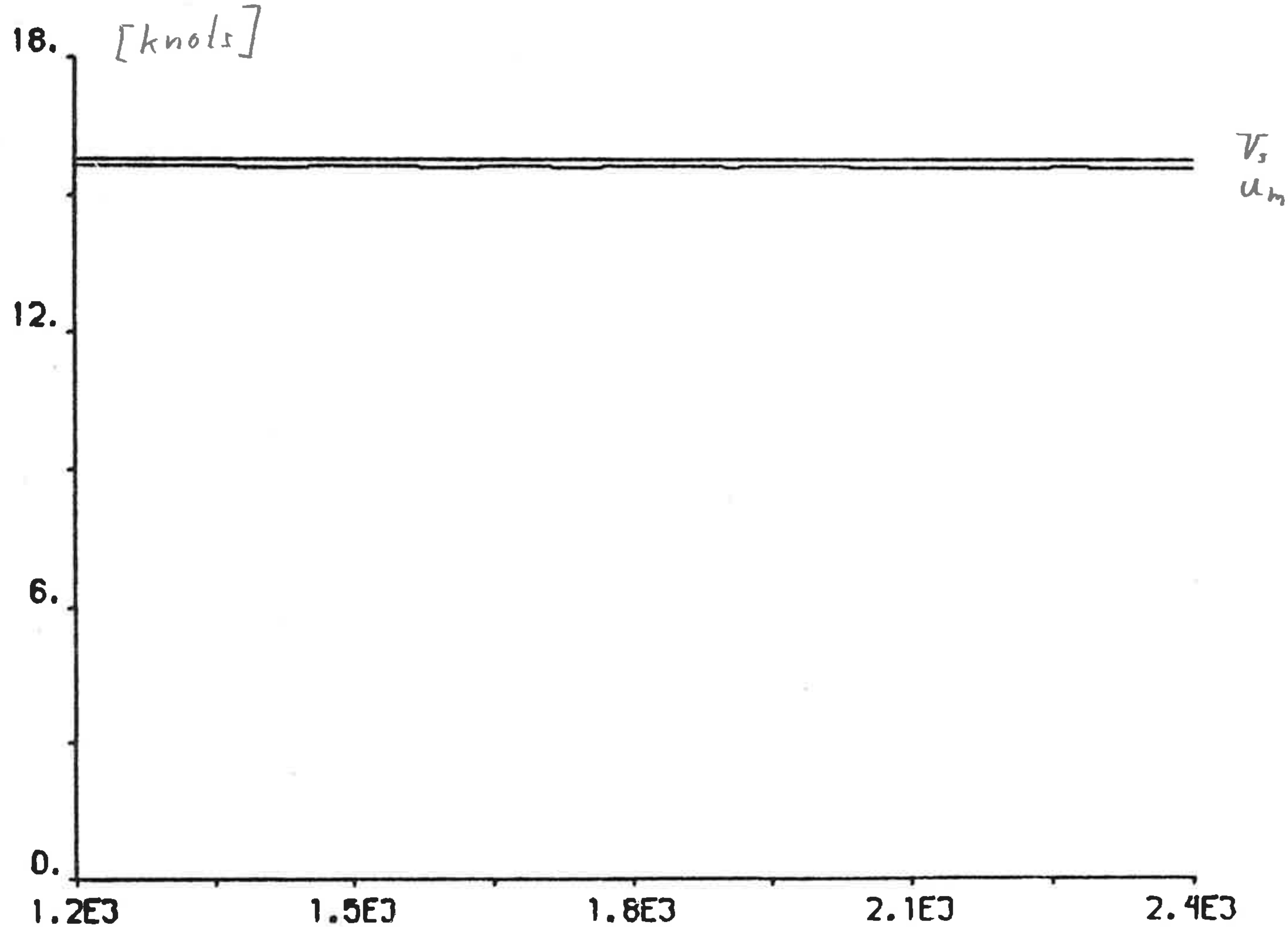
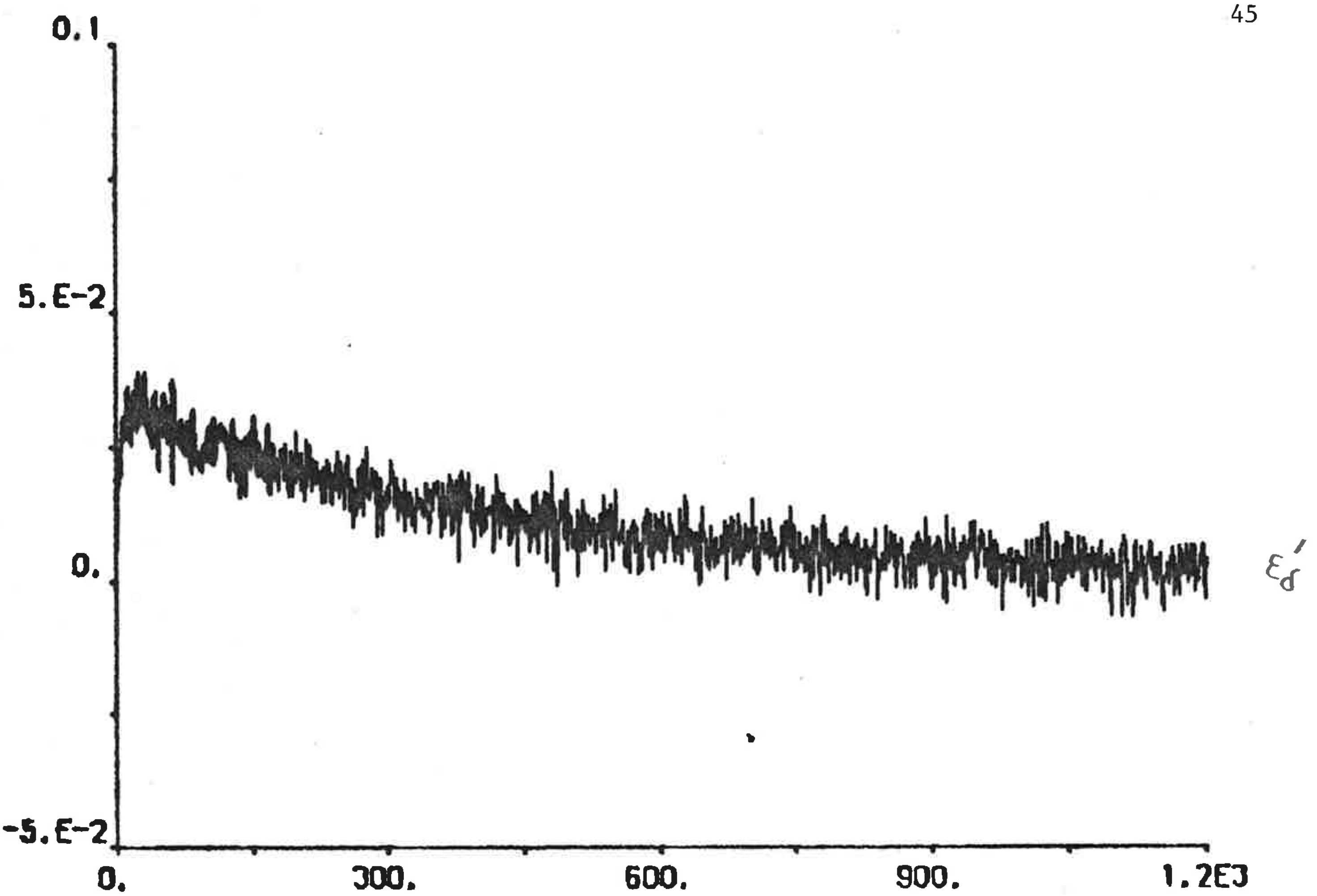

18.
[knots]
Vs
um
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.1i


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_{ρ}'

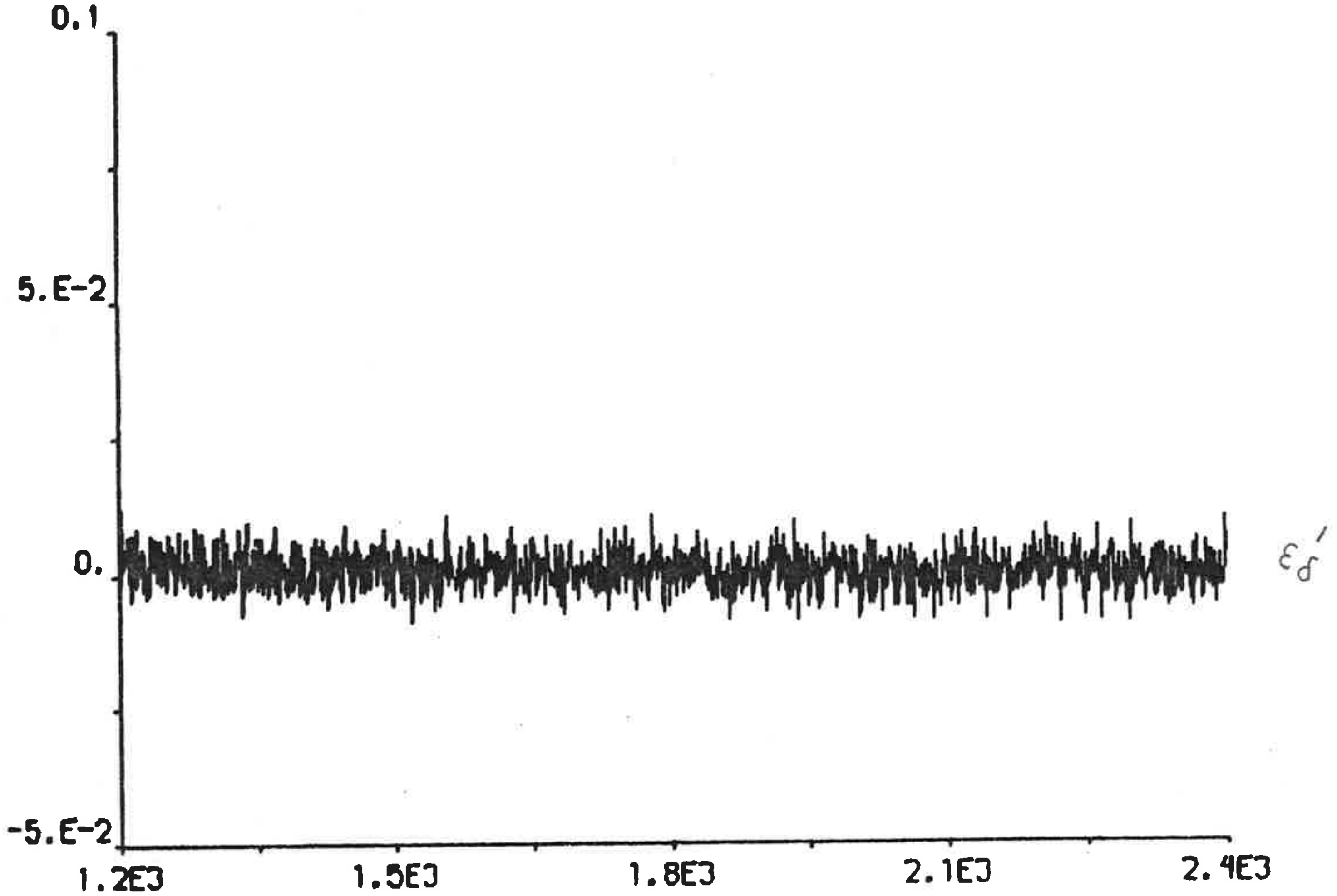

0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_{ρ}'

Fig. 4.1j

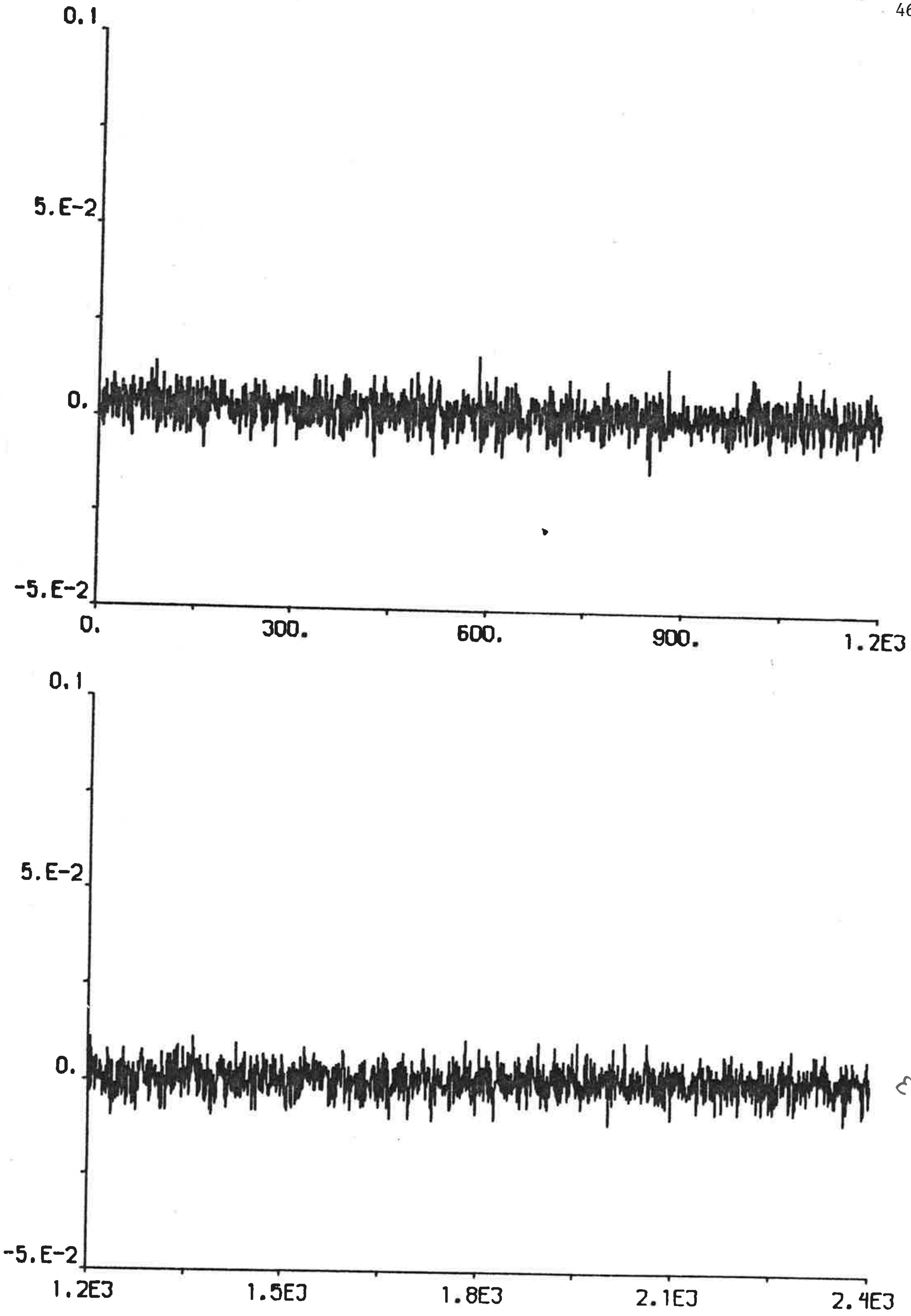
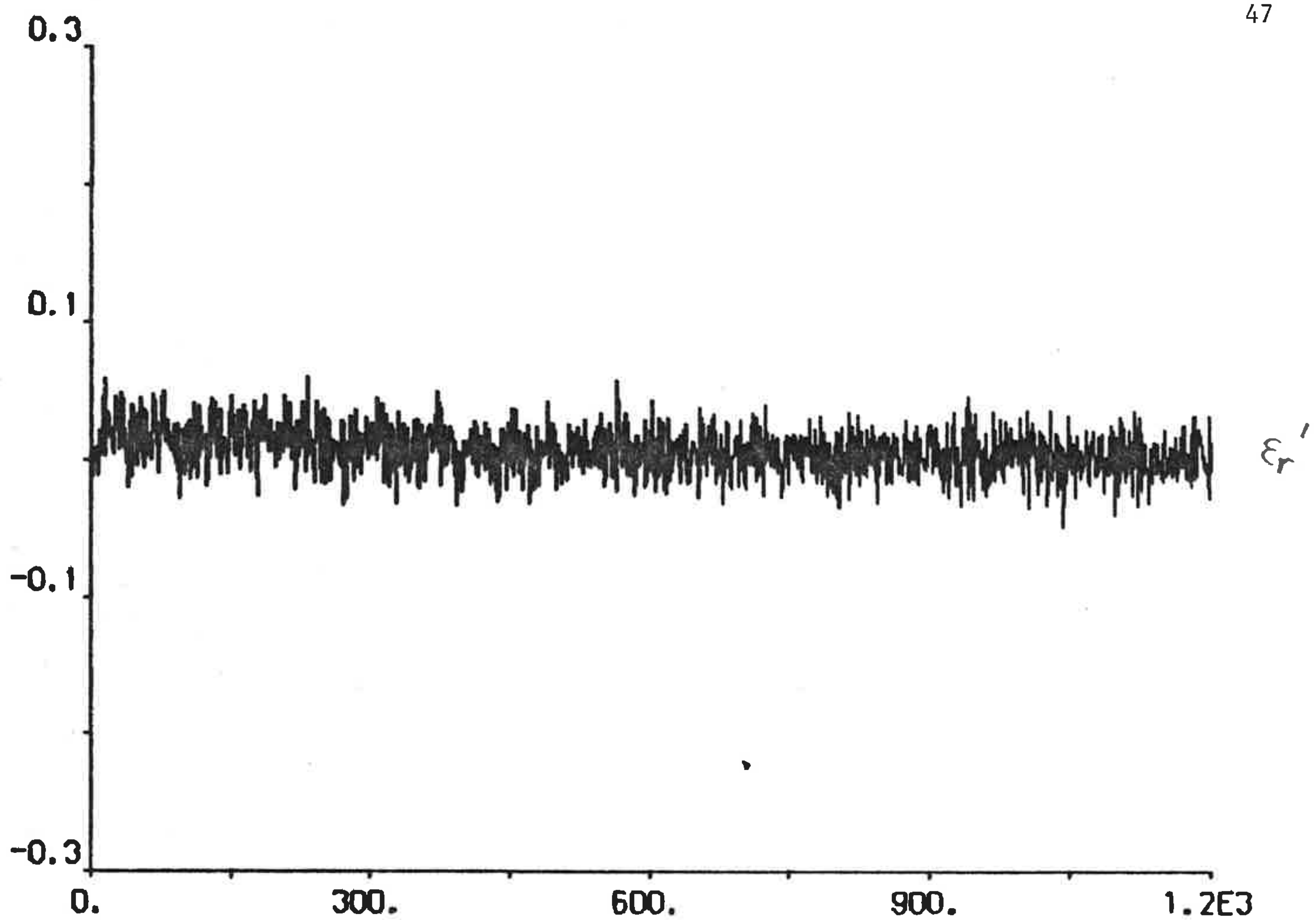

0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.1k


0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
ε_r'

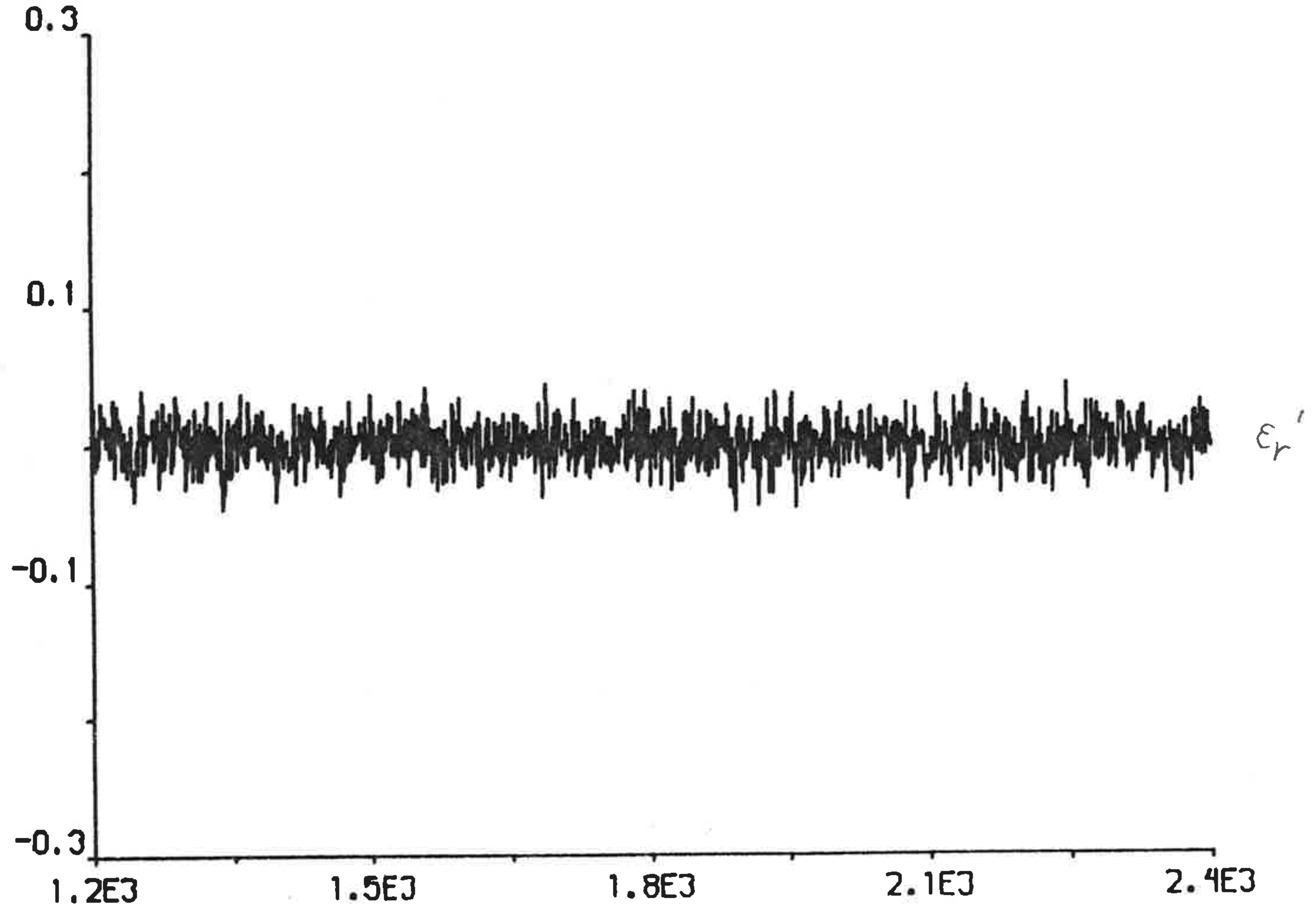

0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_r'

Fig. 4.1ℓ

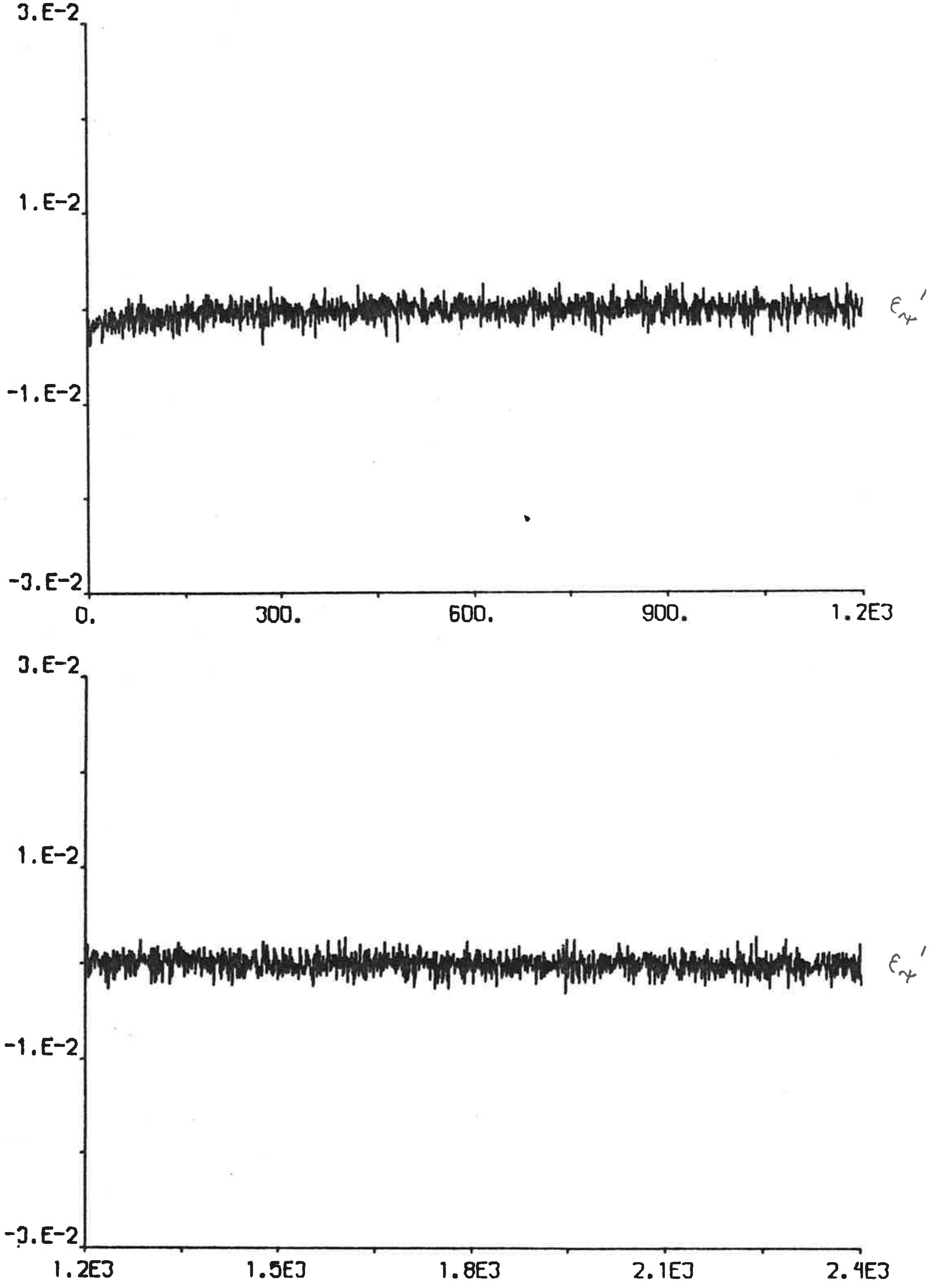

3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.1m

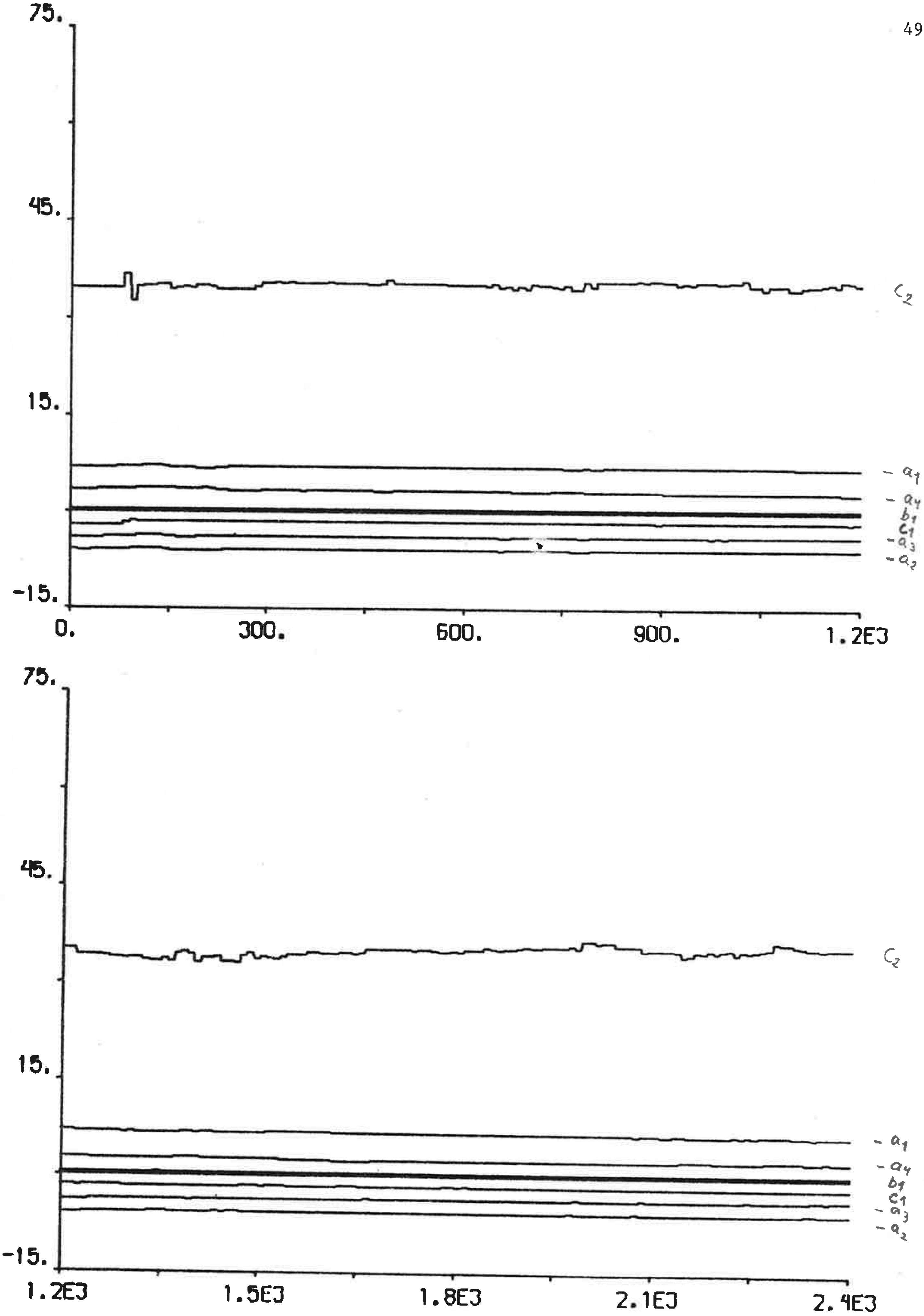
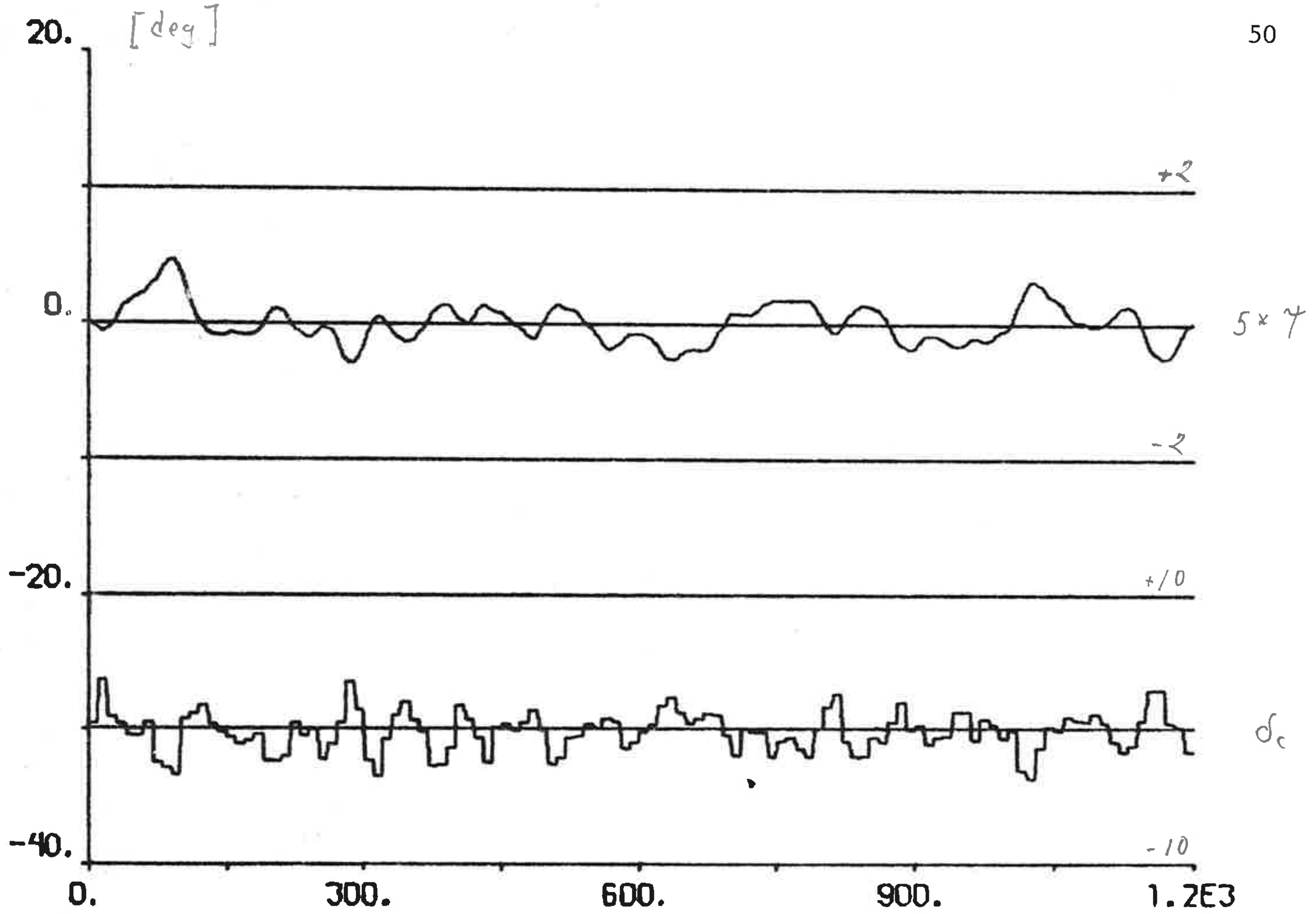

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
a_1
a_4
b_1
c_1
a_3
a_2
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
a_1
a_4
b_1
c_1
a_3
a_2

Fig. 4.1n



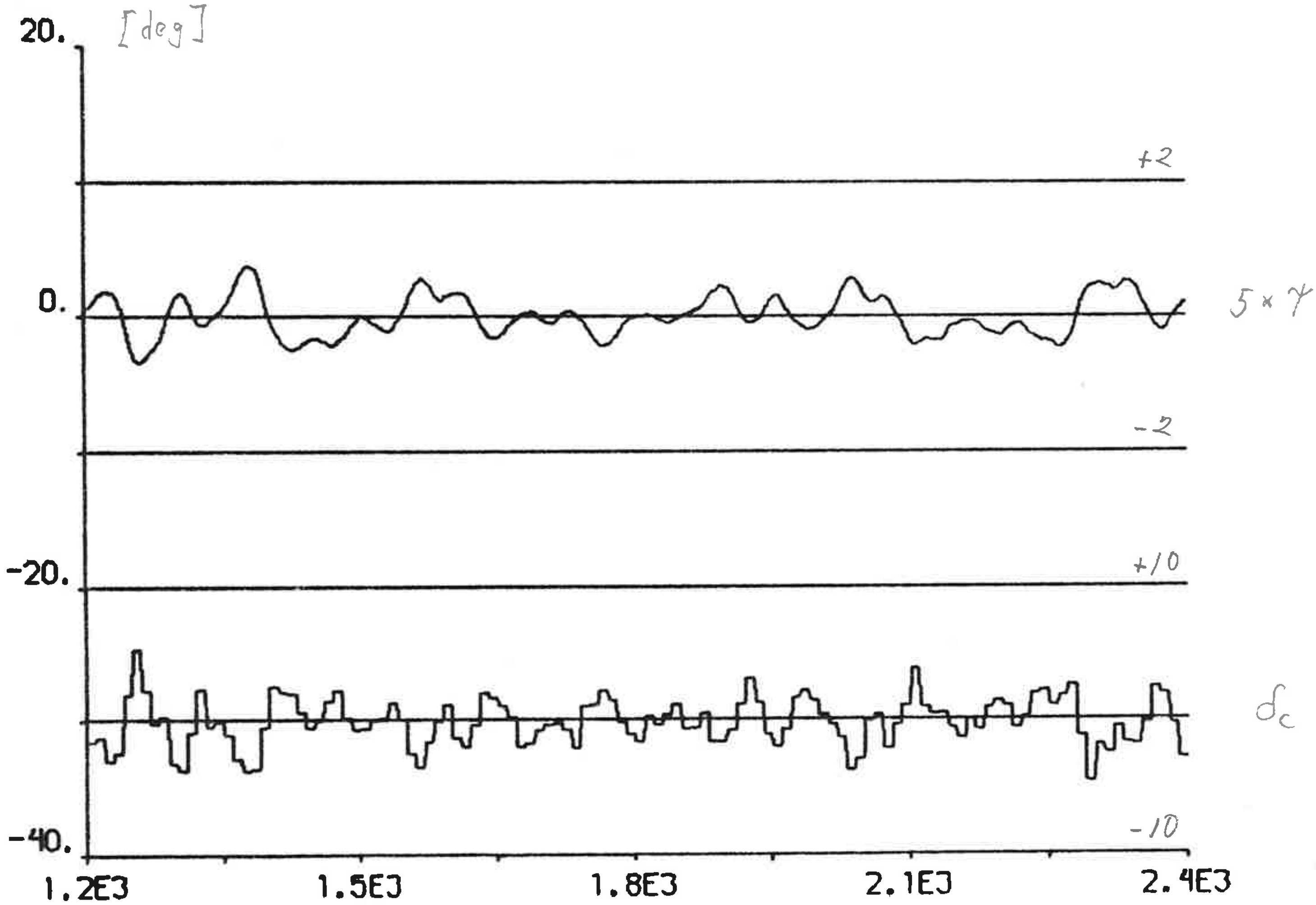
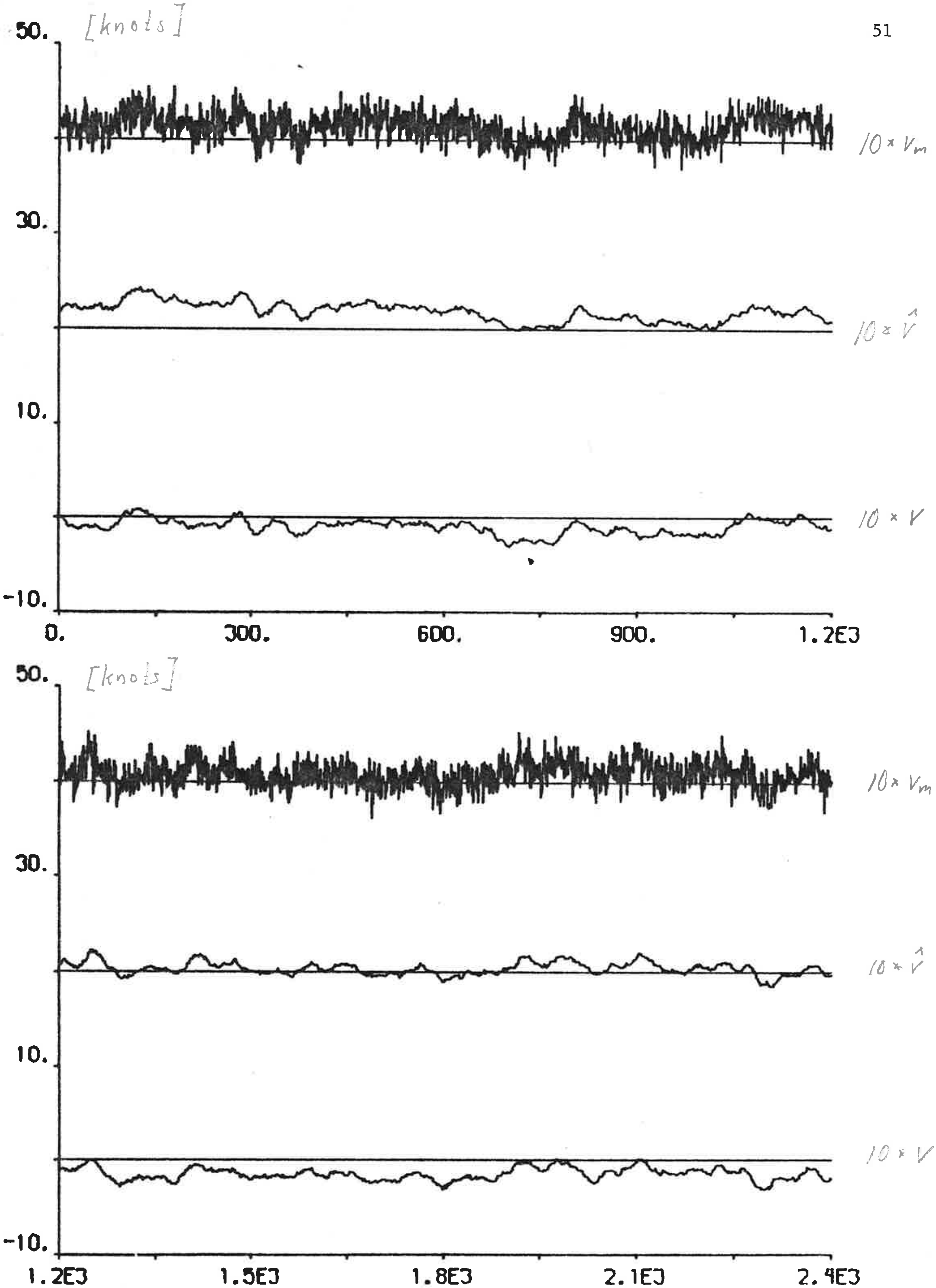


Fig. 4.2a - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using estimates from the Kalman filter.



50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × Vm
10 × V̂
10 × V
50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × Vm
10 × V̂
10 × V

Fig. 4.2b

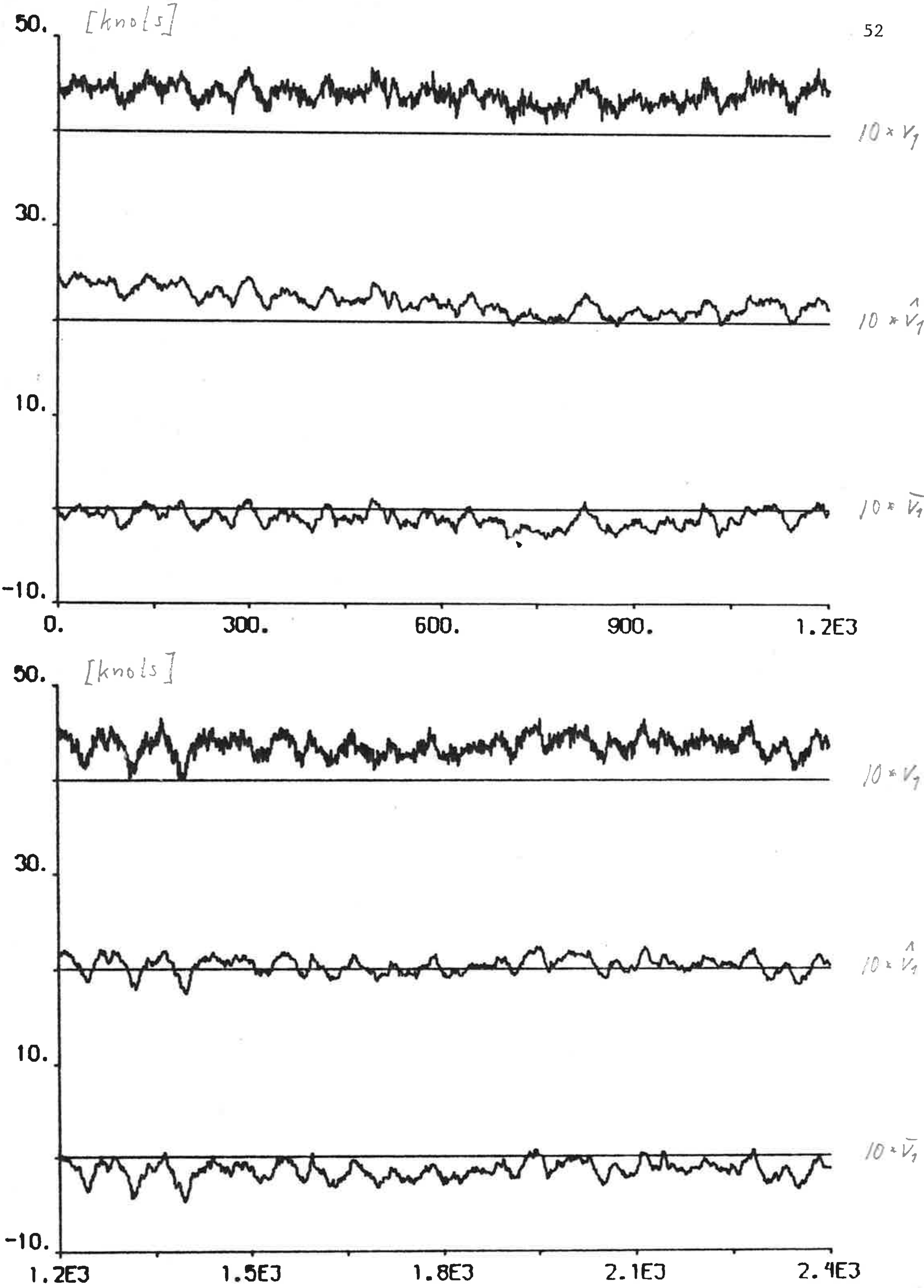

50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × V1
10 × V̂1
10 × V̄1

Fig. 4.2c

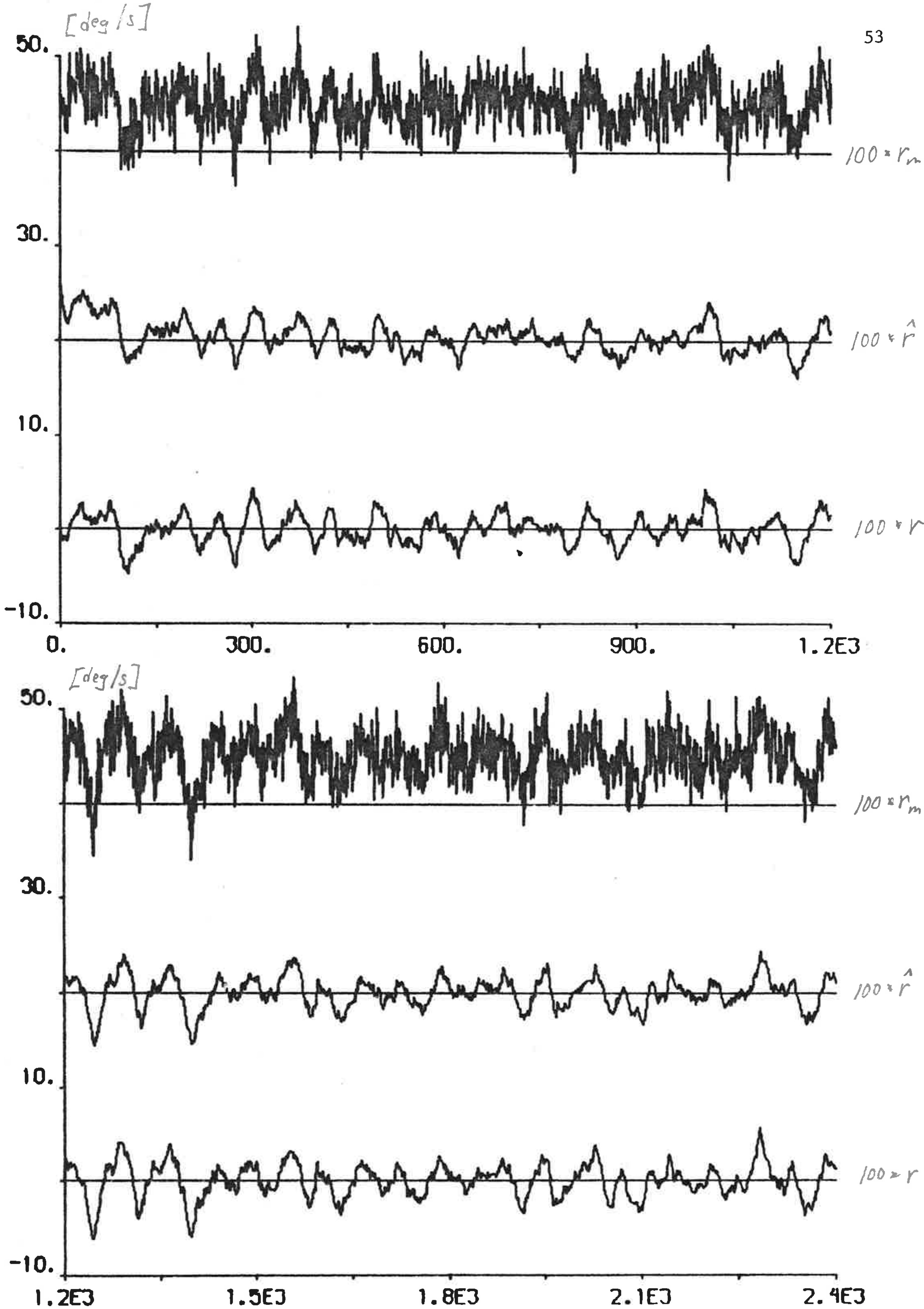

[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 * r_m
100 * $\hat{r}$
100 * r
[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 * r_m
100 * $\hat{r}$
100 * r

Fig. 4.2d

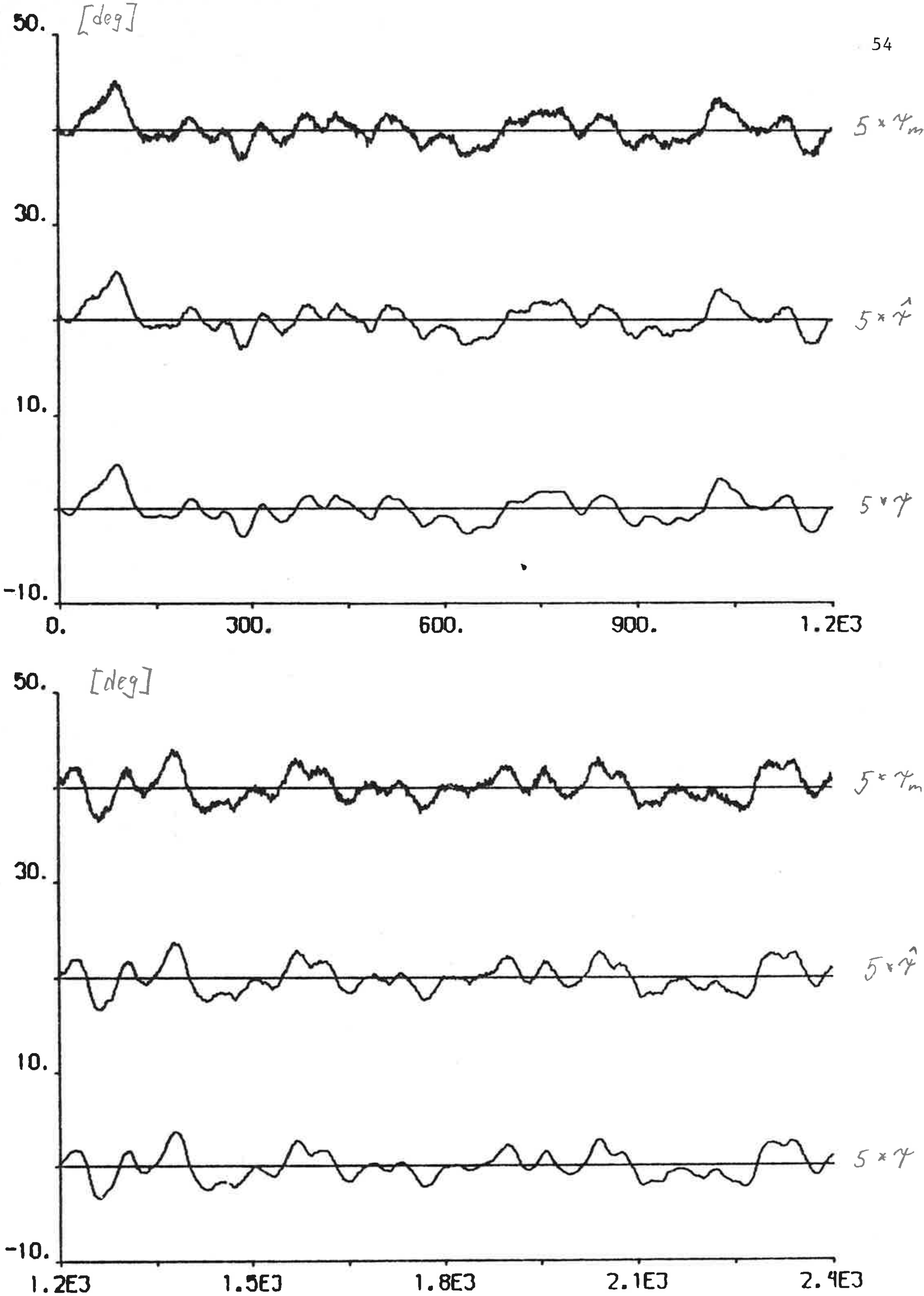

50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5 * ψm
5 * ψ̂
5 * ψ
50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5 * ψm
5 * ψ̂
5 * ψ

Fig. 4.2e

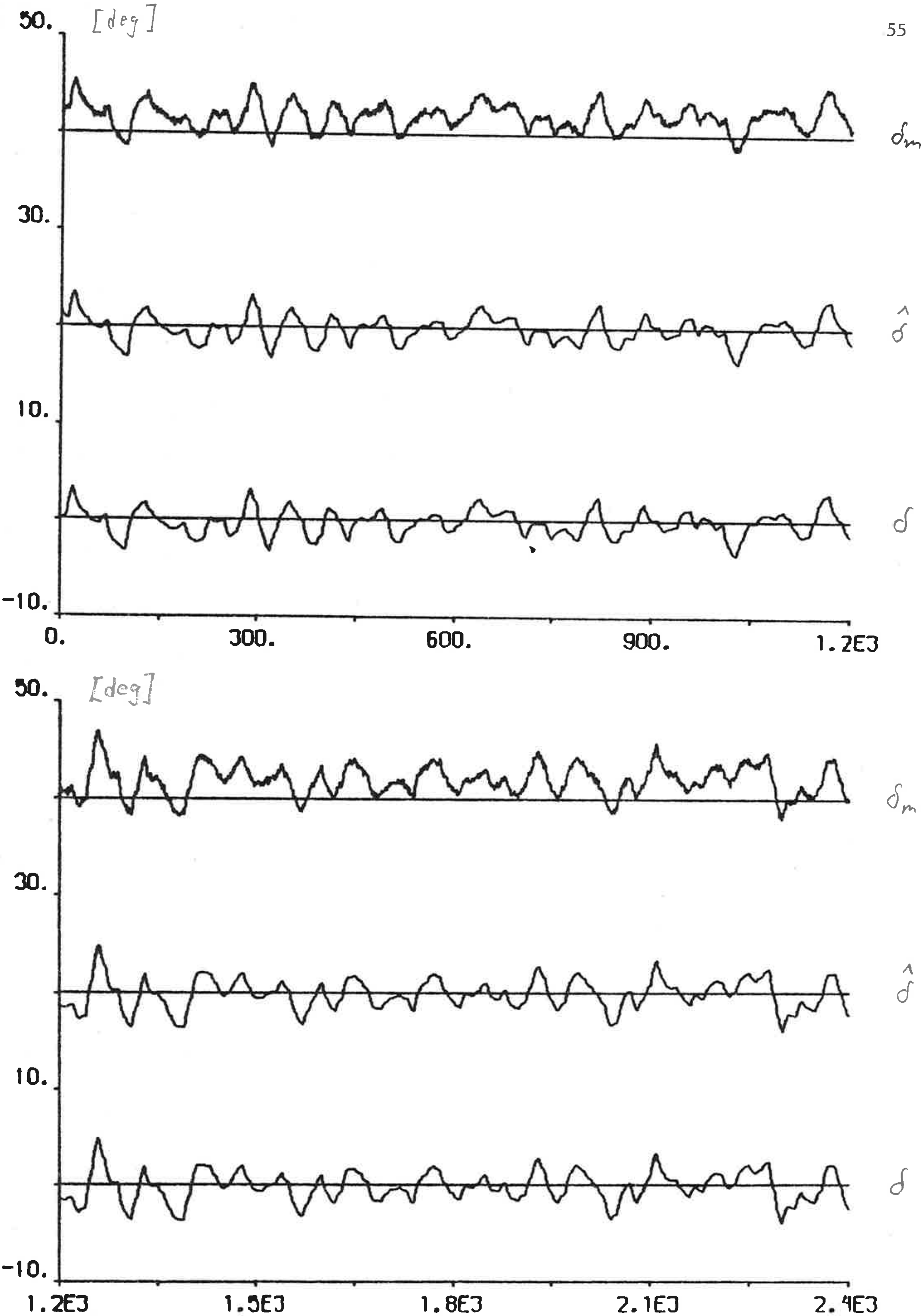
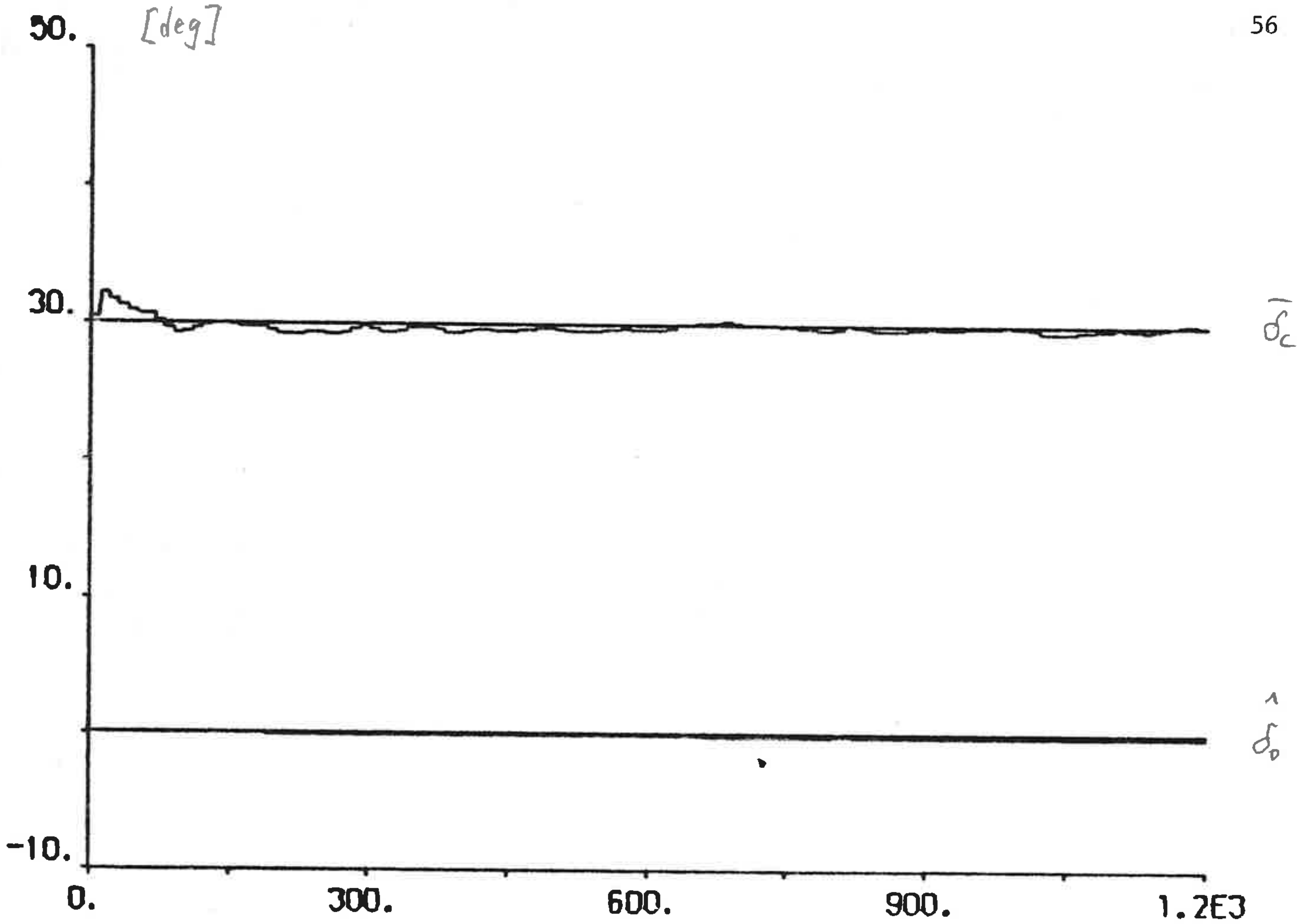

50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
δ_m
$\hat{\delta}$
δ
50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
δ_m
$\hat{\delta}$
δ

Fig. 4.2f


50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$\bar{\delta}_c$
$\hat{\delta}_0$

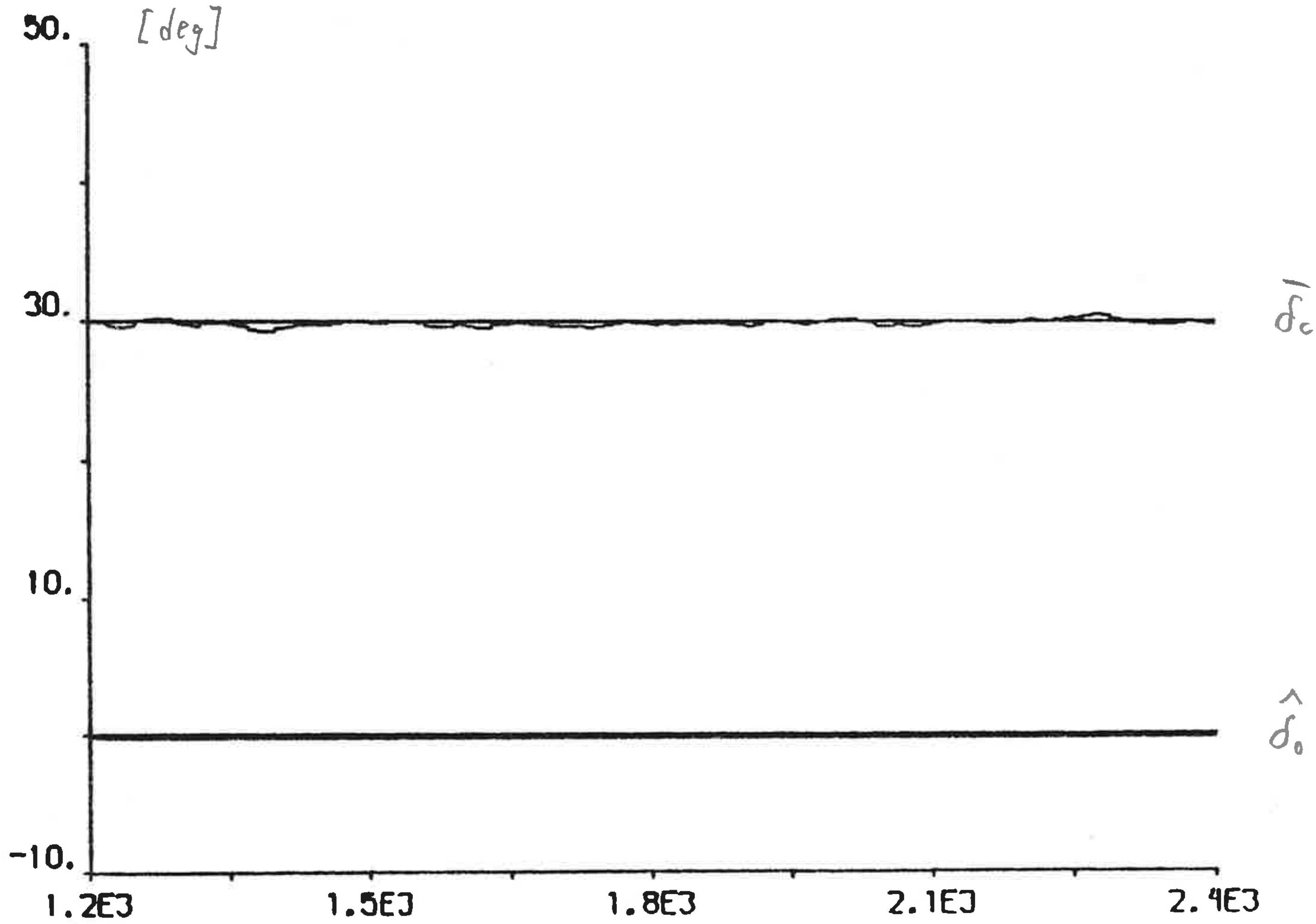
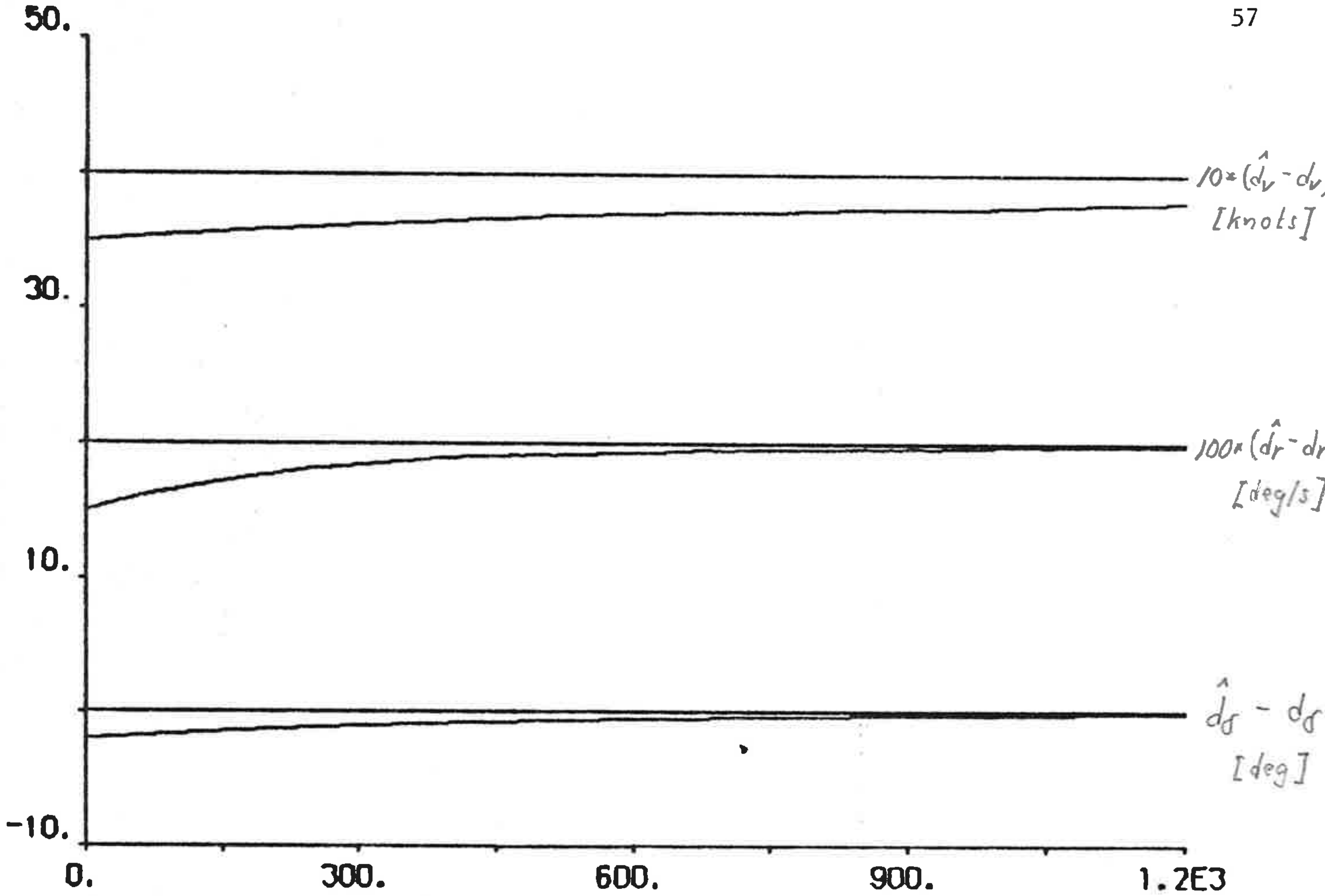

50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
$\bar{\delta}_c$
$\hat{\delta}_0$

Fig. 4.2g


50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[knots]
[deg/s]
[deg]

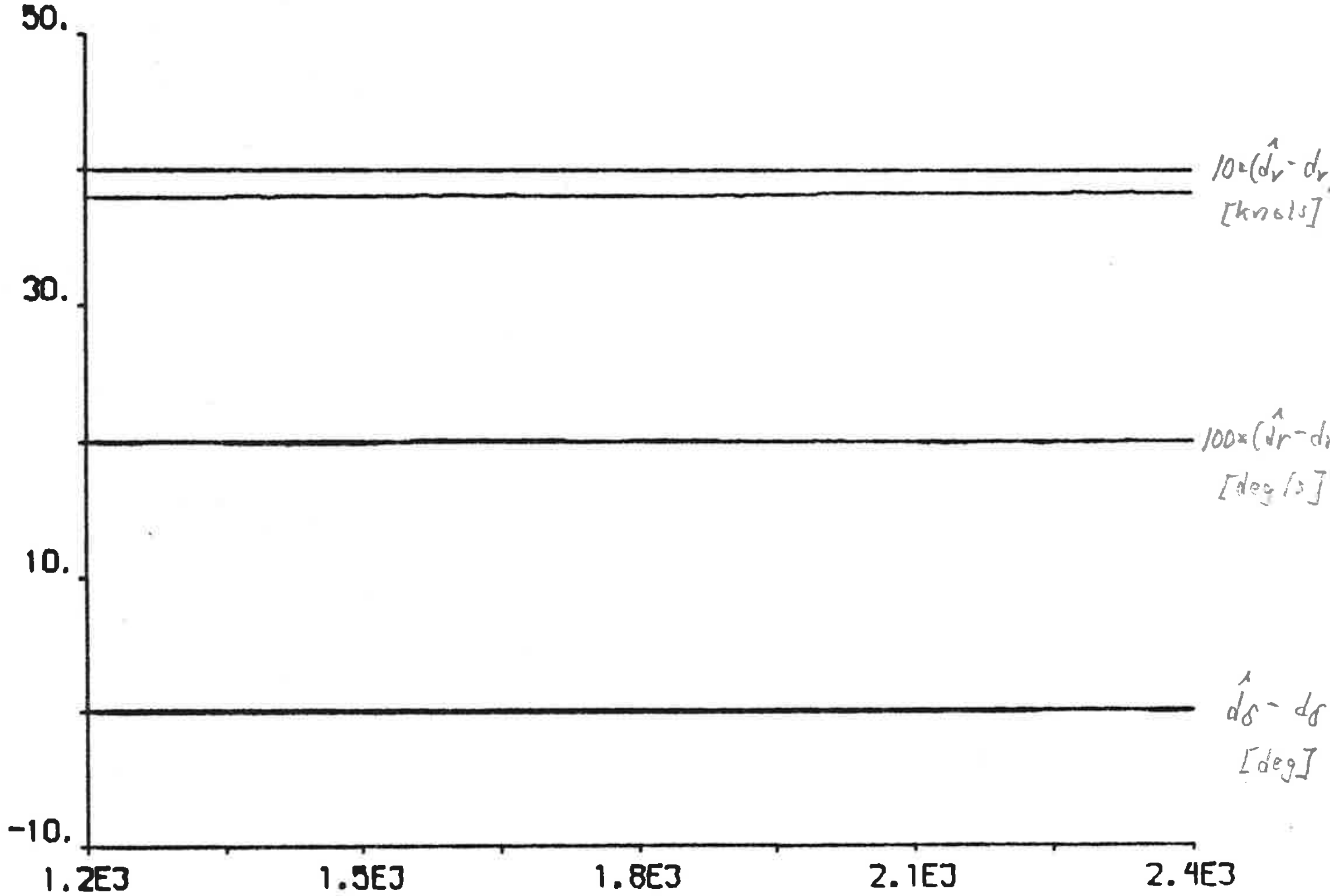
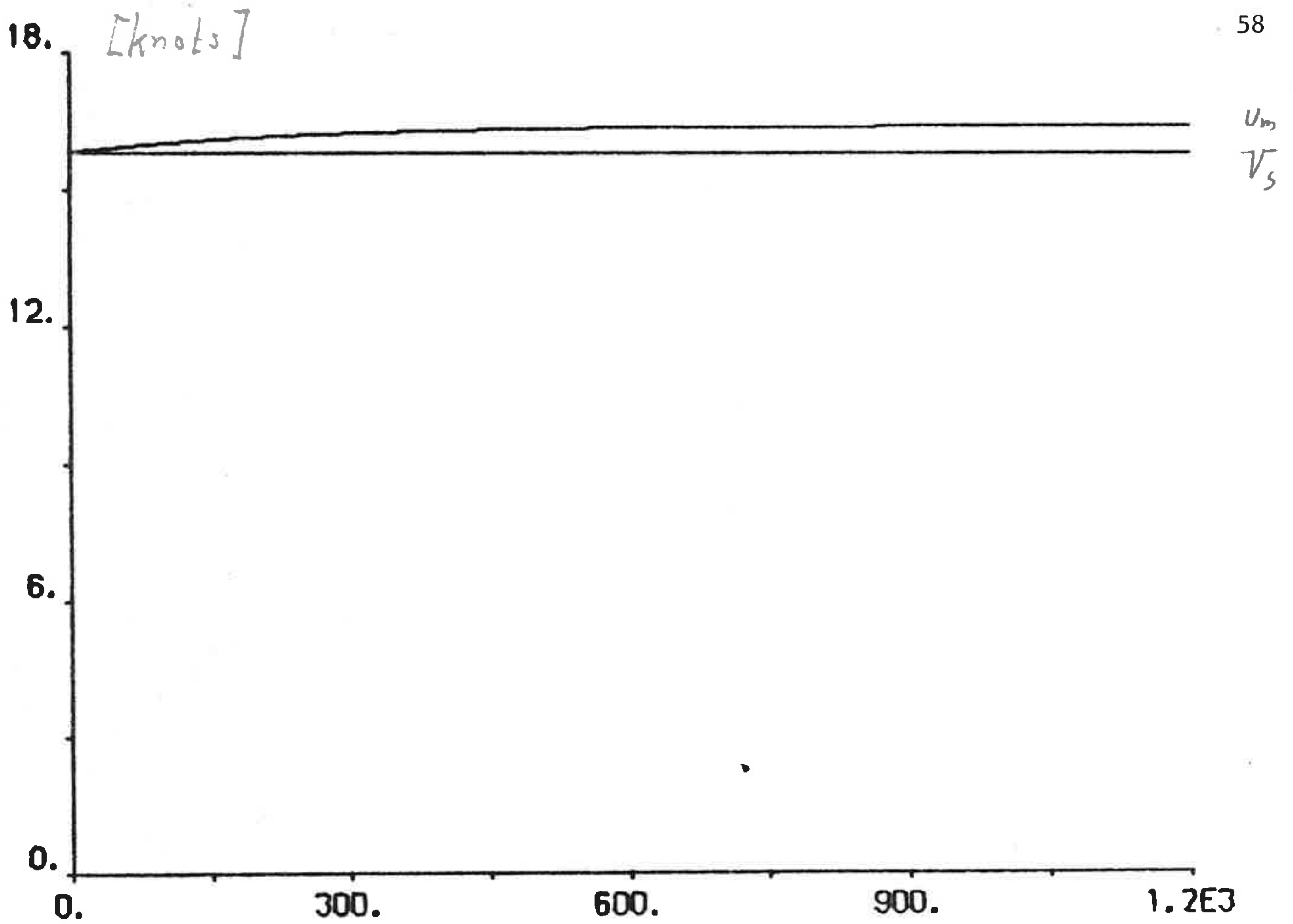

50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
[knots]
[deg/s]
[deg]

Fig. 4.2h


18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
u_m
V_s

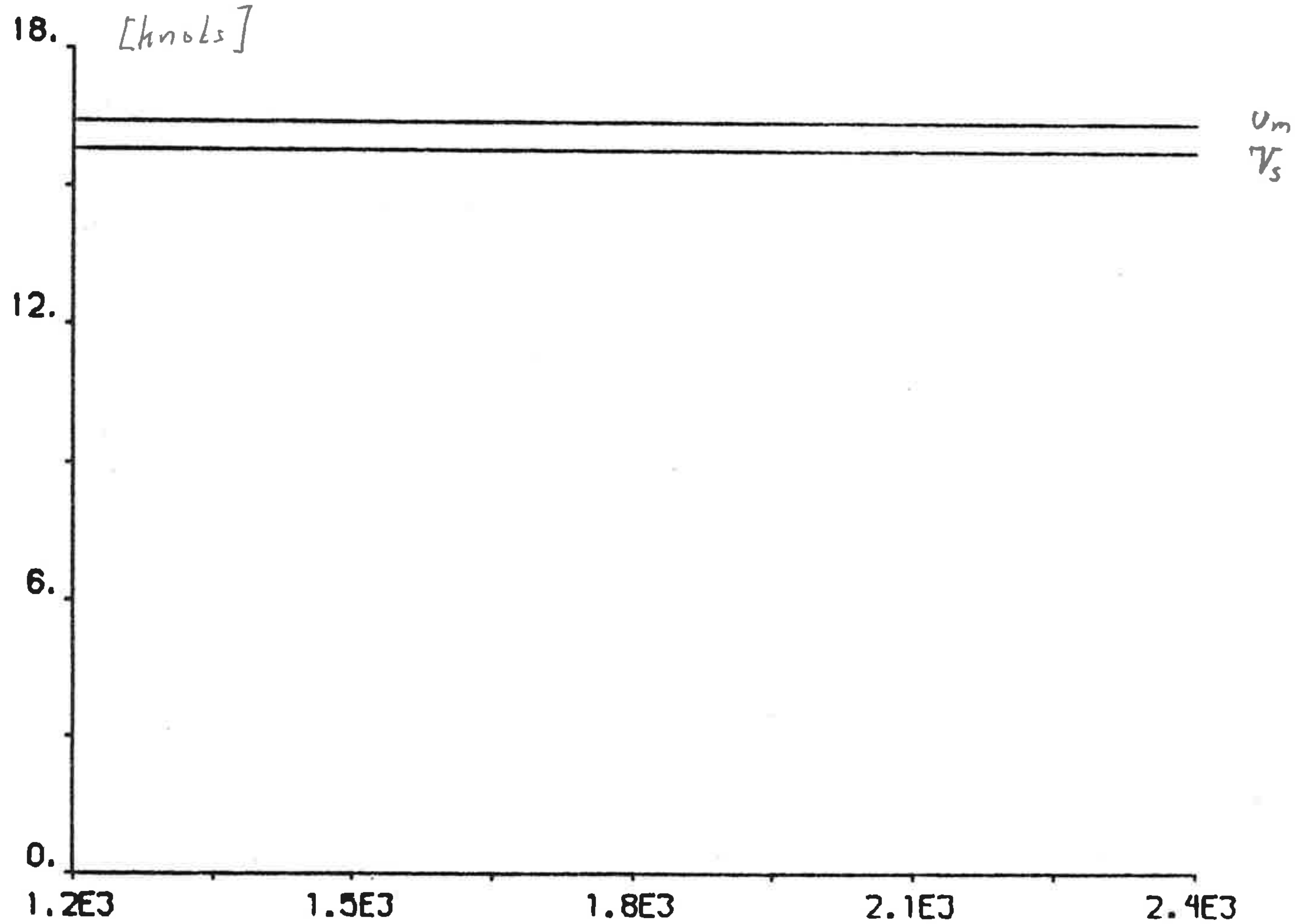
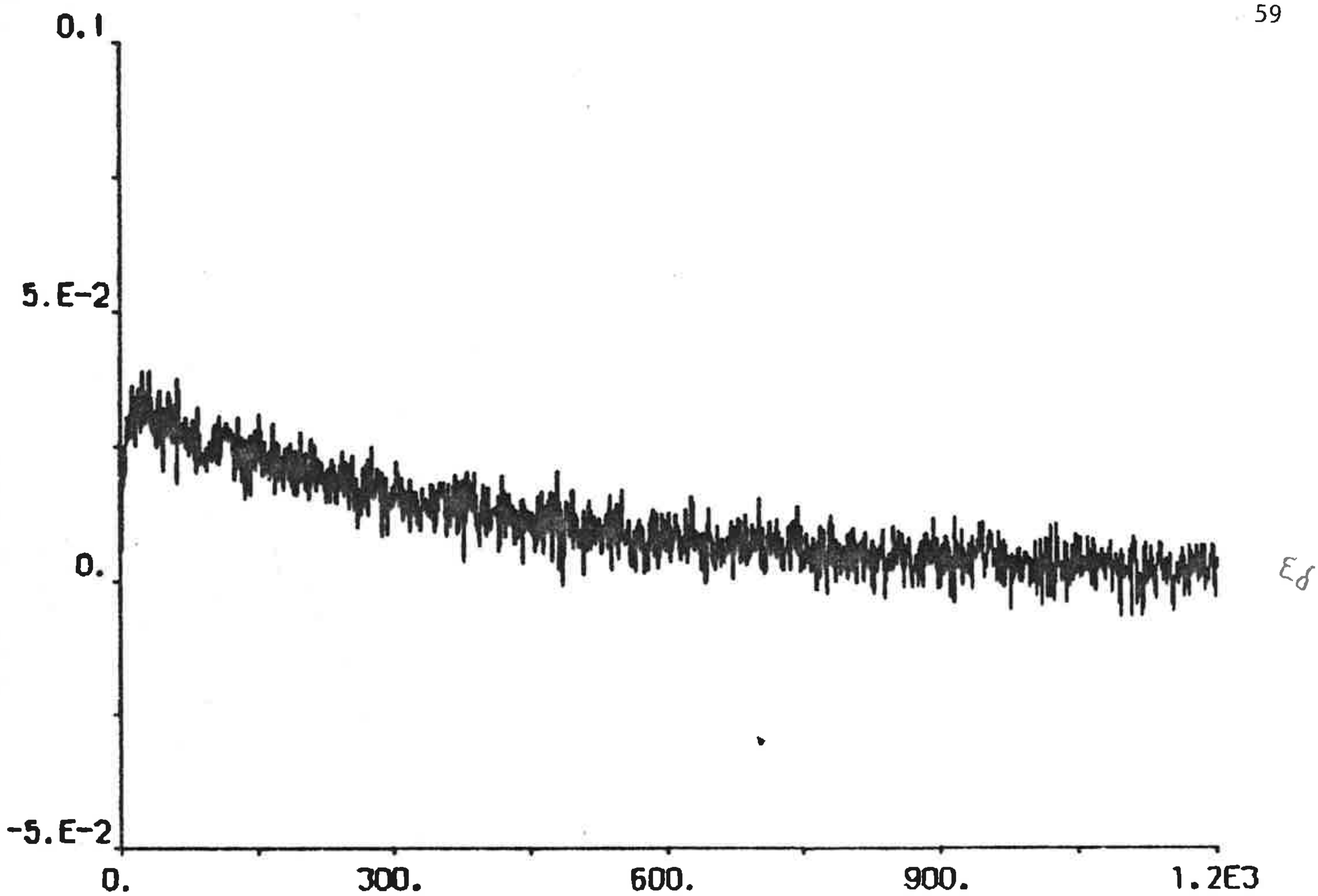

18.
[knots]
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
u_m
V_s

Fig. 4.2i


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_δ'

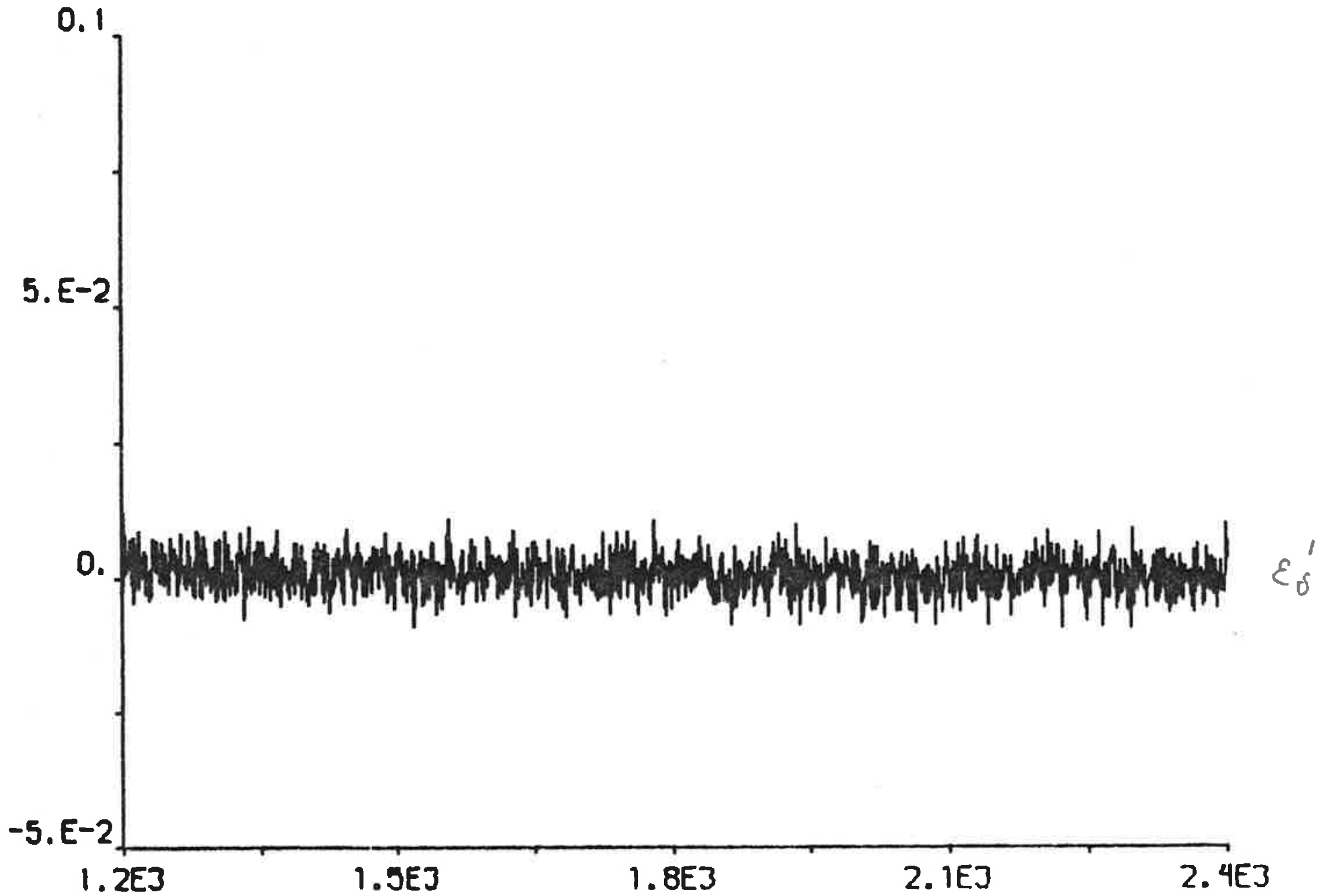

0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_δ'

Fig. 4.2j

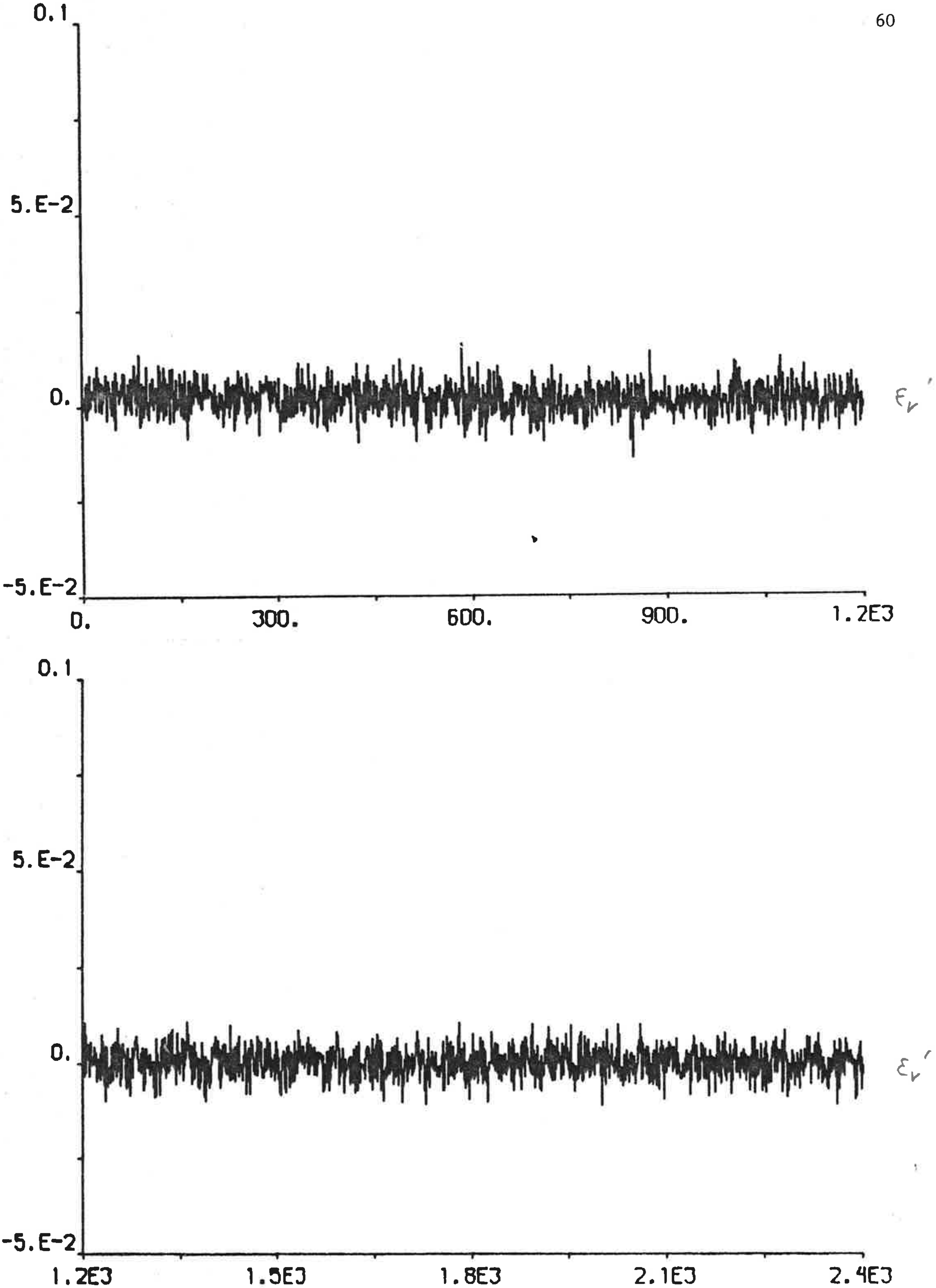
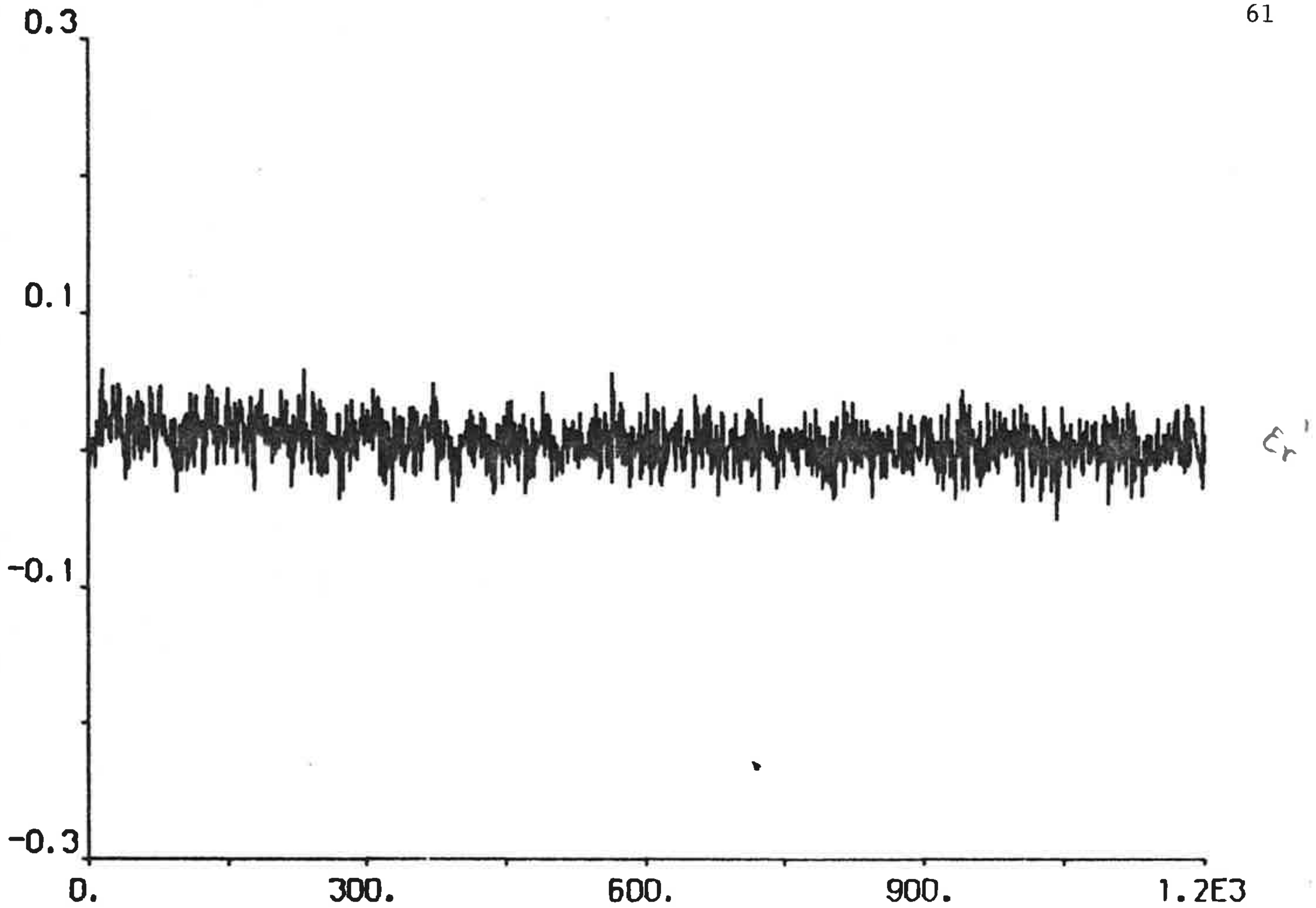

0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_v'
0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_v'

Fig. 4.2k


0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
ε_r'

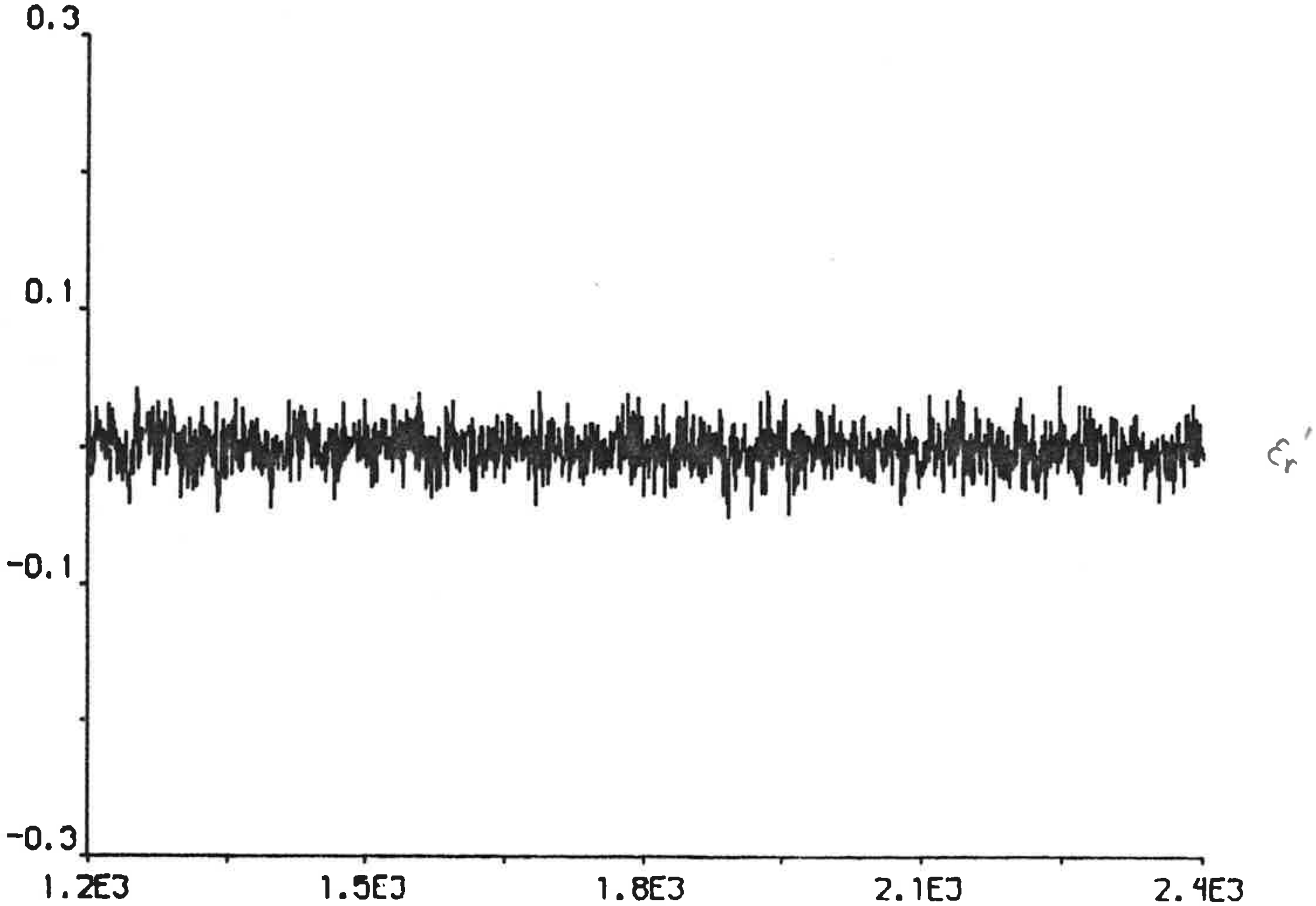
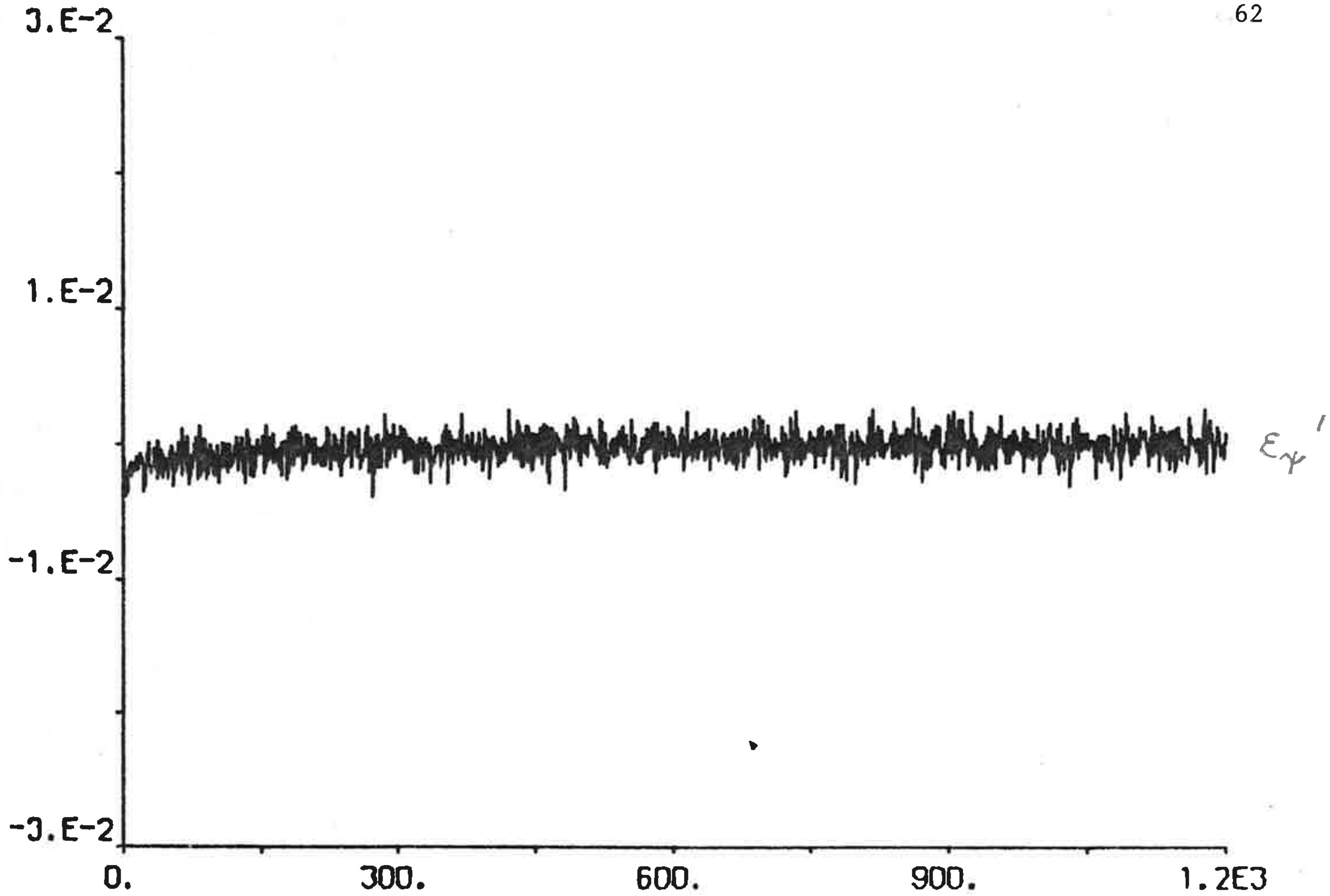
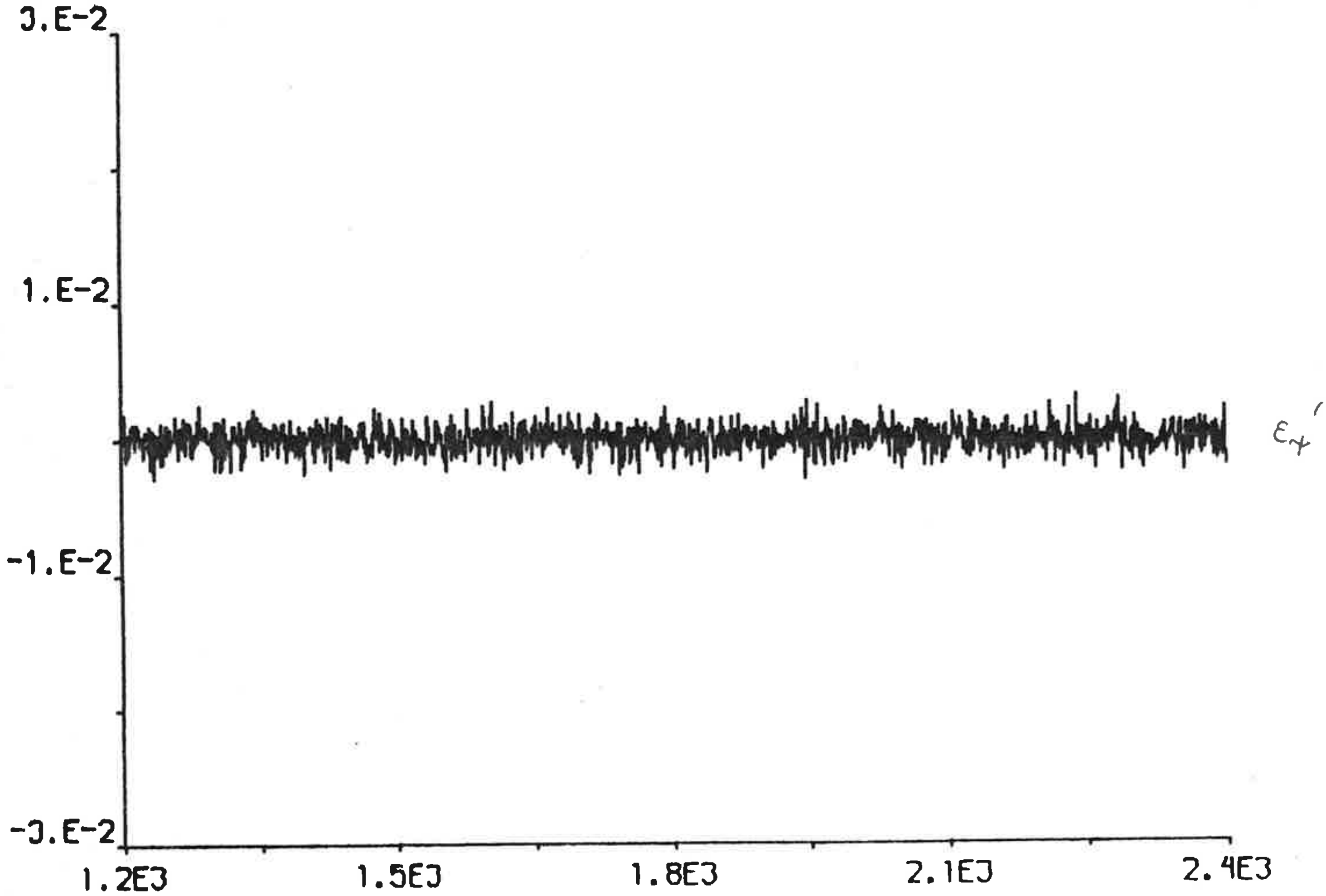

0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_r'

Fig. 4.2ℓ

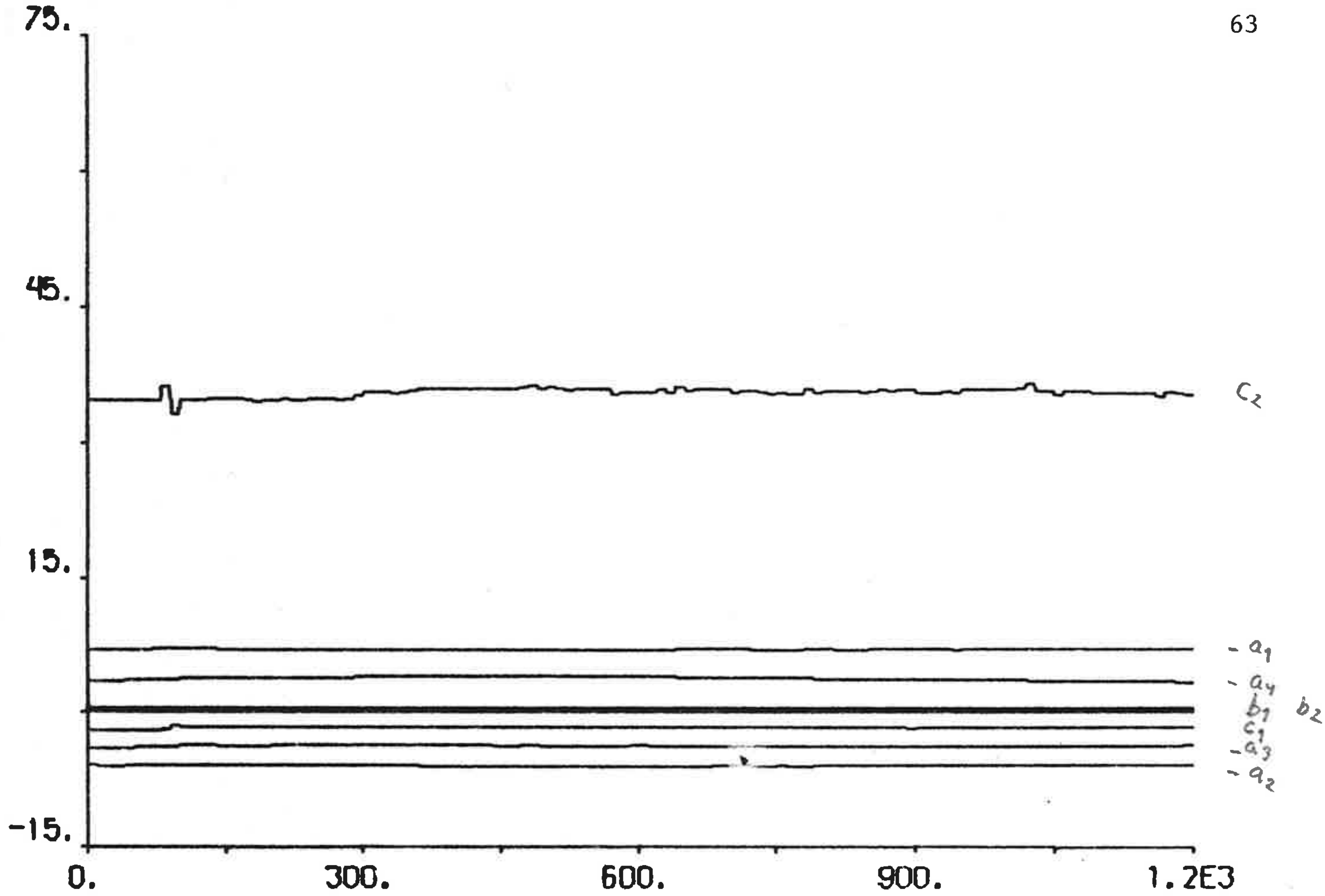


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
ε_γ'



3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_γ'

Fig. 4.2m


75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
a_1
a_4
b_1
b_2
c_1
a_3
a_2

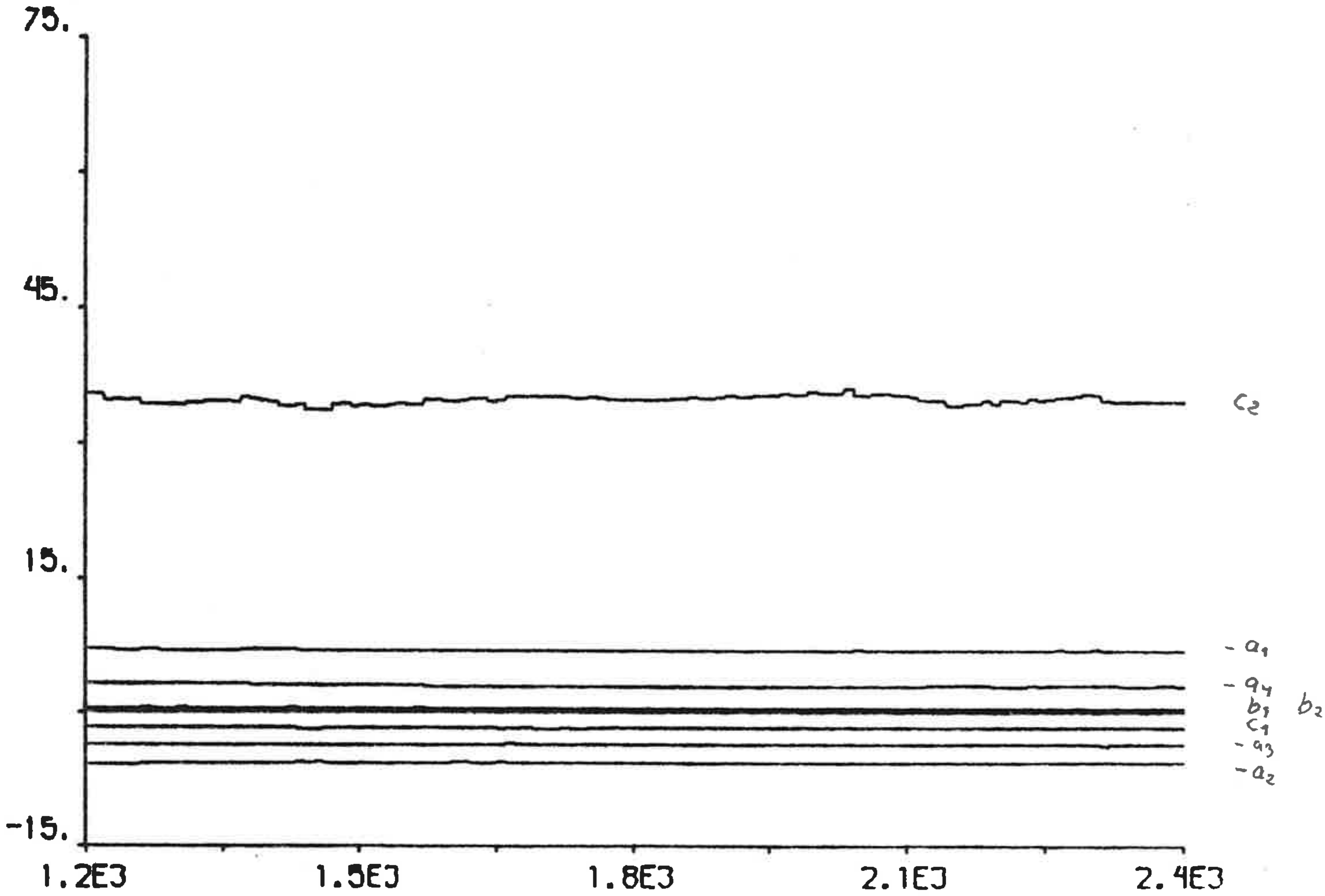
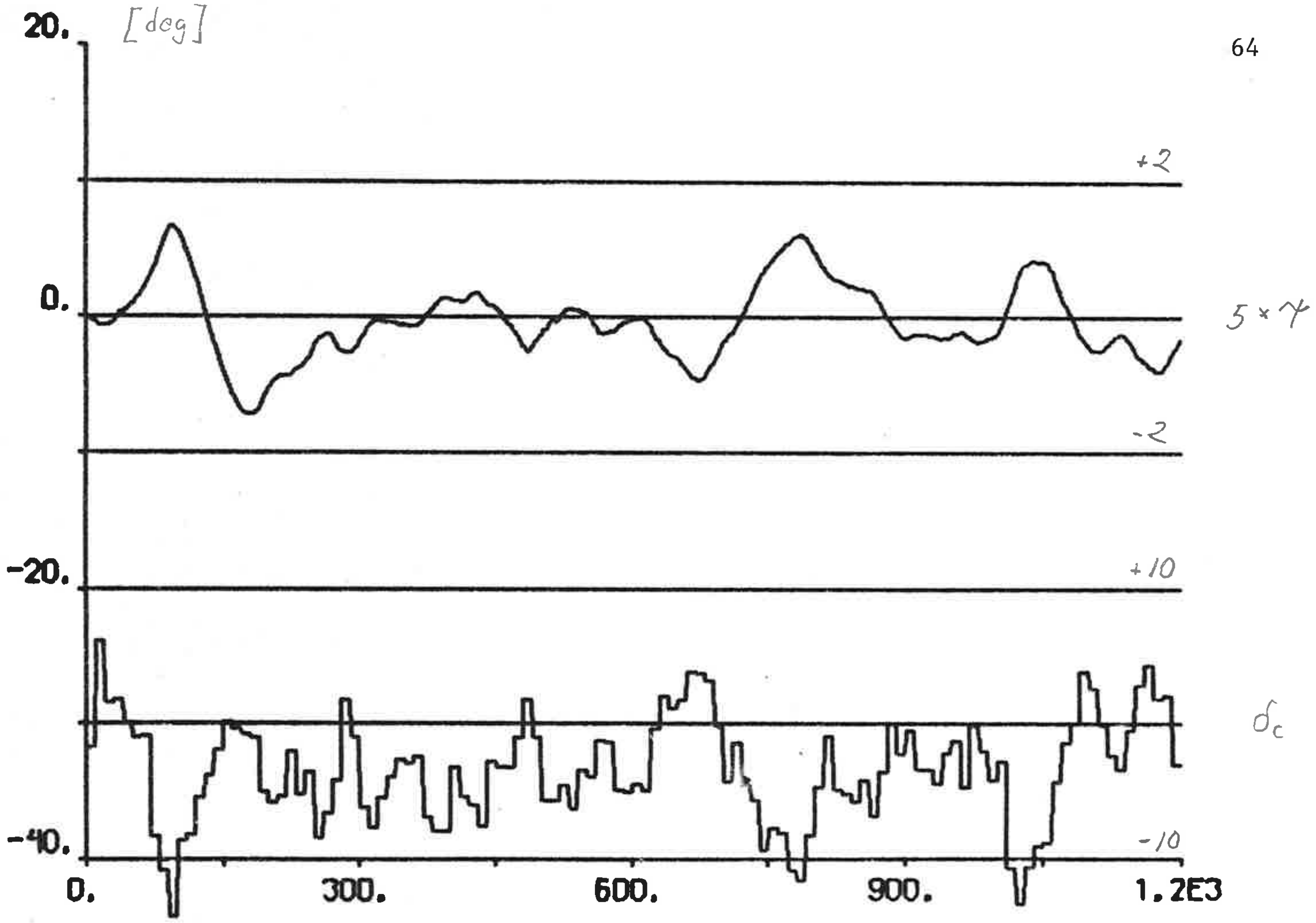

75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
a_1
a_4
b_1
b_2
c_1
a_3
a_2

Fig. 4.2n



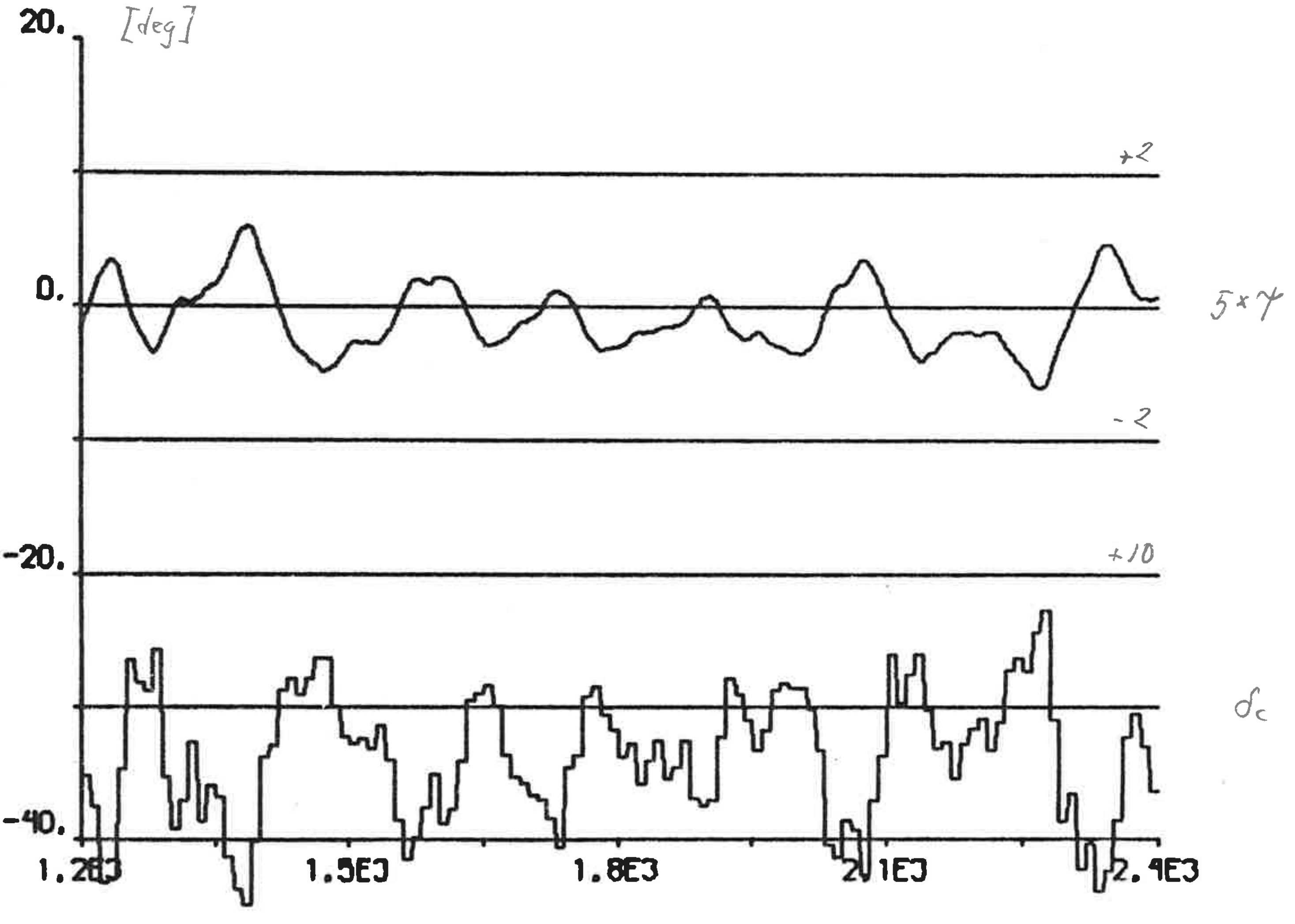
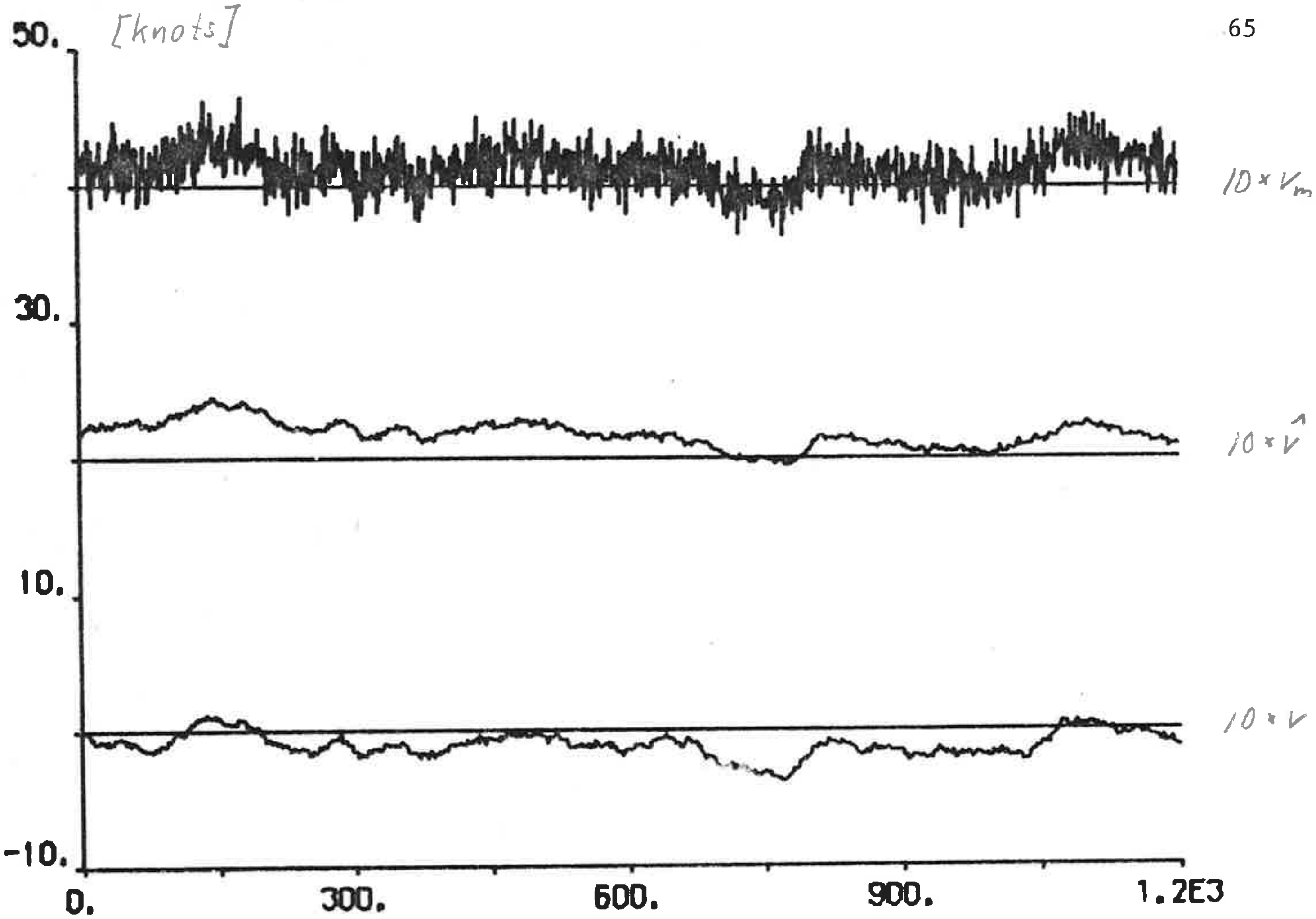
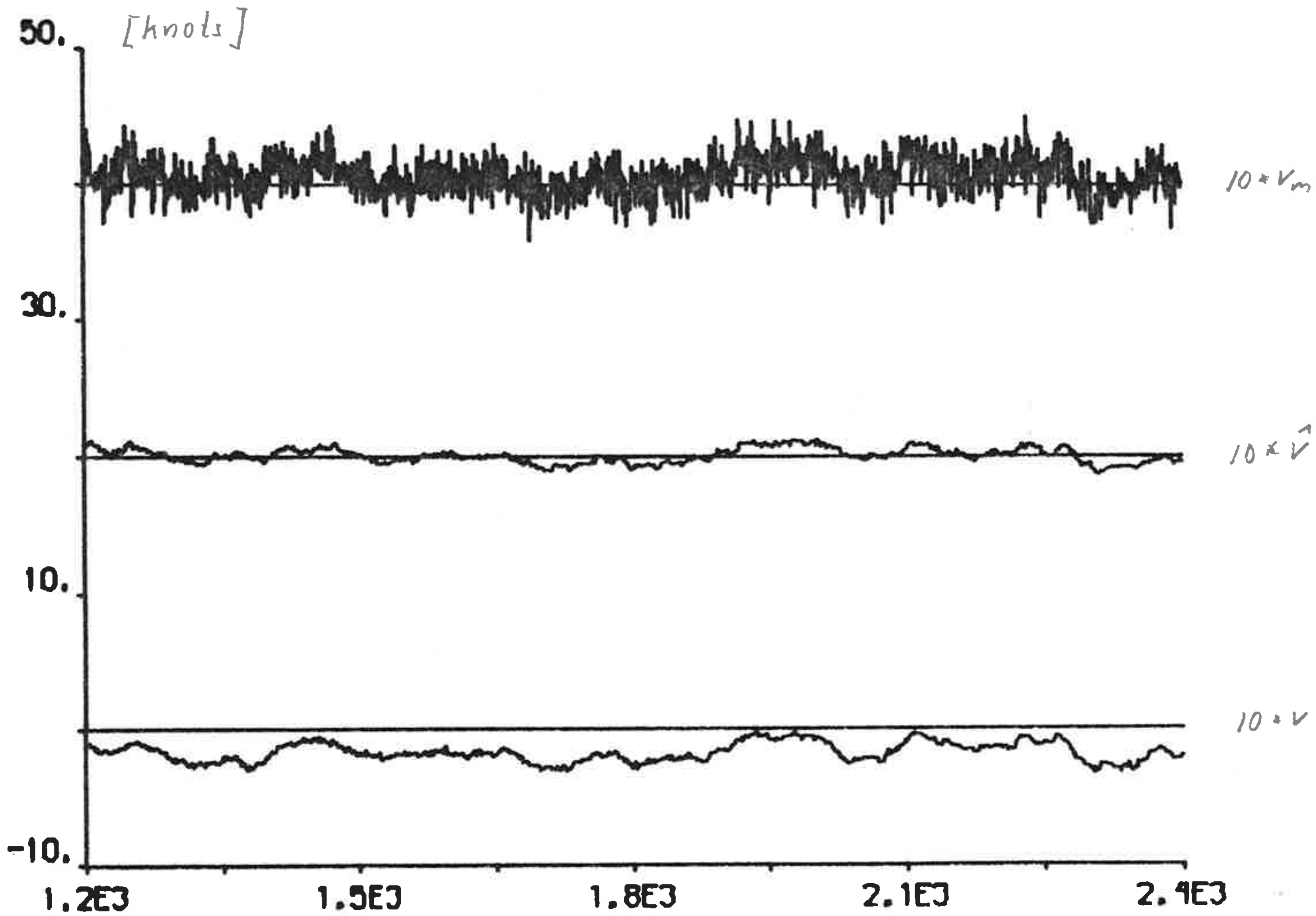


Fig. 4.3a - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, self-tuning regulator using estimates from the Kalman filter.

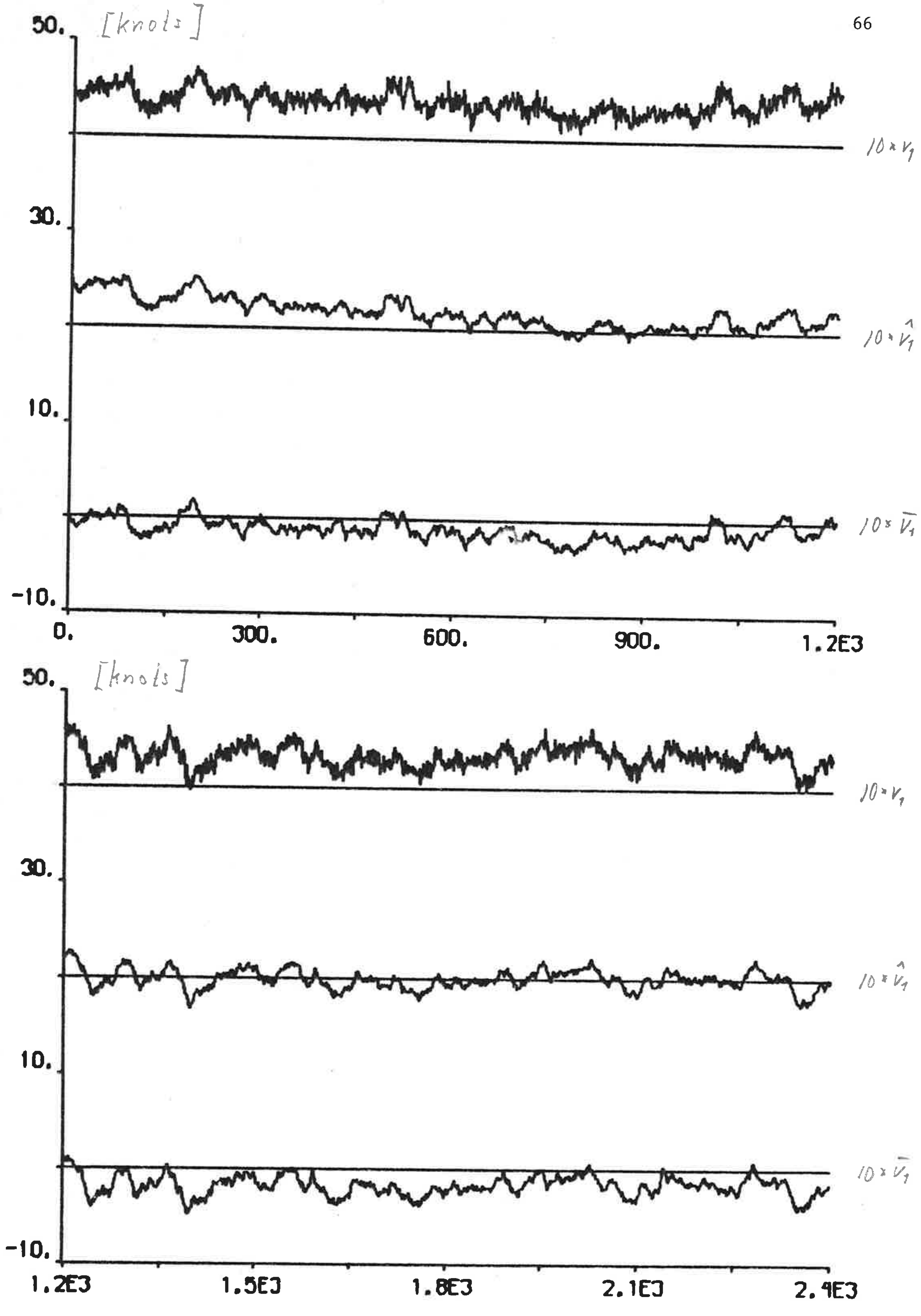


50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 * Vm
10 * V̂
10 * V



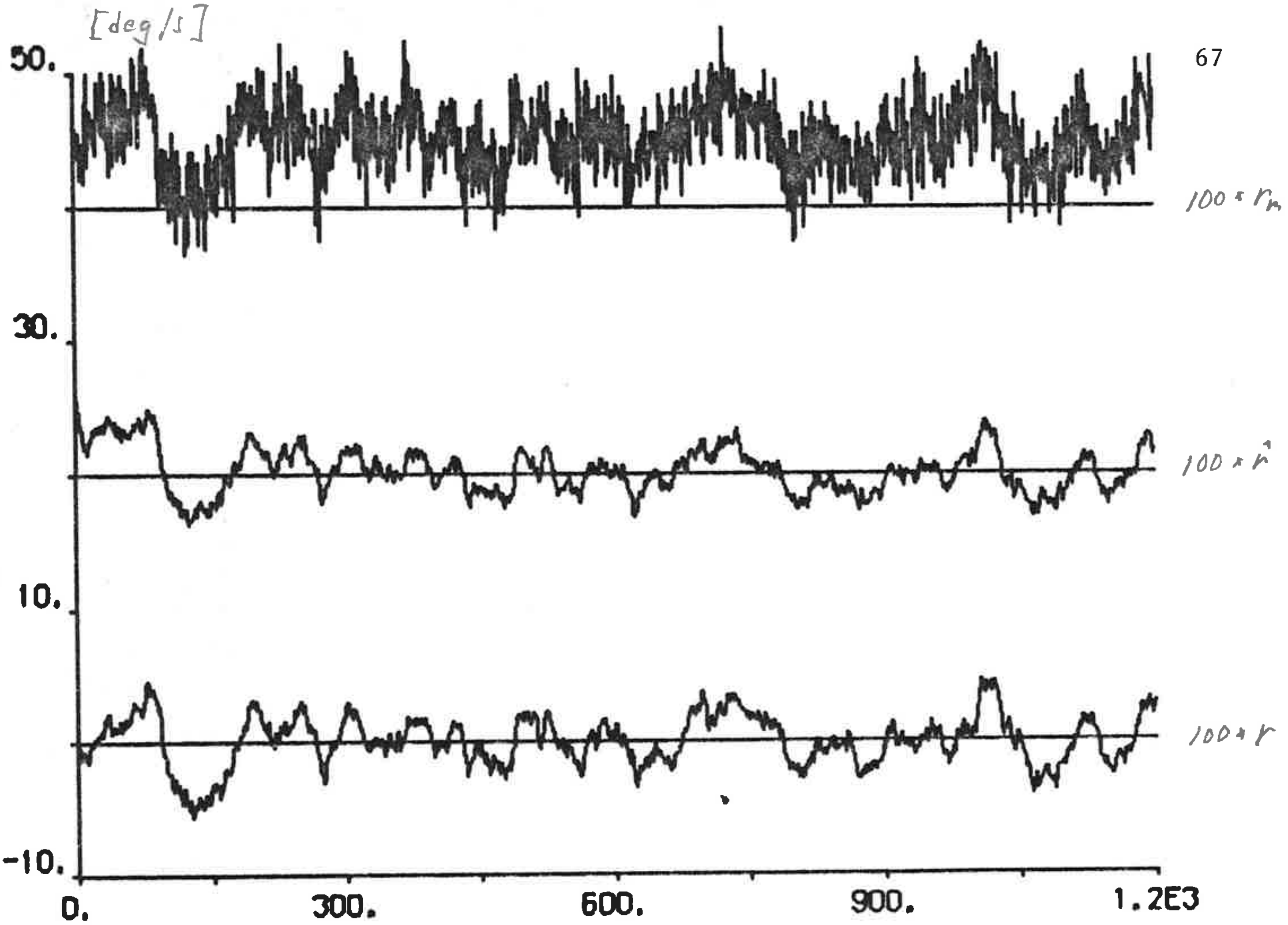
50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 * Vm
10 * V̂
10 * V

Fig. 4.3b

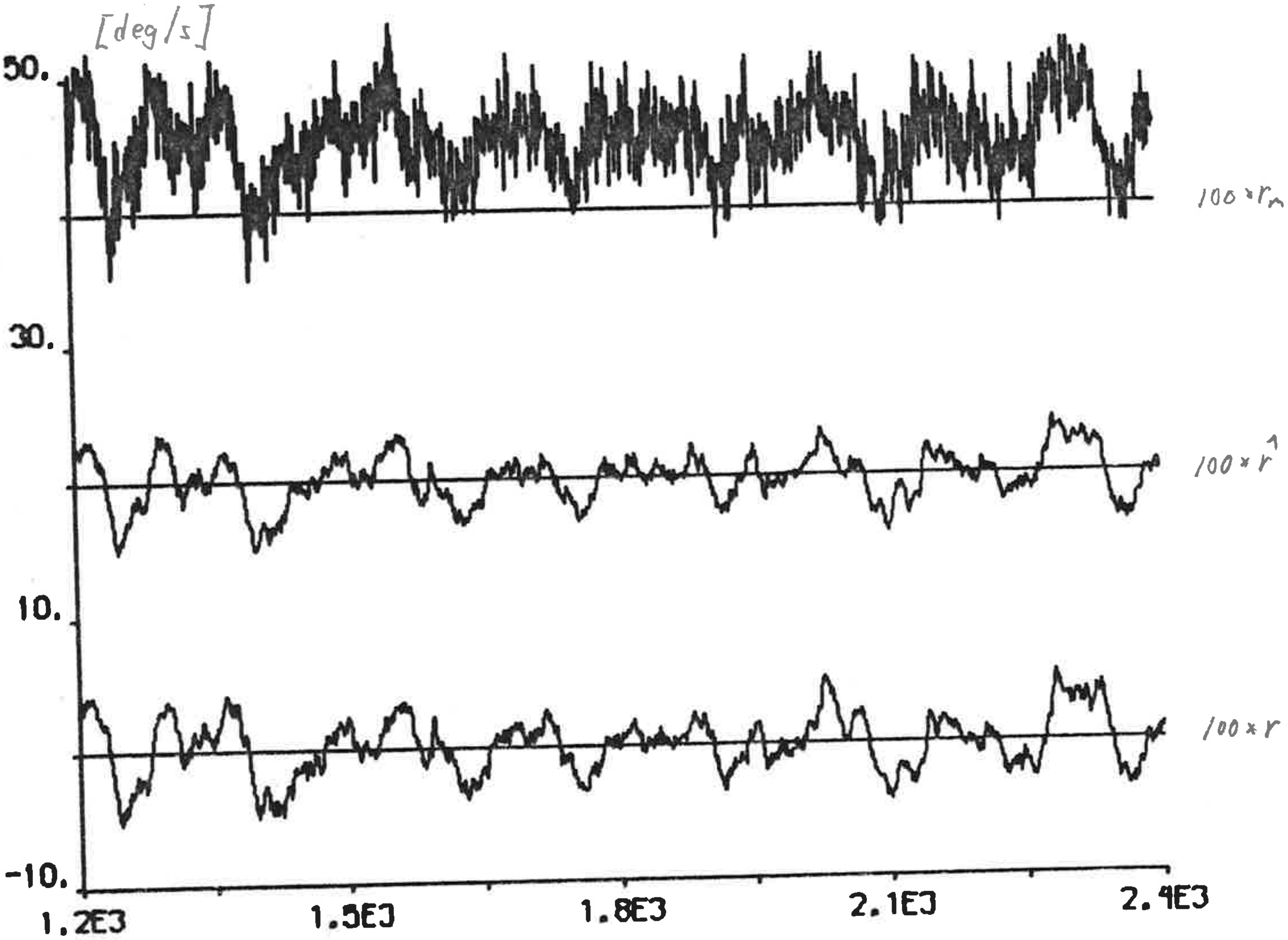


50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × V1
10 × V̂1
10 × V̄1
50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × V1
10 × V̂1
10 × V̄1

Fig. 4.3c

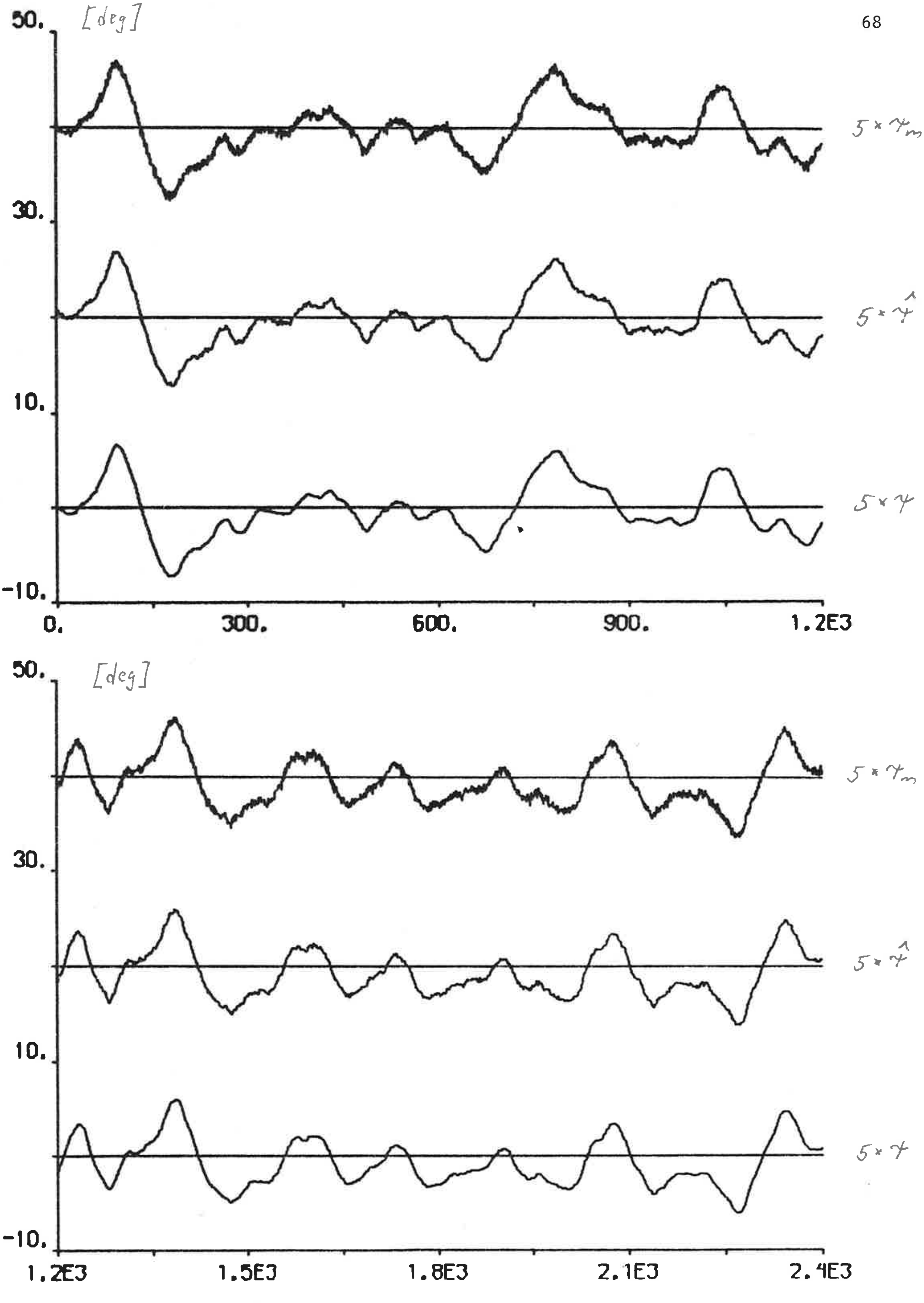


[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 * r_m
100 * $\hat{r}$
100 * r



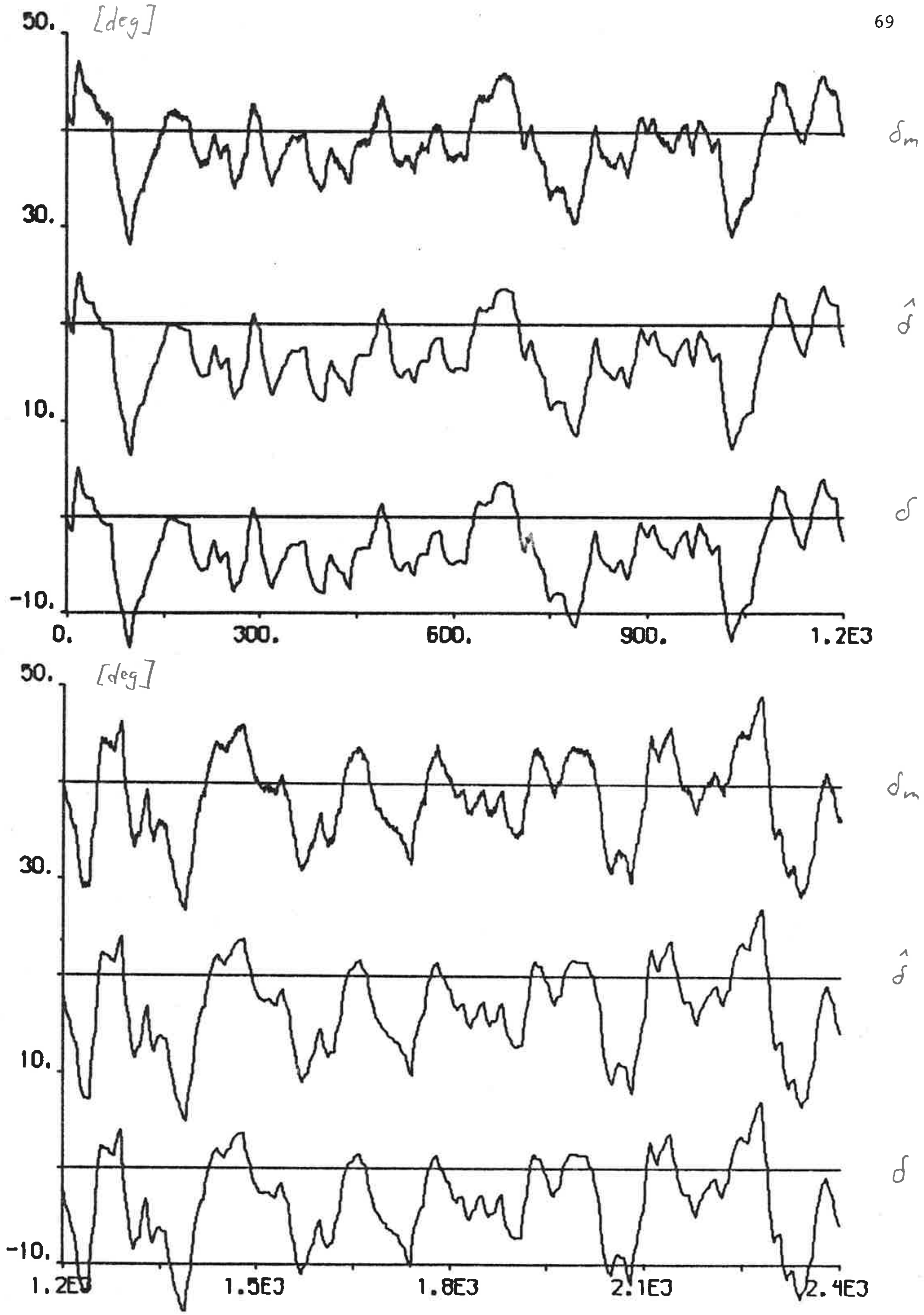
[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 * r_m
100 * $\hat{r}$
100 * r

Fig. 4.3d



[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5 × ψm
5 × ψ̂
5 × ψ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5 × ψm
5 × ψ̂
5 × ψ

Fig. 4.3e



50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
δ_m
$\hat{\delta}$
δ
50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
δ_m
$\hat{\delta}$
δ

Fig. 4.3f

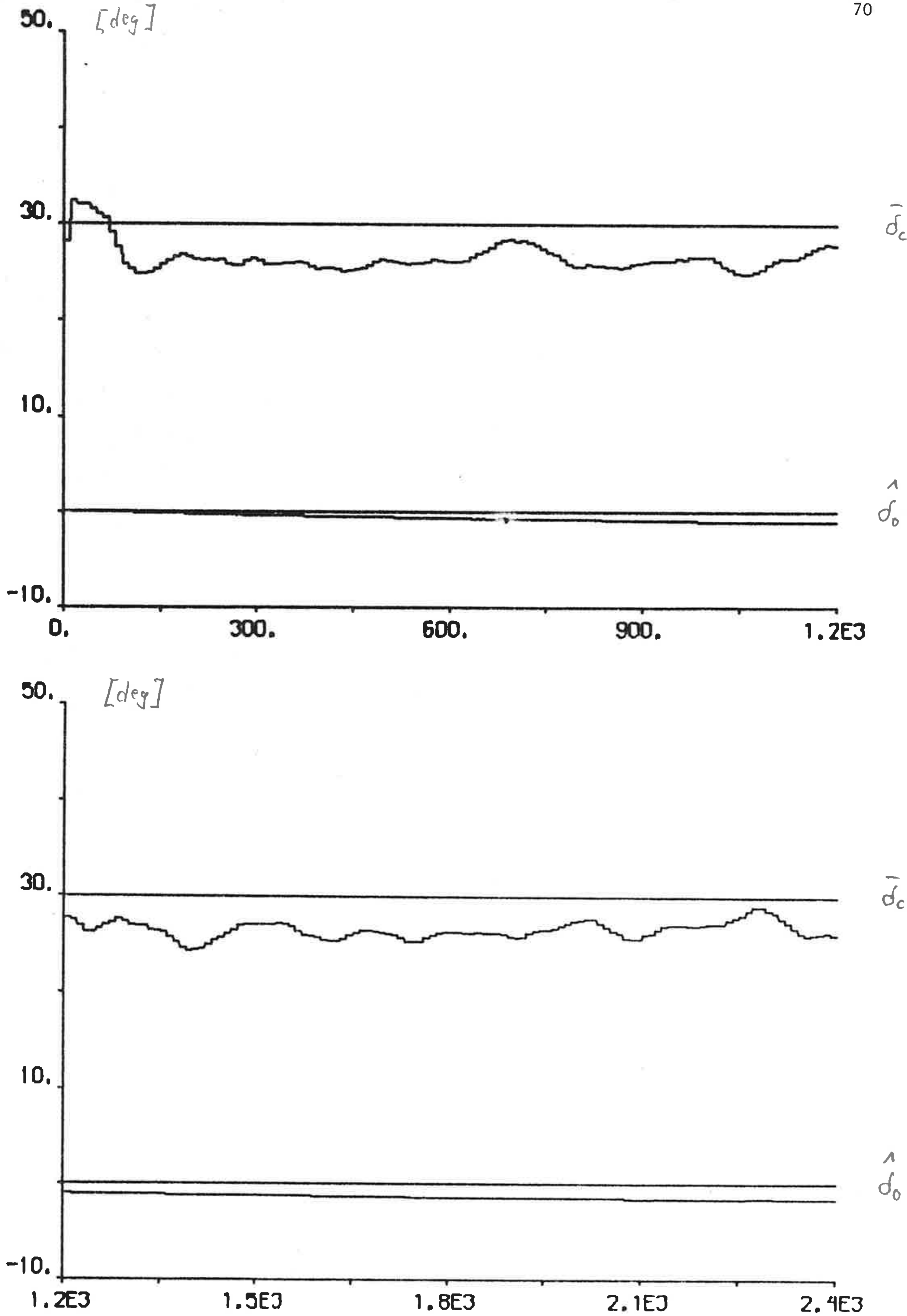
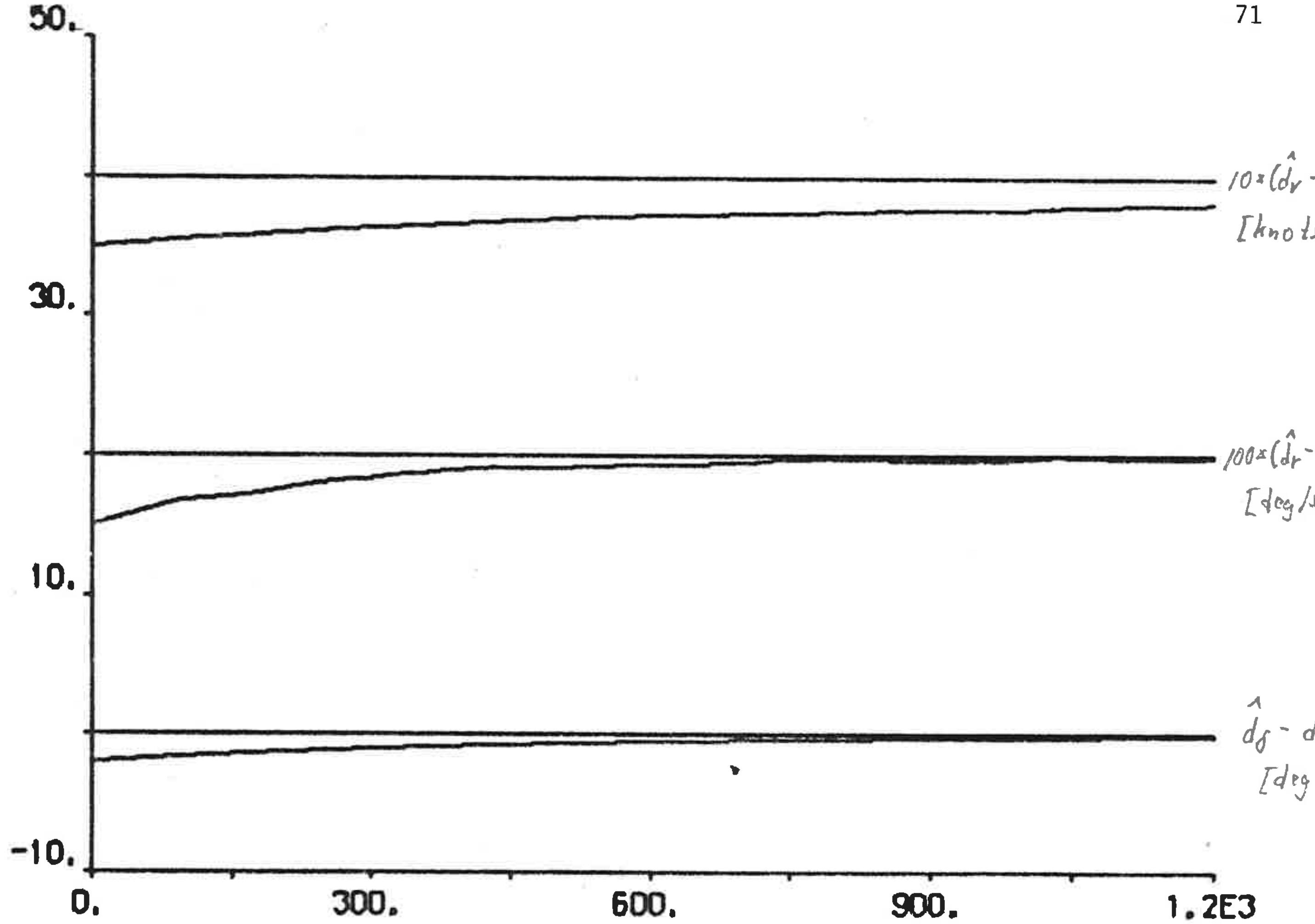

50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$\bar{\delta}_c$
$\hat{\delta}_0$
50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
$\bar{\delta}_c$
$\hat{\delta}_0$

Fig. 4.3g


50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[knot
[deg

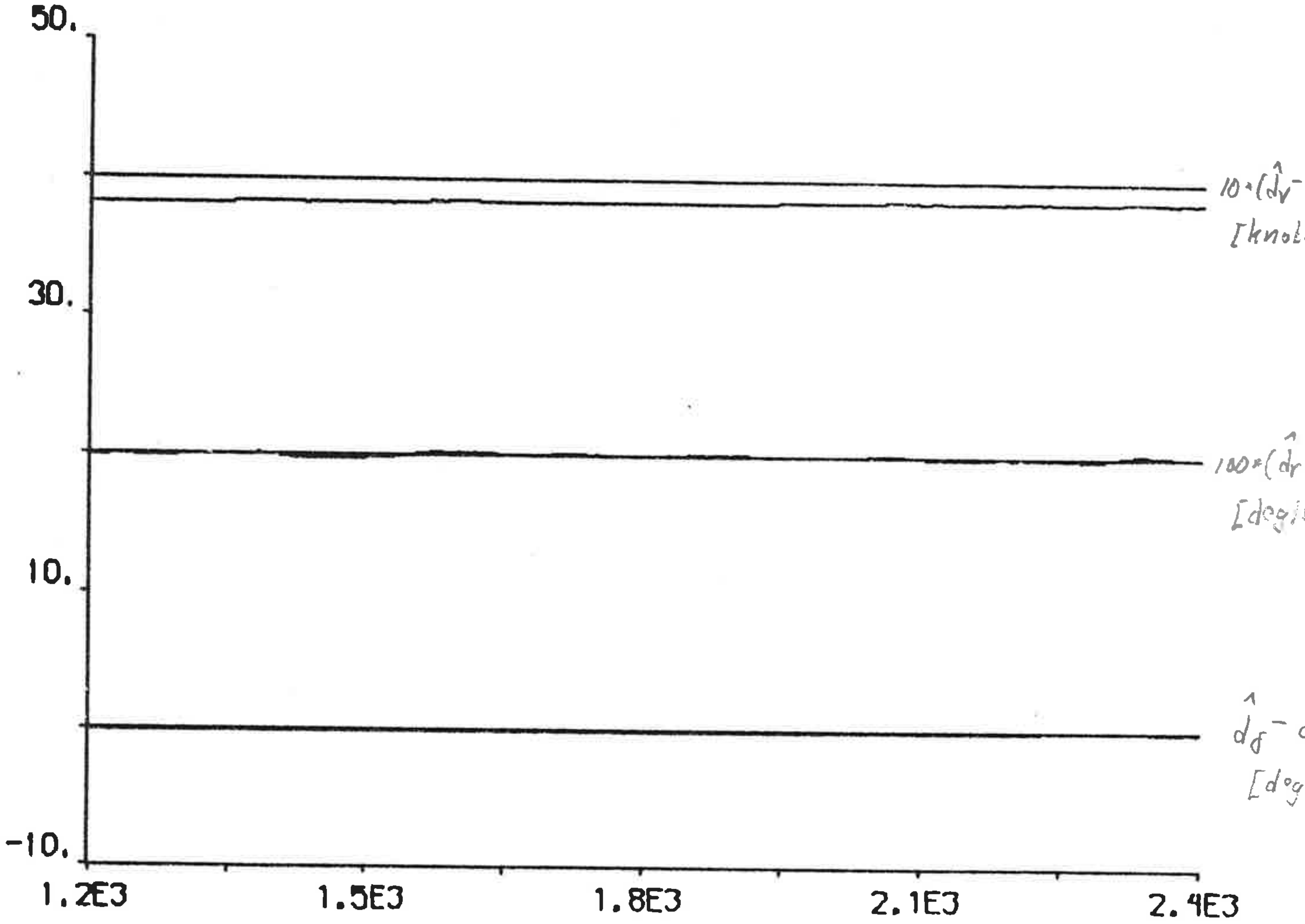
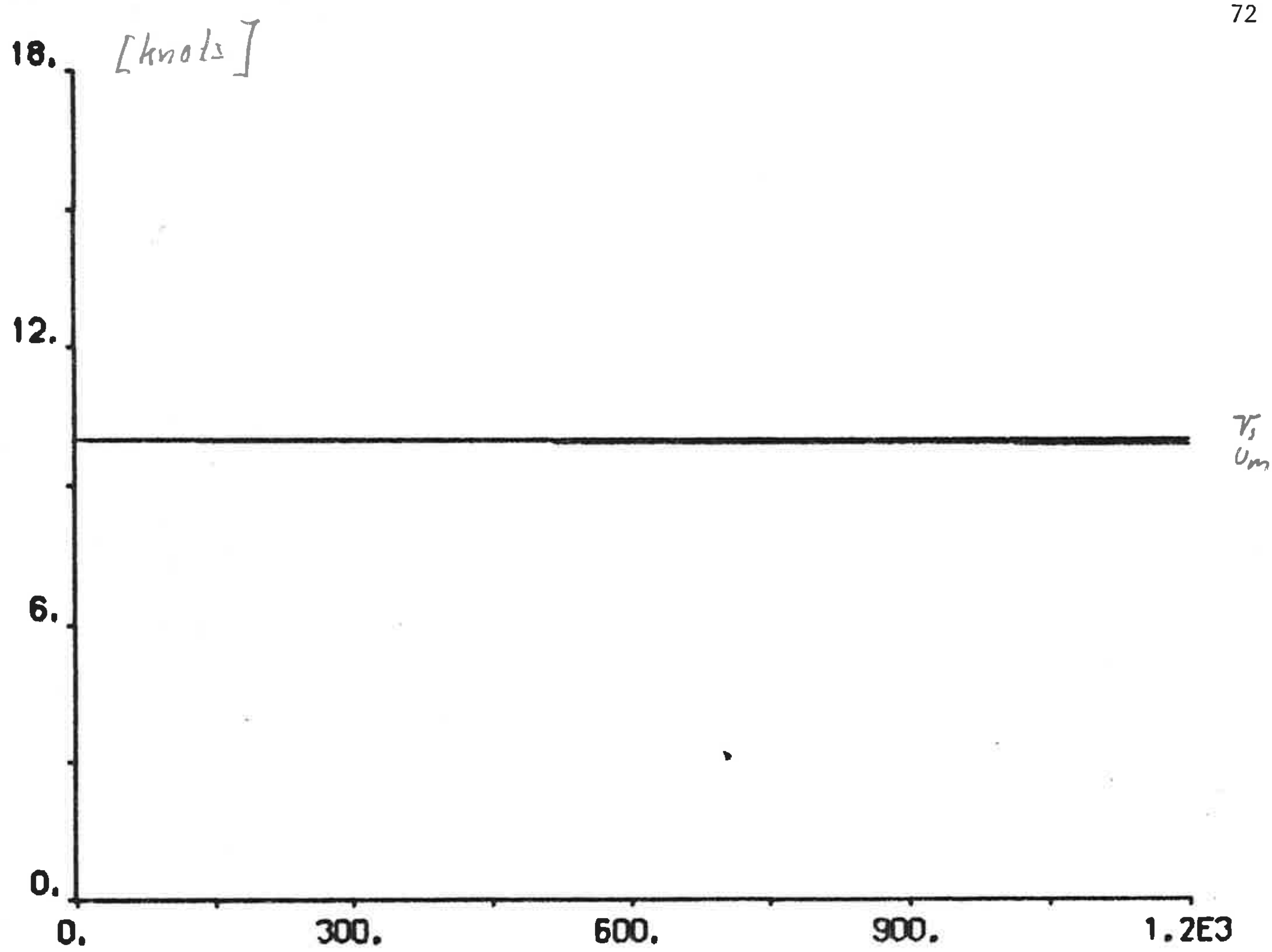
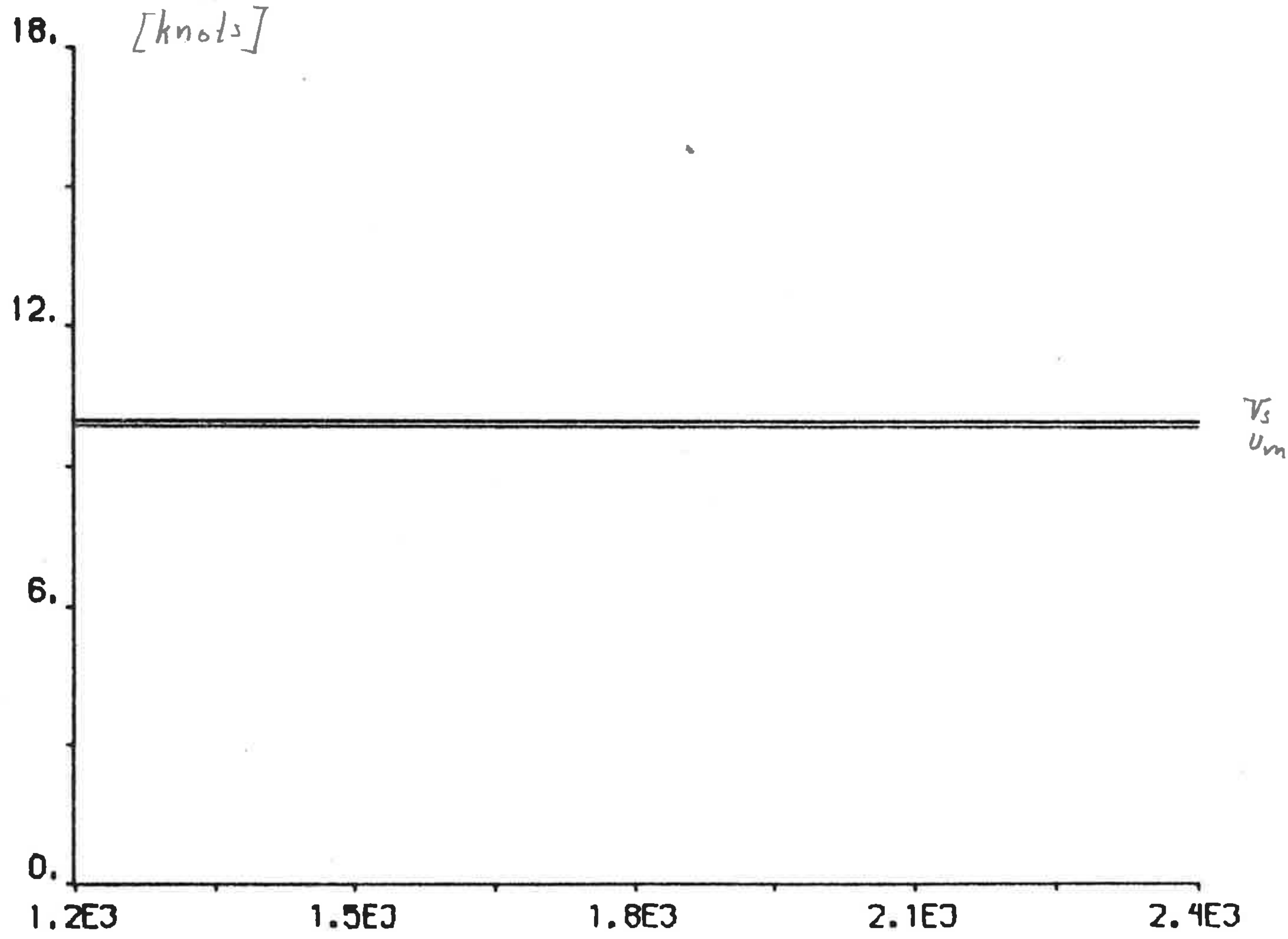

50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
[knot

Fig. 4.3h



[knots]
18.
12.
6.
0.
0.
300.
600.
900.
1.2E3
Vs
Um



[knots]
18.
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
Vs
Um

Fig. 4.3i

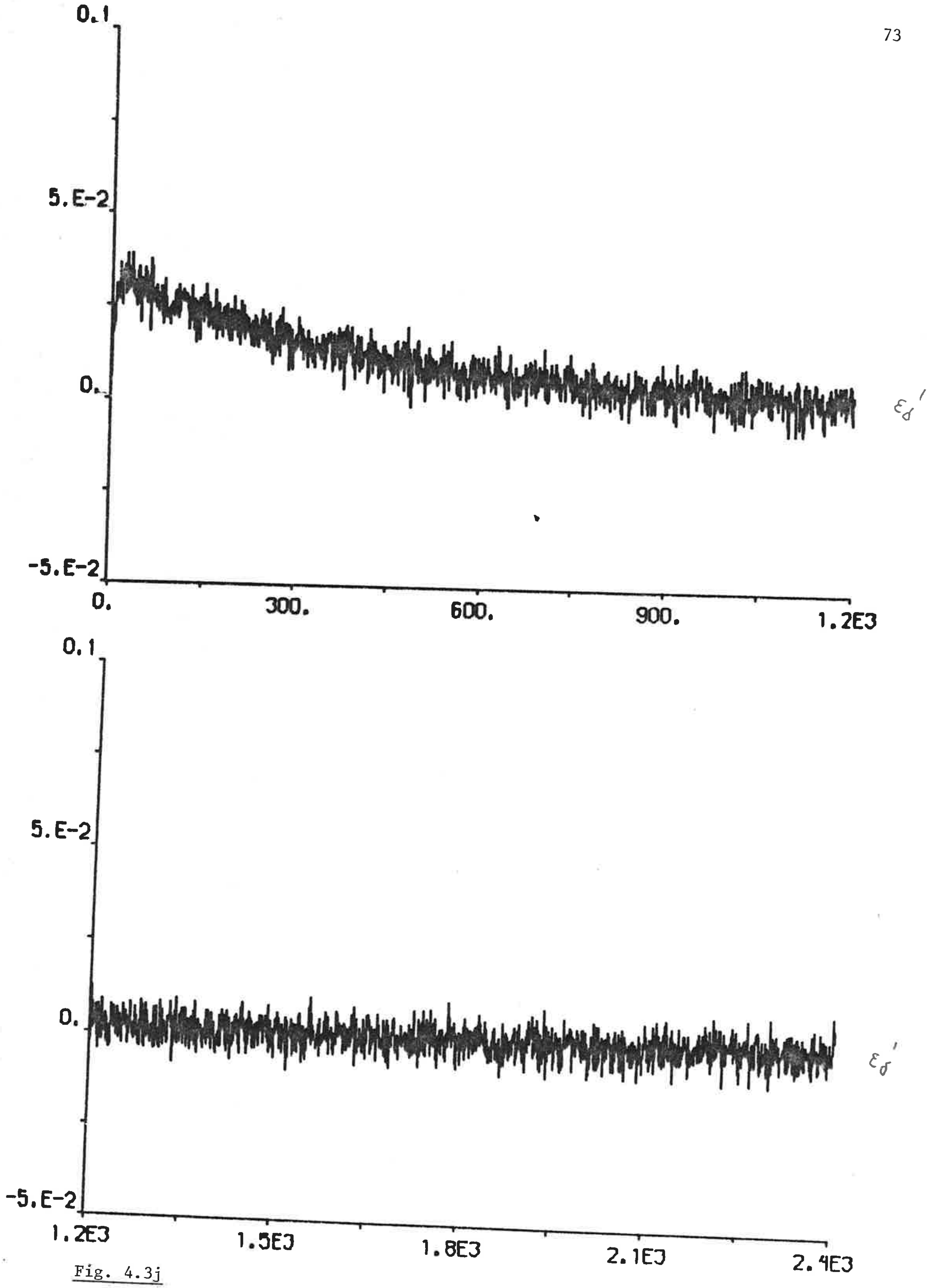
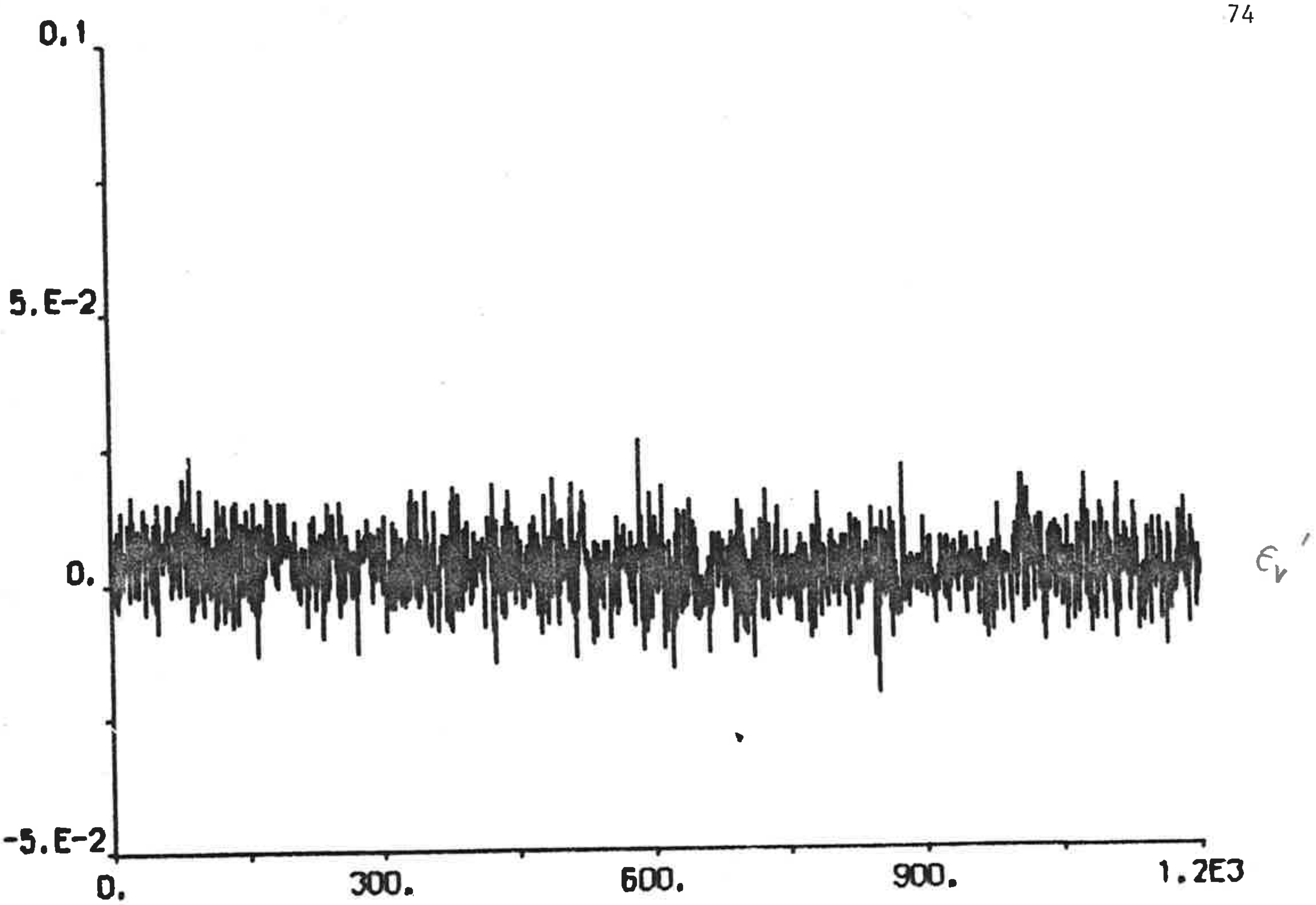

0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_d'
0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_d'

Fig. 4.3j


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_v'

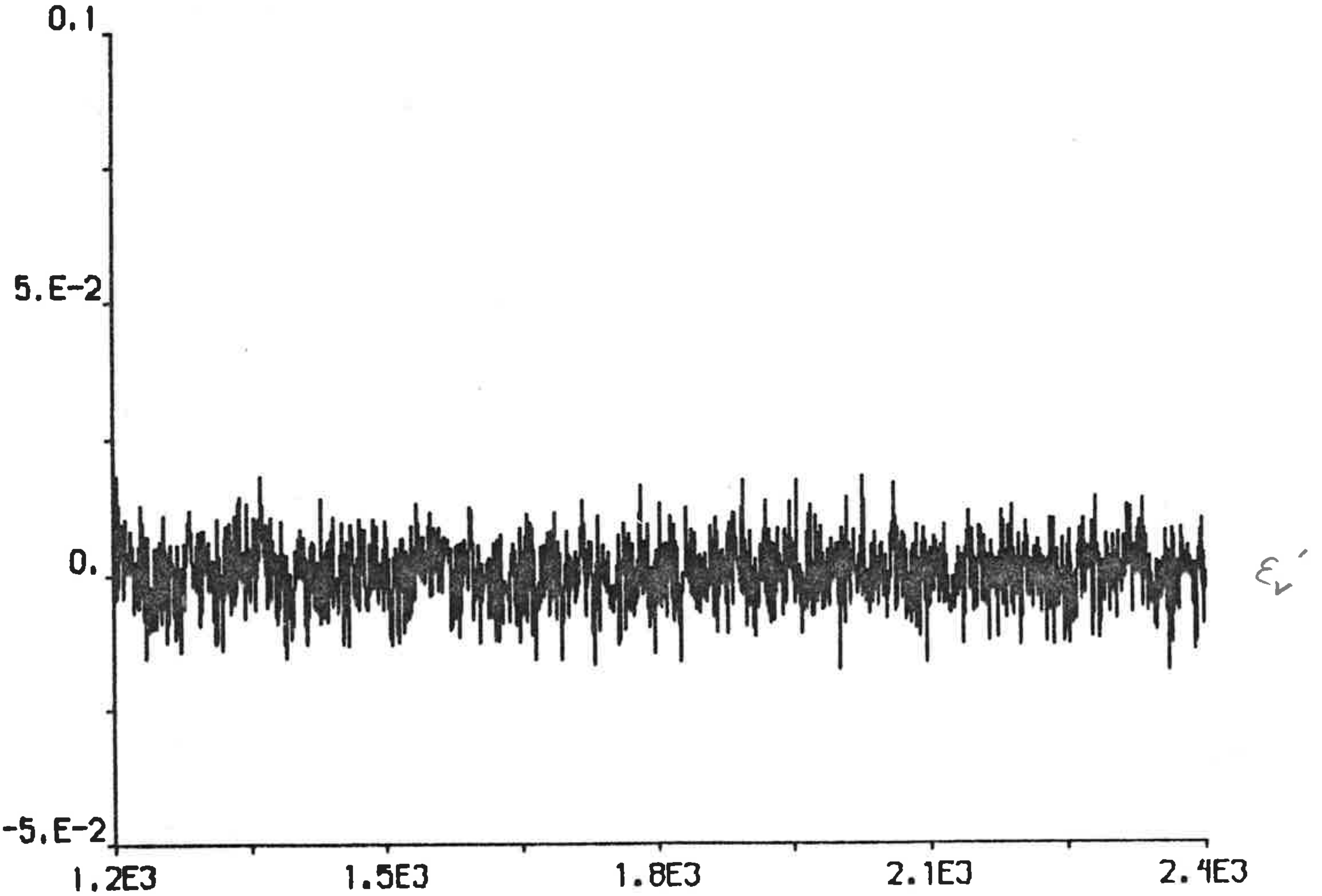
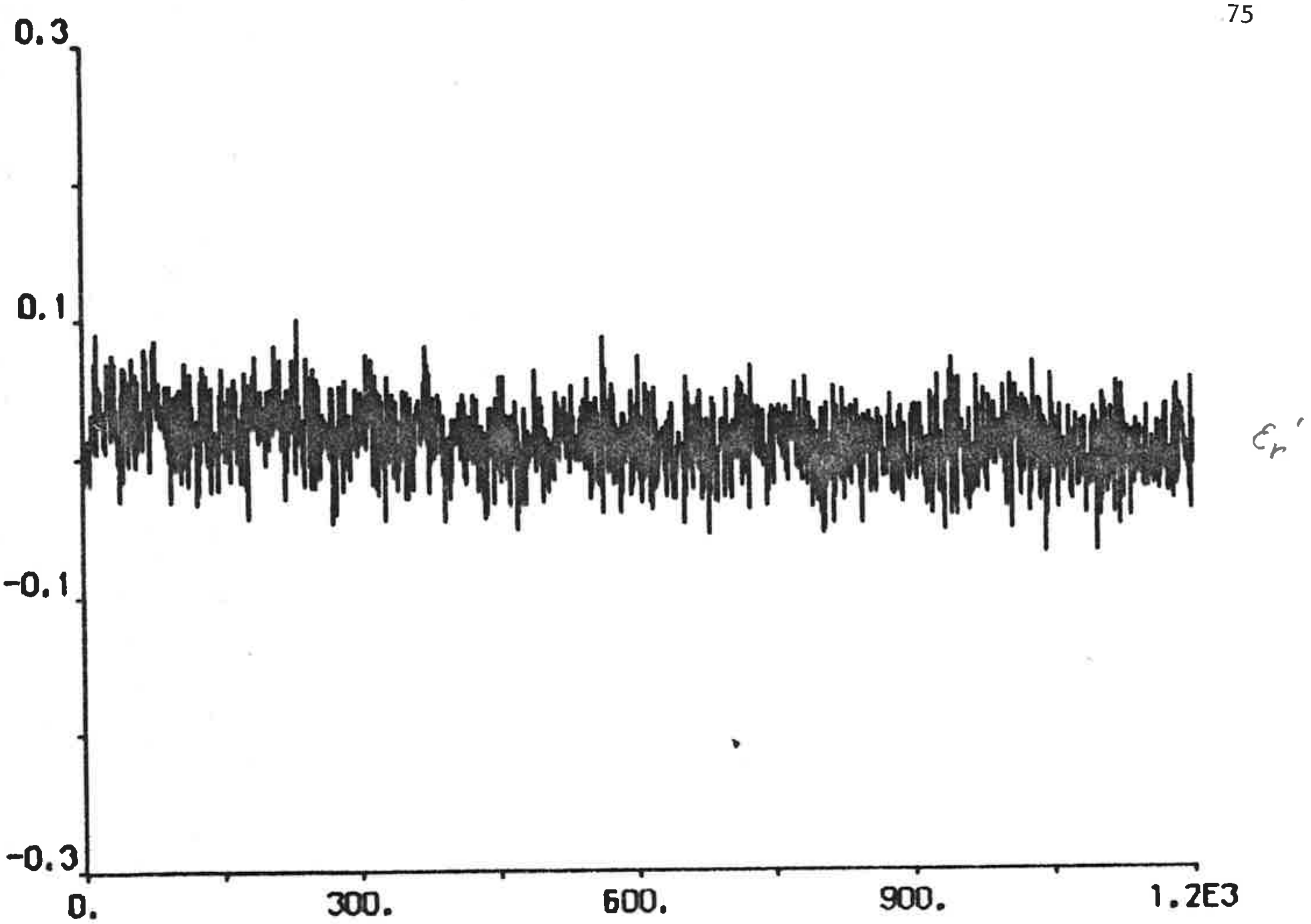

0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_v'

Fig. 4.3k


0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
ε_r'

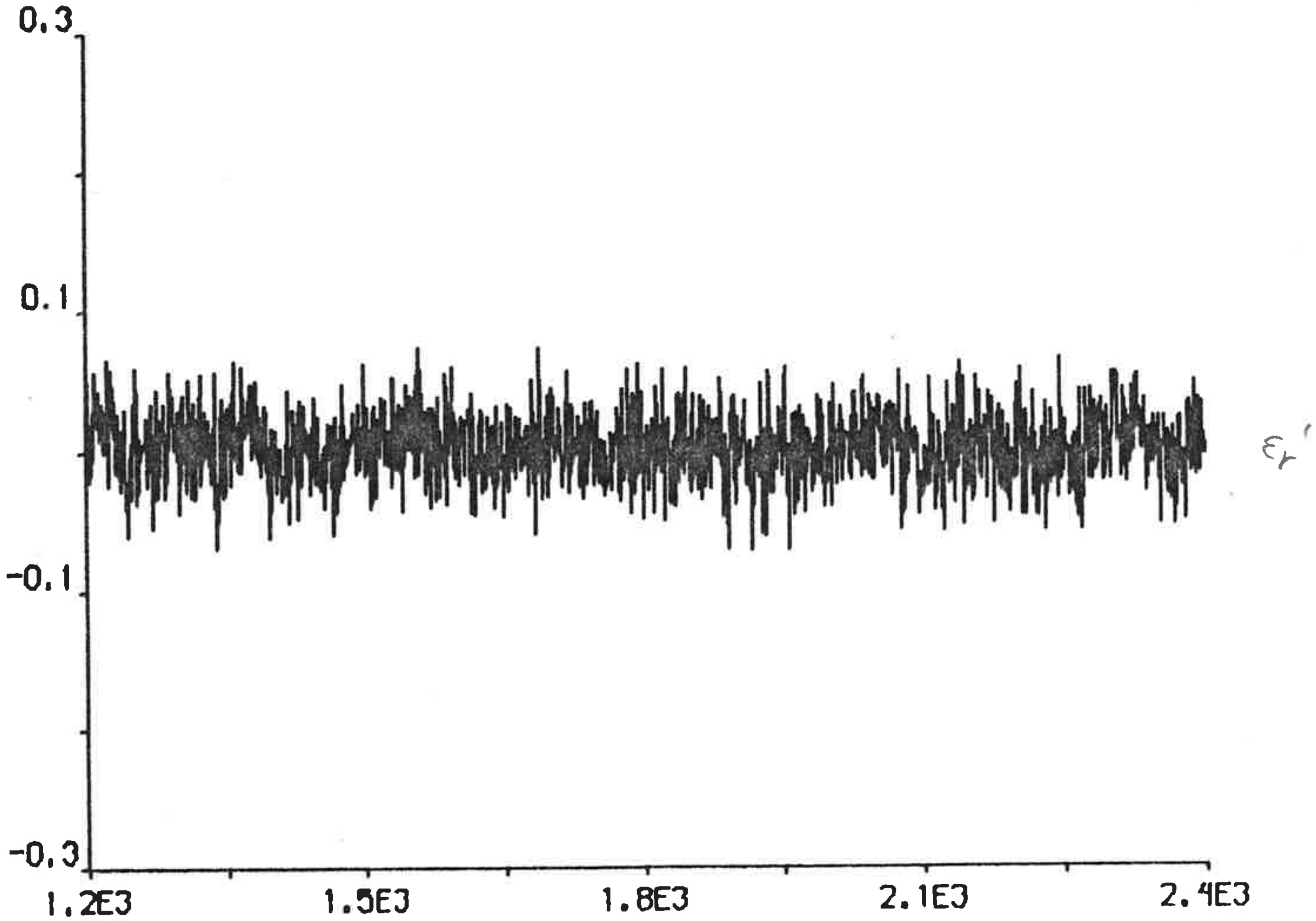
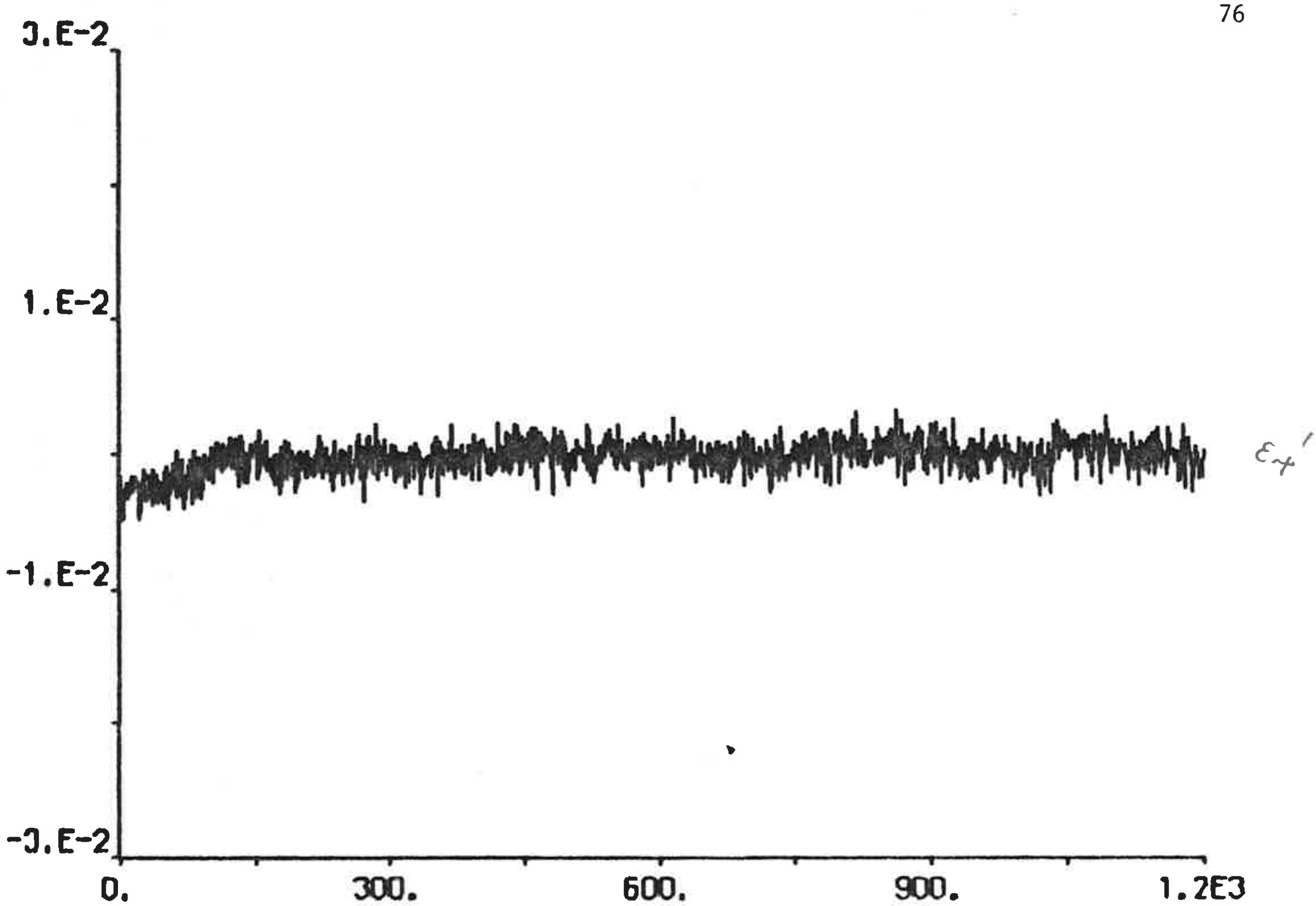

0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_r'

Fig. 4.3ℓ


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
εr'

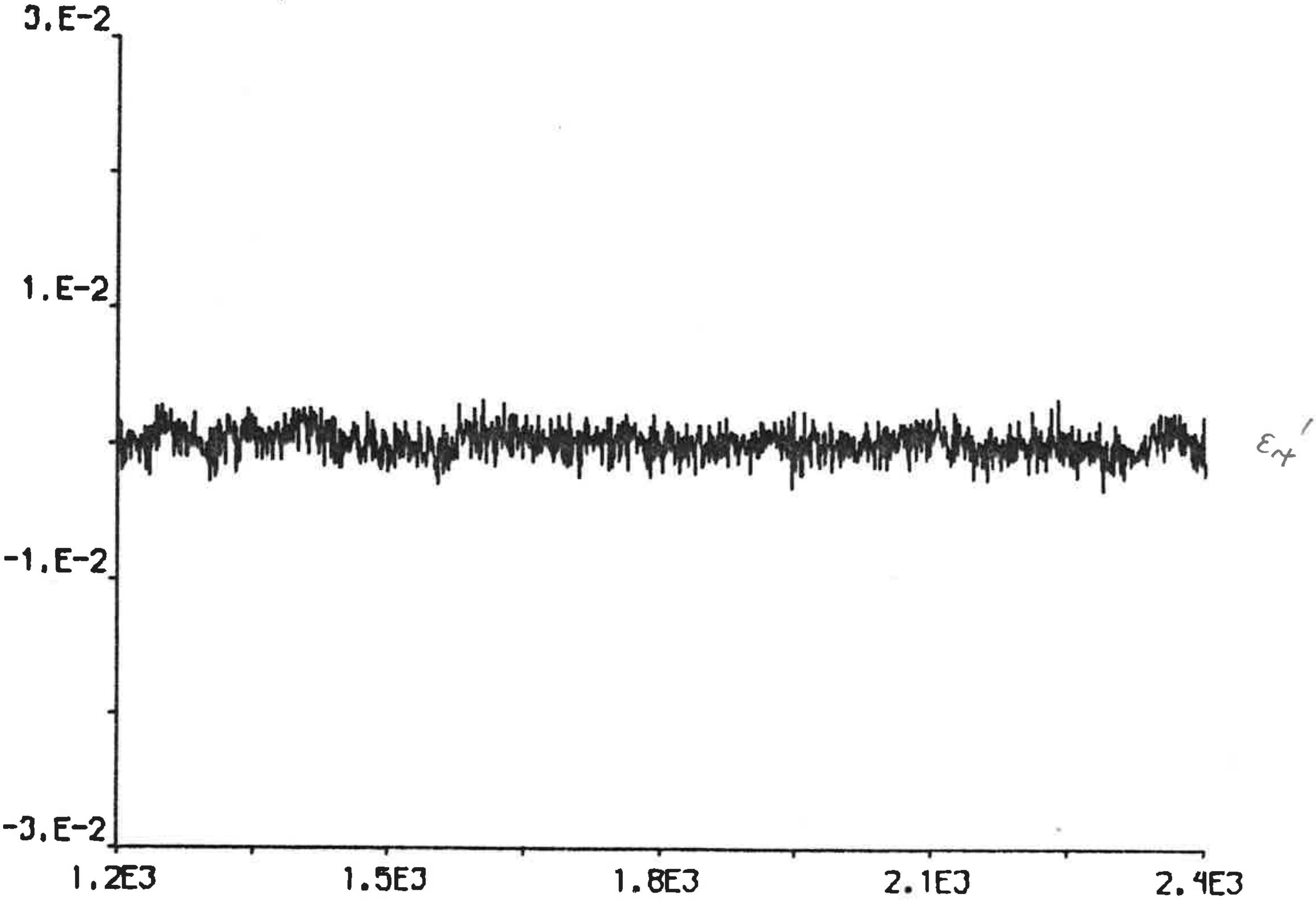

3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εr'

Fig. 4.3m

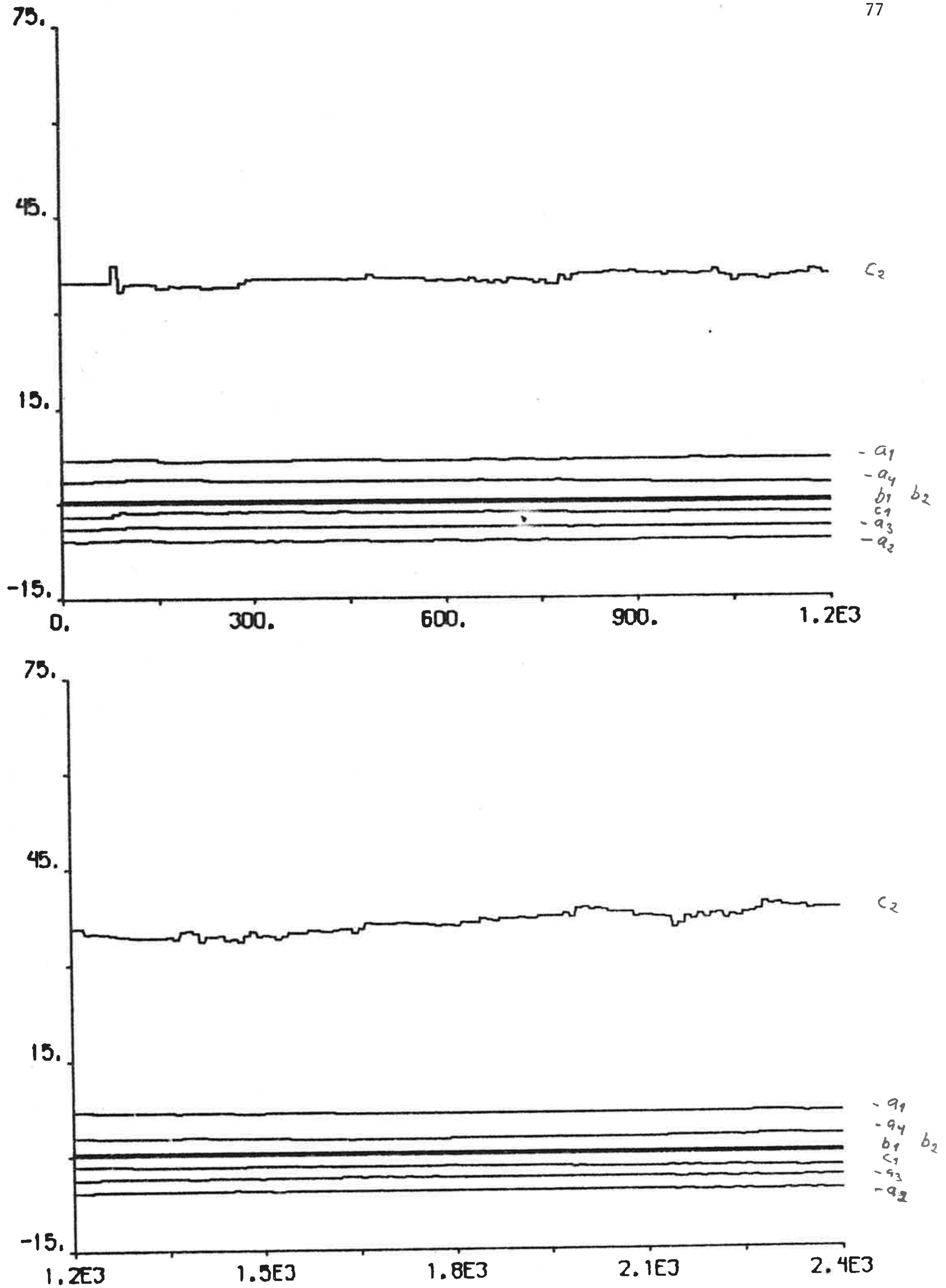

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
a_1
a_4
b_1 b_2
c_1
a_3
a_2
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
a_1
a_4
b_1 b_2
c_1
a_3
a_2

Fig. 4.3n

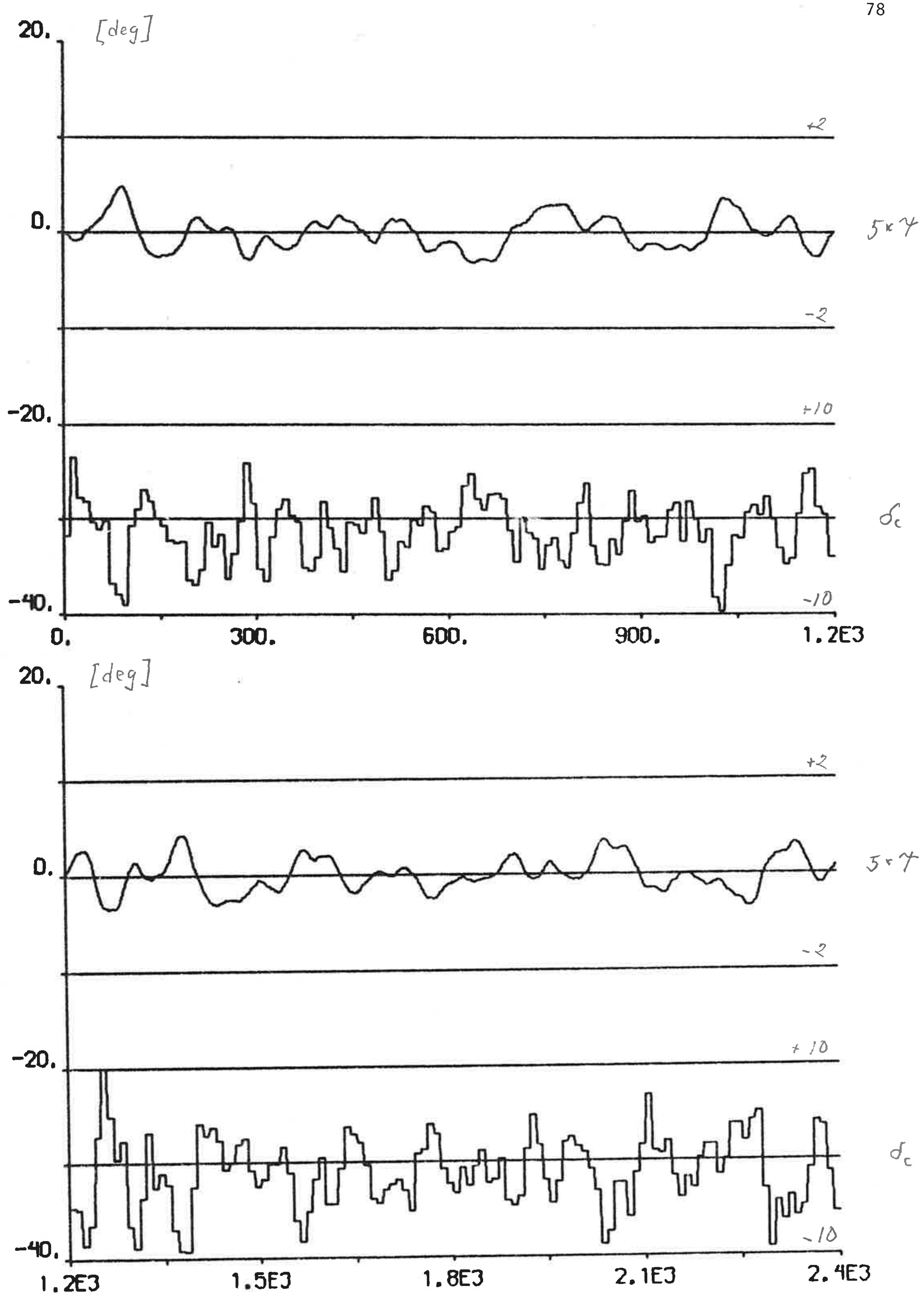
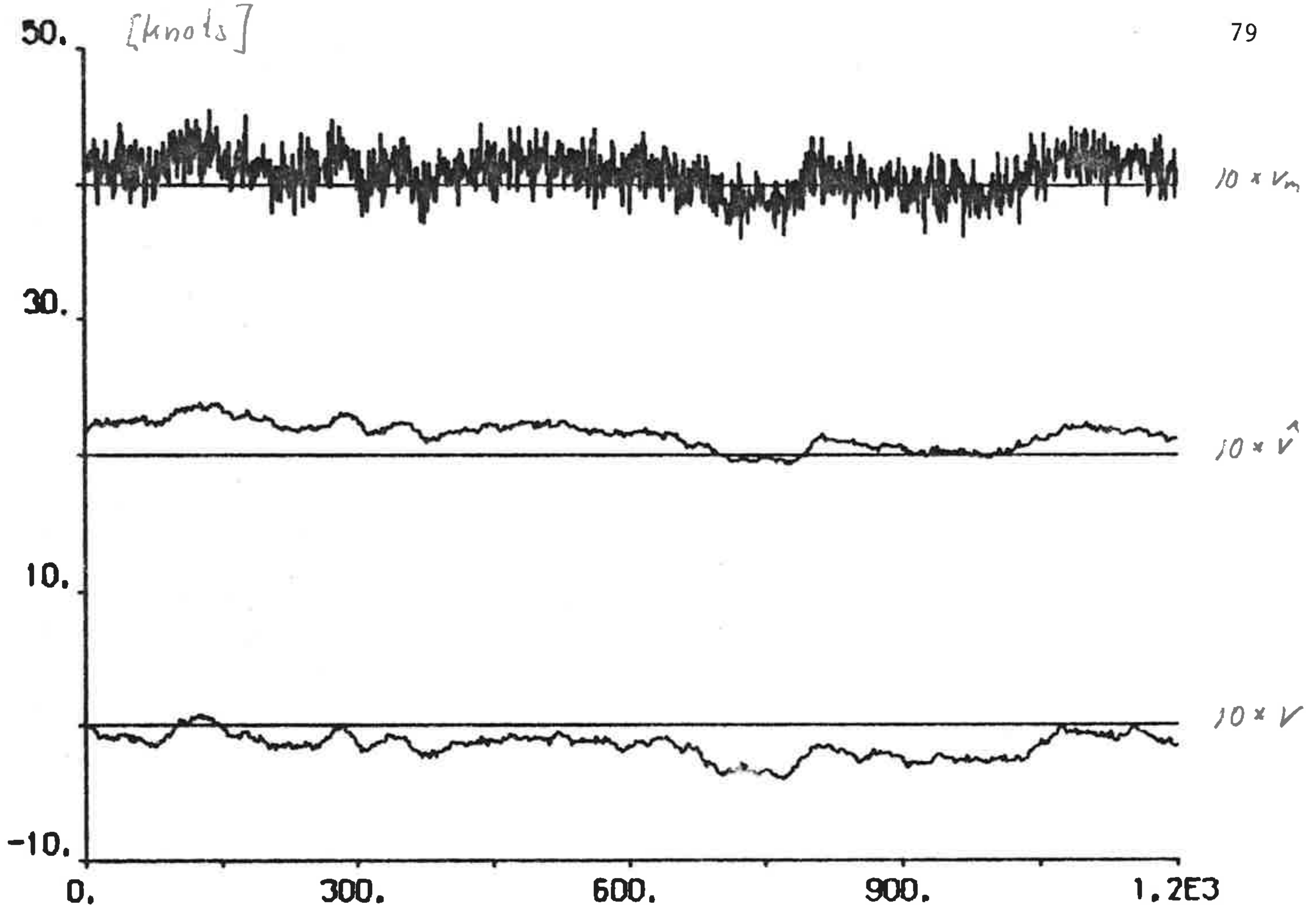
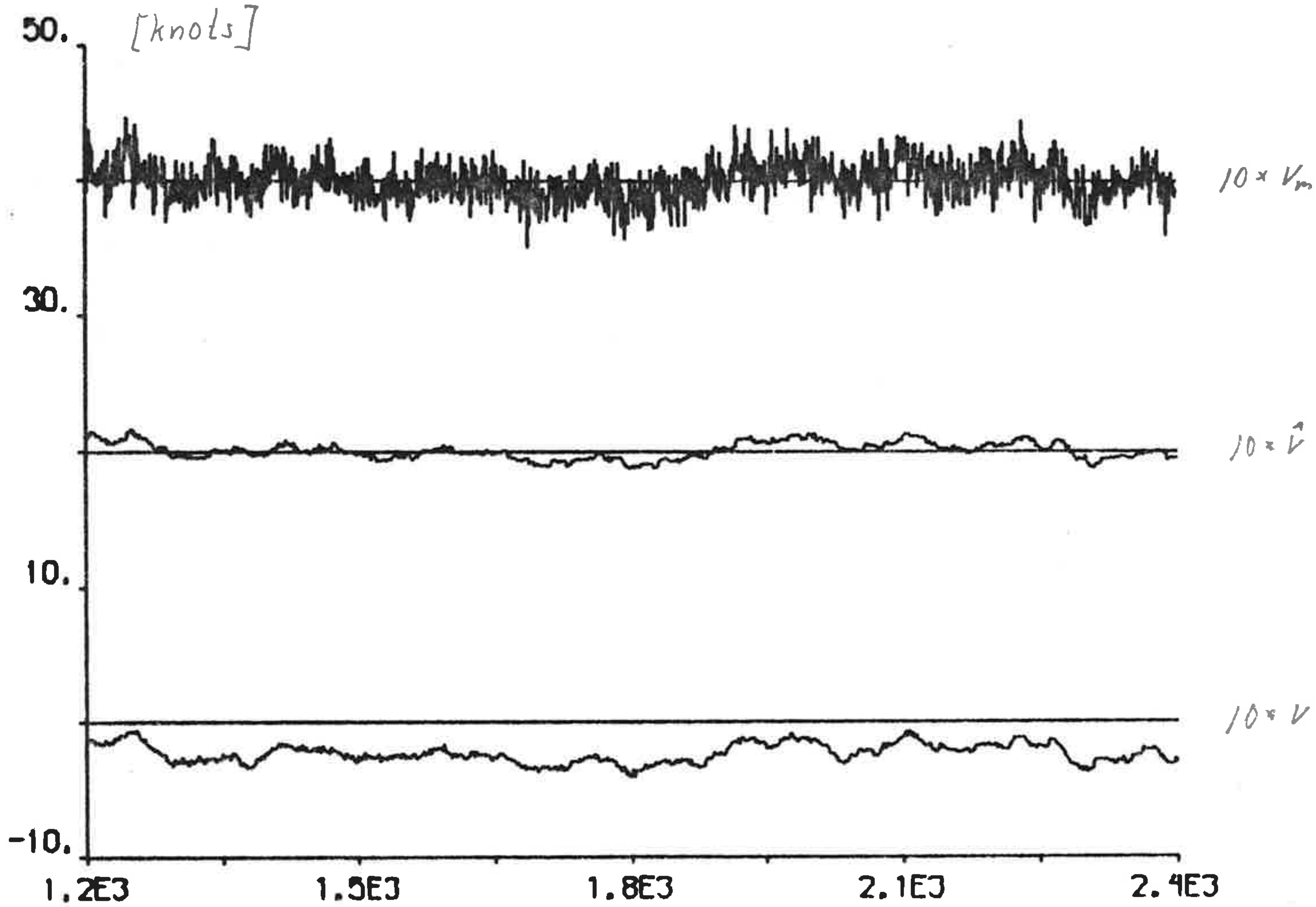


Fig. 4.4a - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, self-tuning regulator using estimates from the Kalman filter.

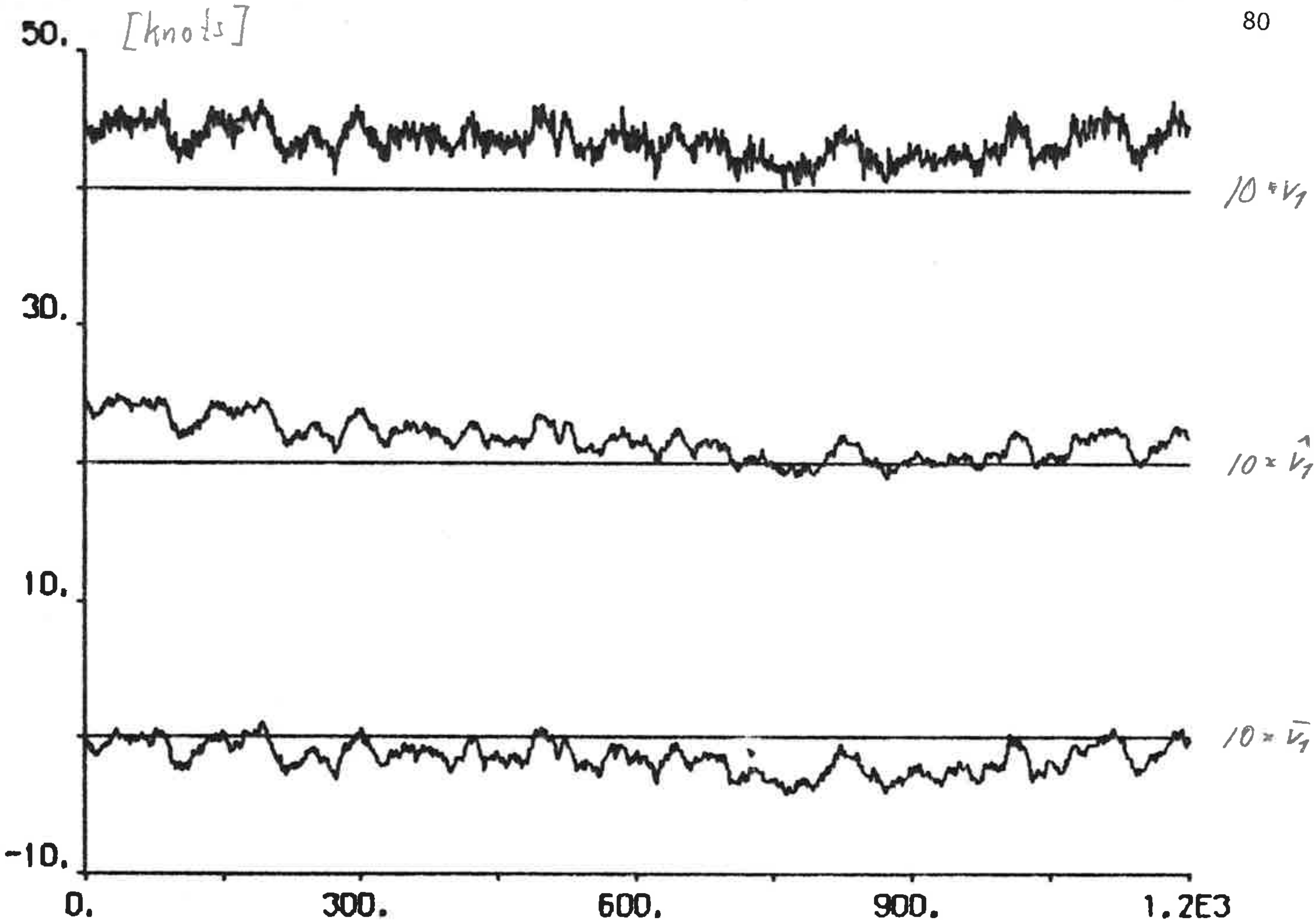


50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × V_m
10 × $\hat{V}$
10 × V

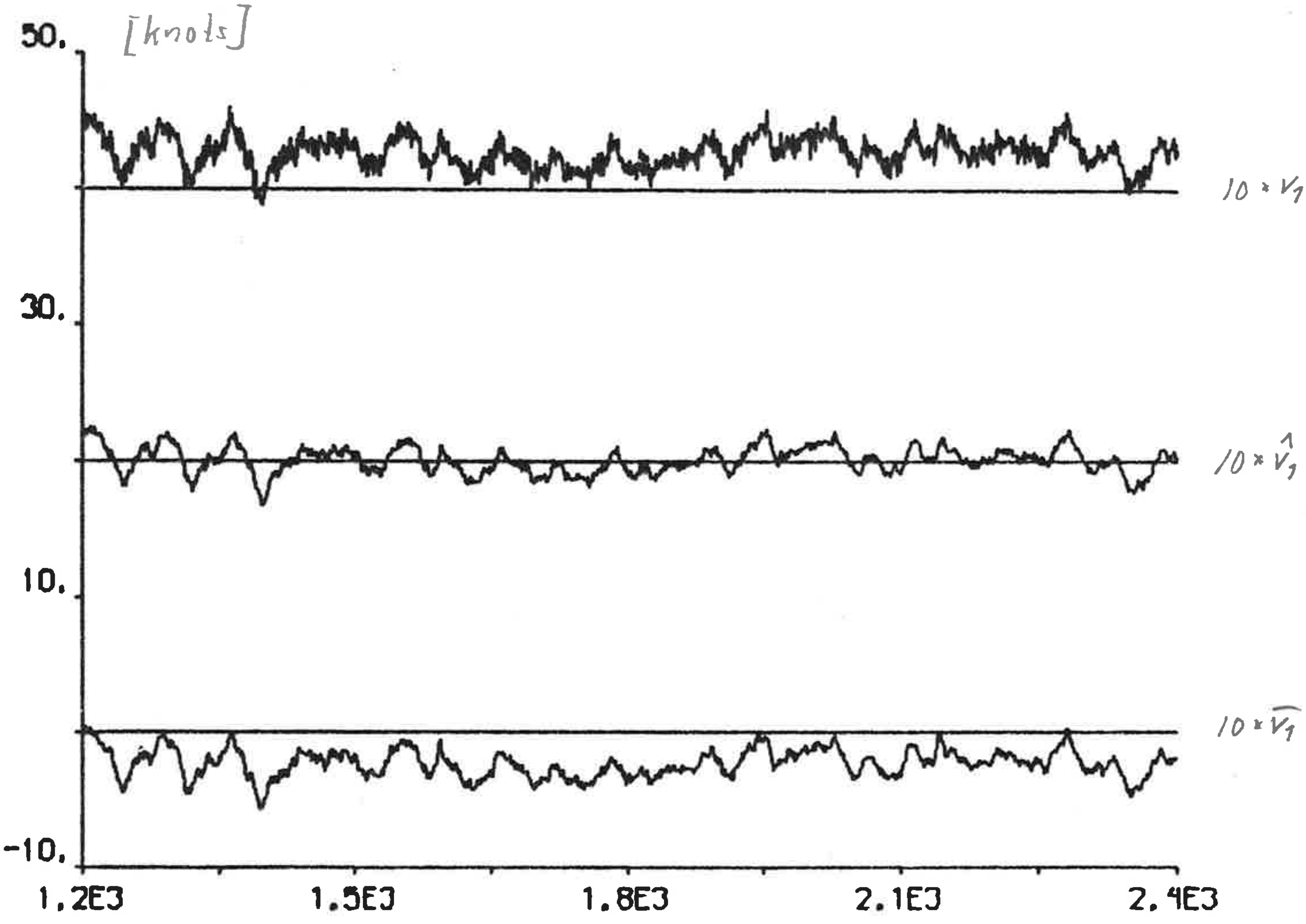


50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × V_m
10 × $\hat{V}$
10 × V

Fig. 4.4b



[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 * V1
10 * V̂1
10 * V̄1



[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 * V1
10 * V̂1
10 * V̄1

Fig. 4.4c

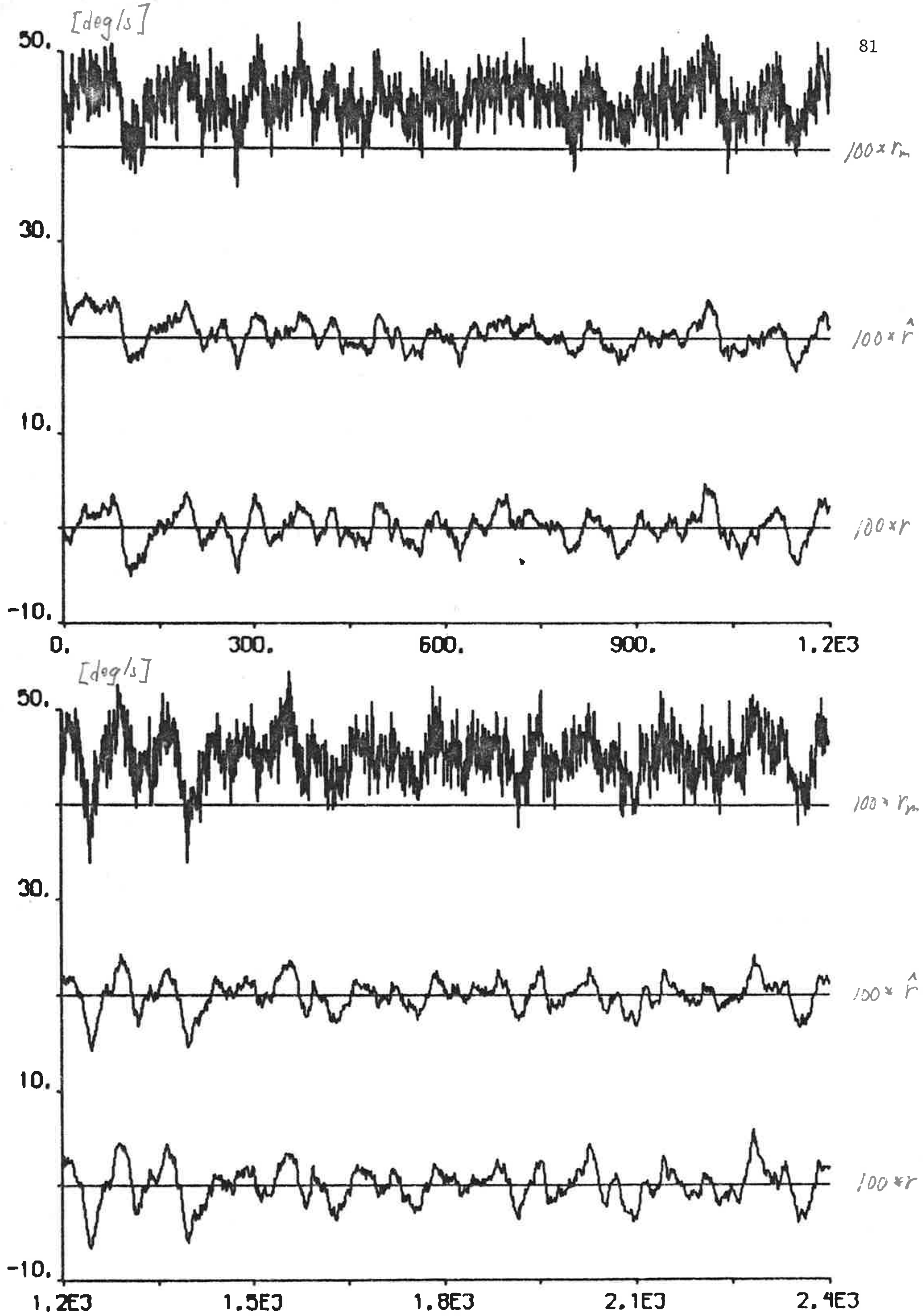

[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 × r_m
100 × $\hat{r}$
100 × r
[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 × r_m
100 × $\hat{r}$
100 × r

Fig. 4.4d

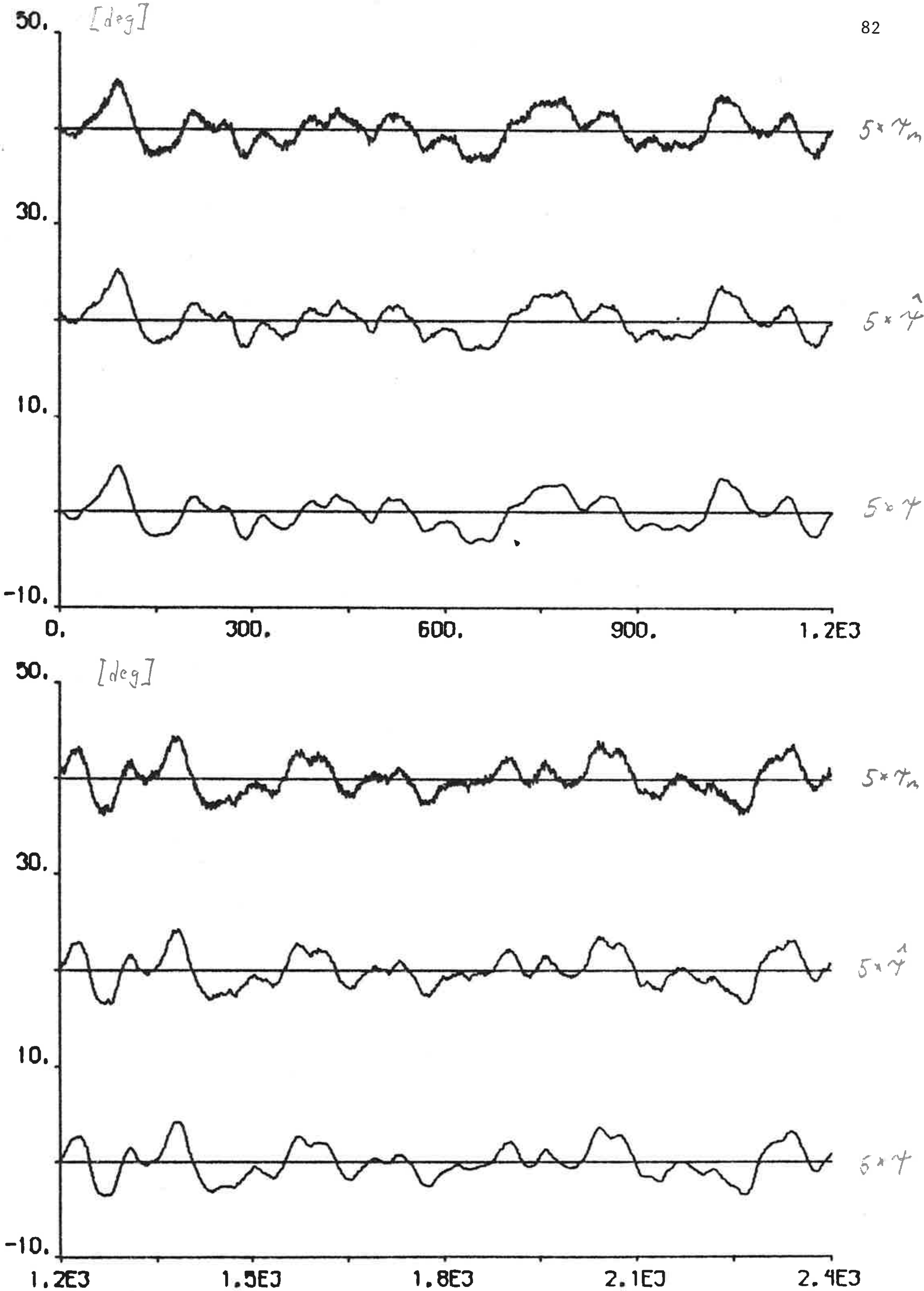

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5*ψm
5*ψ̂
5*ψ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5*ψm
5*ψ̂
5*ψ

Fig. 4.4e

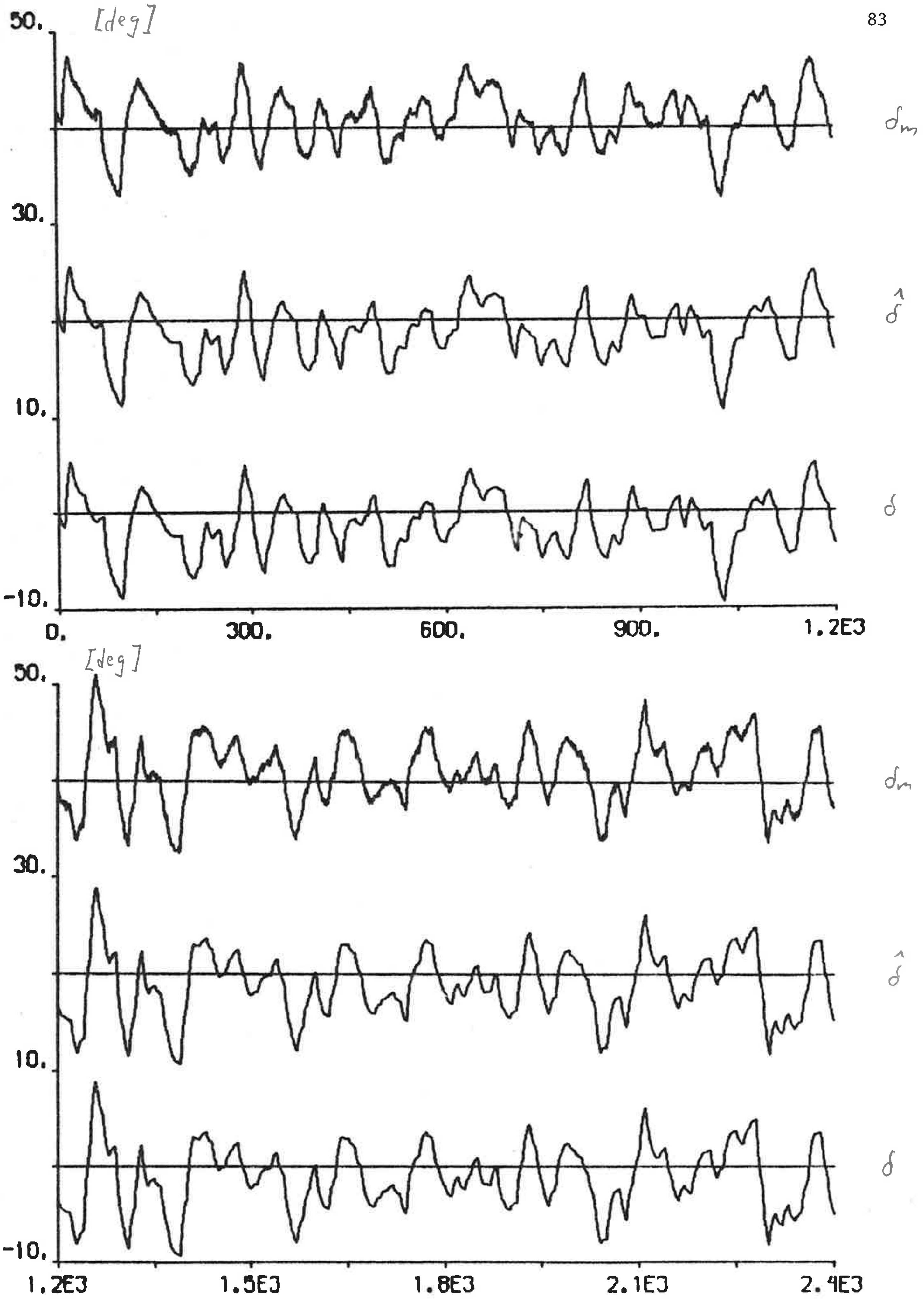
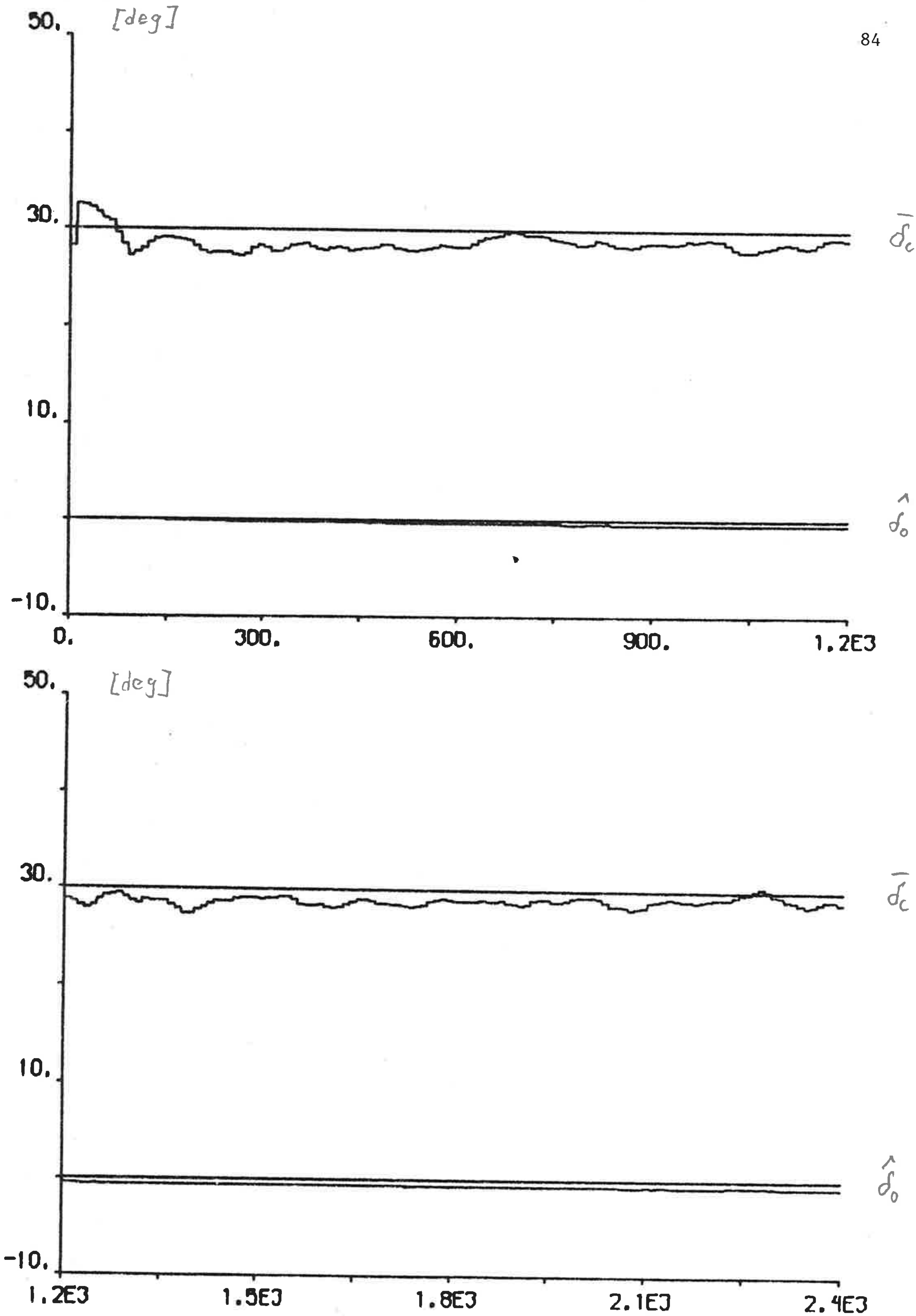

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
δm
δ̂
δ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
δm
δ̂
δ

Fig. 4.4f



[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.4g

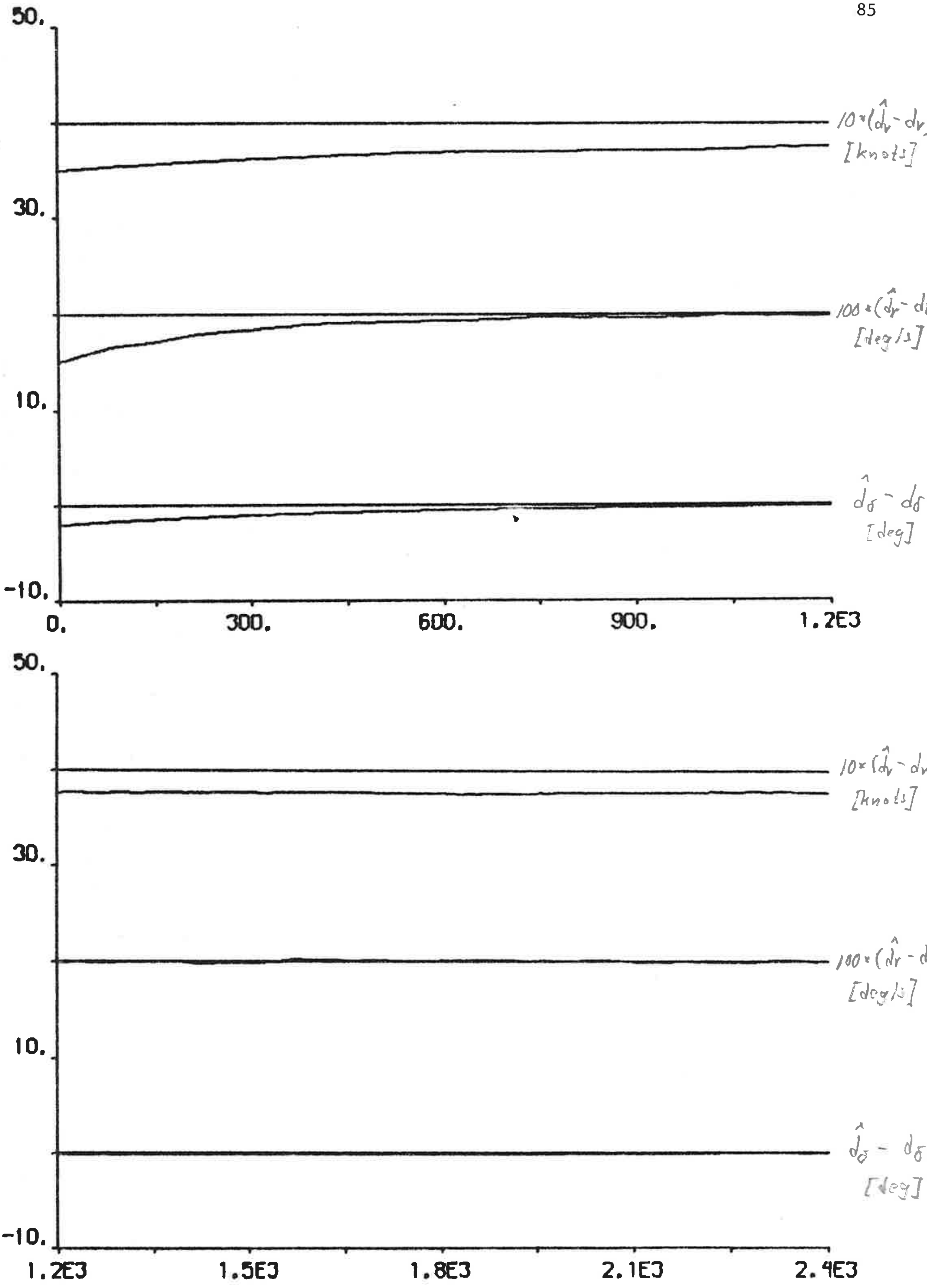
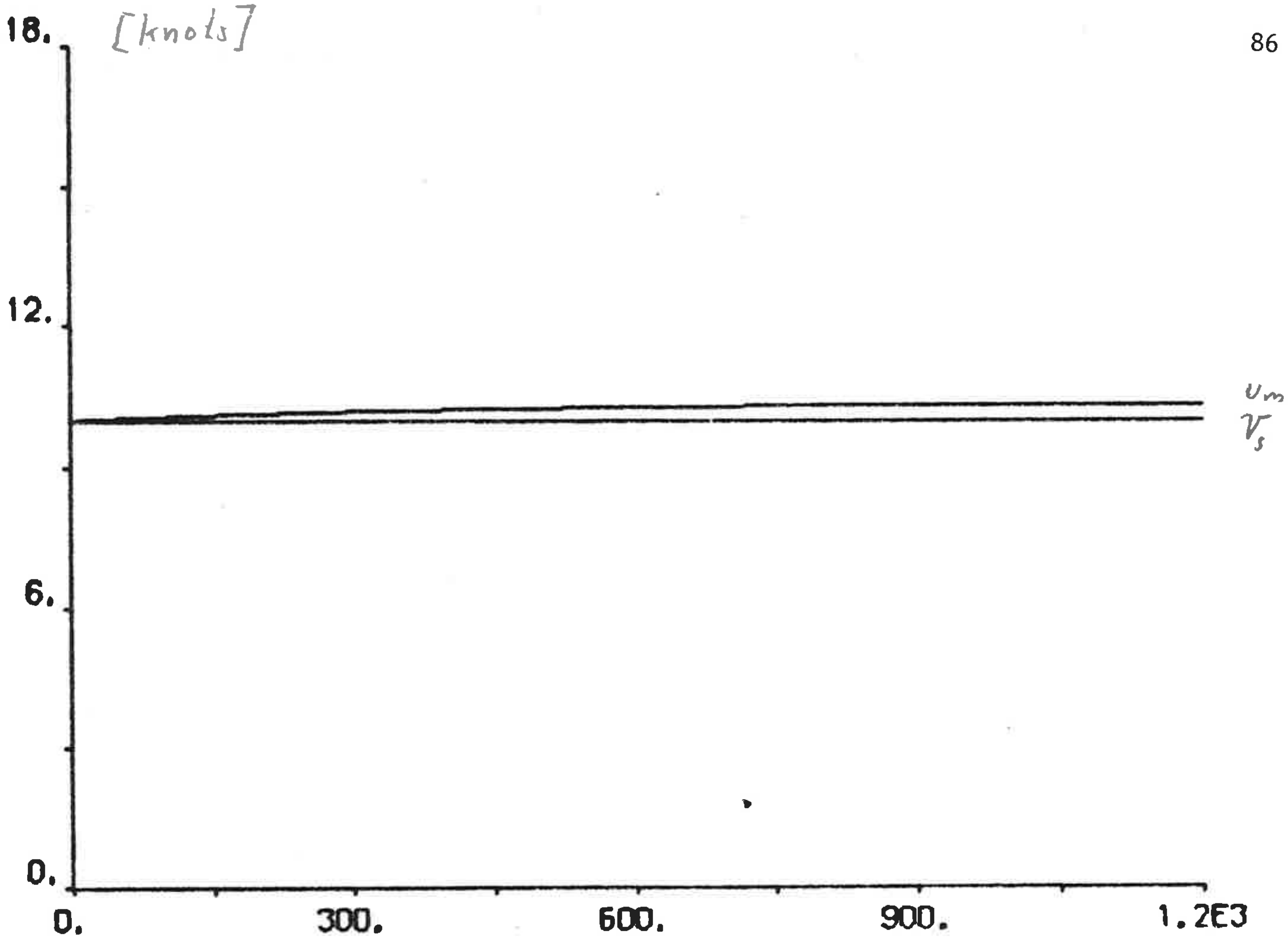
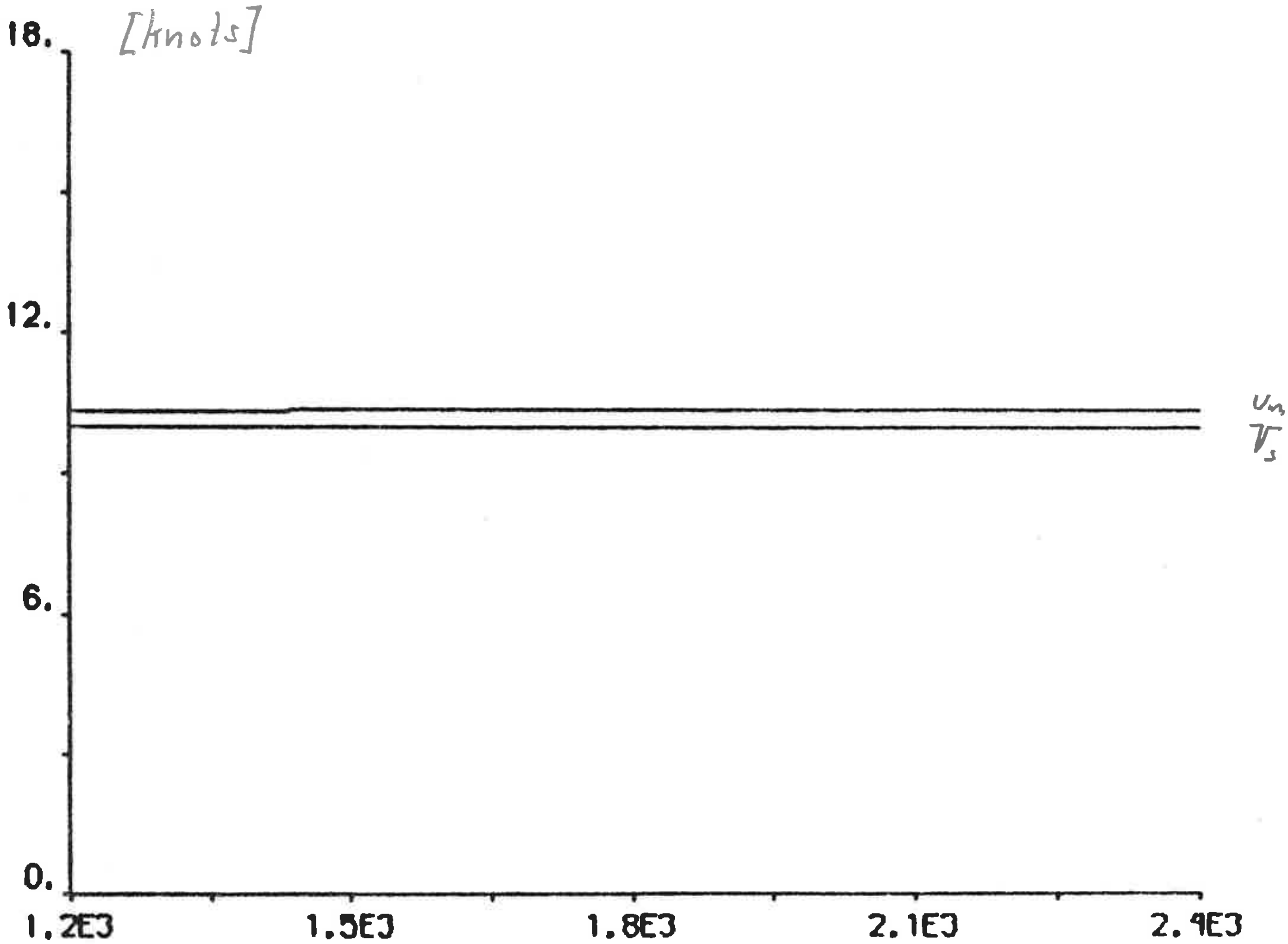


Fig. 4.4h



18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
u_m
V_s



18.
[knots]
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
u_m
V_s

Fig. 4.4i

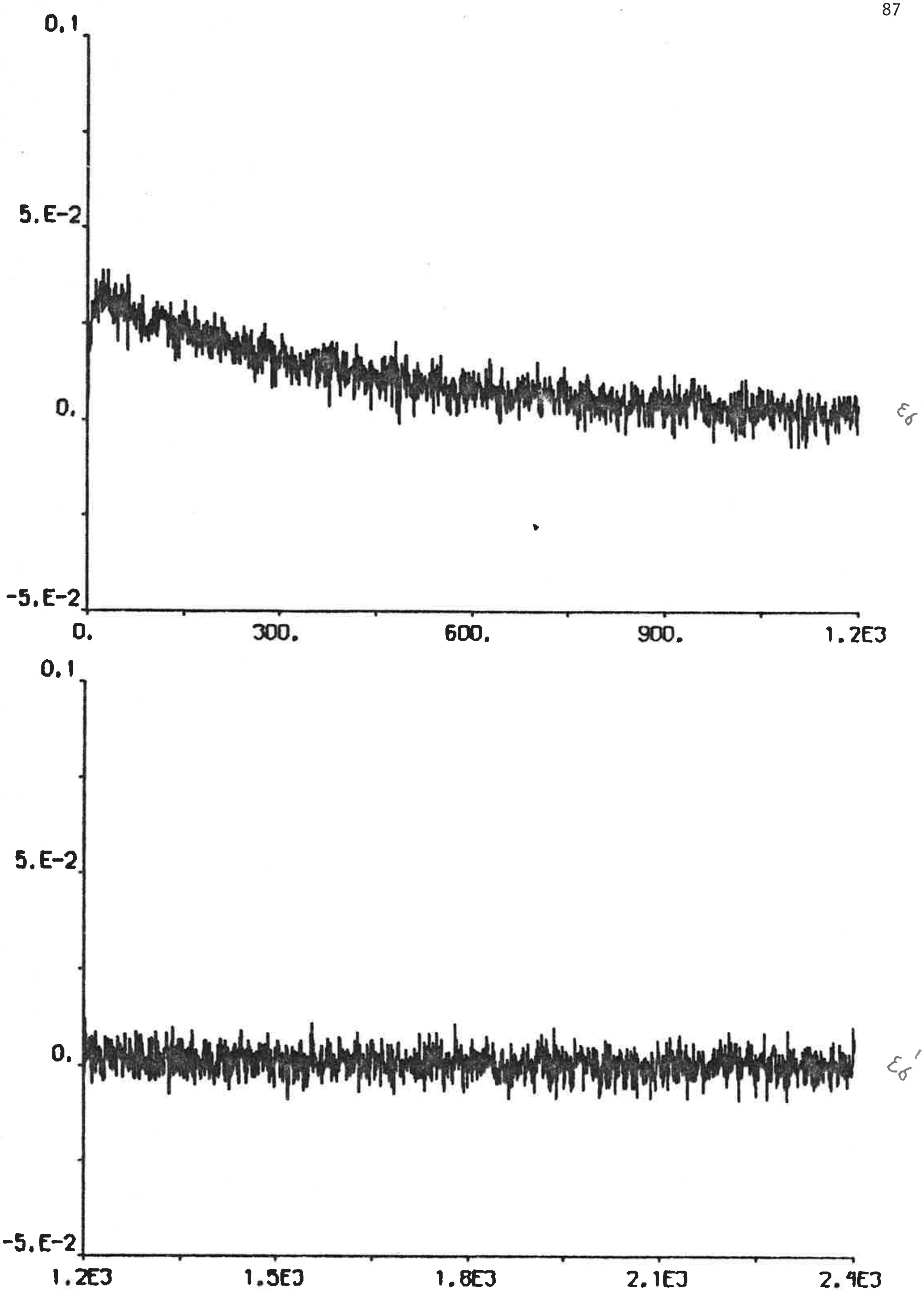

0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.4j

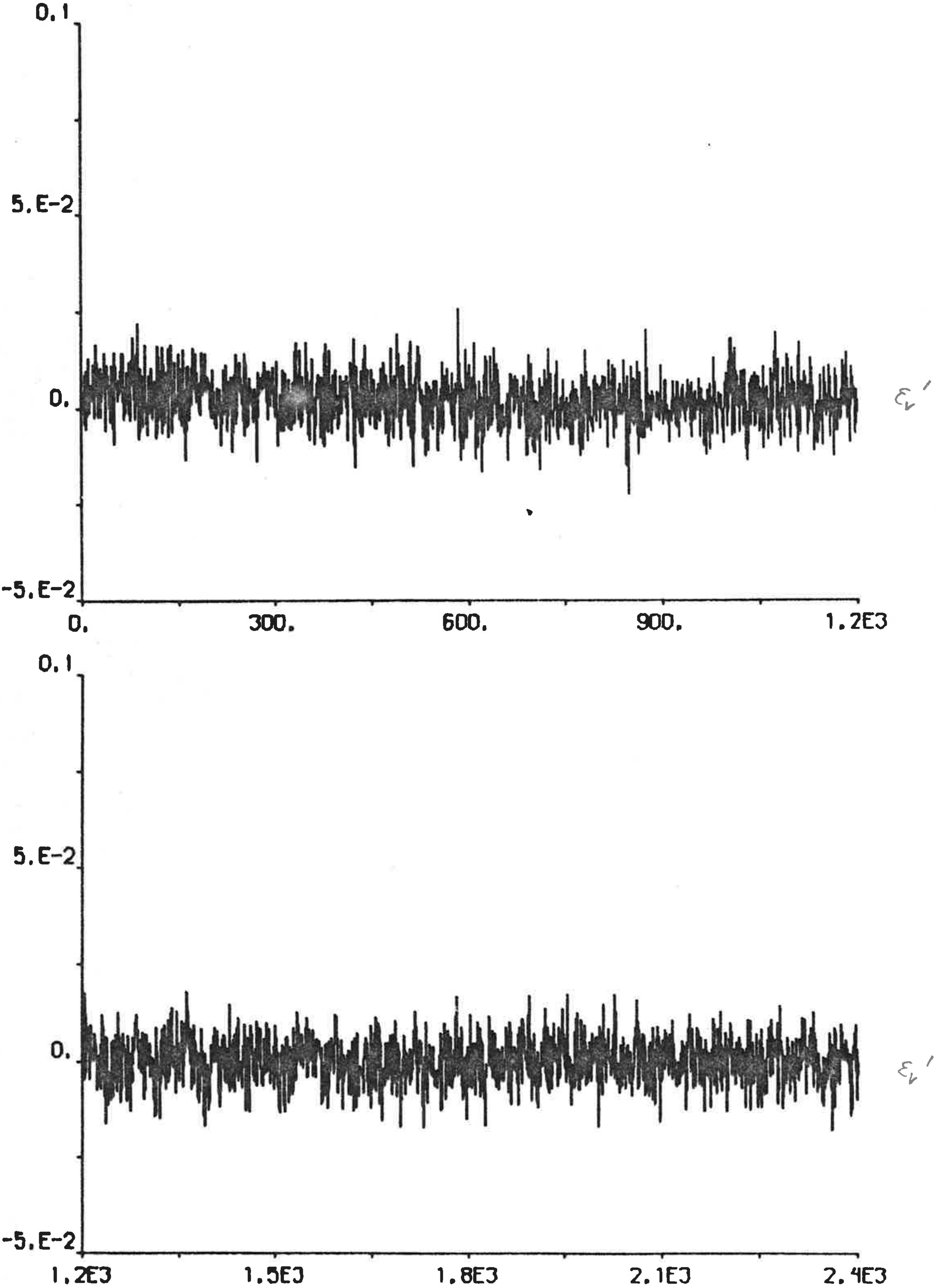
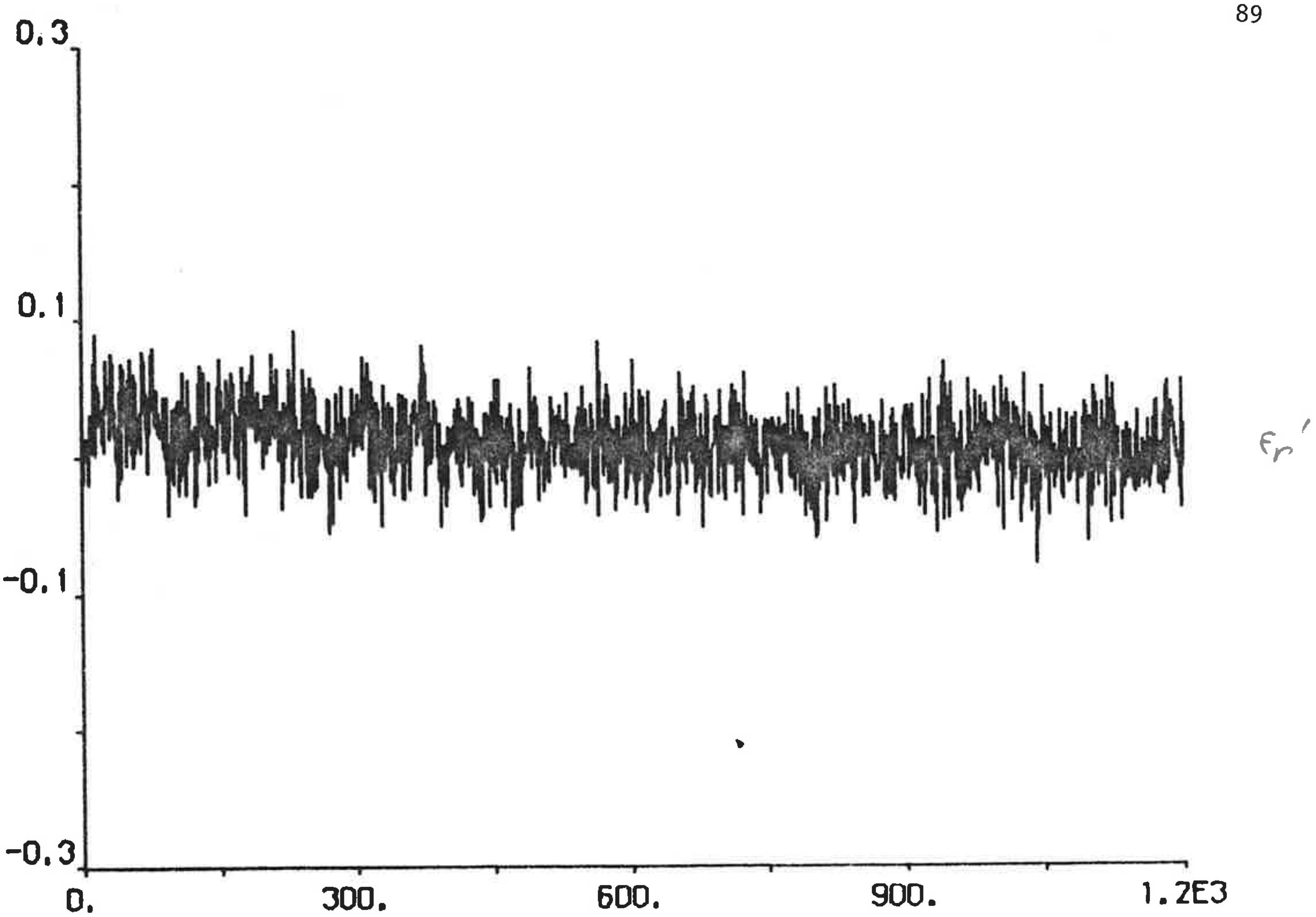

0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.4k


0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
ϵ_r'

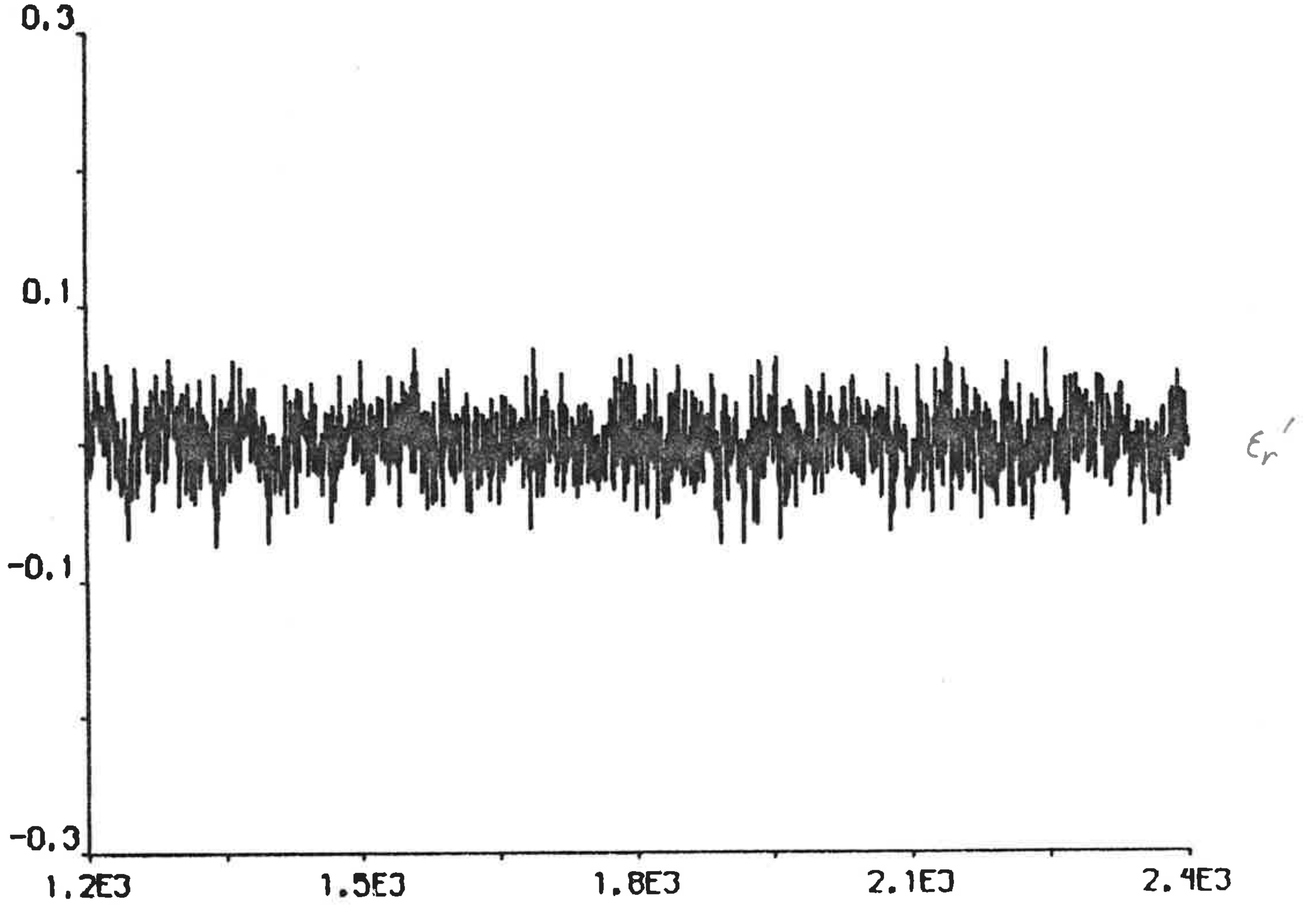
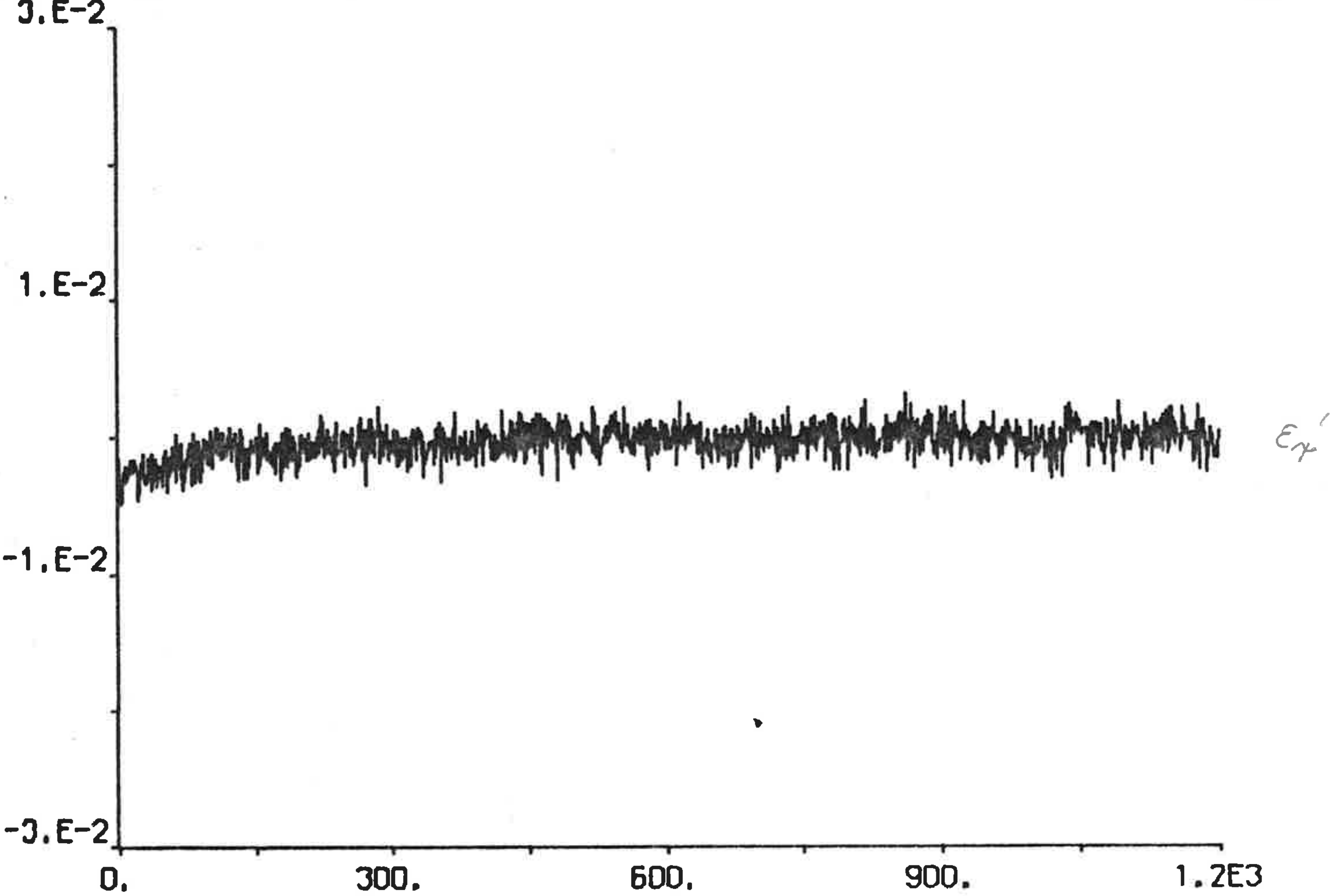

0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ϵ_r'

Fig. 4.4ℓ


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
ε_{γ}'

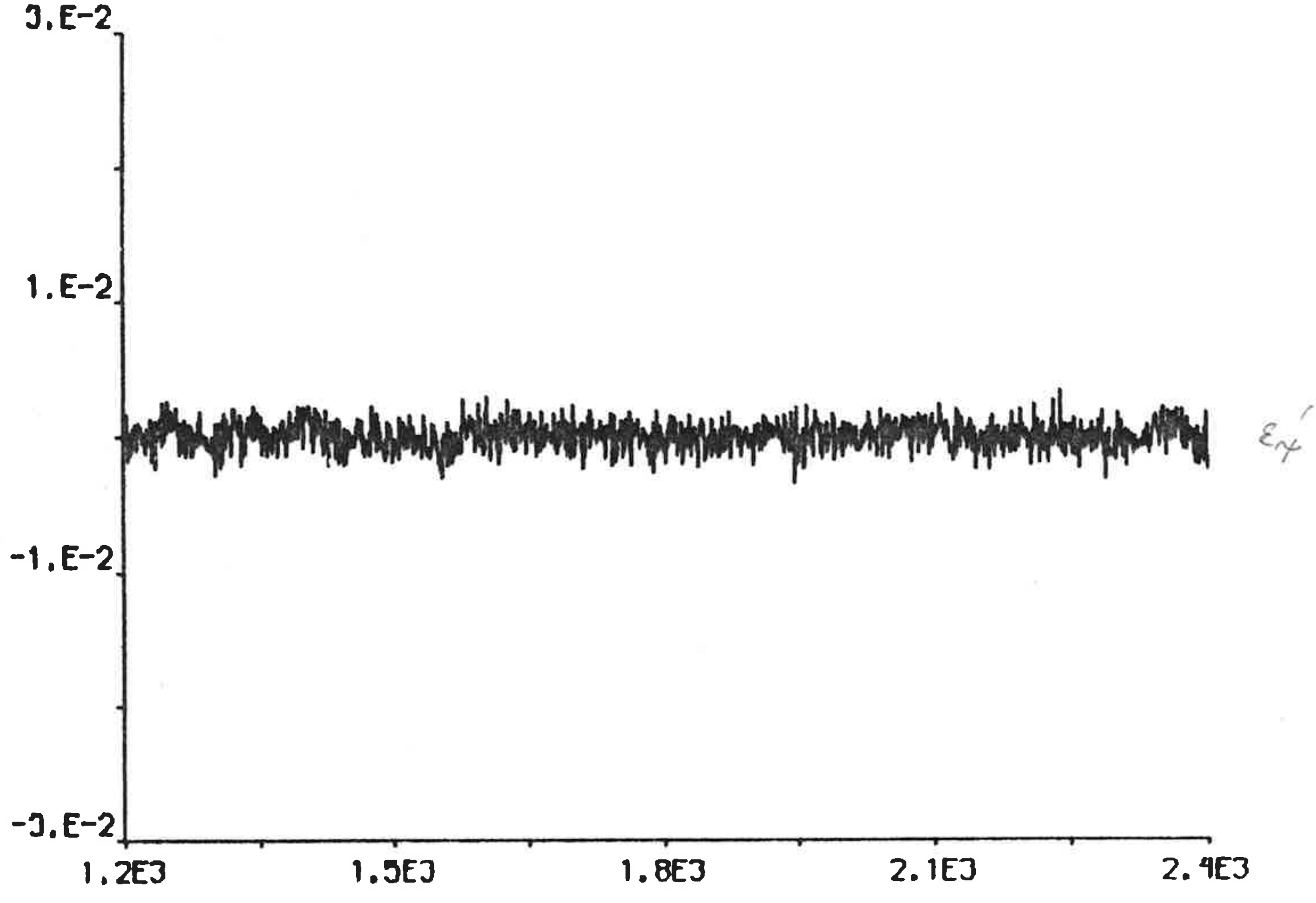

3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_{γ}'

Fig. 4.4m

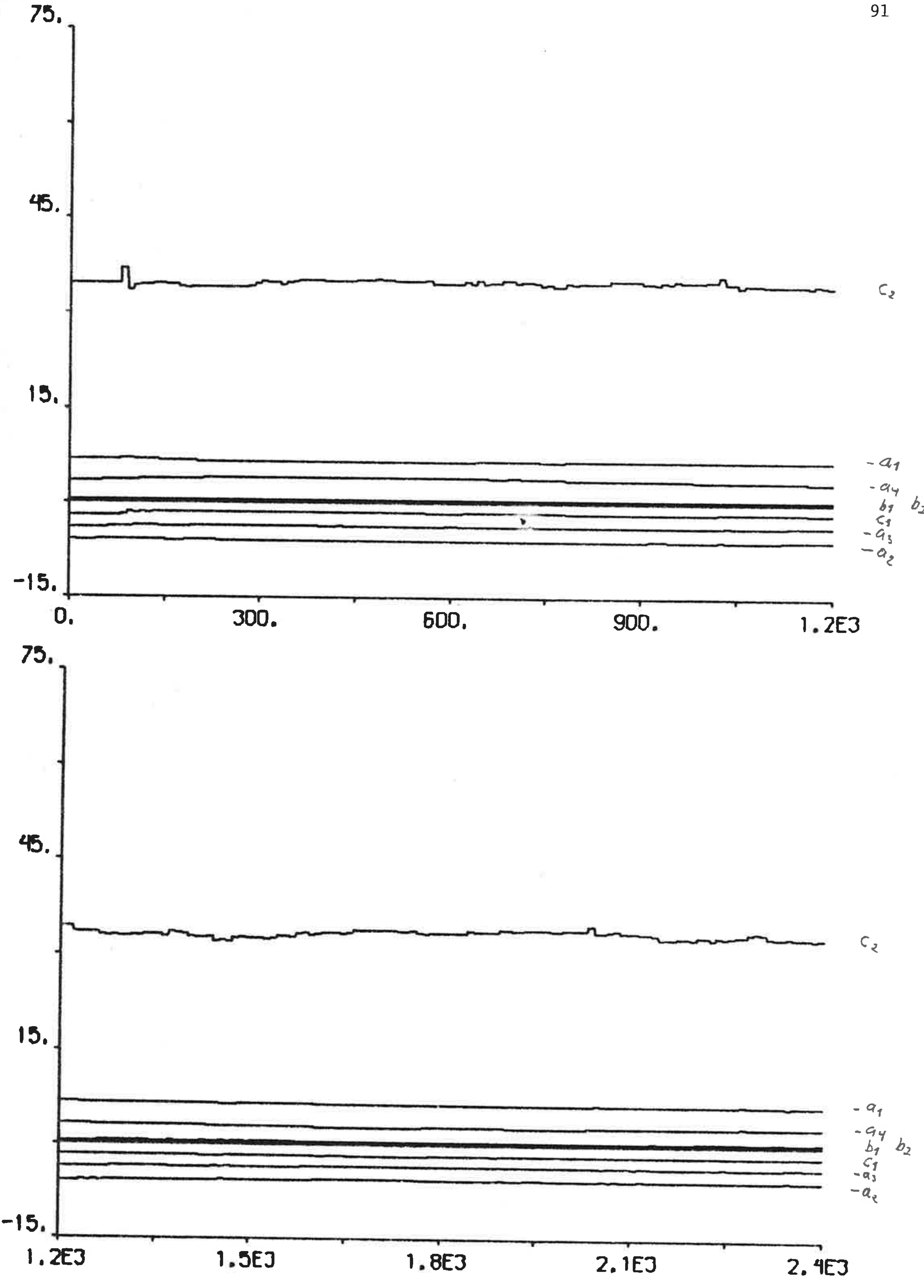

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$

Fig. 4.4n

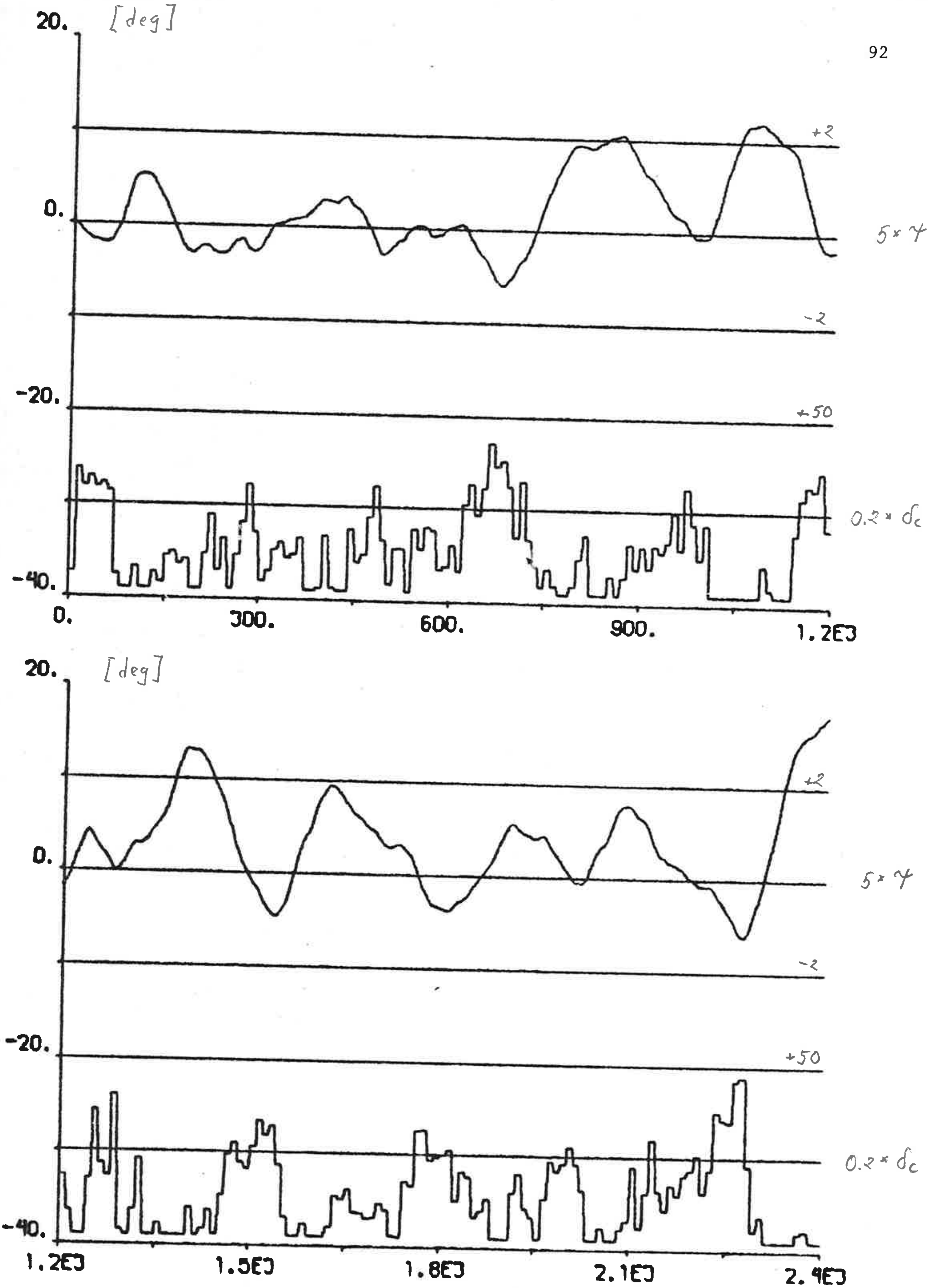


Fig. 4.5a - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using estimates from the Kalman filter.

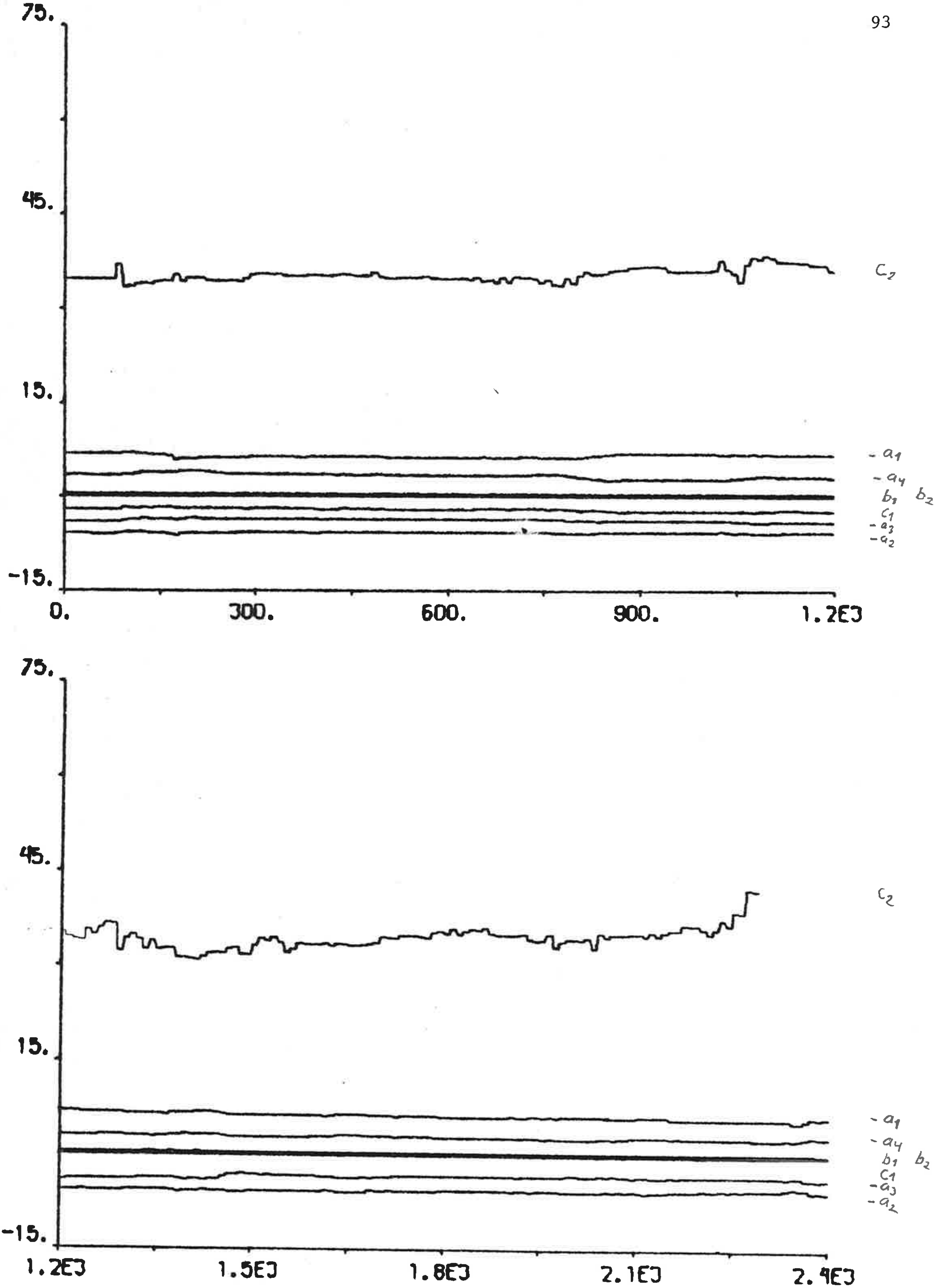

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$

Fig. 4.5b

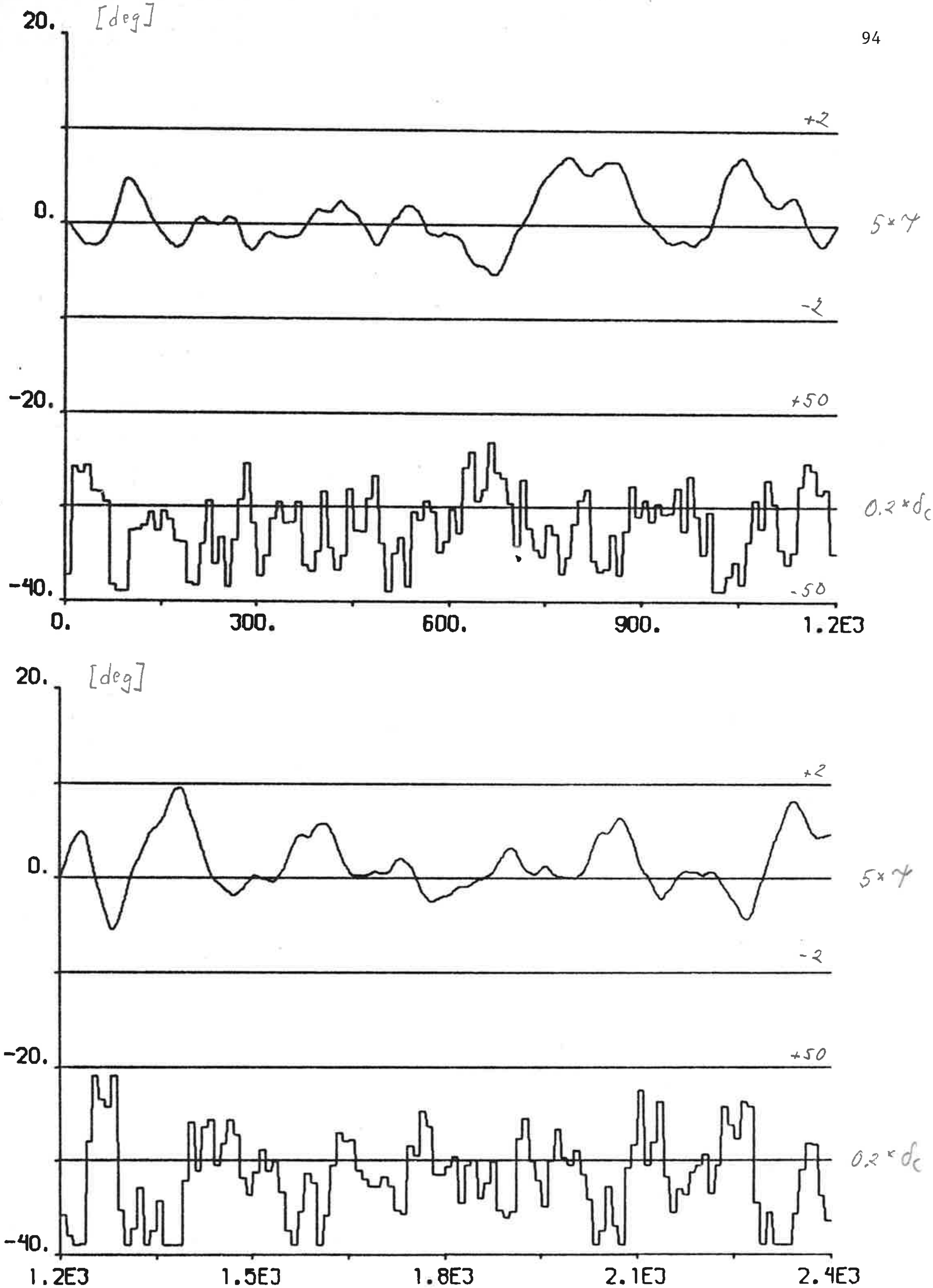
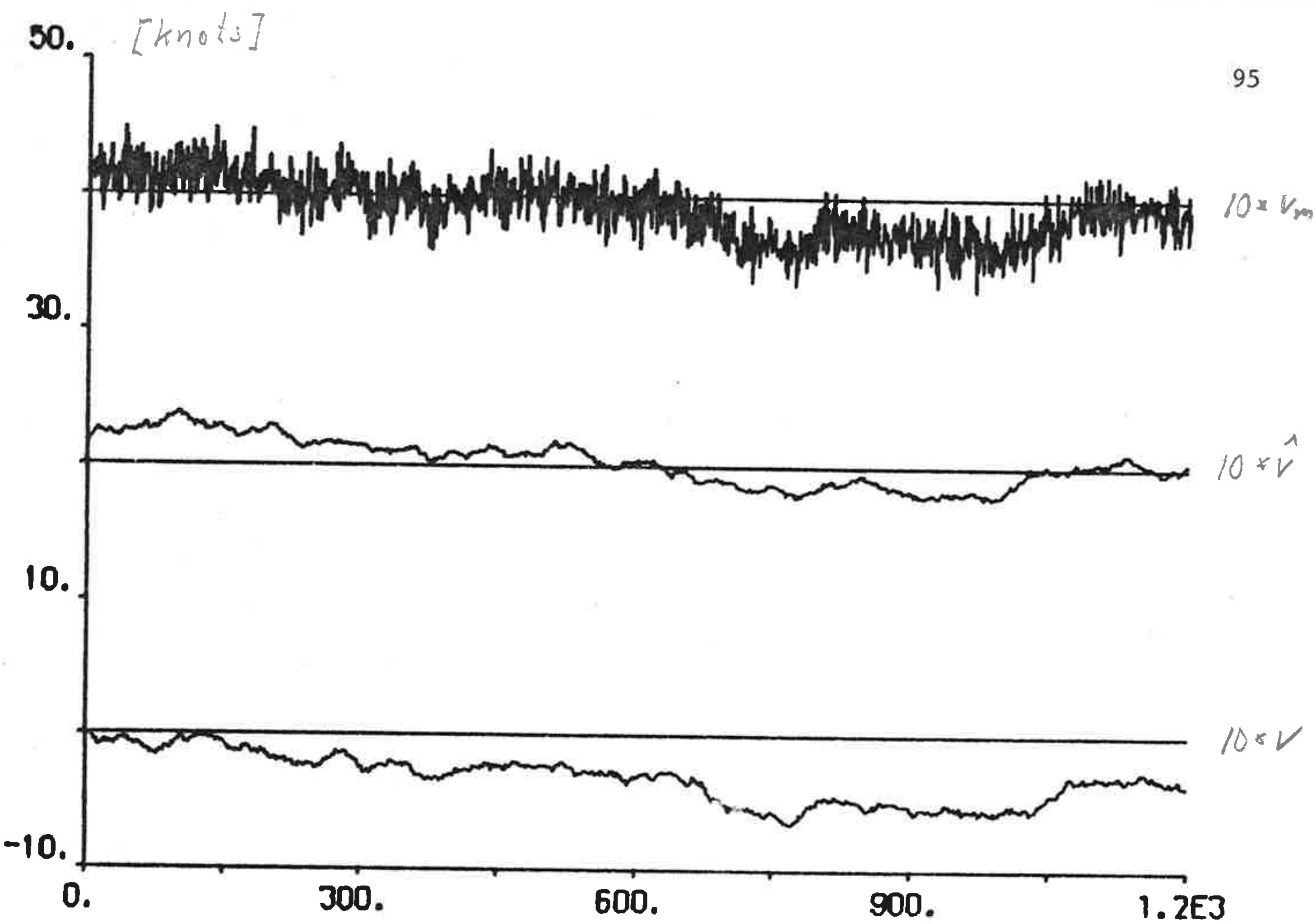
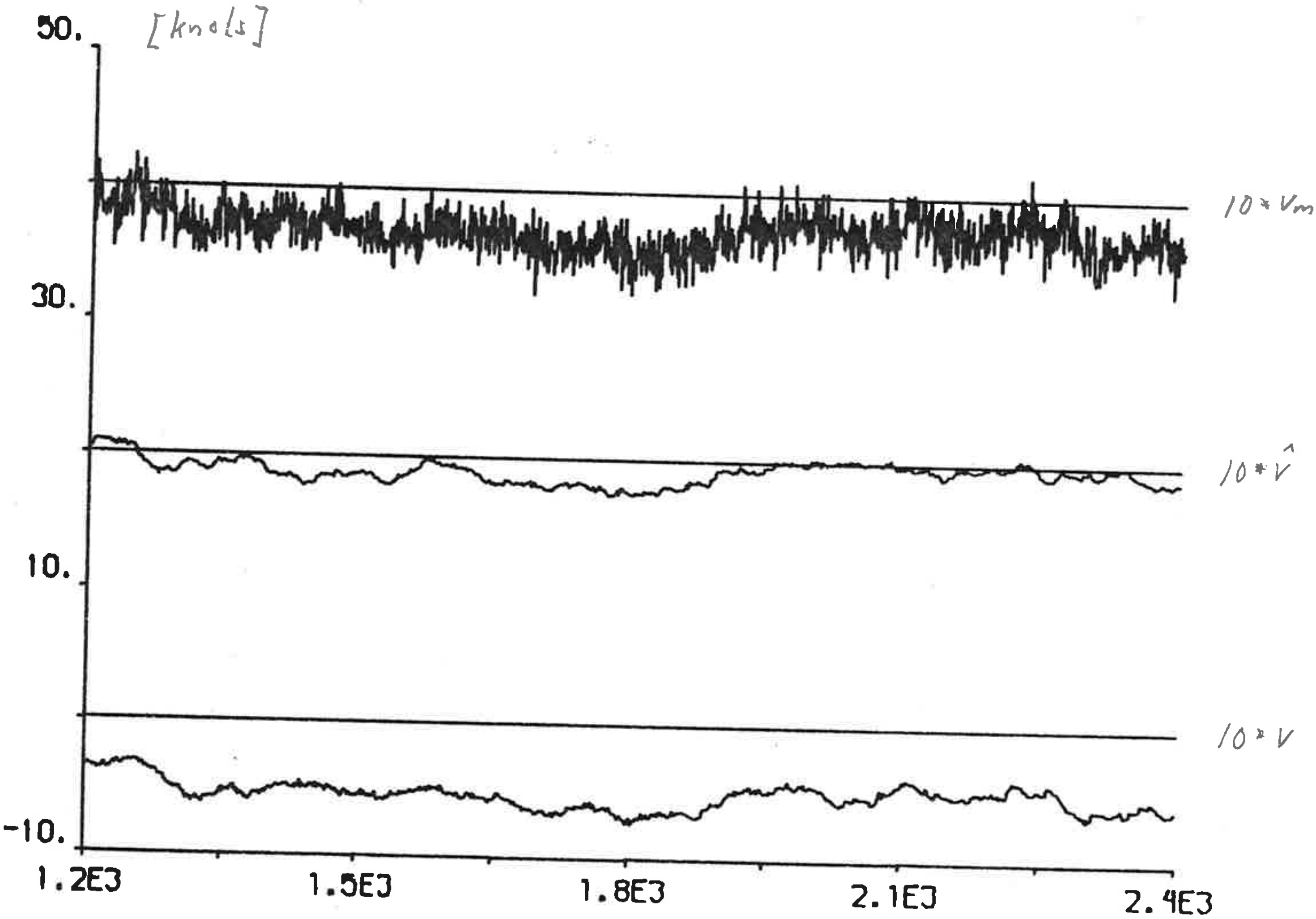


Fig. 4.6a - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using estimates from the Kalman filter.



50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 * Vm
10 * V̂
10 * V



50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 * Vm
10 * V̂
10 * V

Fig. 4.6b

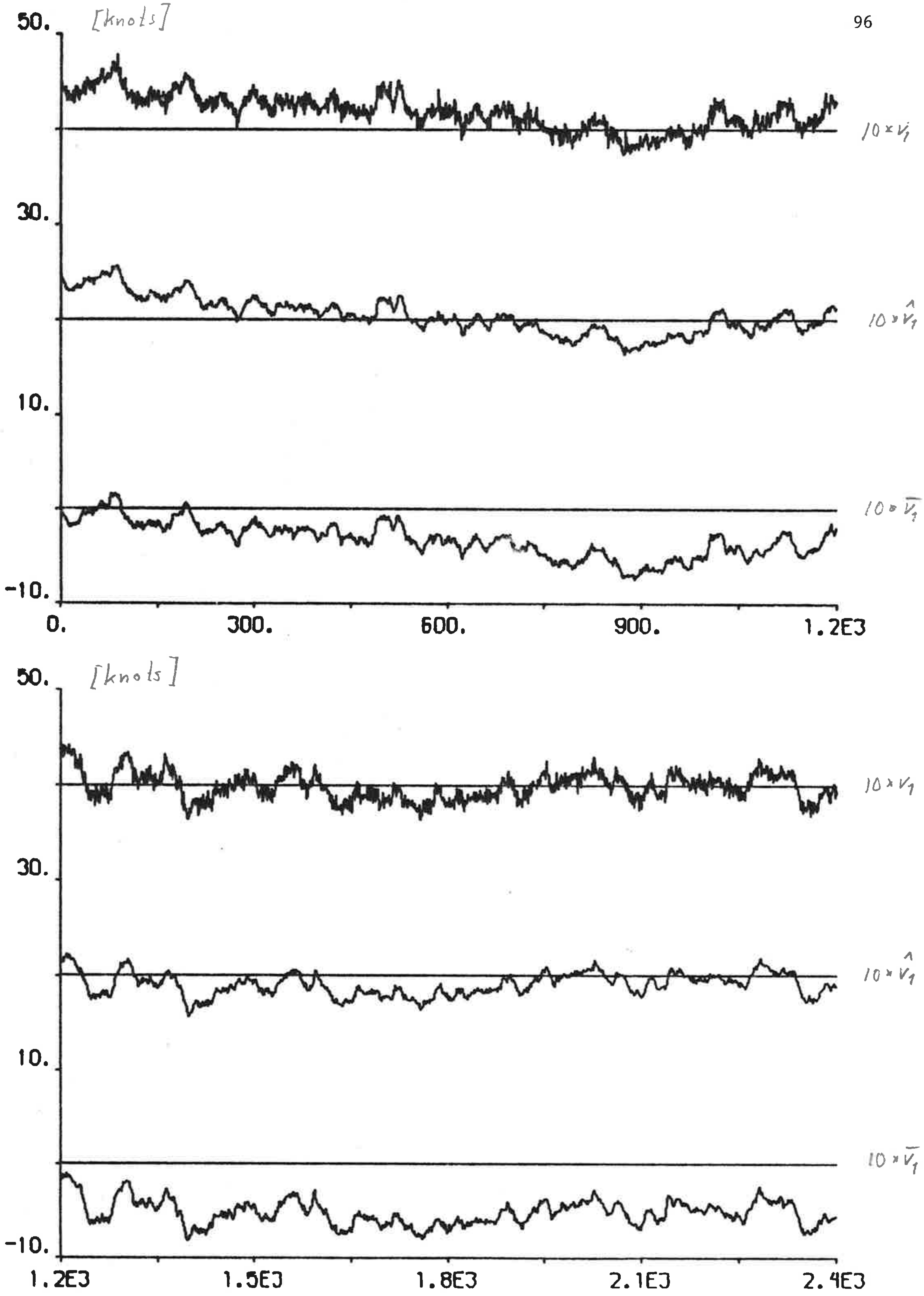

50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × v1
10 × v̂1
10 × v̄1
50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × v1
10 × v̂1
10 × v̄1

Fig. 4.6c

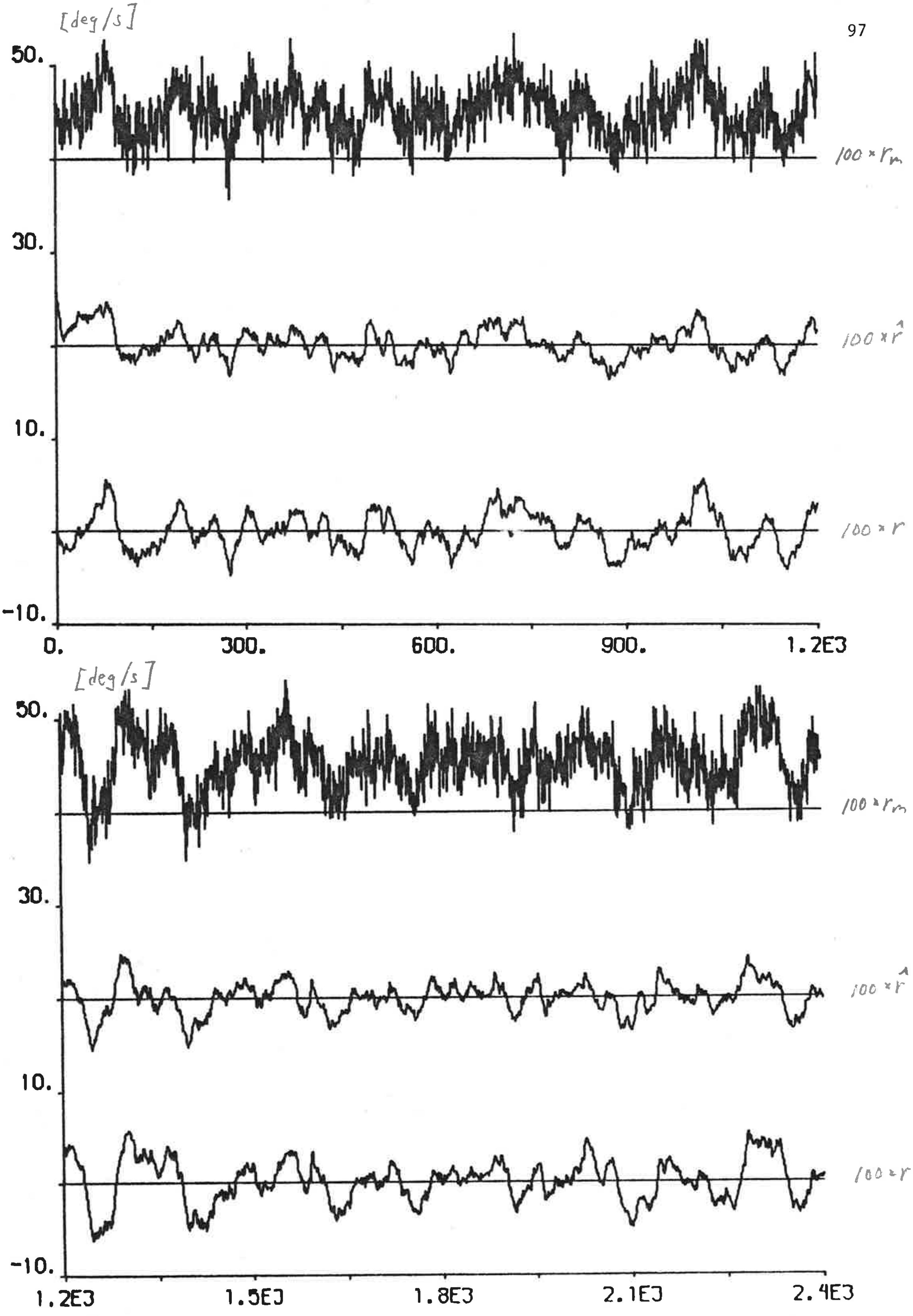
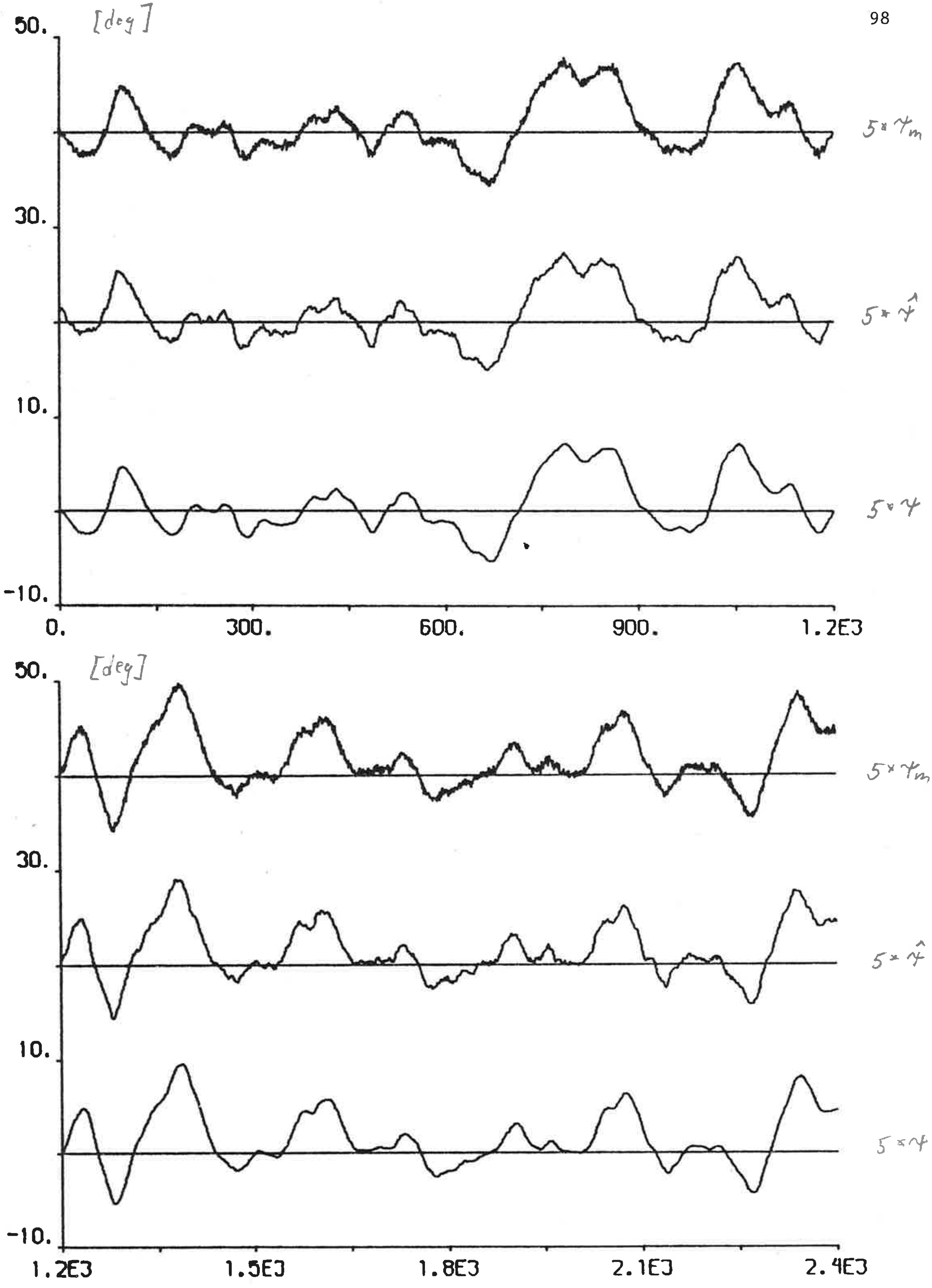
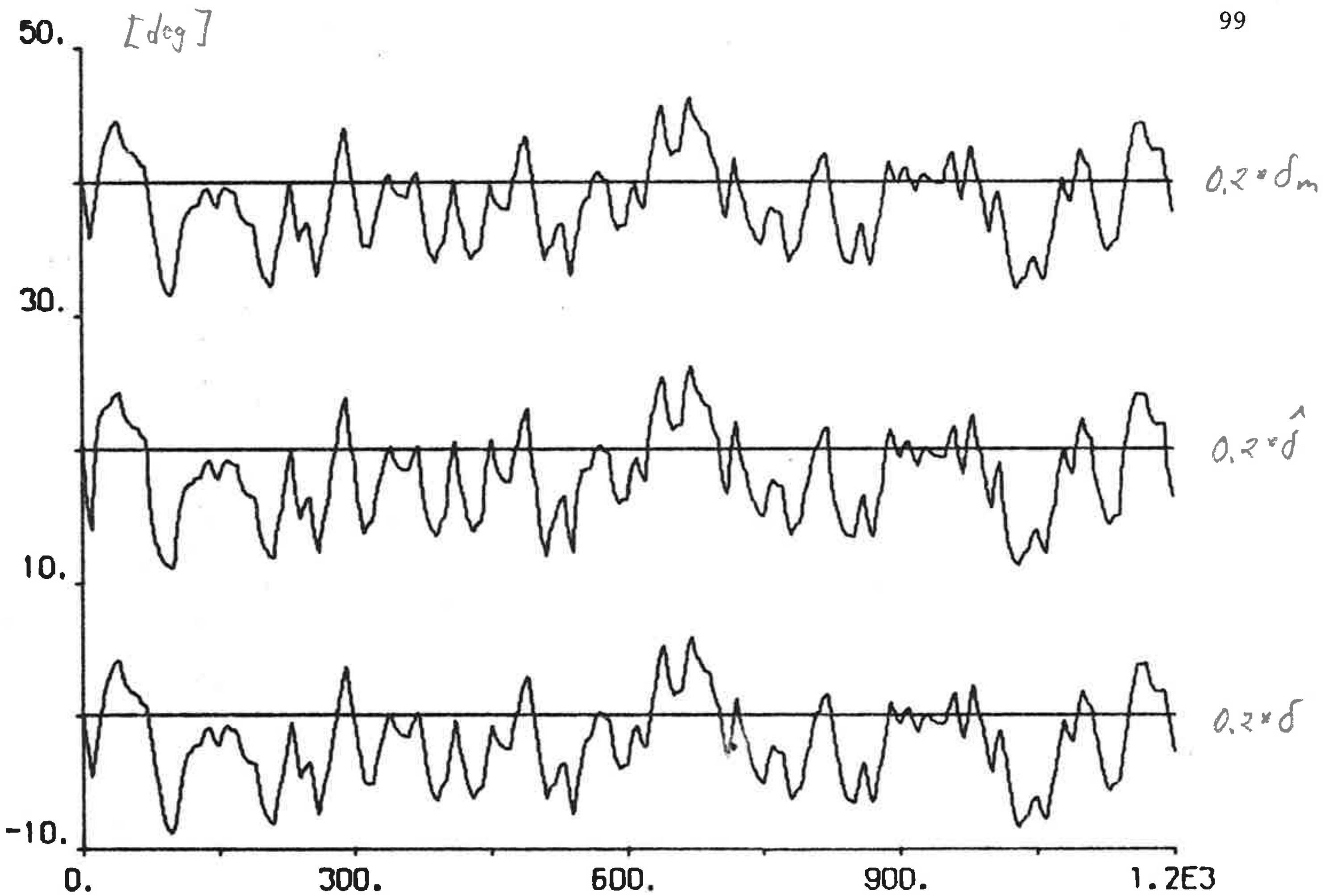

[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 × r_m
100 × $\hat{r}$
100 × r
[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 × r_m
100 × $\hat{r}$
100 × r

Fig. 4.6d



[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5*ψm
5*ψ̂
5*ψ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5*ψm
5*ψ̂
5*ψ

Fig. 4.6e


50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
0.2 * δm
0.2 * δ̂
0.2 * δ

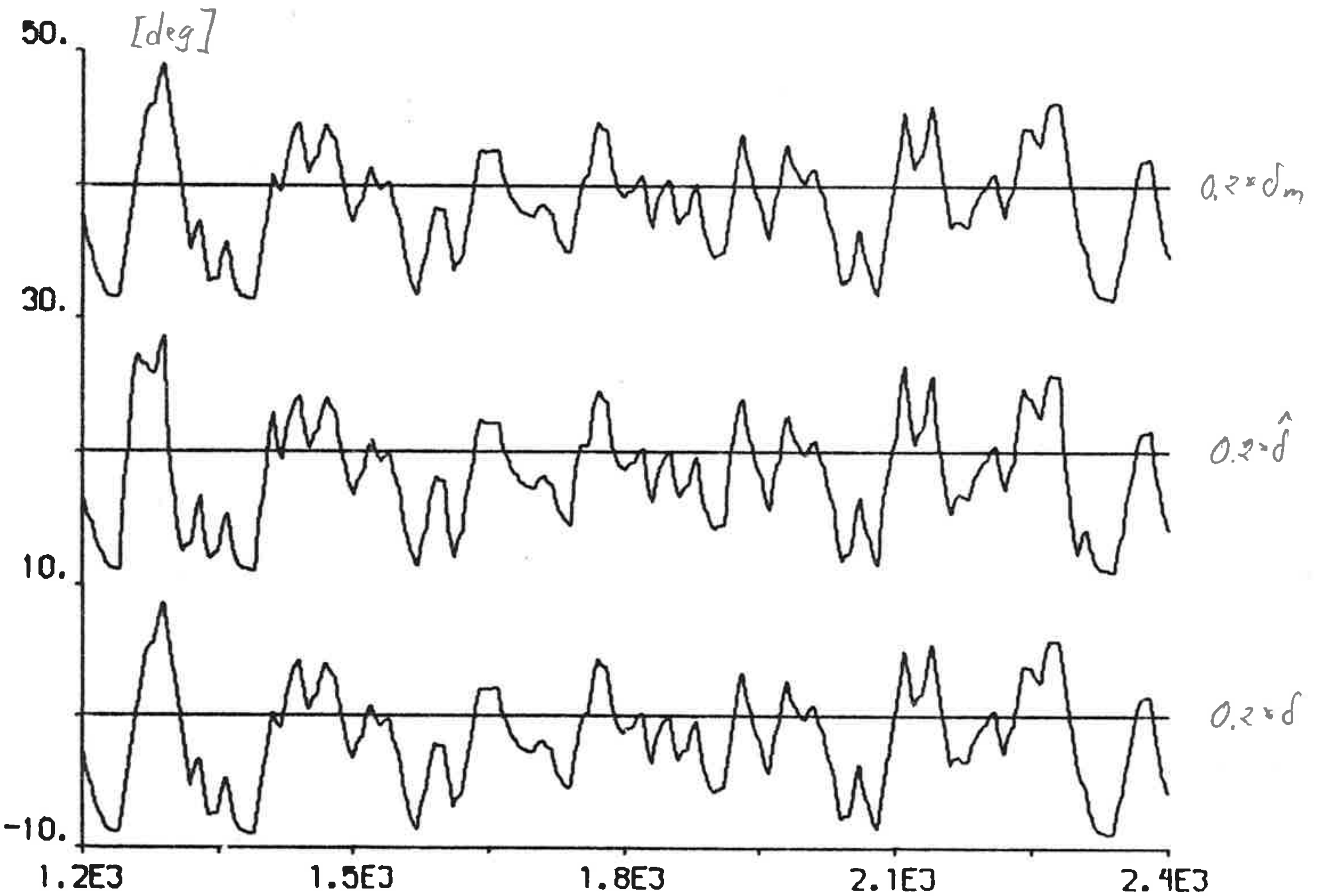
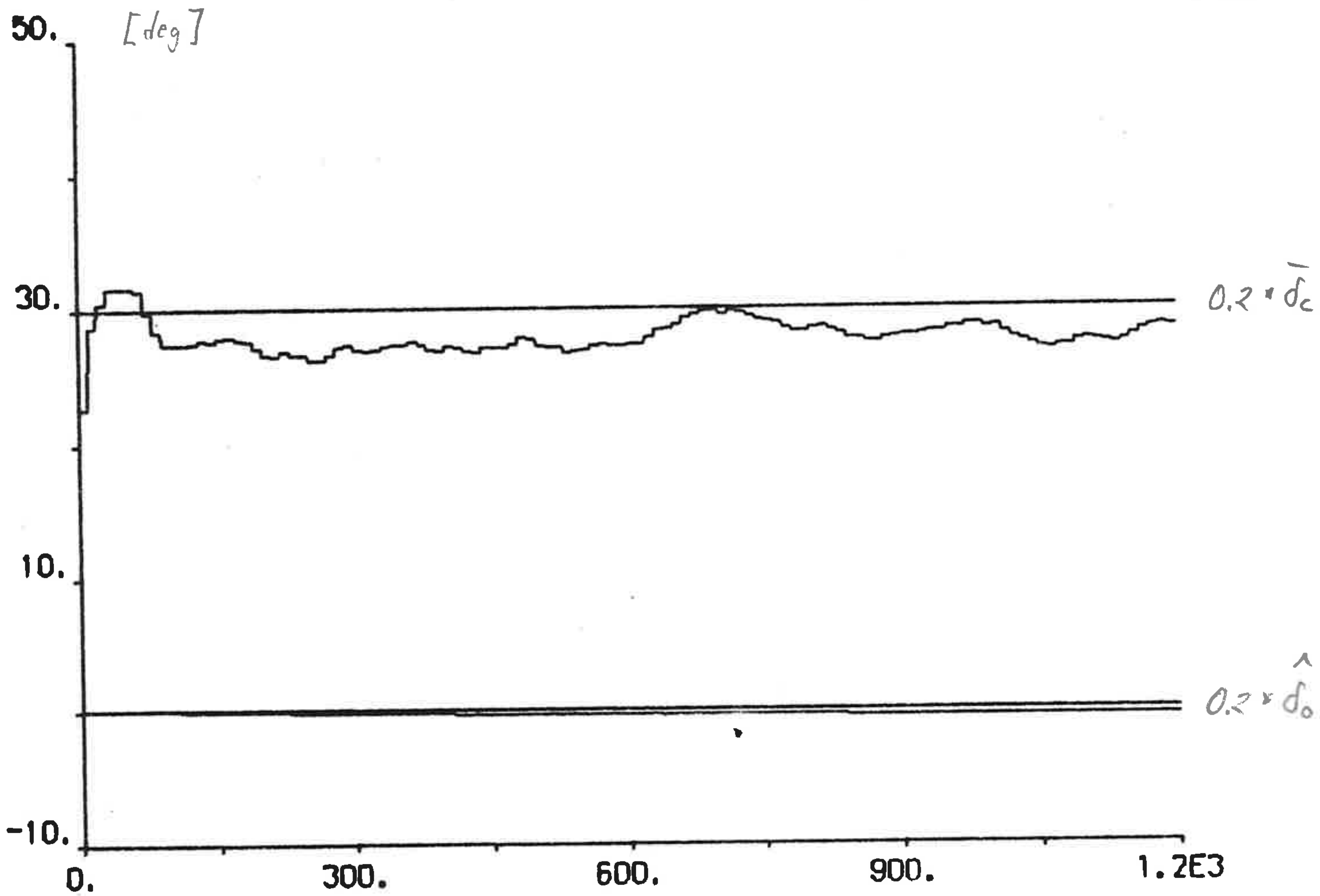
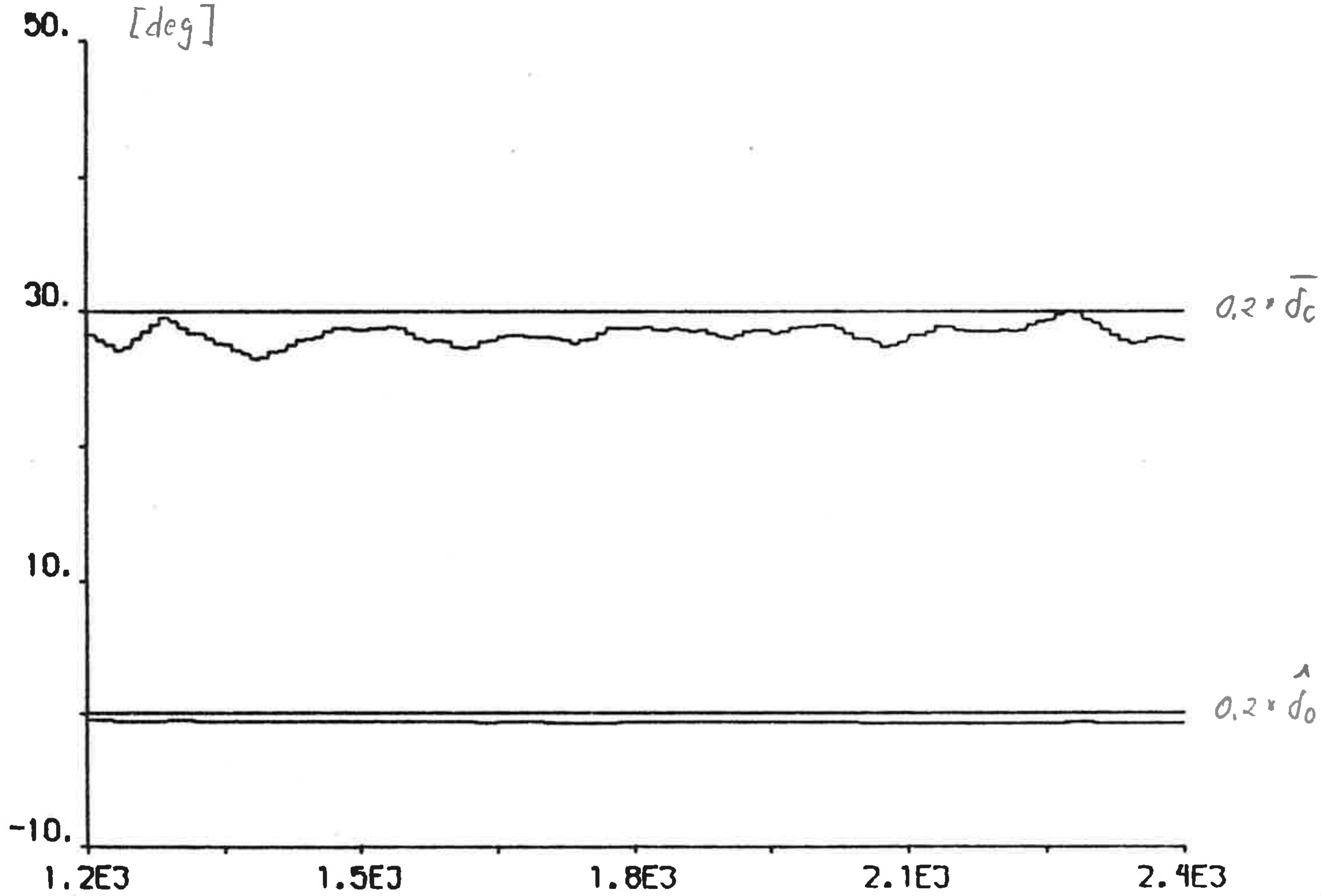

50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
0.2 * δm
0.2 * δ̂
0.2 * δ

Fig. 4.6f



50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
0.2 * $\bar{d}_c$
0.2 * $\hat{d}_o$



50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
0.2 * $\bar{d}_c$
0.2 * $\hat{d}_o$

Fig. 4.6g

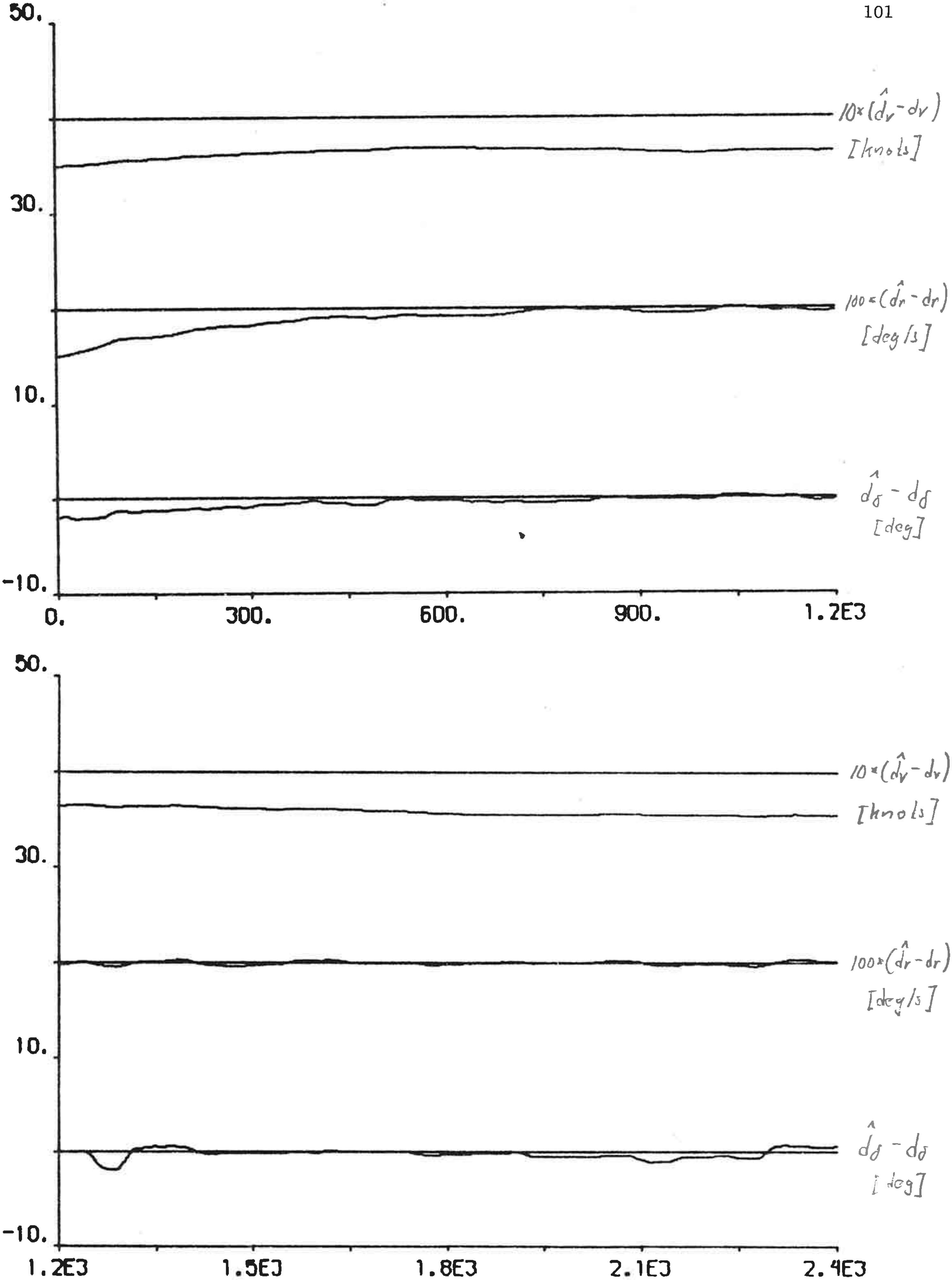
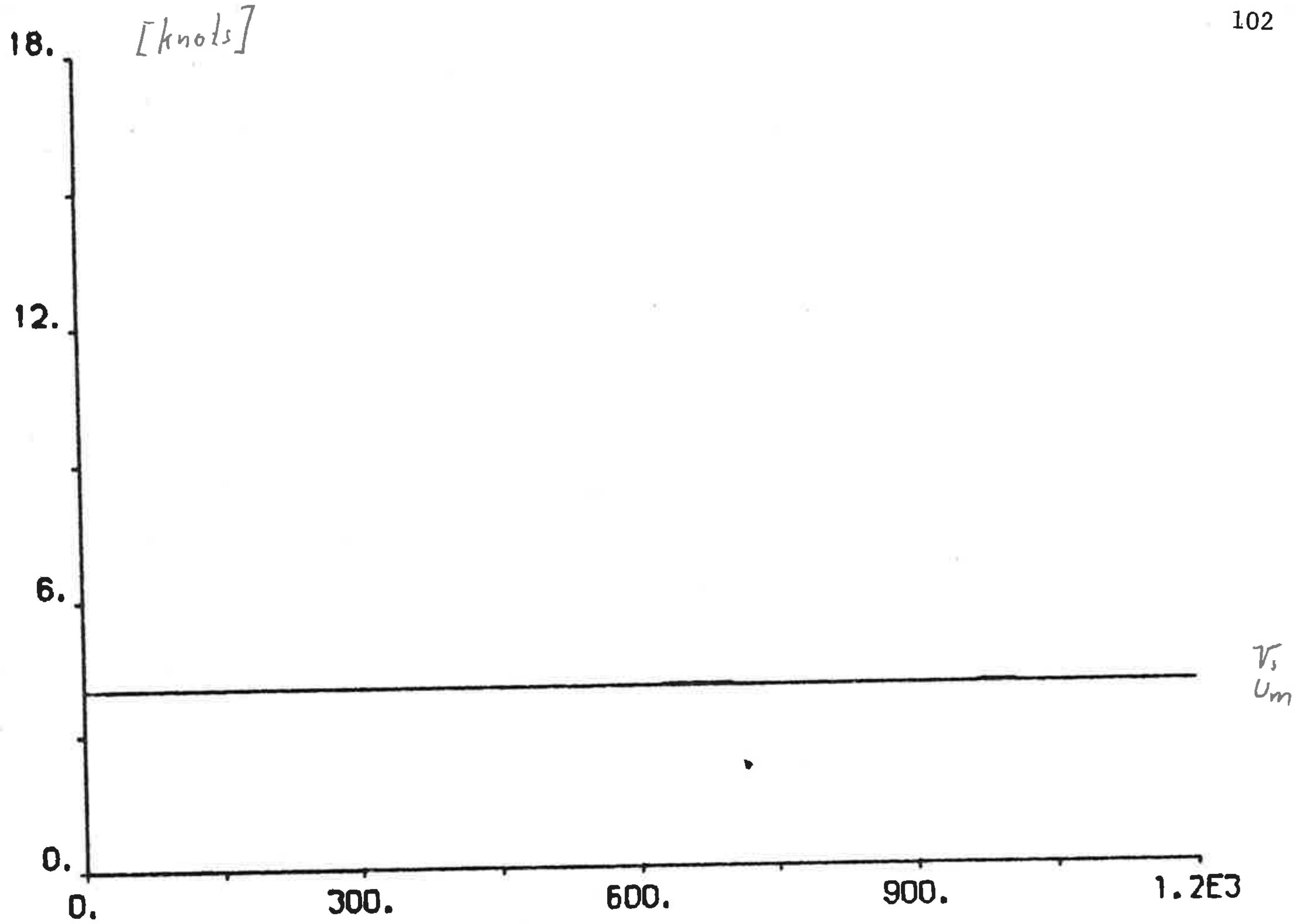

50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10*(d̂v-dv)
[knots]
100*(d̂r-dr)
[deg/s]
d̂δ - dδ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10*(d̂v-dv)
[knots]
100*(d̂r-dr)
[deg/s]
d̂δ - dδ
[deg]

Fig. 4.6h


18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
U_m

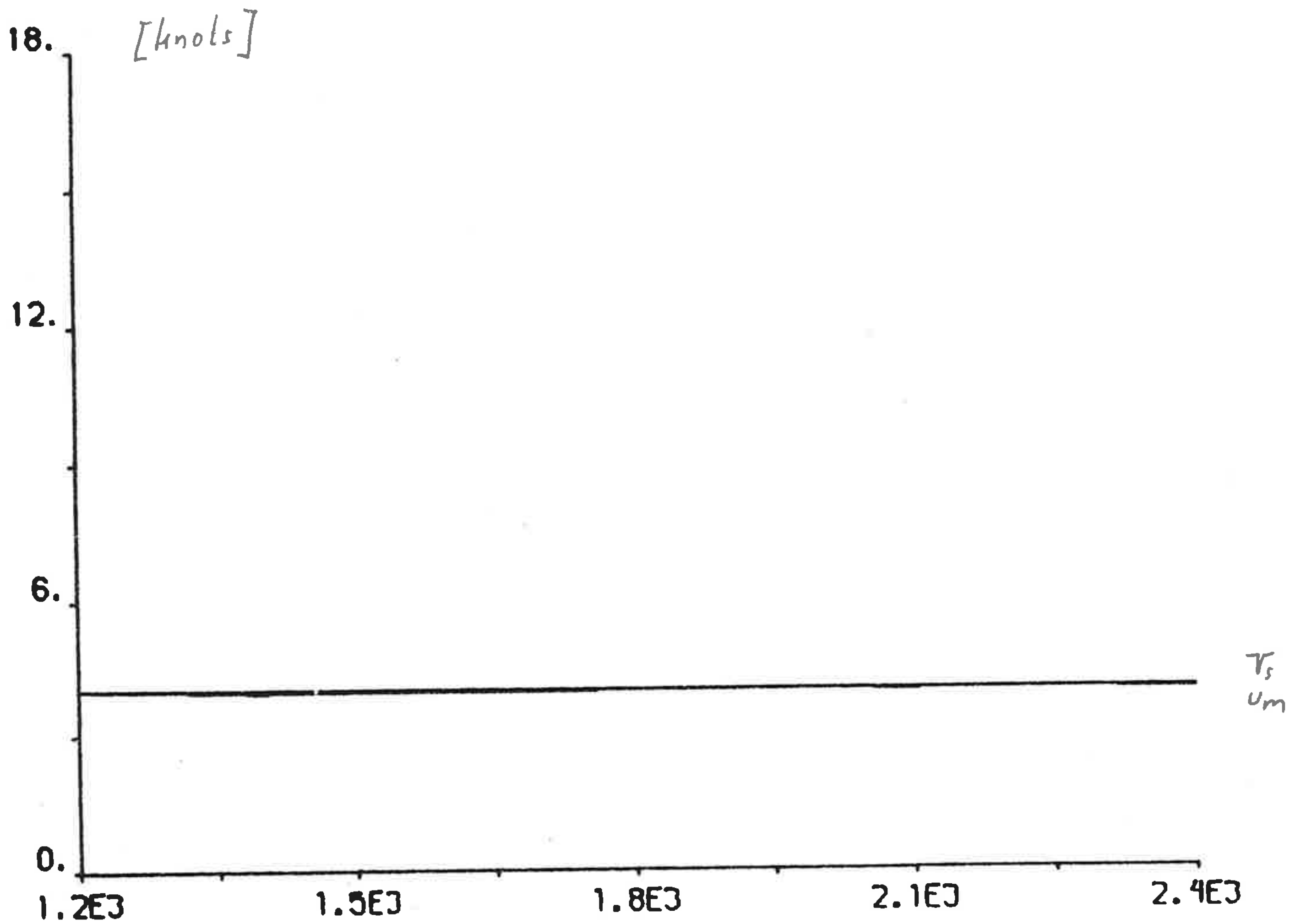

18.
[knots]
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
V_s
U_m

Fig. 4.6i

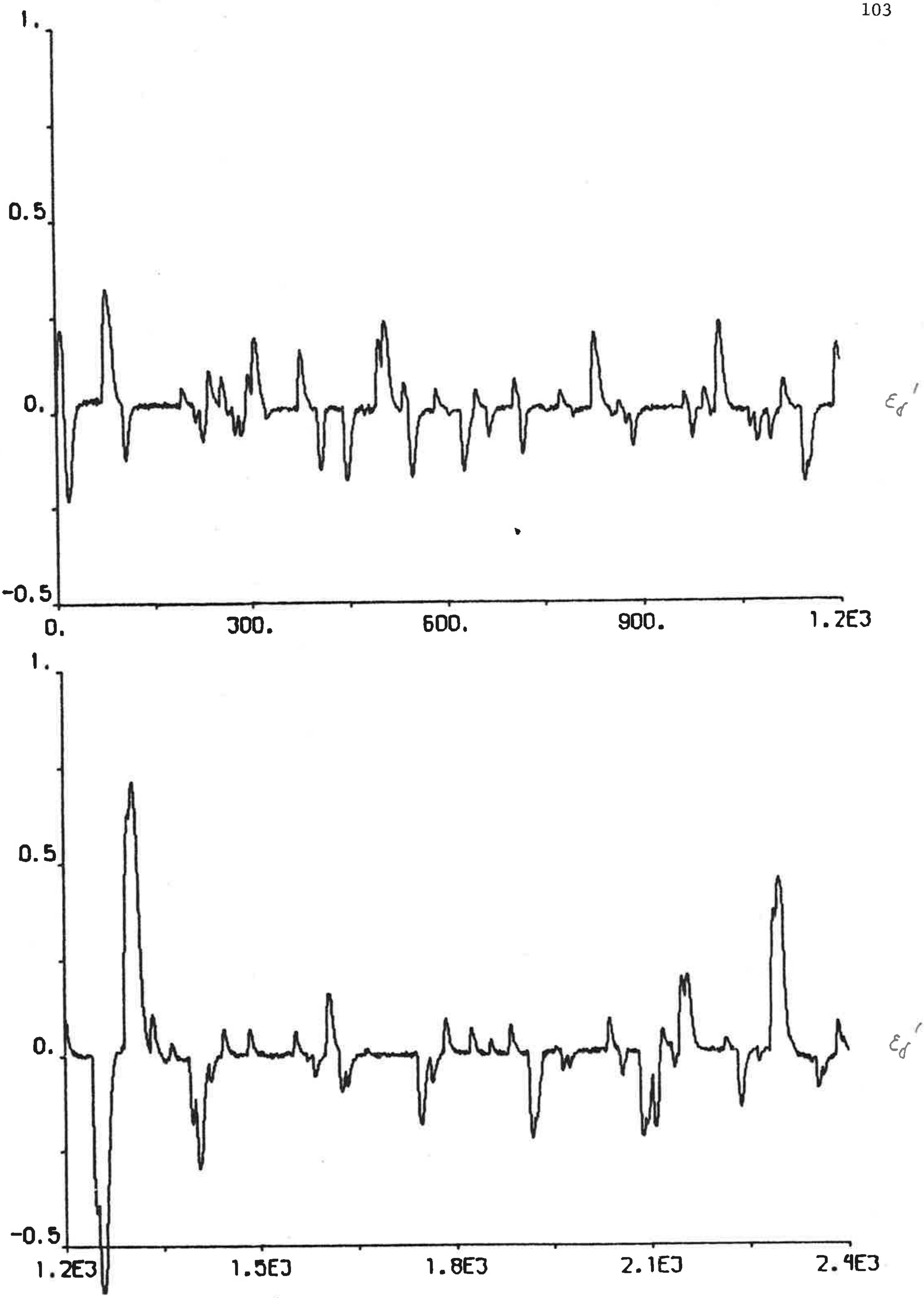
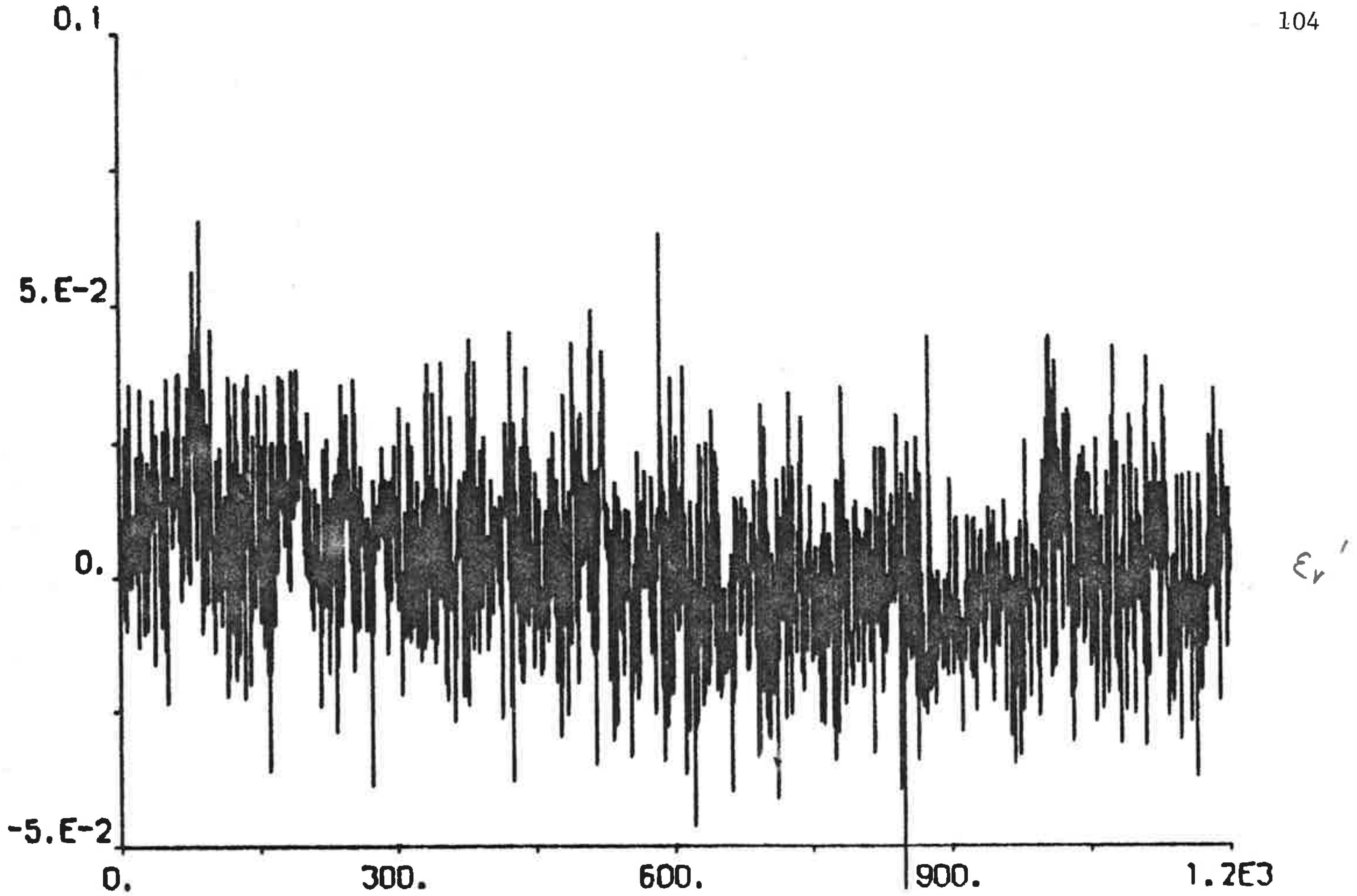

1.
0.5
0.
-0.5
0.
300.
600.
900.
1.2E3
εd'
1.
0.5
0.
-0.5
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εd'

Fig. 4.6j


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
εv'

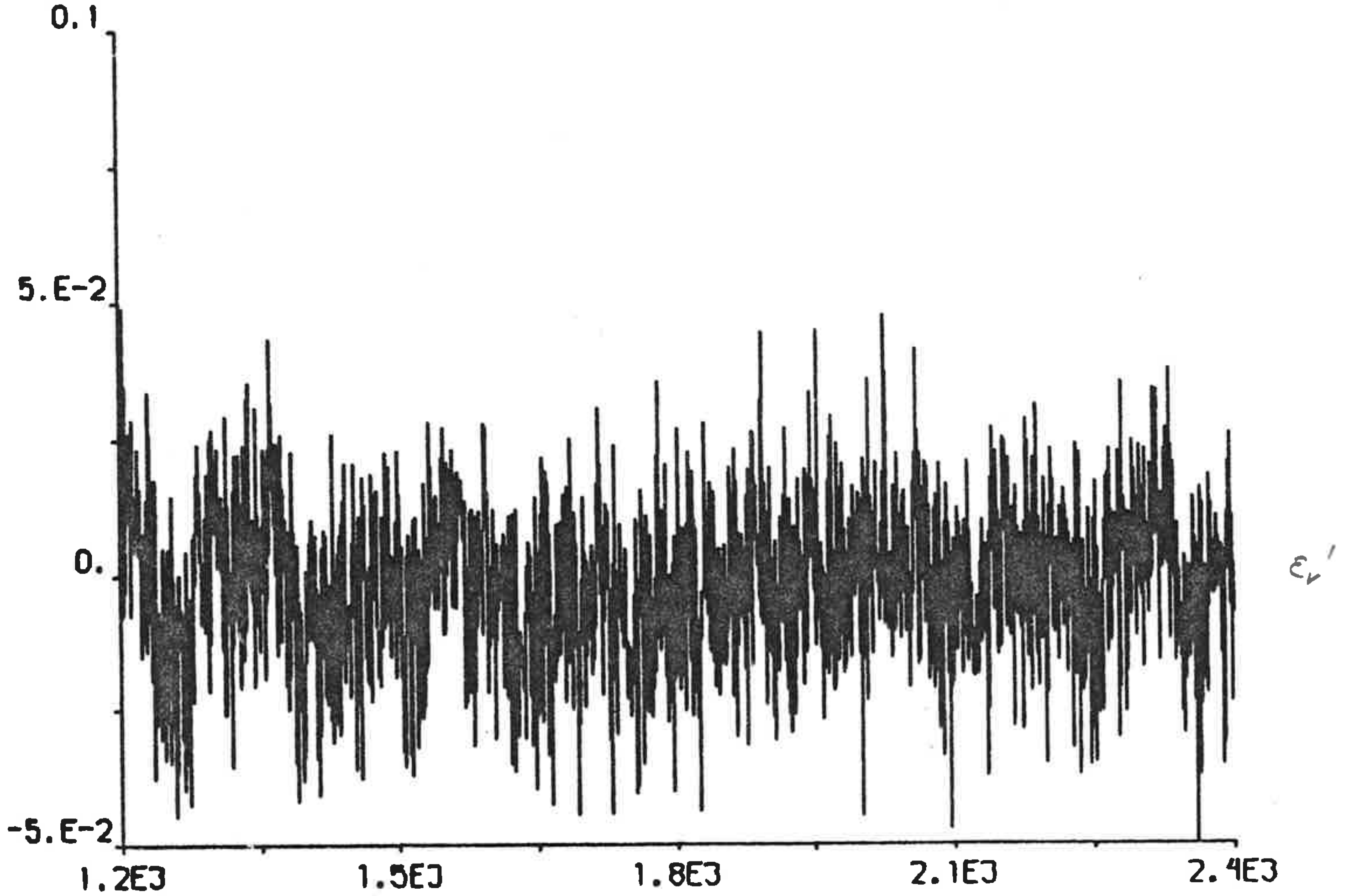
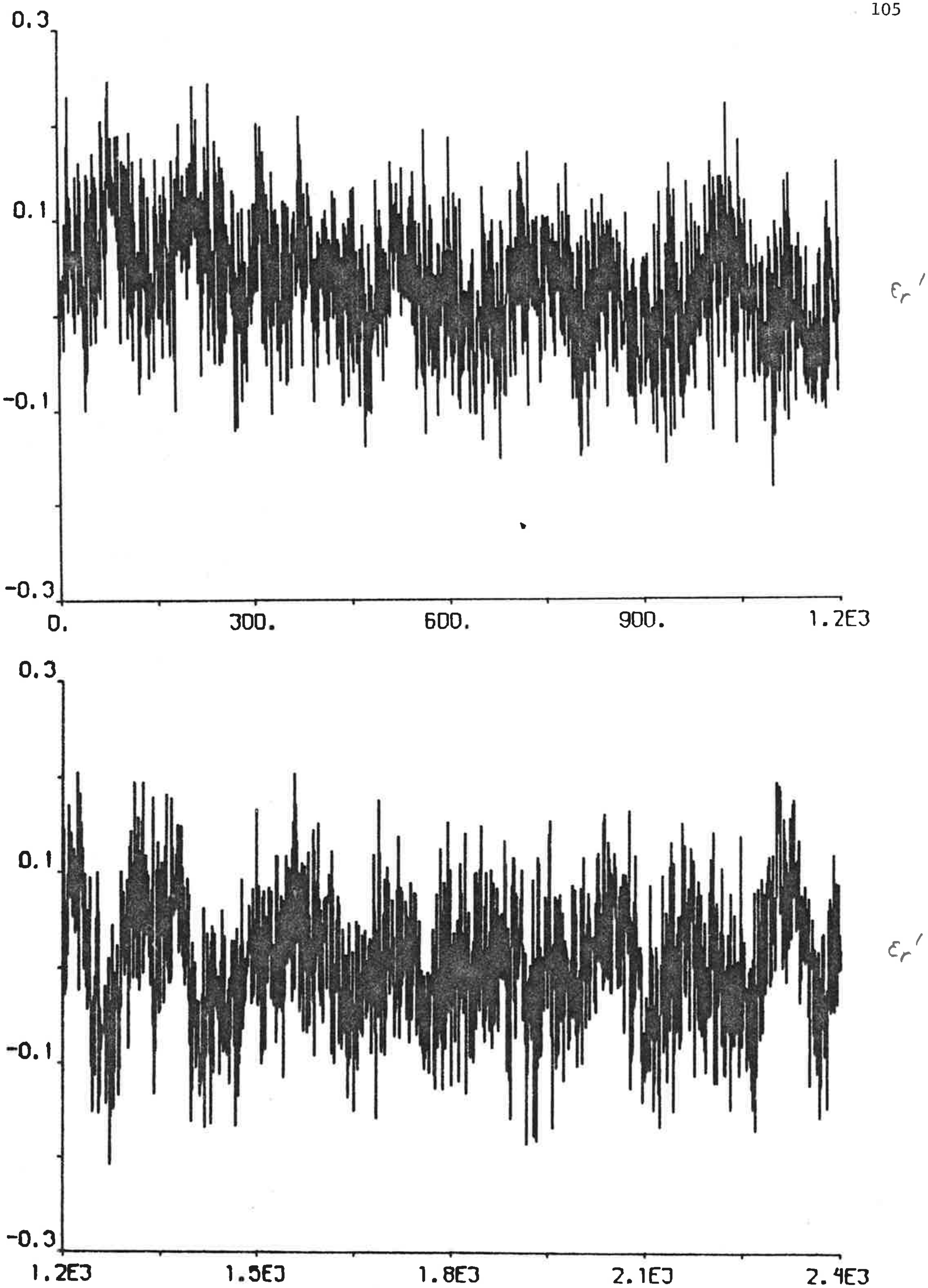
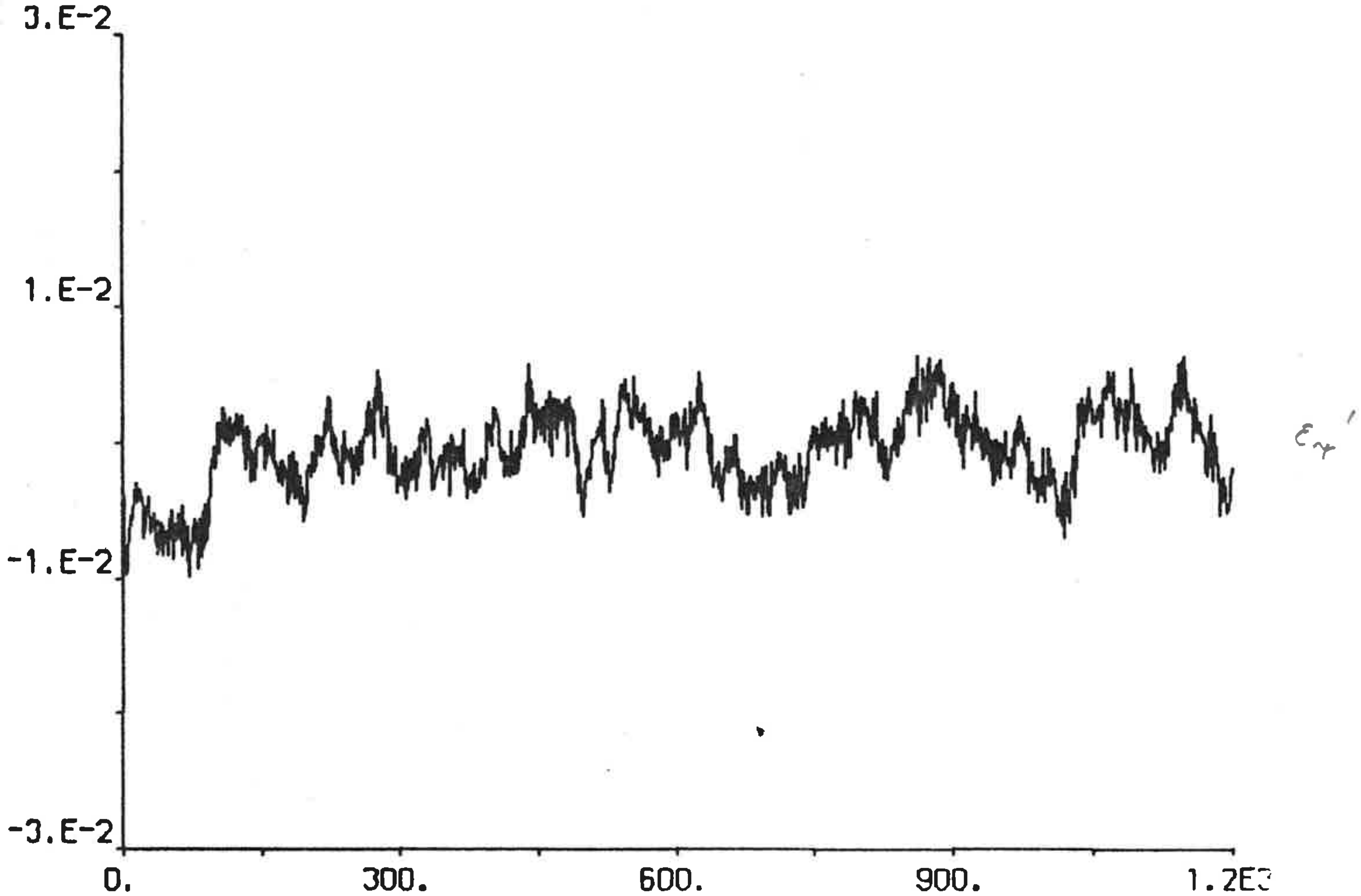

0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εv'

Fig. 4.6k



0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
εr'
0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εr'

Fig. 4.6ℓ


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
ε_r'

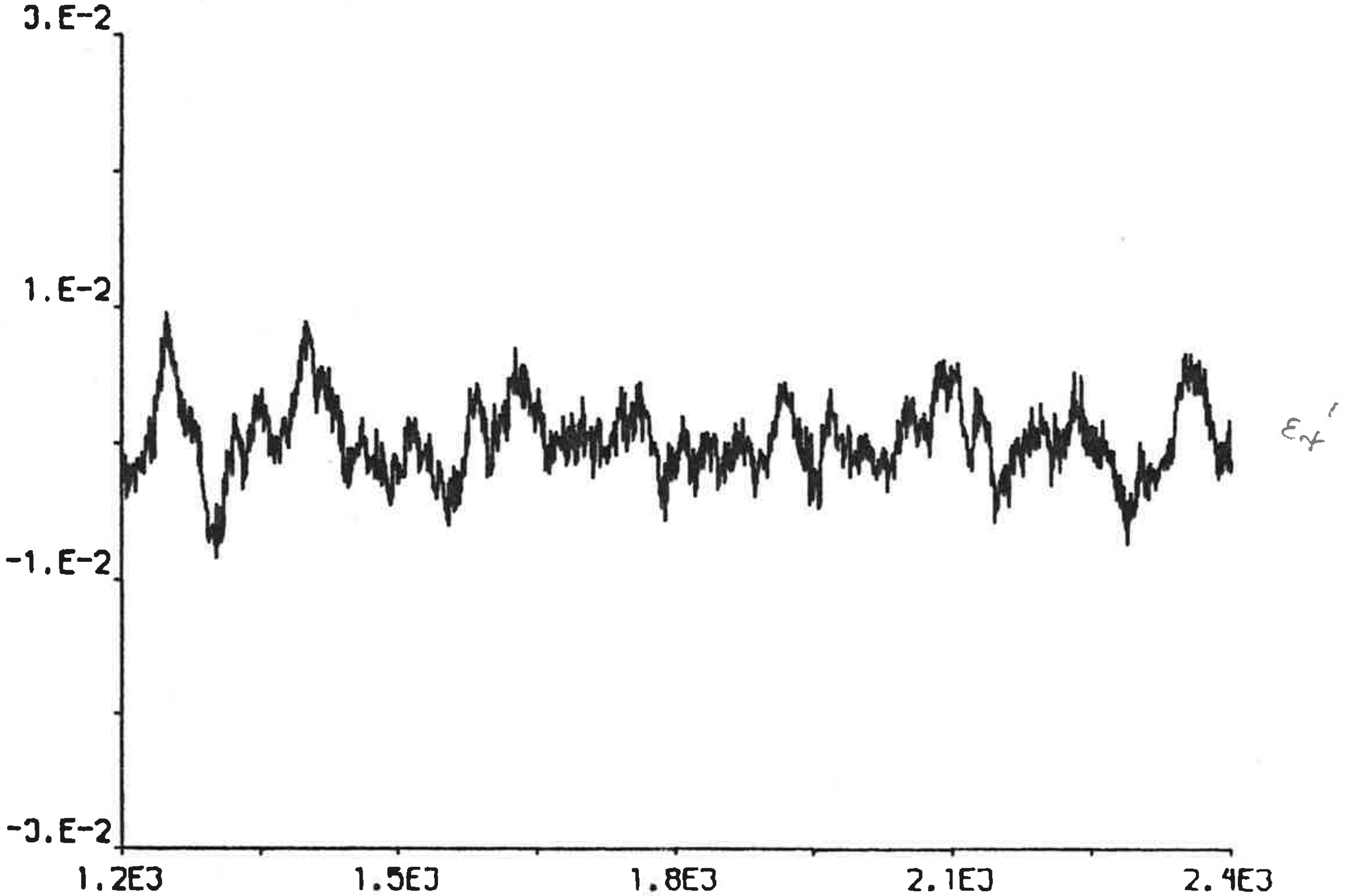
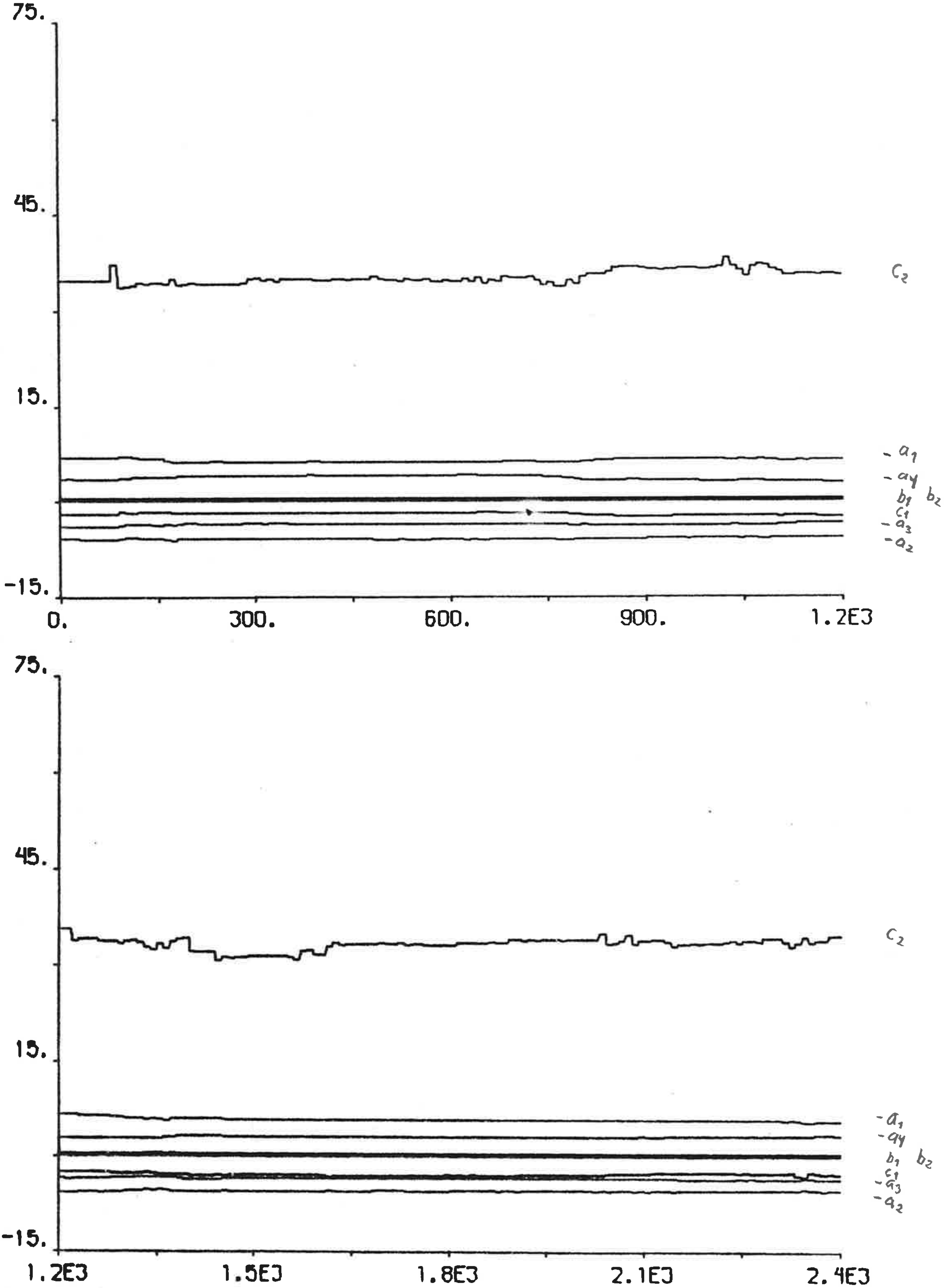

3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_r'

Fig. 4.6m



75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$

Fig. 4.6n

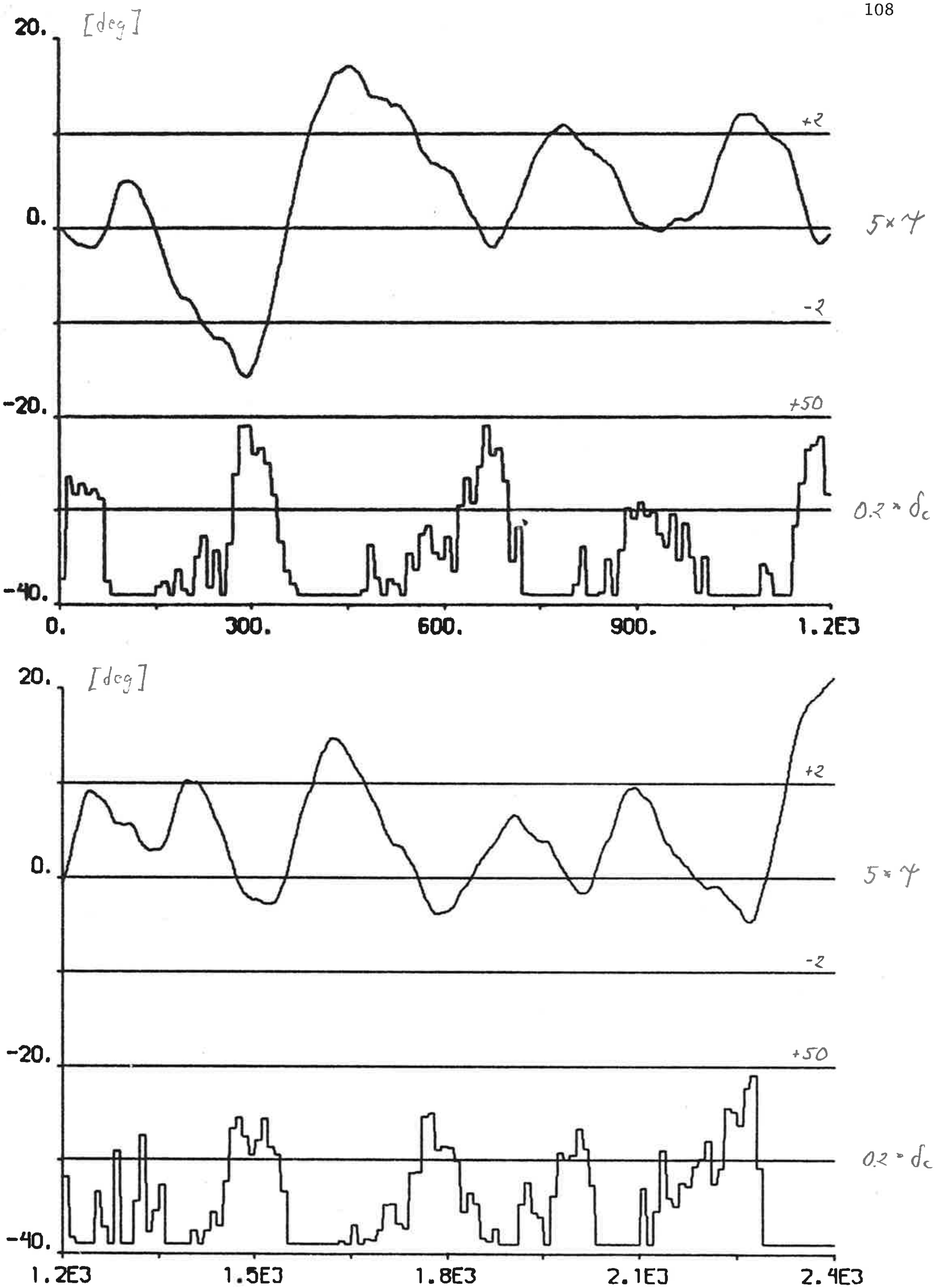


Fig. 4.7a – T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using estimates from the Kalman filter. The initial covariance matrix P of the self-tuning regulator is given by (4.3).

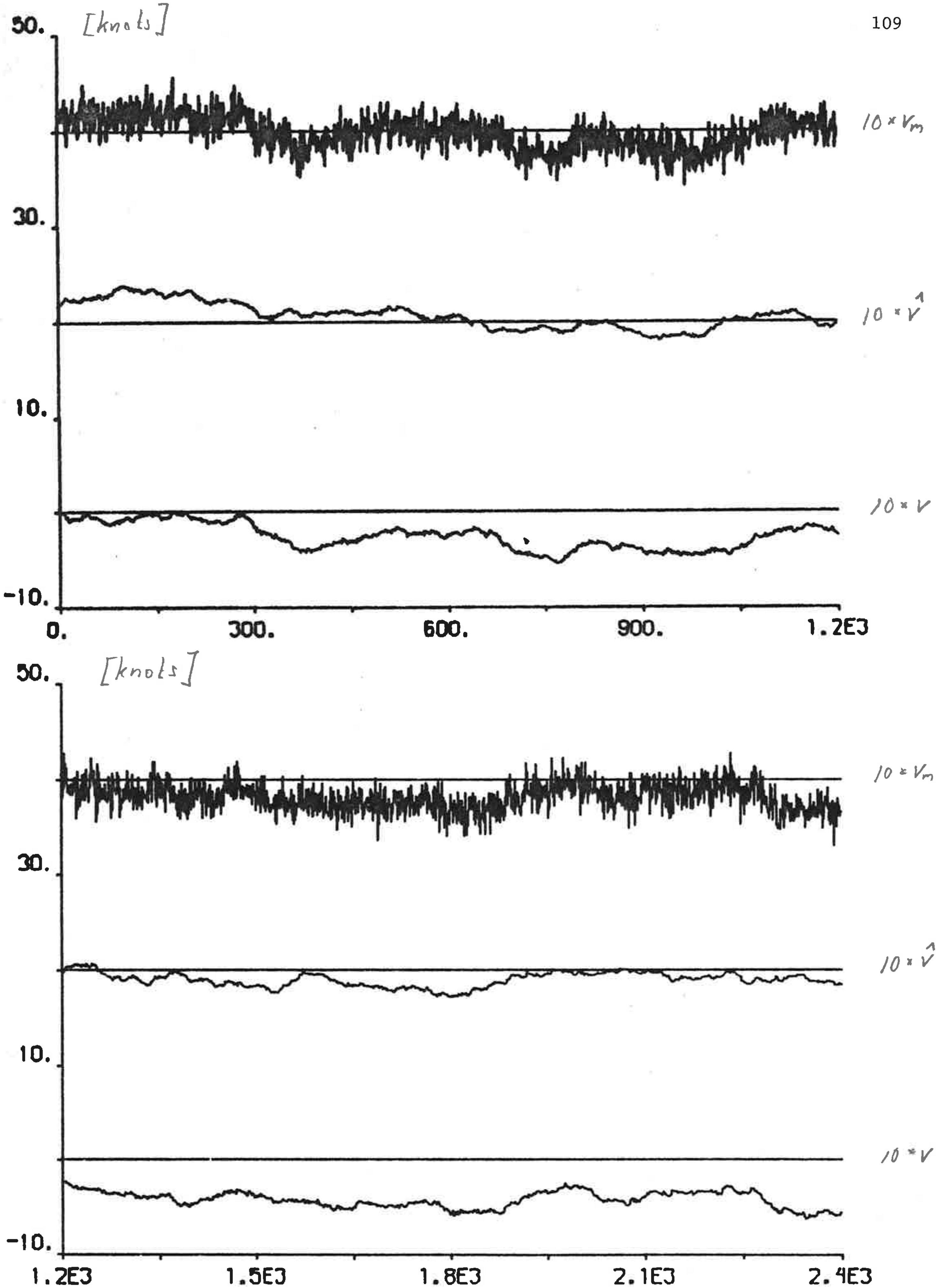
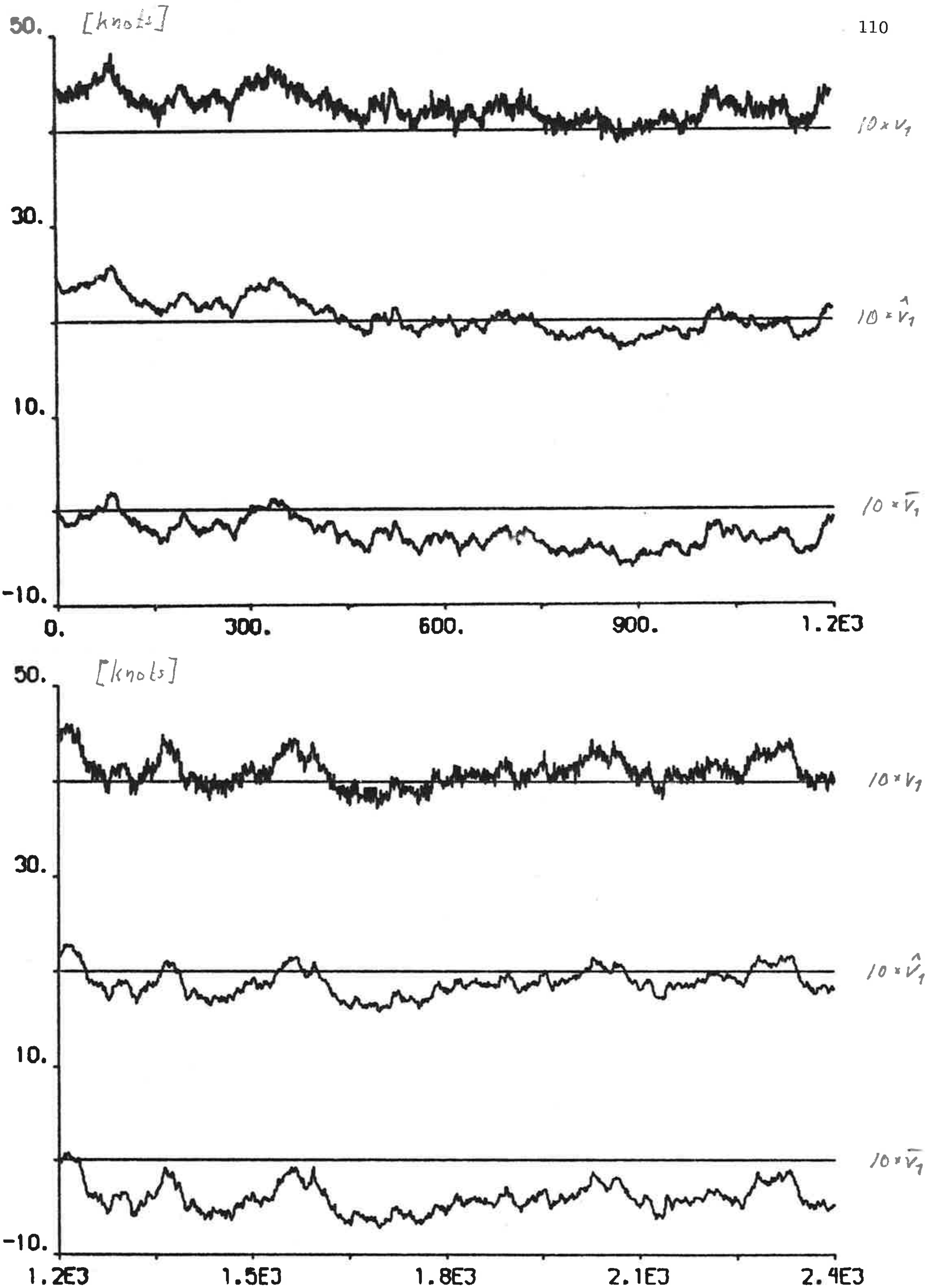
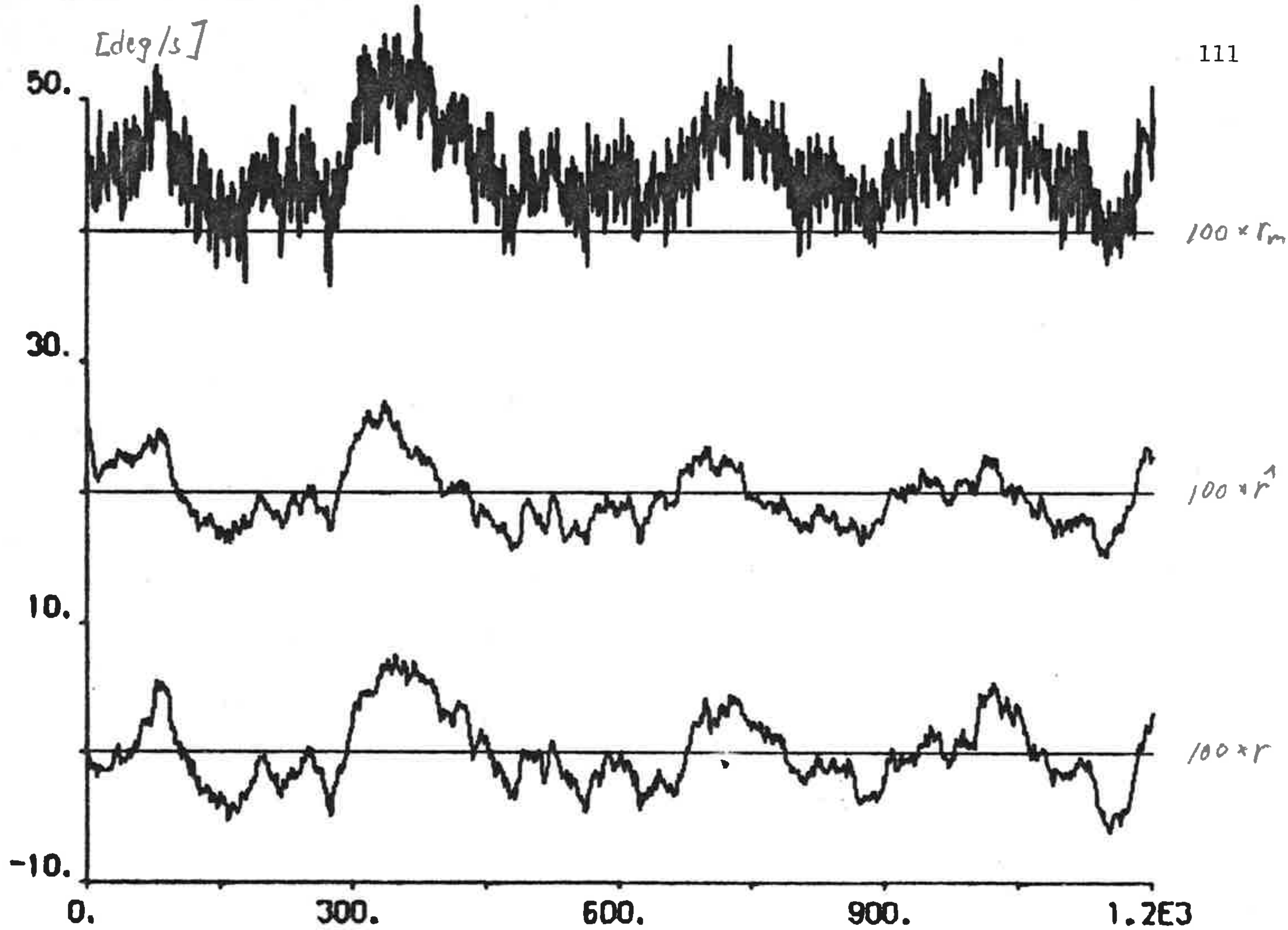

[knots]
50.
30.
10.
-10.
10 * Vm
10 * V̂
10 * V
0.
300.
600.
900.
1.2E3
[knots]
50.
30.
10.
-10.
10 * Vm
10 * V̂
10 * V
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.7b



50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × V1
10 × V̂1
10 × V̄1
50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × V1
10 × V̂1
10 × V̄1

Fig. 4.7c


[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 × r_m
100 × r̂
100 × r

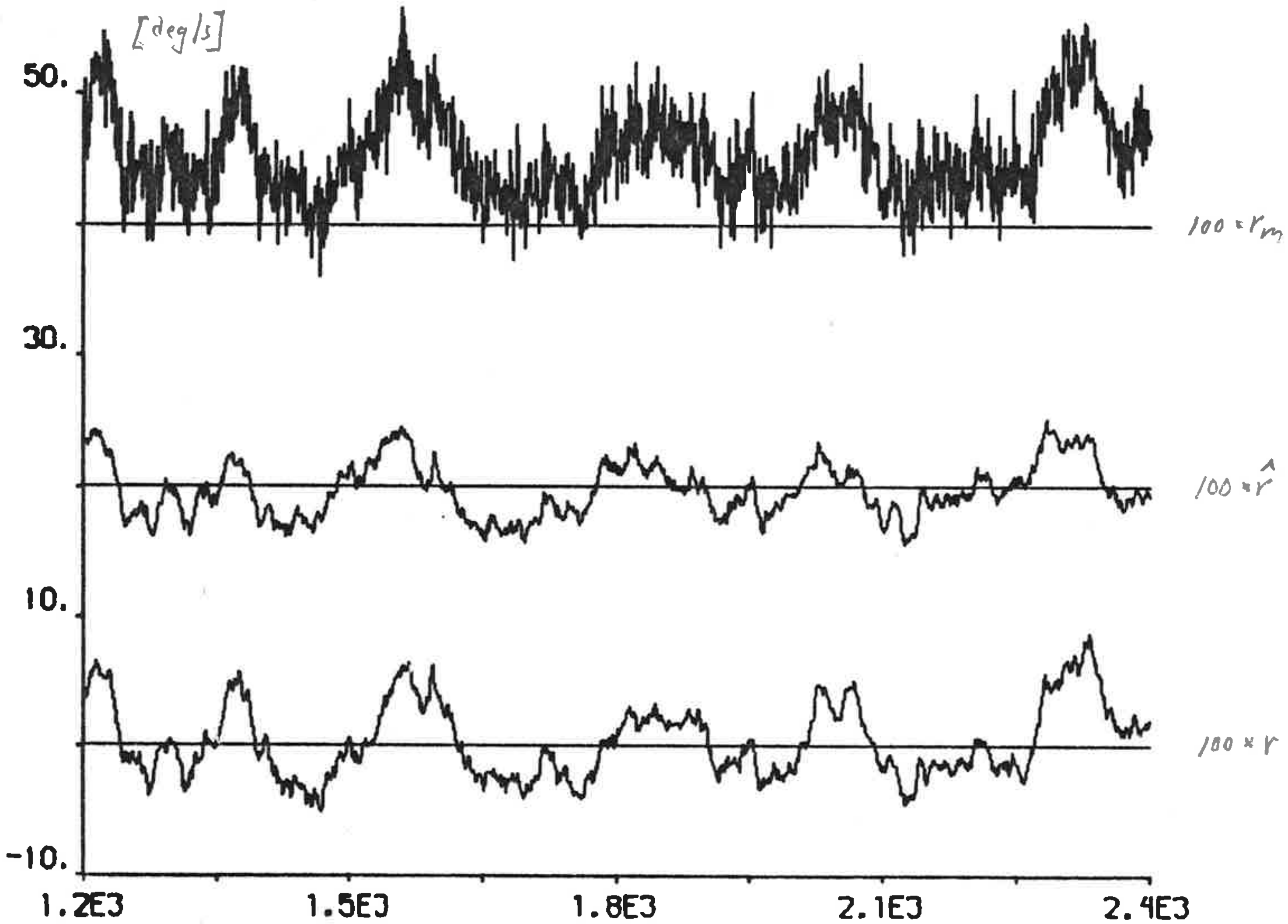
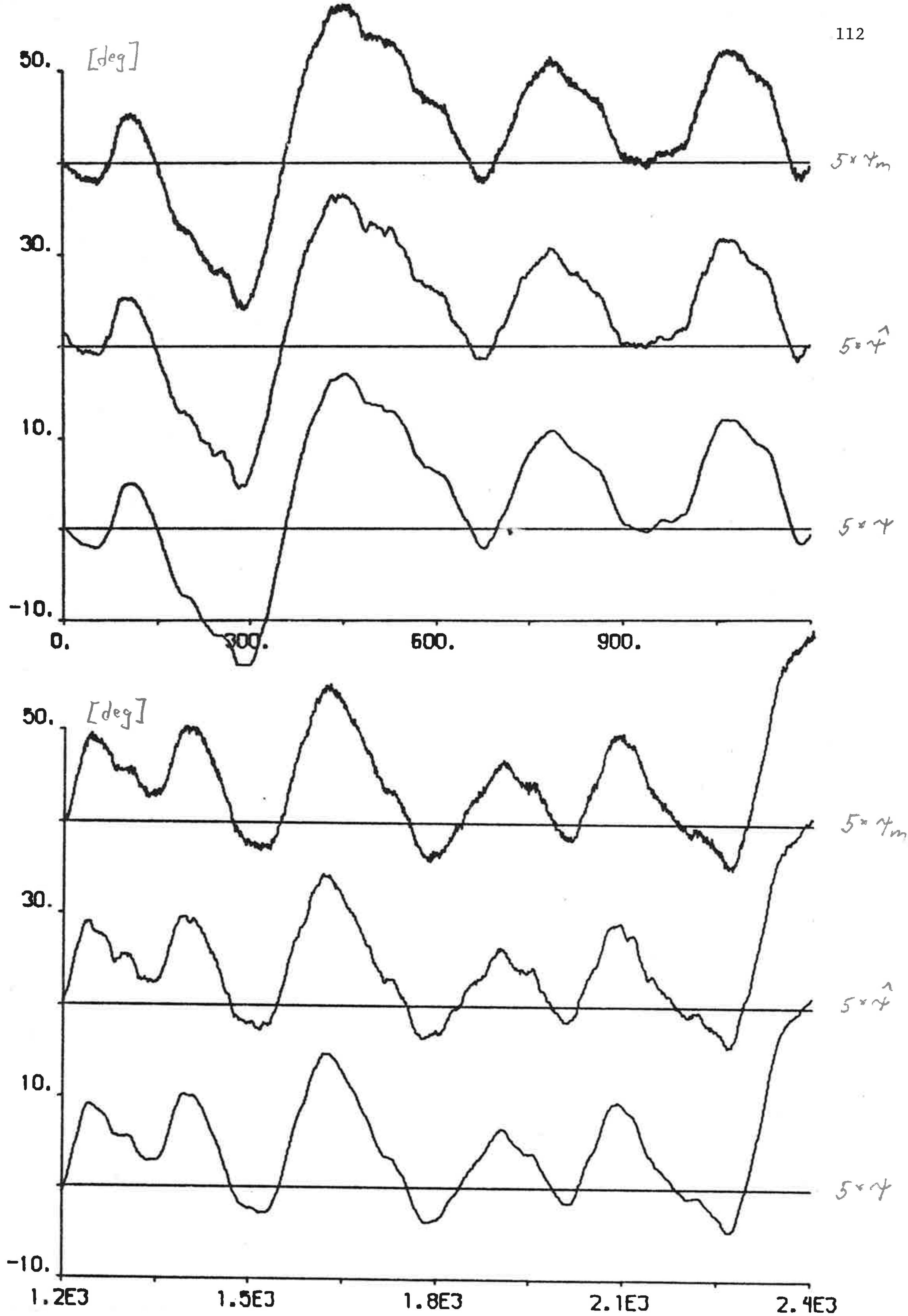
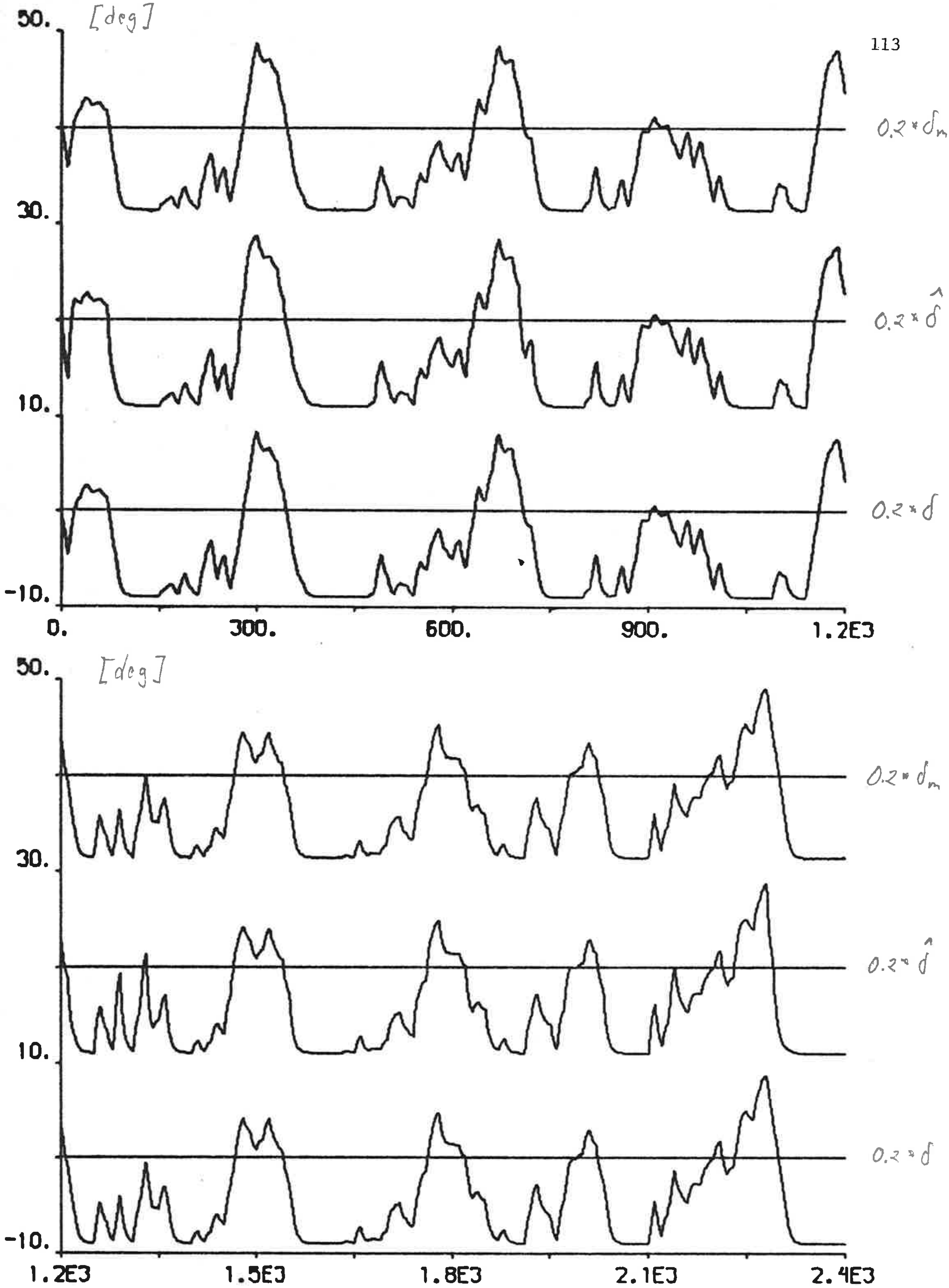

[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 × r_m
100 × r̂
100 × r

Fig. 4.7d



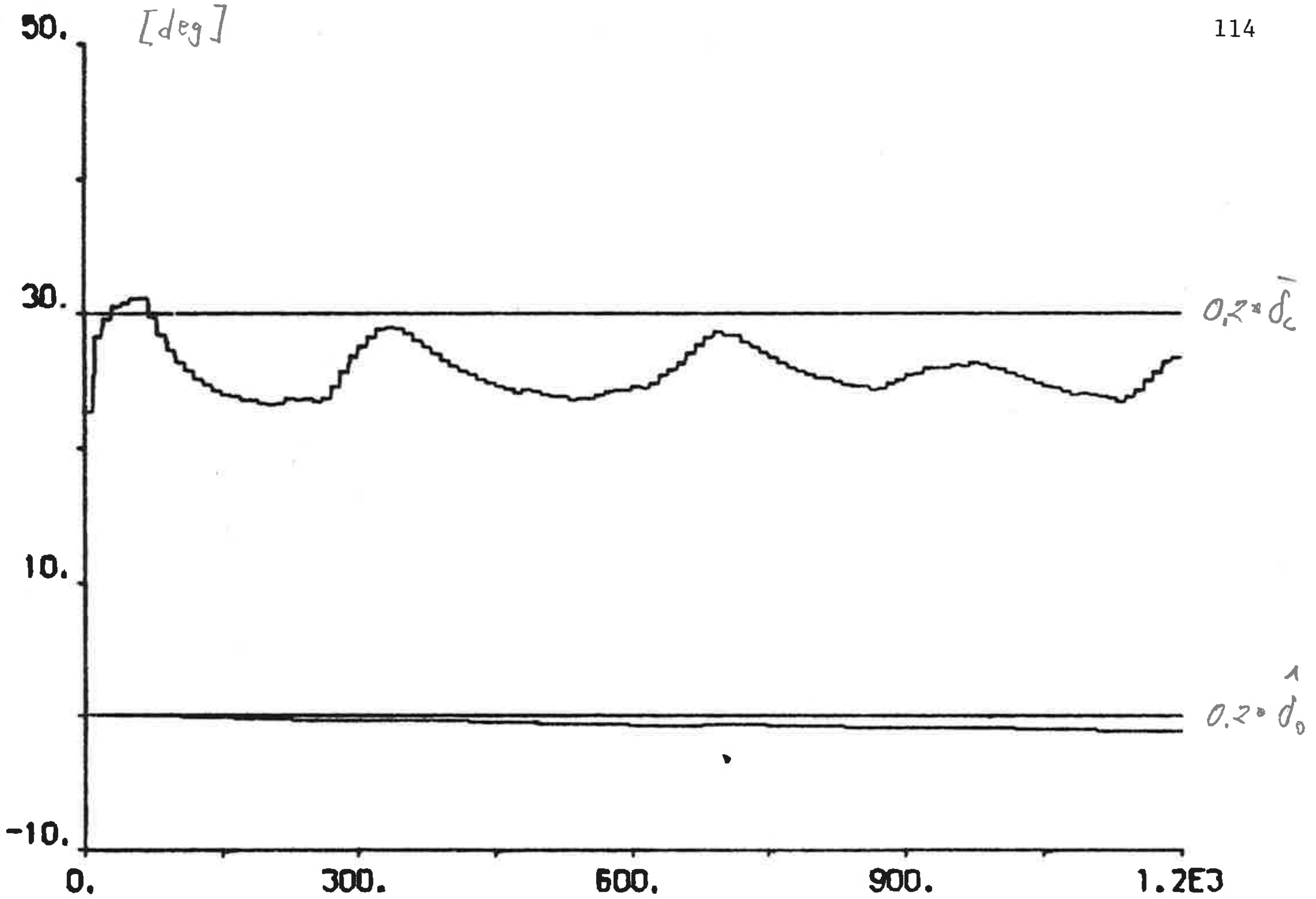
[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
5×ψm
5×ψ̂
5×ψ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5×ψm
5×ψ̂
5×ψ

Fig. 4.7e

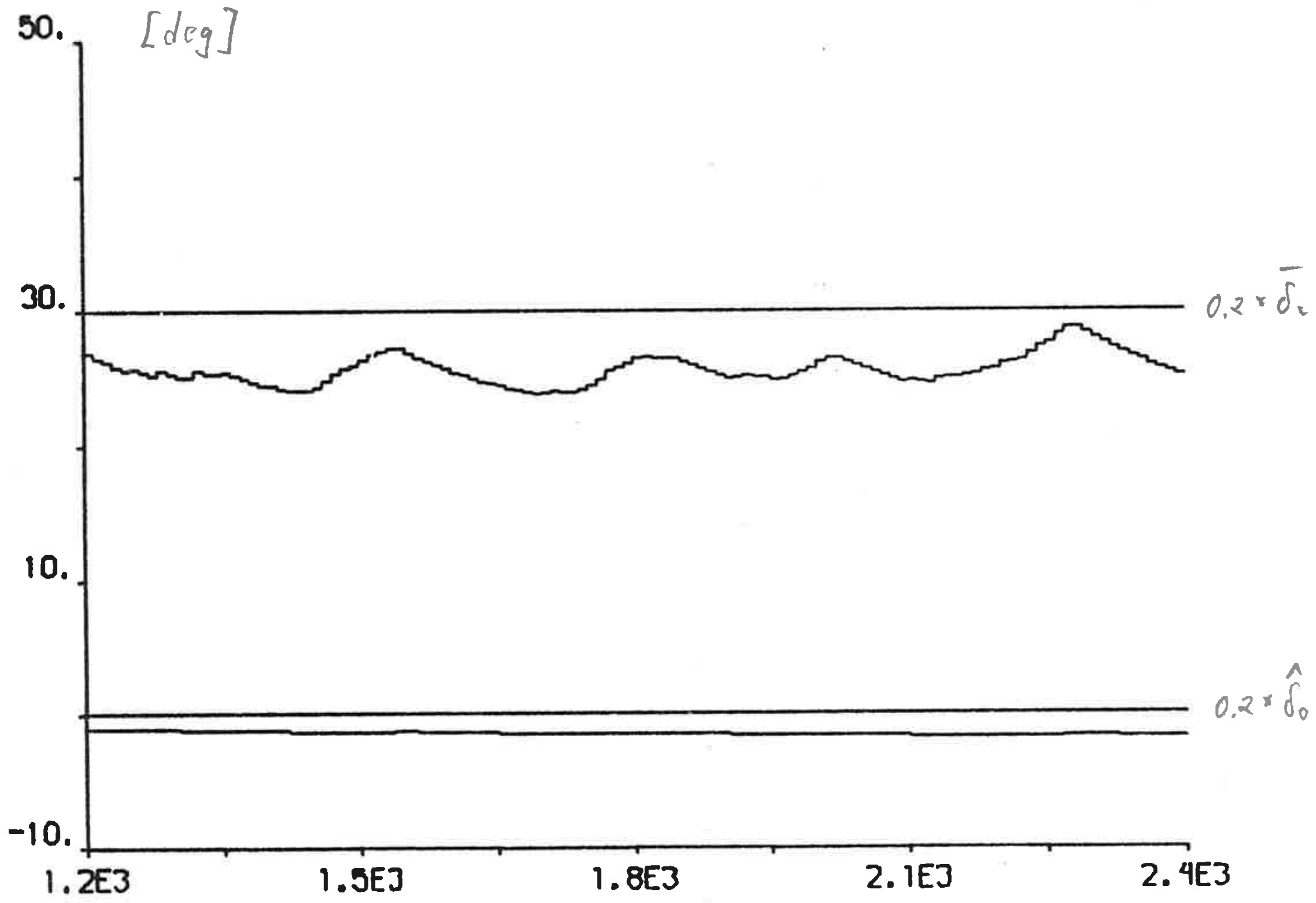


[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
0.2 * δm
0.2 * δ̂
0.2 * δ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
0.2 * δm
0.2 * δ̂
0.2 * δ

Fig. 4.7f



[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
0,2 * $\bar{\delta}_c$
0,2 * $\hat{\delta}_0$



[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
0,2 * $\bar{\delta}_c$
0,2 * $\hat{\delta}_0$

Fig. 4.7g

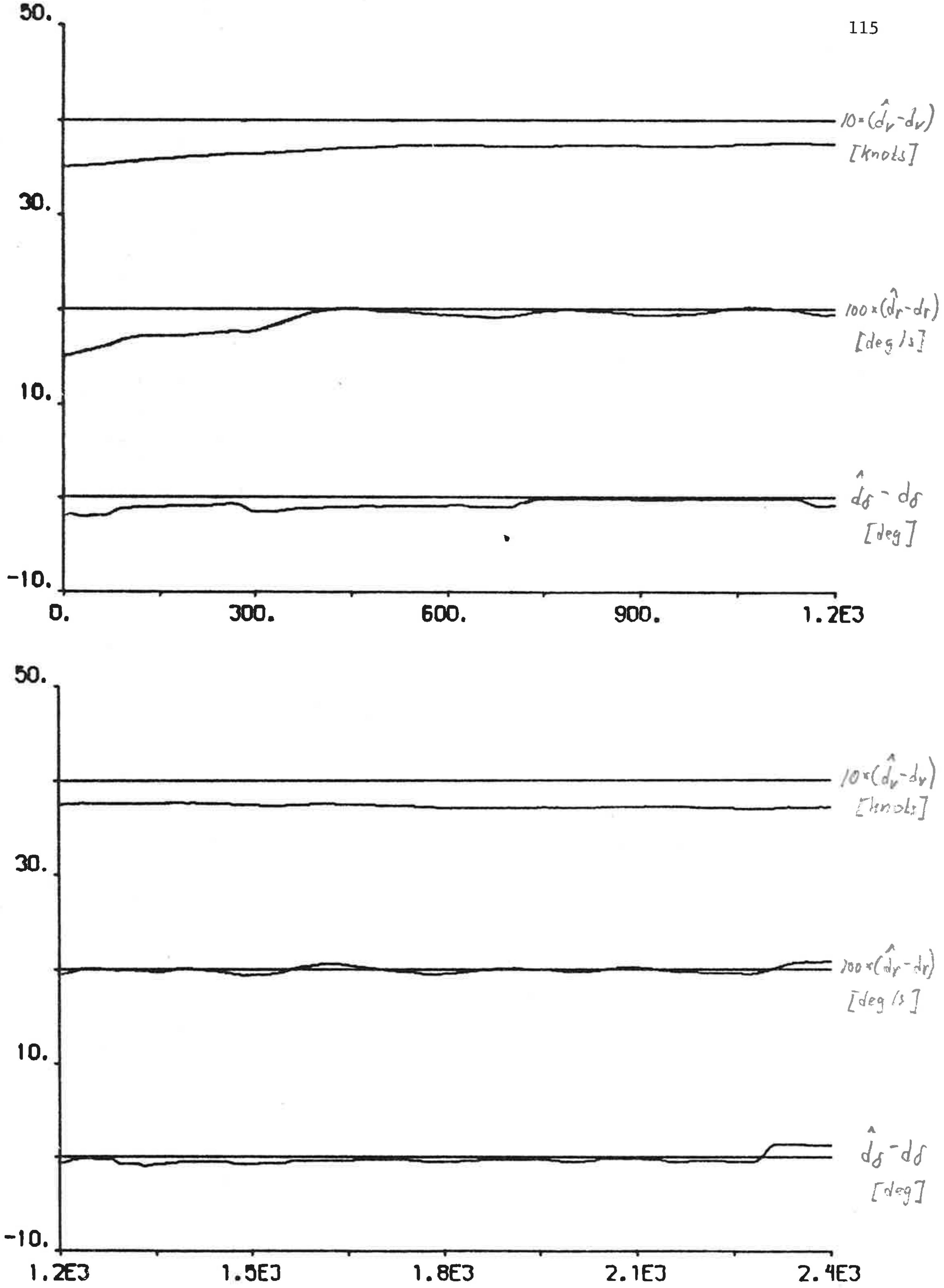
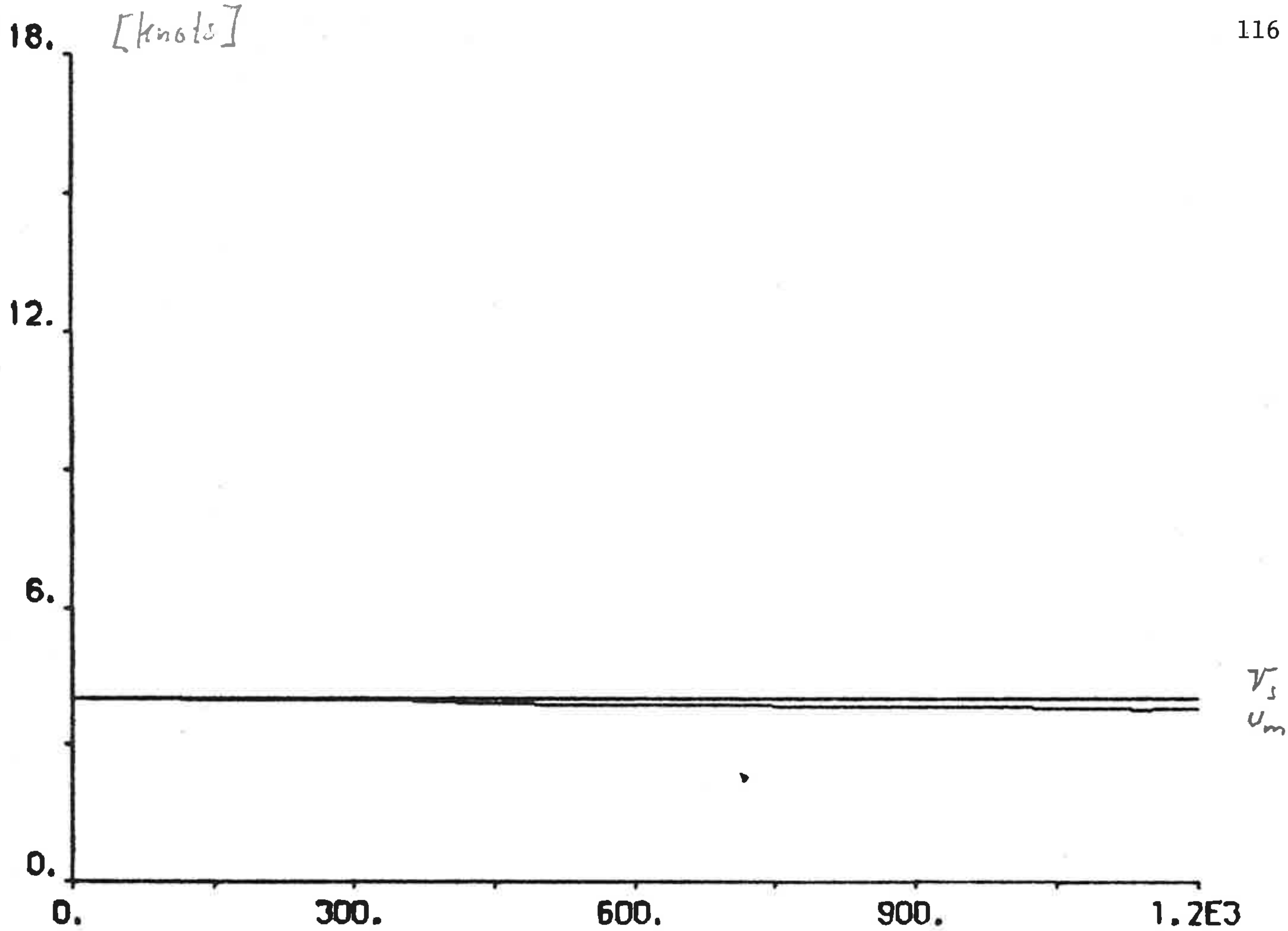

50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$10 \times (\hat{d}_v - d_v)$
[knots]
$100 \times (\hat{d}_r - d_r)$
[deg/s]
$\hat{d}_\delta - d_\delta$
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
$10 \times (\hat{d}_v - d_v)$
[knots]
$100 \times (\hat{d}_r - d_r)$
[deg/s]
$\hat{d}_\delta - d_\delta$
[deg]

Fig. 4.7h


18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
U_m

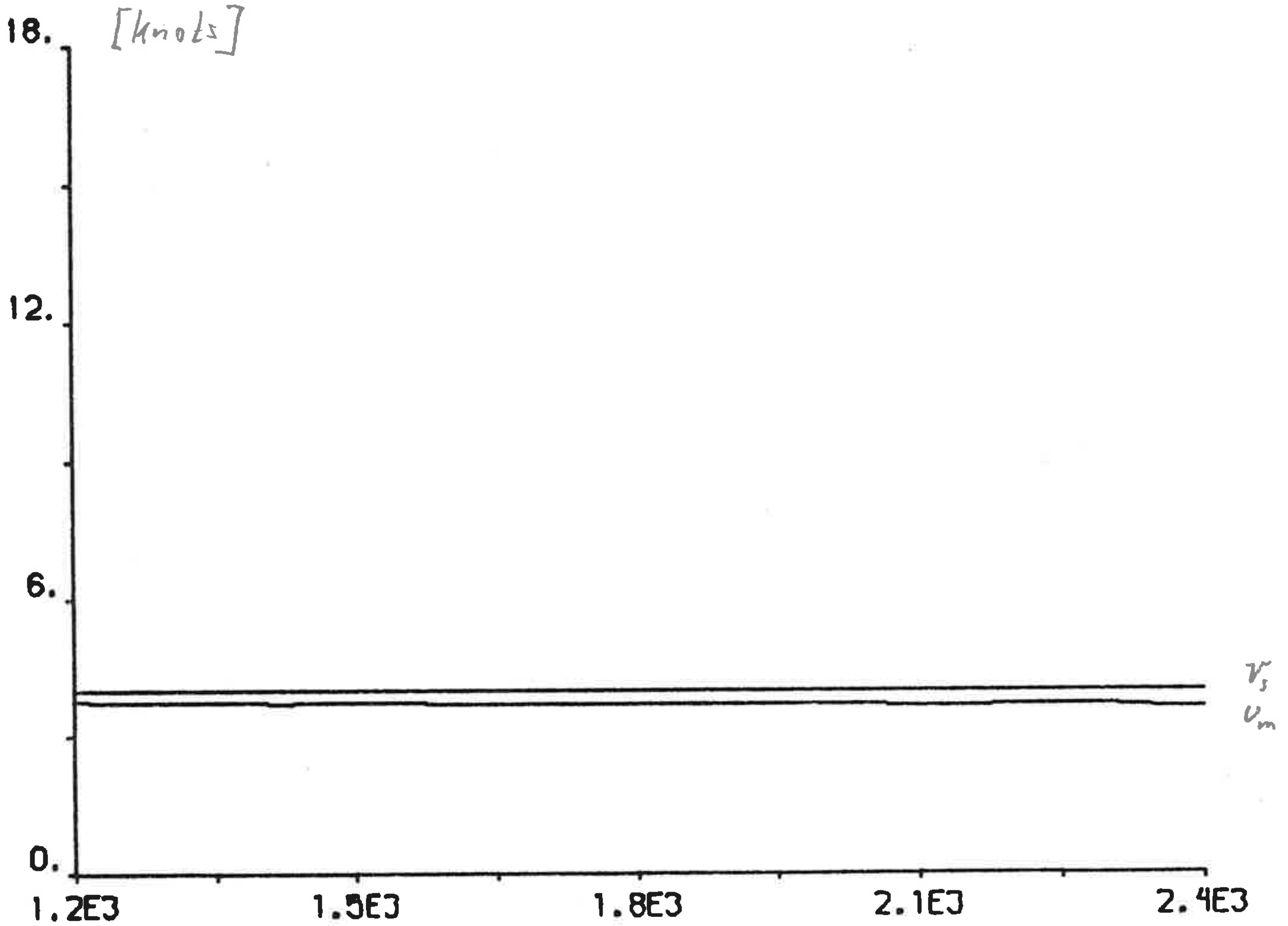

18.
[knots]
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
V_s
U_m

Fig. 4.7i

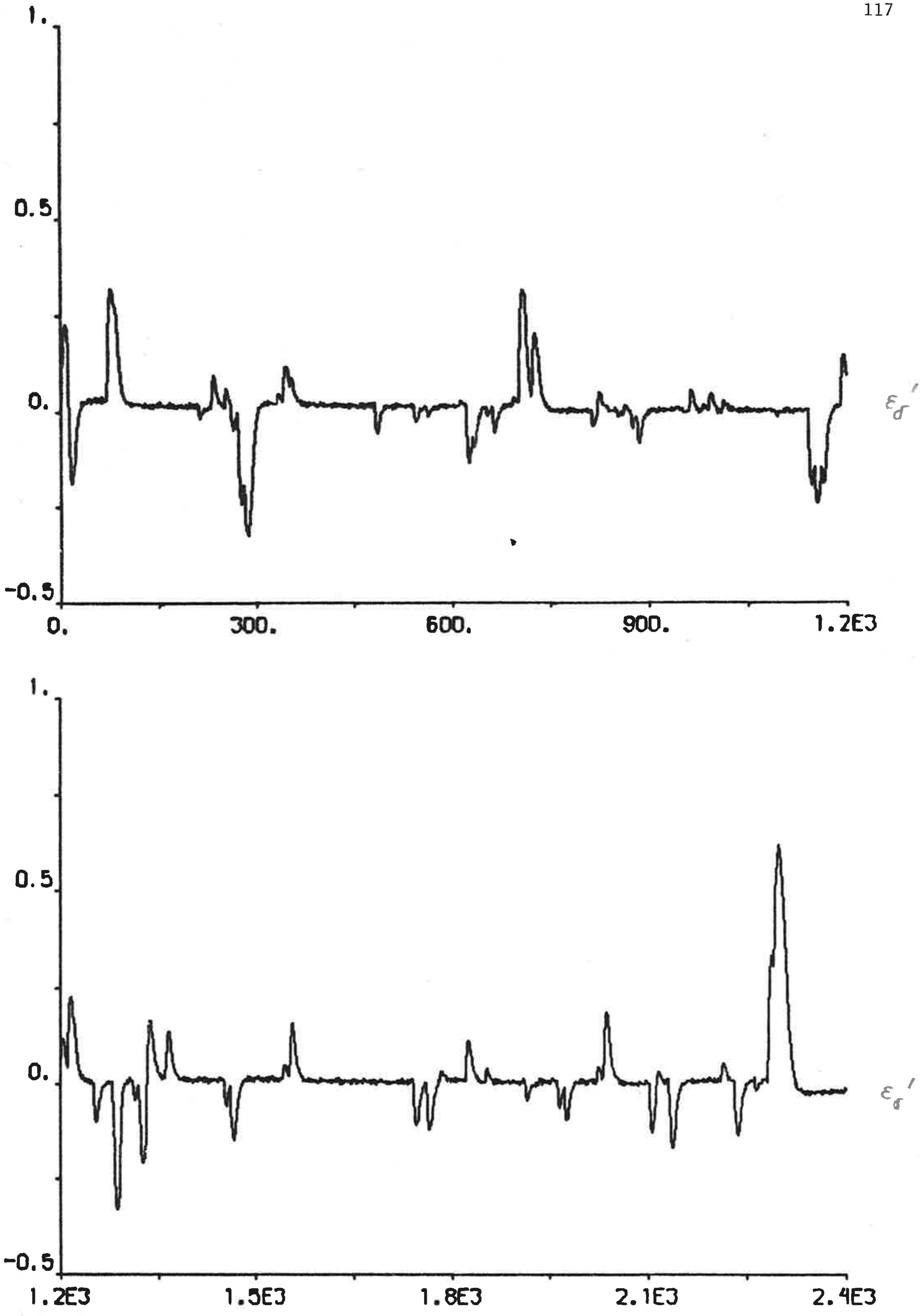
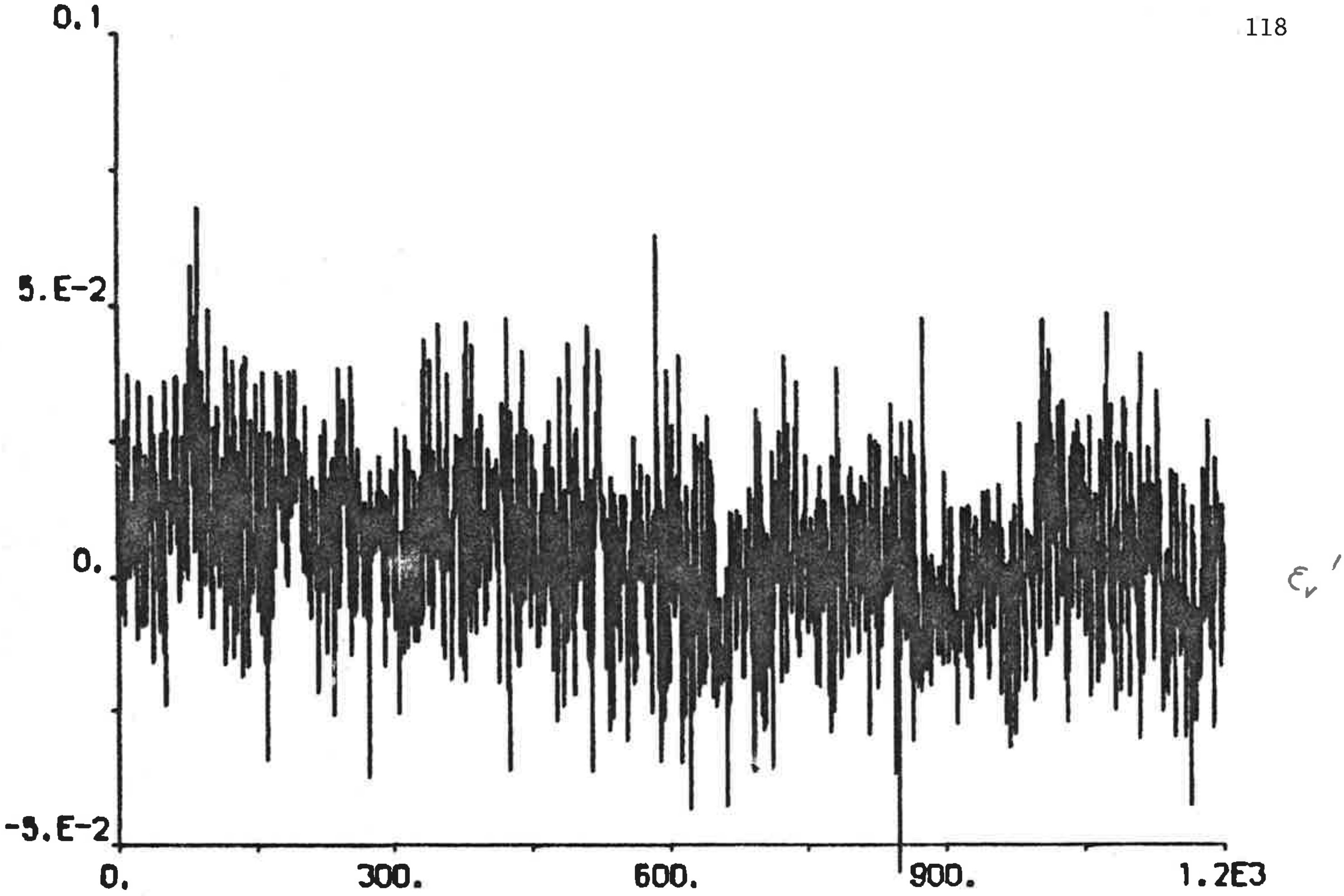

1.
0.5
0.
-0.5
0.
300.
600.
900.
1.2E3
ε_d'
1.
0.5
0.
-0.5
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_d'

Fig. 4.7j


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_v'

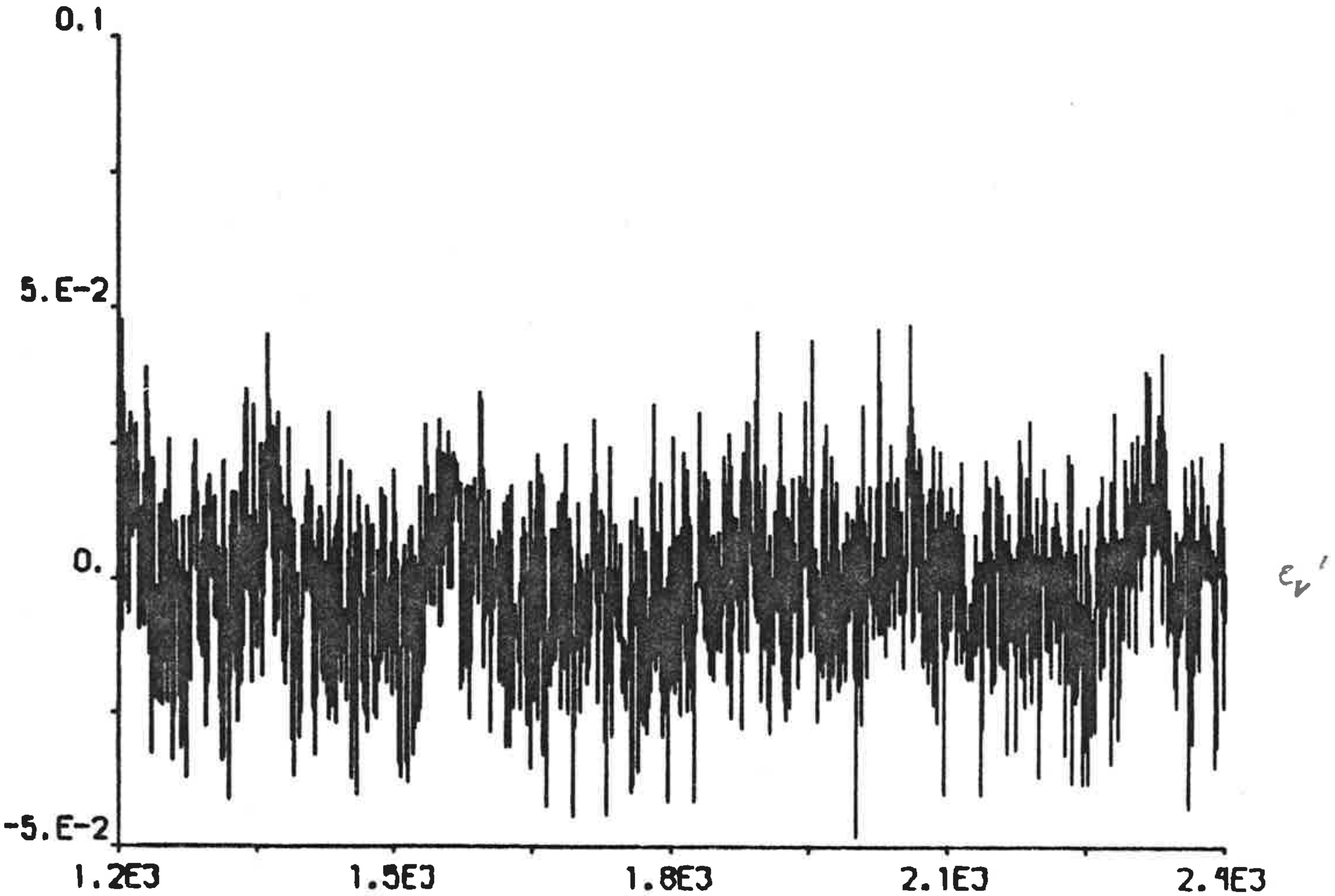
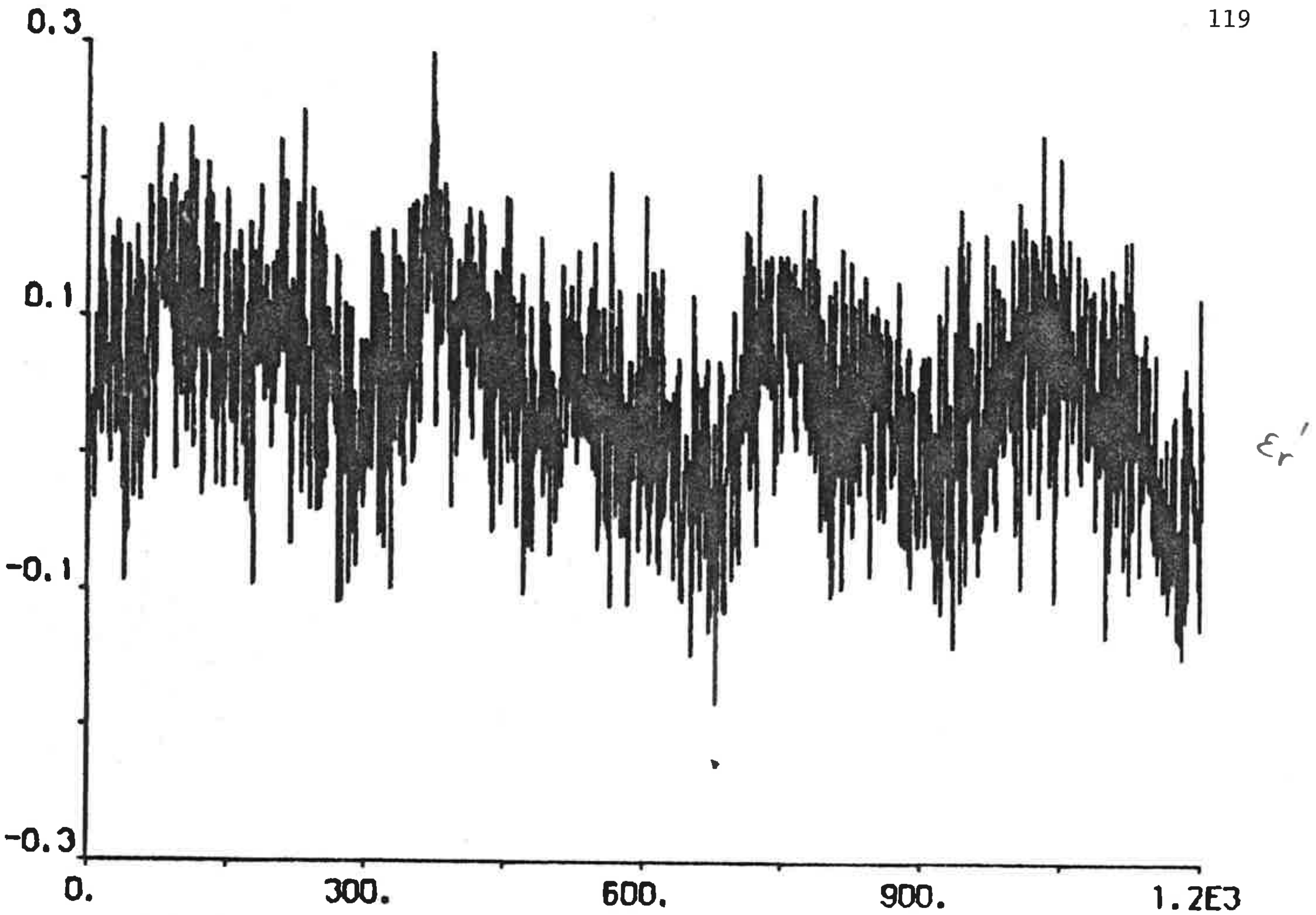

0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_v'

Fig. 4.7k


0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
ε_r'

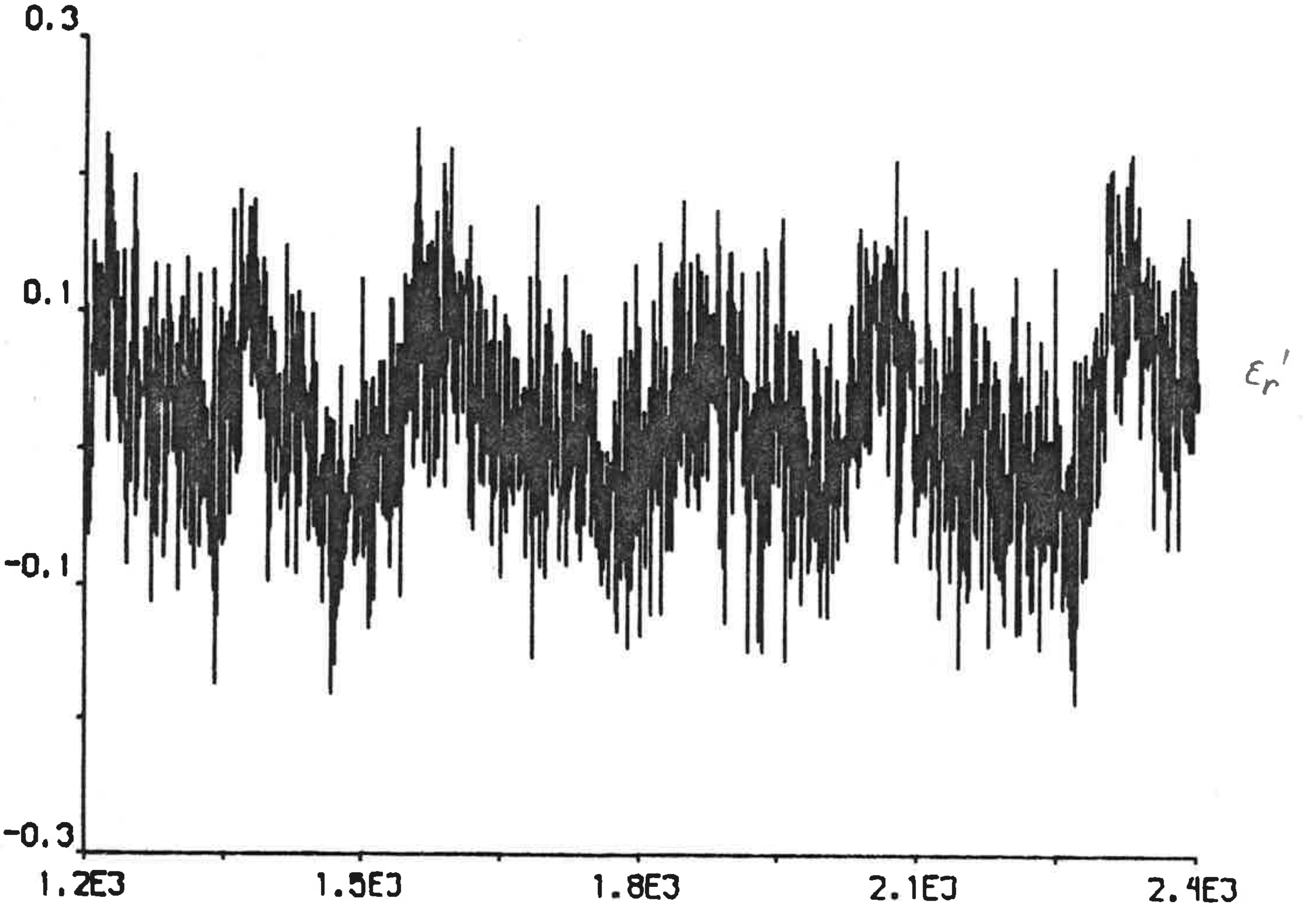

0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_r'

Fig. 4.7 ℓ

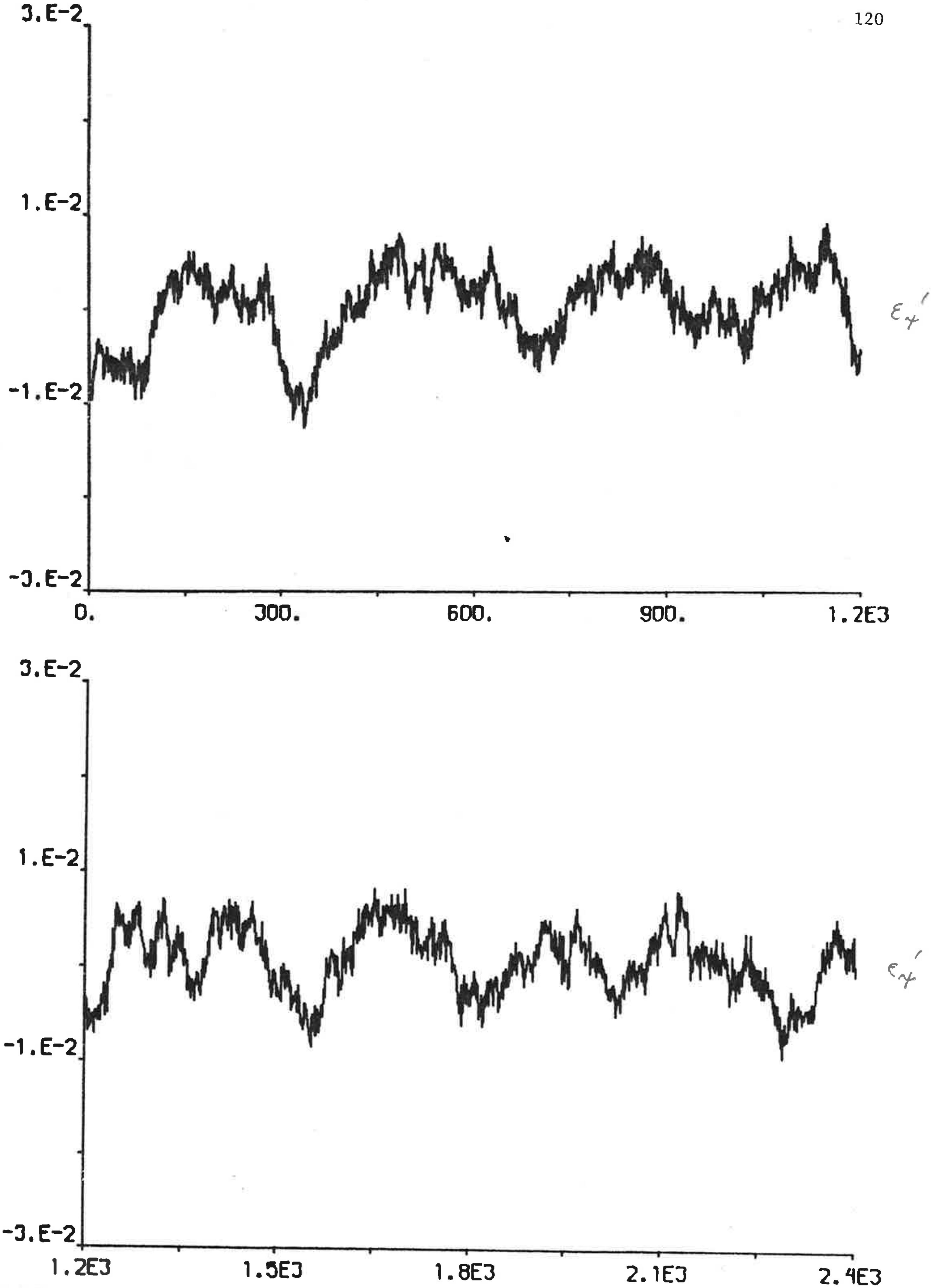

3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
εx'
3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εx'

Fig. 4.7m

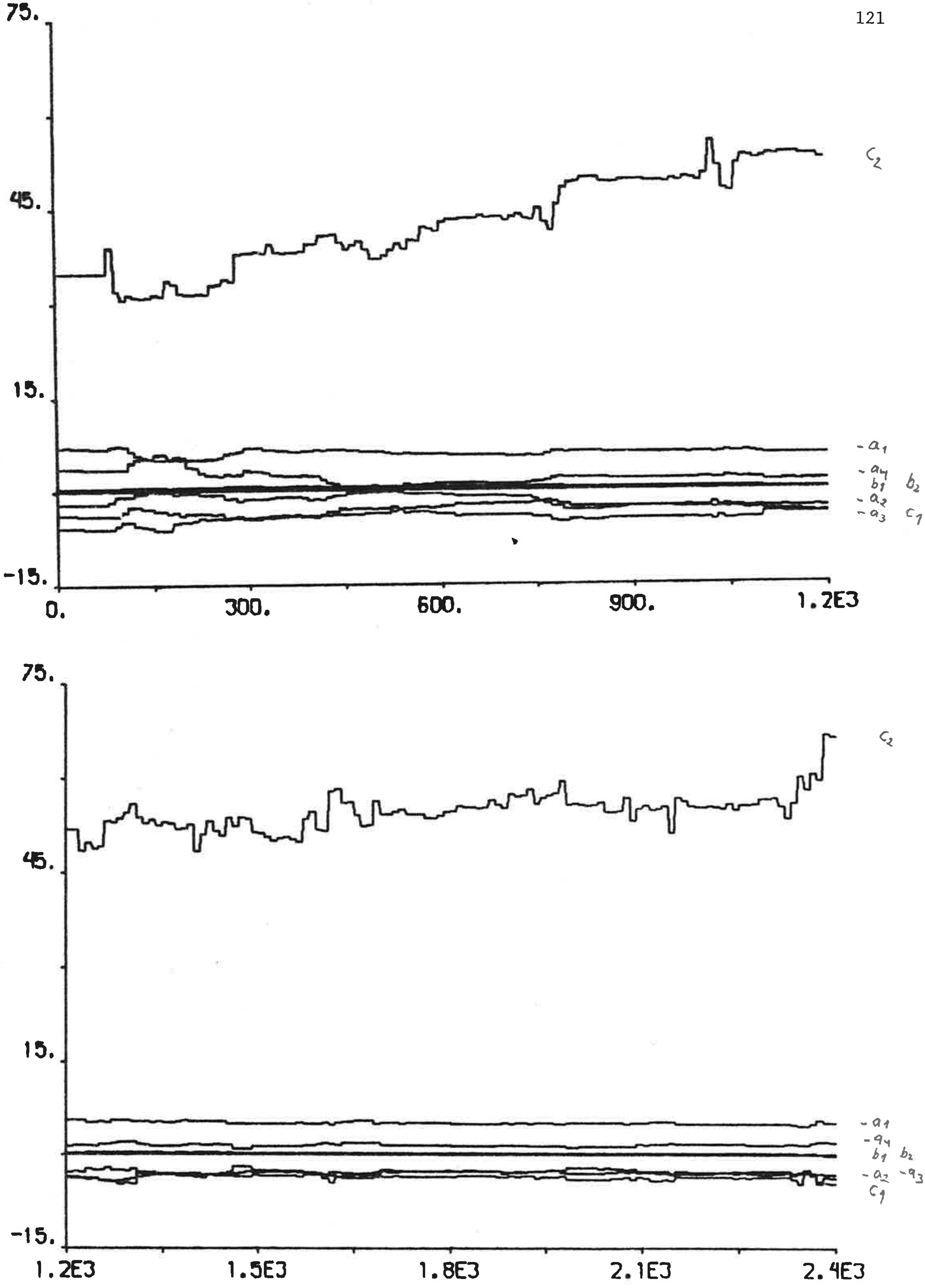

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1
b_2
$-a_2$
$-a_3$
c_1
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1
b_2
$-a_2$
$-a_3$
c_1

Fig. 4.7n

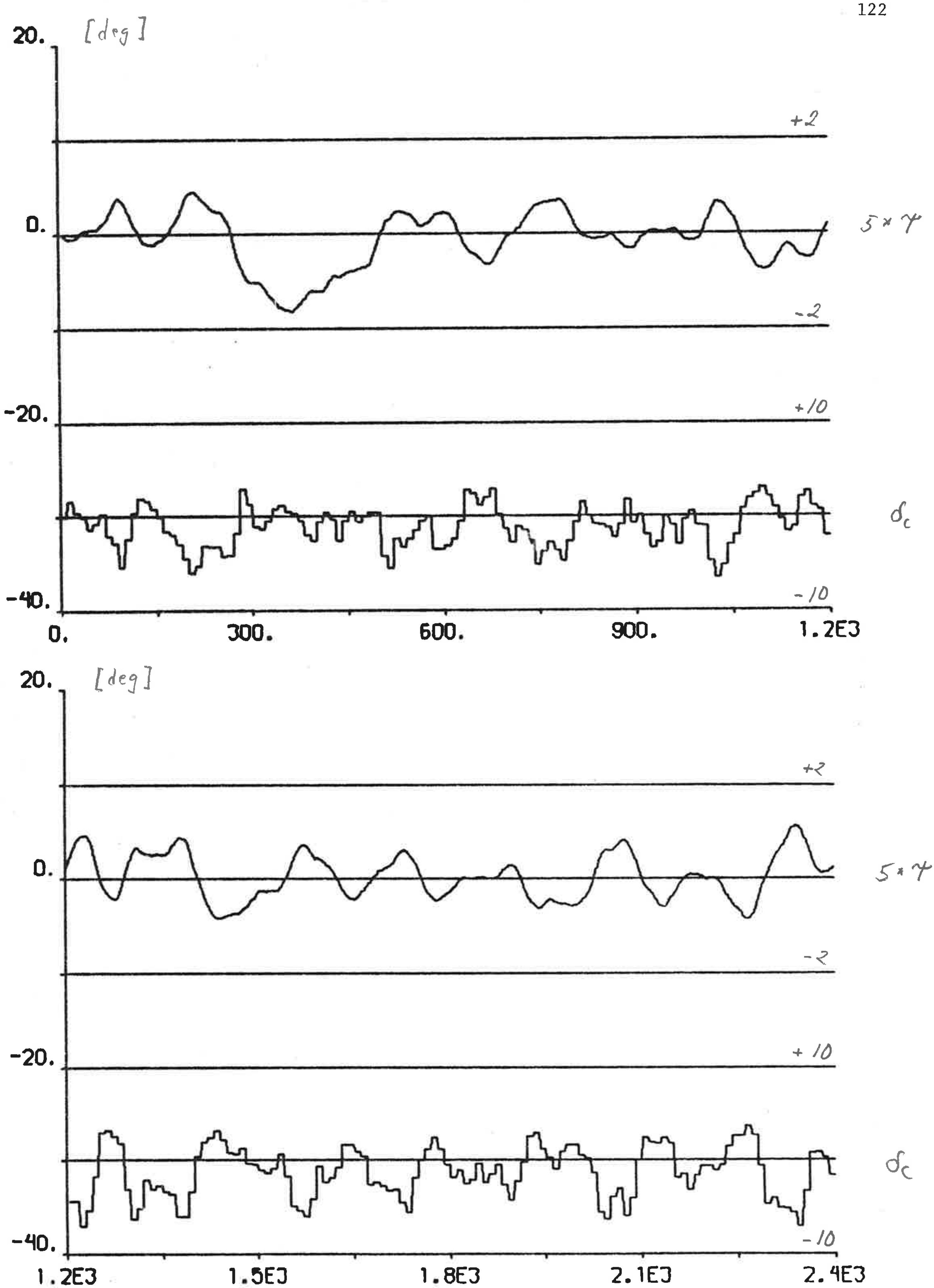
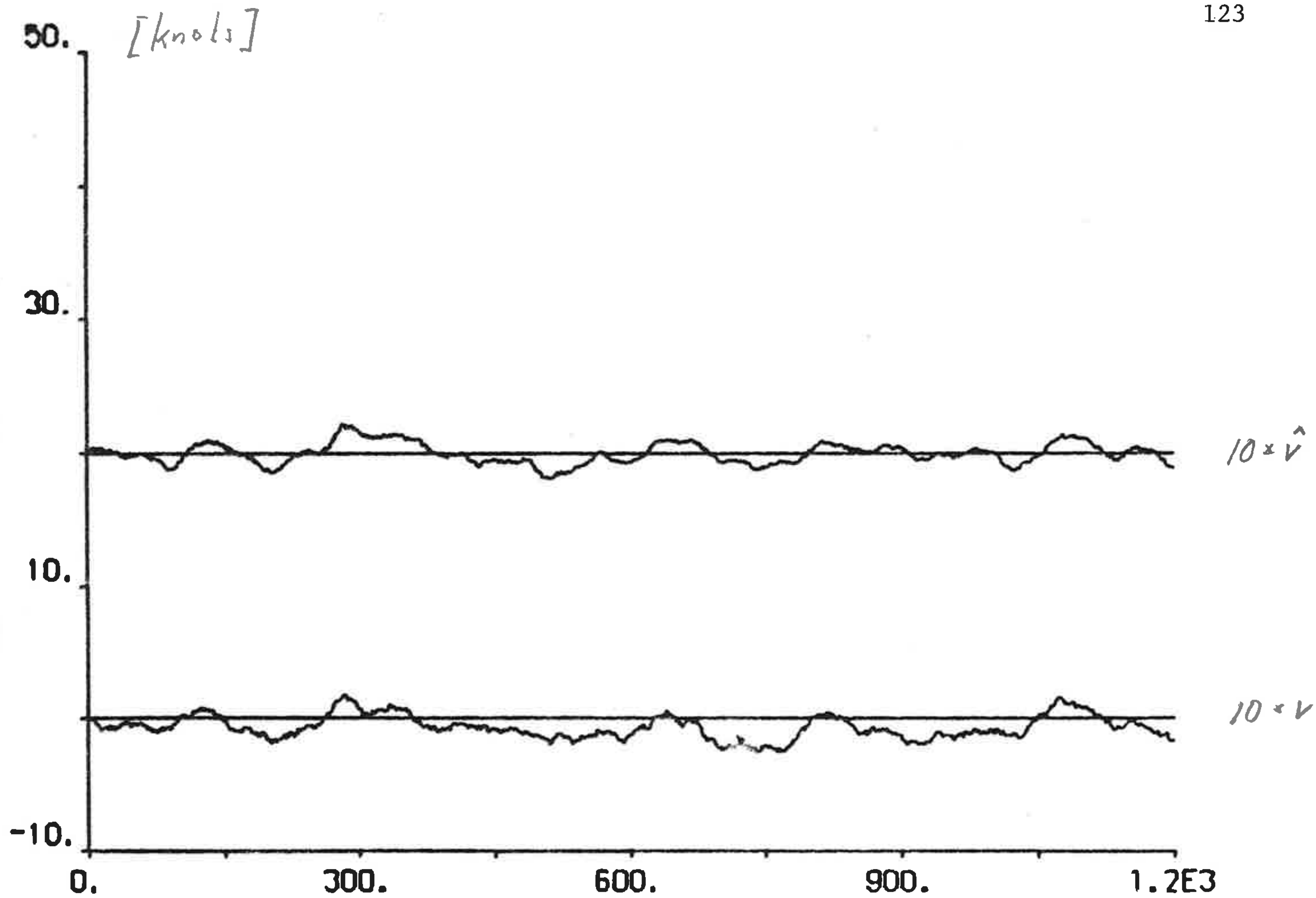


Fig. 4.8a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using estimates from the Kalman filter. The only measurement signal used by the filter is the heading angle.


[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × v̂
10 × v

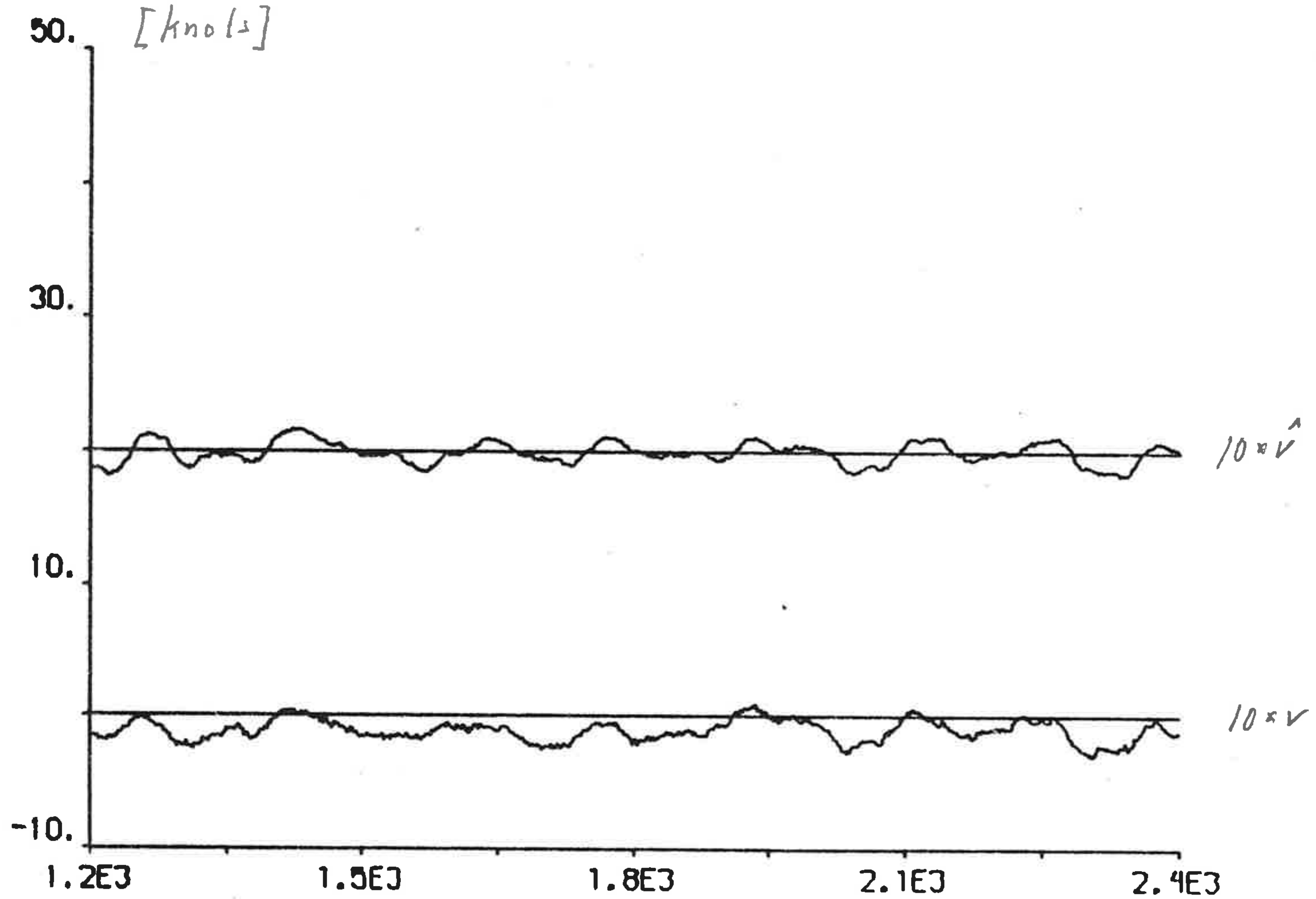

[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × v̂
10 × v

Fig. 4.8b

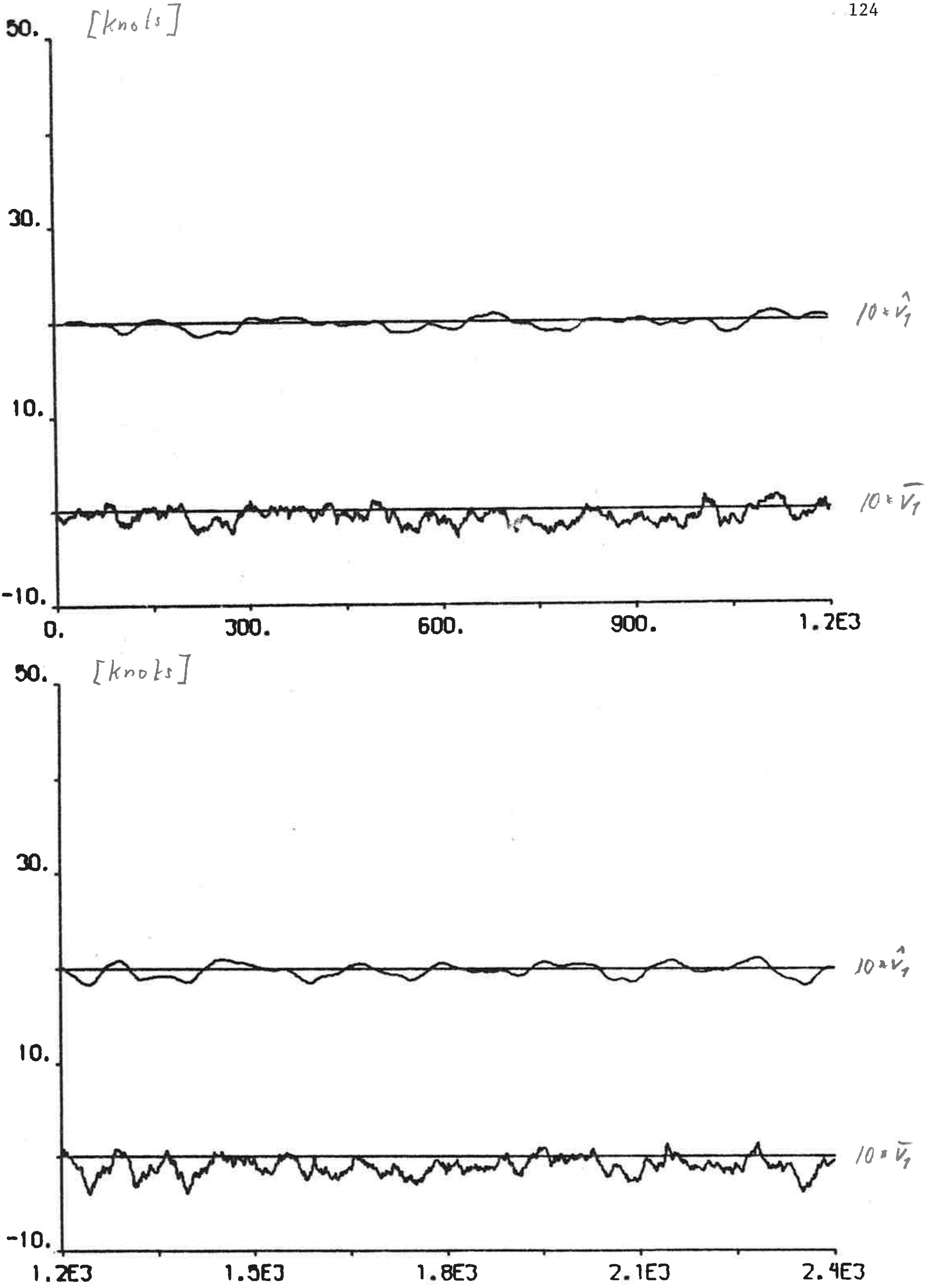
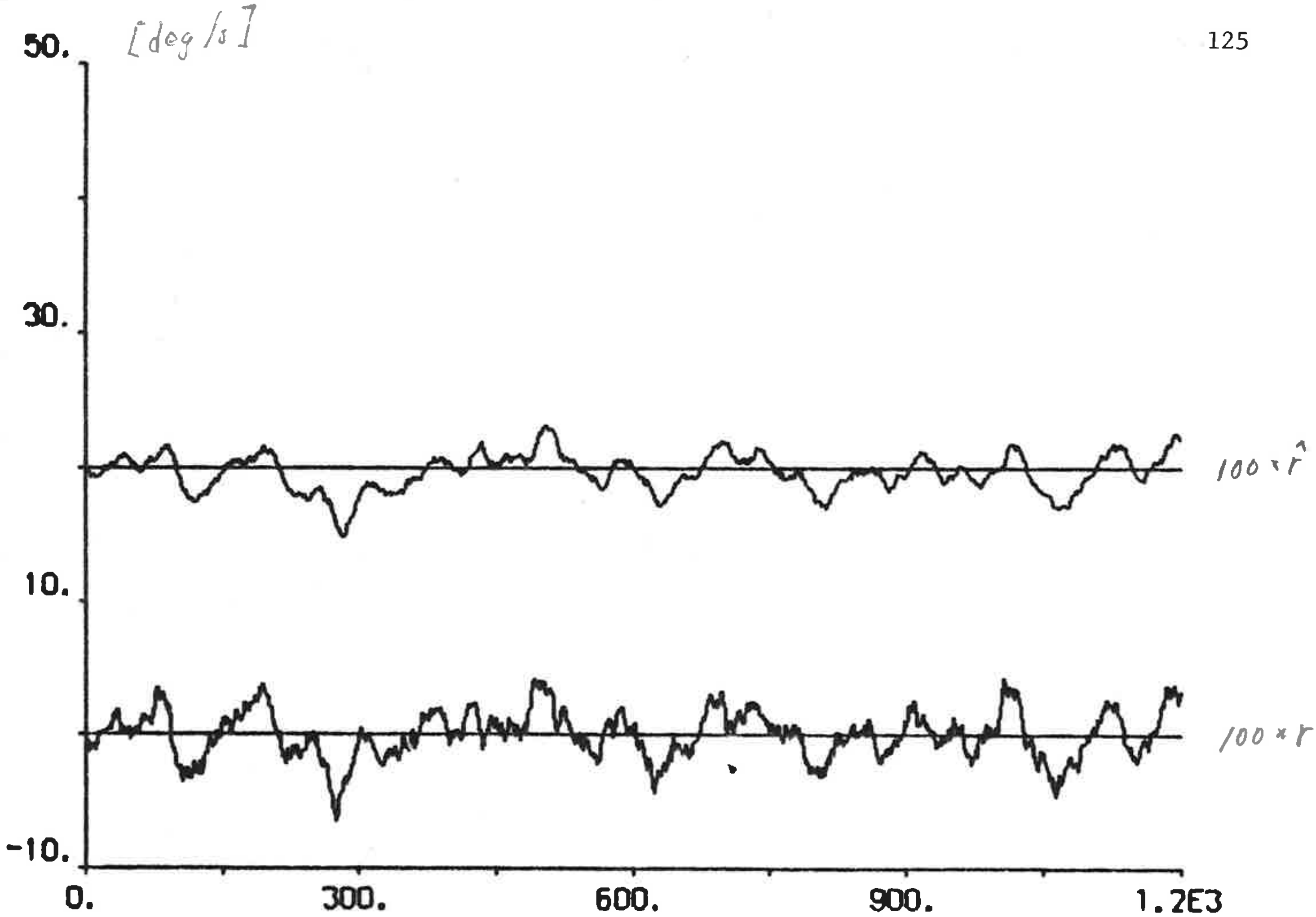

[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 * V̂1
10 * V̄1
[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 * V̂1
10 * V̄1

Fig. 4.8c


50.
[deg/s]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 * r̂
100 * r

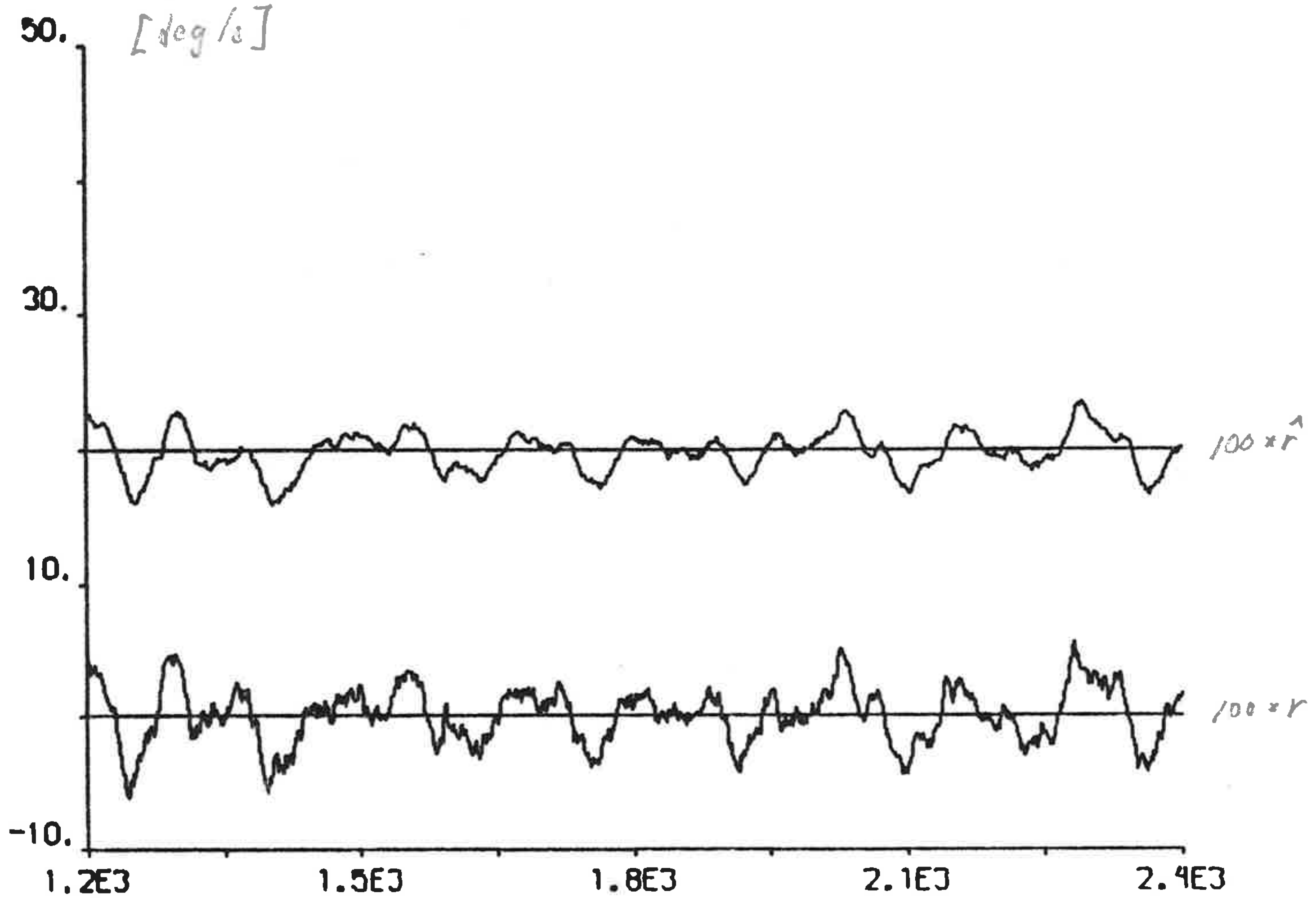

50.
[deg/s]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 * r̂
100 * r

Fig. 4.8d

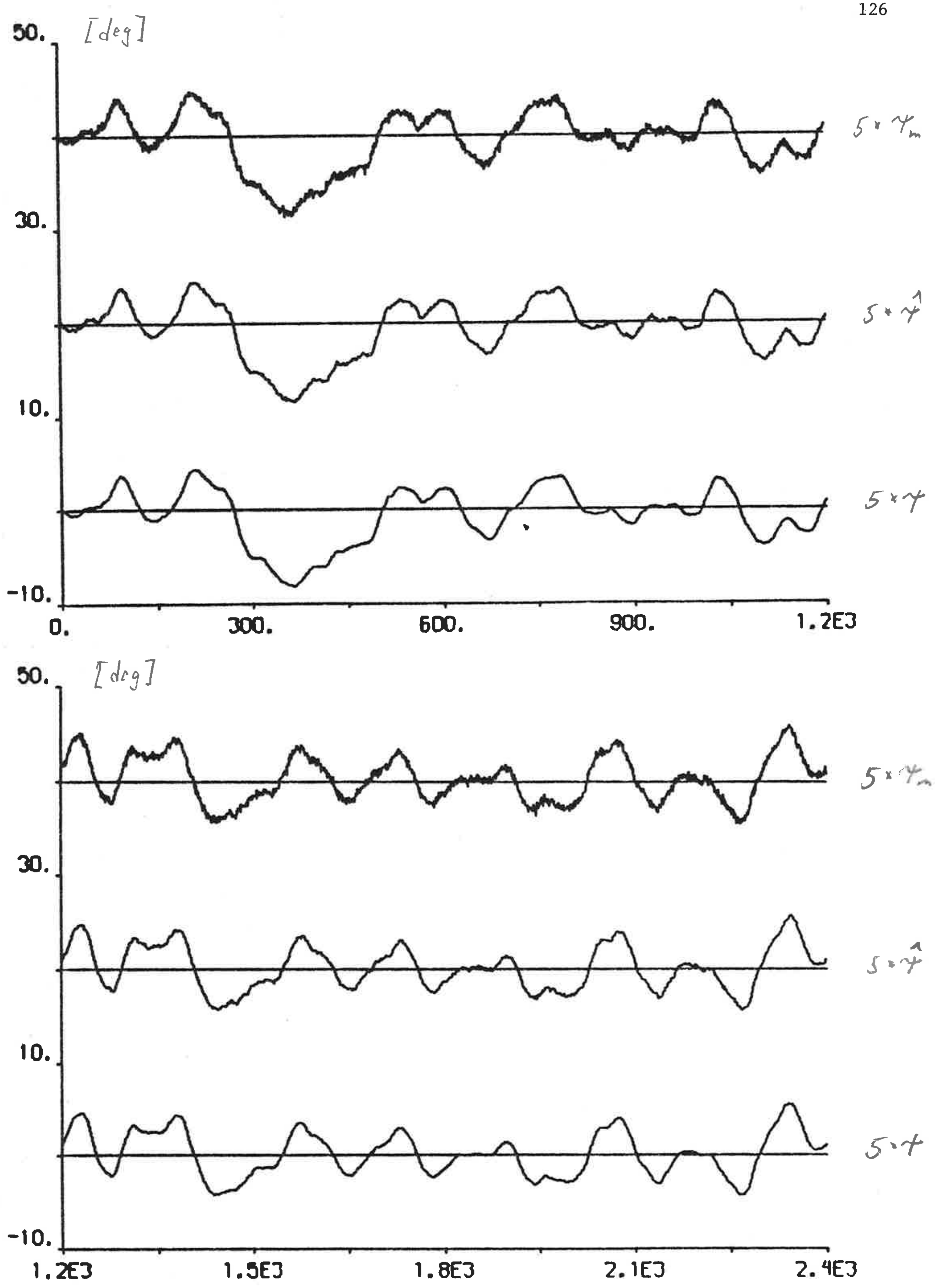

50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5 × ψm
5 × ψ̂
5 × ψ
50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5 × ψm
5 × ψ̂
5 × ψ

Fig. 4.8e

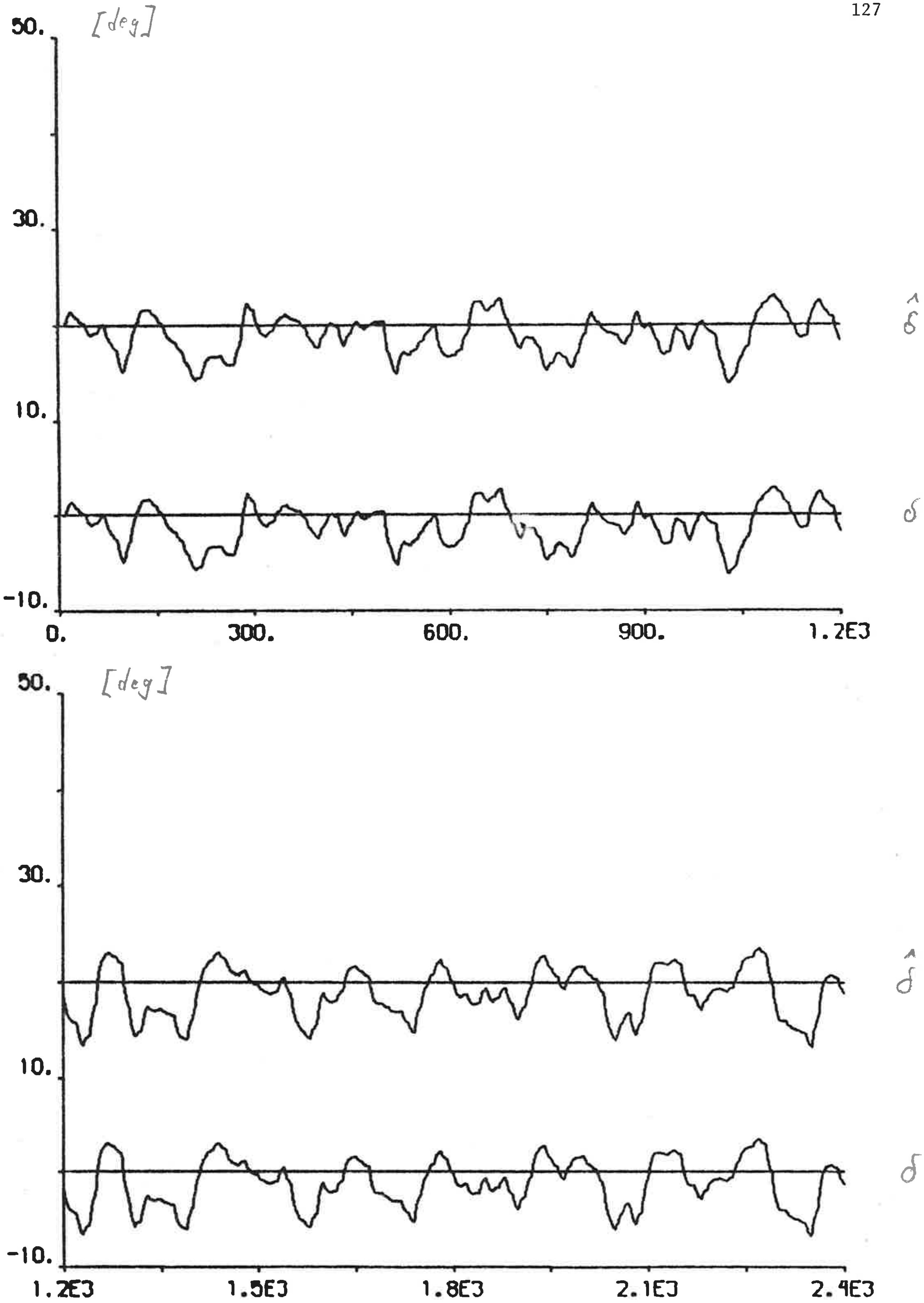

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
δ̂
δ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
δ̂
δ

Fig. 4.8f

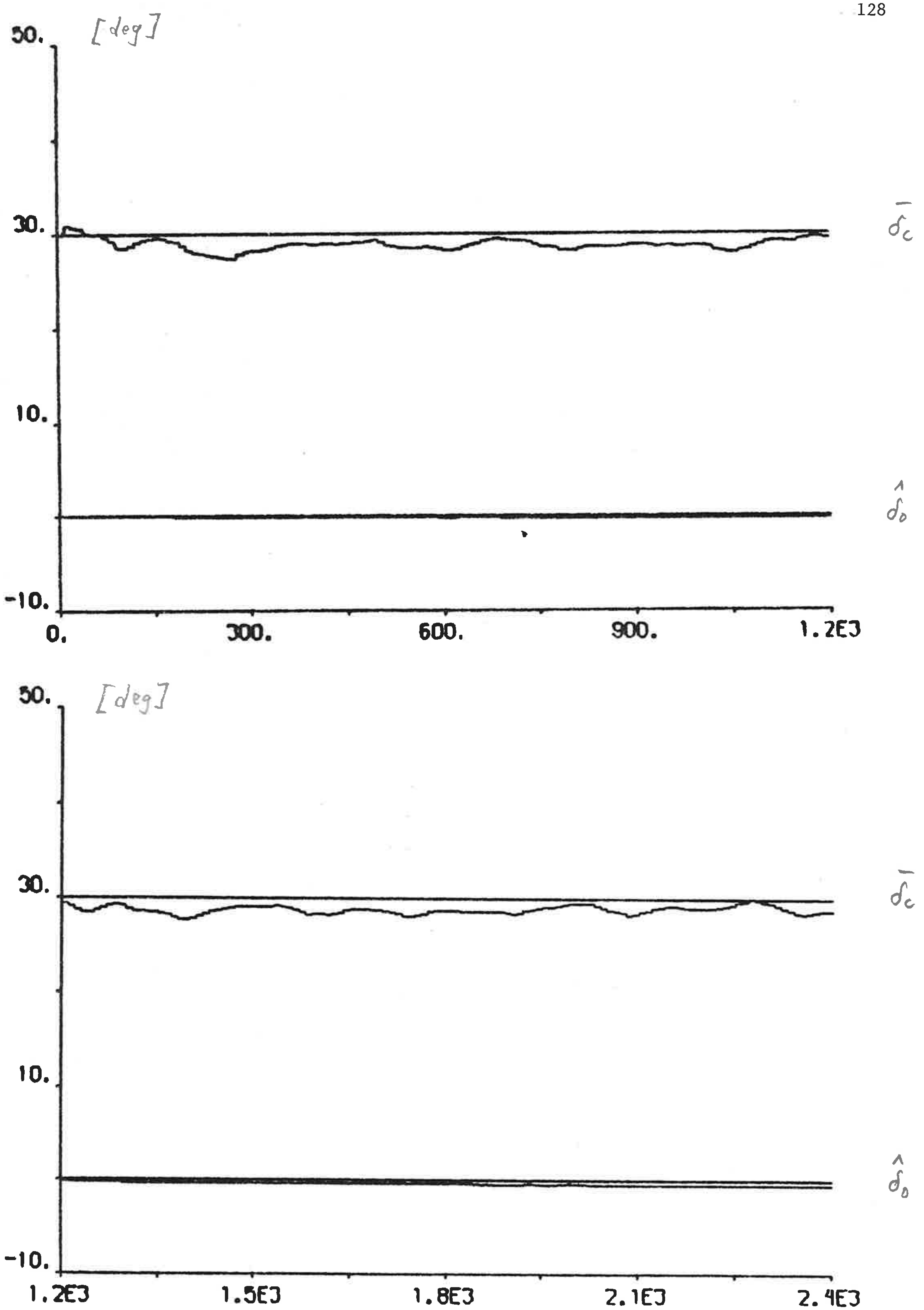
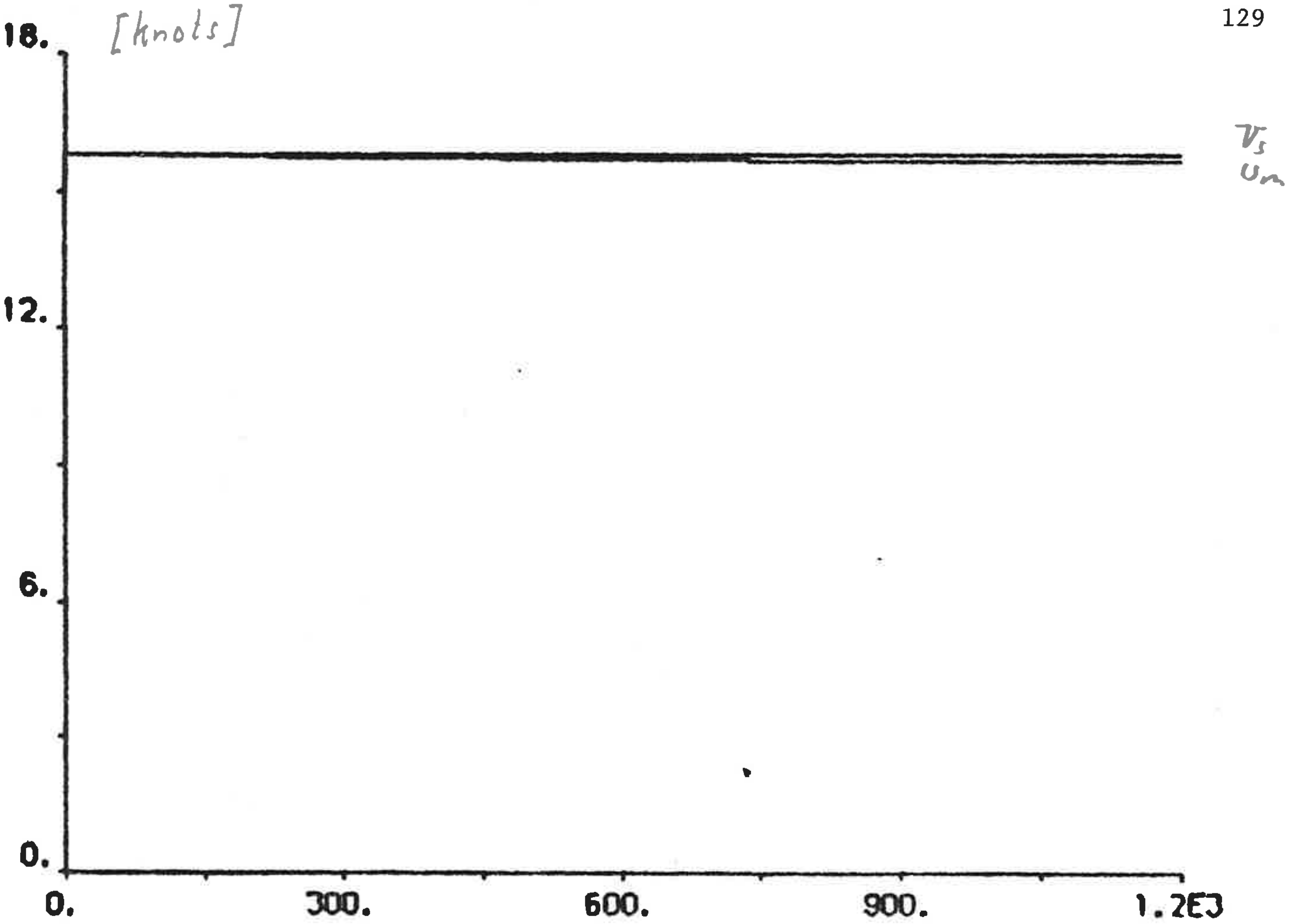

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.8g


[knots]
18.
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
U_m

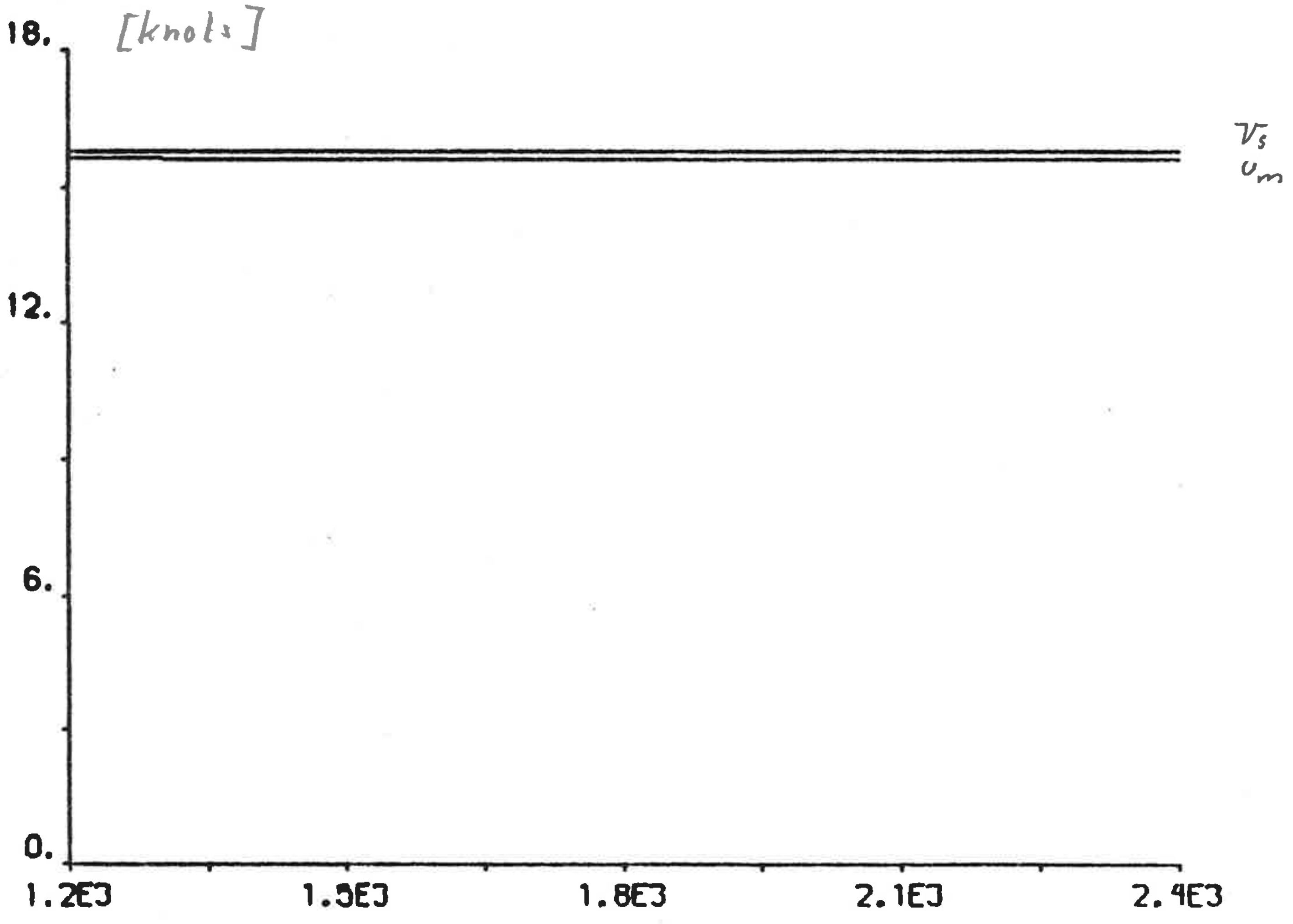
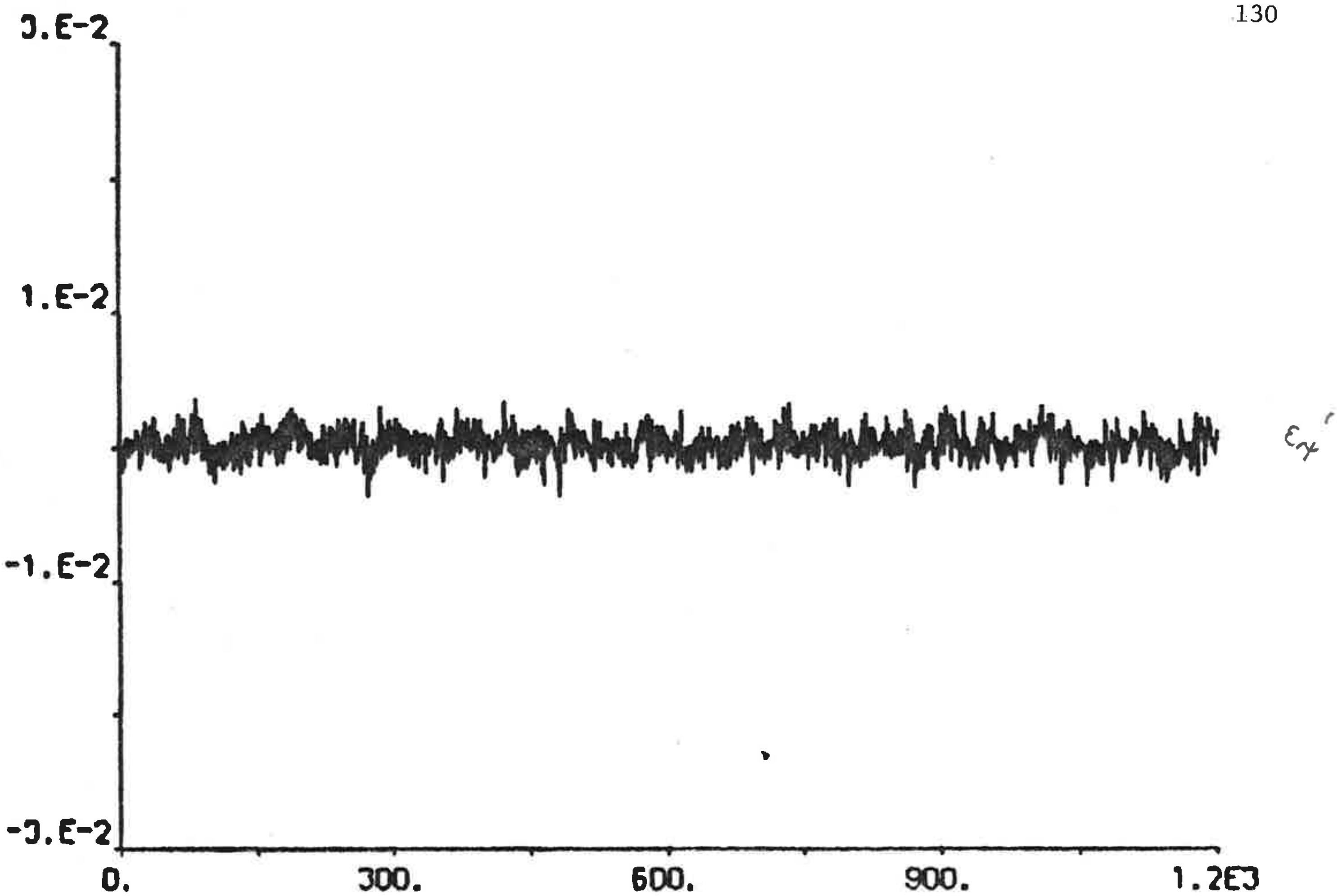

[knots]
18.
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
V_s
U_m

Fig. 4.8h


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
εx'

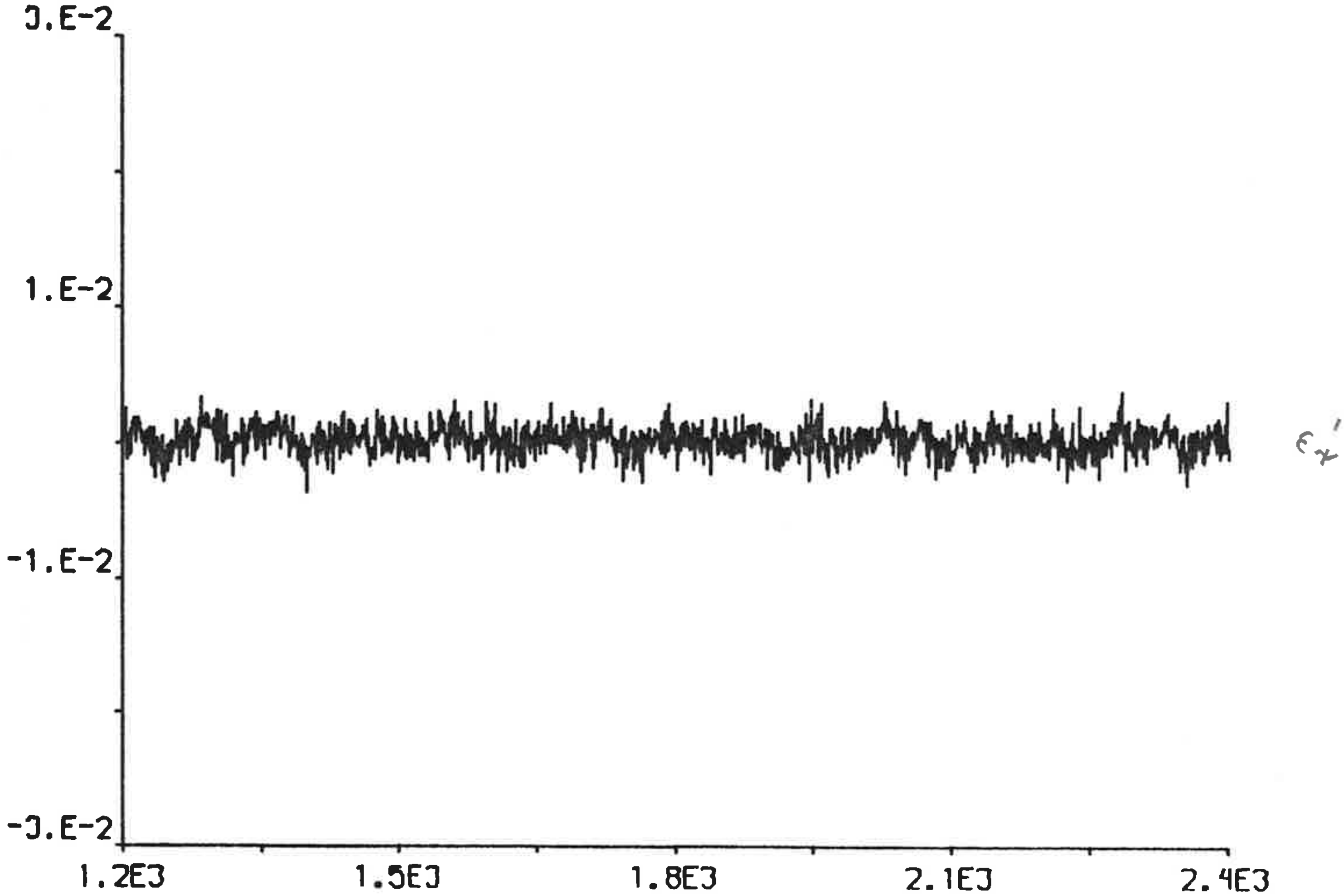
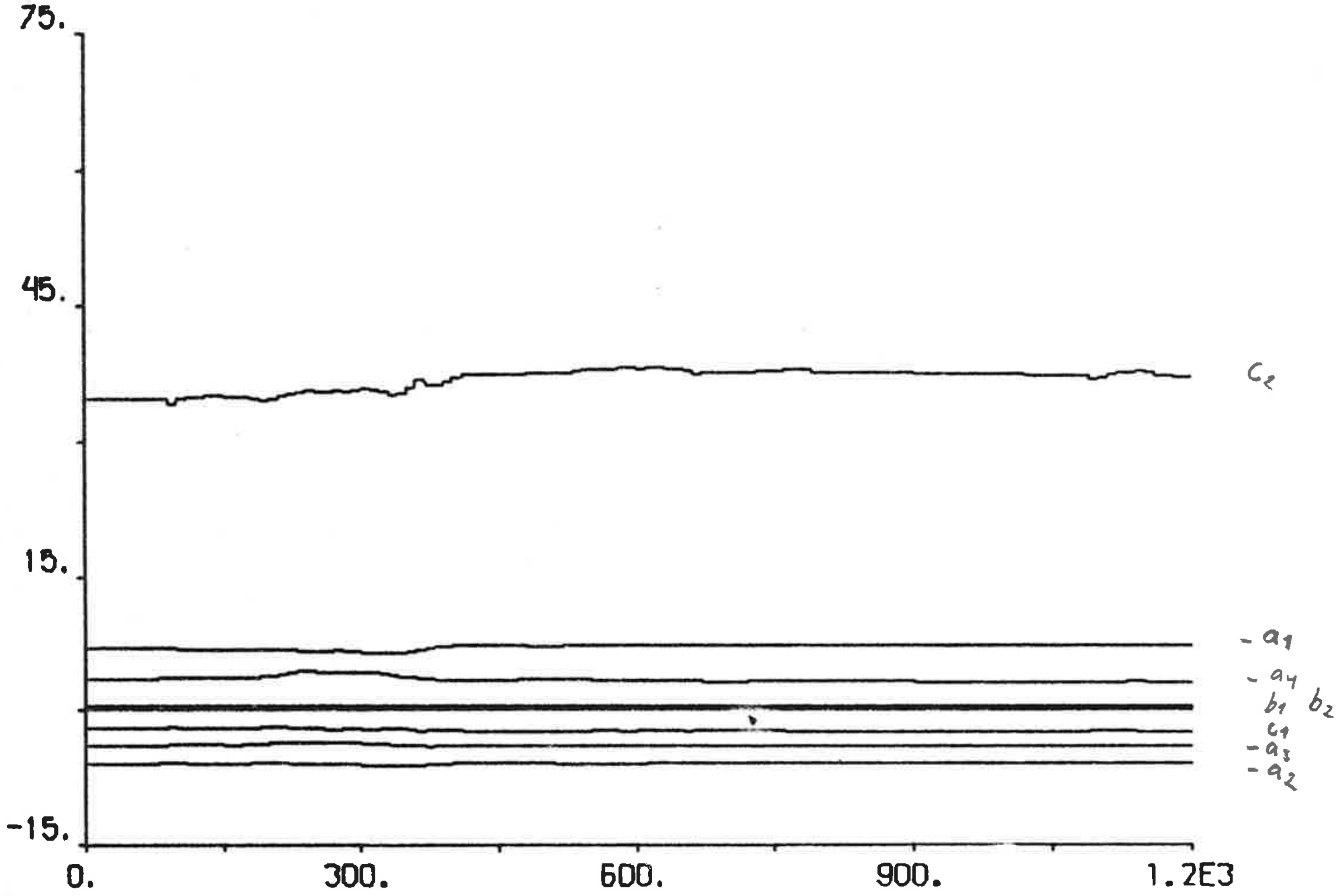

3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εx'

Fig. 4.8i


75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1 b_2
c_1
$-a_3$
$-a_2$

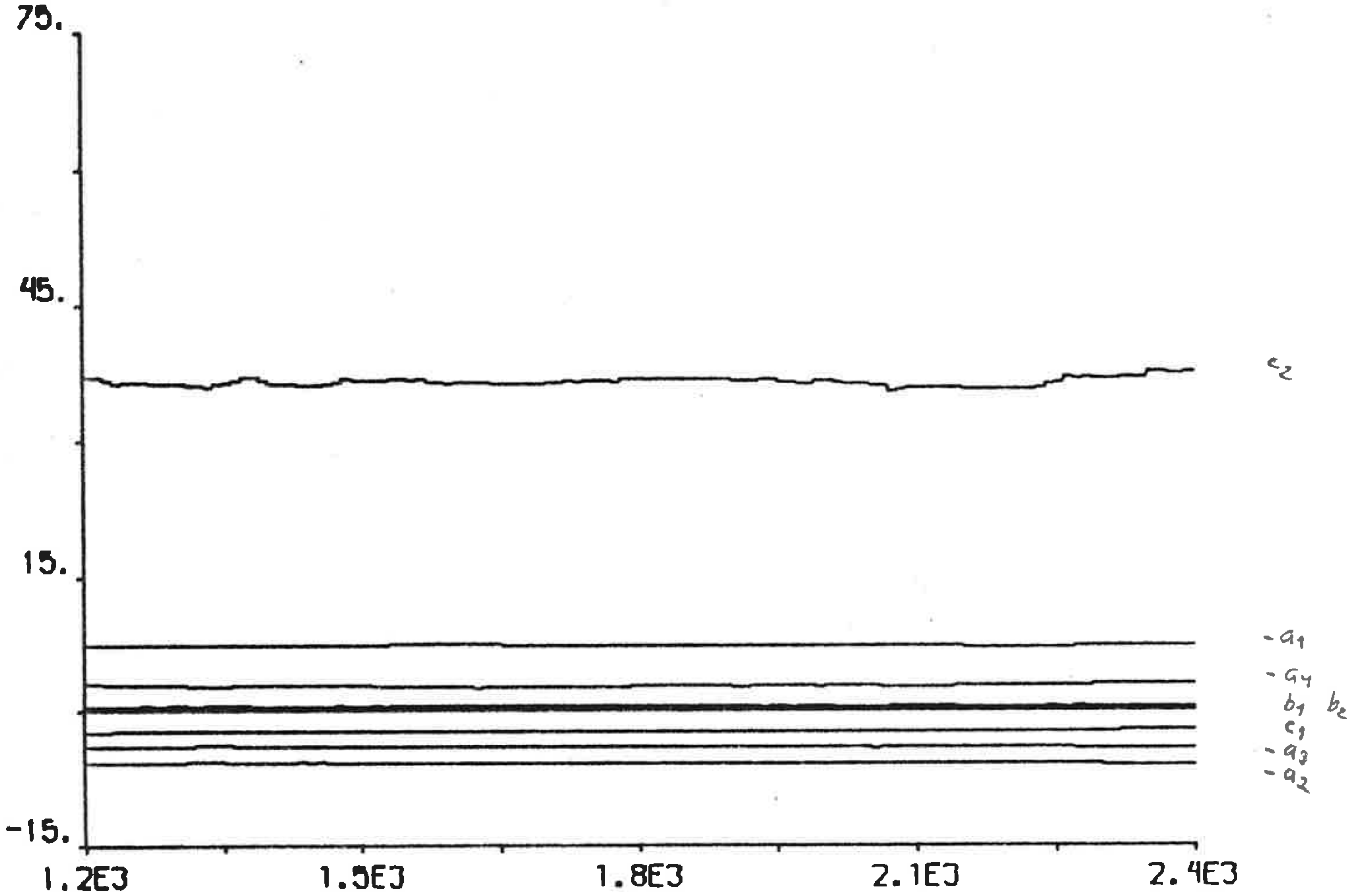

75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1 b_2
c_1
$-a_3$
$-a_2$

Fig. 4.8j

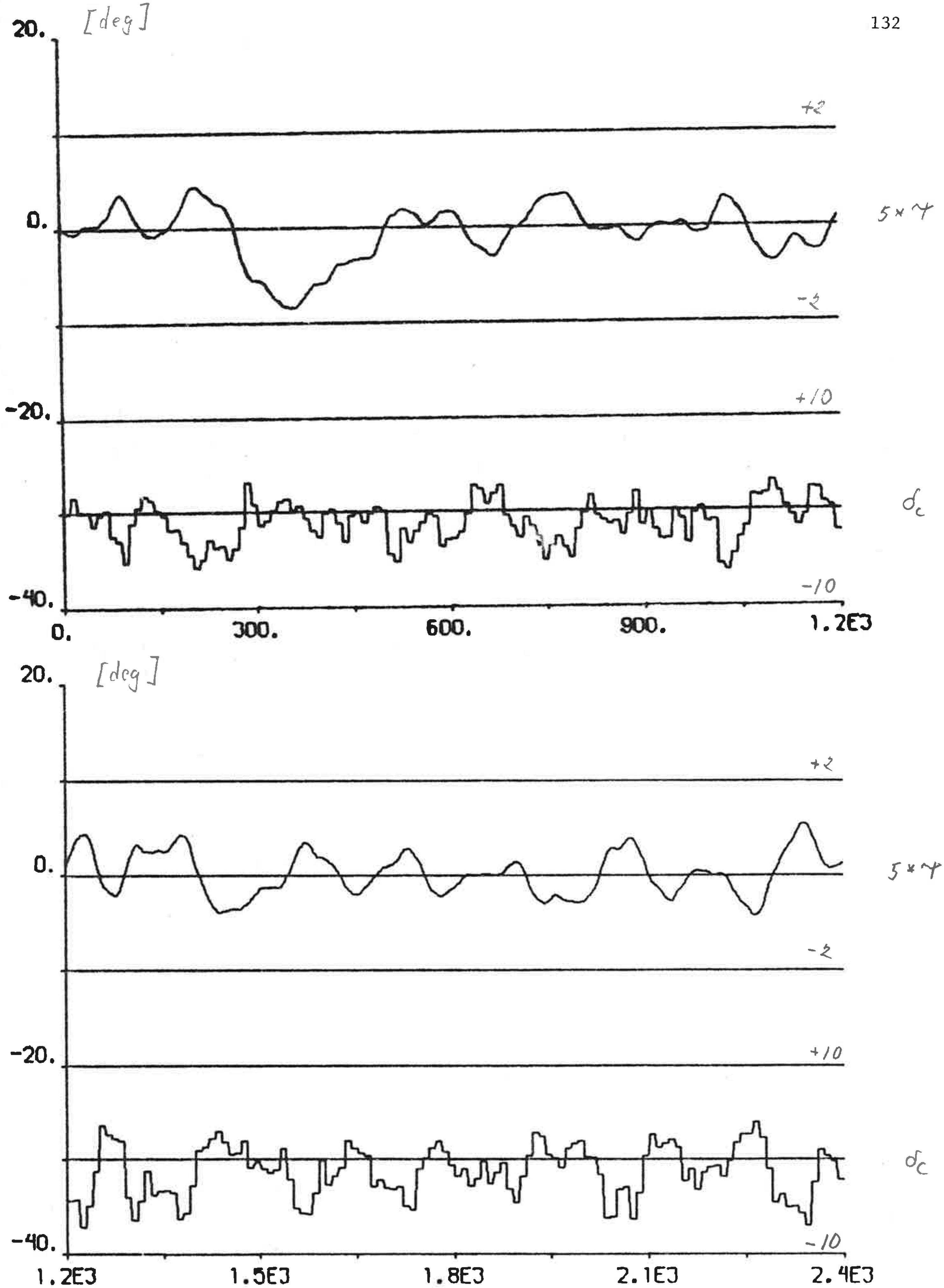


Fig. 4.9a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using estimates from the Kalman filter. The only measurement signal used by the filter is the heading angle. The correct filter gain K given by (4.4) is used.

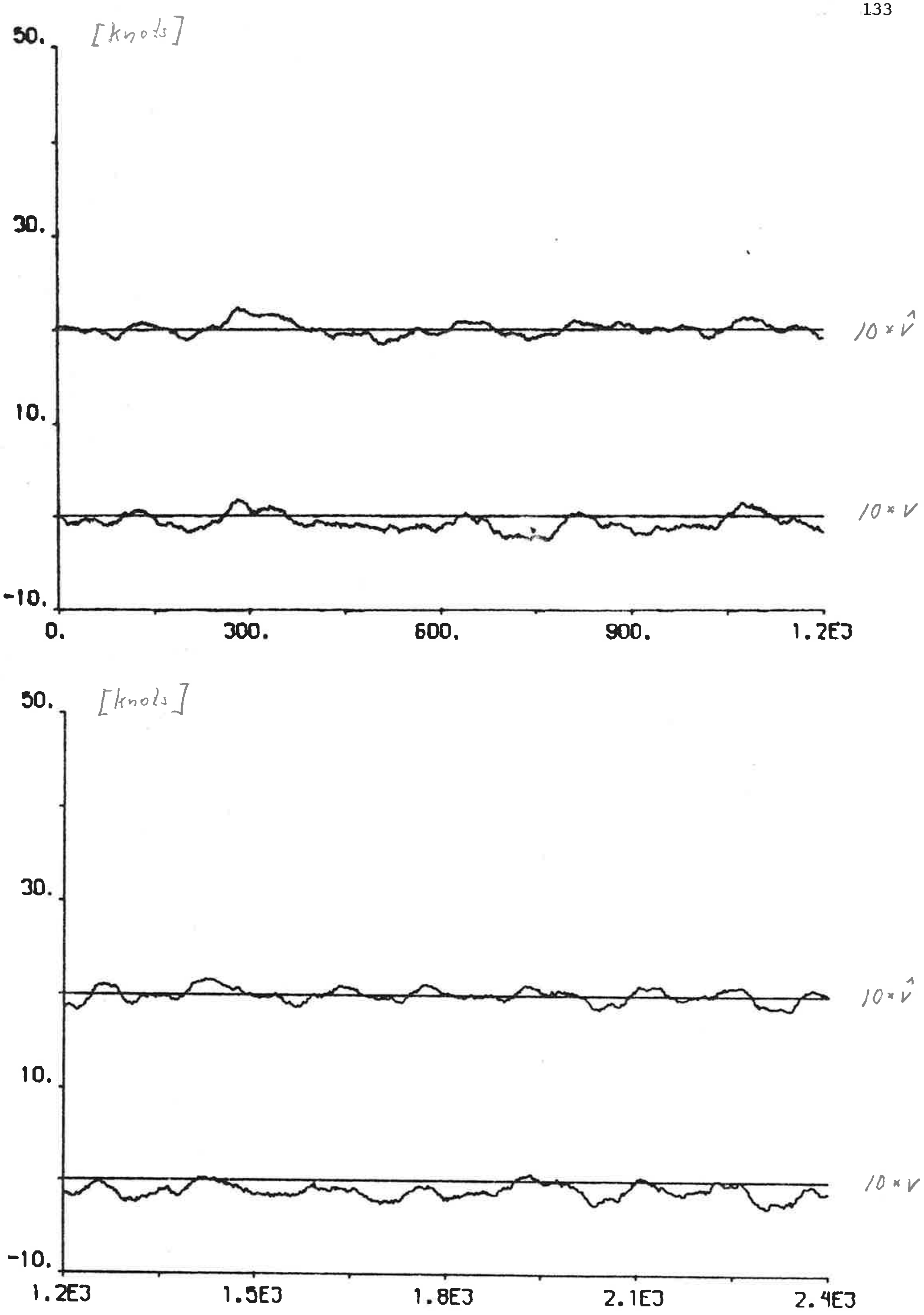
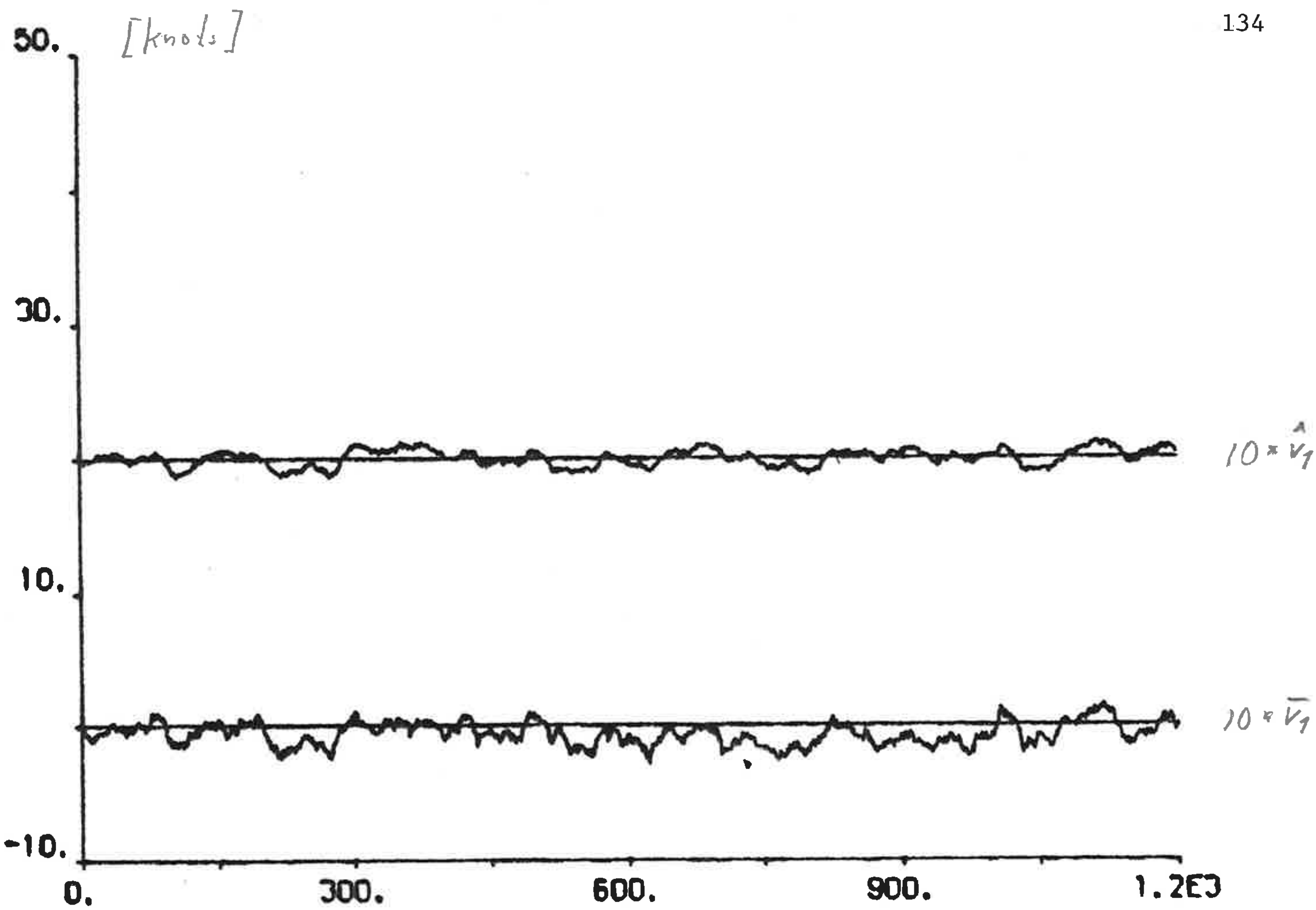

50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × v̂
10 × v
50.
[knots]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × v̂
10 × v

Fig. 4.9b


[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$10 \times \hat{V}_1$
$10 \times \bar{V}_1$

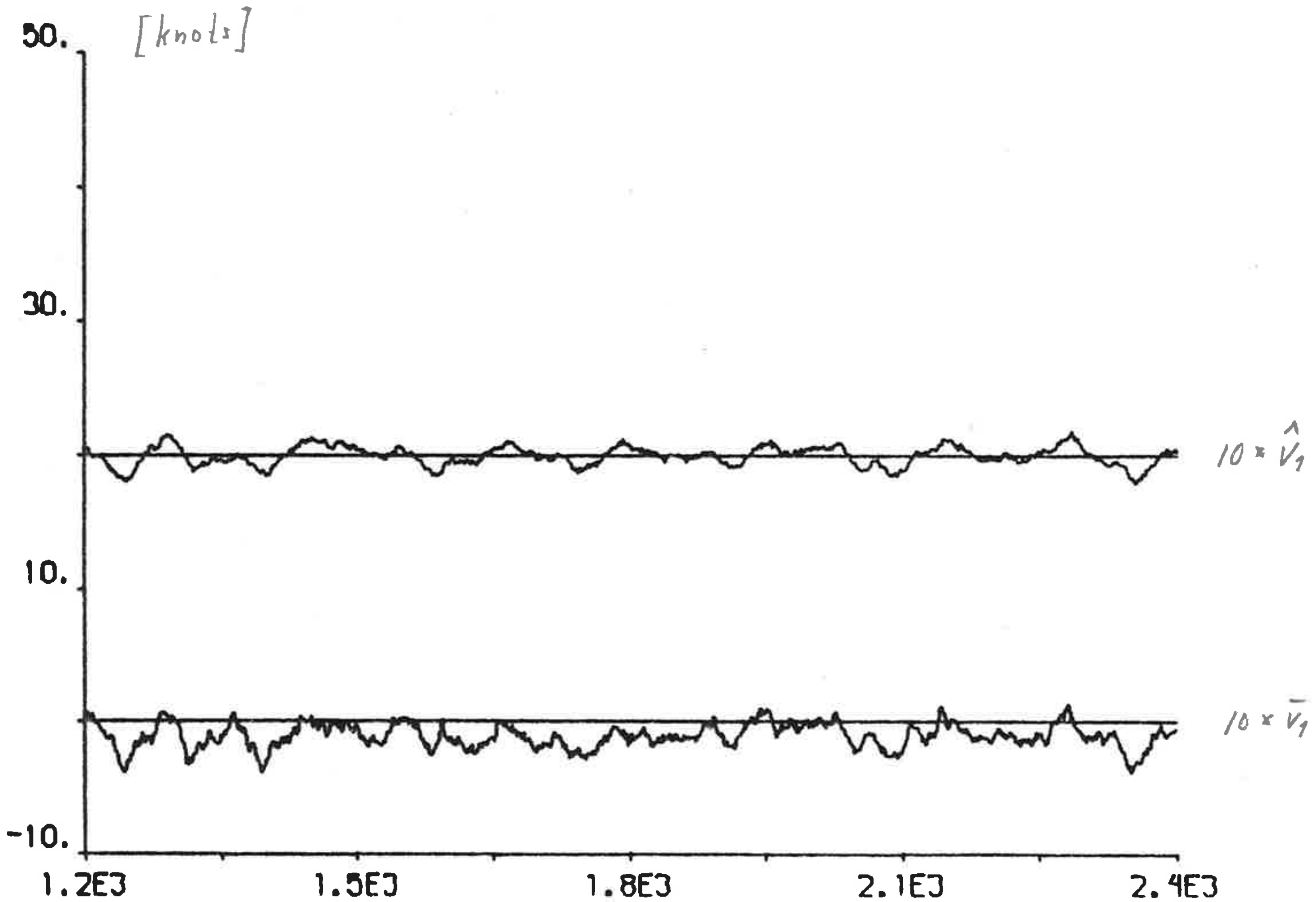
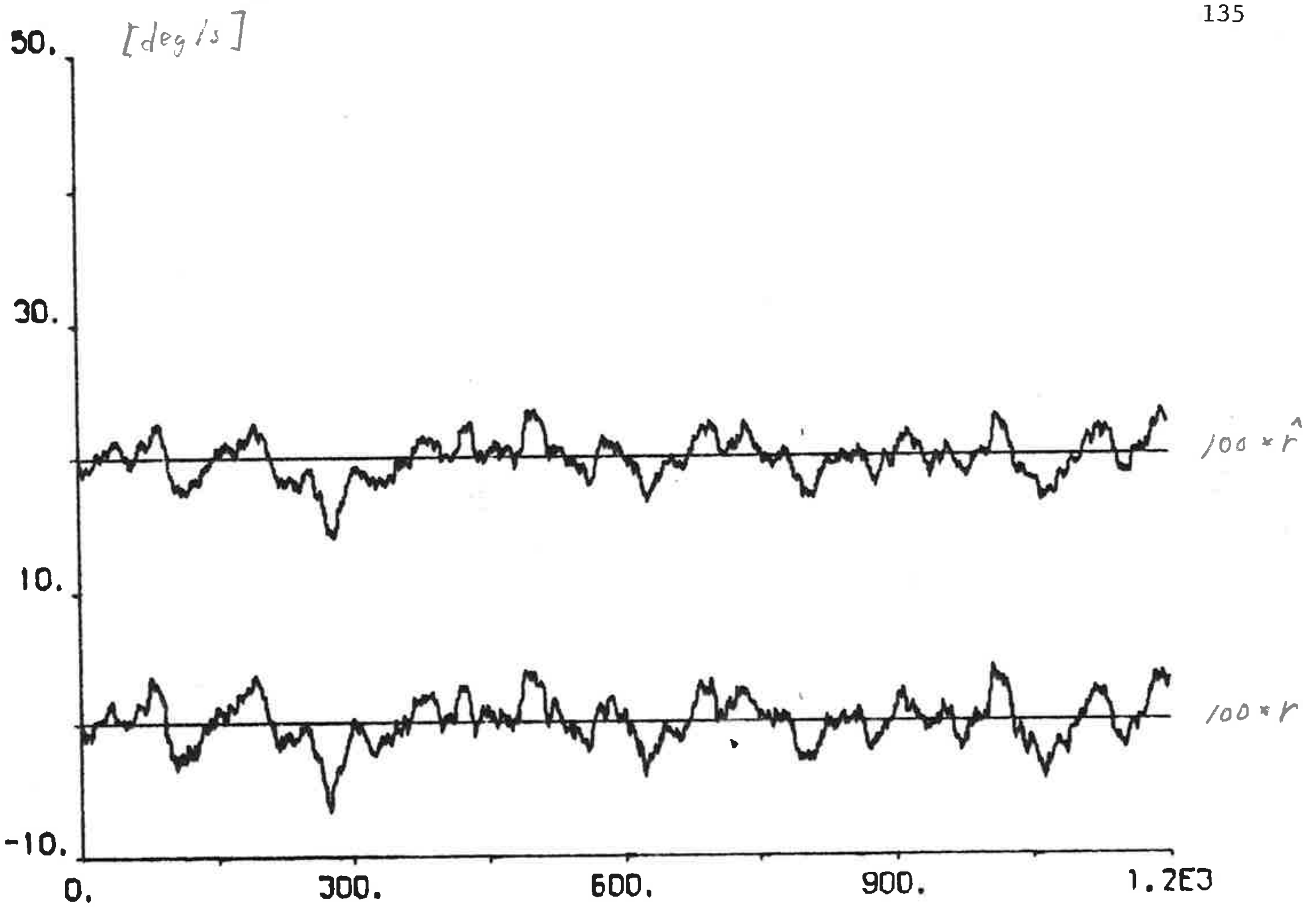
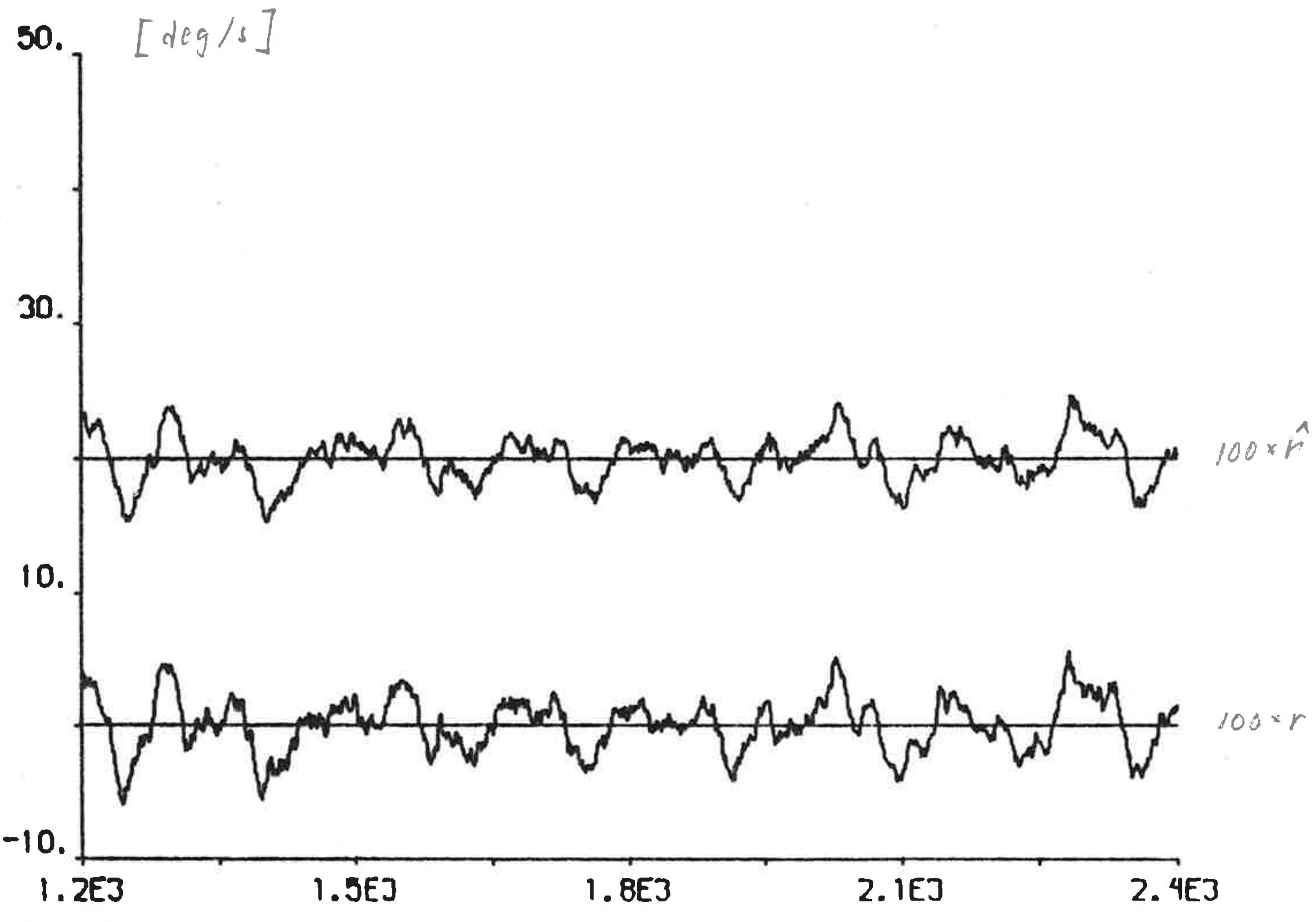

[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
$10 \times \hat{V}_1$
$10 \times \bar{V}_1$

Fig. 4.9c

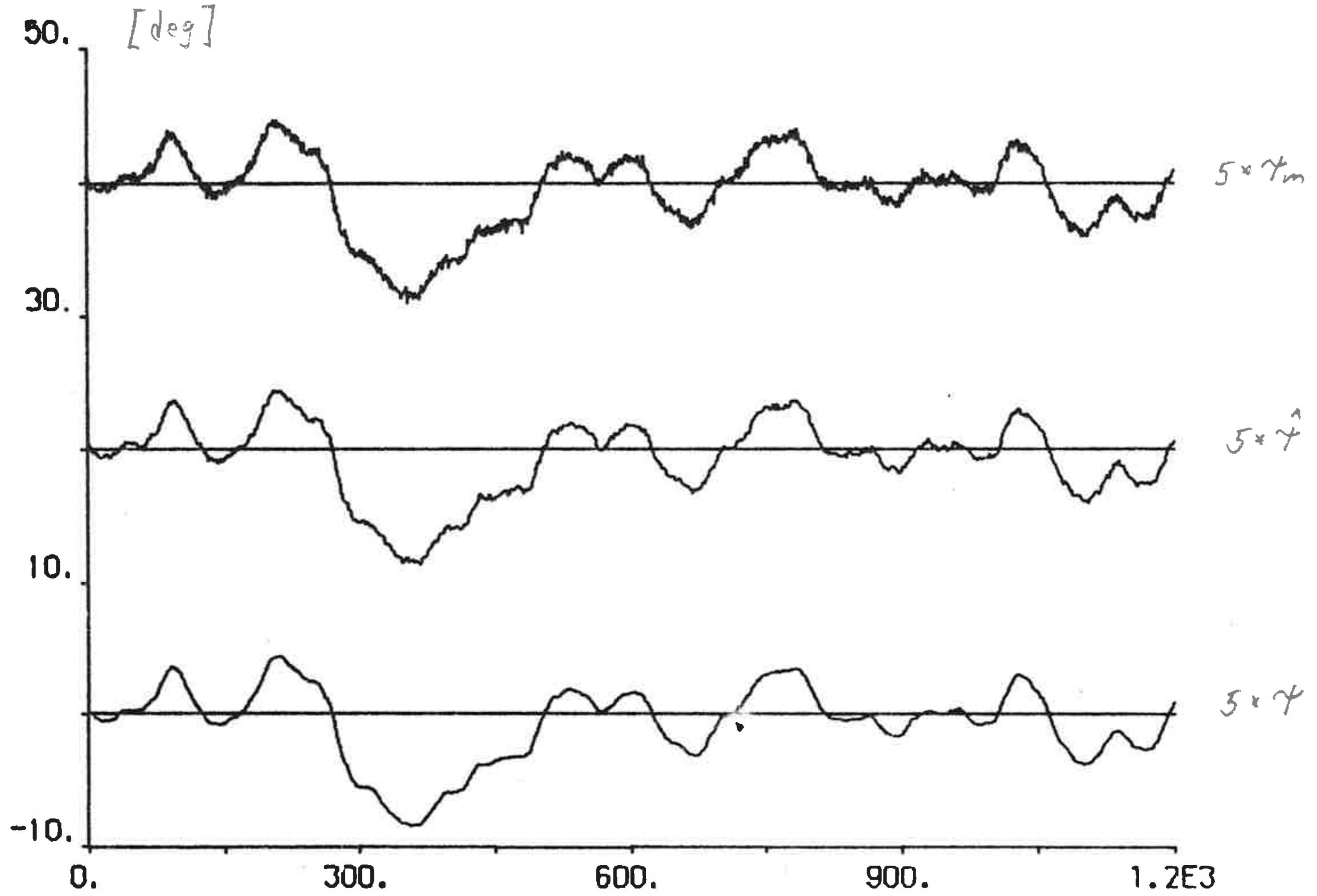


[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 * r̂
100 * r

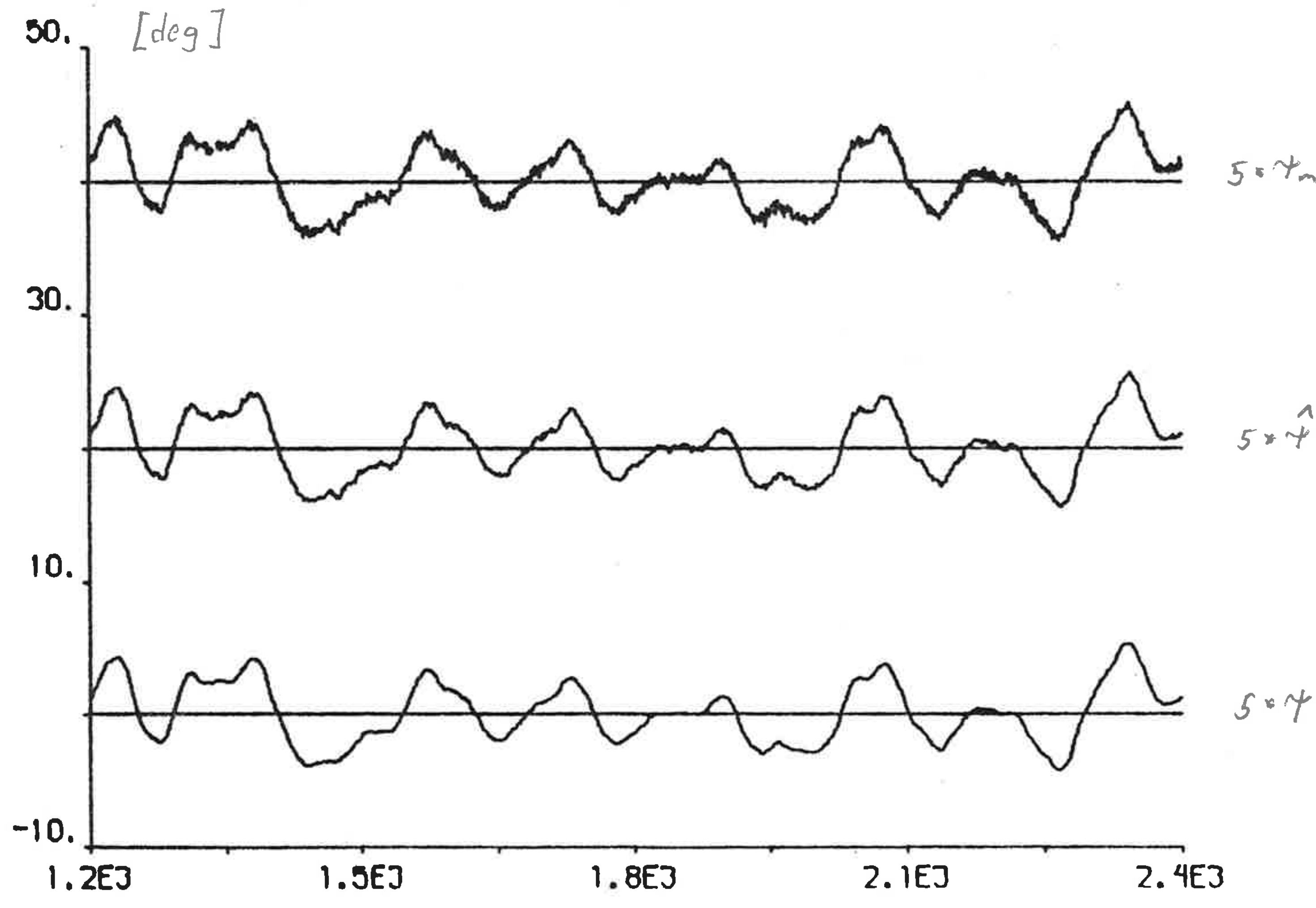


[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 * r̂
100 * r

Fig. 4.9d

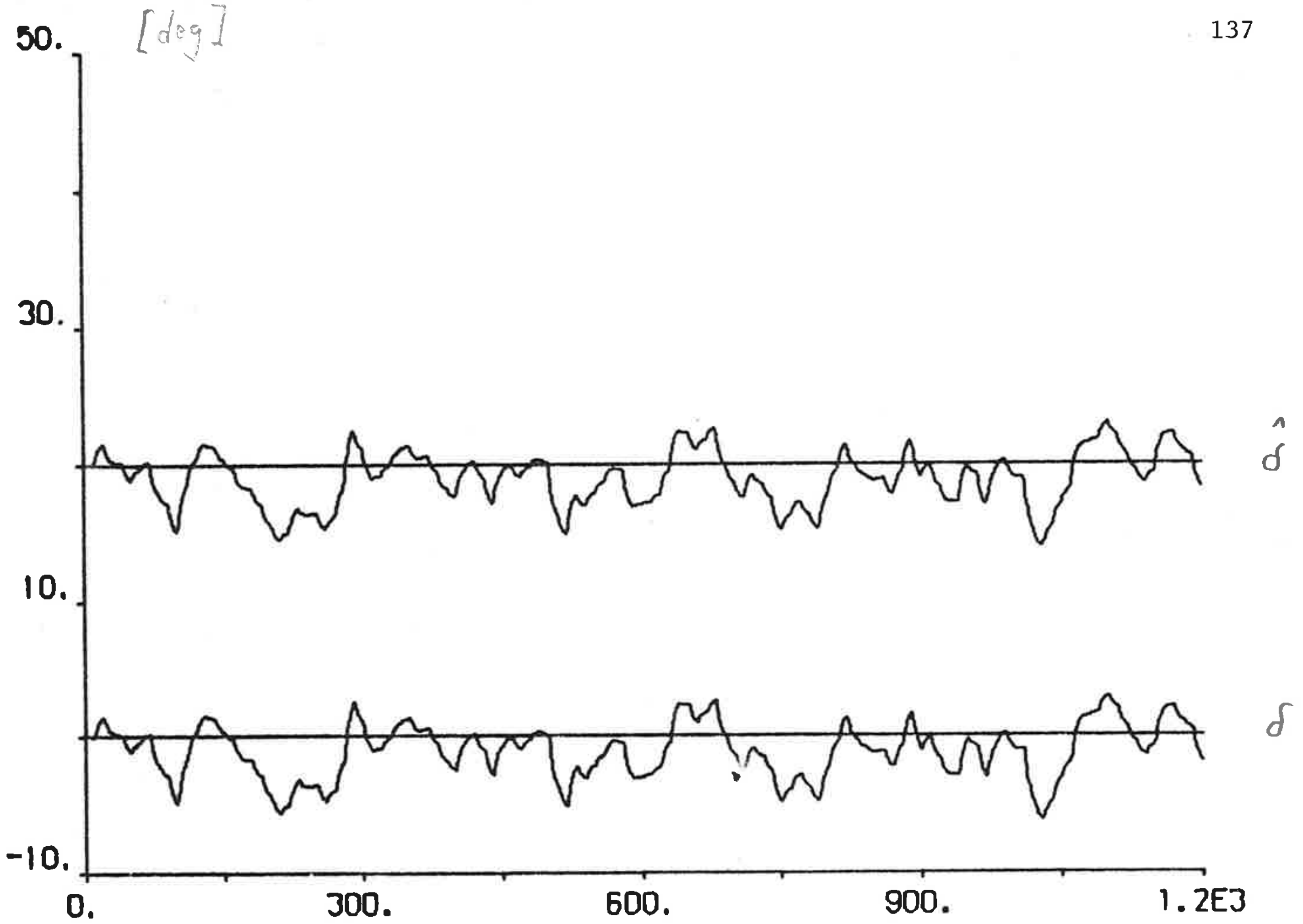


[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5*ψm
5*ψ̂
5*ψ



[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5*ψm
5*ψ̂
5*ψ

Fig. 4.9e


[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
δ̂
δ

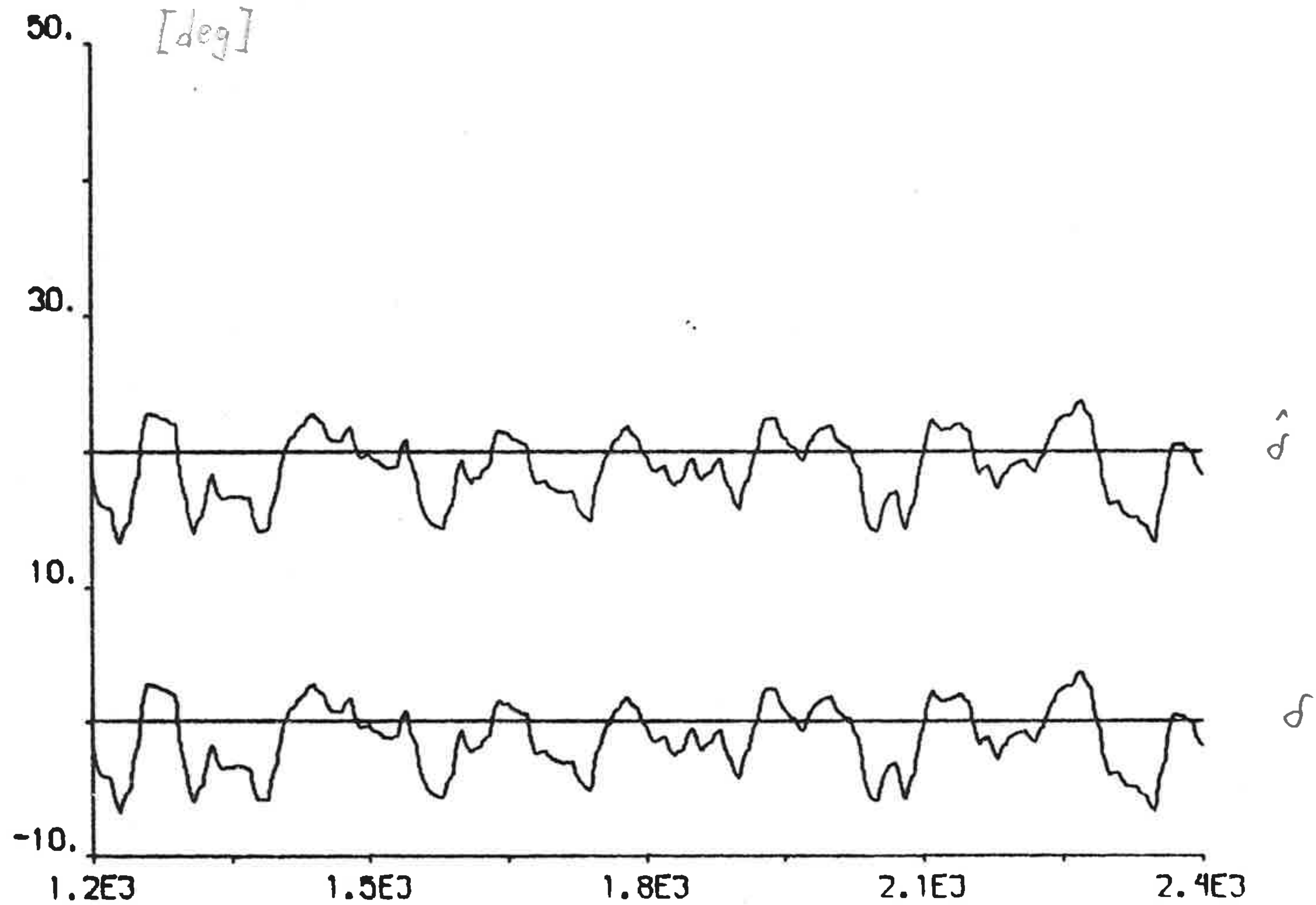
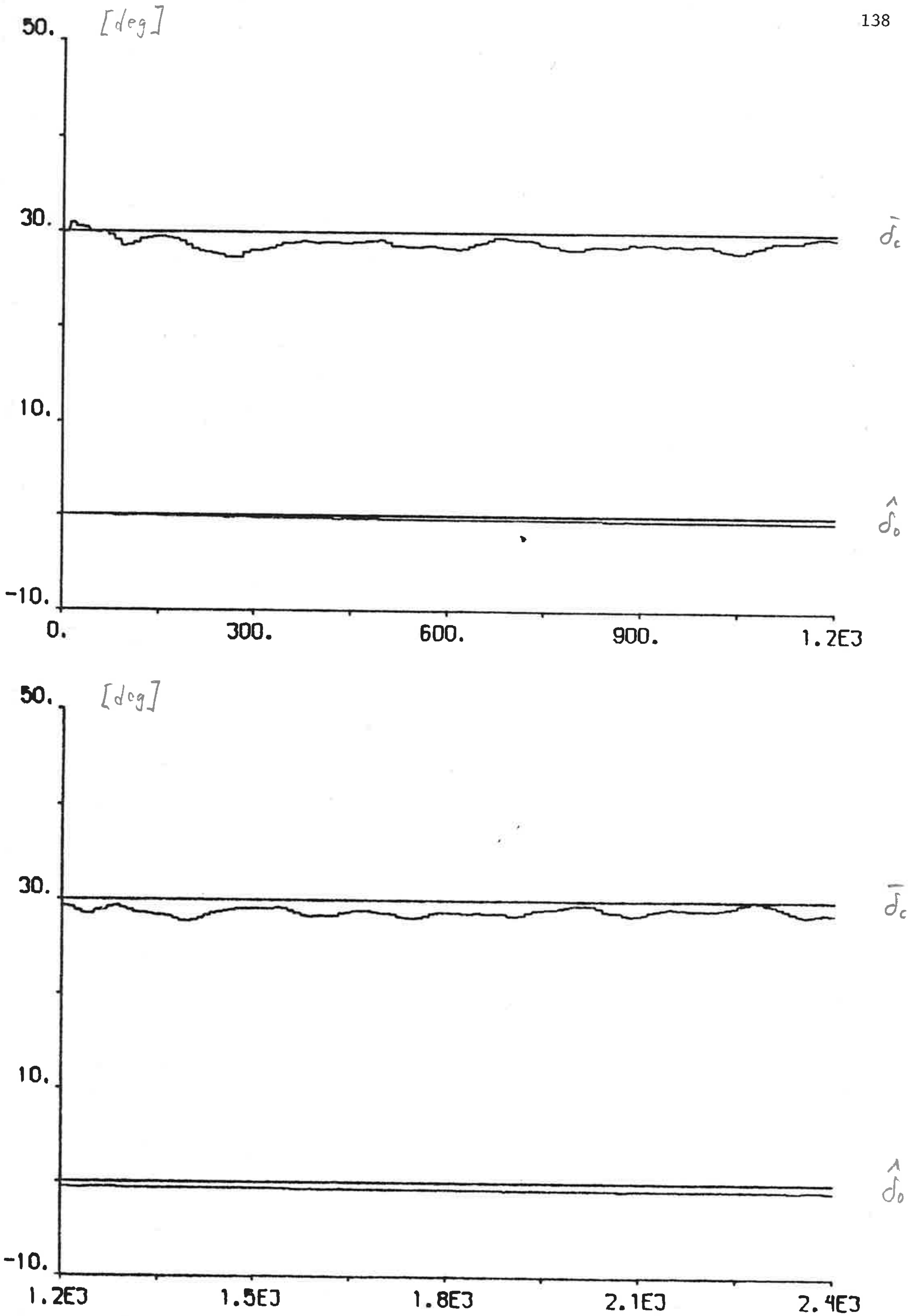
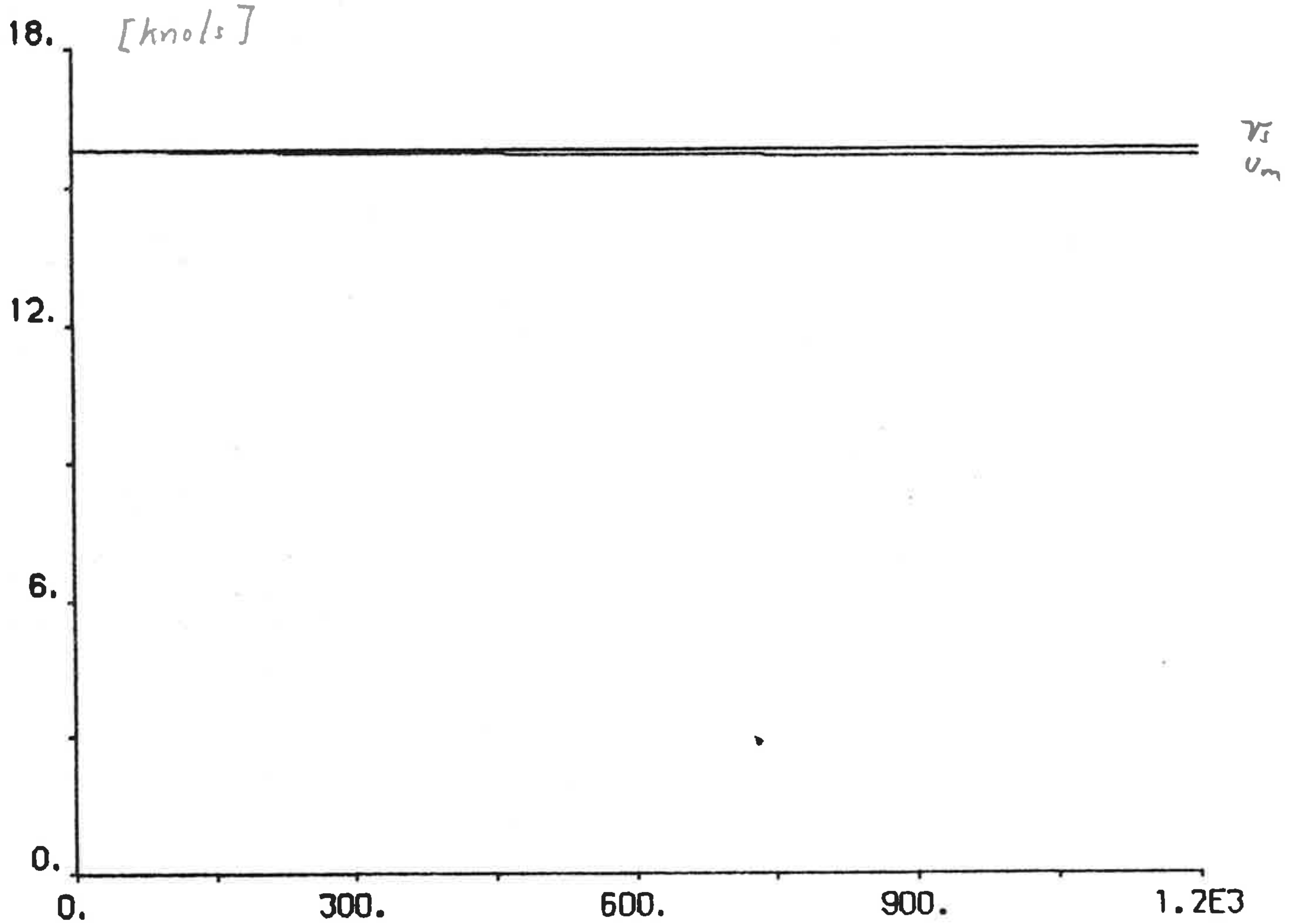

[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
δ̂
δ

Fig. 4.9f

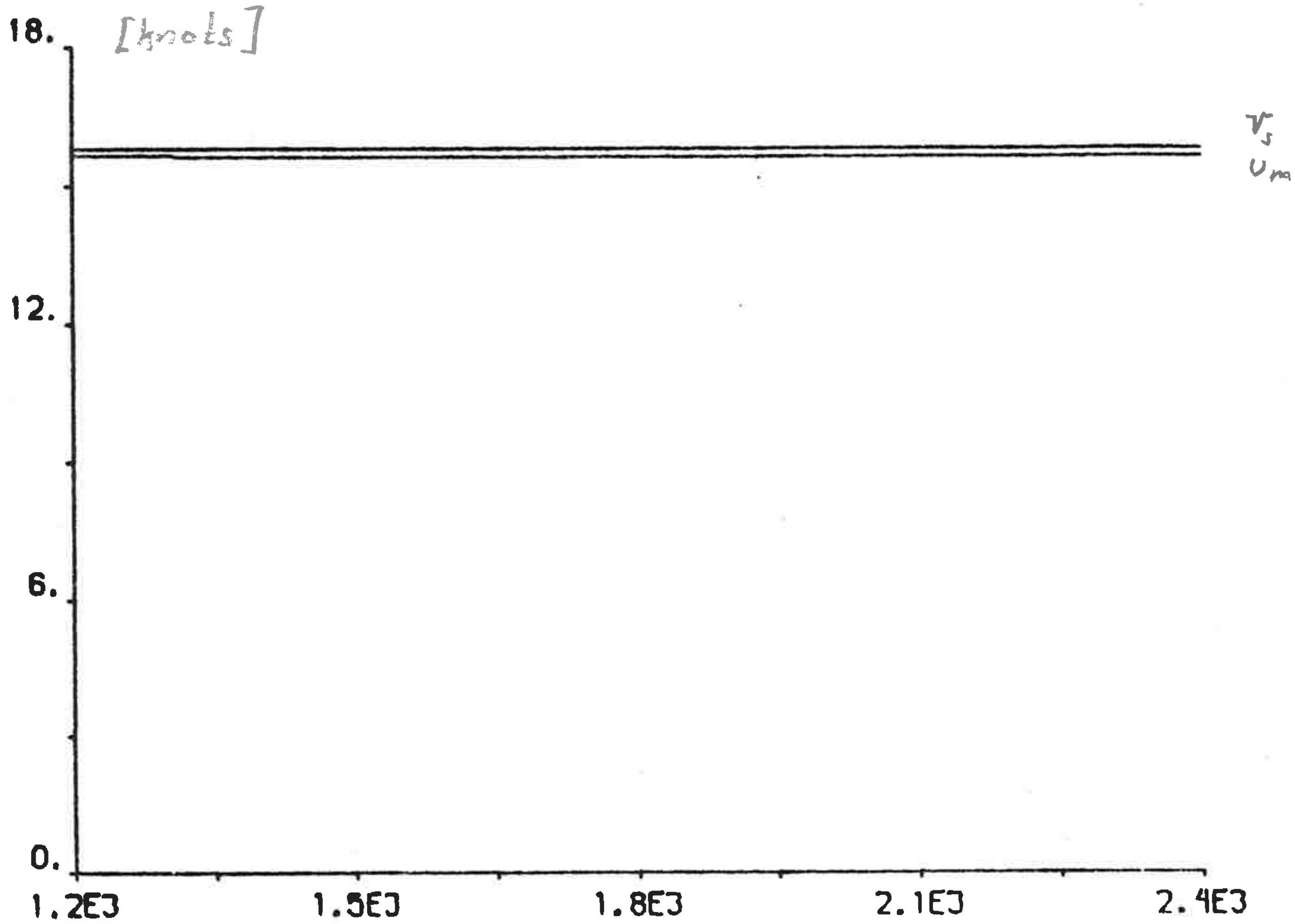


50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$\bar{\delta}_c$
$\hat{\delta}_0$
50.
[deg]
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
$\bar{\delta}_c$
$\hat{\delta}_0$

Fig. 4.9g



18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
U_m



18.
[knots]
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
V_s
U_m

Fig. 4.9h

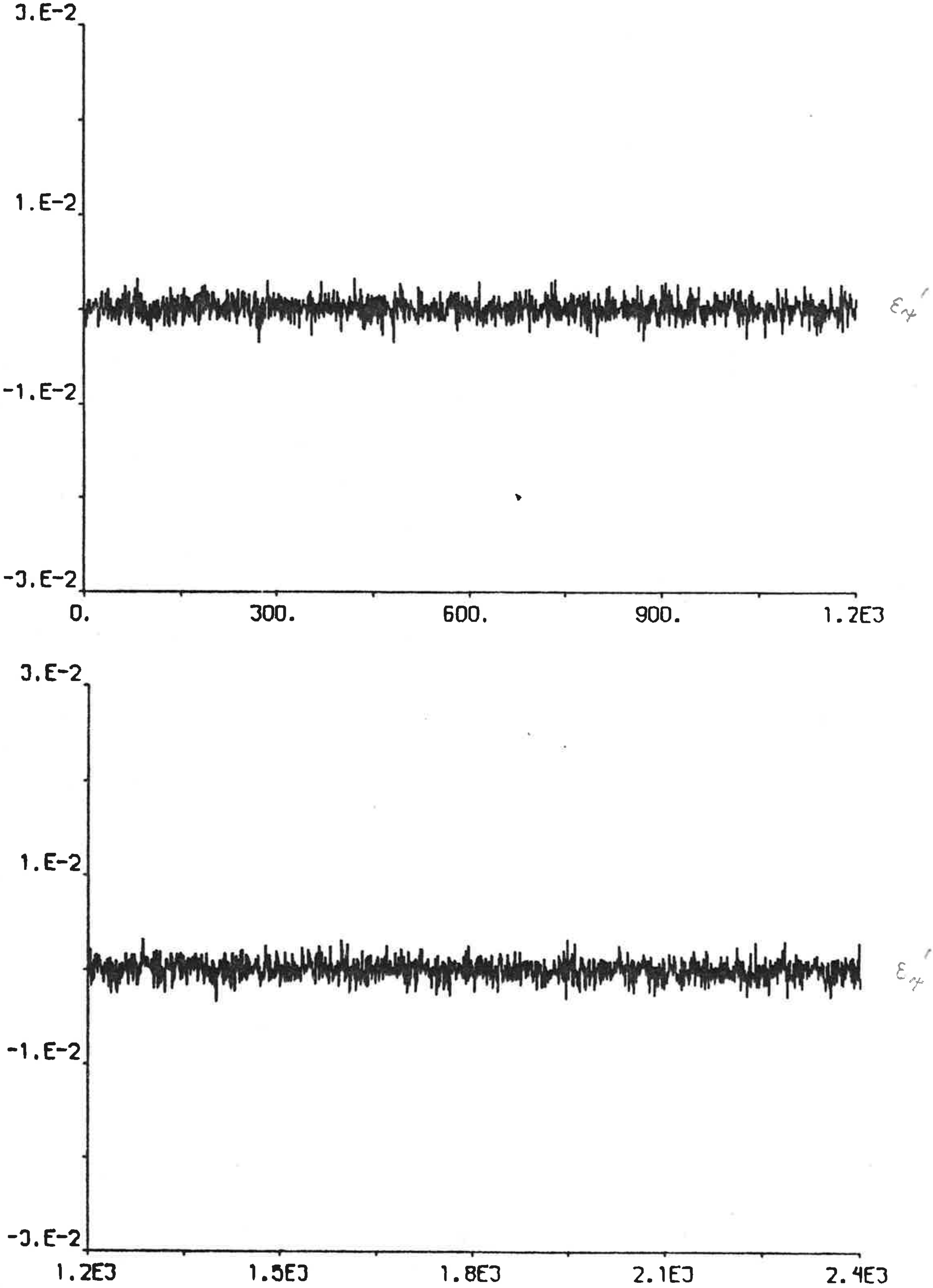
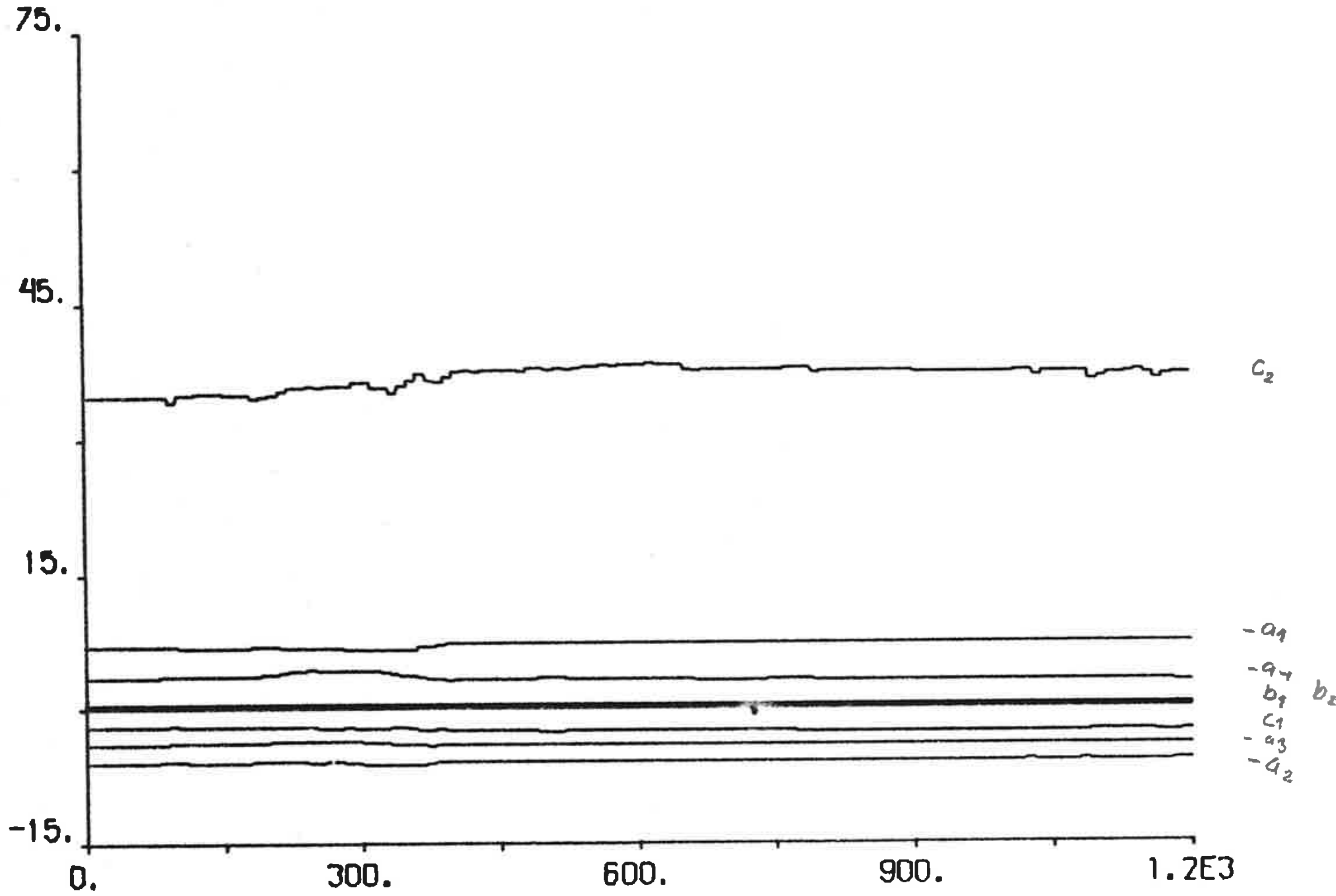
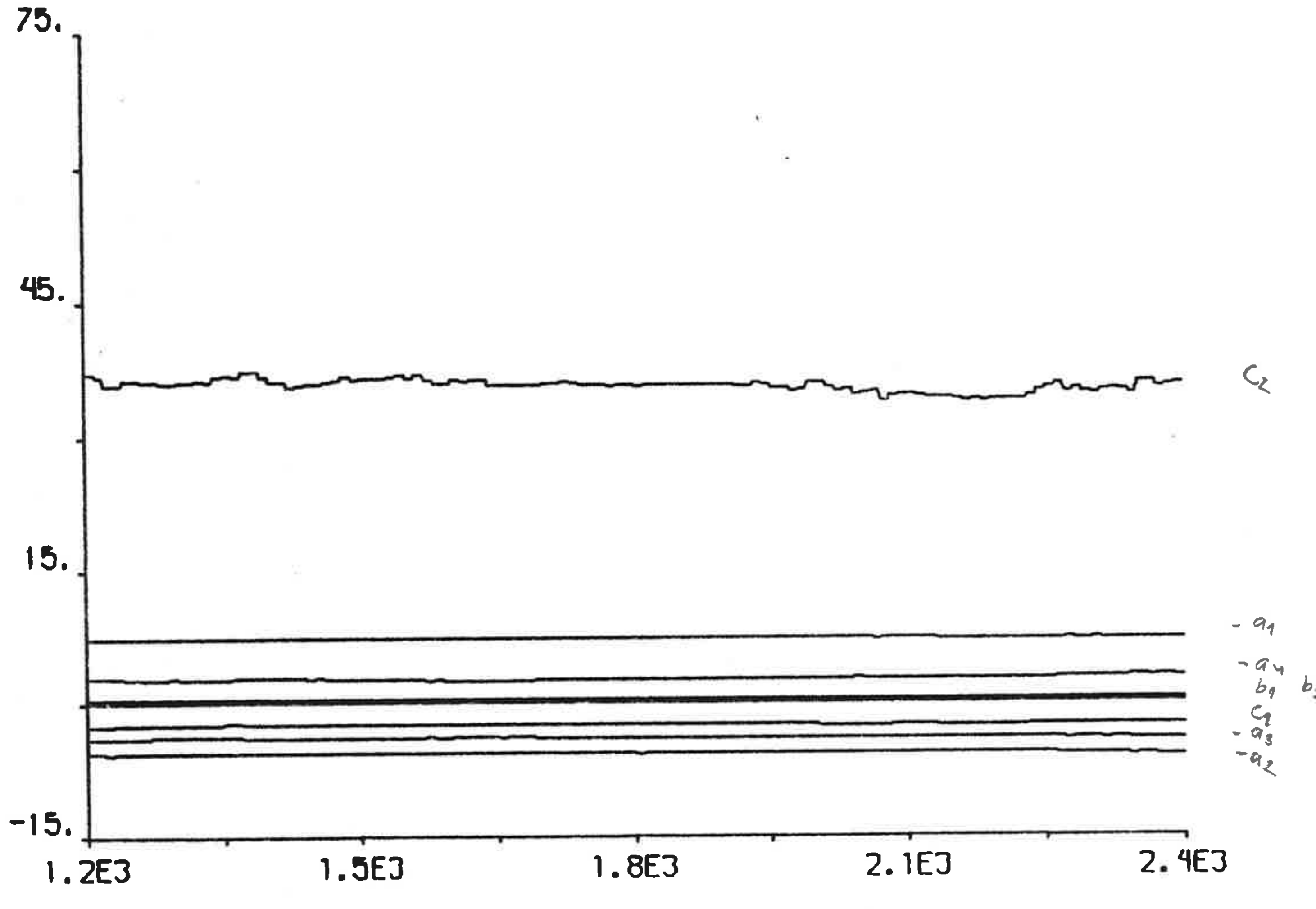

3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
εx'
3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εx'

Fig. 4.9i

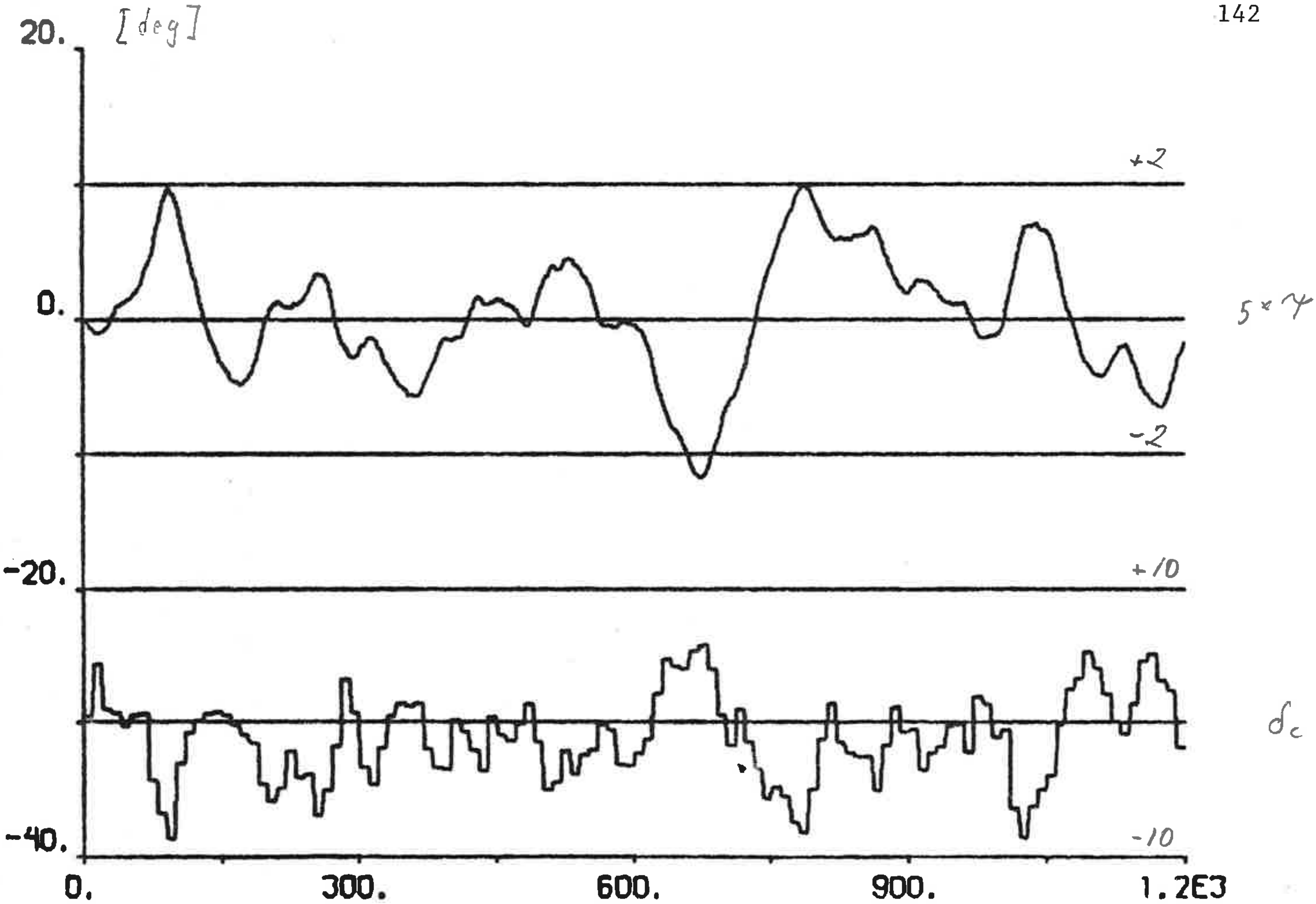


75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$



75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1
c_1
$-a_3$
$-a_2$

Fig. 4.9j



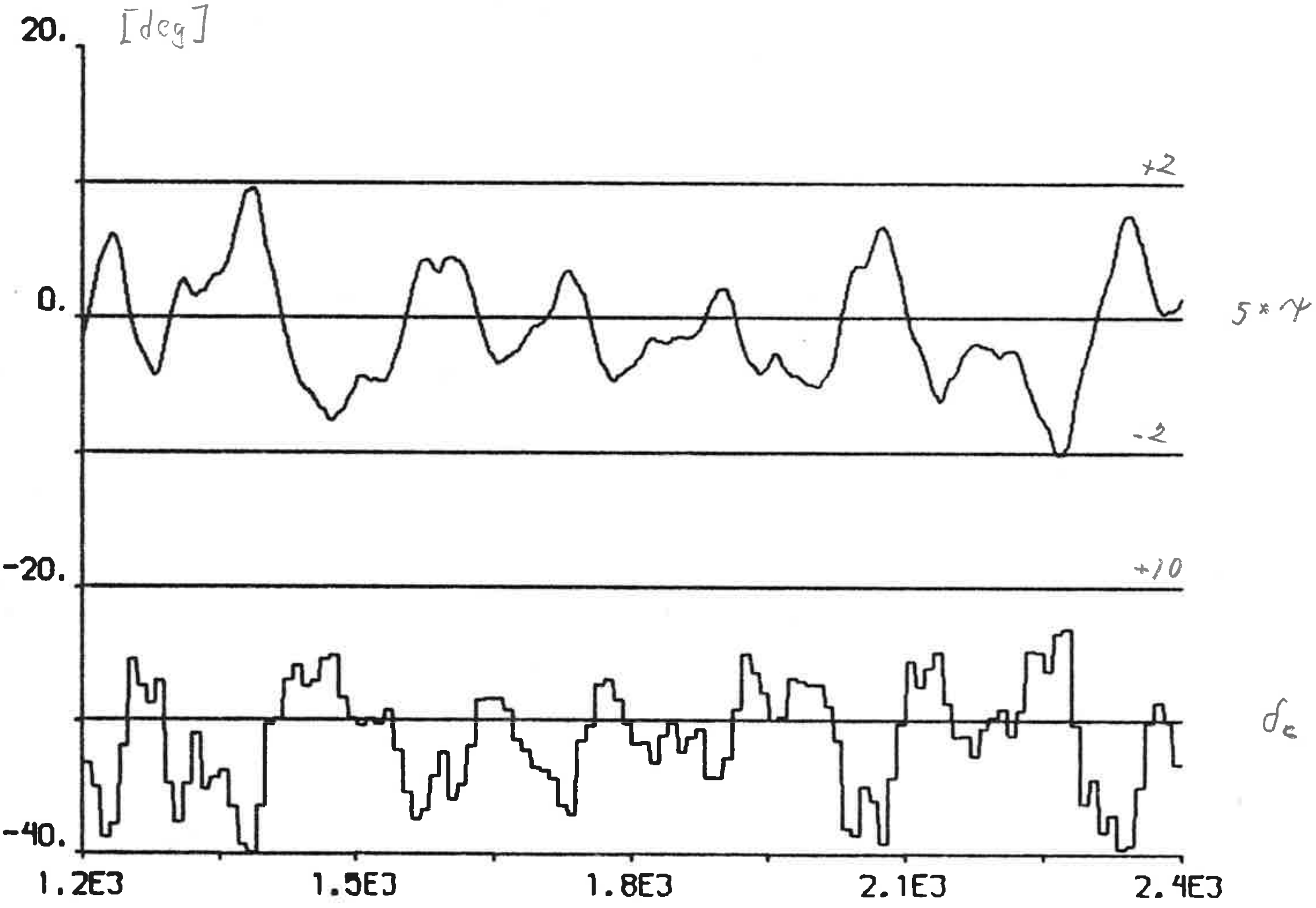


Fig. 4.10a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using estimates from the Kalman filter. The covariance matrix R_w is given by (4.5).

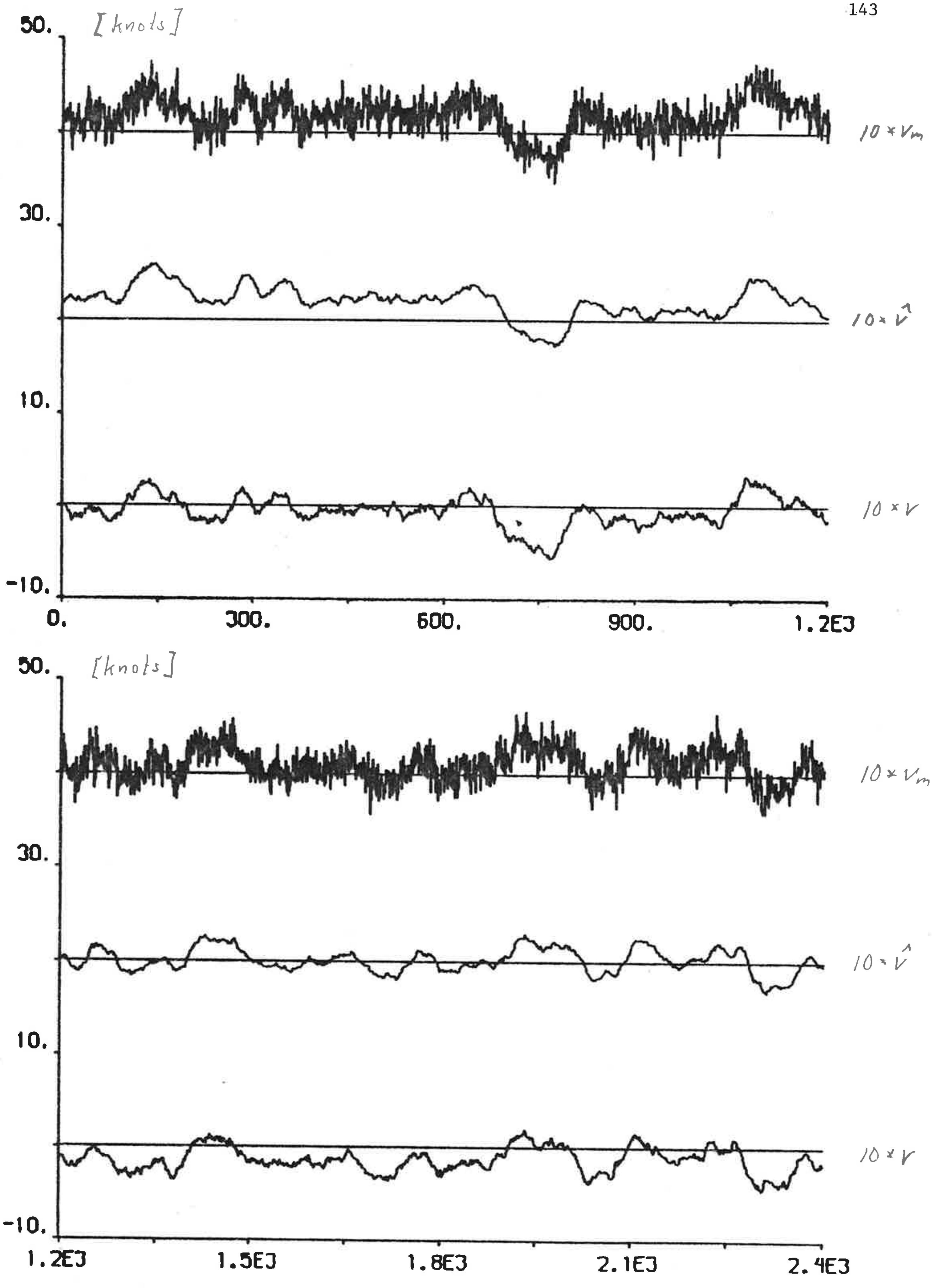

50.
[knots]
30.
10.
-10.
10 * Vm
10 * V̂
10 * V
0.
300.
600.
900.
1.2E3
50.
[knots]
30.
10.
-10.
10 * Vm
10 * V̂
10 * V
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.10 b

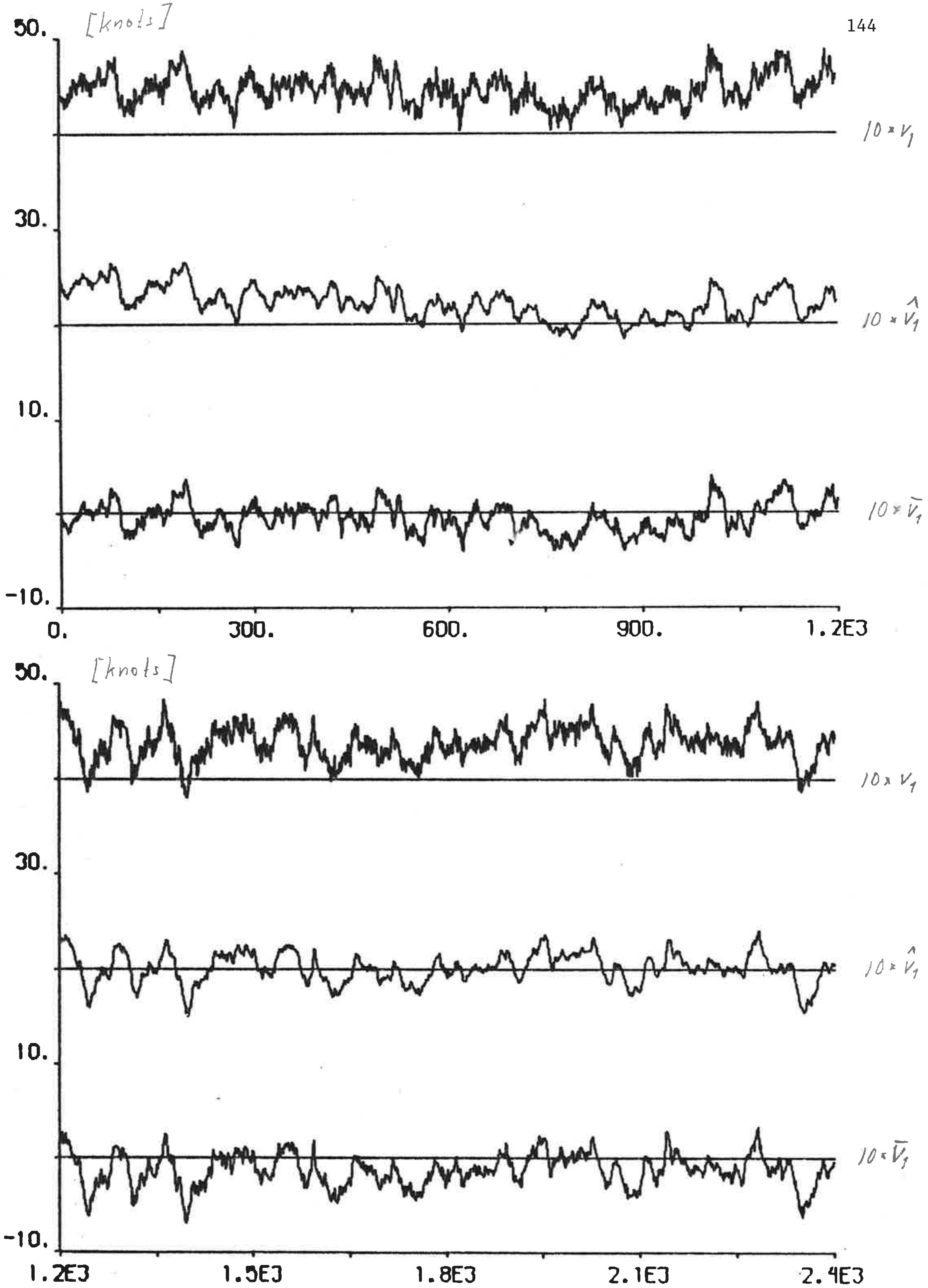

[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × V_1
10 × $\hat{V}_1$
10 × $\tilde{V}_1$
[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × V_1
10 × $\hat{V}_1$
10 × $\tilde{V}_1$

Fig. 4.10 c

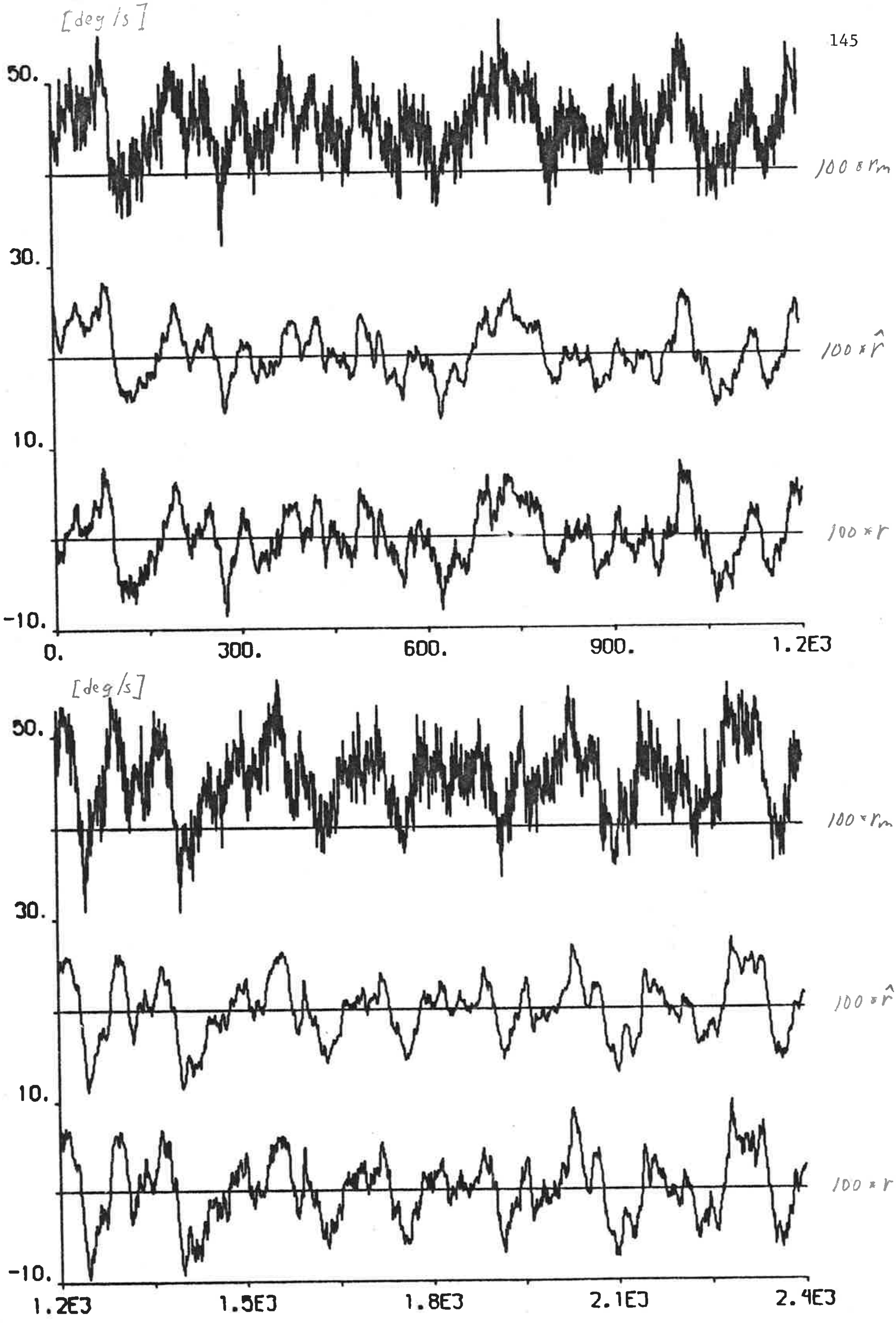

[deg/s]
50.
30.
10.
-10.
100 * rm
100 * r̂
100 * r
0.
300.
600.
900.
1.2E3
[deg/s]
50.
30.
10.
-10.
100 * rm
100 * r̂
100 * r
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.10 d

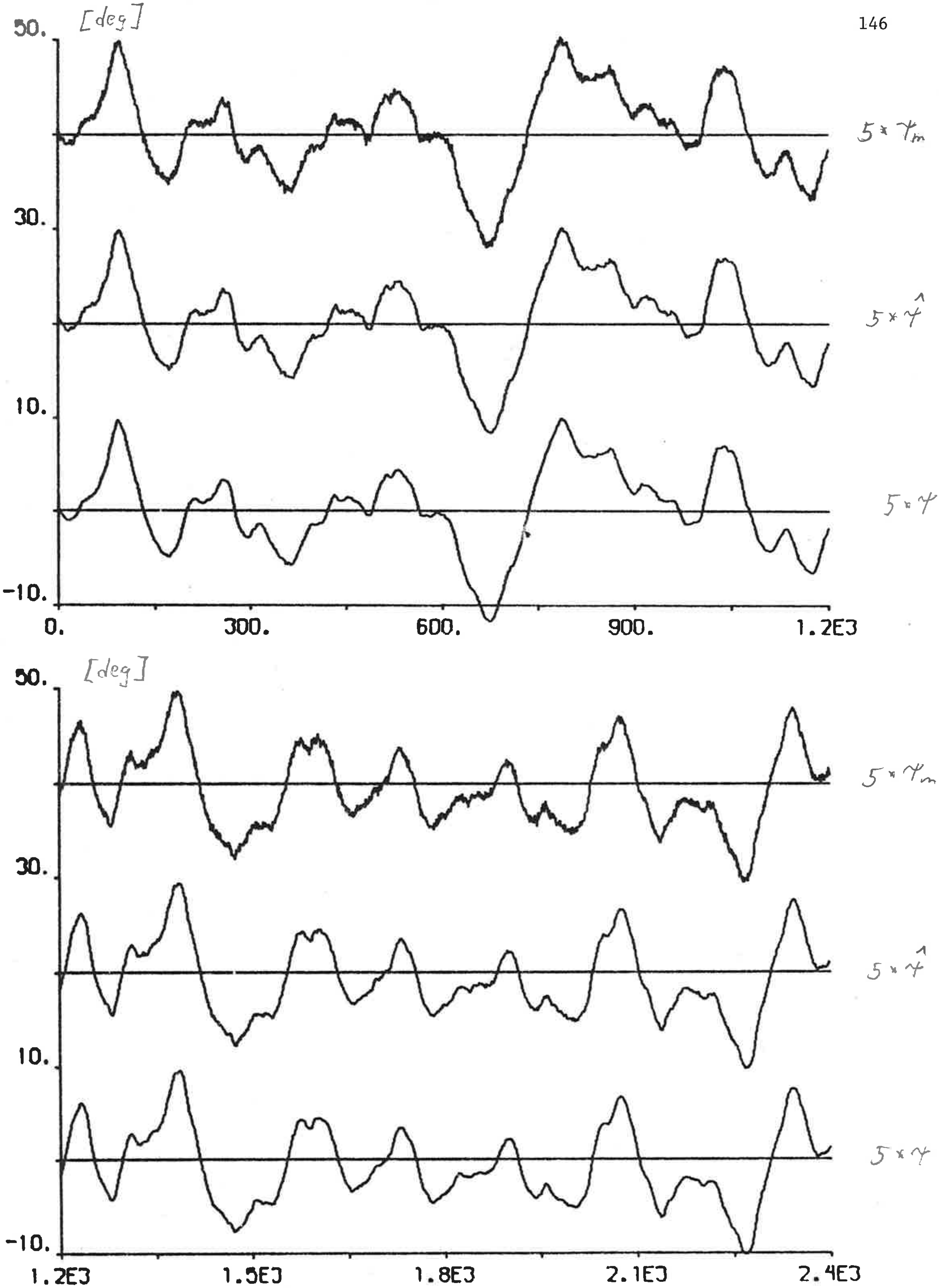
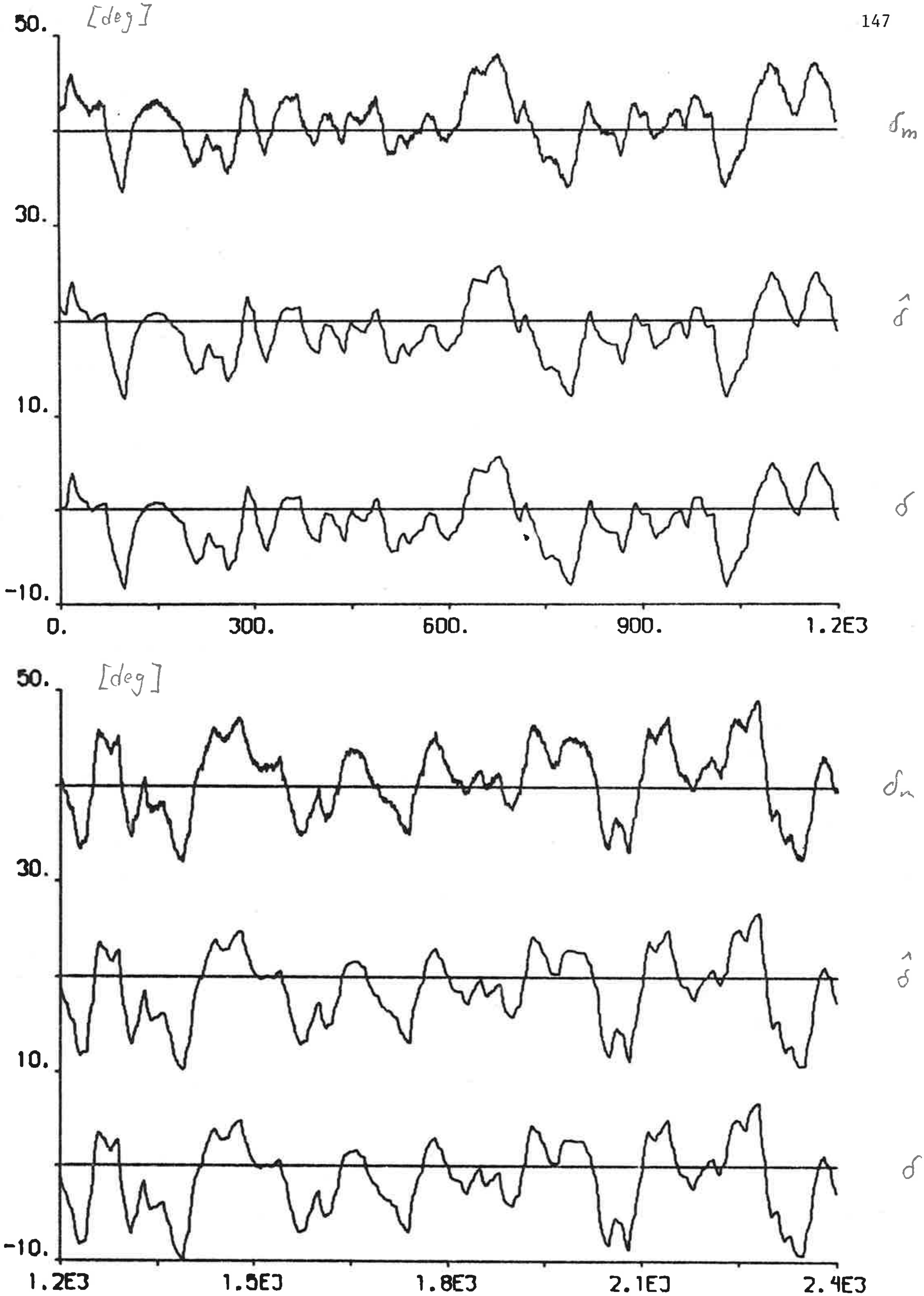

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5 × ψm
5 × ψ̂
5 × ψ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5 × ψm
5 × ψ̂
5 × ψ

Fig. 4.10 e



[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.10 f

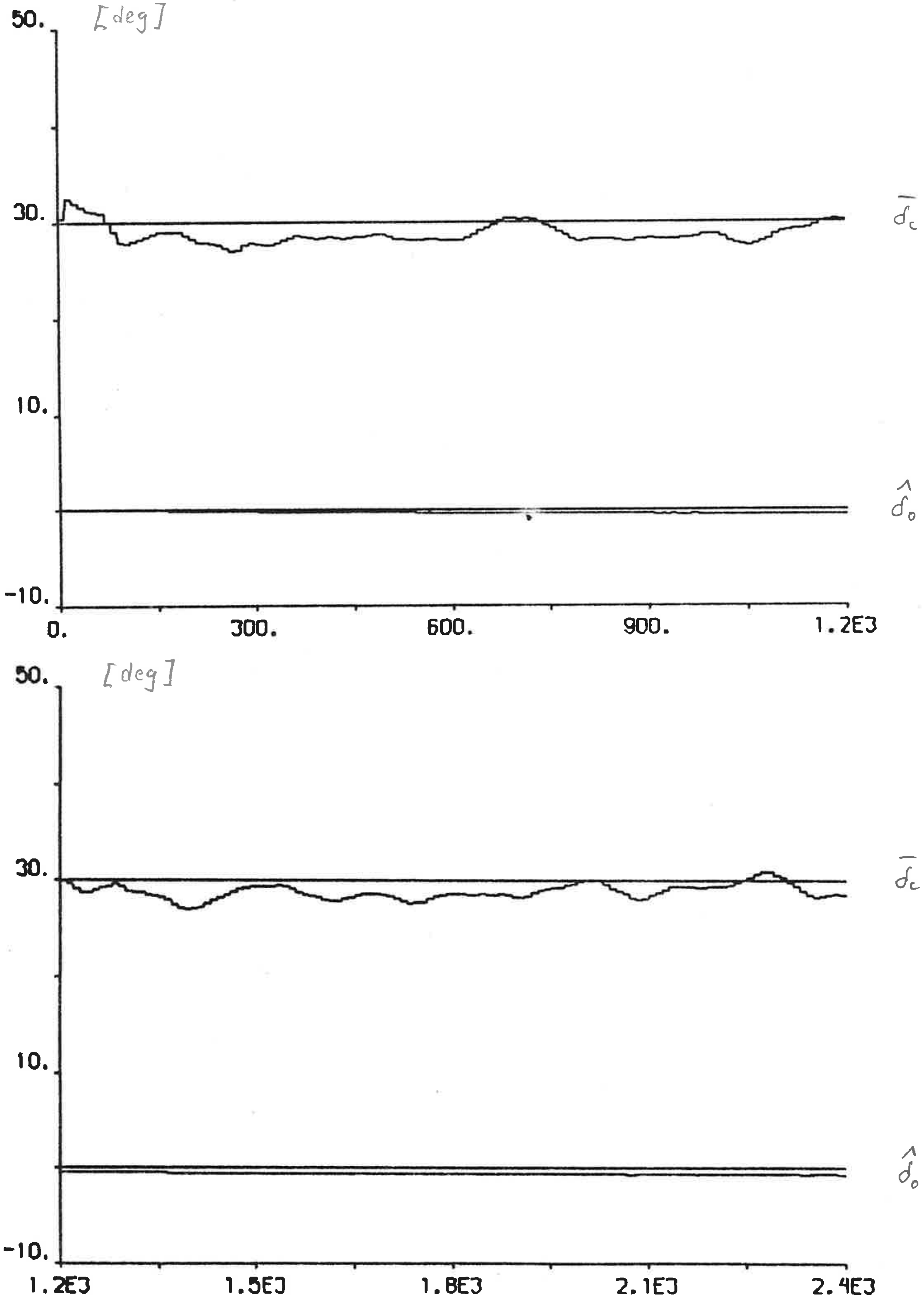

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$\bar{\delta}_c$
$\hat{\delta}_o$
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
$\bar{\delta}_c$
$\hat{\delta}_o$

Fig. 4.10 g

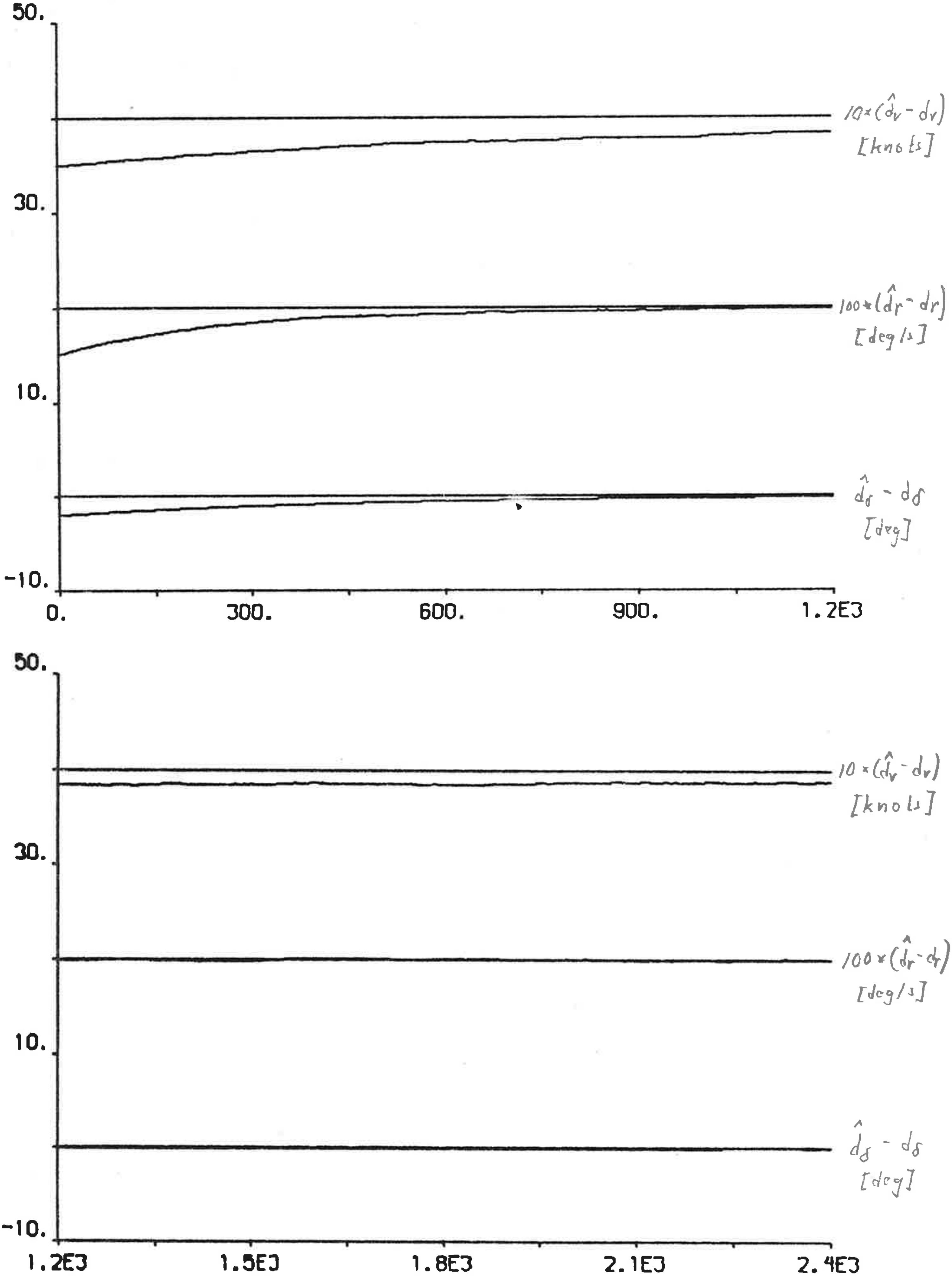
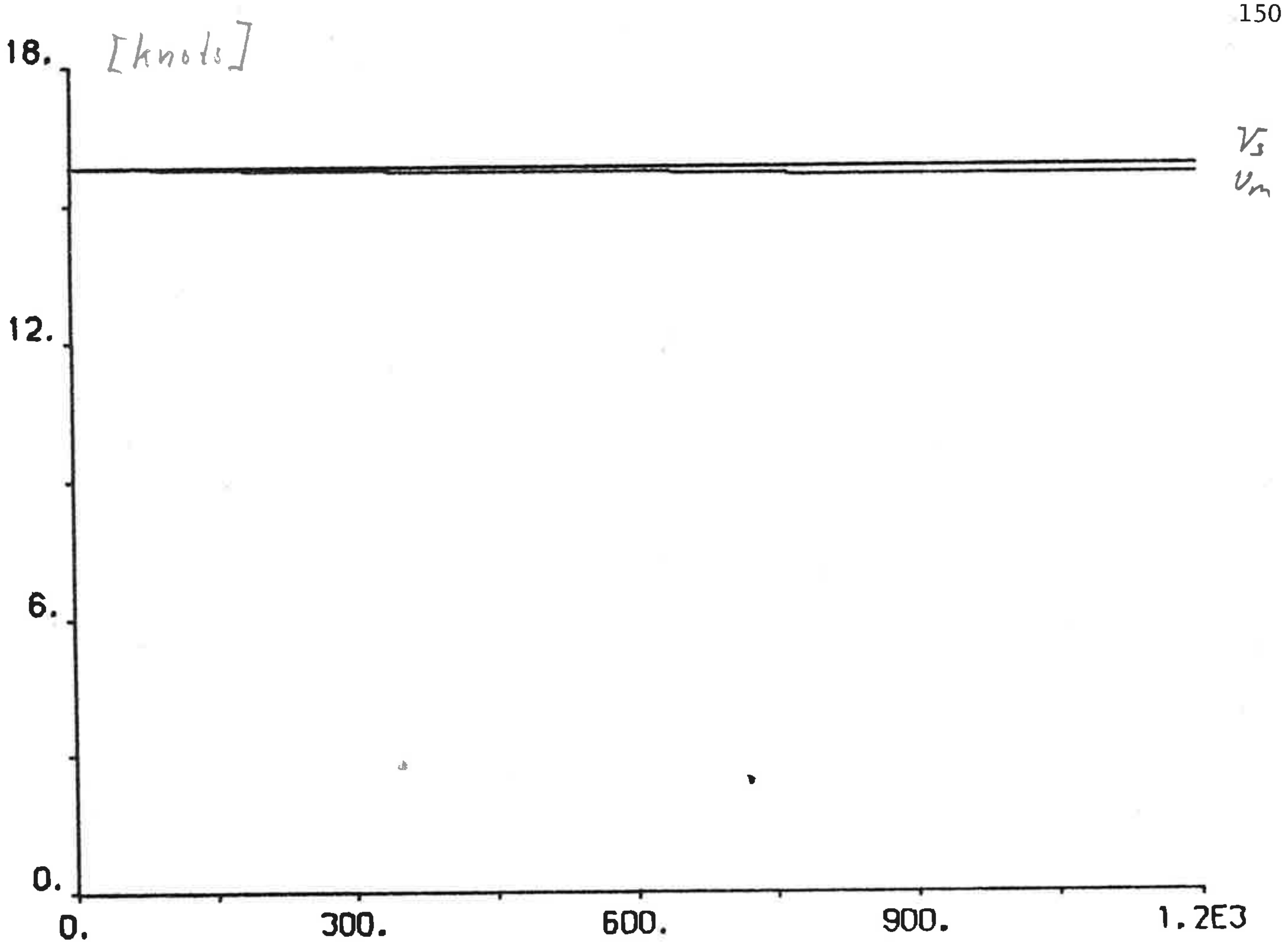

50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10×($\hat{d}_v$ - d_v) [knots]
100×($\hat{d}_r$ - d_r) [deg/s]
$\hat{d}_\delta$ - d_δ [deg]
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.10 h


18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
Vs
Um

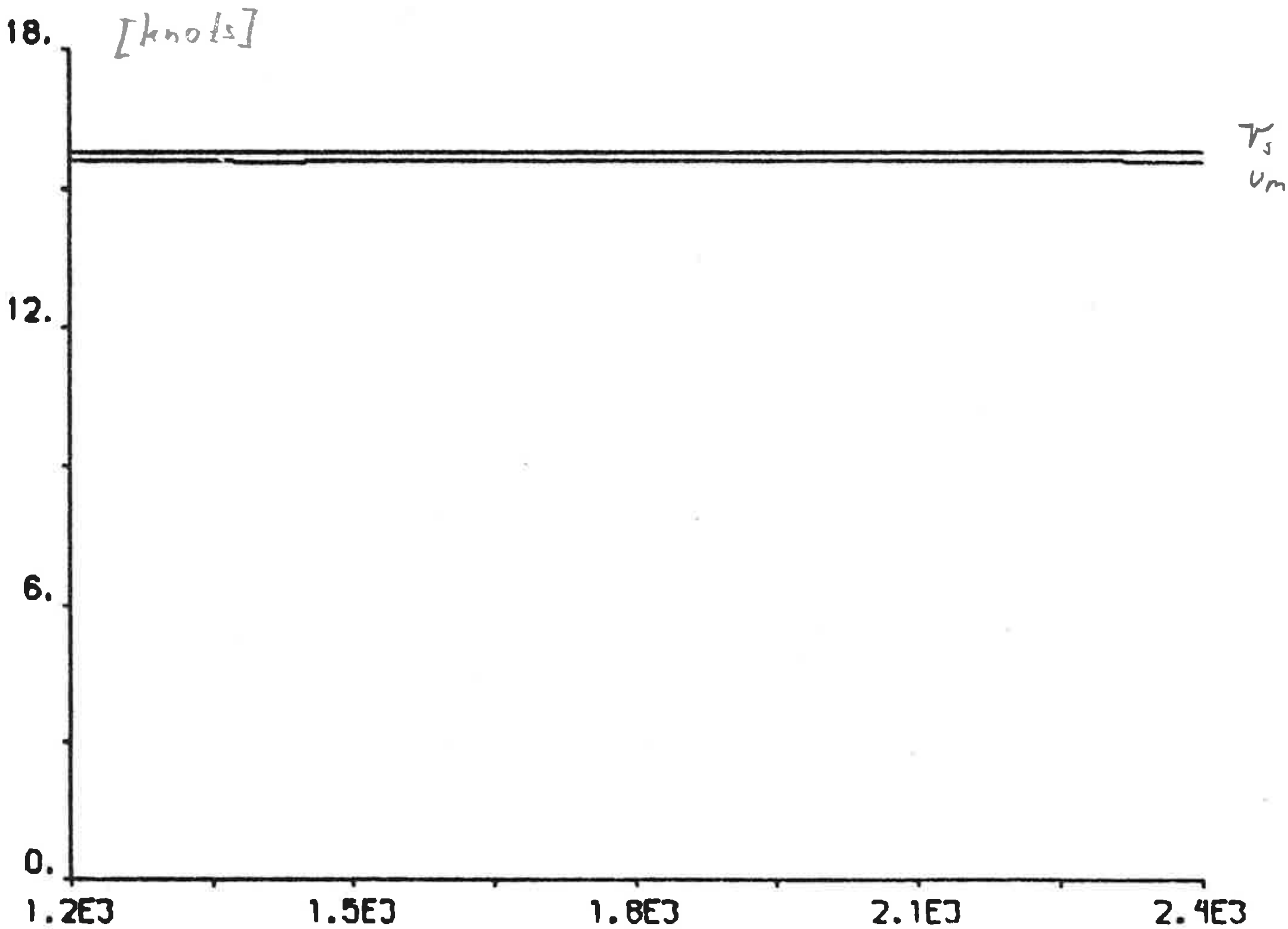

18.
[knots]
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
Vs
Um

Fig. 4.10 i

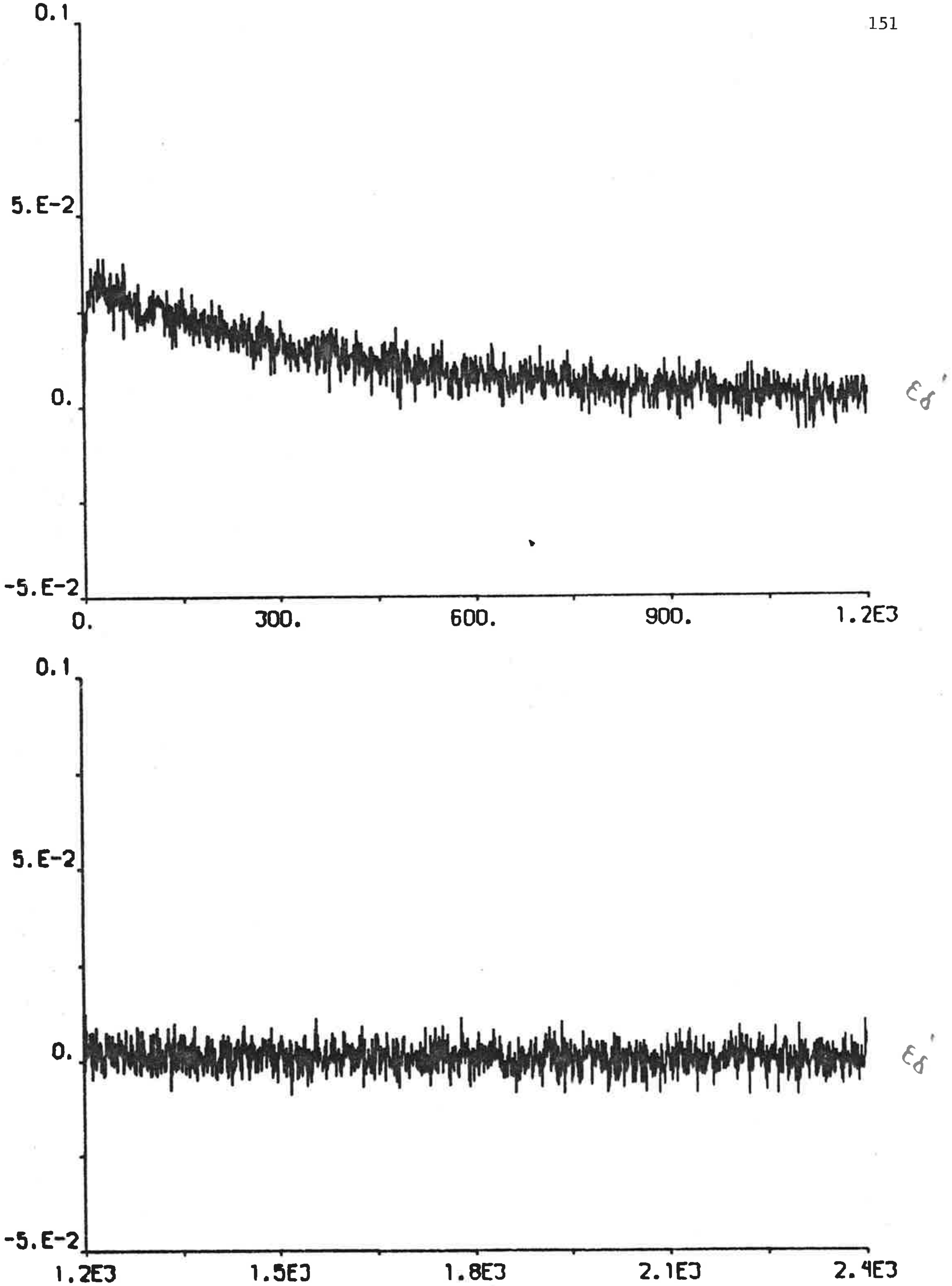
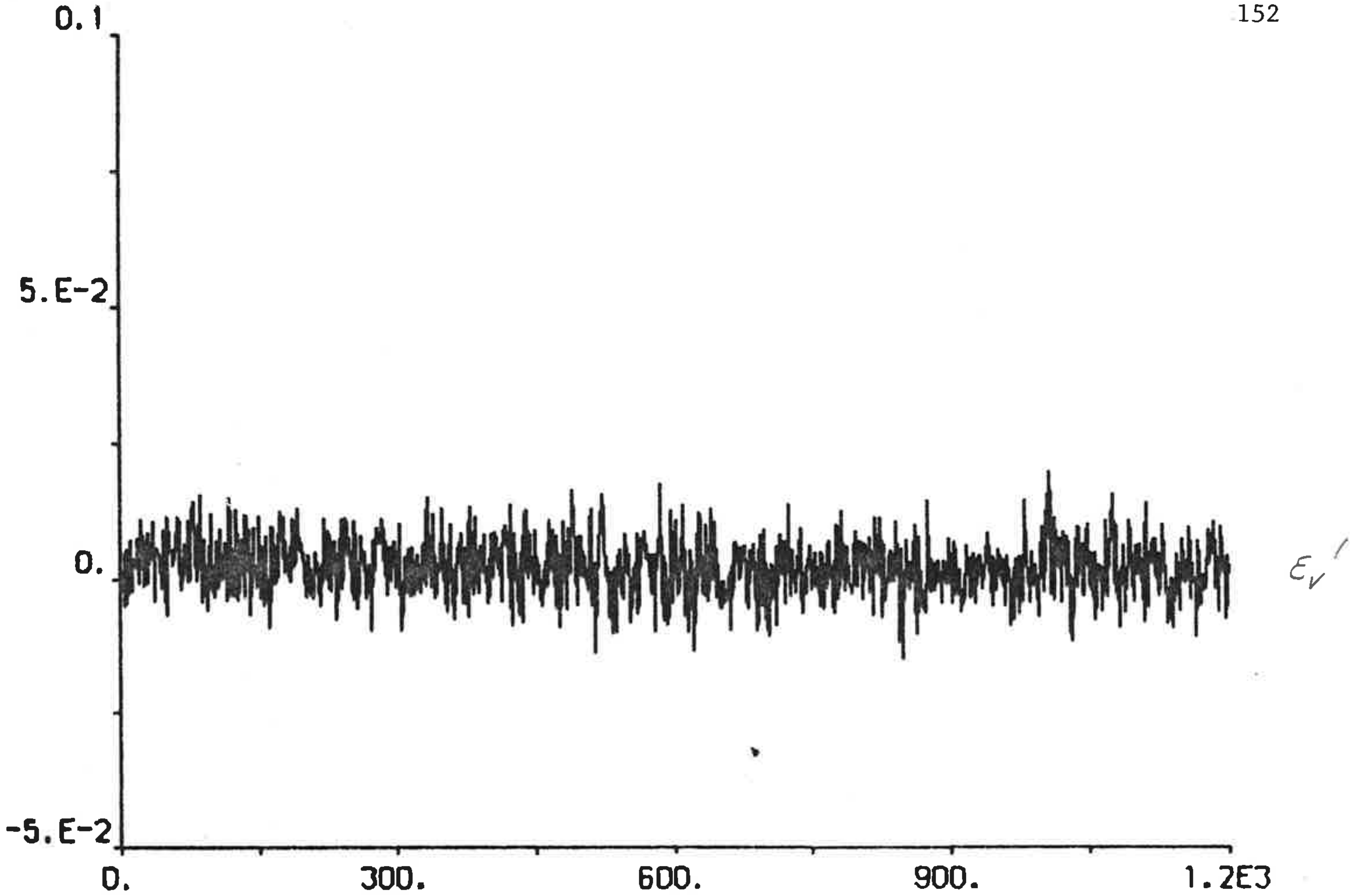

0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.10 j


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_v'

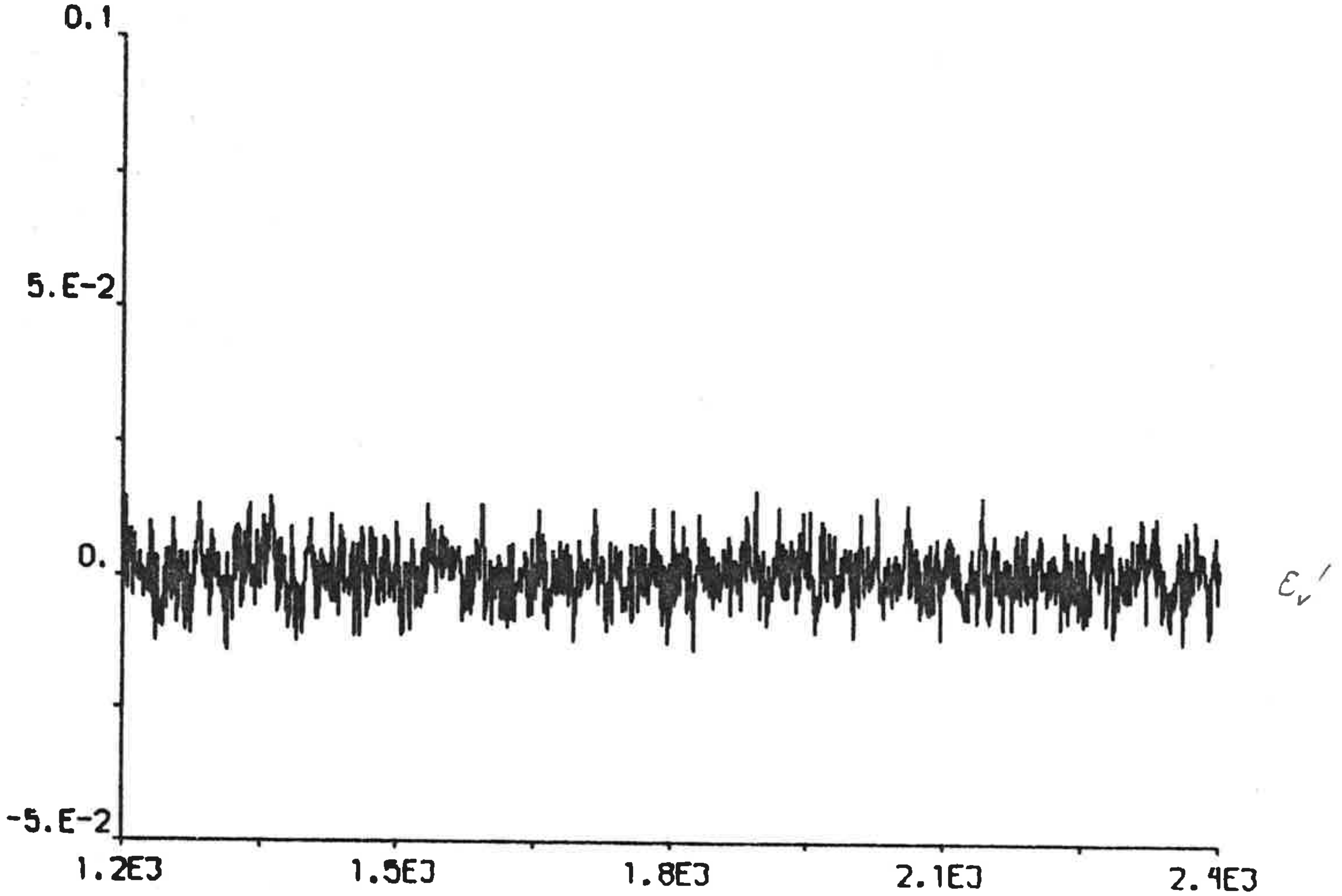
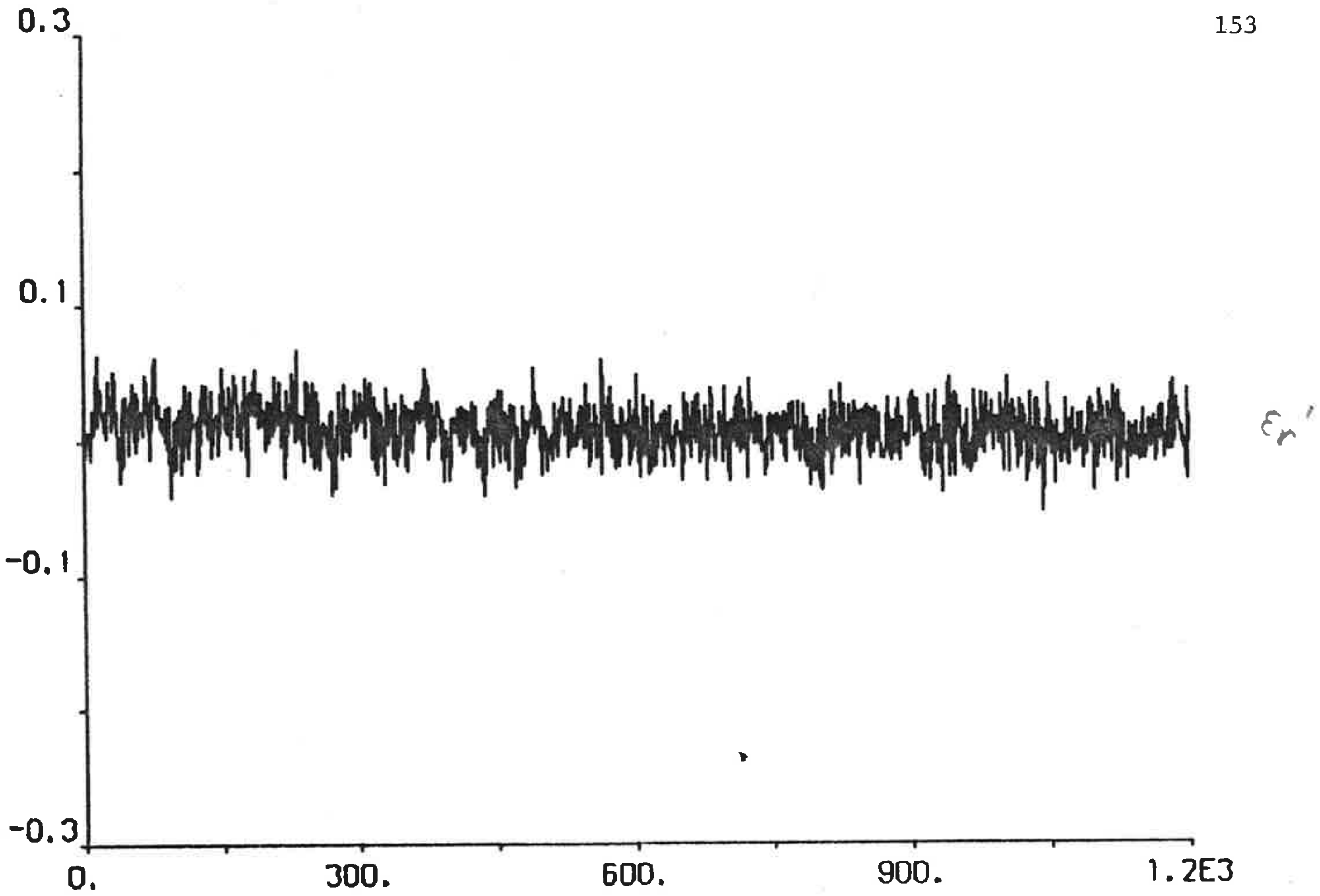

0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_v'

Fig. 4.10 k


0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
εr'

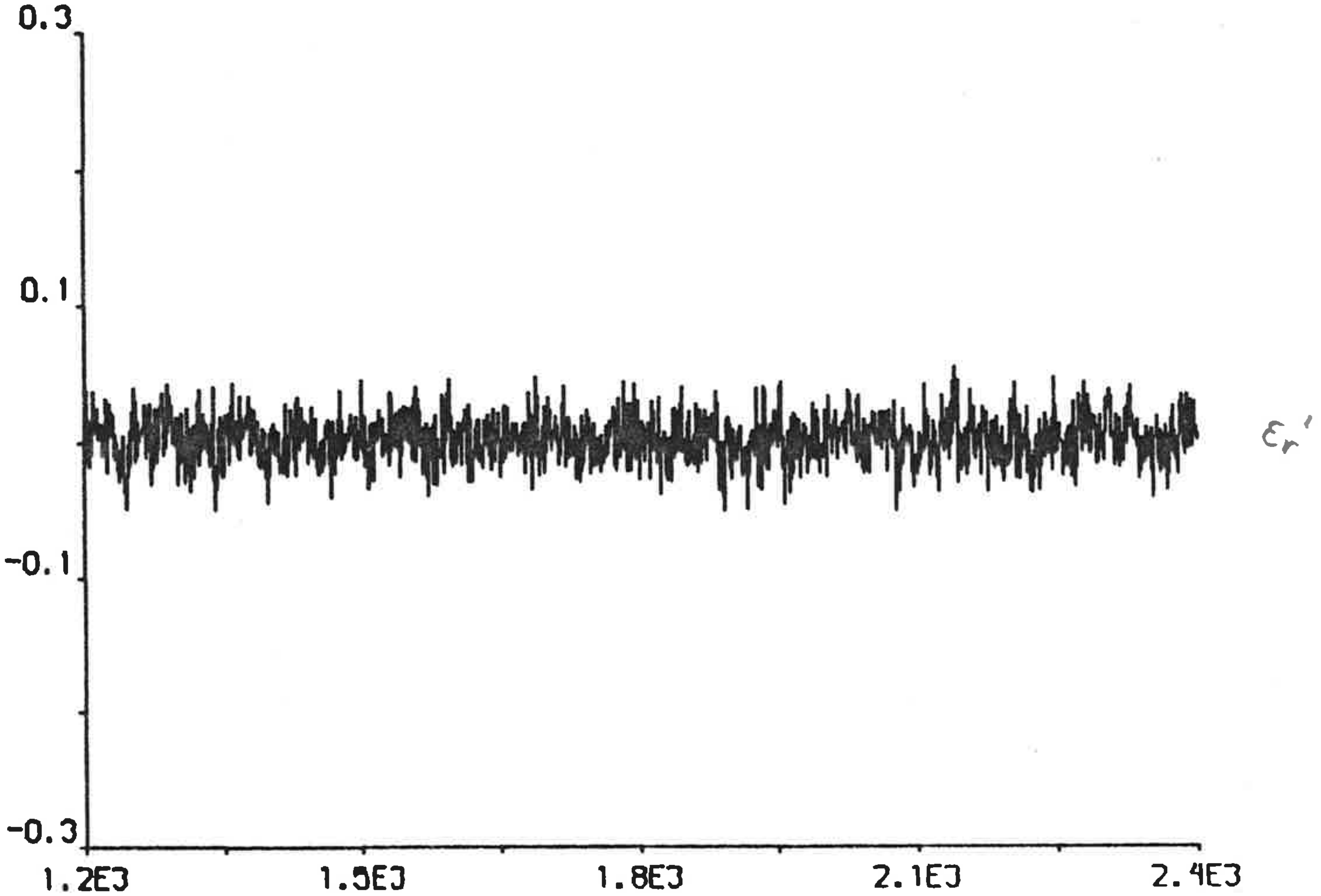
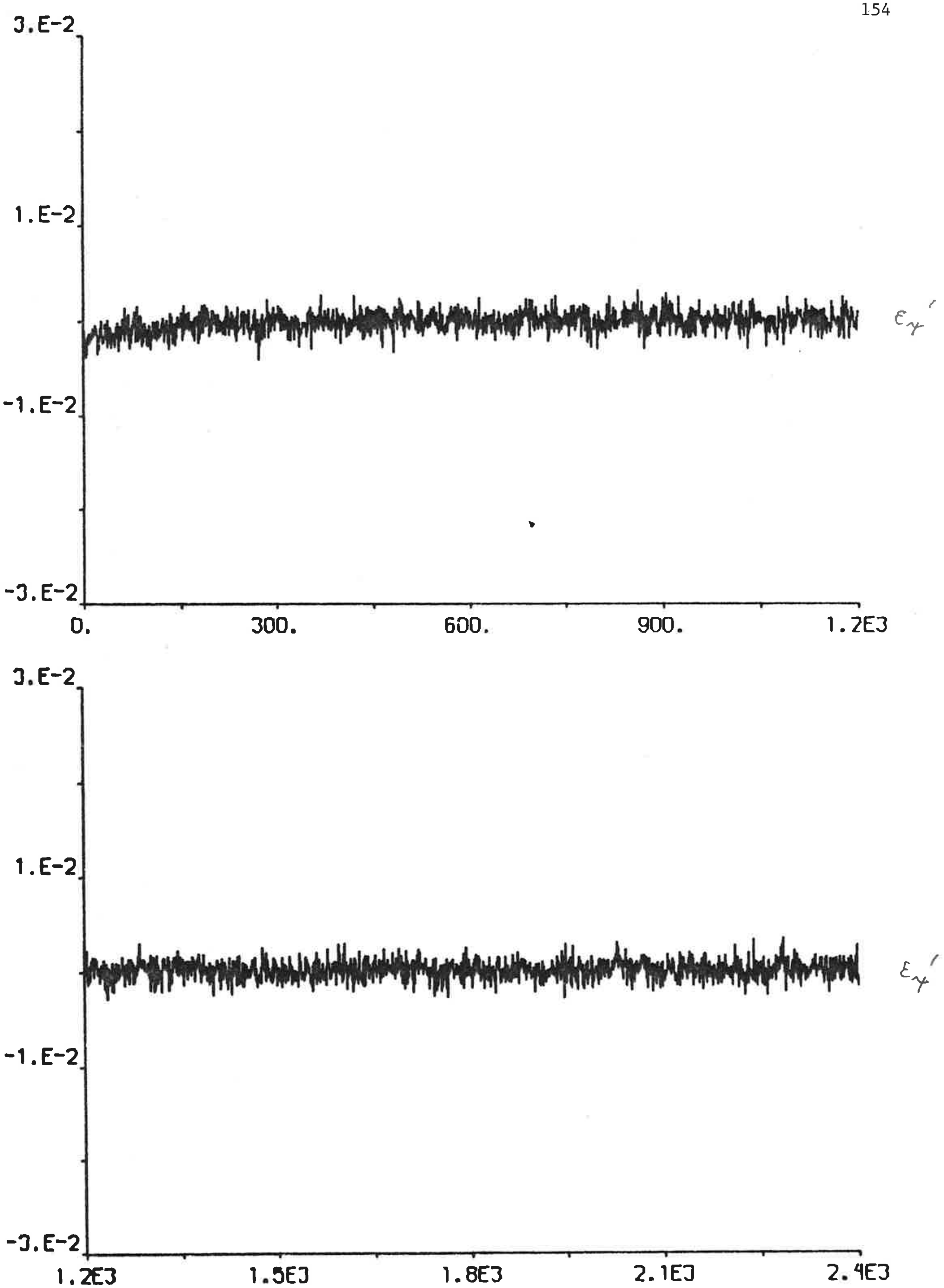
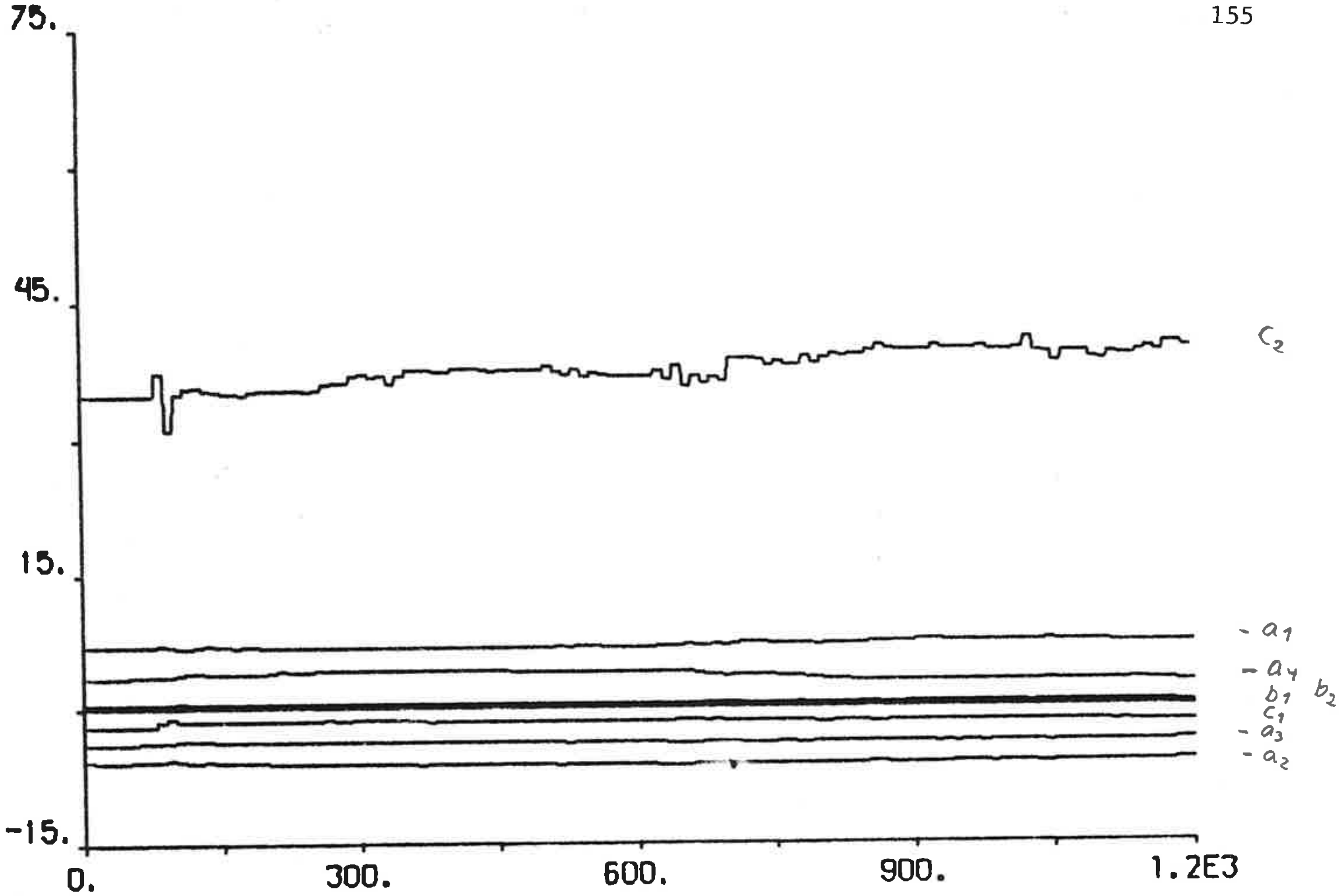

0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εr'

Fig. 4.10 ℓ

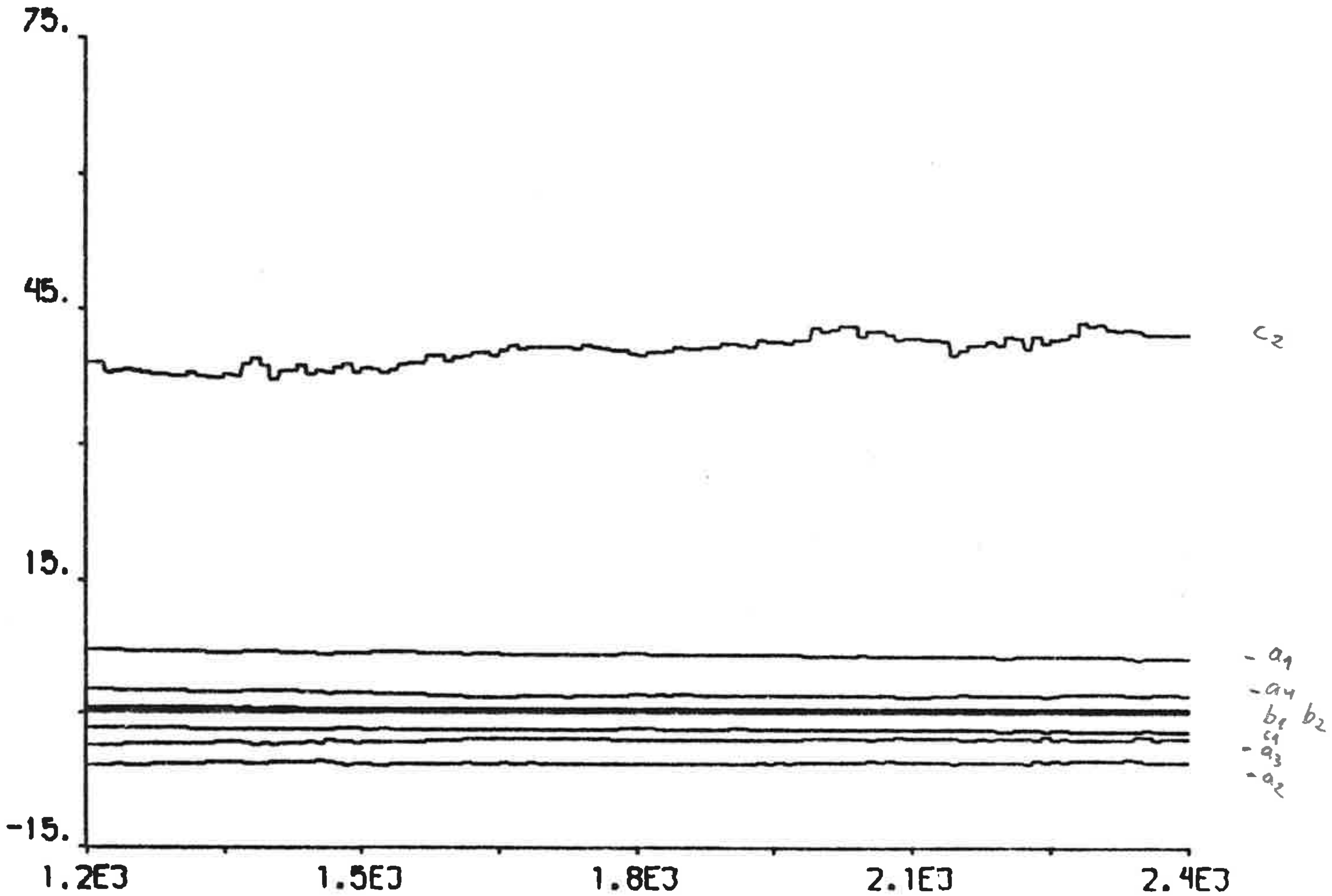


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
ε_γ'
3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_γ'

Fig. 4.10 m

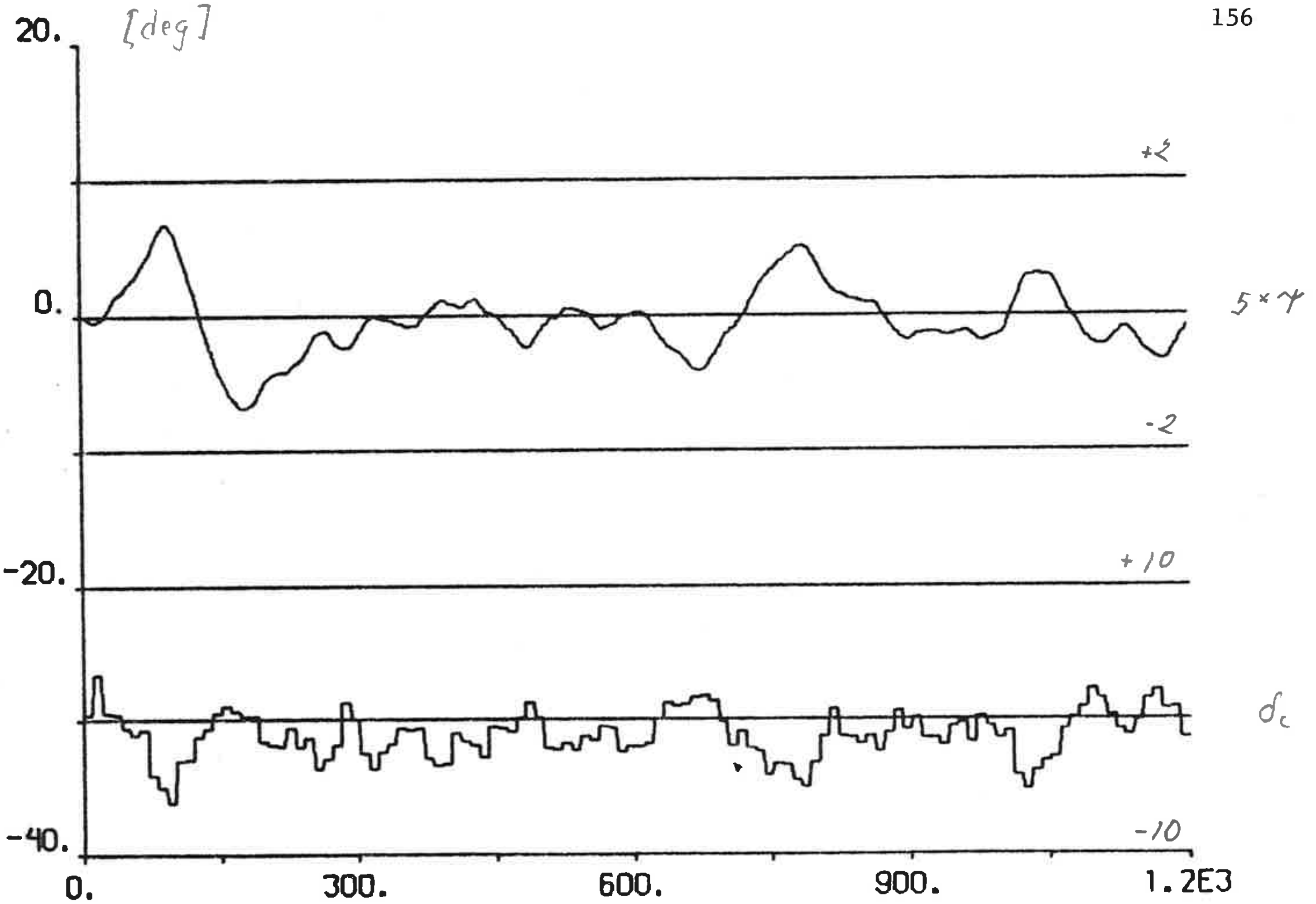


75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
a_1
a_4
b_1
b_2
c_1
a_3
a_2



75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
a_1
a_4
b_1
b_2
c_1
a_3
a_2

Fig. 4.10 n



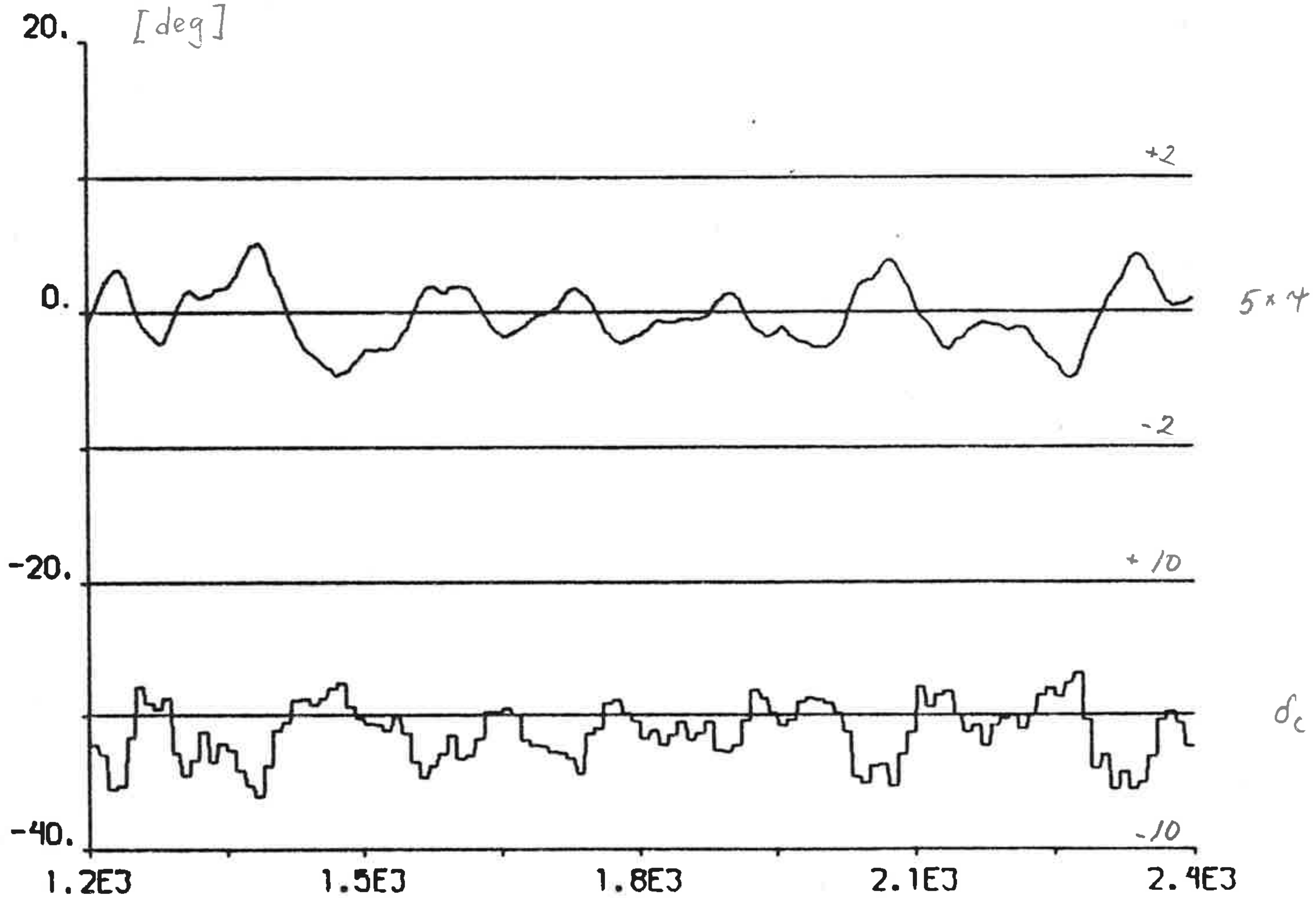
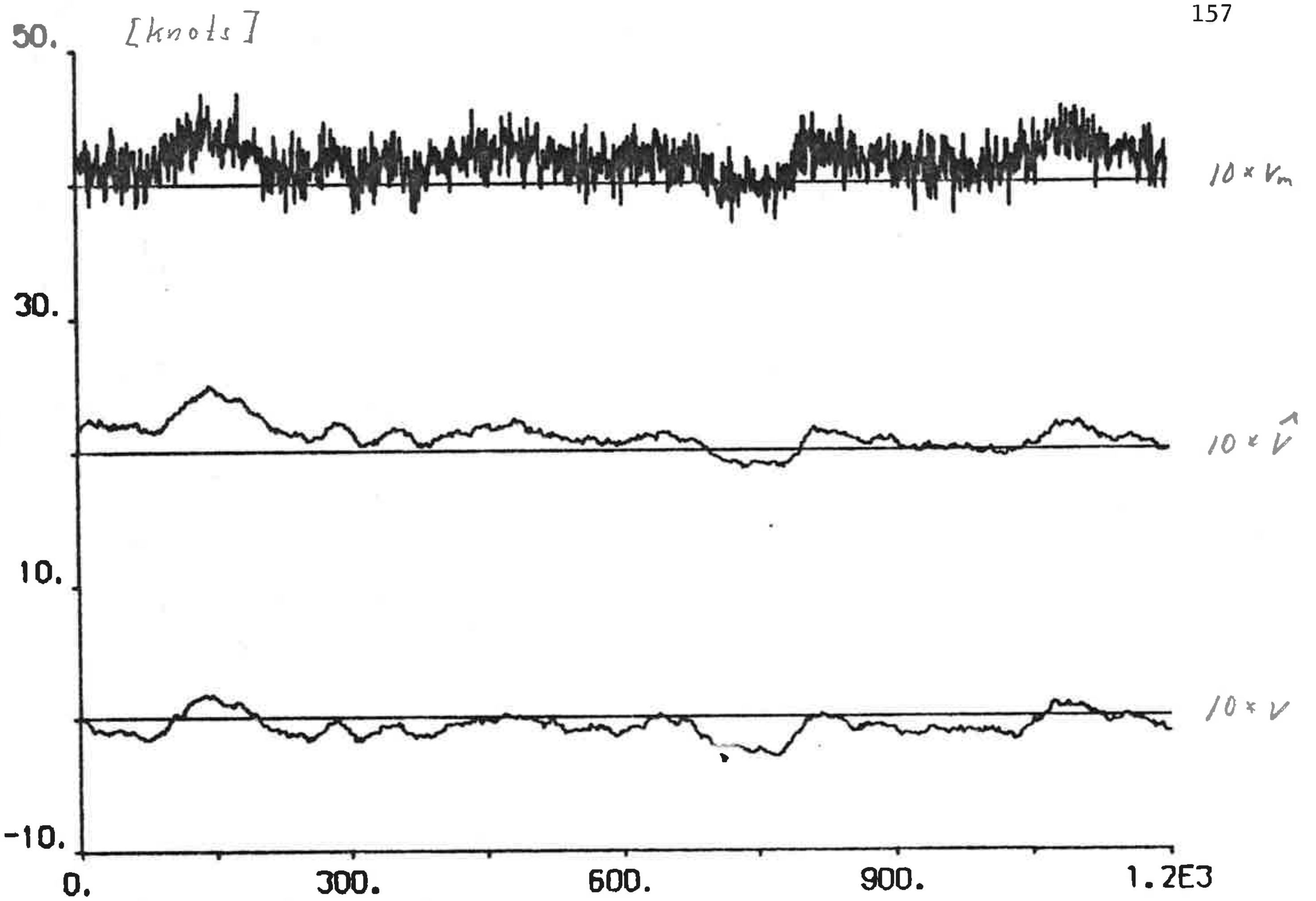
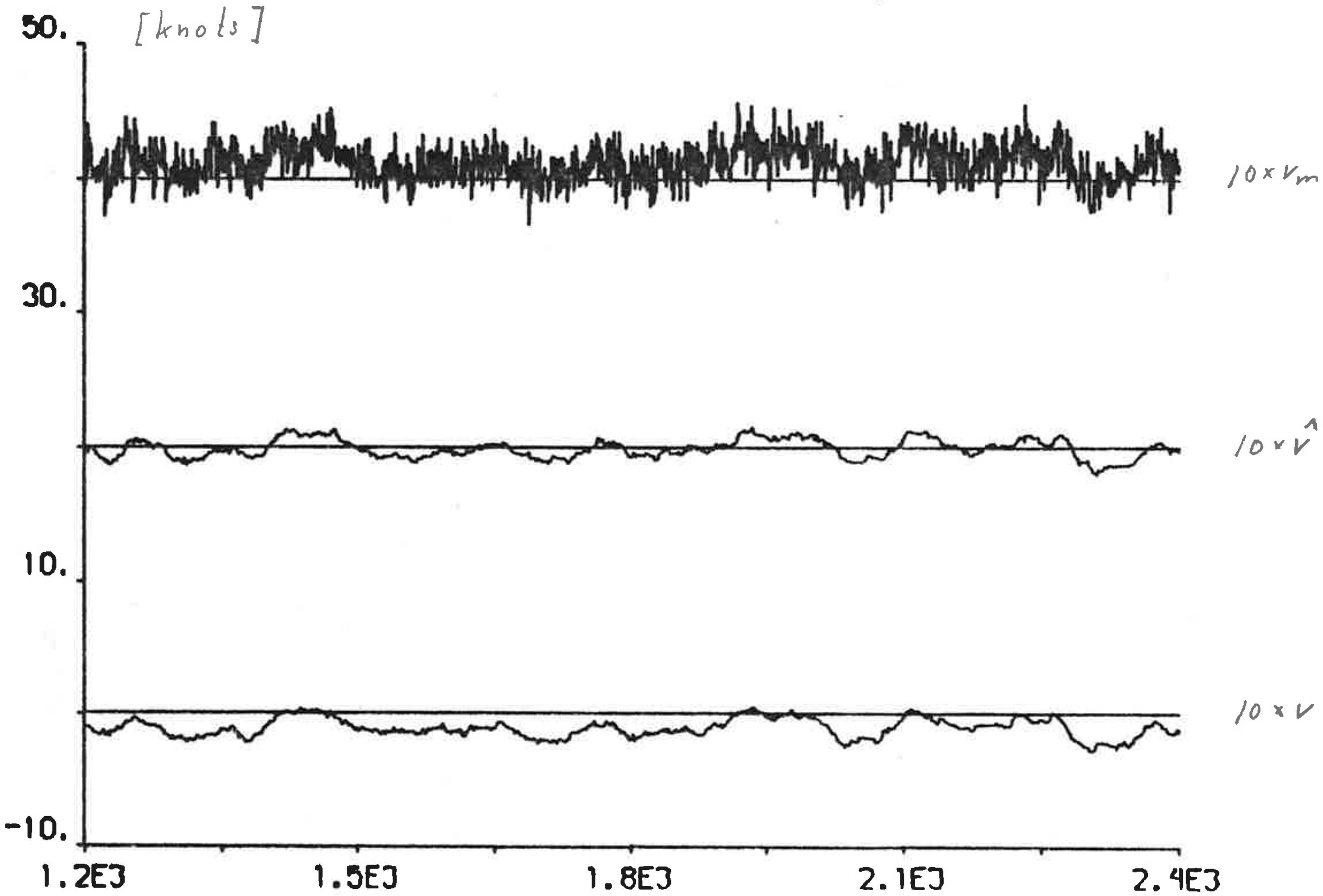


Fig. 4.11 a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using estimates from the Kalman filter. The filter gain K is given by (4.6).

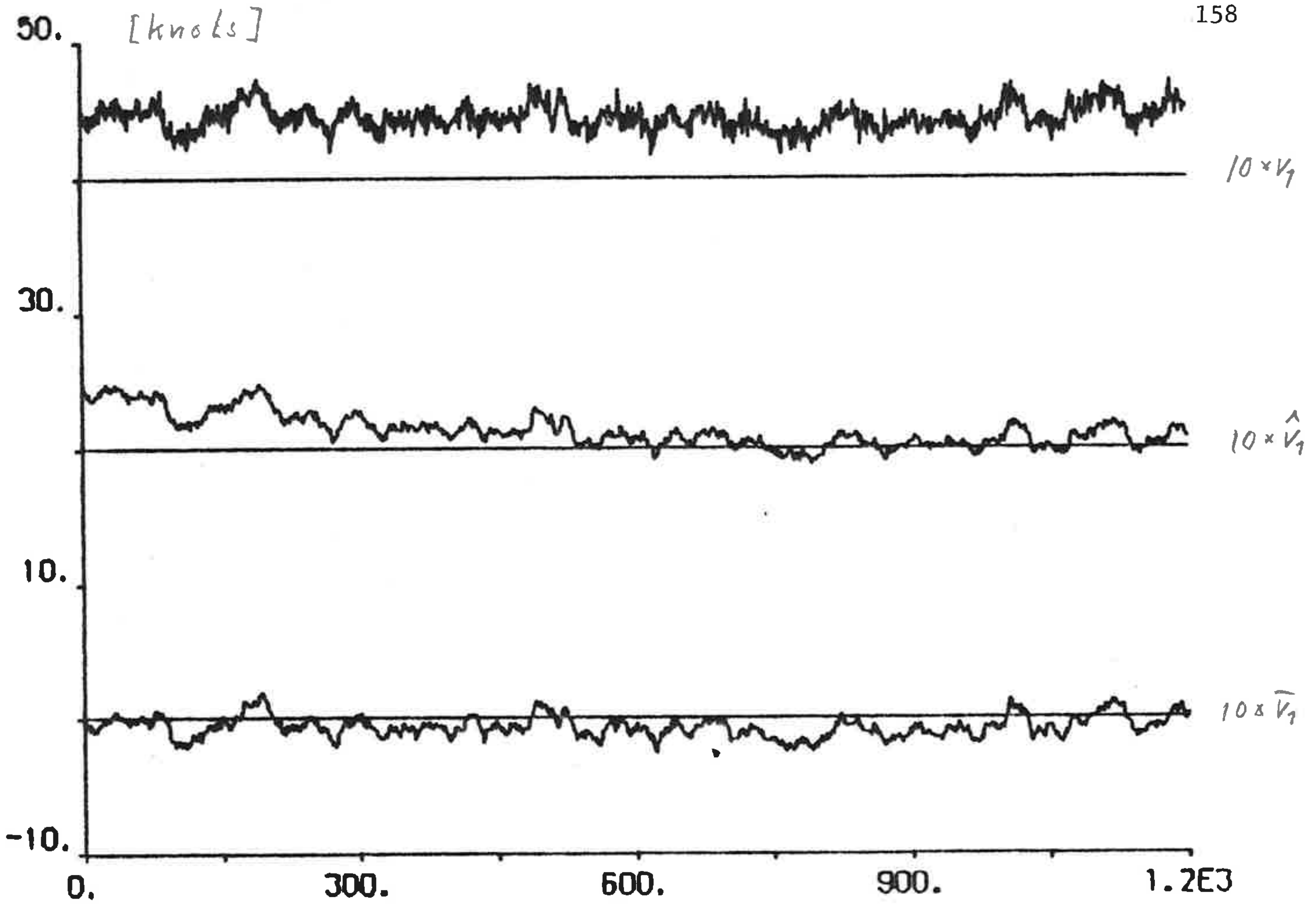


[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × Vm
10 × V̂
10 × V

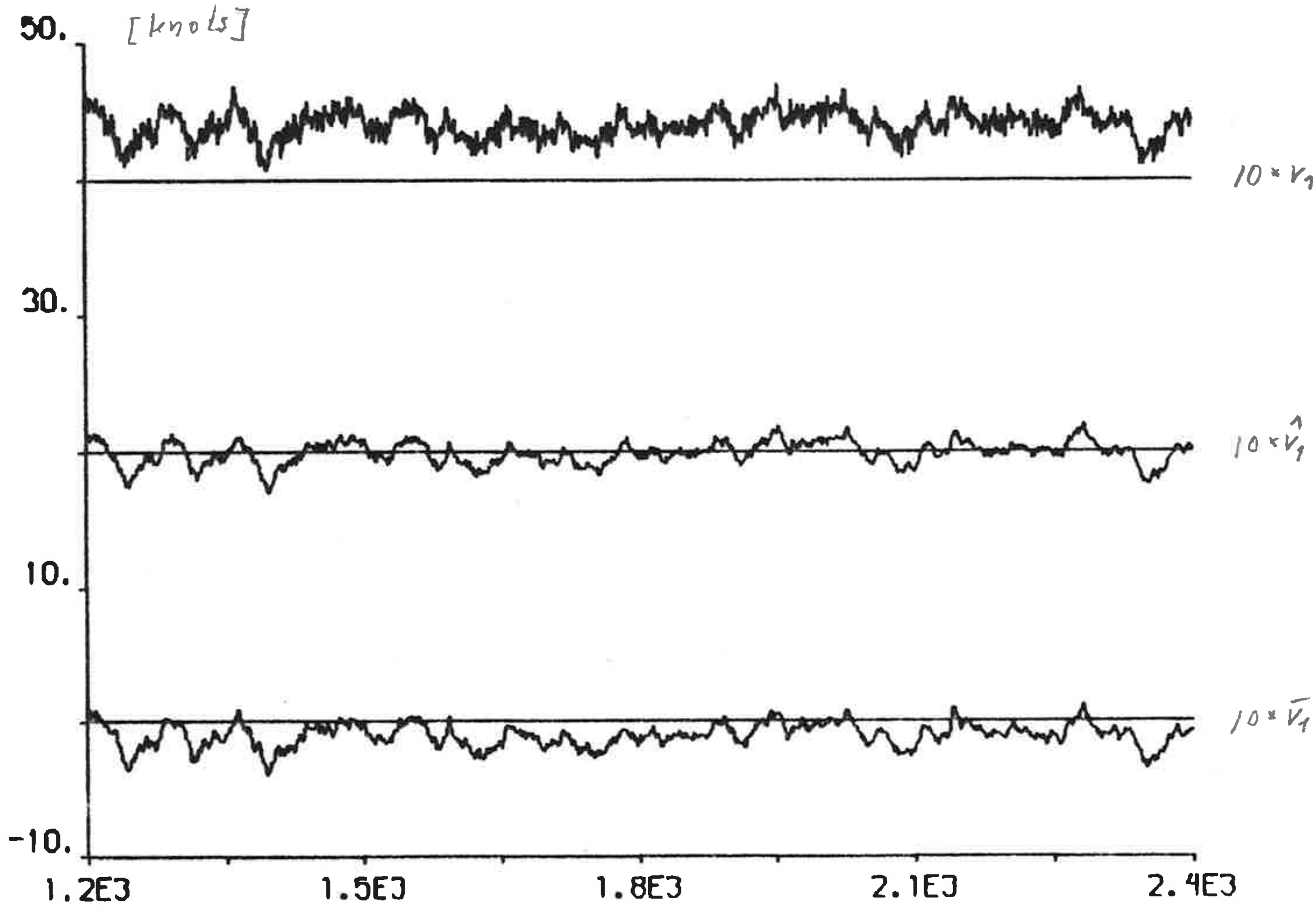


[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × Vm
10 × V̂
10 × V

Fig. 4.11 b

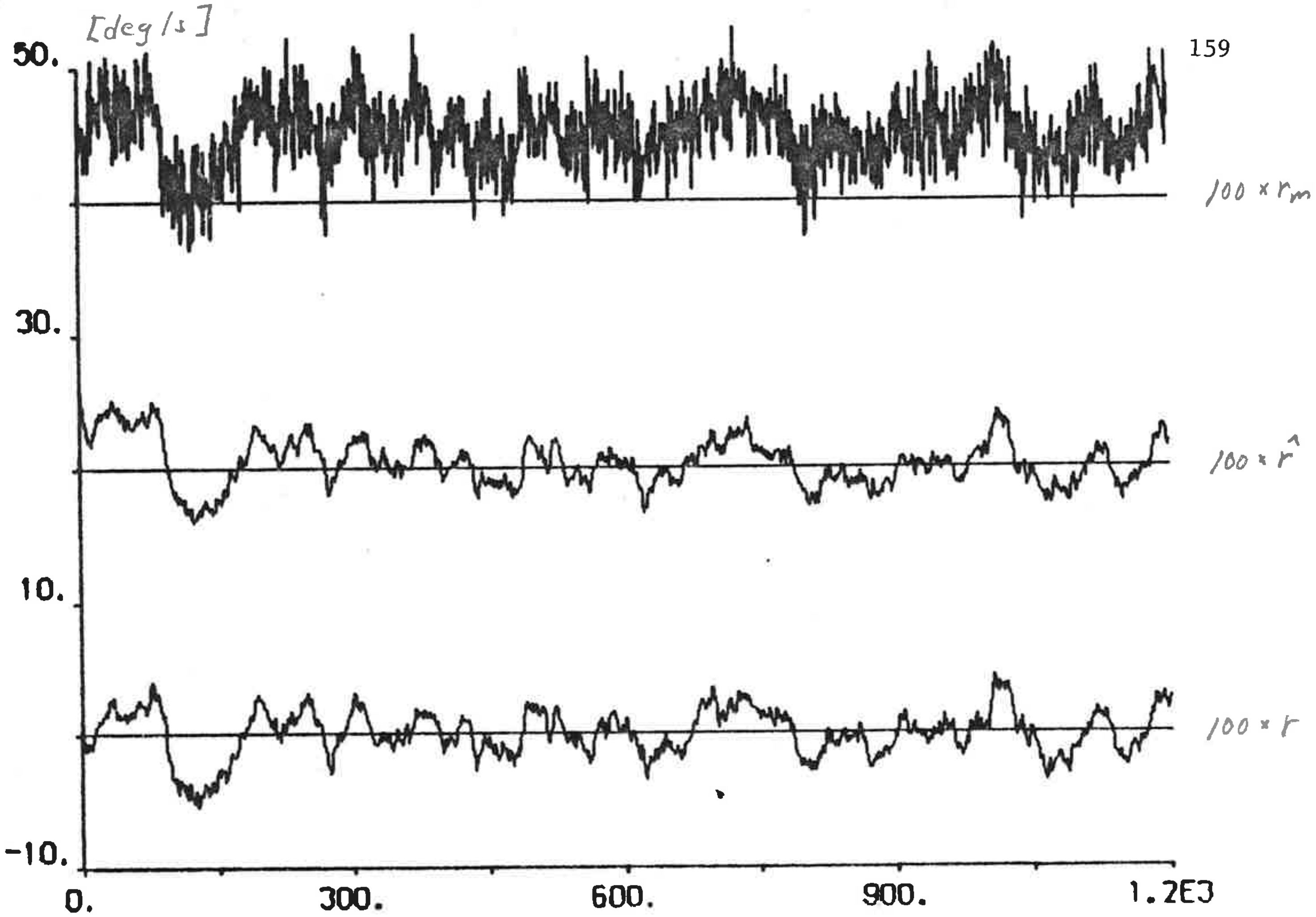


[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10 × V1
10 × V̂1
10 × V̄1



[knots]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10 × V1
10 × V̂1
10 × V̄1

Fig. 4.11 c


[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
100 × r_m
100 × $\hat{r}$
100 × r

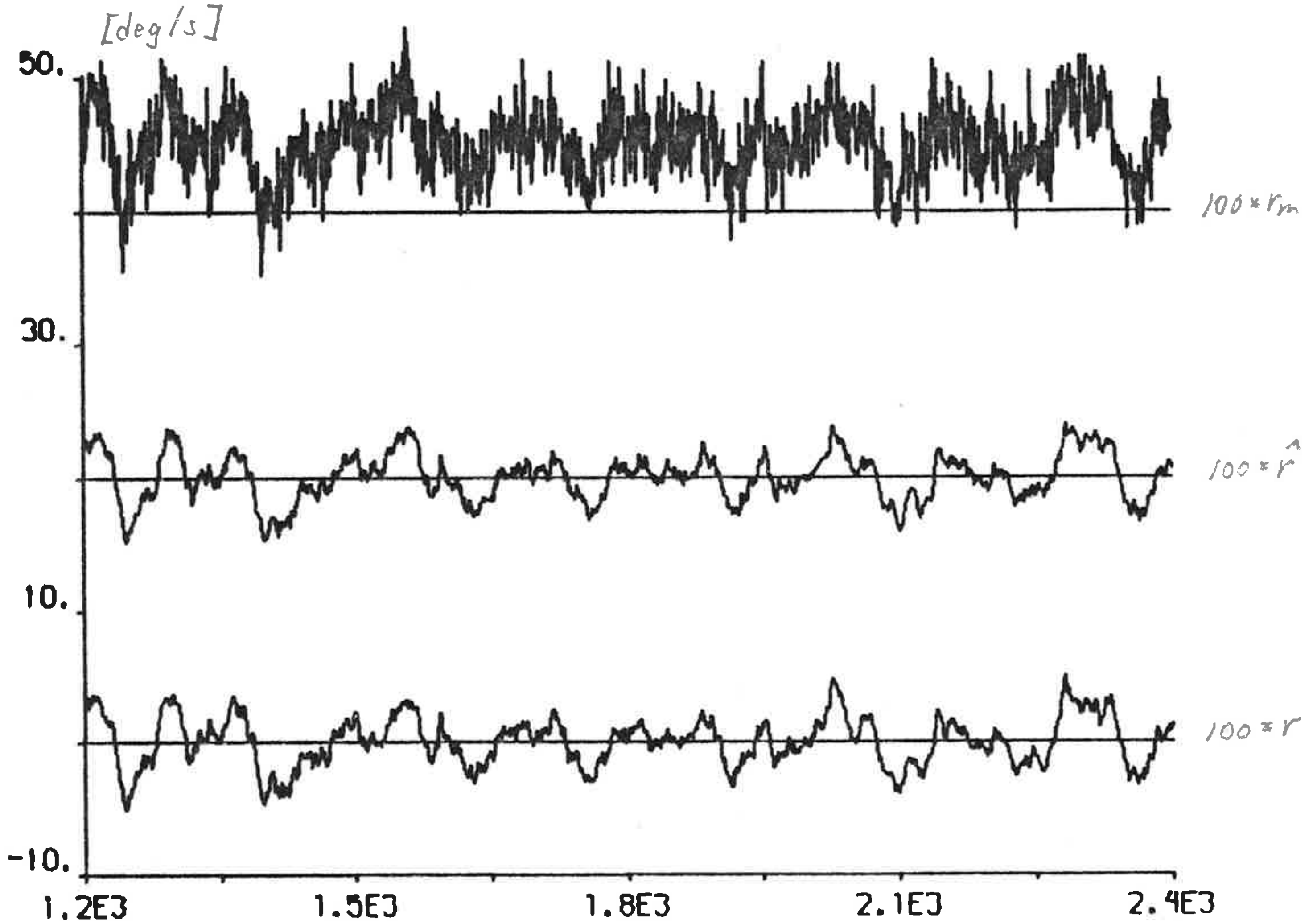

[deg/s]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
100 × r_m
100 × $\hat{r}$
100 × r

Fig. 4.11 d

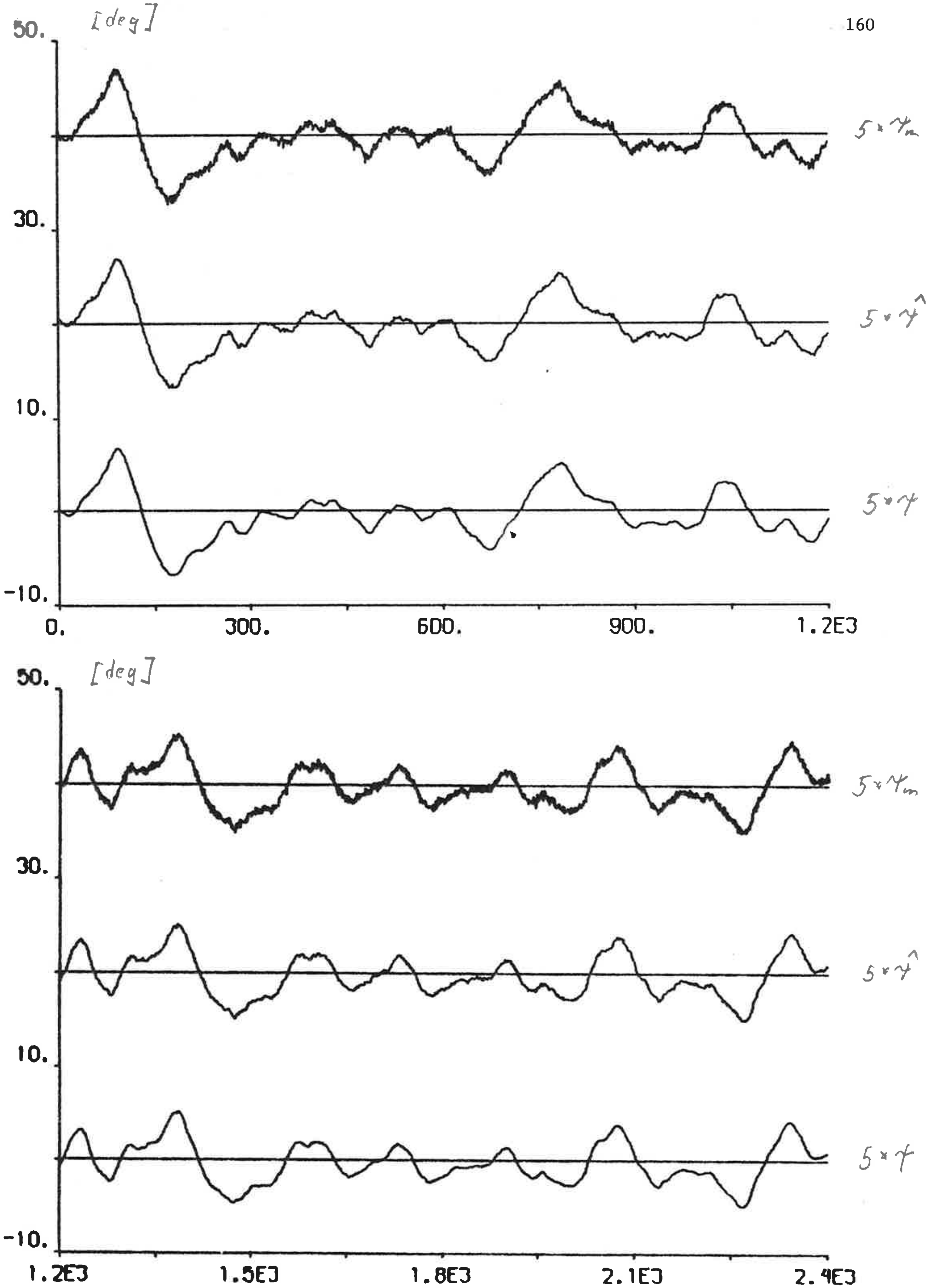
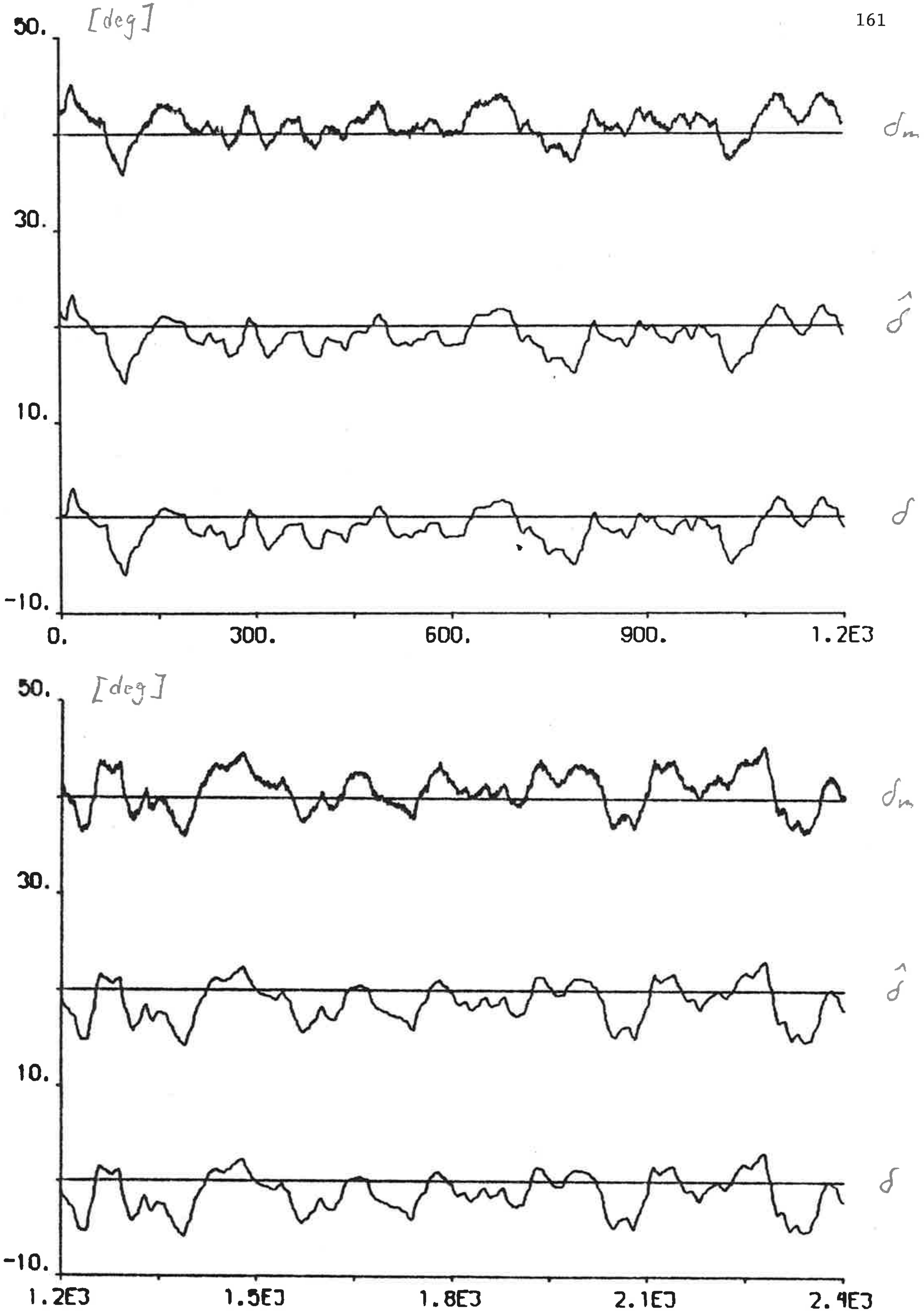
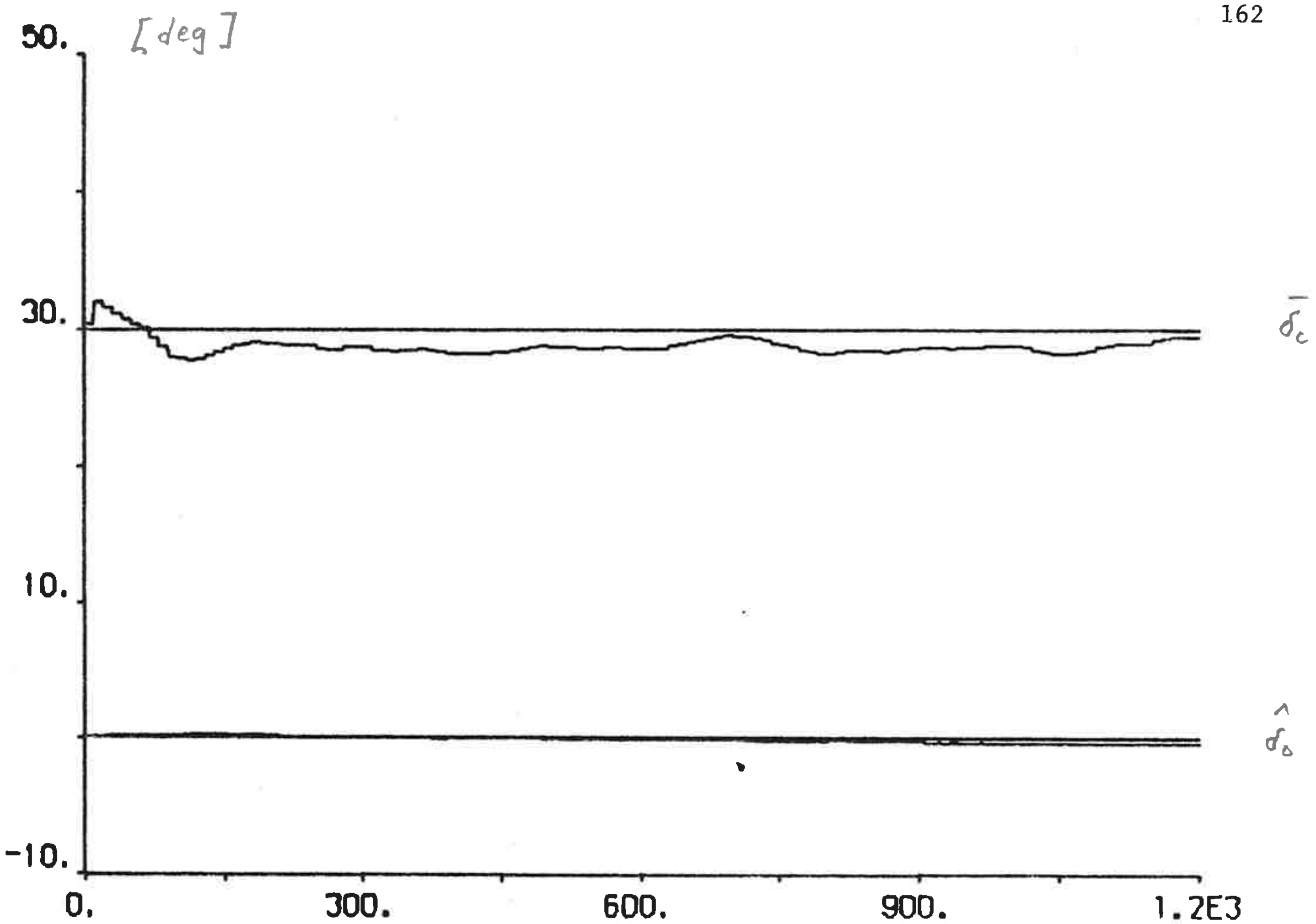

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5 * ψm
5 * ψ̂
5 * ψ
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
5 * ψm
5 * ψ̂
5 * ψ

Fig. 4.11 e

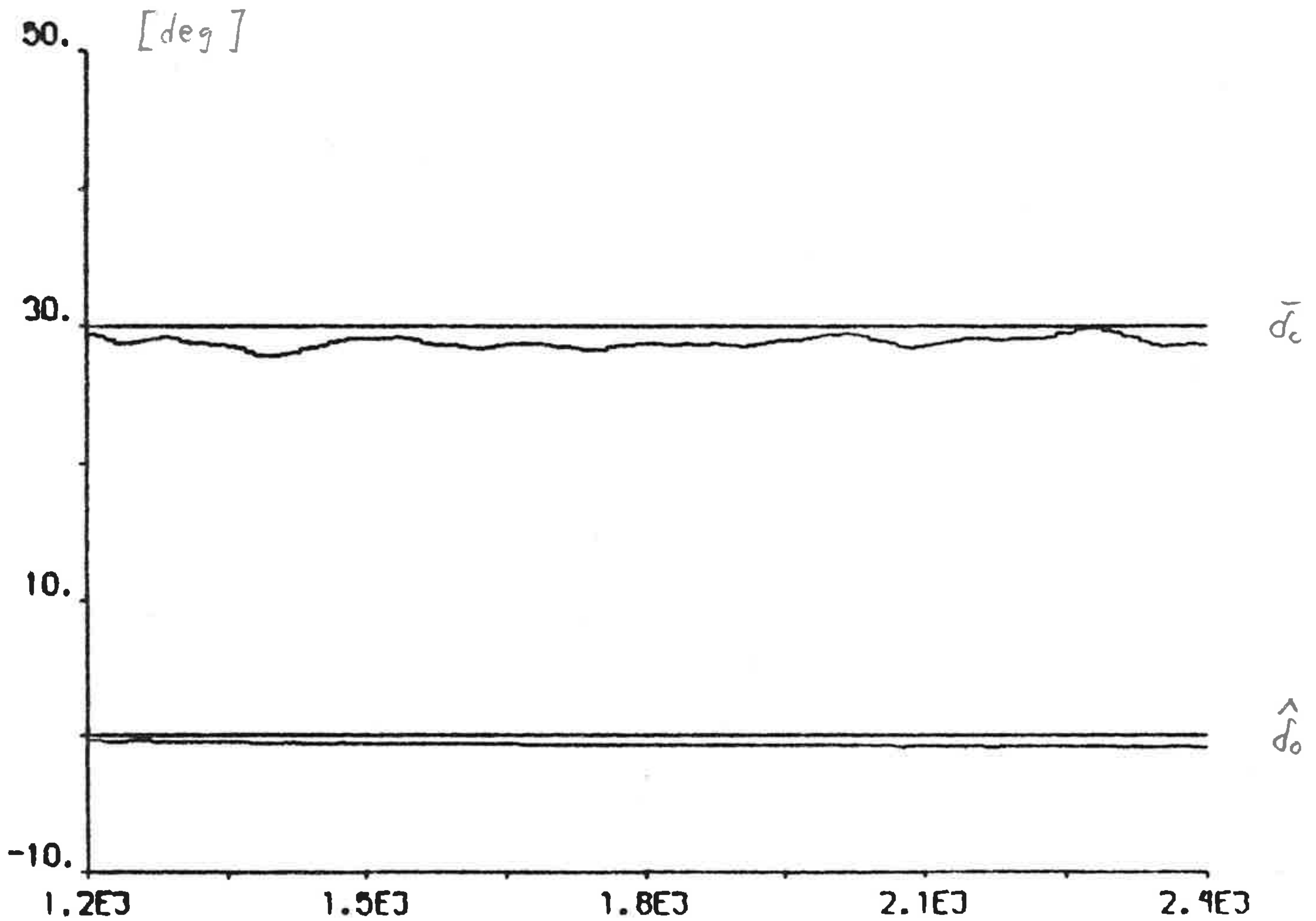


[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.11 f

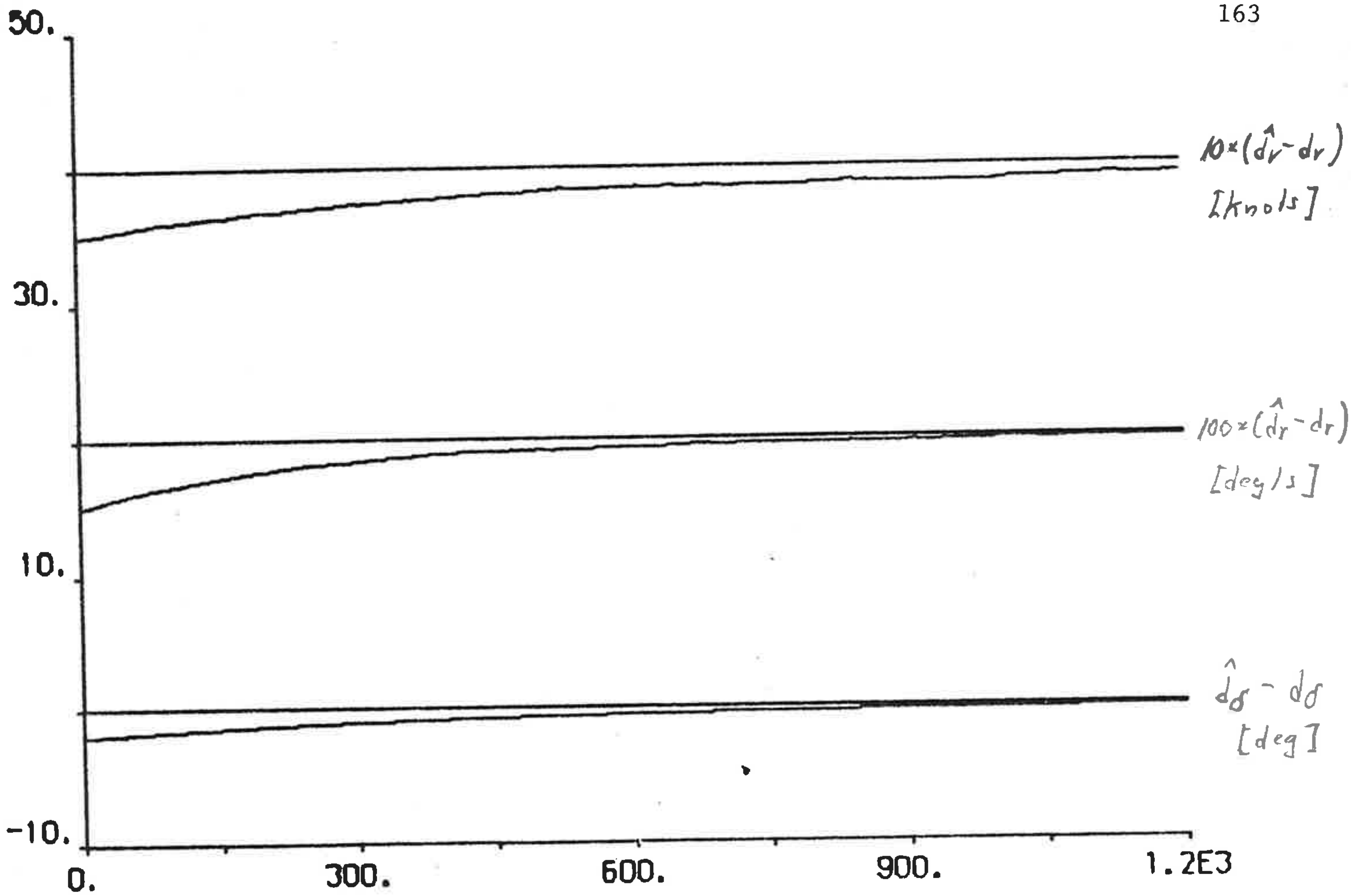


[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3



[deg]
50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3

Fig. 4.11 g


50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10*(d̂v-dv) [knots]
100*(d̂r-dr) [deg/s]
d̂δ - dδ [deg]

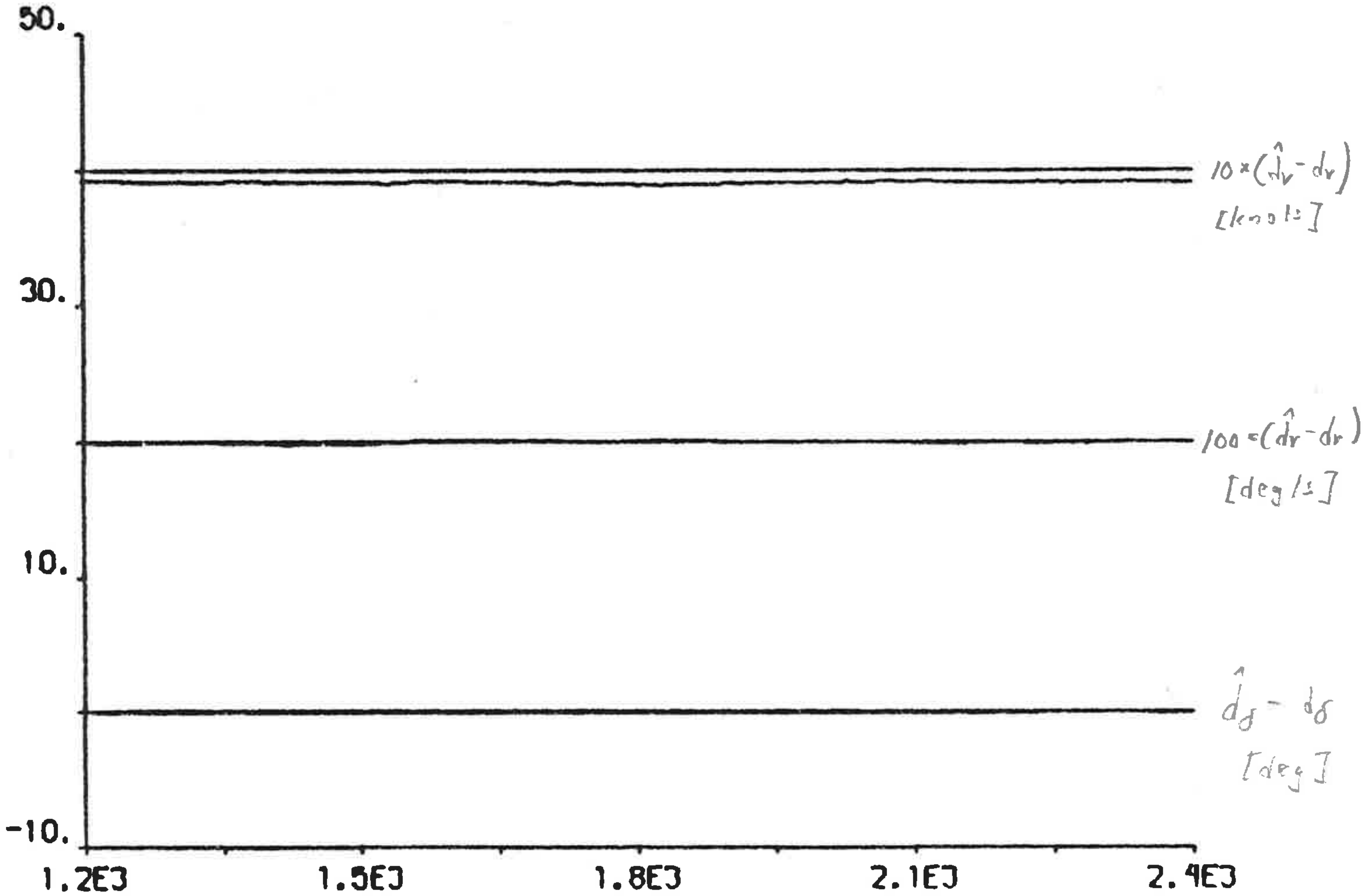
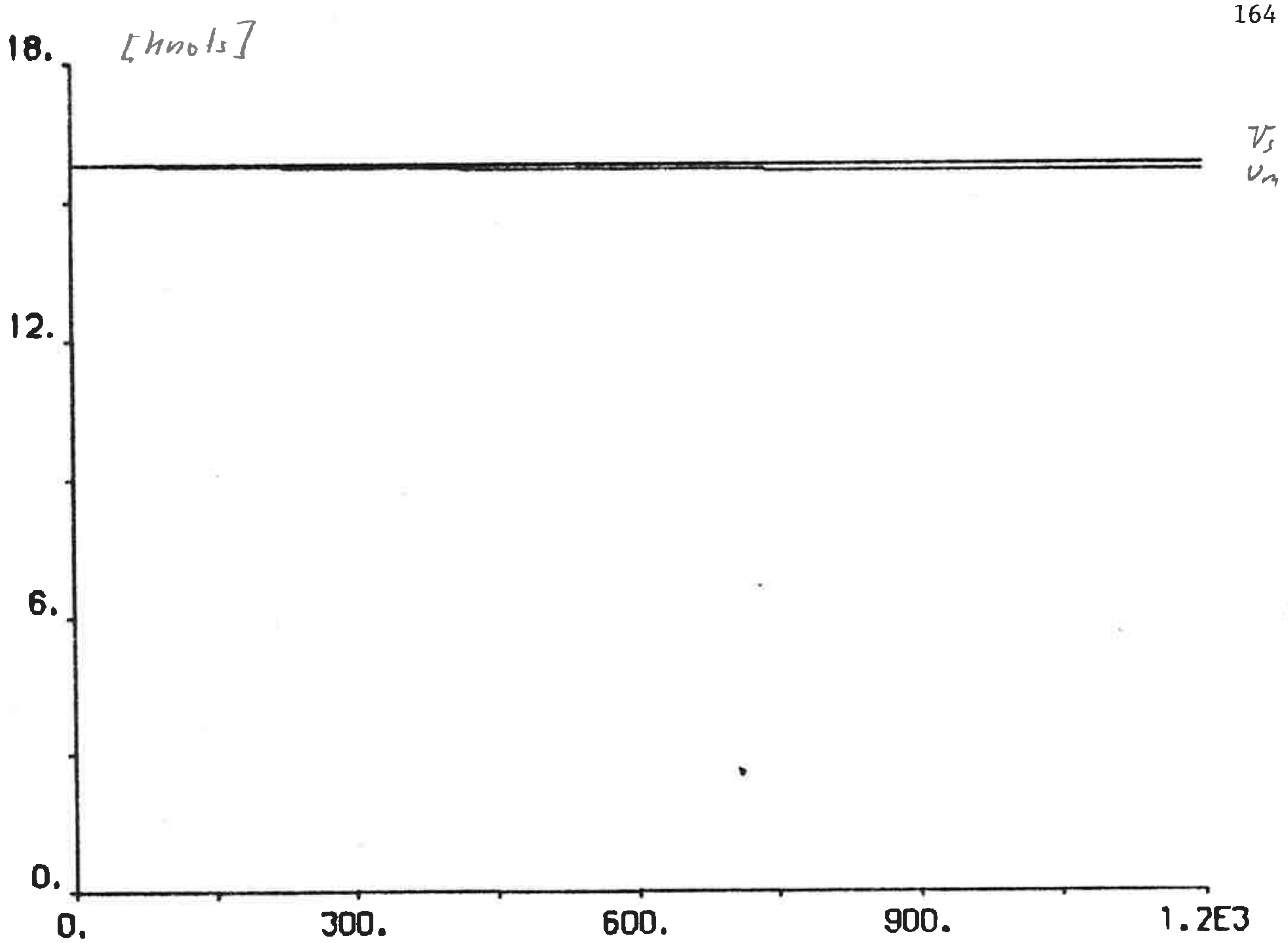
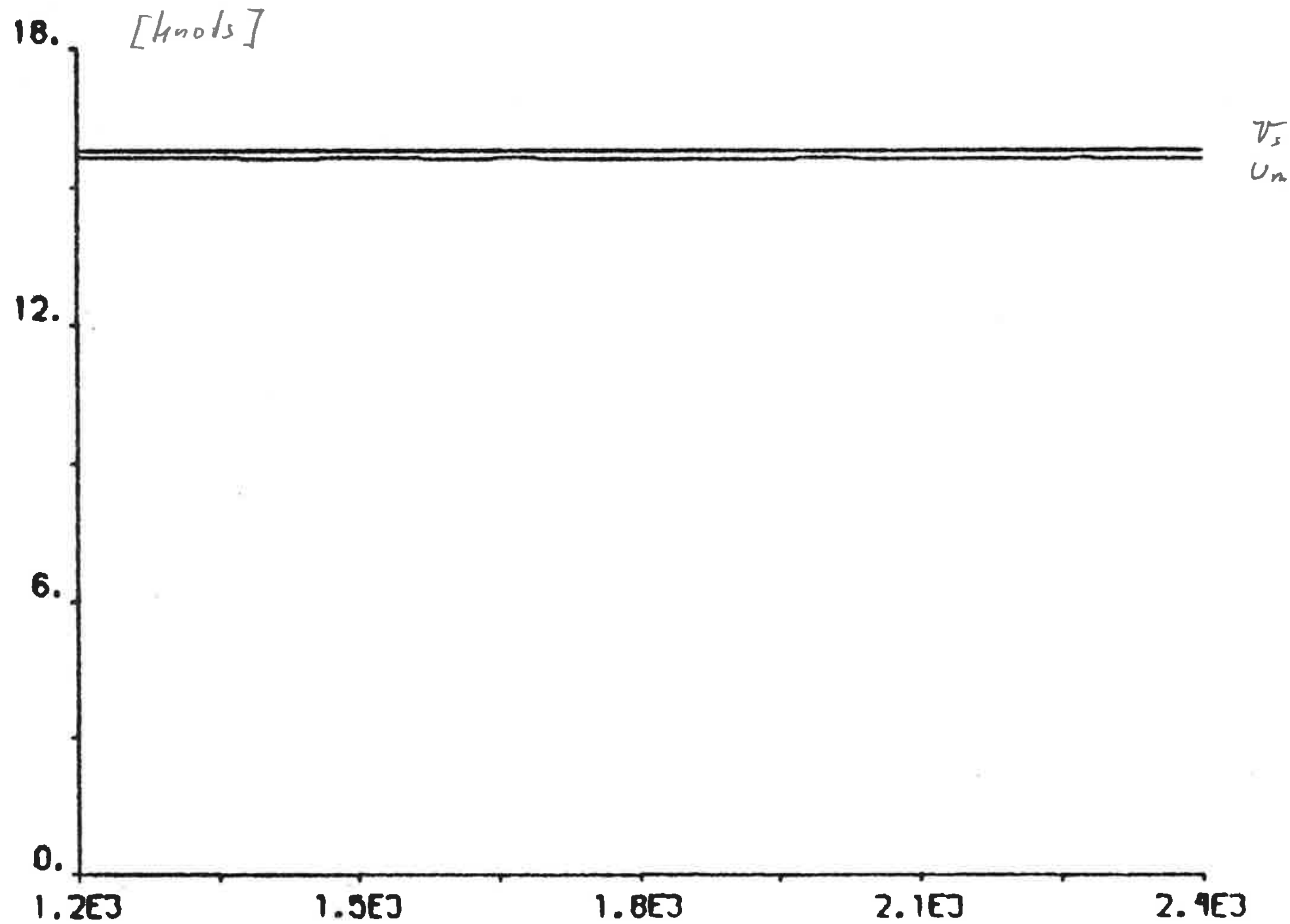

50.
30.
10.
-10.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
10*(d̂v-dv) [knots]
100*(d̂r-dr) [deg/s]
d̂δ - dδ [deg]

Fig. 4.11 h

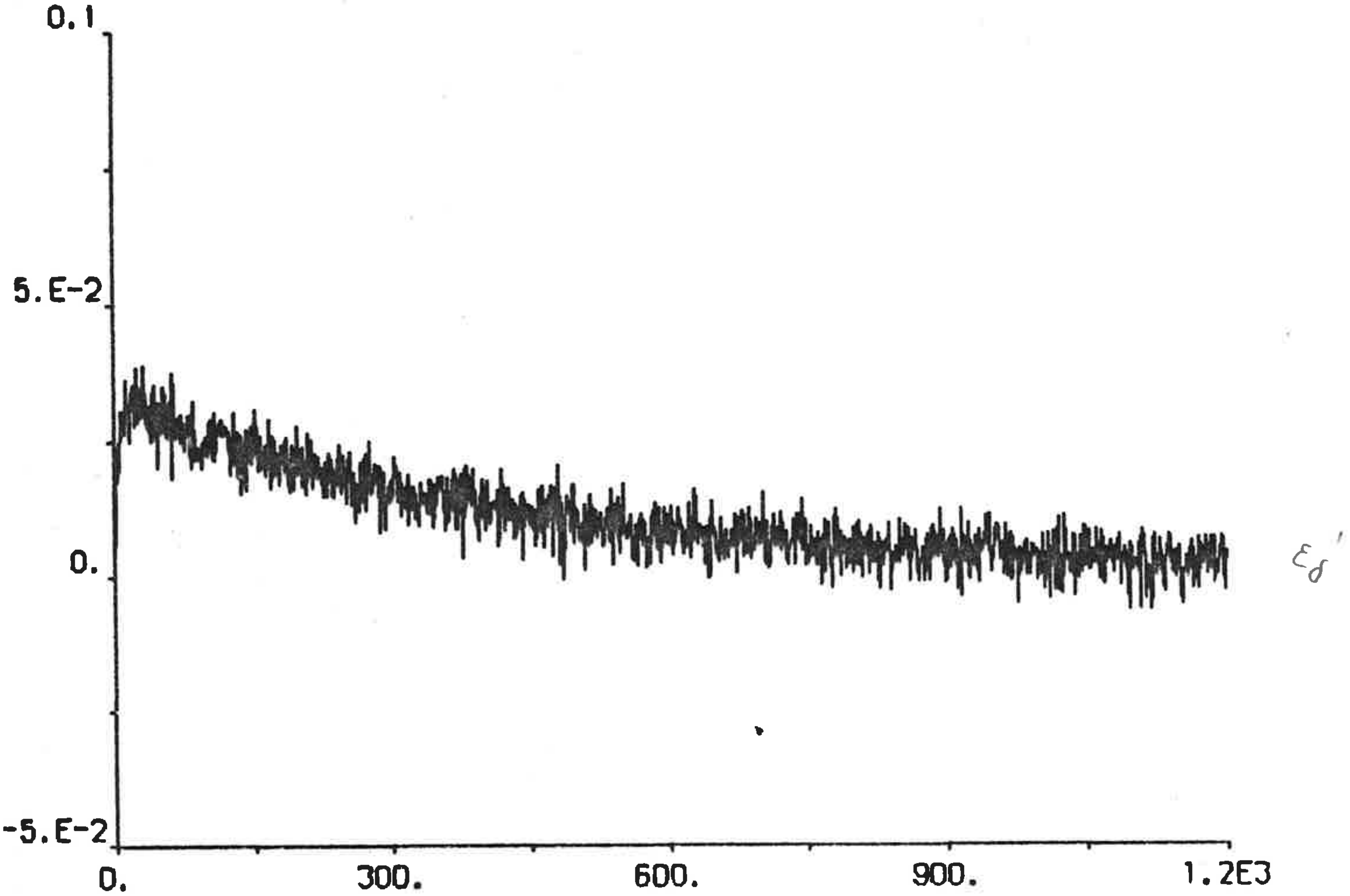


18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
Vs
Um



18.
[knots]
12.
6.
0.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
Vs
Um

Fig. 4.11 i


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_δ'

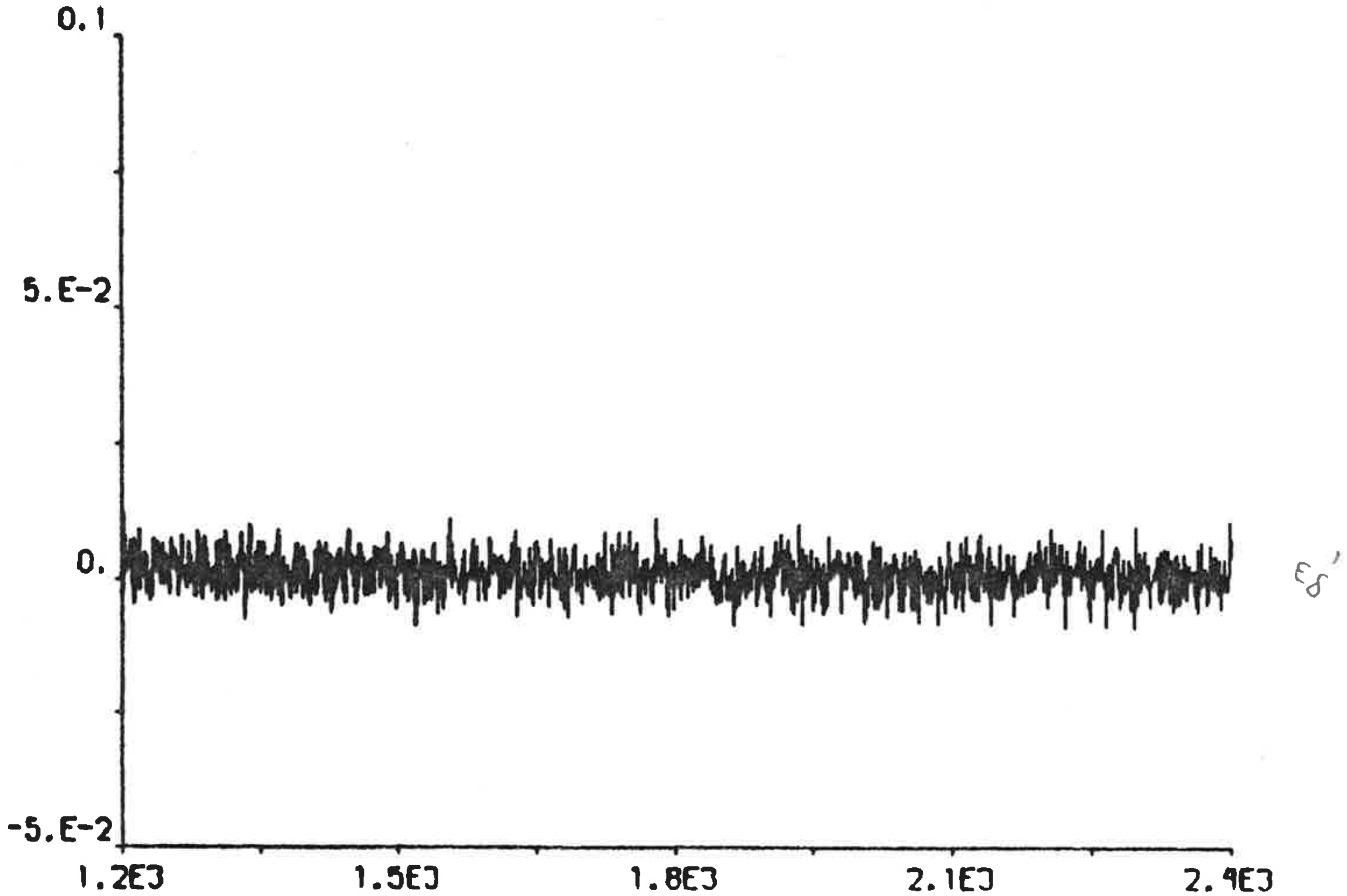

0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_δ'

Fig. 4.11 j

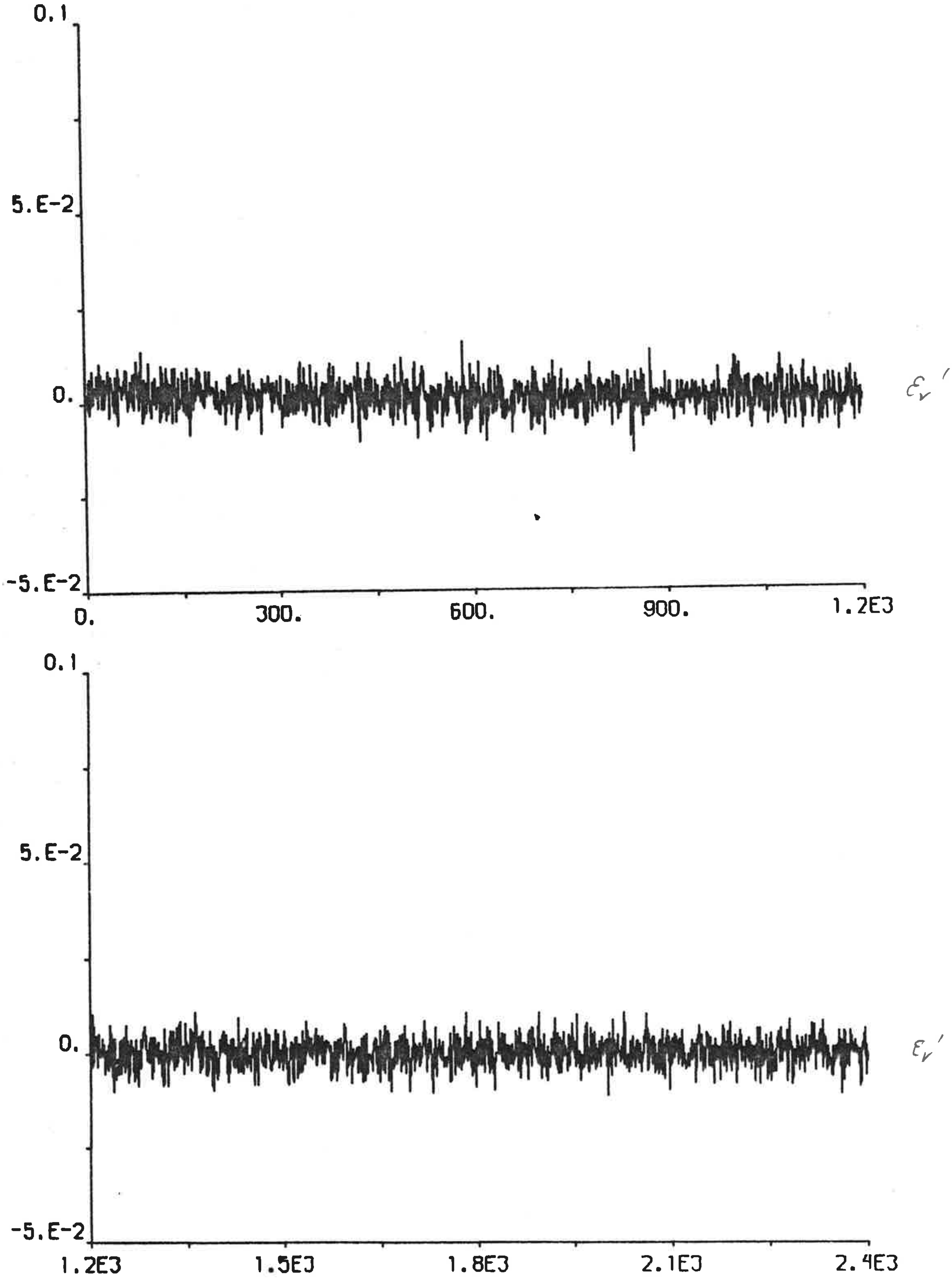
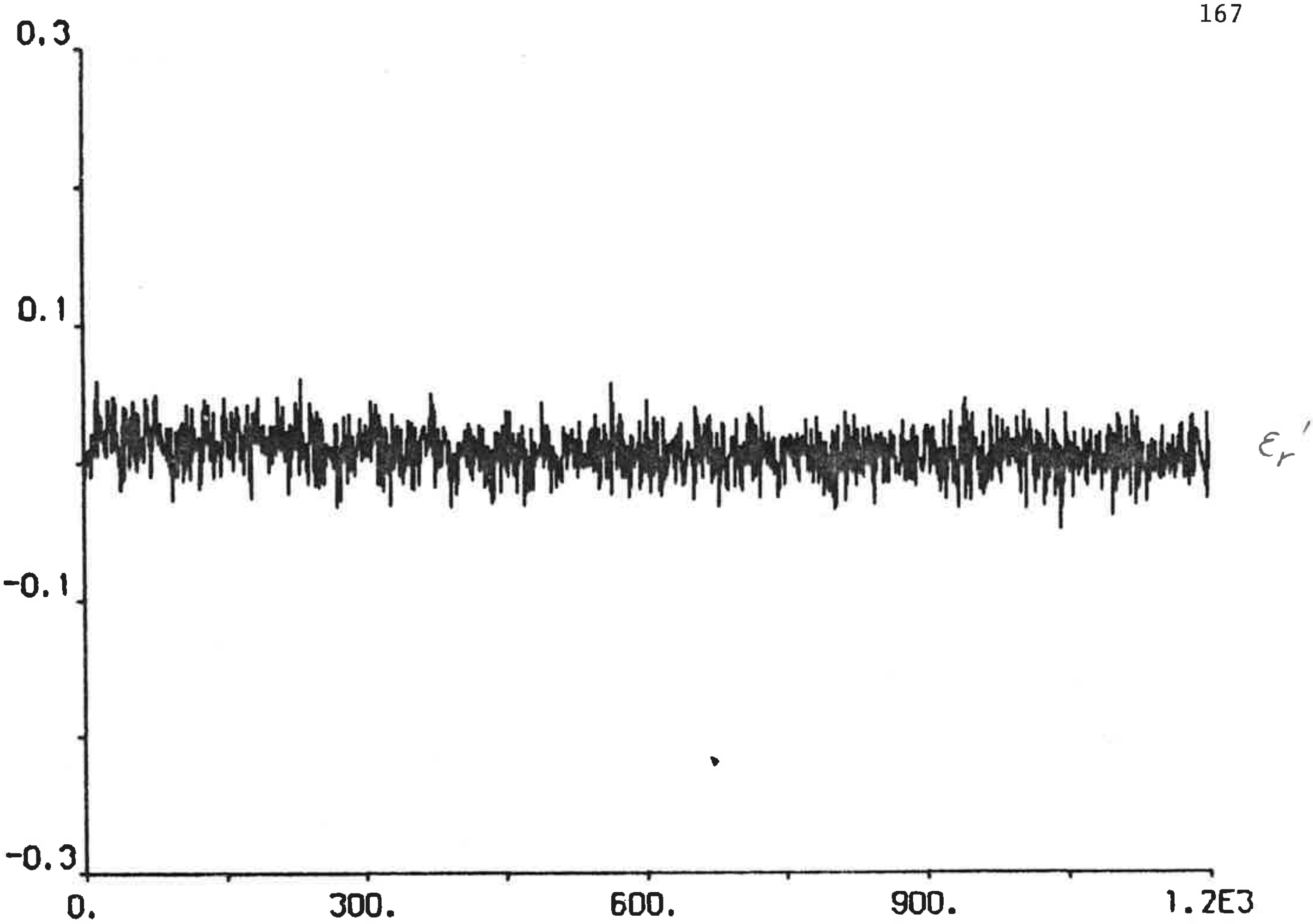

0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_v'
0.1
5.E-2
0.
-5.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε_v'

Fig. 4.11 k


0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
εr'

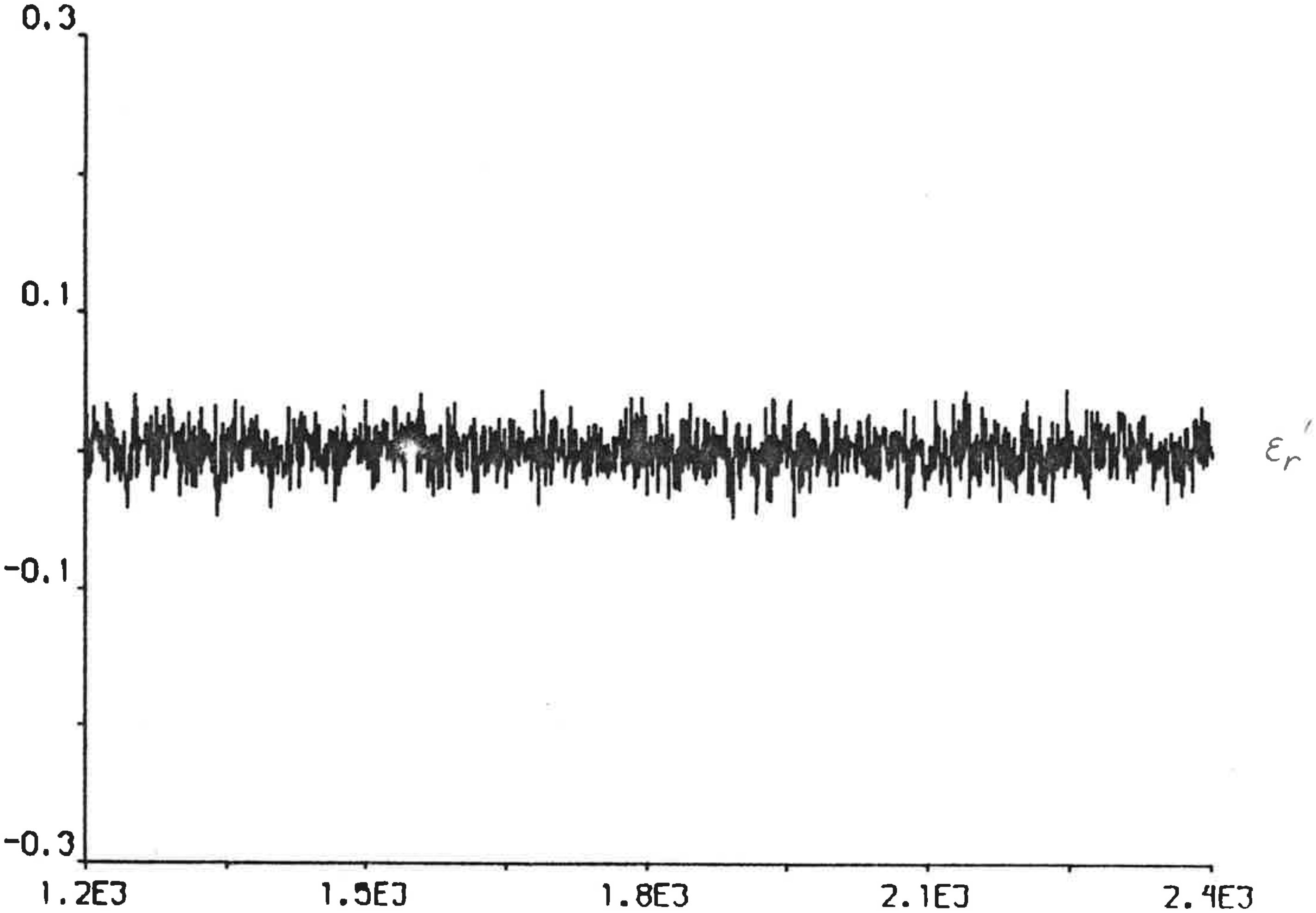

0.3
0.1
-0.1
-0.3
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
εr'

Fig. 4.11 ℓ

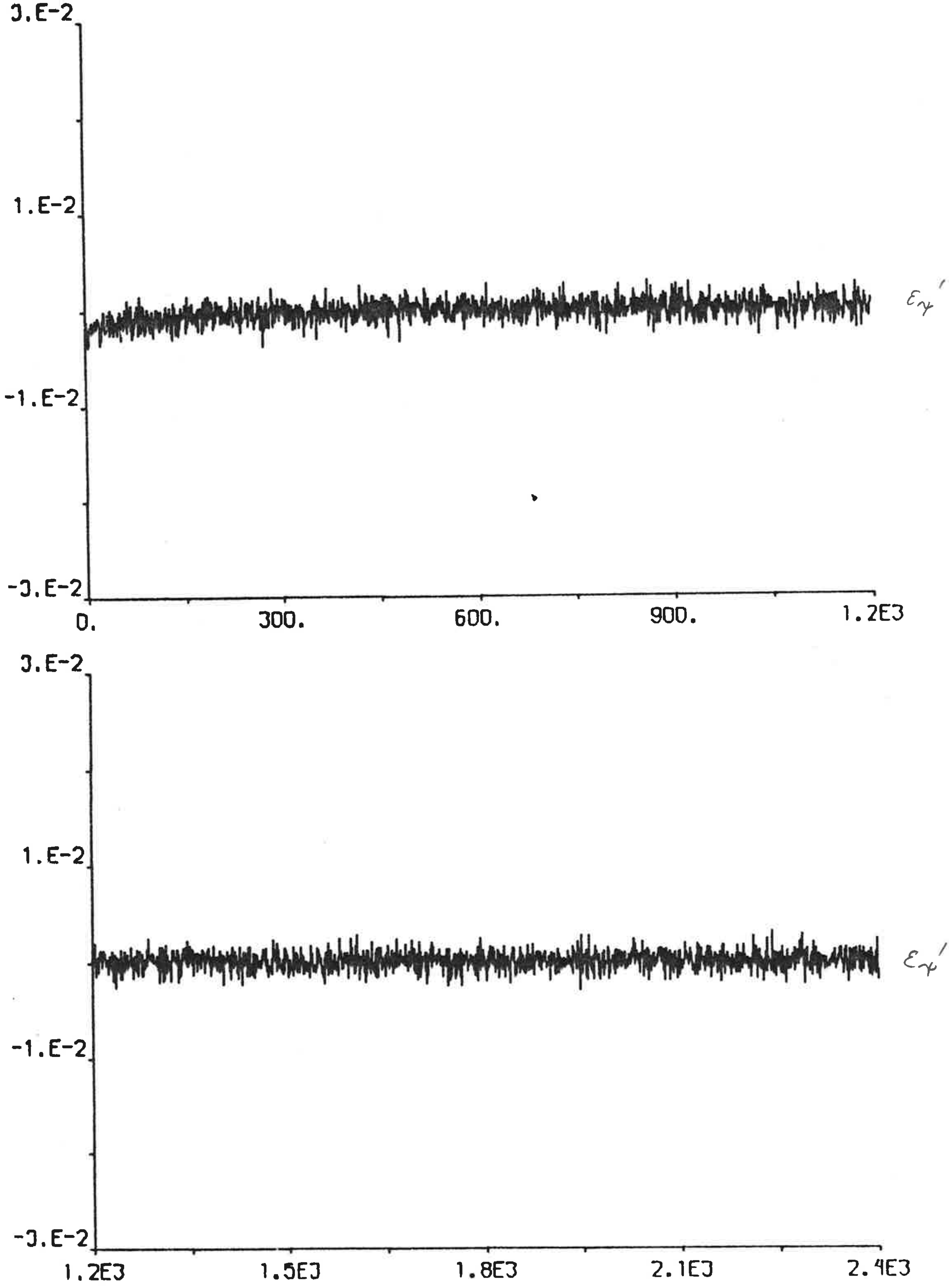
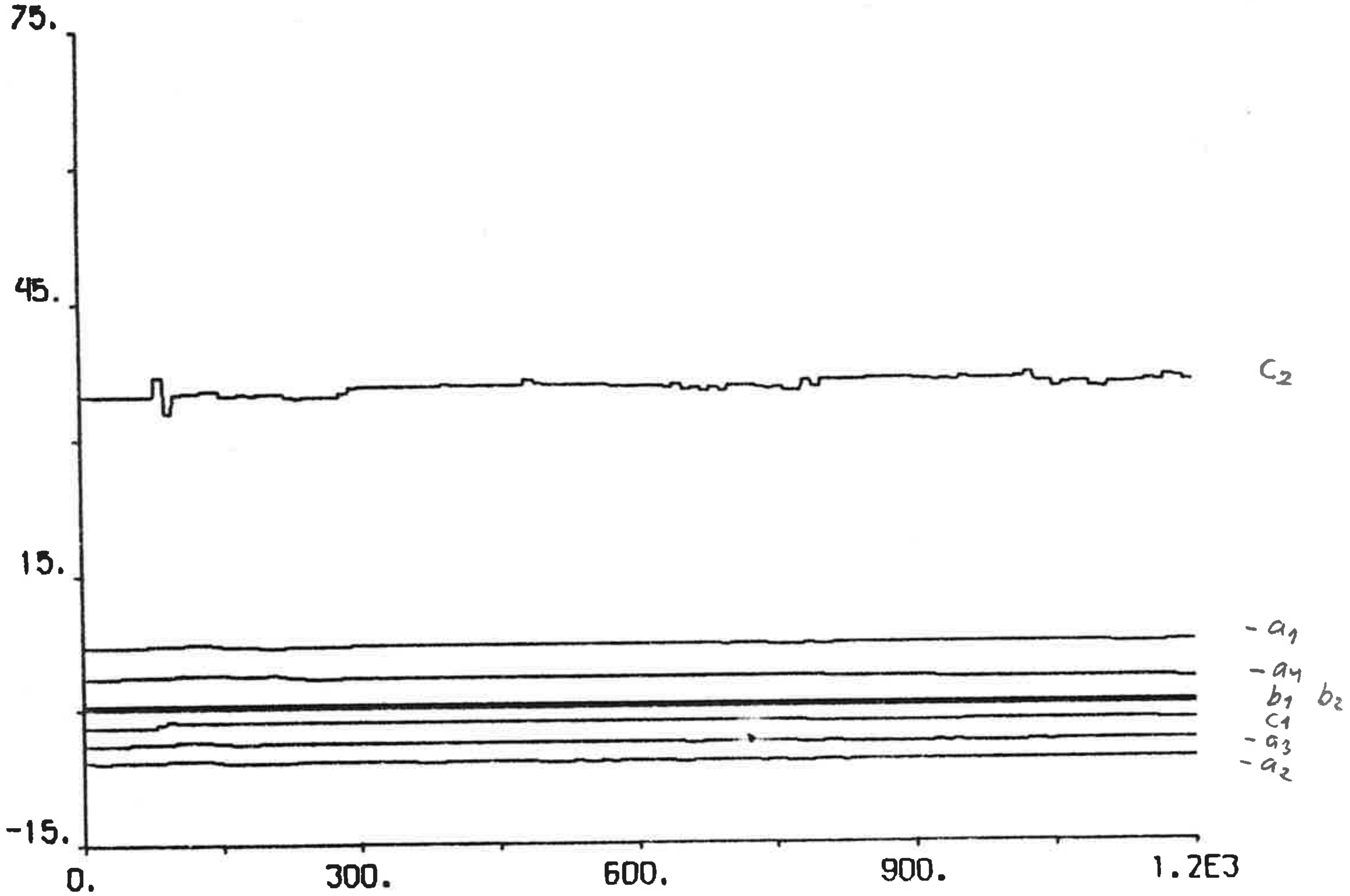

3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
ε'
3.E-2
1.E-2
-1.E-2
-3.E-2
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
ε'

Fig. 4.11 m


75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1 b_2
c_1
$-a_3$
$-a_2$

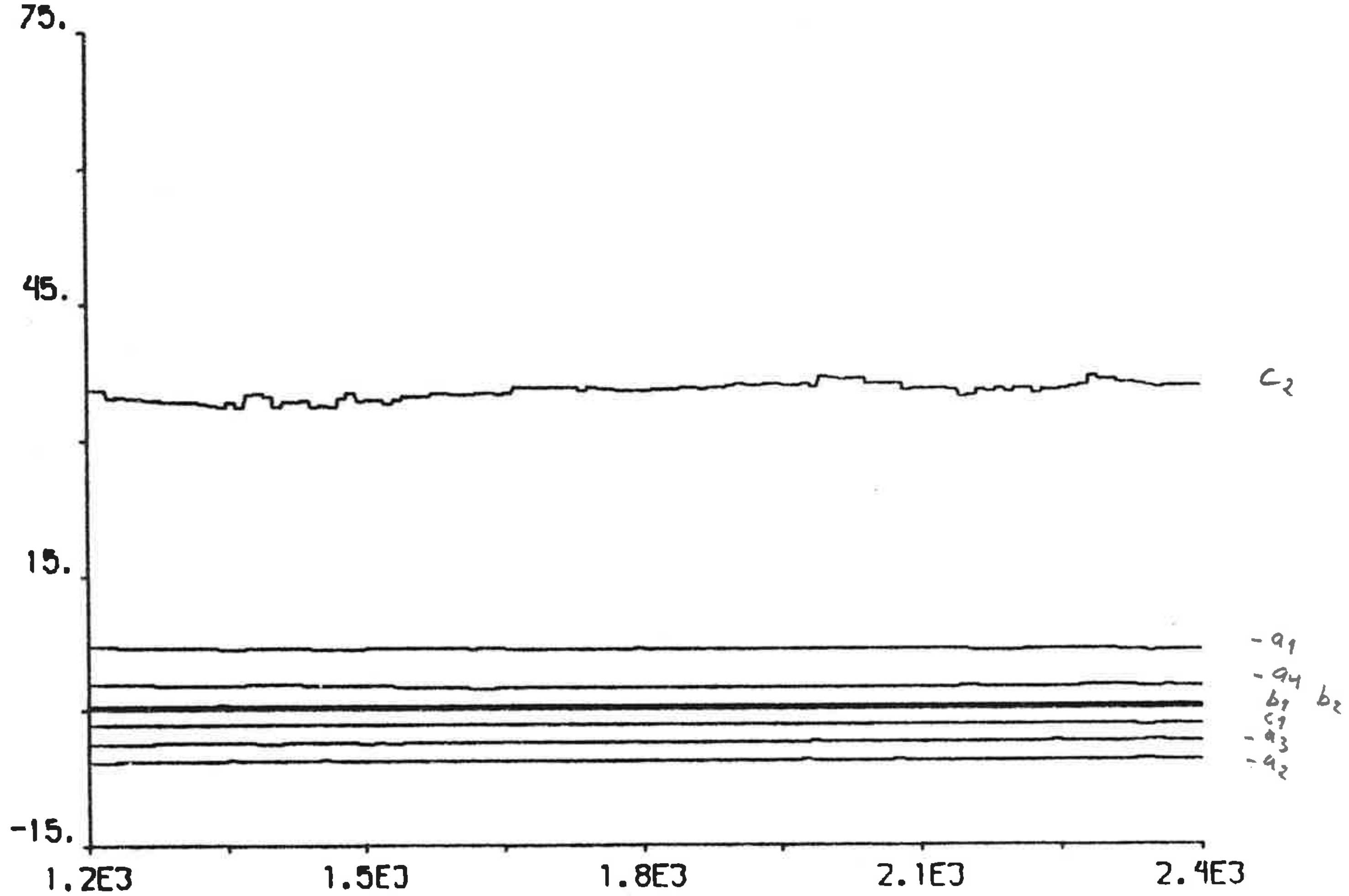

75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1 b_2
c_1
$-a_3$
$-a_2$

Fig. 4.11 n

4.2 Straight Course Keeping

Simulations of straight course keeping with the self-tuning regulator using non-filtered measurements are shown in Figs 4.12 - 4.25, where the mean draught T is equal to 22.3 m and k, T_s and q_2^* are varied. Two different initial speeds, u_0 = 15.8 knots and u_0 = 4 knots, are used. The initial parameter values and the initial covariance matrix are

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -10.92 \\ 10.38 \\ 4.717 \\ -4.871 \\ 0.8884 \\ 0.2482 \end{bmatrix} \qquad P = \begin{bmatrix} 100 & & & & & \\ & 100 & & & & \\ & & 100 & & & \\ & & & 100 & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \tag{4.7}$$

or

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -13.88 \\ 12.85 \\ 7.866 \\ -7.302 \\ 0.6101 \\ -0.01241 \end{bmatrix} \qquad P = \begin{bmatrix} 100 & & & & & \\ & 100 & & & & \\ & & 100 & & & \\ & & & 100 & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \tag{4.8}$$

or

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -8.105 \\ 8.189 \\ 2.845 \\ -3.605 \\ 0.4698 \\ 0.2522 \end{bmatrix} \qquad P = \begin{bmatrix} 10 & & & & & \\ & 10 & & & & \\ & & 10 & & & \\ & & & 10 & & \\ & & & & 0.1 & \\ & & & & & 0.1 \end{bmatrix} \tag{4.9}$$

or

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -9.47 \\ 9.67 \\ 3.55 \\ -4.42 \\ 0.150 \\ 0.266 \end{bmatrix} \qquad P = \begin{bmatrix} 1 & & & & & \\ & 10 & & & & \\ & & 10 & & & \\ & & & 1 & & \\ & & & & 0.1 & \\ & & & & & 0.1 \end{bmatrix} \tag{4.10}$$

Notice that $c_1 = c_2 = 0$. The speed V_s (cf (3.1)) is computed according to

$$V_s = V_c \tag{4.11}$$

The simulations are summarized in Table 4.2. When $u_0 = 15.8$ knots, it can be concluded that the lowest value of V_ℓ (0.75) is obtained for $k = 7$, $T_s = 10$ s and $q_2^* = 0$. These values are also chosen as standard values. Notice, however, that $k = 6$, $T_s = 10$ s, $q_2^* = 0$ ($V_\ell = 0.76$) and $k = 5$, $T_s = 15$ s, $q_2^* = 0$ ($V_\ell = 0.79$) are good alternatives. It can also be concluded that the performance of the self-tuning regulator is not improved when $q_2^* \neq 0$. When $u_0 = 4$ knots, the best choice is $k = 8$, $T_s = 10$ s, $q_2^* = 0$. The only difference compared to the standard values is that $k = 8$ instead of $k = 7$.

The performance of the self-tuning regulator using estimates from the Kalman filter, when the speed is decreased and increased, is shown in Figs 4.26 and 4.27, resp. A summary is given in Table 4.3. The standard parameter values are used, but the speed V_s (cf (3.1)) is computed according to

$$V_s = u_m / CMK \tag{4.12}$$

Notice that the parameters of the self-tuning regulator are changed very little and that the performance of the regulator is very good in both cases. This may be an indication that the speed scaling introduced in the self-tuning regulator is acceptable.

n_0 [rpm]	u_0 [knots]	δ_ℓ [deg]	k	T_s [s]	q_2^*	V_c [m/s]	m_δ [deg]	σ_δ [deg]	m_ψ [deg]	σ_ψ [deg]	V_ℓ [deg^2]	λ	Fig.	Remarks
87.6	15.8	10	4	15	0	8	- 1.31	2.71	0.05	0.51	0.87	1/12	4.12	Initial values (4.7)
87.6	15.8	10	5	15	0	8	- 1.32	2.37	0.05	0.57	0.79	1/12	4.13	" -
87.6	15.8	10	6	15	0	8	- 1.27	3.73	0.06	0.64	1.57	1/12	4.14	" -
87.6	15.8	10	5	10	0	8	- 1.28	3.12	0.01	0.44	1.01	1/12	4.15	Initial values (4.8)
87.6	15.8	10	6	10	0	8	- 1.29	2.58	-0.05	0.45	0.76	1/12	4.16	" -
87.6	15.8	10	7	10	0	8	- 1.30	2.58	0.00	0.45	0.75	1/12	4.17	" -
87.6	15.8	10	8	10	0	8	- 1.29	3.62	0.02	0.64	1.50	1/12	4.18	" -
87.6	15.8	10	5	10	0.05	8	- 1.29	3.04	0.01	0.52	1.04	1/12	4.19	" -
87.6	15.8	10	6	10	0.05	8	- 1.30	2.43	-0.10	0.53	0.78	1/12	4.20	" -
87.6	15.8	10	6	10	0.1	8	- 1.31	2.33	-0.16	1.61	0.84	1/12	4.21	" -
22.1772	4	45	6	10	0	2	-21.34	28.57	1.21	1.48	3.65	0	4.22	Initial values (4.9)
22.1772	4	45	7	10	0	2	-22.04	26.28	1.22	1.49	3.71	0	4.23	" -
22.1772	4	45	8	10	0	2	-22.56	25.86	1.18	1.30	3.08	0	4.24	" -
22.1772	4	45	6	10	0.05	2	-22.28	29.46	1.24	1.39	3.47	0	4.25	Initial values (4.10)

Table 4.2 - Summary of straight course keeping simulations (ψ_{ref} = 0 deg) with the self-tuning regulator using non-filtered measurements, when k, T_s, and q_2^* are varied. The mean draught T is equal to 22.3 m. The speed V_s is computed according to (4.11). The duration of each simulation is 2400 s, but the values of m_δ, σ_δ, m_ψ, σ_ψ, and V_ℓ are computed for the part 1200 - 2400 s.

T [m]	n_0 [rpm]	u_0 [knots]	δ_ℓ [deg]	m_δ [deg]	σ_δ [deg]	m_ψ [deg]	σ_ψ [deg]	V_ℓ [deg^2]	λ	Fig.
22.3	22.1772	15.8	45	-4.47	5.60	-0.11	0.85	3.34	1/12	4.26
22.3	87.6	4	45	-1.85	9.36	-0.07	0.71	7.81	1/12	4.27

Table 4.3 - Summary of straight course keeping simulations (ψ_{ref} = 0 deg) with the self-tuning regulator using estimates from the Kalman filter, when the speed is changed significantly. The speed V_s is computed according to (4.12).

Simulations of straight course keeping with the self-tuning regulator and the PID-regulator, when the Kalman filter estimates as well as the non-filtered measurements are used, are shown in Figs 4.28 - 4.53. The initial speed u_0 is equal to 15.8, 10 or 4 knots and the mean draught T is equal to 22.3 or 10.5 m. A summary is given in Tables 4.4, 4.5 and 4.6, where also simulations from Section 4.1 are included.

The speed scaling used in the PID-regulator is $(V_0/V_s)^2$ (cf (3.25)). By putting V_0 = 6.3 m/s when V_s = 5 m/s, and V_0 = 4 m/s when V_s = 2 m/s, the speed scaling V_0/V_s may be simulated (cf Figs 4.38, 4.43, 4.48 and 4.53). The speed scaling used in the self-tuning regulator is also $(V_0/V_s)^2$ (cf (3.24)), since q_2^* = 0. It is, however, possible to obtain the speed scaling V_0/V_s instead, if q_2^* = 0.6 when V_s = 5 m/s and if q_2^* = 3 when V_s = 2 m/s (cf Figs 4.37, 4.42, 4.47, and 4.52).

T	Kalman filter estimates used		Non-filtered measurements used		m_δ	σ_δ	m_ψ	σ_ψ	V_ℓ	λ	Fig.
[m]	Self-tuning regulator	PID-regulator	Self-tuning regulator	PID-regulator	[deg]	[deg]	[deg]	[deg]	[deg^2]		
22.3	X				-1.28	2.04	-0.09	0.47	0.55	1/12	4.1
22.3		X			-1.36	2.08	0.07	0.66	0.80	1/12	4.28
22.3			X		-1.32	2.34	-0.22	0.64	0.91	1/12	4.29
22.3				X	-1.28	2.40	0.03	0.80	1.12	1/12	4.30
10.5	X				-0.15	1.55	-0.01	0.29	0.29	1/12	4.2
10.5		X			-0.16	1.29	0.01	0.32	0.24	1/12	4.31
10.5			X		-0.17	1.94	0.01	0.43	0.50	1/12	4.32
10.5				X	-0.13	1.63	-0.01	0.42	0.39	1/12	4.33

Table 4.4 - Summary of straight course keeping simulations (ψ_{ref} = 0 deg), when n_0 = 87.6 rpm, u_0 = 15.8 knots, and δ_ℓ = 10 deg. The duration of each simulation is 2400 s, but the values of m_δ, σ_δ, m_ψ, σ_ψ, and V_ℓ are computed for the part 1200-2400 s.

T [m]	Kalman filter estimates used		Non-filtered measurements used		m_δ [deg]	σ_δ [deg]	m_ψ [deg]	σ_ψ [deg]	V_ℓ [deg^2]	λ	Fig.	Remarks
	Self-tuning regulator	PID-regulator	Self-tuning regulator	PID-regulator								
22.3	X				-3.71	4.61	-0.16	0.51	2.05	1/12	4.3	
22.3		X			-3.82	4.62	0.07	0.65	2.21	1/12	4.34	
22.3			X		-3.76	5.64	-0.19	0.66	3.12	1/12	4.35	
22.3				X	-3.65	5.33	0.01	0.65	2.79	1/12	4.36	
22.3	X				-3.77	4.43	-0.26	0.83	2.38	1/12	4.37	$q_2^* = 0.6$
22.3		X			-3.64	4.46	0.06	1.08	2.83	1/12	4.38	$V_0 = 6.3$ m/s
10.5	X				-1.18	3.36	-0.01	0.35	1.06	1/12	4.4	
10.5		X			-1.19	3.32	0.01	0.37	1.06	1/12	4.39	
10.5			X		-1.19	5.54	0.00	0.53	2.83	1/12	4.40	
10.5				X	-1.12	4.47	-0.01	0.42	1.84	1/12	4.41	
10.5	X				-1.19	2.31	-0.18	0.70	0.97	1/12	4.42	$q_2^* = 0.6$
10.5		X			-1.22	2.56	0.03	0.52	0.81	1/12	4.43	$V_0 = 6.3$ m/s

Table 4.5 - Summary of straight course keeping simulations (ψ_{ref} = 0 deg), when n_0 = 55.443 rpm, u_0 = 10 knots, and δ_ℓ = 35 deg. The duration of each simulation is 2400 s, but the values of m_δ, σ_δ, m_ψ, σ_ψ, and V_ℓ are computed for the part 1200 - 2400 s.

T [m]	Kalman filter estimates used		Non-filtered measurements used		m_δ [deg]	σ_δ [deg]	m_ψ [deg]	σ_ψ [deg]	V_ℓ [deg^2]	λ	Fig.	Remarks
	Self-tuning regulator	PID-regulator	Self-tuning regulator	PID-regulator								
22.3	X				-21.62	19.96	0.66	1.01	1.46	0	4.5	
22.3		X			-20.44	22.44	-0.03	1.54	2.37	0	4.44	
22.3			X		-21.89	27.55	1.25	1.48	3.75	0	4.45	
22.3				X	-18.00	31.25	-0.17	2.05	4.23	0	4.46	
22.3	X				-20.02	24.21	0.83	1.87	4.19	0	4.47	$q_2^* = 3$
22.3		X			-19.55	13.95	-0.19	1.31	1.75	0	4.48	$V_0 = 4$ m/s
10.5	X				-8.93	19.24	0.30	0.61	0.46	0	4.6	
10.5		X			-9.23	22.26	0.05	0.68	0.46	0	4.49	
10.5			X		-9.08	23.44	0.38	0.82	0.82	0	4.50	
10.5				X	-9.31	31.12	0.03	1.21	1.47	0	4.51	
10.5	X				-8.47	13.73	-0.48	1.41	2.22	0	4.52	$q_2^* = 3$
10.5		X			-7.83	12.05	-0.04	1.24	1.54	0	4.53	$V_0 = 4$ m/s

Table 4.6 - Summary of straight course keeping simulations (ψ_{ref} = 0 deg), when n_0 = 22.1772 rpm, u_0 = 4 knots, and δ_ℓ = 45 deg. The duration of each simulation is 2400 s, but the values of m_δ, σ_δ, m_ψ, σ_ψ, and V_ℓ are computed for the part 1200 - 2400 s.

The simulations show that 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. This is true for each of the three different initial speeds. When Kalman filter estimates are used, the performance of the self-tuning regulator is significantly better than the performance of the PID-regulator in full load condition (T = 22.3 m). However, when T = 10.5 m, the difference between the two regulators is hardly noticable. When non-filtered measurements are used, a comparison between the self-tuning regulator and the PID-regulator is rather confusing; sometimes the self-tuning regulator is to prefer in front of the PID--regulator and sometimes vice versa. However, the performance of the self-tuning regulator seems to be somewhat better compared to the PID-regulator when T = 22.3 m. It can also be concluded that the self-tuning regulator using Kalman filter estimates always is significantly better than the PID-regulator using non-filtered measurements, and that the PID-regulator using Kalman filter estimates always is significantly better than the self-tuning regulator using non-filtered measurements.

In general, the rudder deviations are decreased when the speed scaling V_0/V_s is used instead of $(V_0/V_s)^2$. When u_0 = 10 knots, the speed scaling V_0/V_s is to prefer if T = 10.5 m, but the speed scaling $(V_0/V_s)^2$ is to prefer if T = 22.3 m. When u_0 = 4 knots, the speed scaling $(V_0/V_s)^2$, with one exception, is preferable.

The final parameter values of the self-tuning regulator for all the simulations presented in Sections 4.1 and 4.2 are shown in Table 4.7. It can be concluded that the values don't change very much when the speed and the draught are changed.

Fig.	a_1	a_2	a_3	a_4	b_1	b_2	c_1	c_2	$\Sigma\ a_i$
4.1	-6.53	5.67	3.43	-2.56	0.50	0.15	-1.65	36.28	0.01
4.2	-6.93	5.70	3.58	-2.97	0.53	0.20	-1.64	34.93	-0.62
4.3	-6.49	5.76	3.61	-2.94	0.47	0.12	-2.08	38.72	-0.06
4.4	-6.28	5.61	3.45	-2.90	0.53	0.20	-1.60	33.07	-0.12
4.5	-6.34	5.31	4.01	-3.24	0.36	-0.01	-3.42	43.48	-0.26
4.6	-5.60	5.11	3.79	-3.37	0.51	0.11	-2.56	35.57	-0.07
4.7	-5.32	3.33	3.83	-2.29	0.08	-0.04	-4.32	67.13	-0.45
4.8	-7.26	6.10	4.11	-3.01	0.53	0.18	-2.07	37.39	-0.06
4.9	-7.20	5.95	4.06	-2.96	0.52	0.18	-2.36	35.55	-0.15
4.10	-6.20	5.46	2.80	-2.02	0.48	0.23	-1.97	42.28	0.04
4.11	-6.53	5.69	3.46	-2.55	0.50	0.16	-1.69	35.92	0.07
4.12	-12.15	13.10	2.62	-4.14	0.83	0.22	-	-	-0.57
4.13	-10.68	11.86	2.18	-3.63	0.86	0.28	-	-	-0.27
4.14	-11.18	12.08	1.01	-2.77	0.62	-0.02	-	-	-0.86
4.15	-14.45	15.38	4.81	-5.94	0.47	0.10	-	-	-0.20
4.16	-13.80	15.07	5.55	-6.78	0.54	0.06	-	-	0.04
4.17	-12.66	12.82	5.84	-5.88	0.61	0.15	-	-	0.12
4.18	-12.76	17.64	-3.86	-1.75	0.09	0.23	-	-	-0.73
4.19	-12.31	11.34	6.77	-5.95	0.52	0.09	-	-	-0.15
4.20	-11.43	11.22	6.52	-6.29	0.55	0.05	-	-	0.02
4.21	-9.91	9.11	6.43	-5.67	0.53	0.03	-	-	-0.04
4.22	-9.47	9.67	3.55	-4.42	0.15	0.27	-	-	-0.67
4.23	-9.24	10.28	2.30	-3.86	0.26	0.20	-	-	-0.52
4.24	-9.62	10.96	2.09	-3.97	0.38	0.19	-	-	-0.54
4.25	-8.08	8.55	2.24	-3.24	-0.14	0.33	-	-	-0.53
4.26	-7.57	5.76	3.81	-2.39	0.47	0.15	-1.32	36.42	-0.39
4.27	-6.19	5.42	3.26	-2.81	0.52	0.19	-2.09	35.16	-0.32
4.29	-8.21	9.19	2.44	-3.46	0.04	0.17	-	-	-0.04
4.32	-6.75	7.14	1.31	-1.84	0.09	0.27	-	-	-0.14
4.35	-7.66	8.77	2.25	-3.46	0.07	0.18	-	-	-0.10
4.37	-4.63	3.26	3.31	-2.00	0.45	0.07	-1.25	22.26	-0.06
4.40	-6.16	6.76	1.02	-1.71	0.08	0.29	-	-	-0.09
4.42	-3.63	2.94	2.47	-1.84	0.52	0.09	-0.64	12.48	-0.06
4.45	-8.35	9.41	1.83	-3.31	0.04	0.19	-	-	-0.42
4.47	-4.61	1.90	3.01	-0.66	0.53	0.20	-2.54	28.74	-0.36
4.50	-6.38	8.24	0.59	-2.56	0.22	0.31	-	-	-0.11
4.52	-3.46	1.72	2.61	-1.01	0.64	0.25	-2.87	21.31	-0.14

Table 4.7 - Final parameter values of the self-tuning regulator.

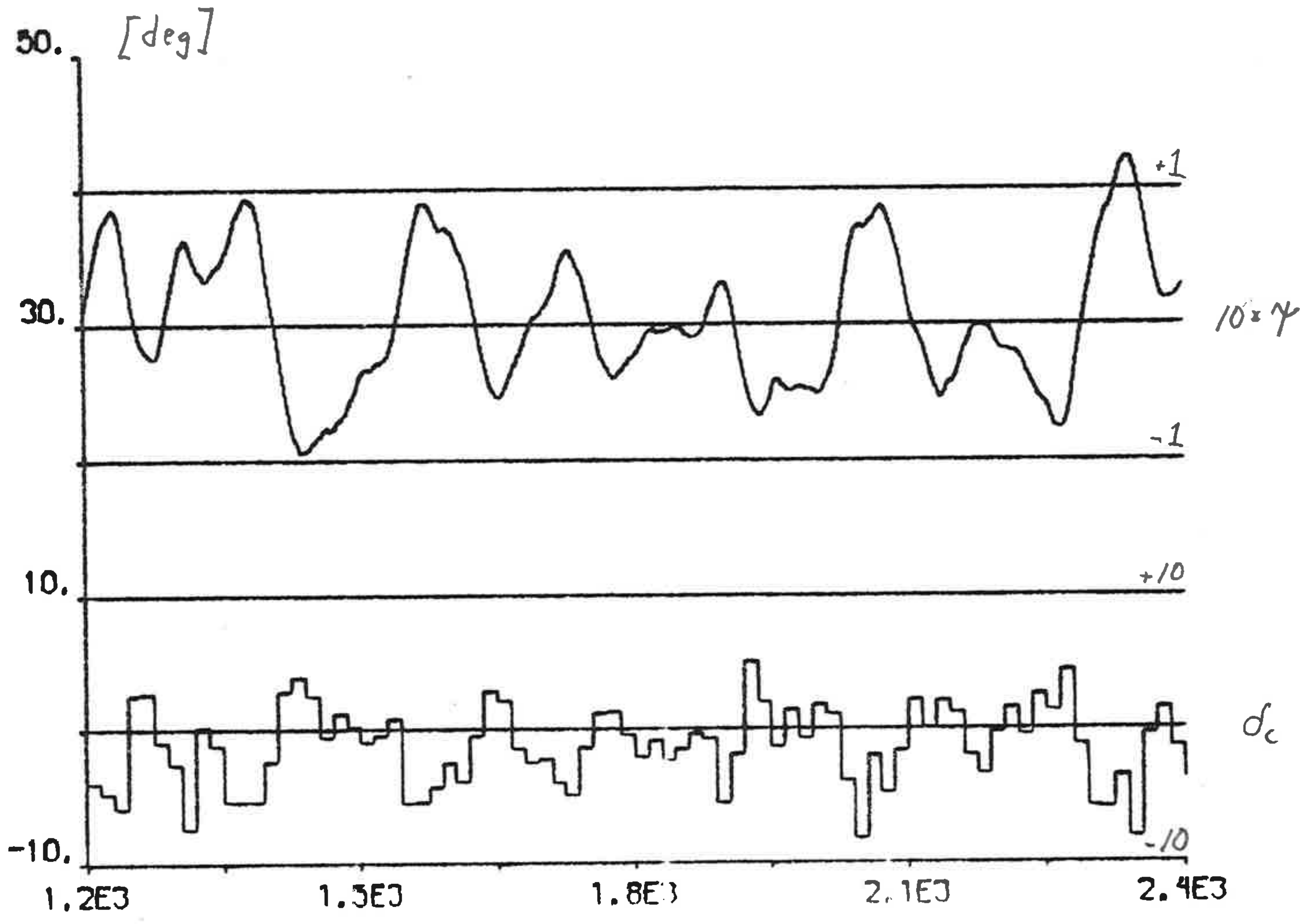


Fig. 4.12 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 4, T_s = 15 s, q_2^* = 0, V_c = 8 m/s).

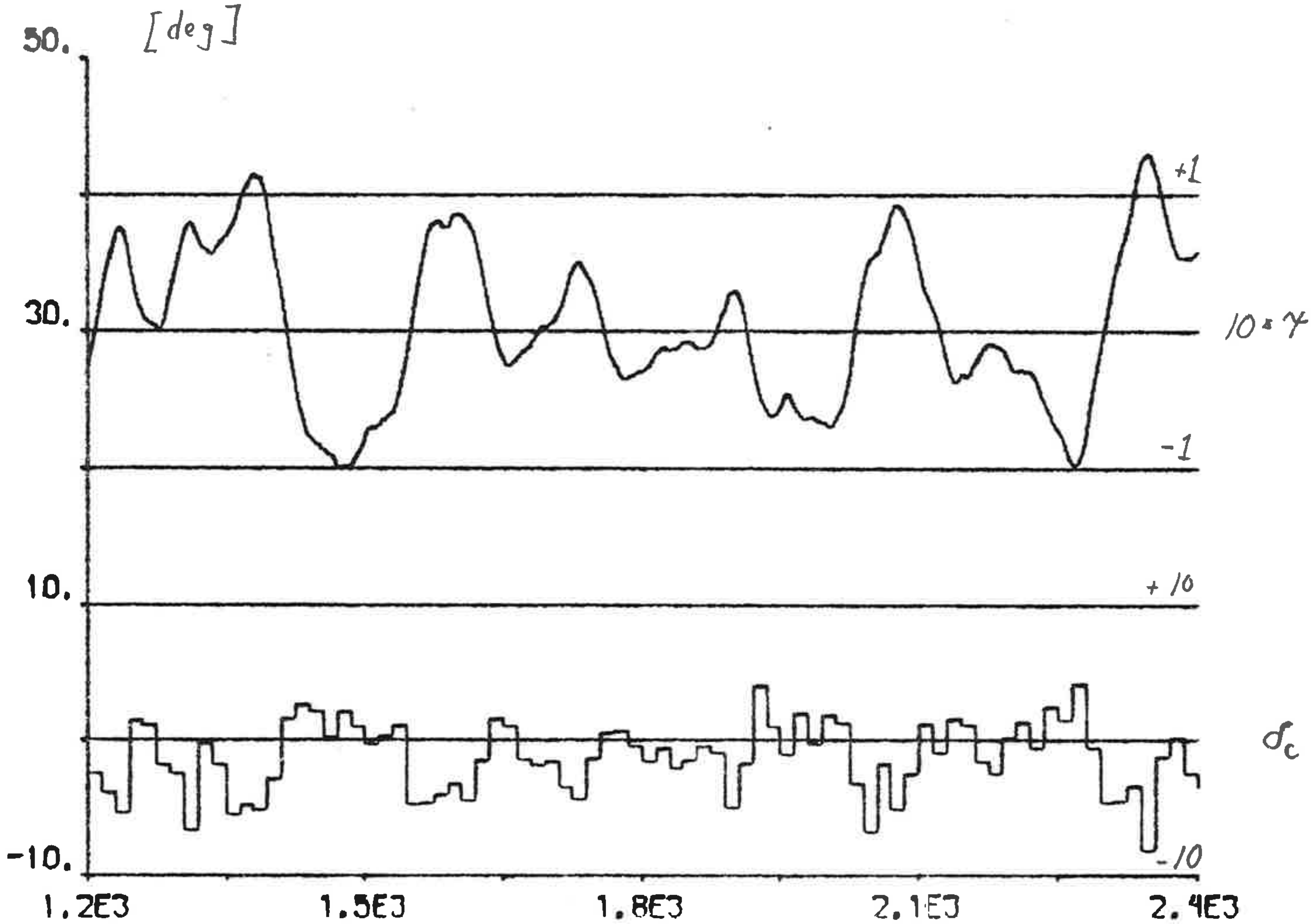


Fig. 4.13 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 5, T_s = 15 s, q_2^* = 0, V_c = 8 m/s).

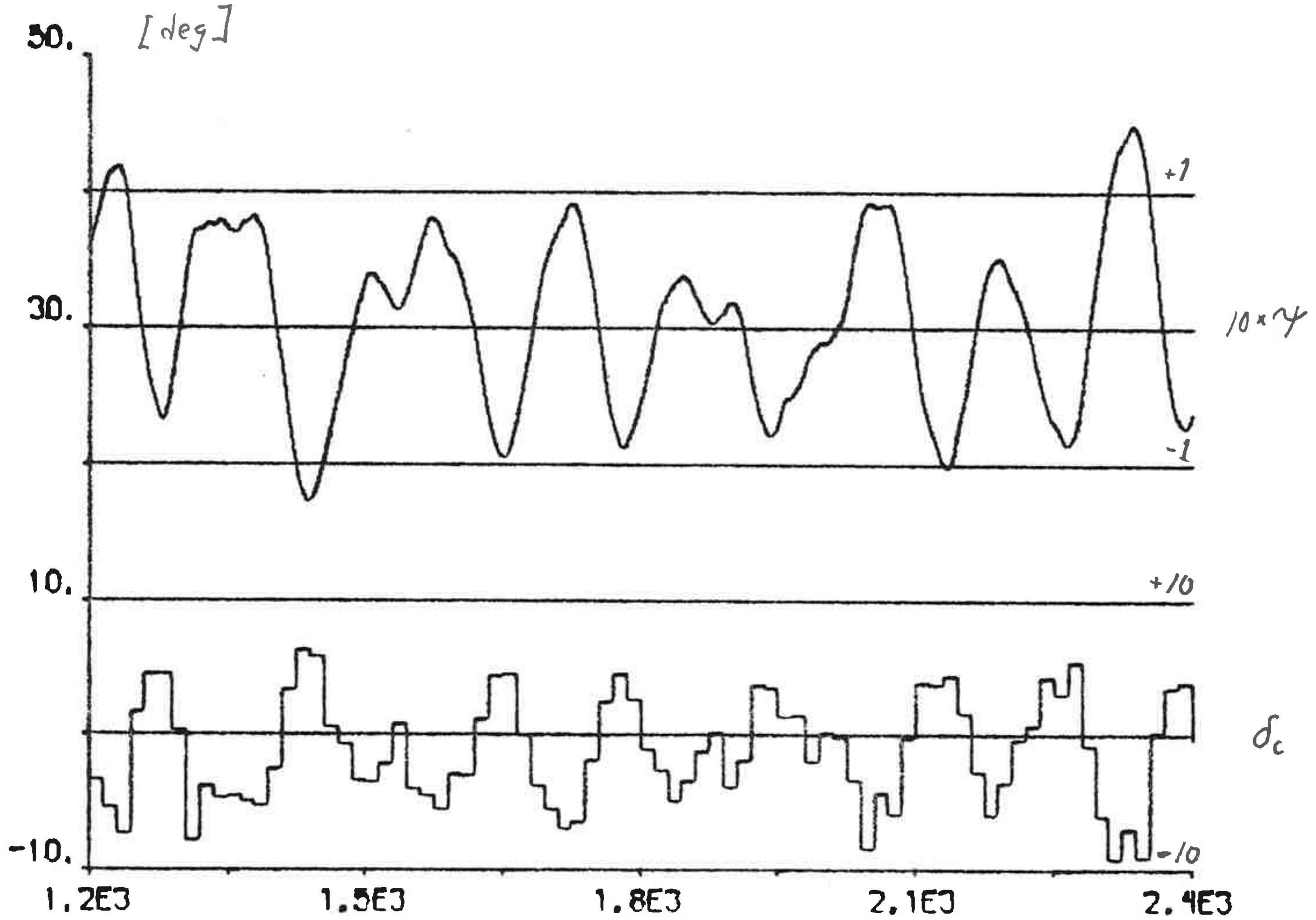


Fig. 4.14 - T = 22.3 m, $n_0 = 87.6$ rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 6, T_s = 15 s, $q_2^* = 0$, V_c = 8 m/s).

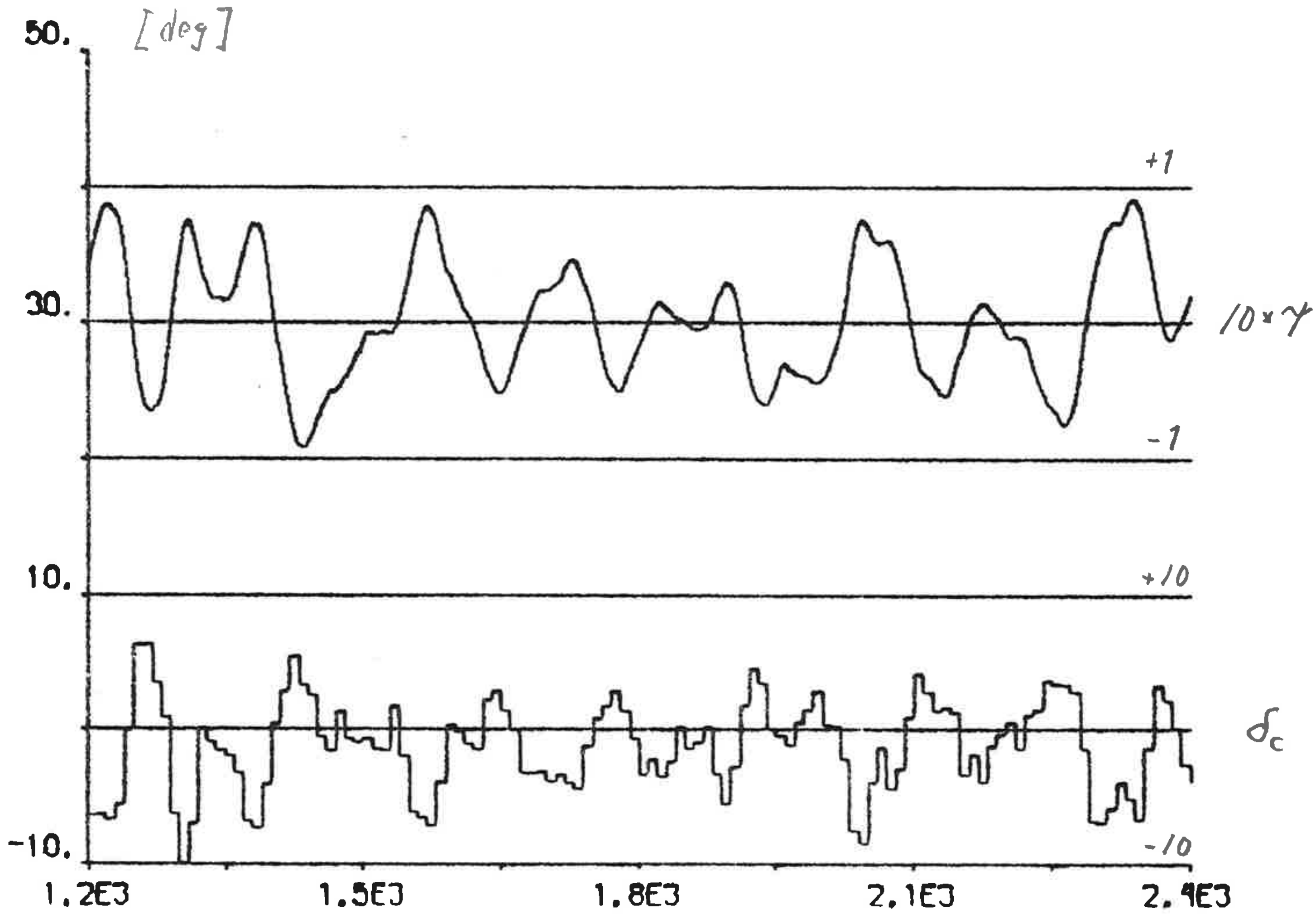


Fig. 4.15 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 5, T_s = 10 s, q_2^* = 0, V_c = 8 m/s).

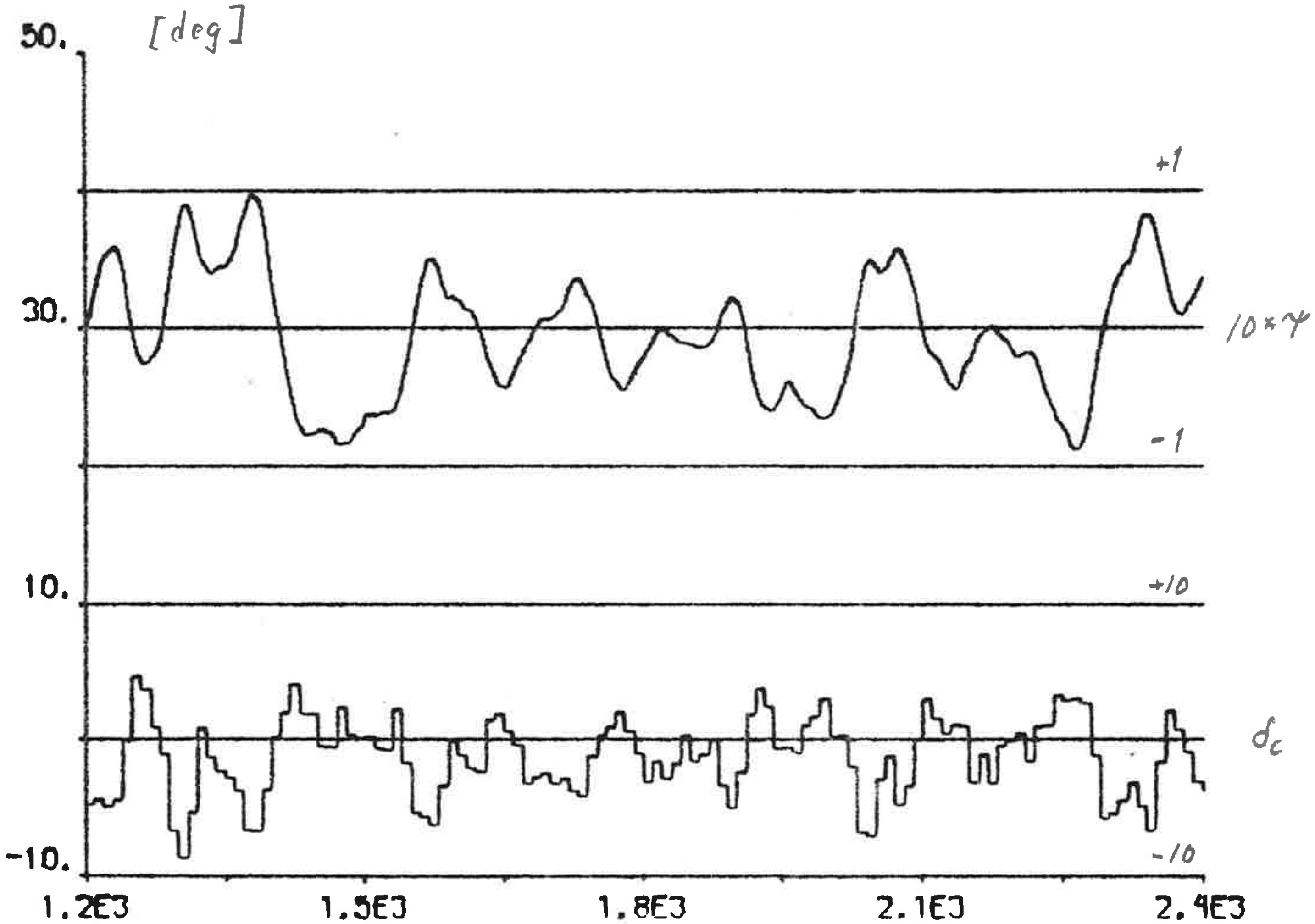


Fig. 4.16 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 6, T_s = 10 s, q_2^* = 0, V_c = 8 m/s).

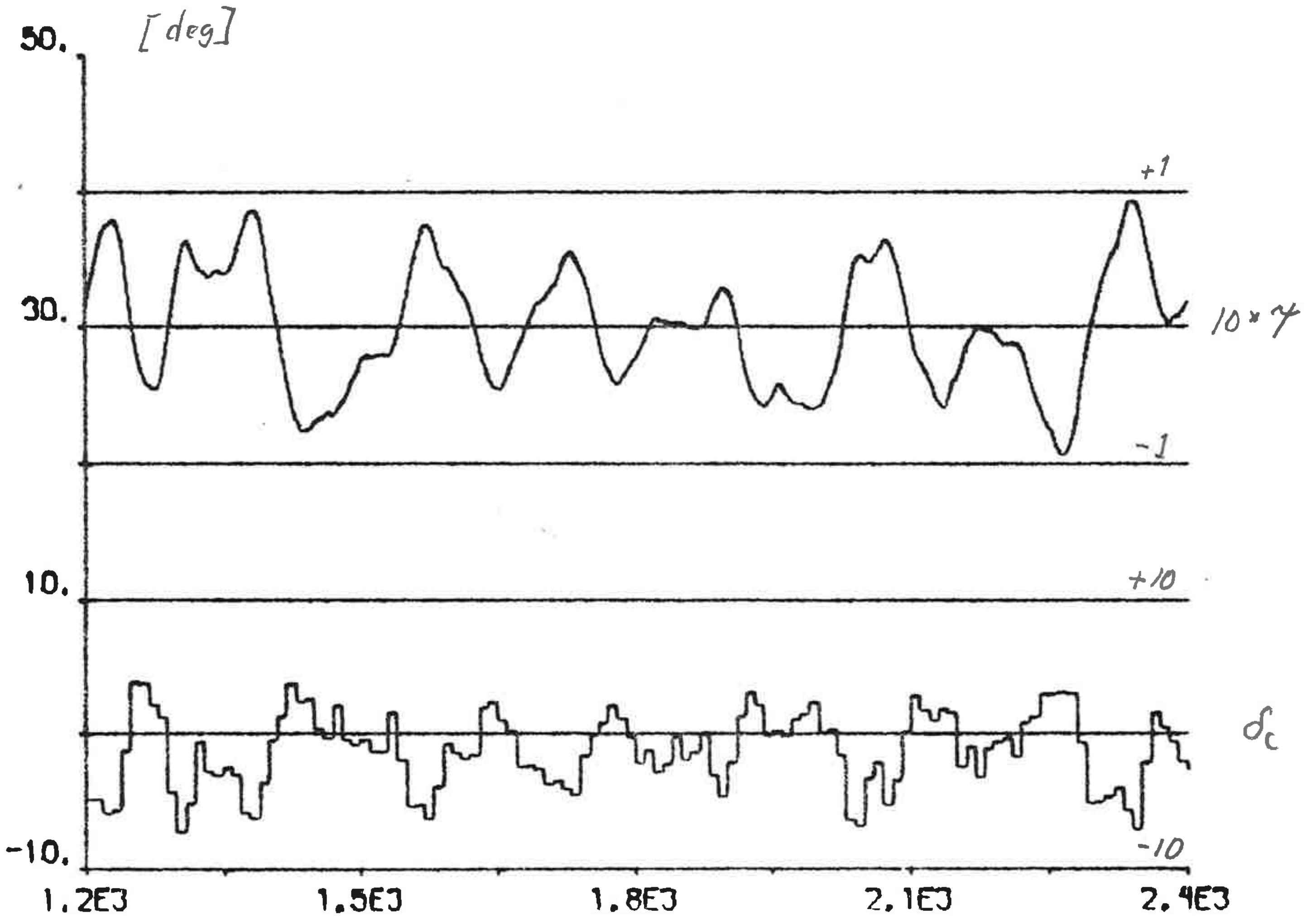


Fig. 4.17 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 7, T_s = 10 s, q_2^* = 0, V_c = 8 m/s).

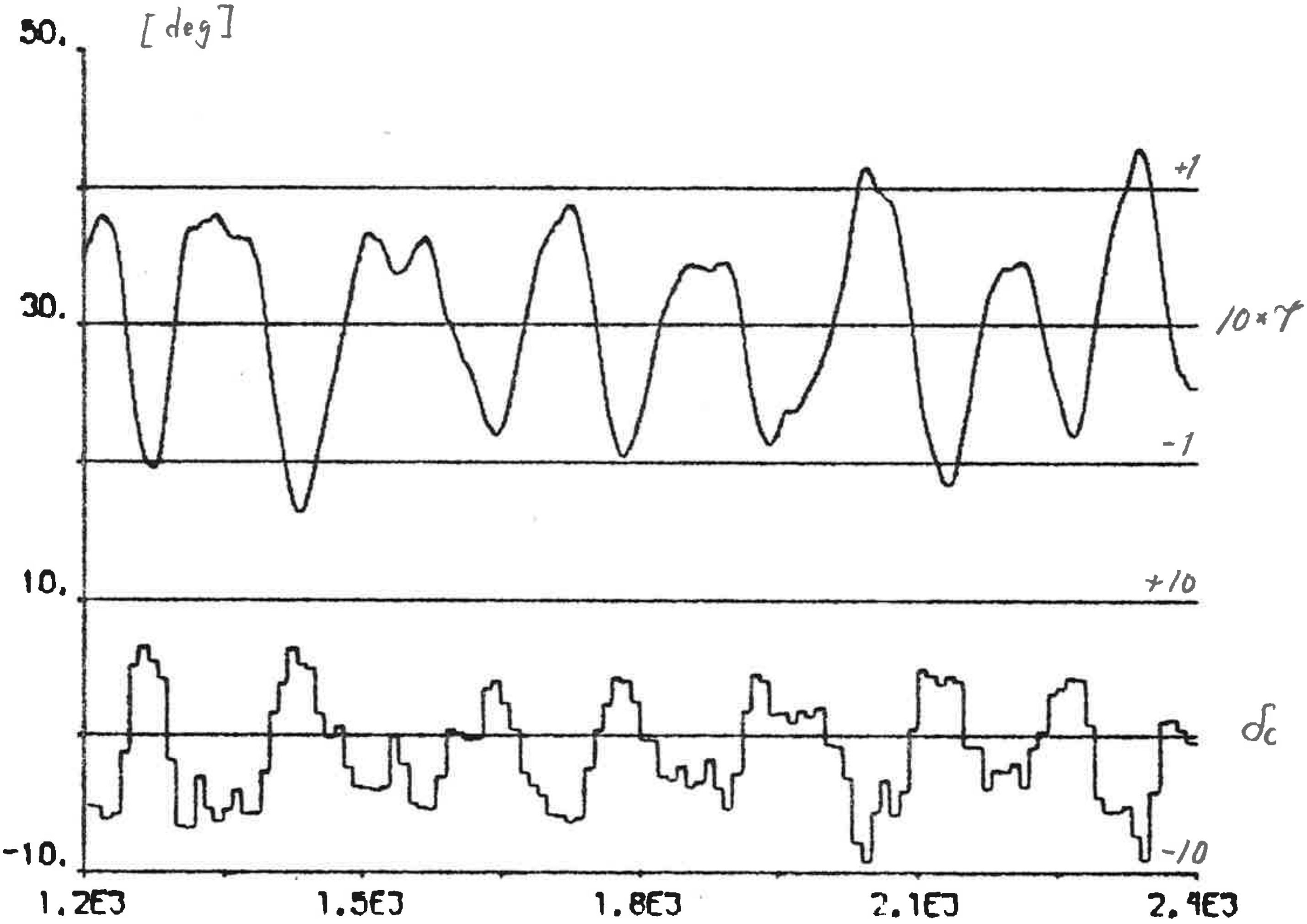


Fig. 4.18 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 8, T_s = 10 s, q_2^* = 0, V_c = 8 m/s).

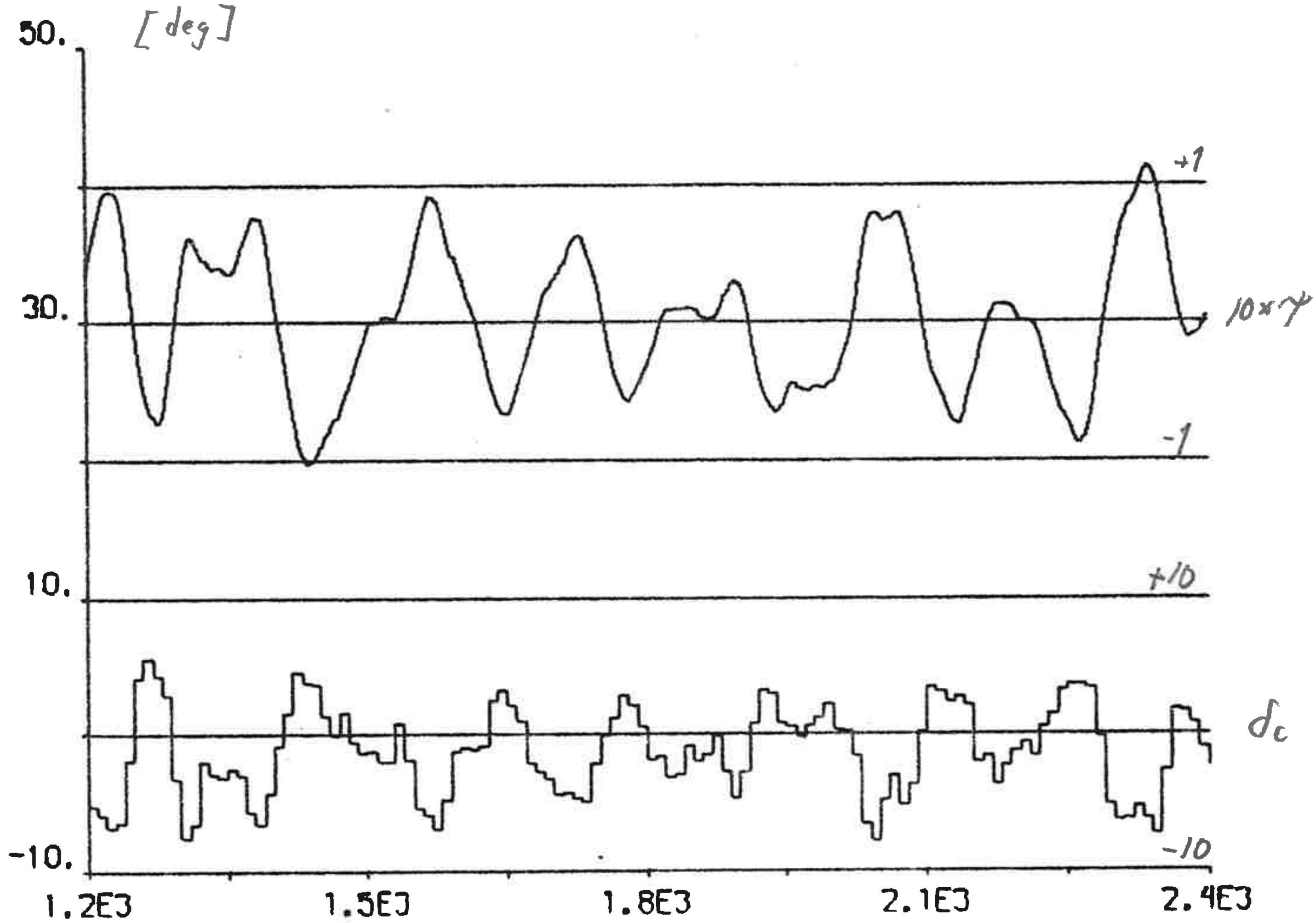


Fig. 4.19 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 5, T_s = 10 s, q_2^* = 0.05, V_c = 8 m/s).

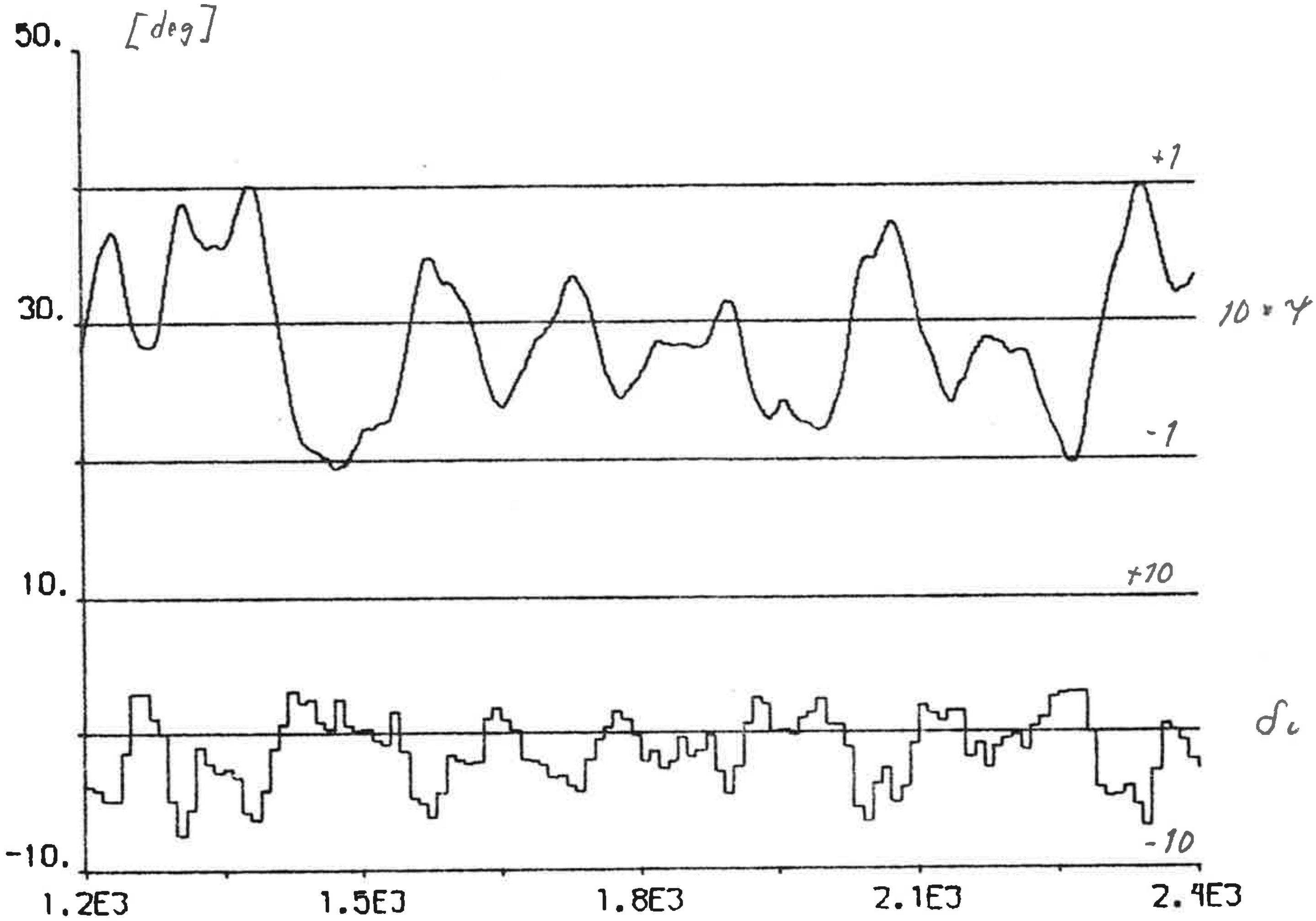


Fig. 4.20 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 6, T_s = 10 s, q_2^* = 0.05, V_c = 8 m/s).

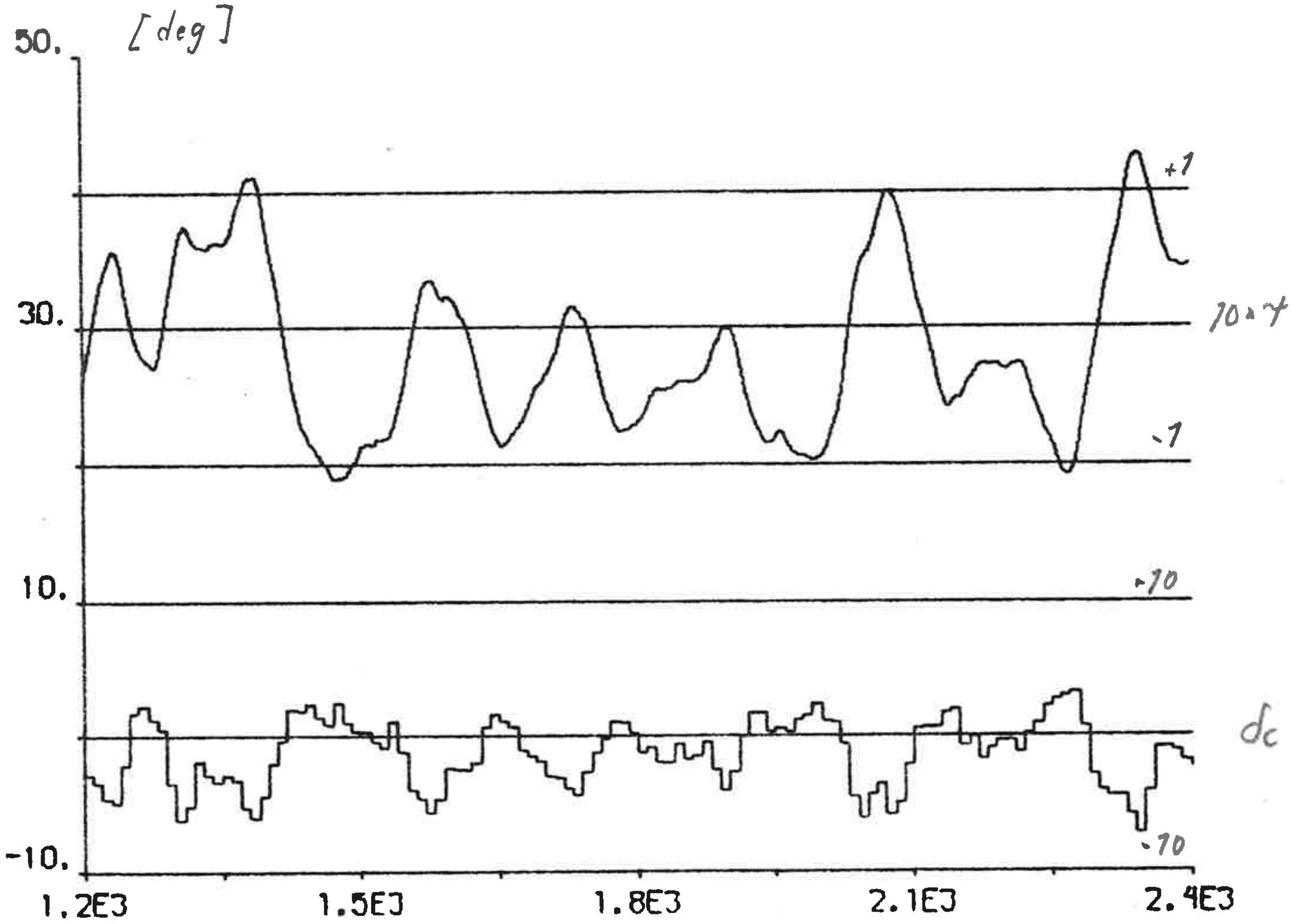


Fig. 4.21 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements (k = 6, T_s = 10 s, q_2^* = 0.1, V_c = 8 m/s).

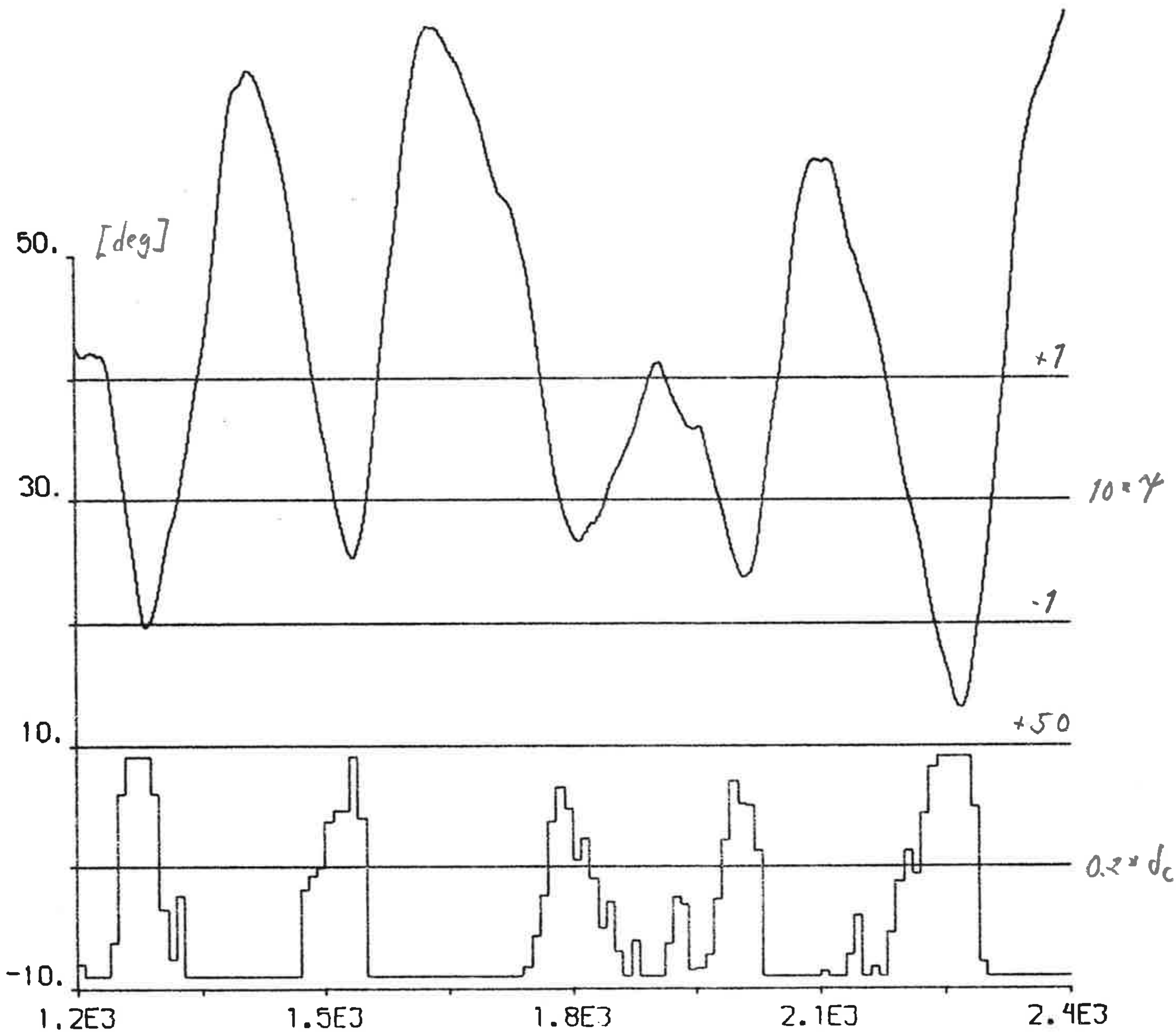


Fig. 4.22 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using non-filtered measurements (k = 6, T_s = 10 s, q_2^* = 0, V_c = 2 m/s).

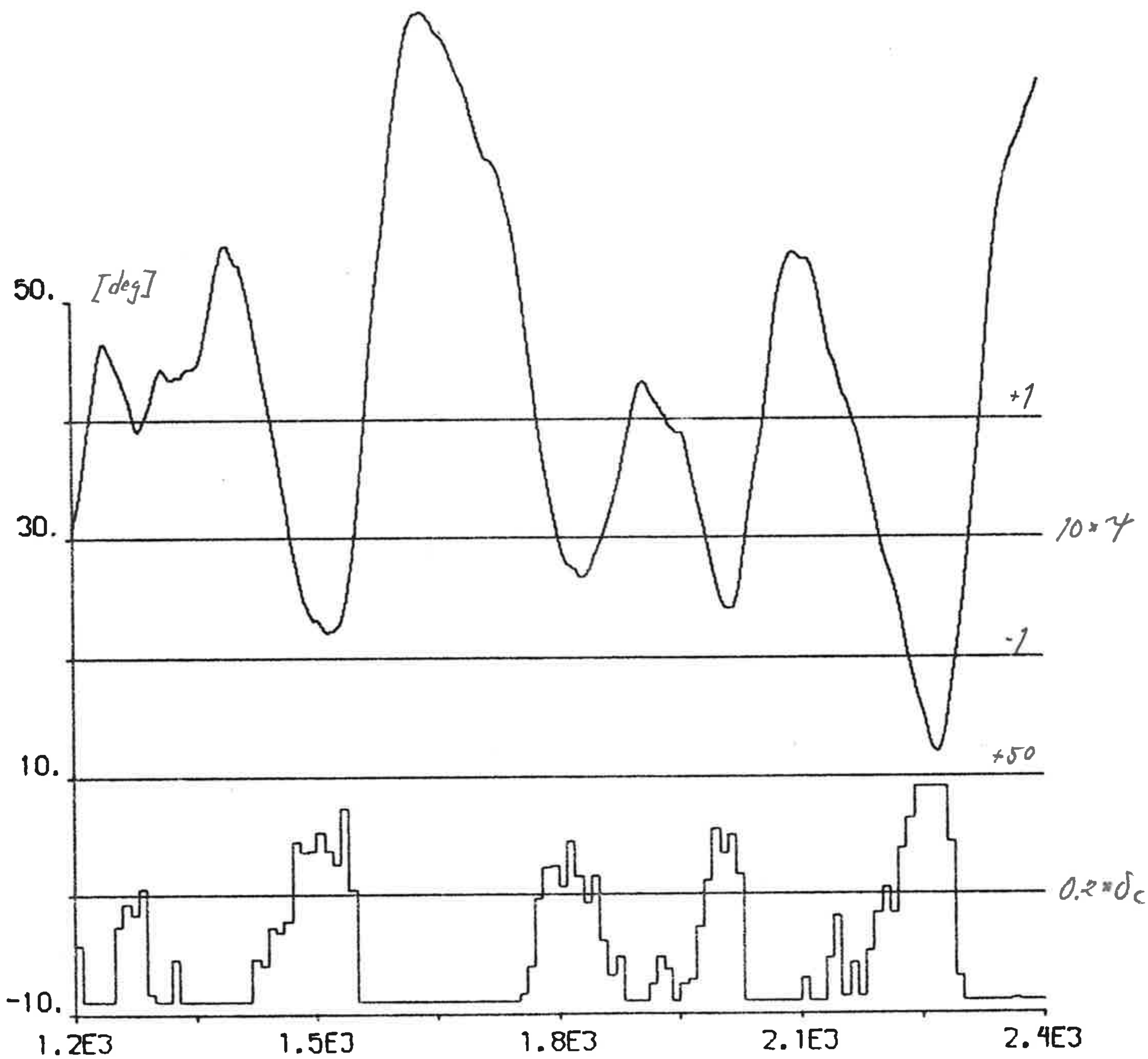


Fig. 4.23 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using non-filtered measurements (k = 7, T_s = 10 s, q_2^* = 0, V_c = 2 m/s).

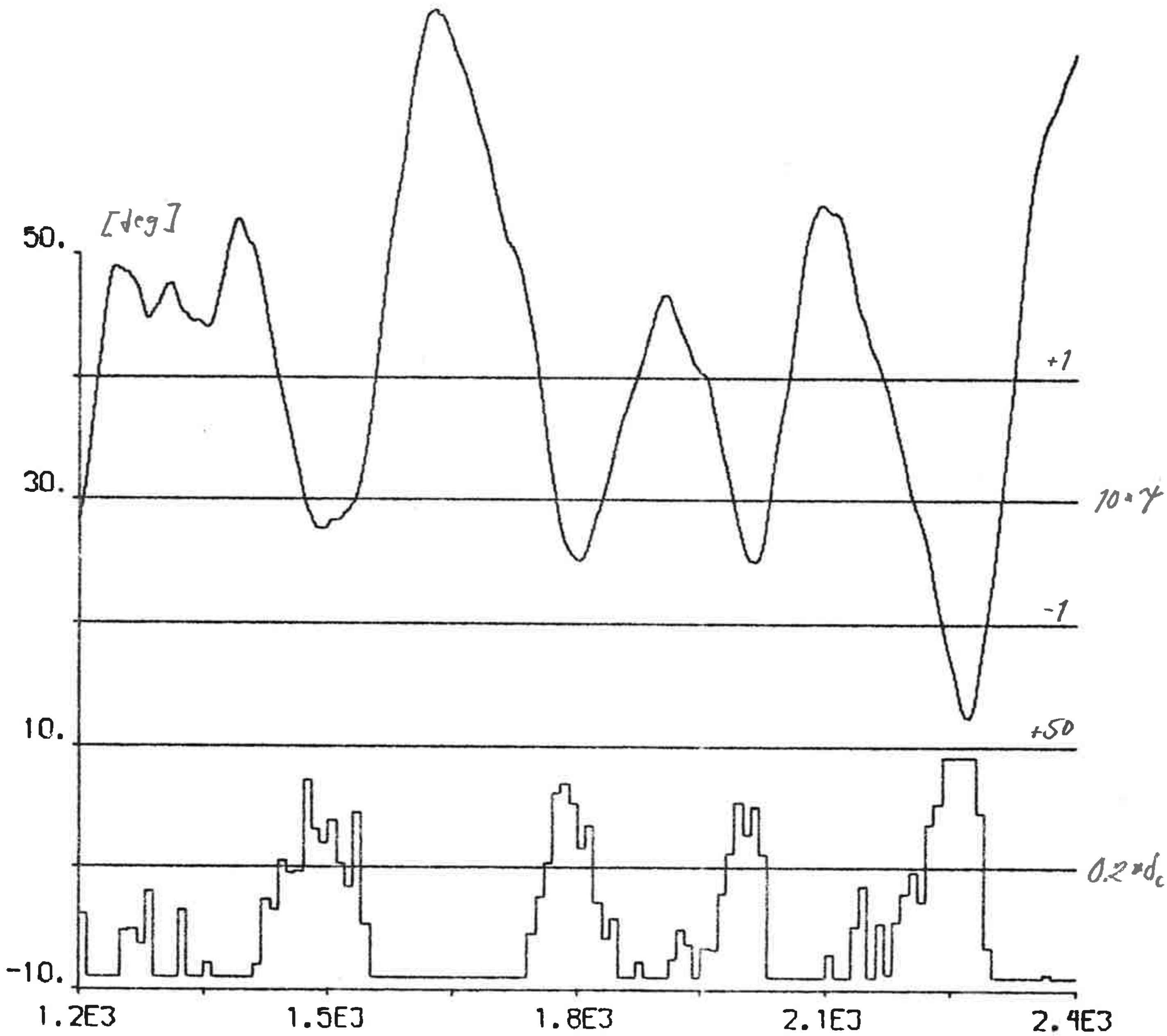


Fig. 4.24 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using non-filtered measurements (k = 8, T_s = 10 s, q_2^* = 0, V_c = 2 m/s).

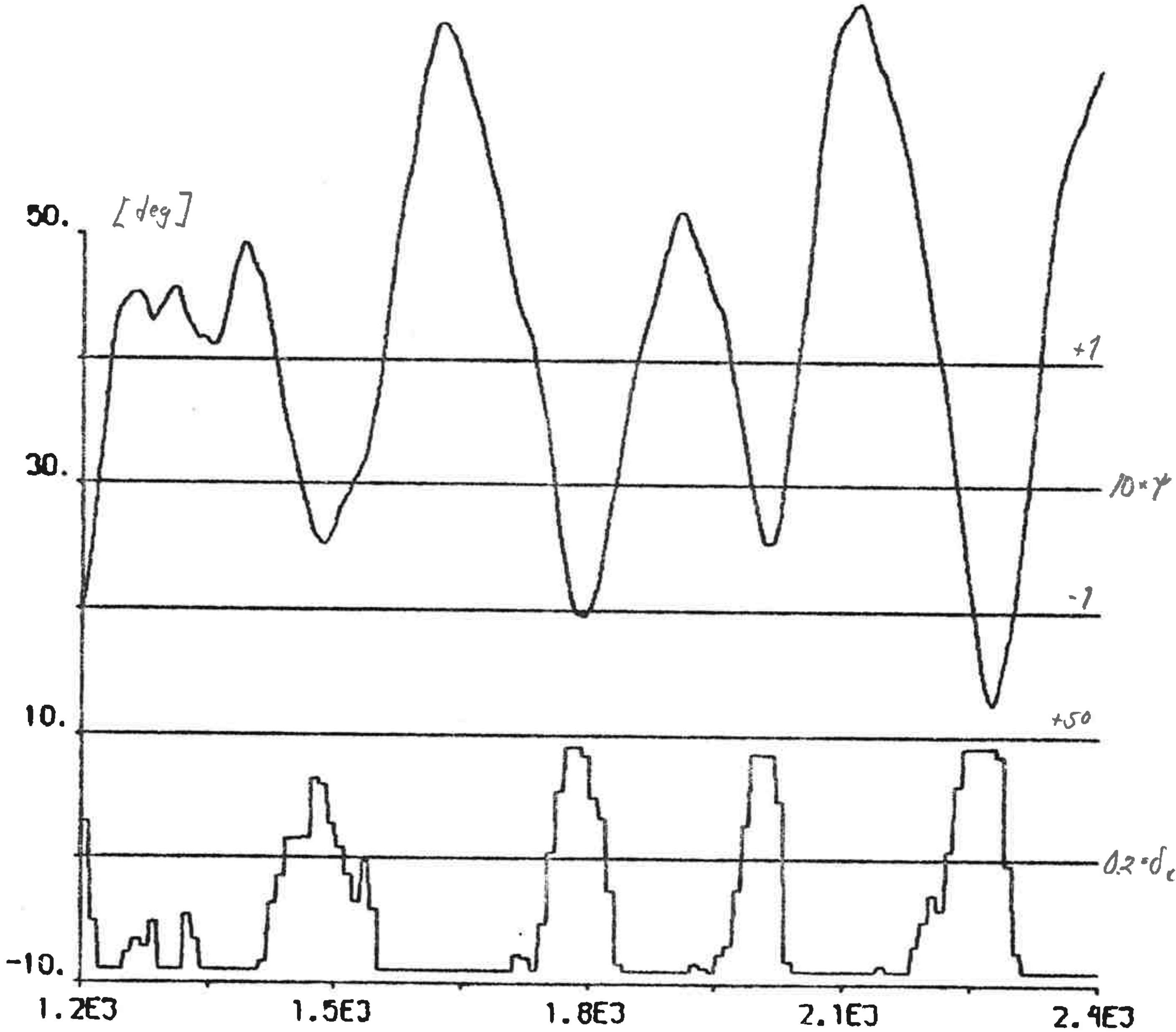


Fig. 4.25 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using non-filtered measurements (k = 6, T_s = 10 s, q_2^* = 0.05, V_c = 2 m/s).

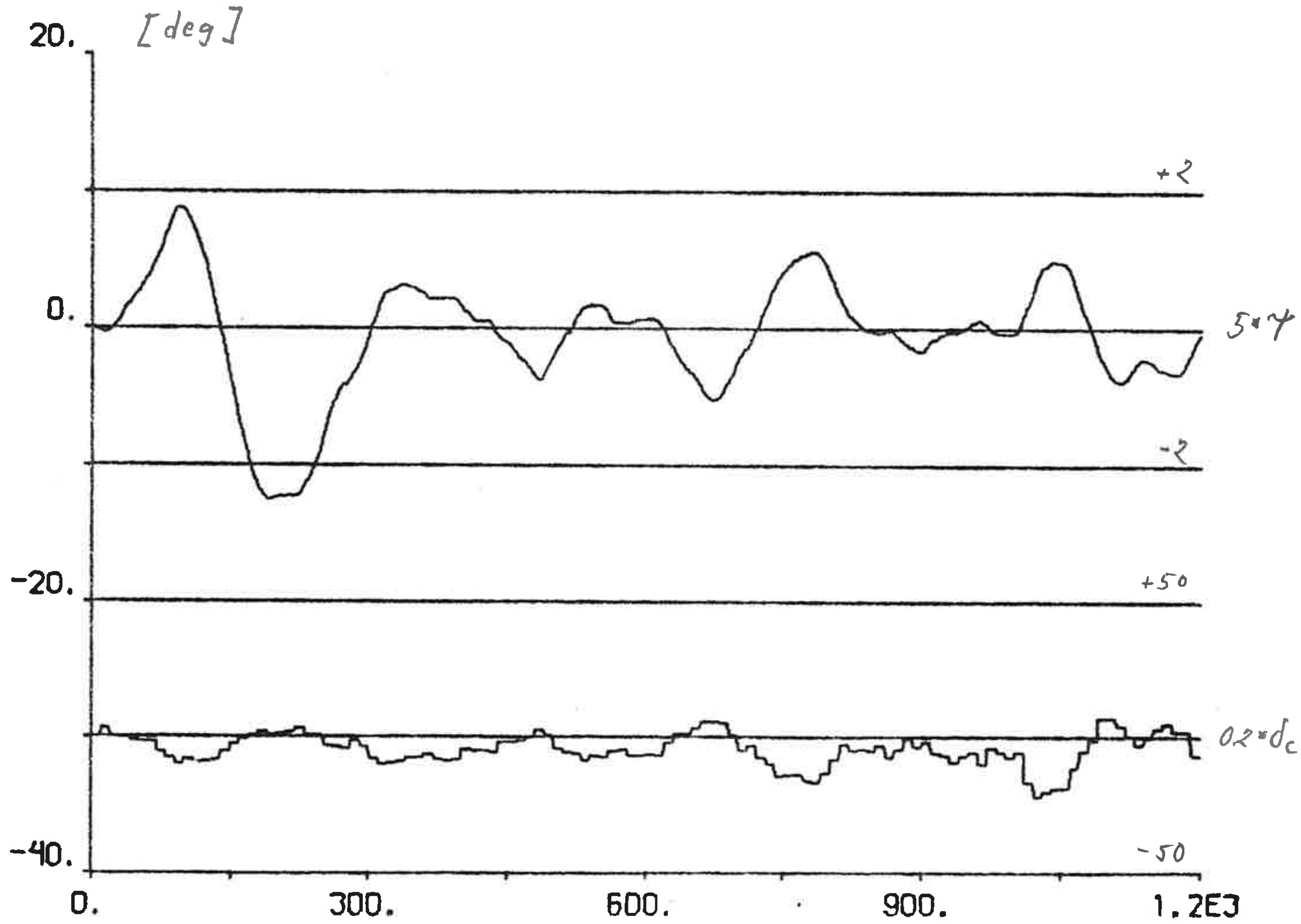
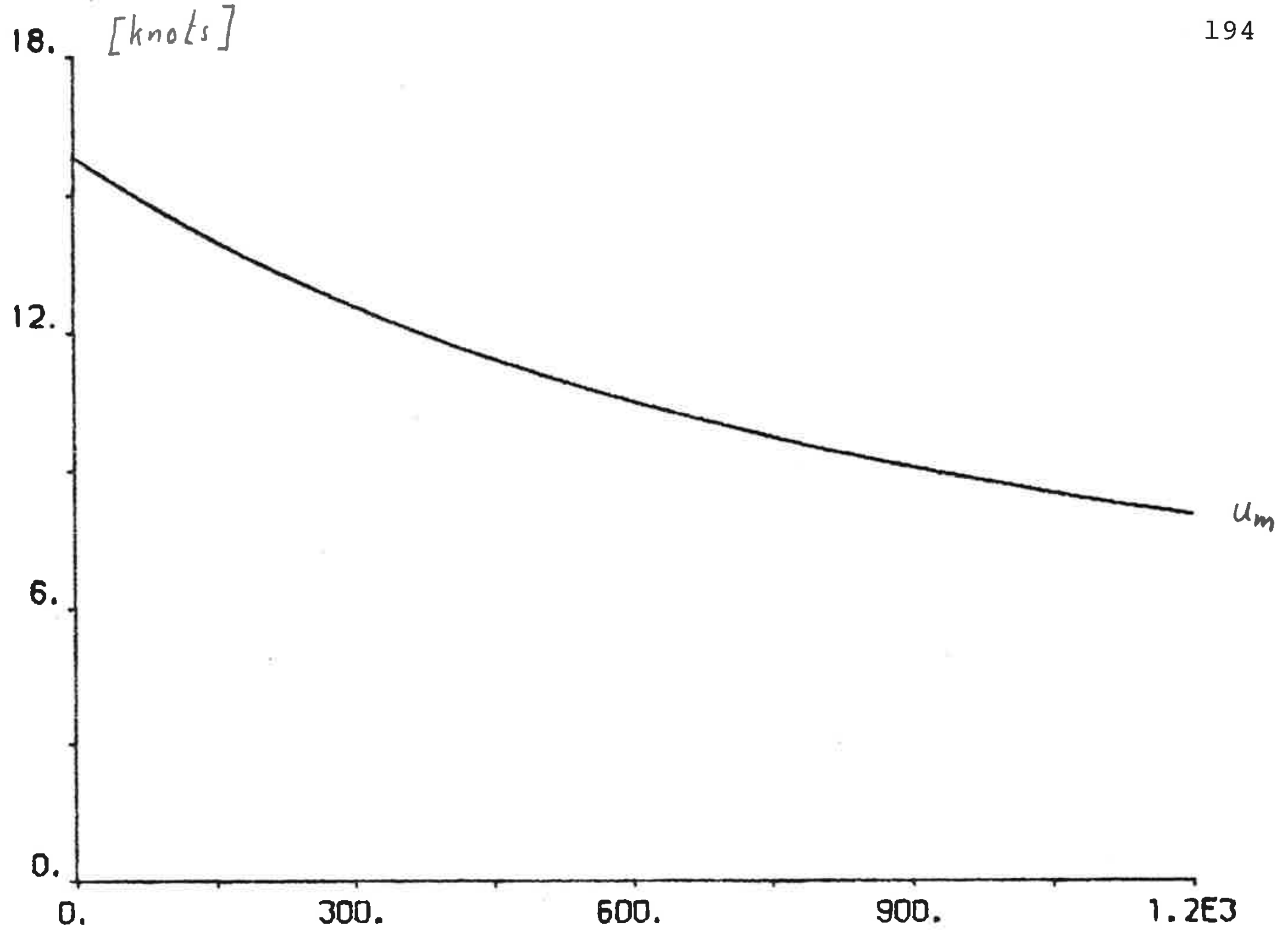
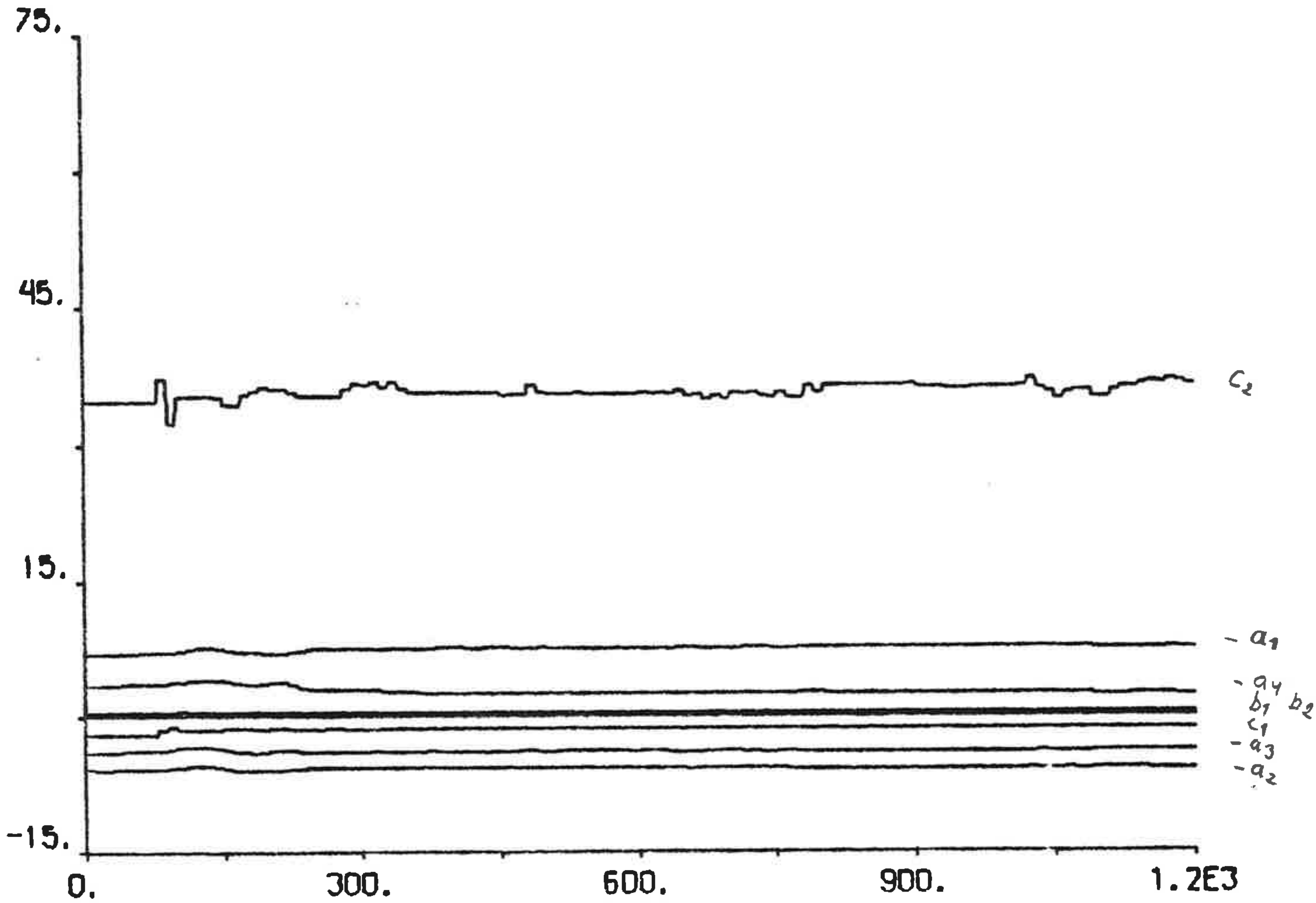


Fig. 4.26 a - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 15.8 knots, δ_ℓ = 45 deg, self-tuning regulator using estimates from the Kalman filter.



[knots]
18.
12.
6.
0.
0.
300.
600.
900.
1.2E3
u_m



75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$

Fig. 4.26 b

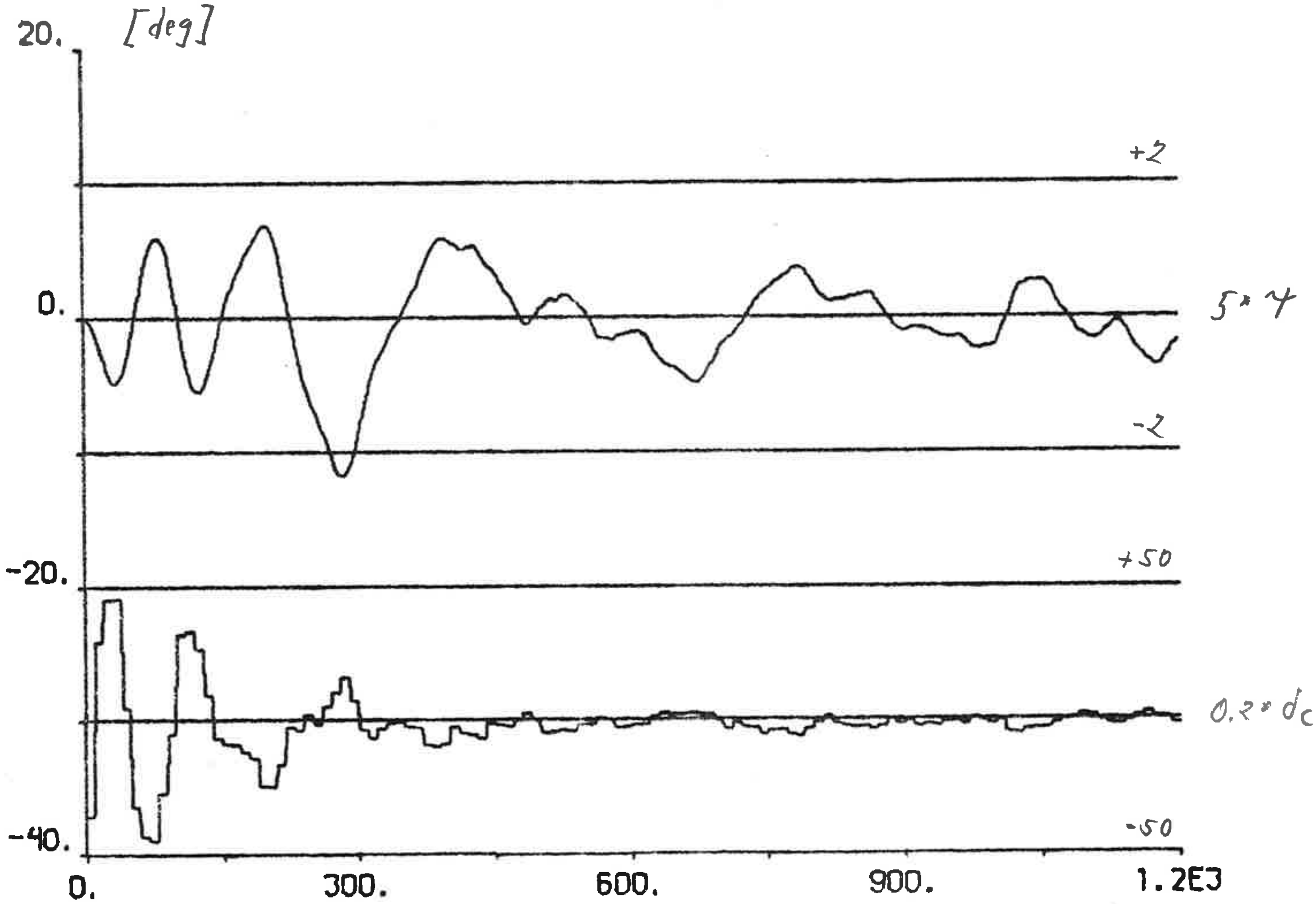
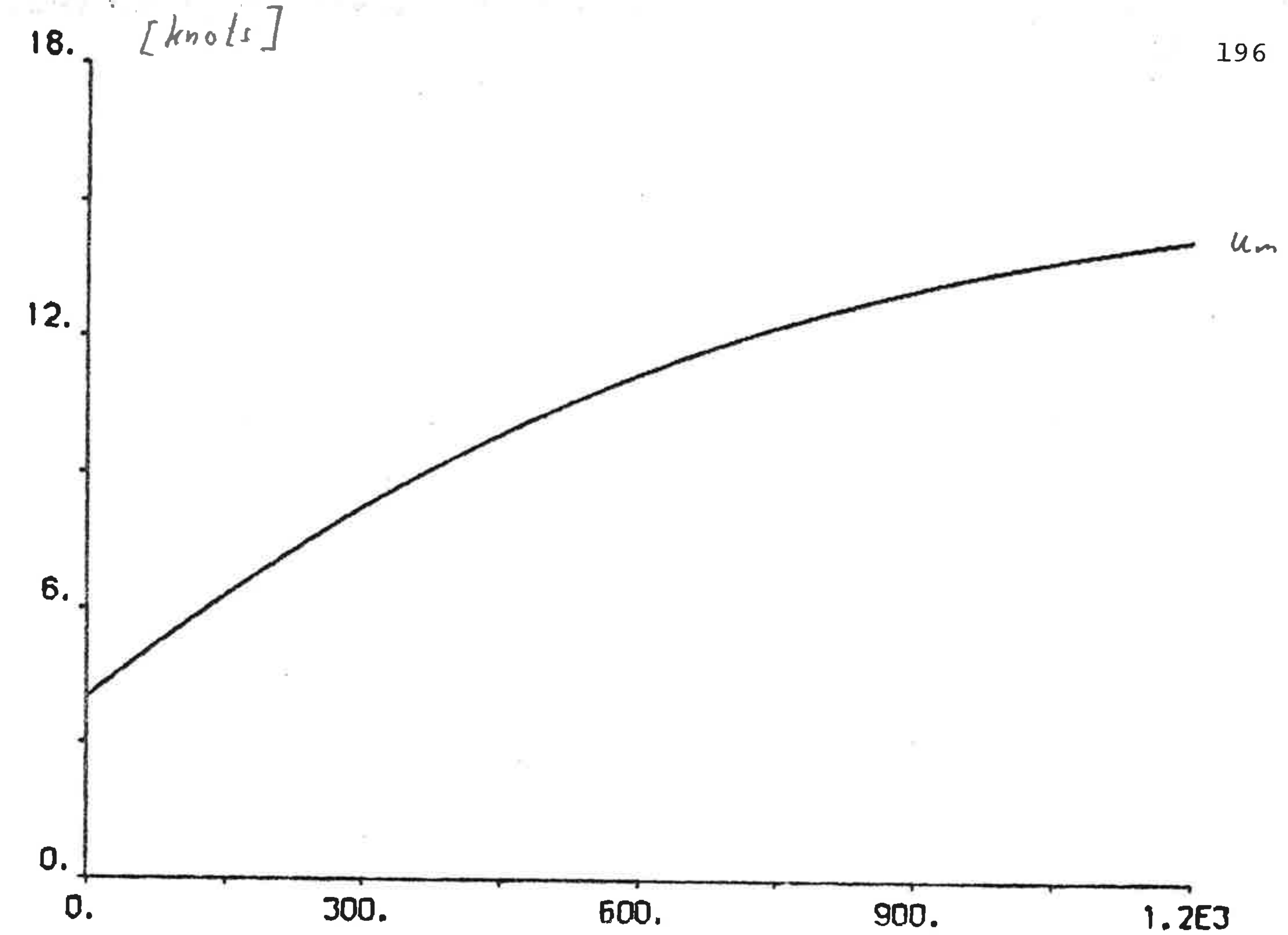
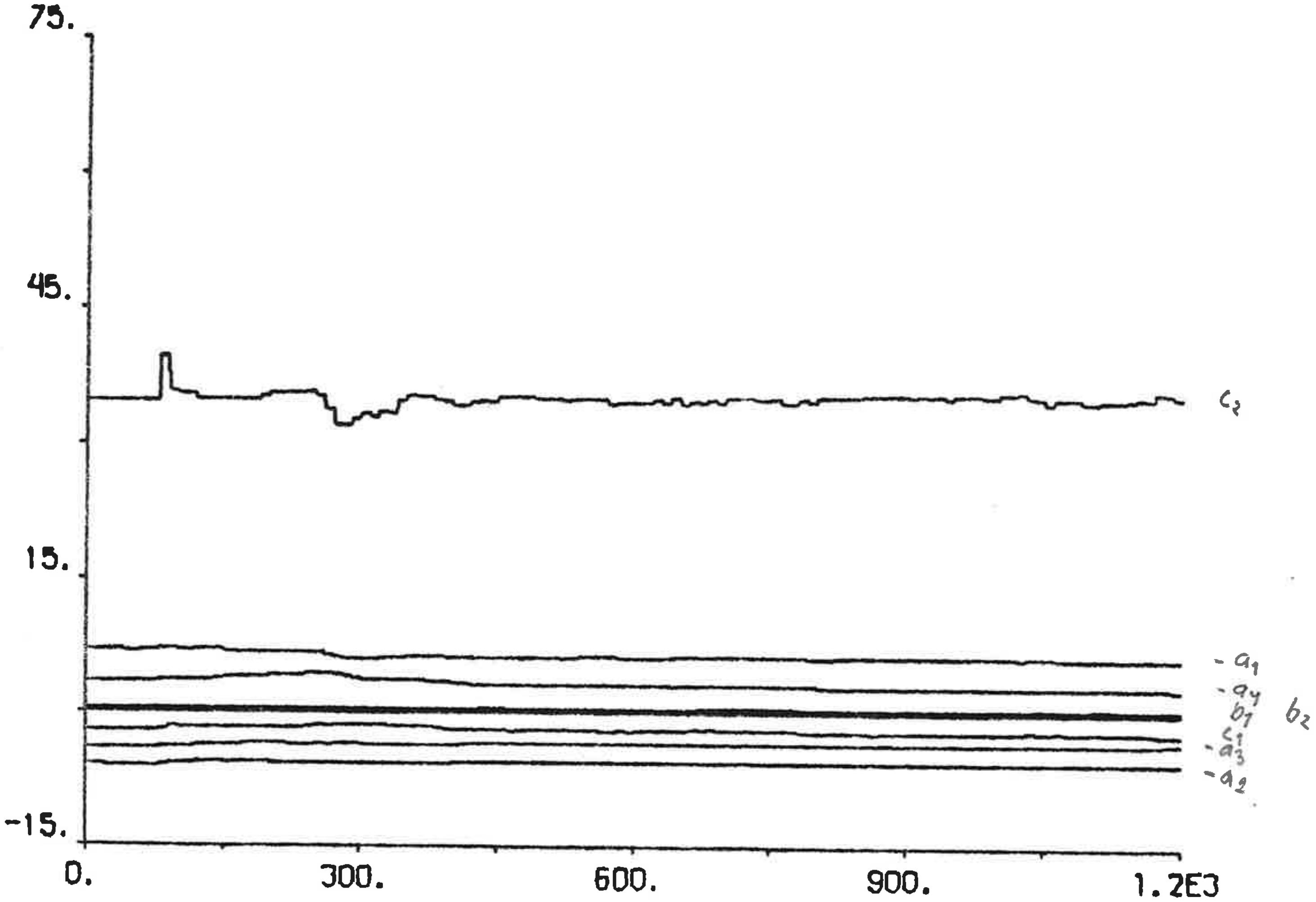


Fig. 4.27 a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using estimates from the Kalman filter.



[knots]
18.
12.
6.
0.
0.
300.
600.
900.
1.2E3
um



75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c2
-a1
-a4
b1
b2
c1
-a3
-a2

Fig. 4.27 b

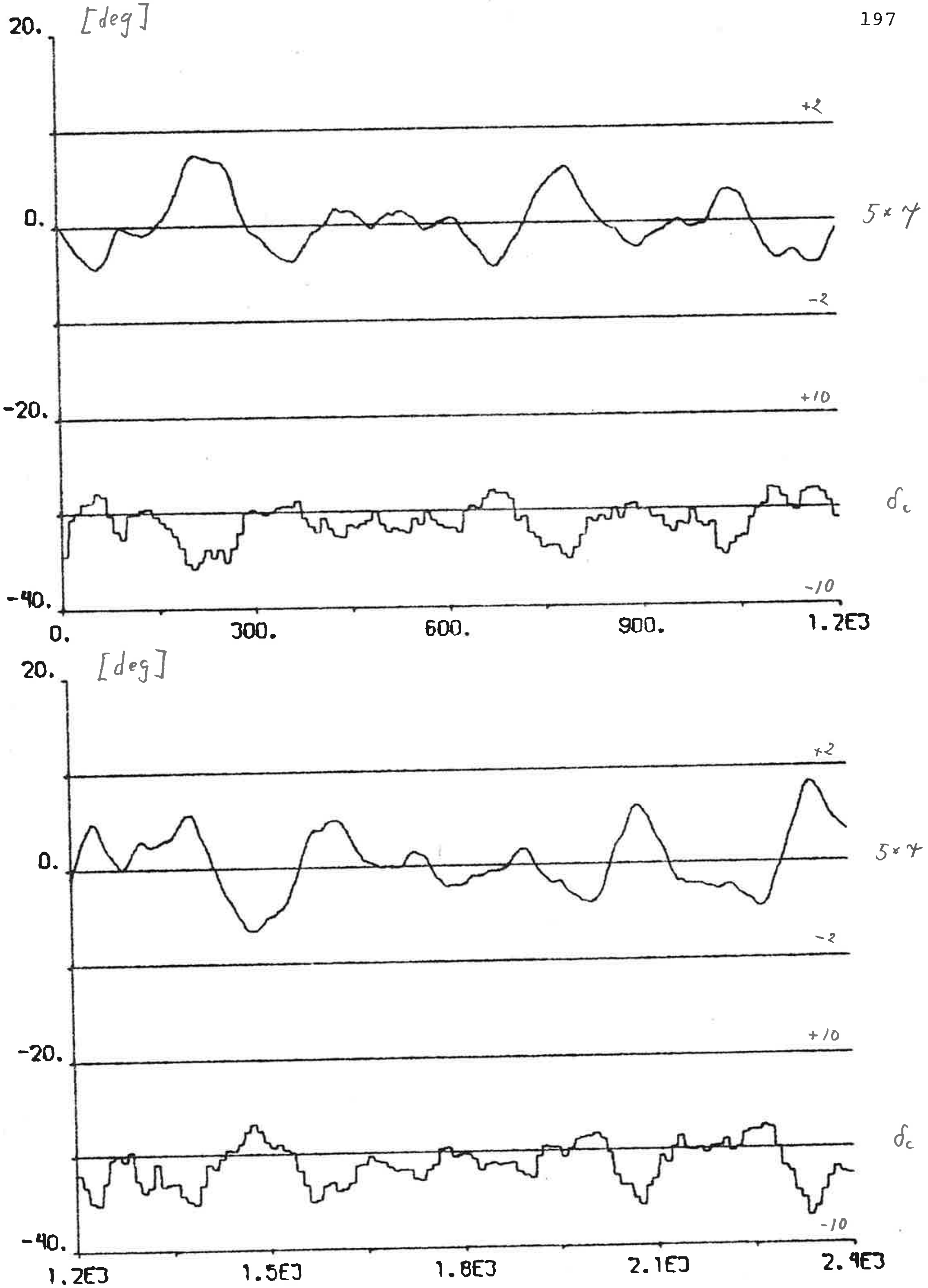


Fig. 4.28 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, PID-regulator using estimates from the Kalman filter.

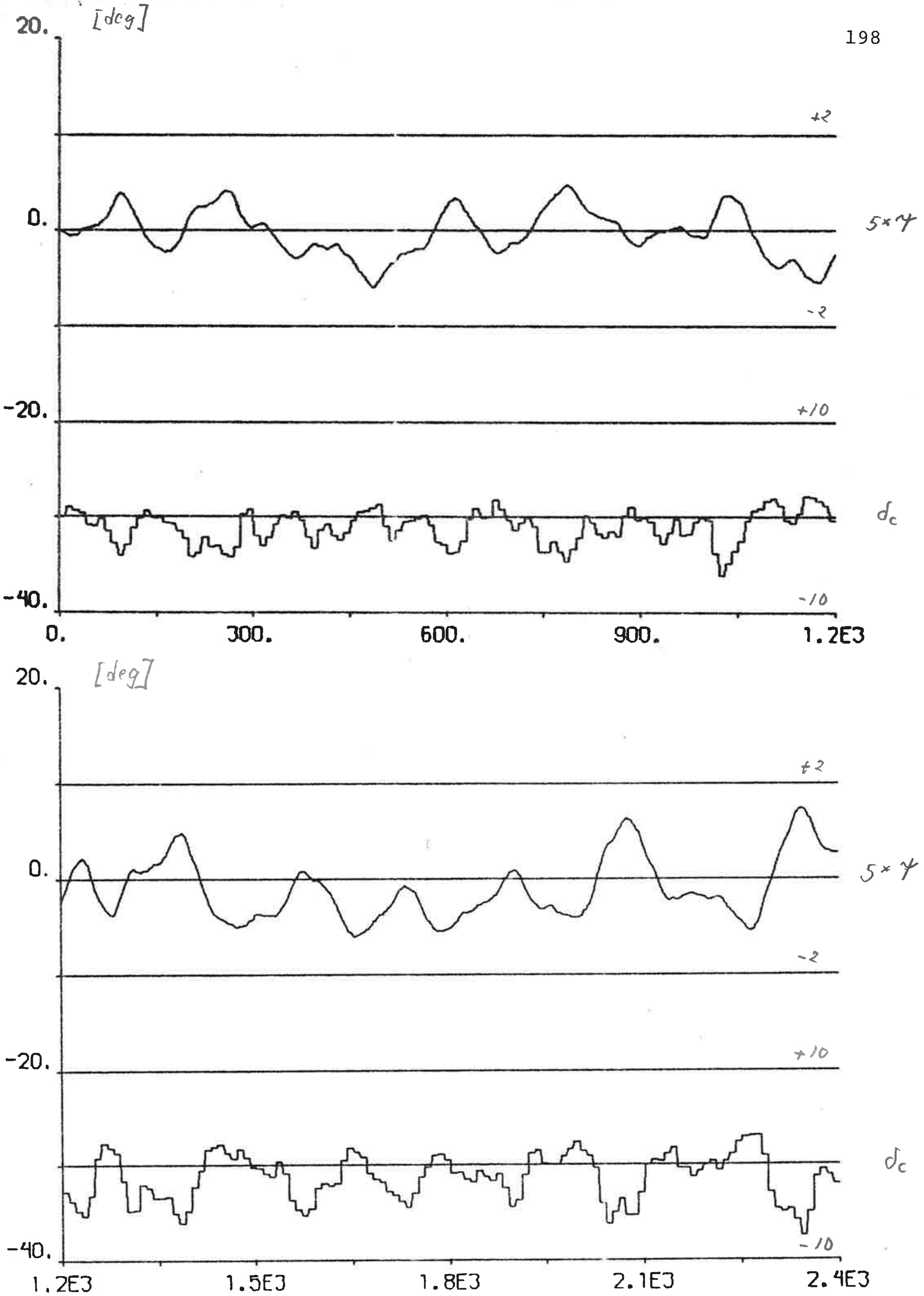


Fig. 4.29 a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements.

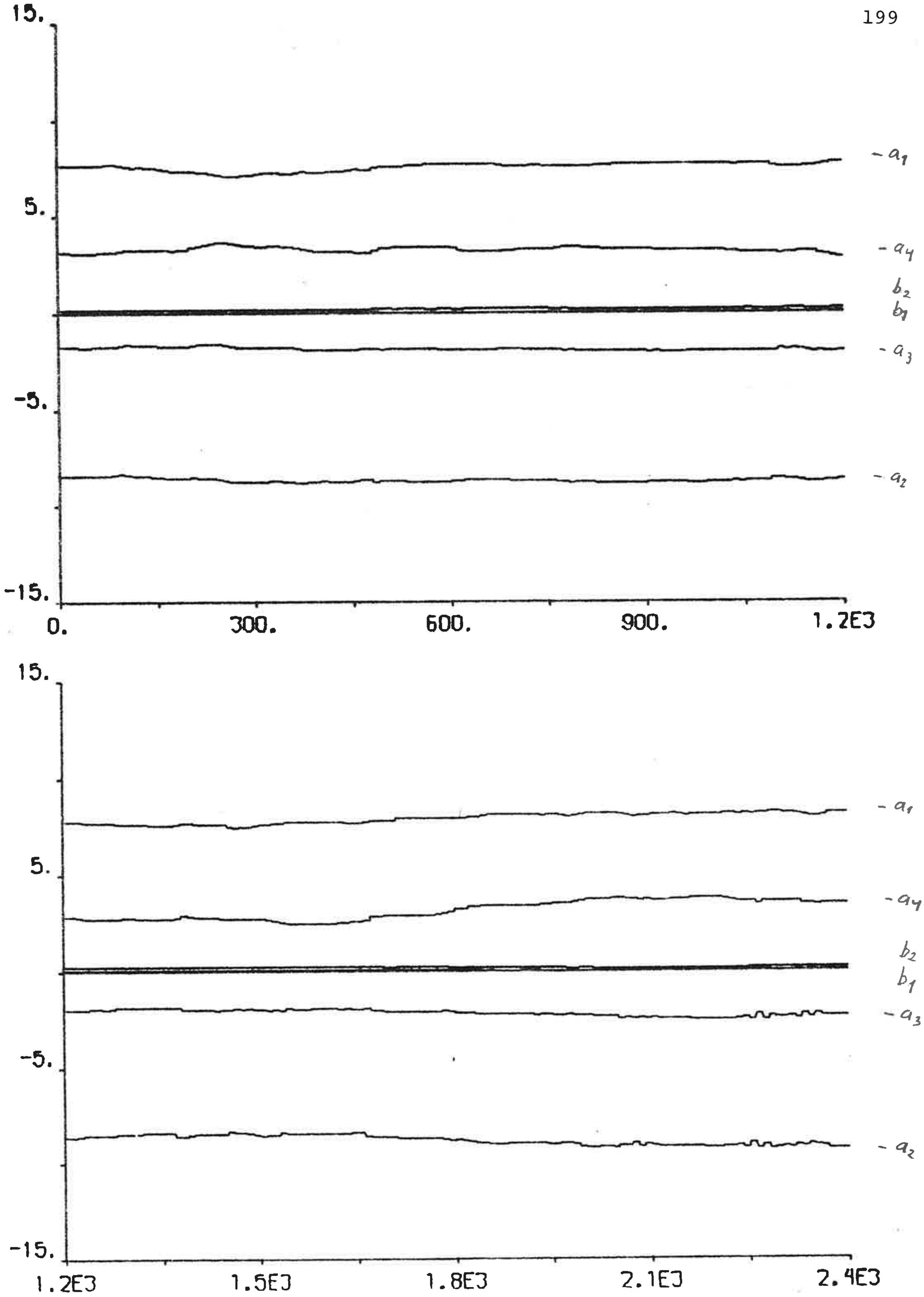

15.
5.
-5.
-15.
0.
300.
600.
900.
1.2E3
- a_1
- a_4
b_2
b_1
- a_3
- a_2
15.
5.
-5.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
- a_1
- a_4
b_2
b_1
- a_3
- a_2

Fig. 4.29 b

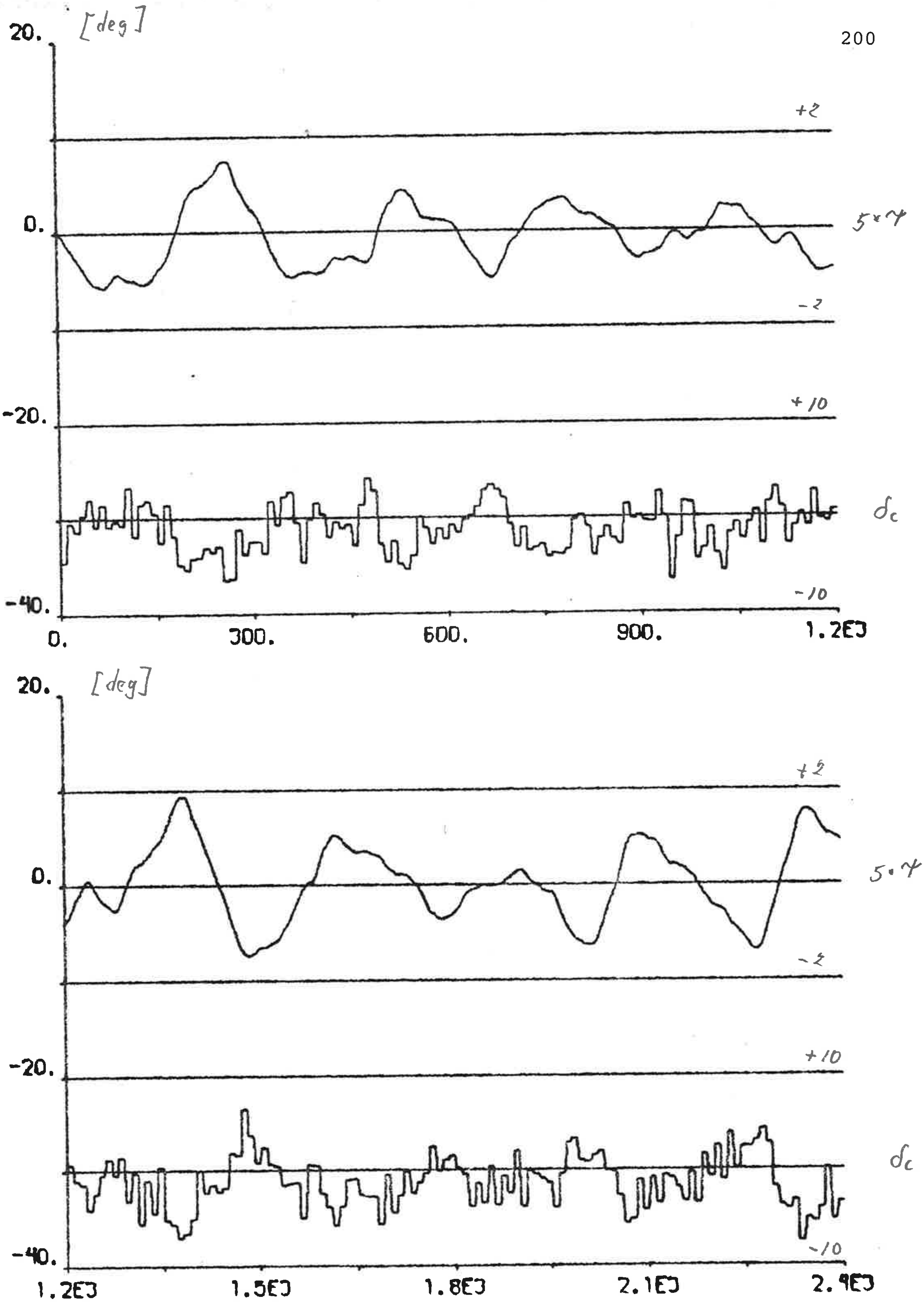


Fig. 4.30 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, PID-regulator using non-filtered measurements.

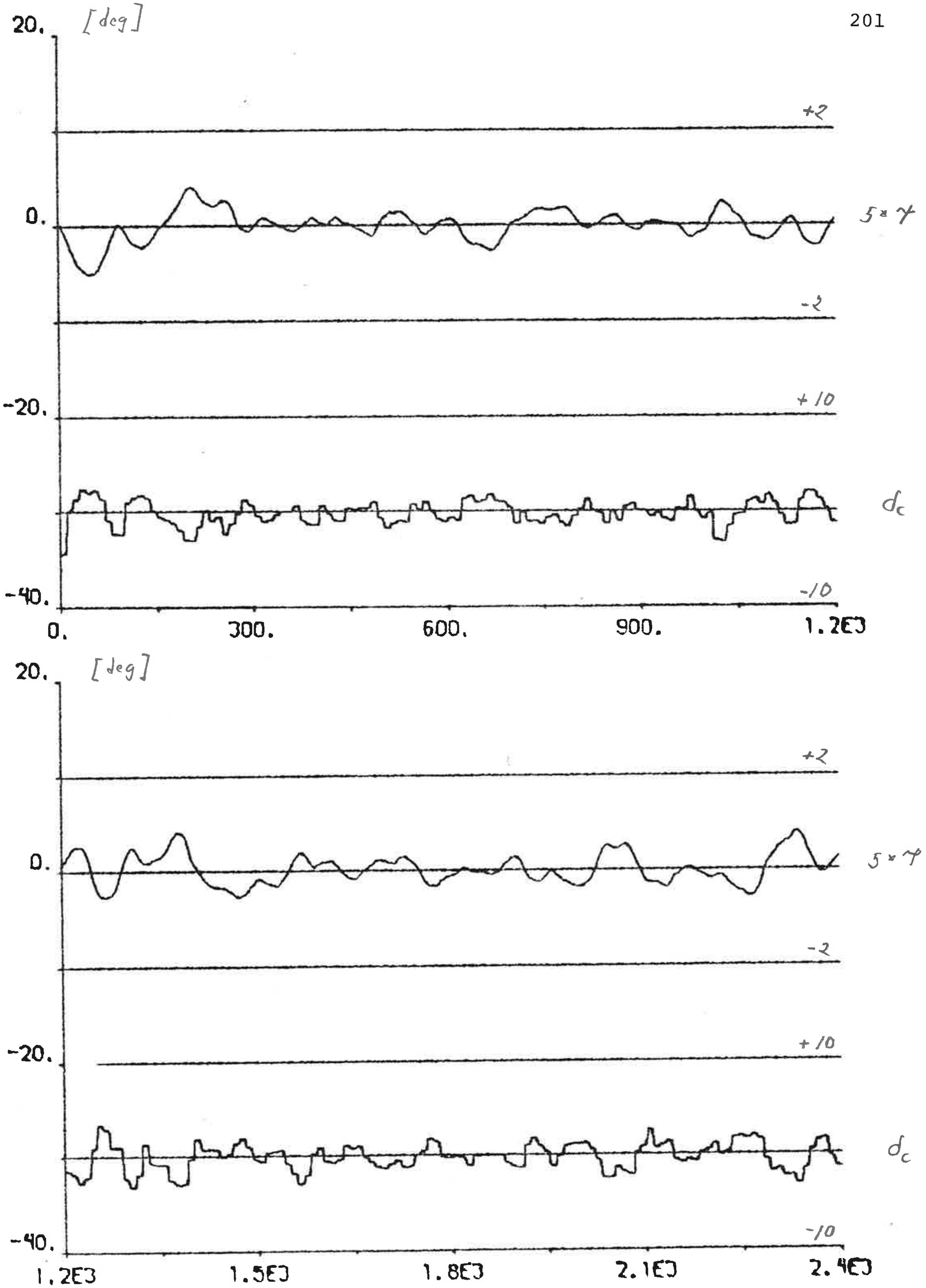
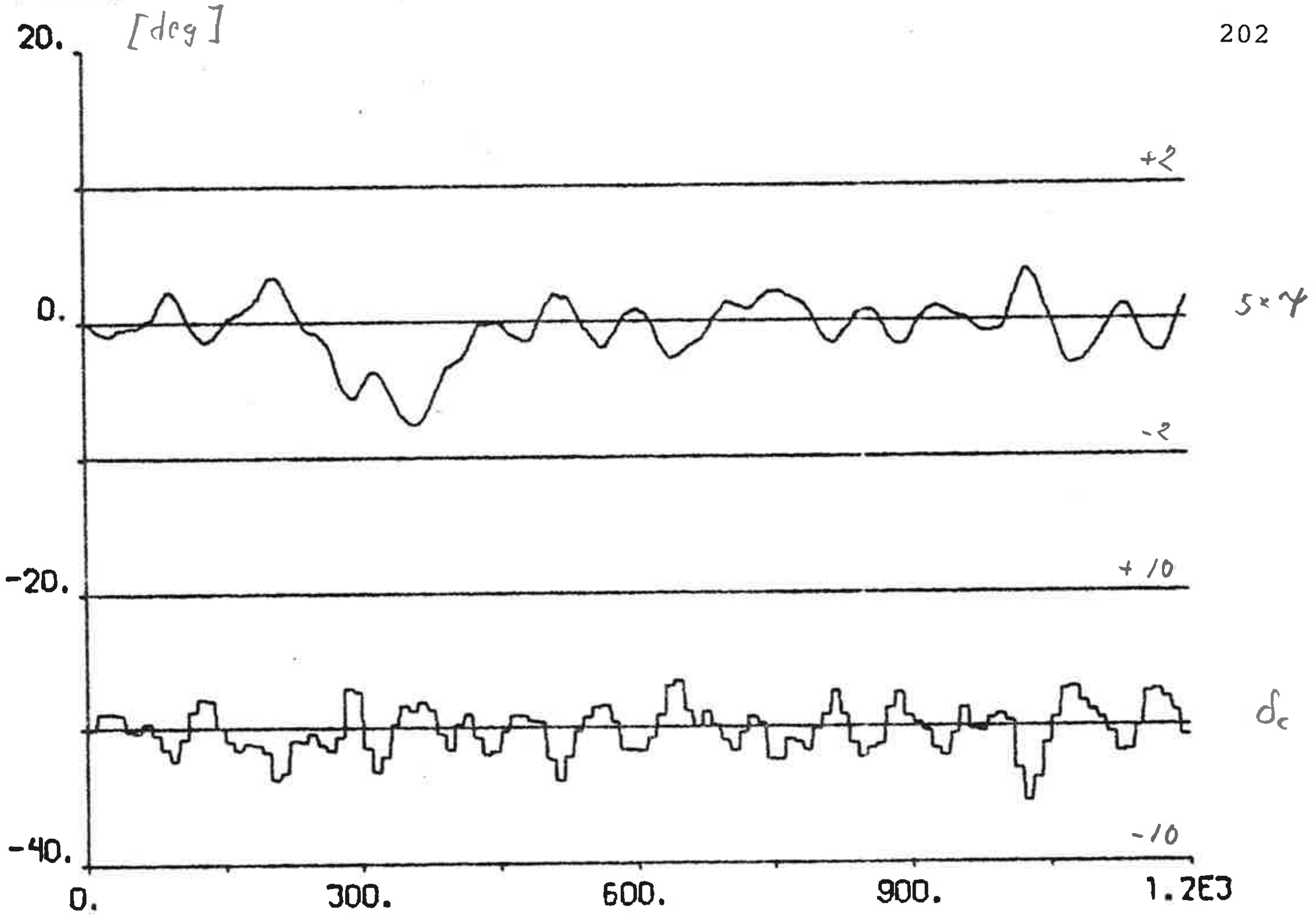


Fig. 4.31 - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, PID-regulator using estimates from the Kalman filter.



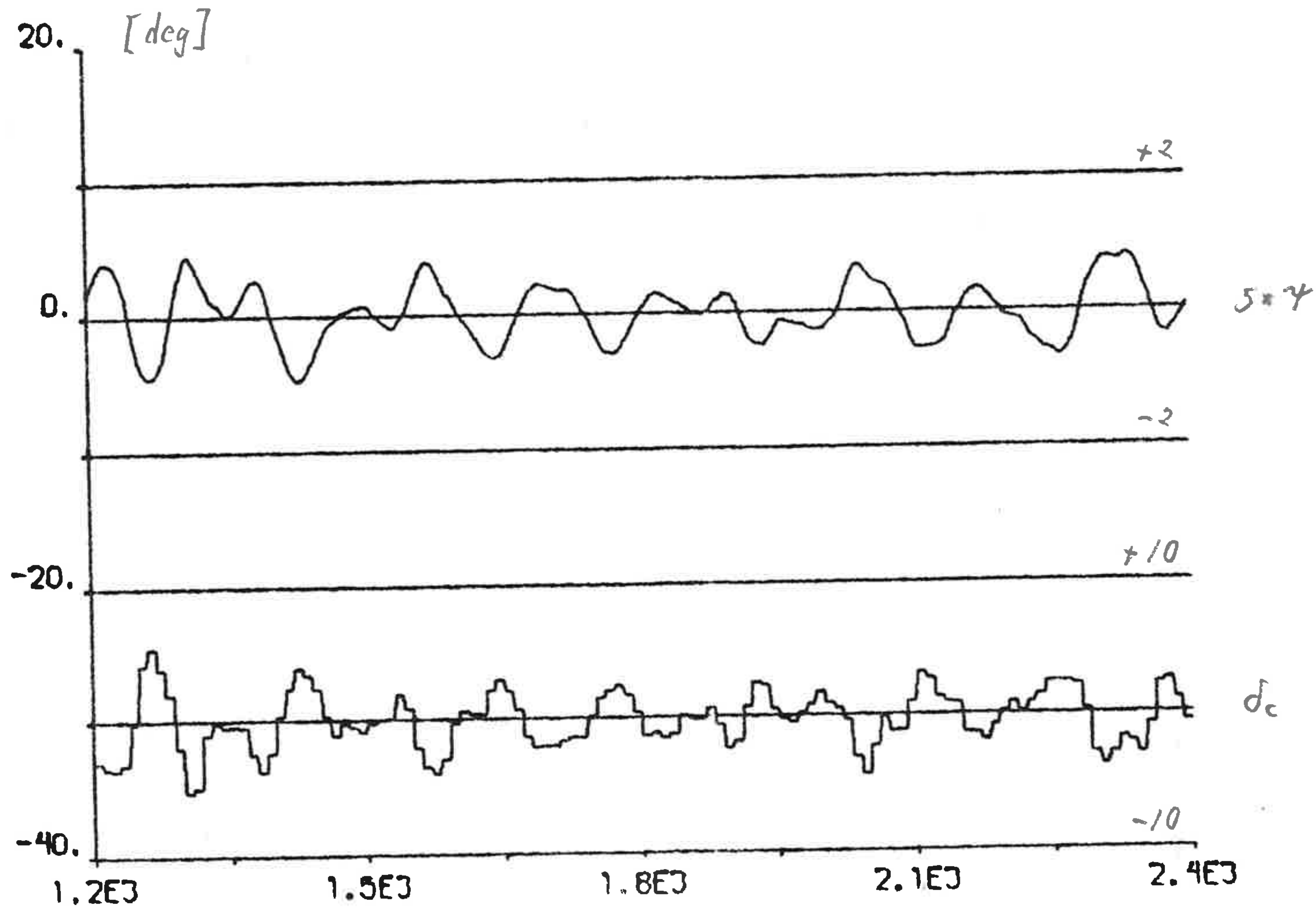
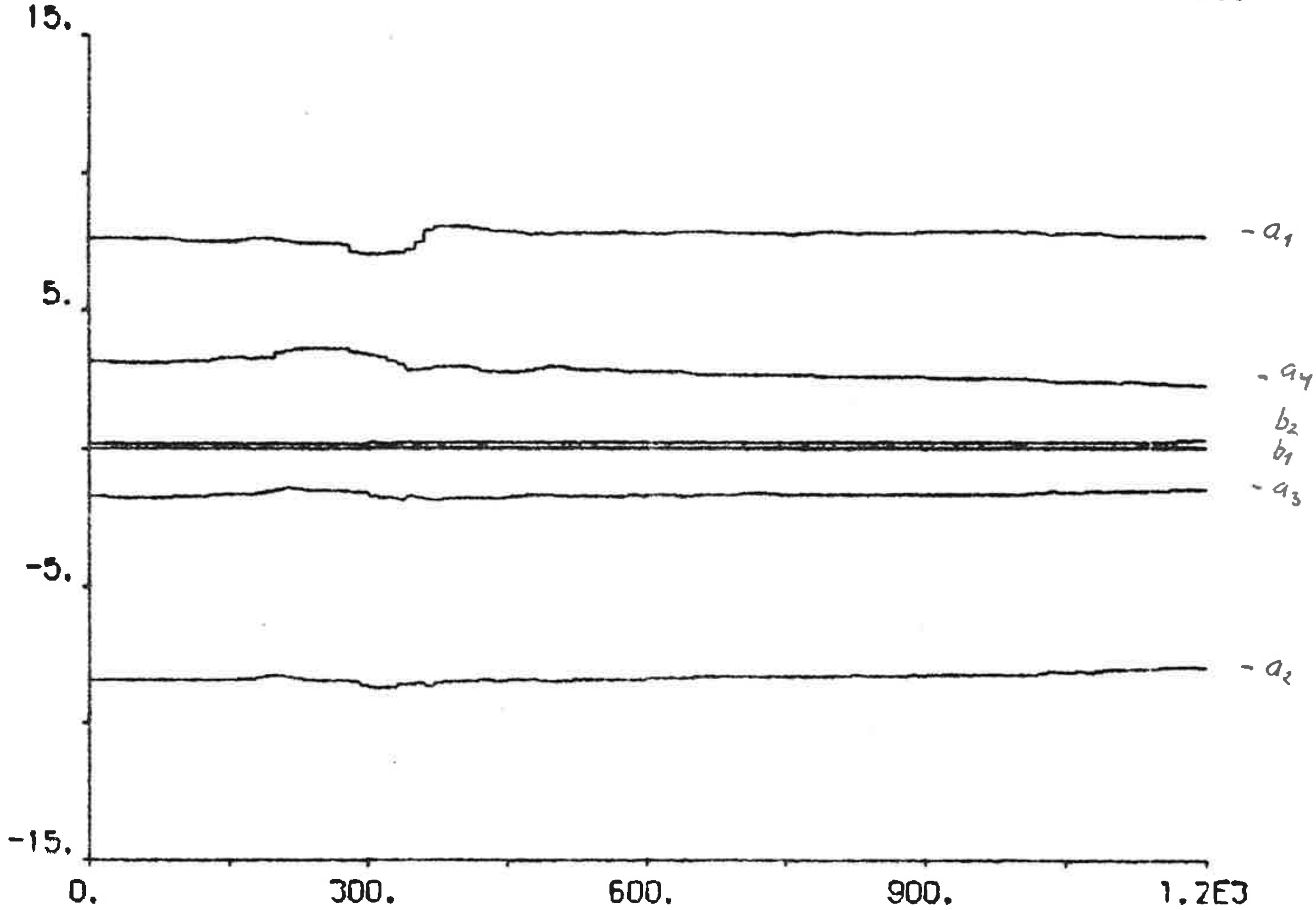


Fig. 4.32 a - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, self-tuning regulator using non-filtered measurements.


15.
5.
-5.
-15.
0.
300.
600.
900.
1.2E3
- a_1
- a_4
b_2
b_1
- a_3
- a_2

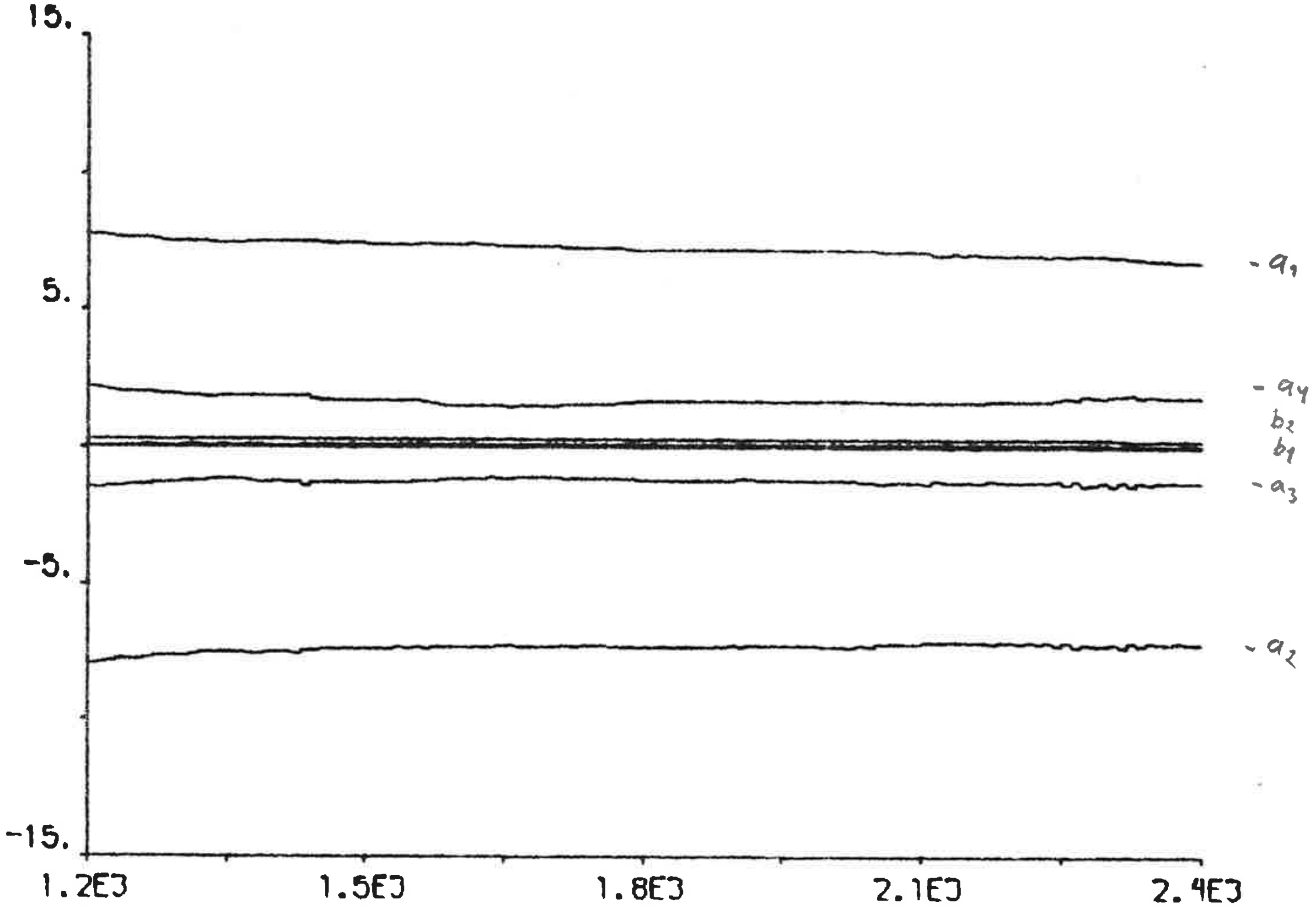
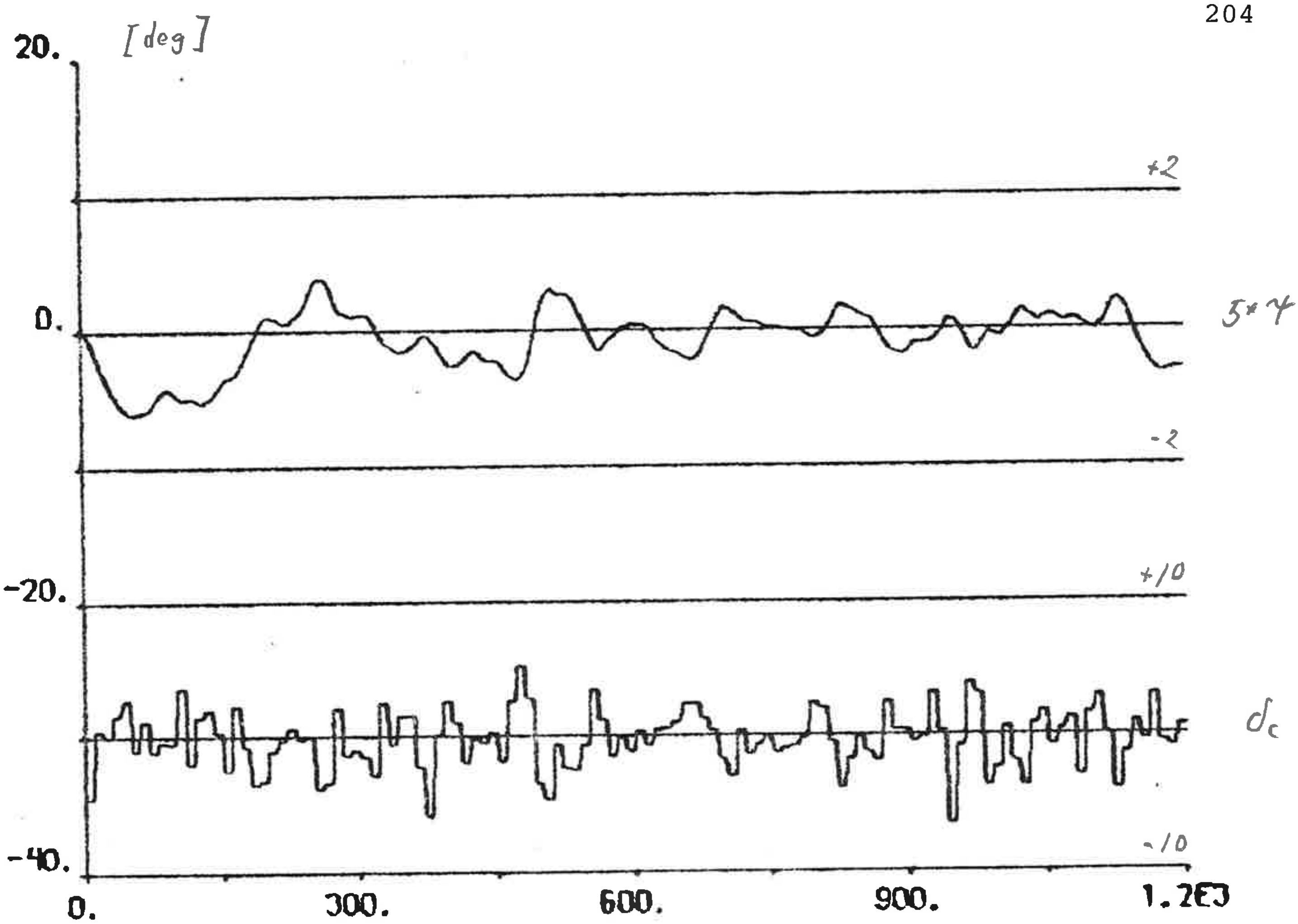

15.
5.
-5.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
- a_1
- a_4
b_2
b_1
- a_3
- a_2

Fig. 4.32 b



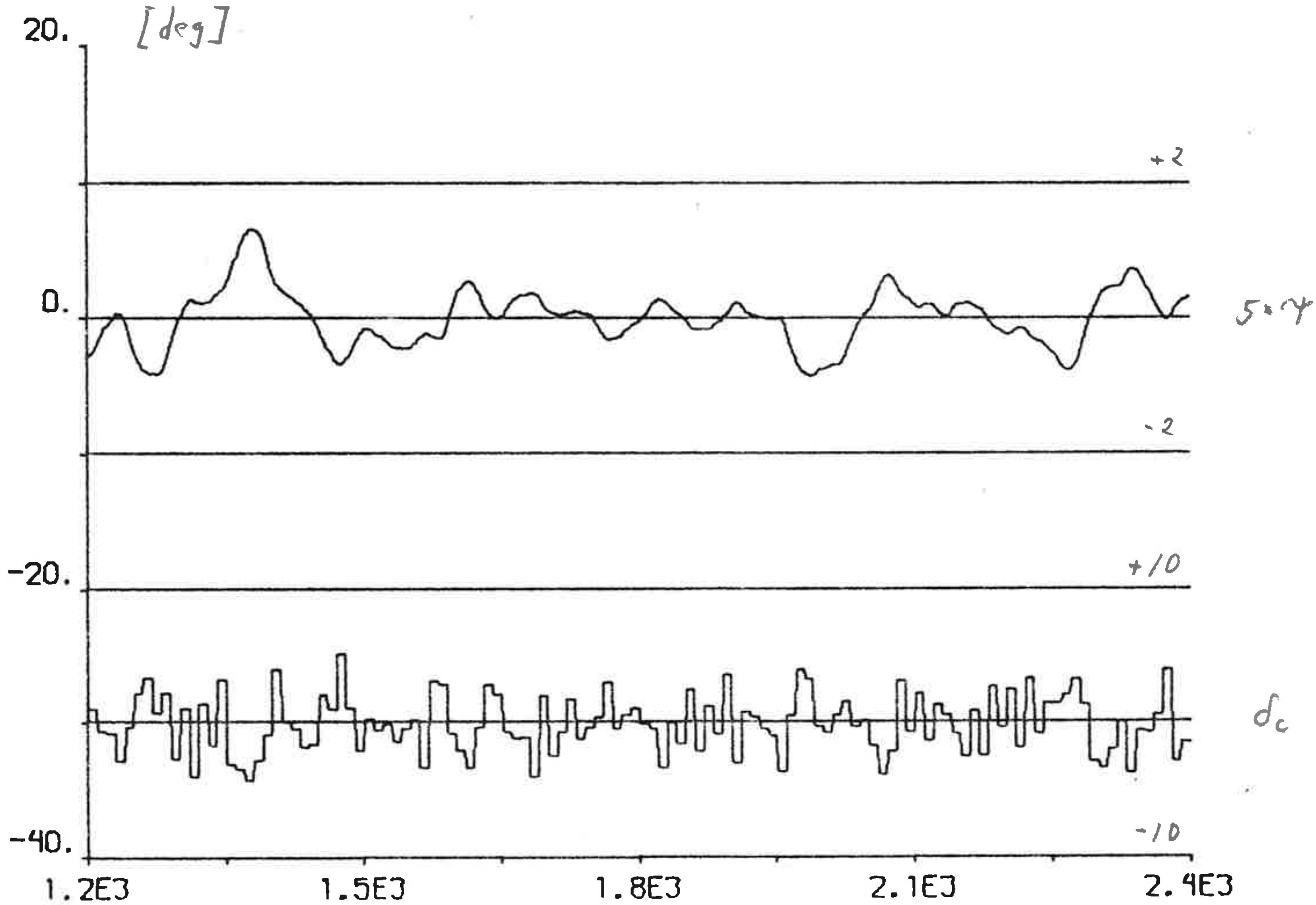


Fig. 4.33 - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, δ_ℓ = 10 deg, PID-regulator using non-filtered measurements.

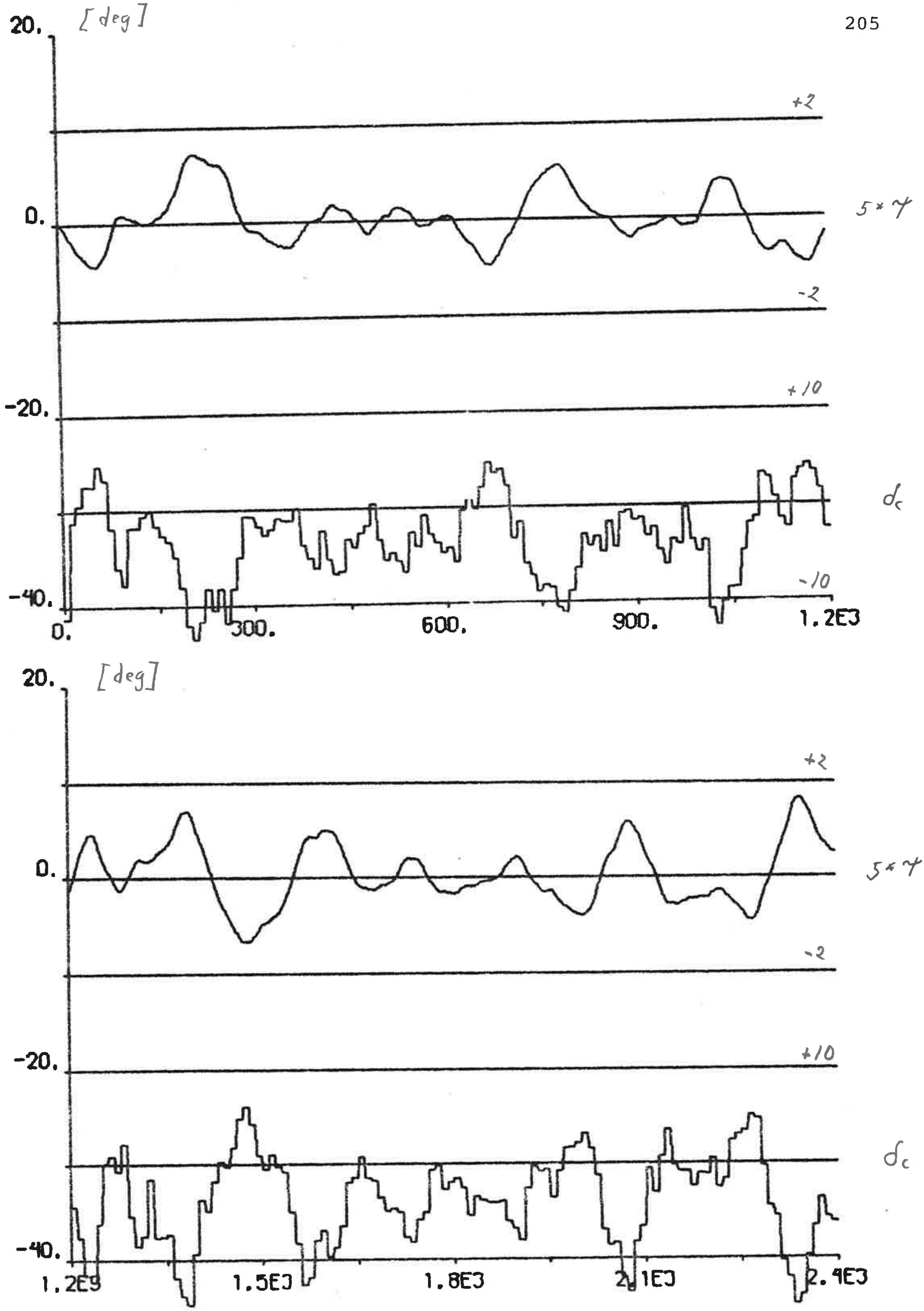


Fig. 4.34 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, PID-regulator using estimates from the Kalman filter.

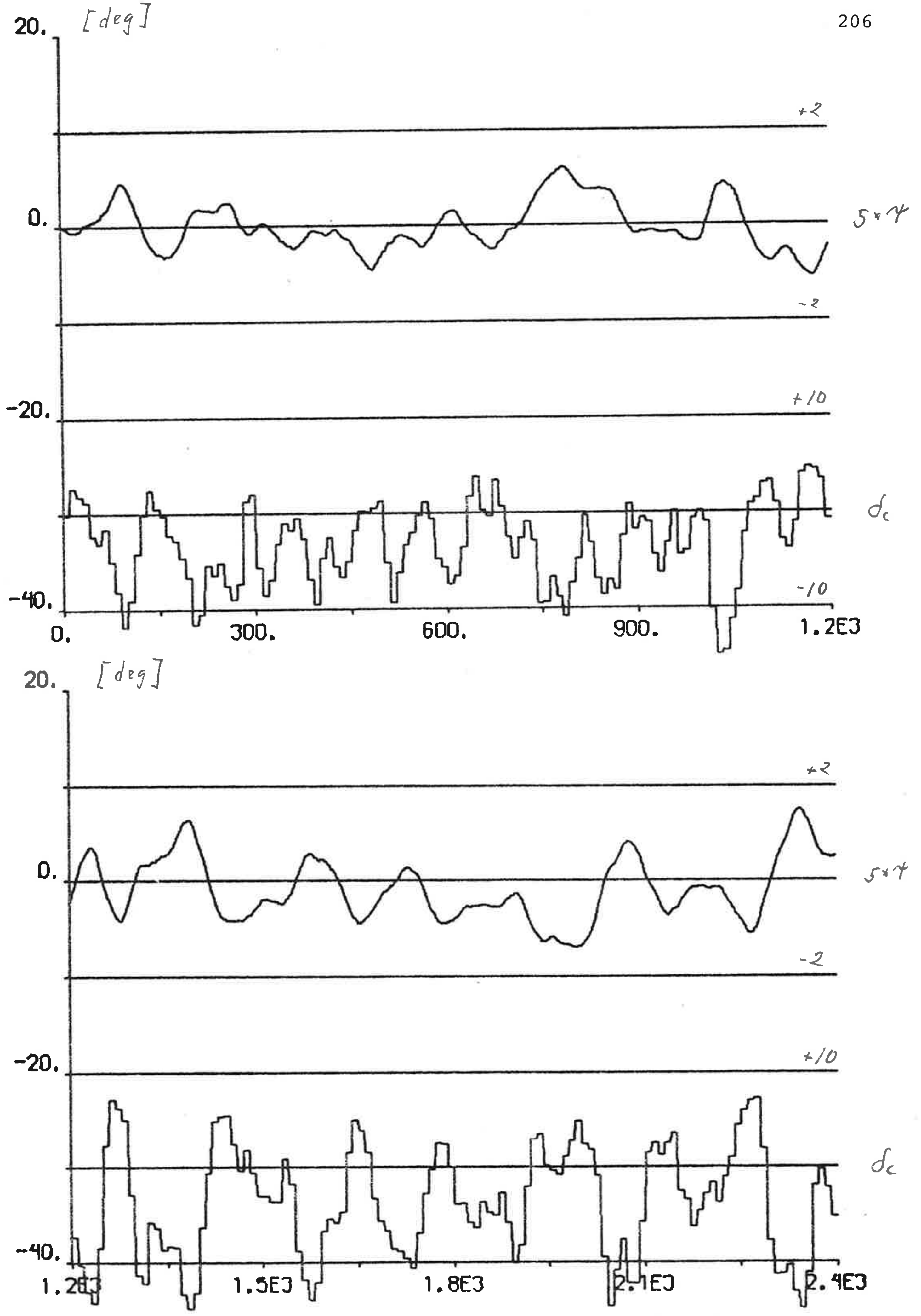
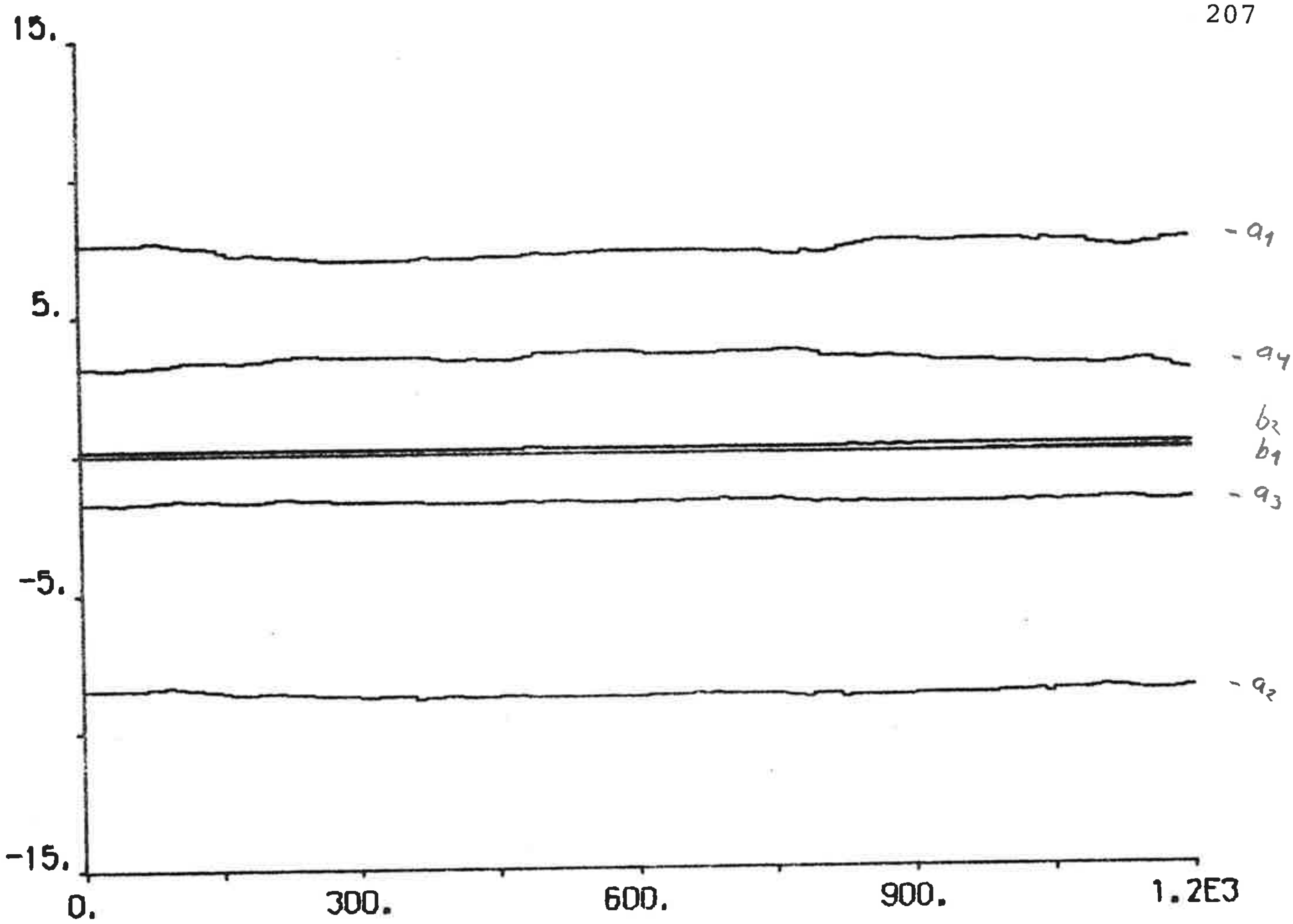
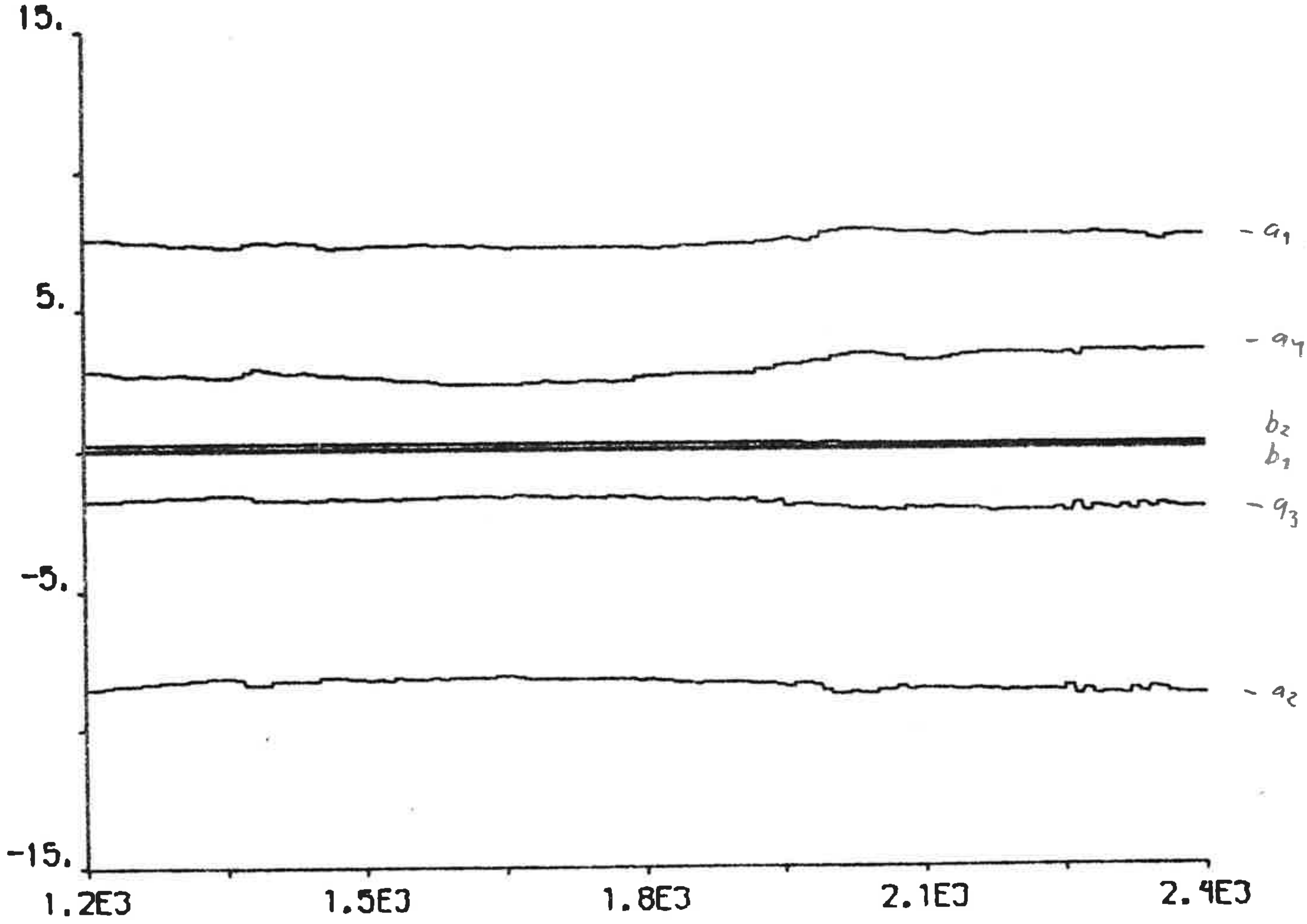


Fig. 4.35 a - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, self-tuning regulator using non-filtered measurements.

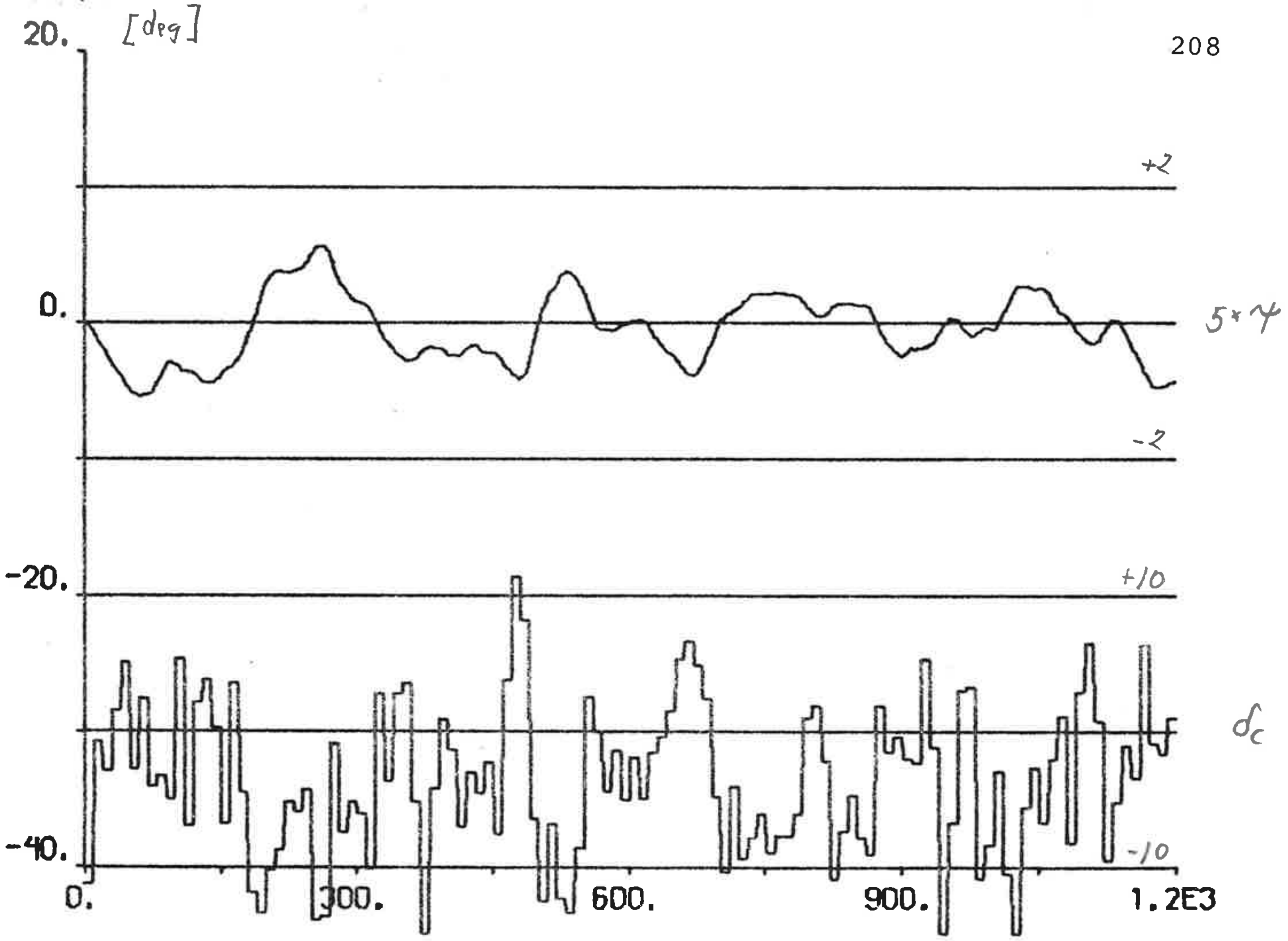


15.
5.
-5.
-15.
0.
300.
600.
900.
1.2E3
a1
a4
b2
b1
a3
a2



15.
5.
-5.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
a1
a4
b2
b1
a3
a2

Fig. 4.35 b



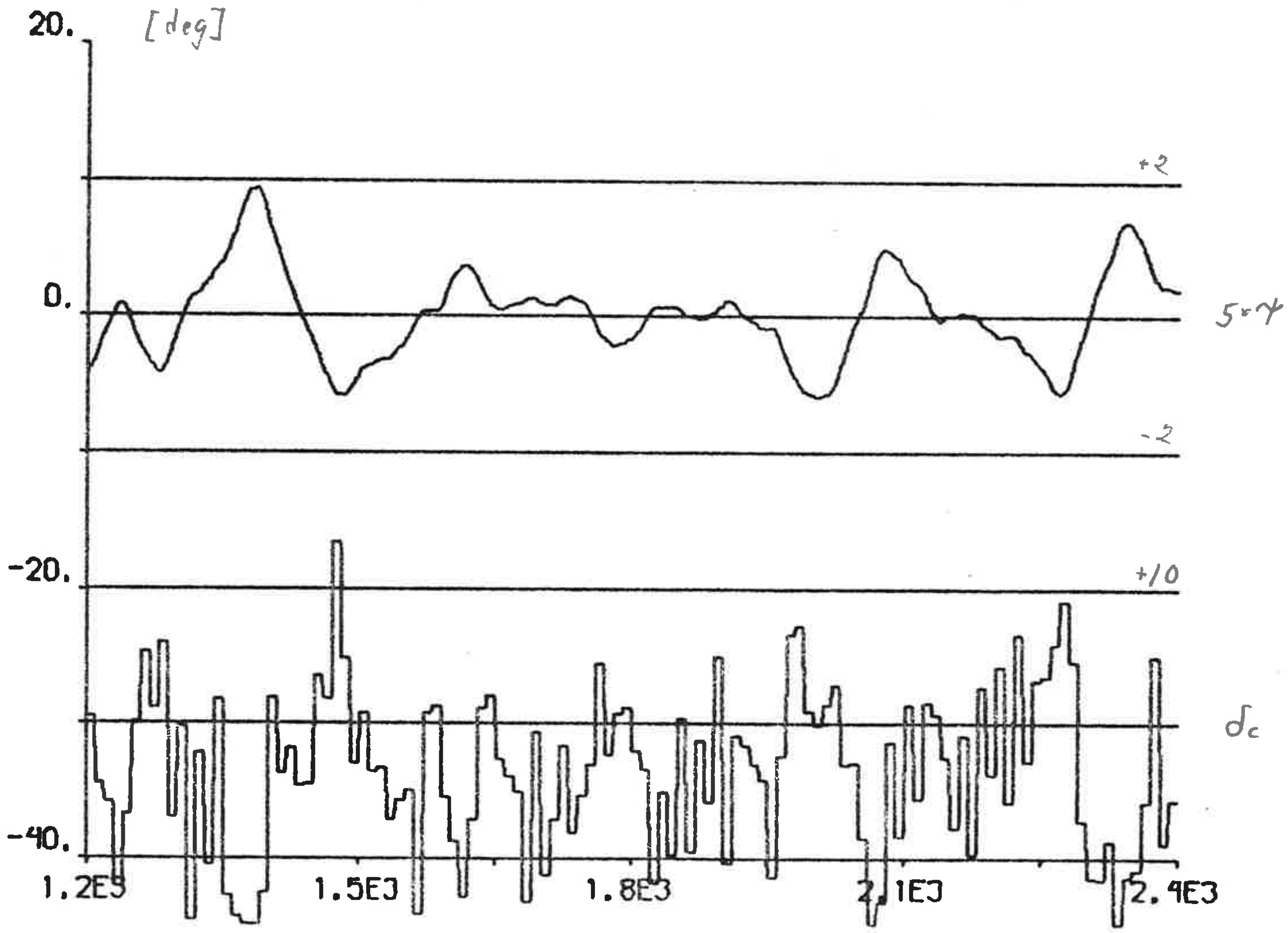
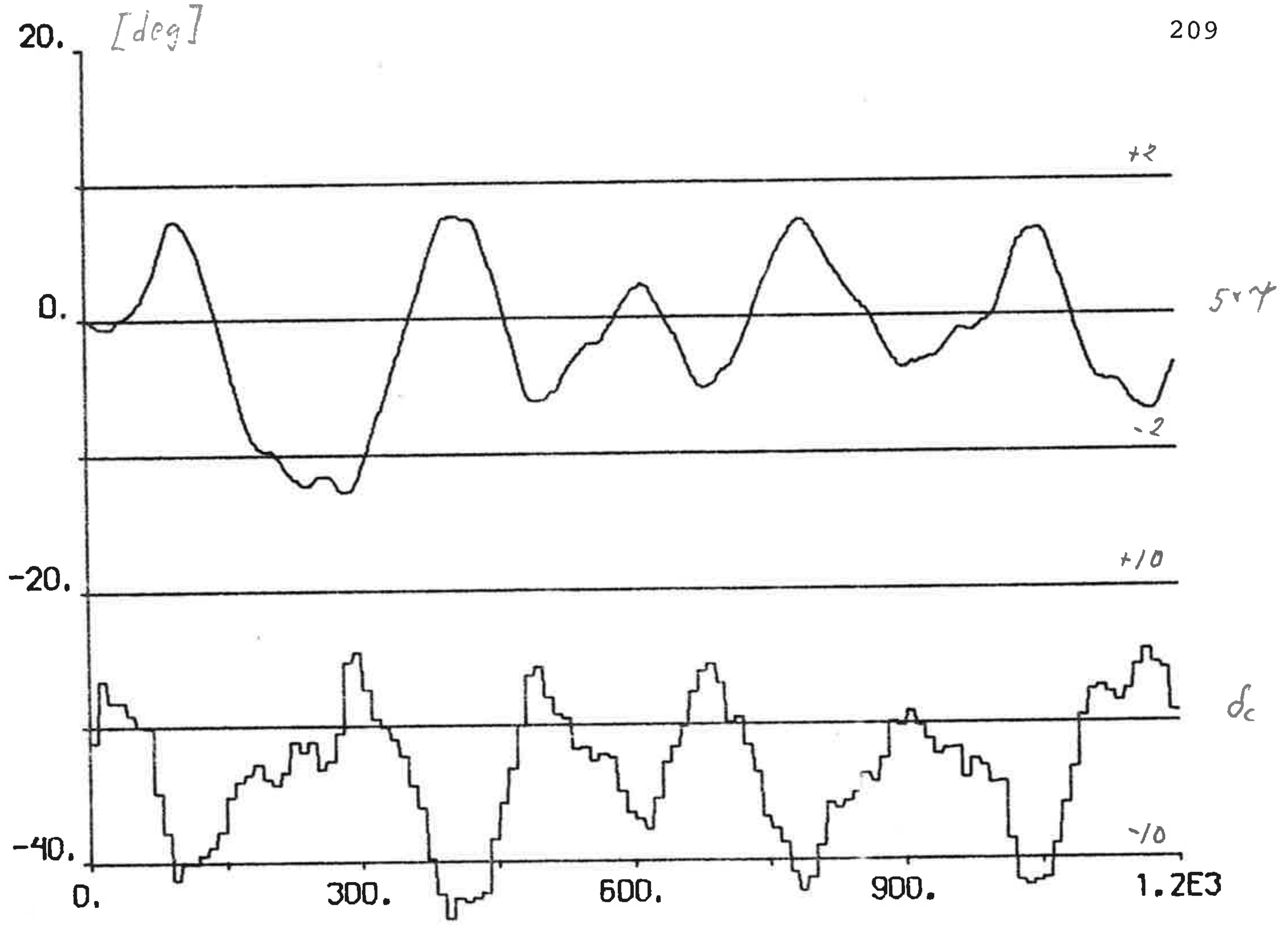


Fig. 4.36 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, PID-regulator using non-filtered measurements.



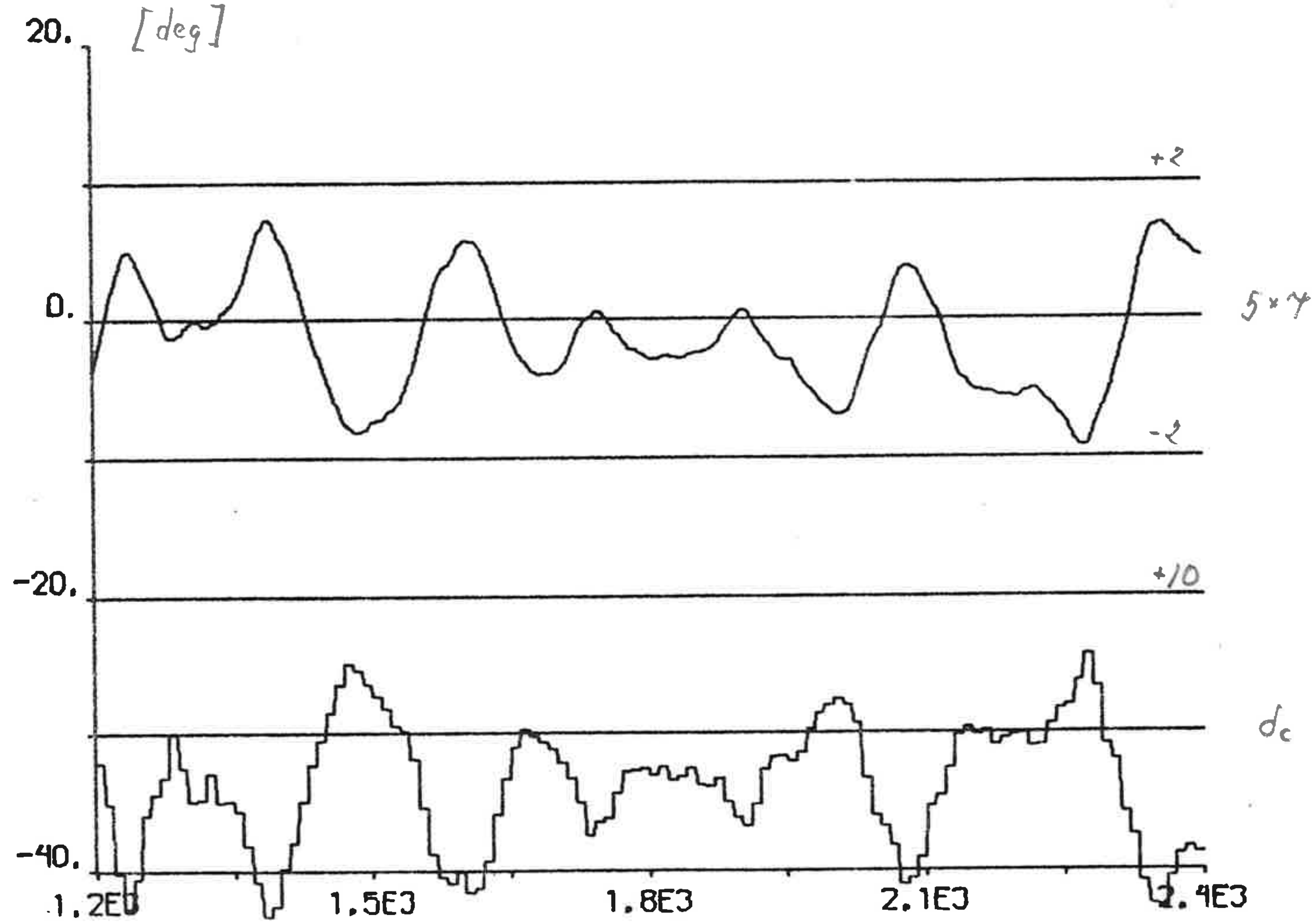
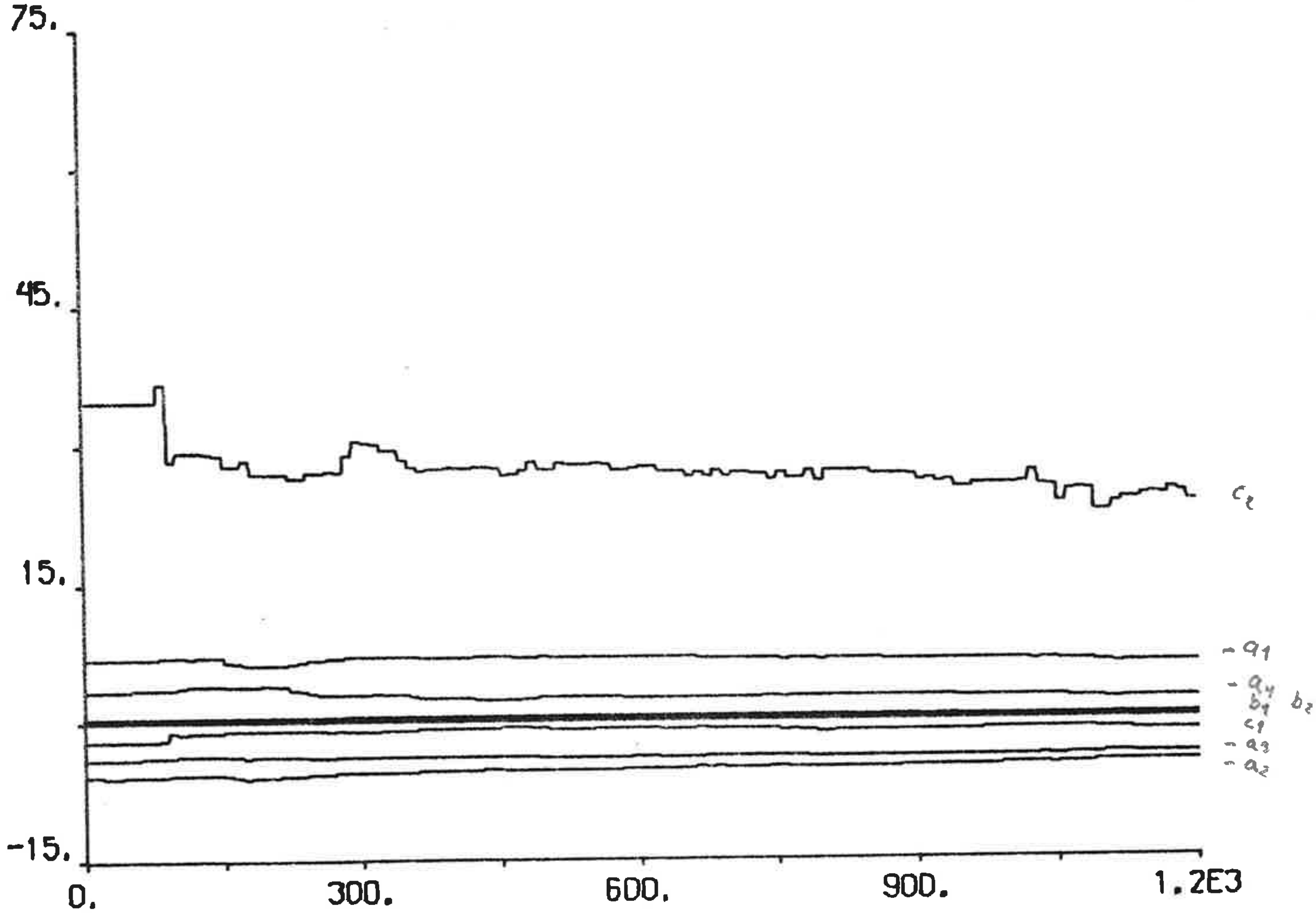


Fig. 4.37 a - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, self-tuning regulator using estimates from the Kalman filter (q_2^* = 0.6).


75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c₁
a1
a4
b1
b2
c1
a3
a2

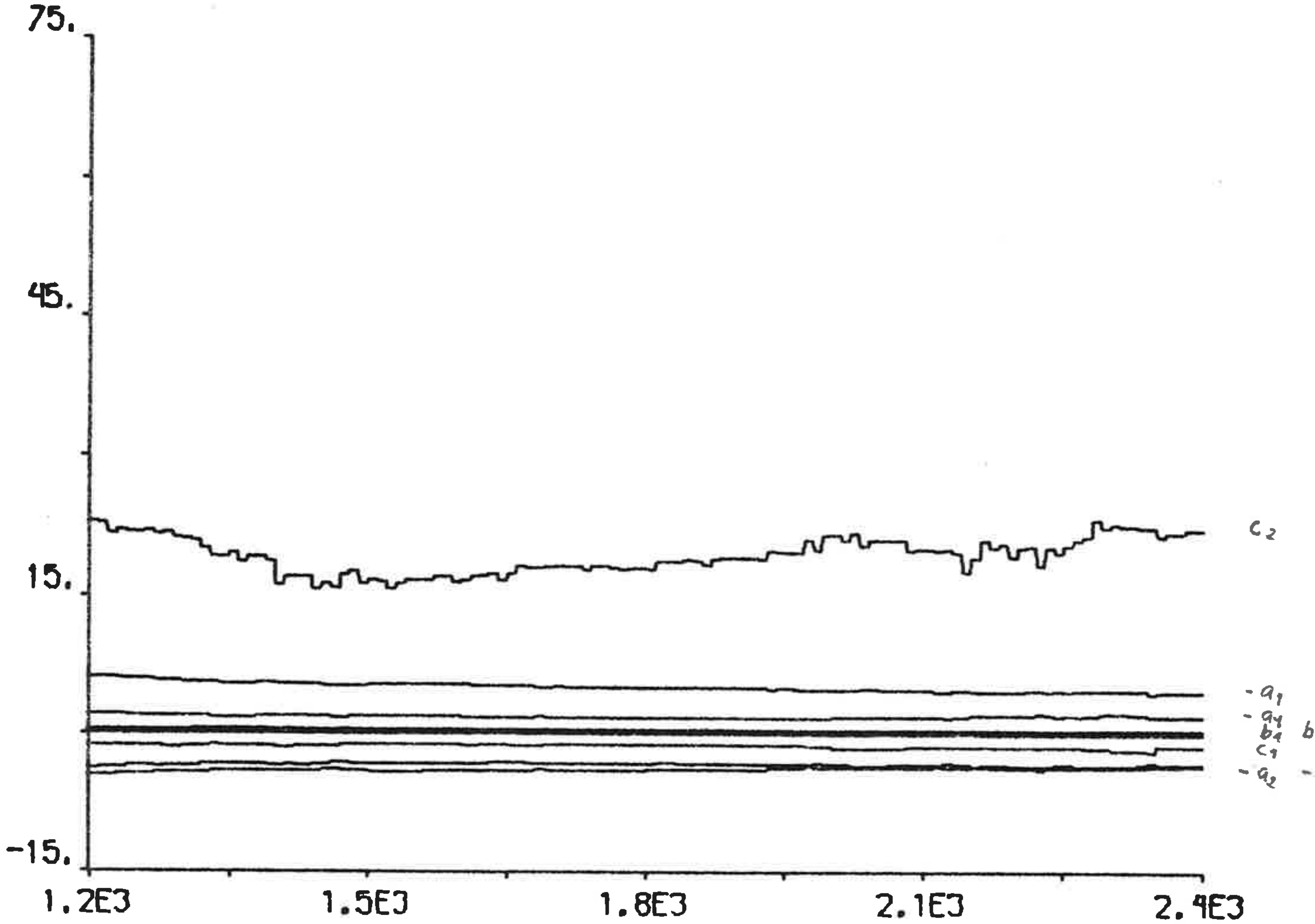
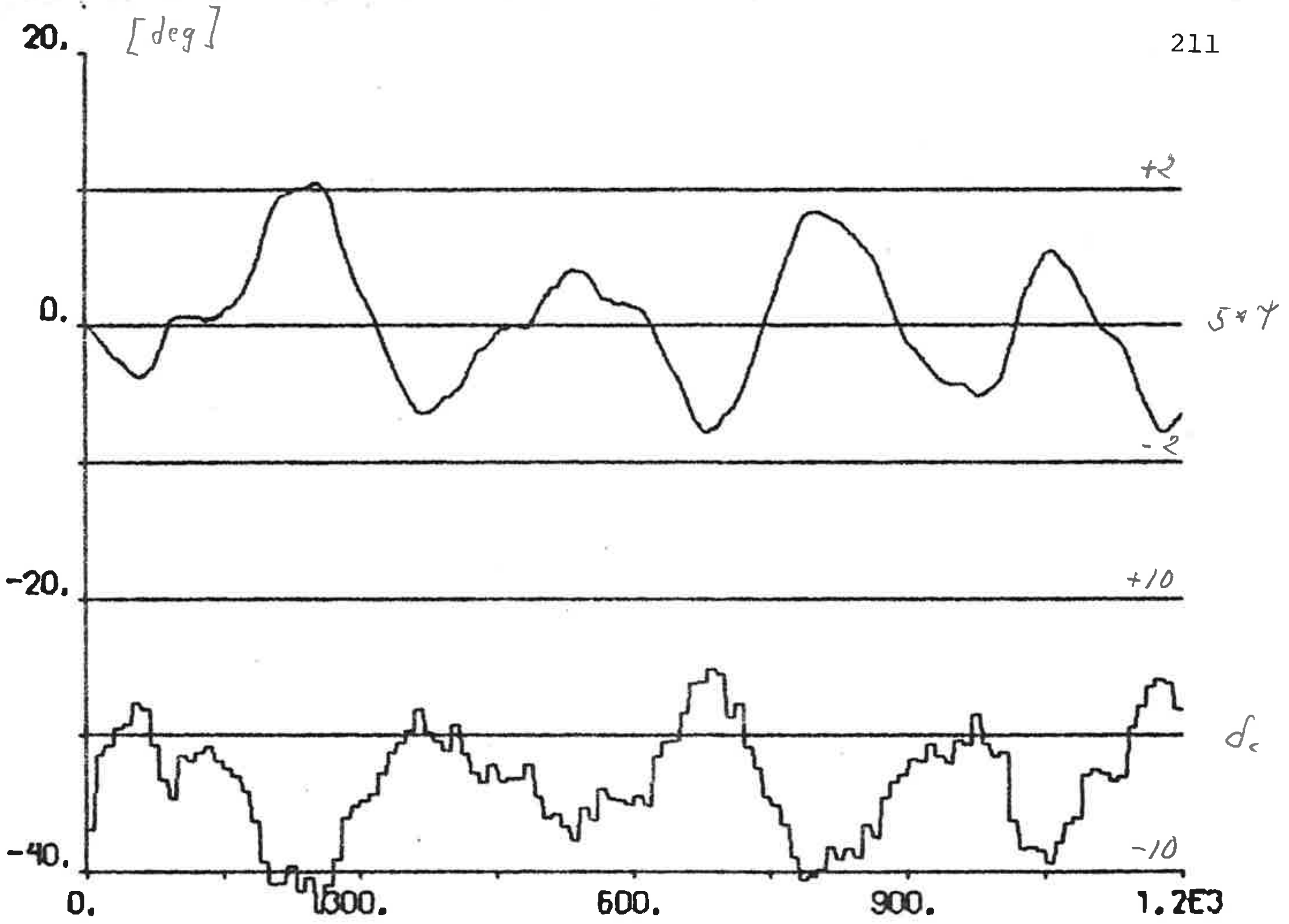

75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c2
a1
a4
b1
c1
a2

Fig. 4.37 b



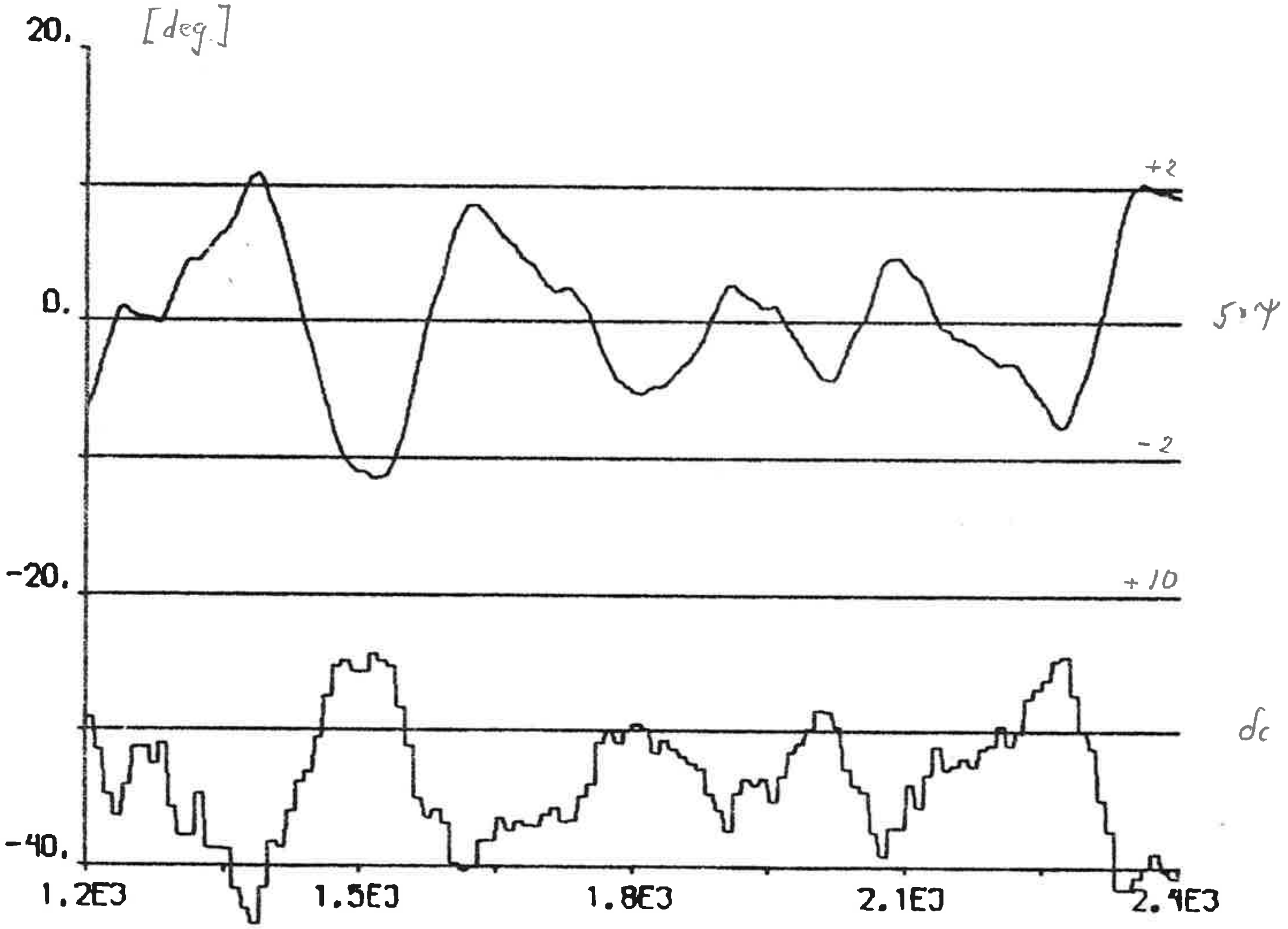


Fig. 4.38 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, PID-regulator using estimates from the Kalman filter (V_0 = 6.3 m/s).

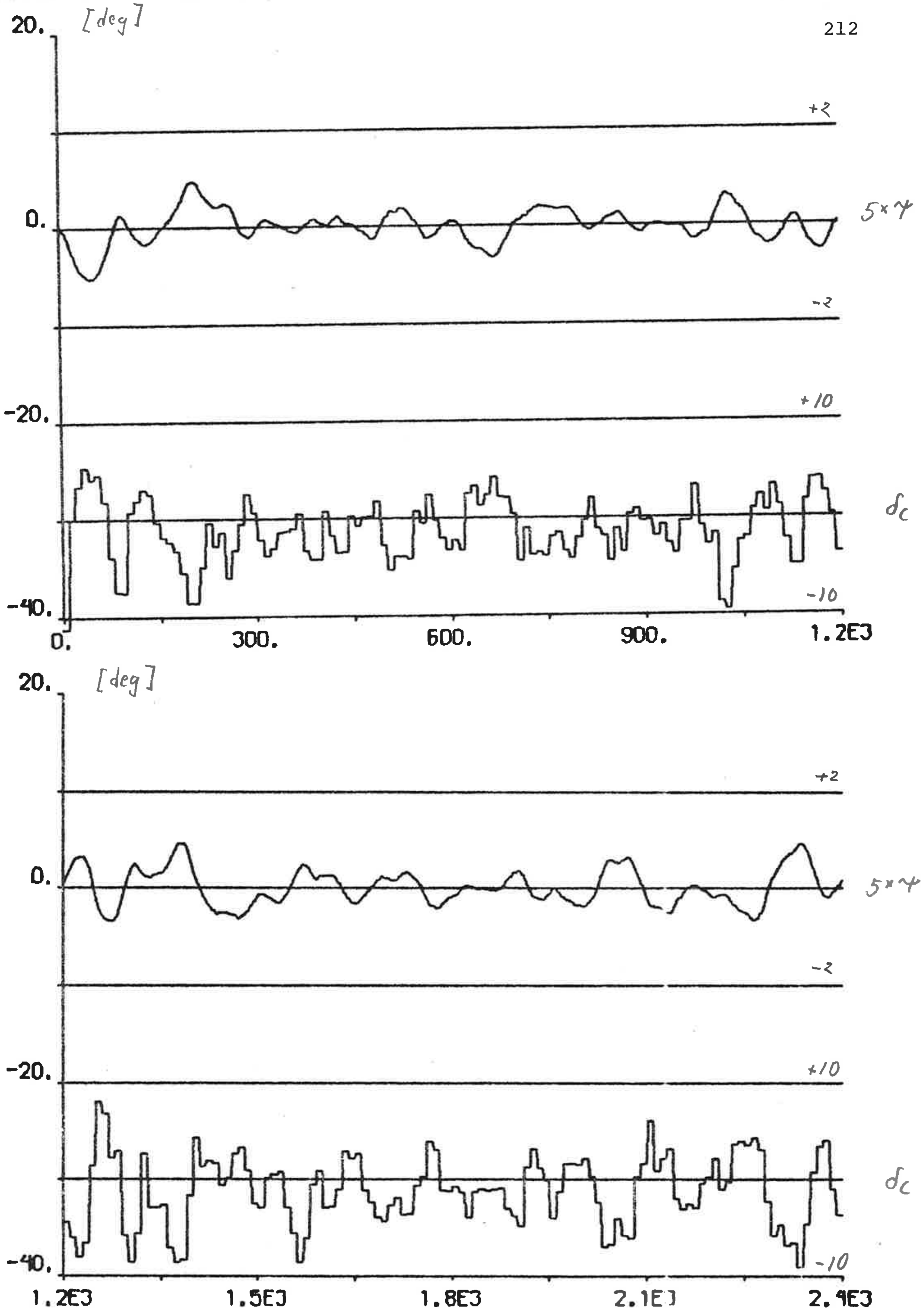


Fig. 4.39 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, PID-regulator using estimates from the Kalman filter.

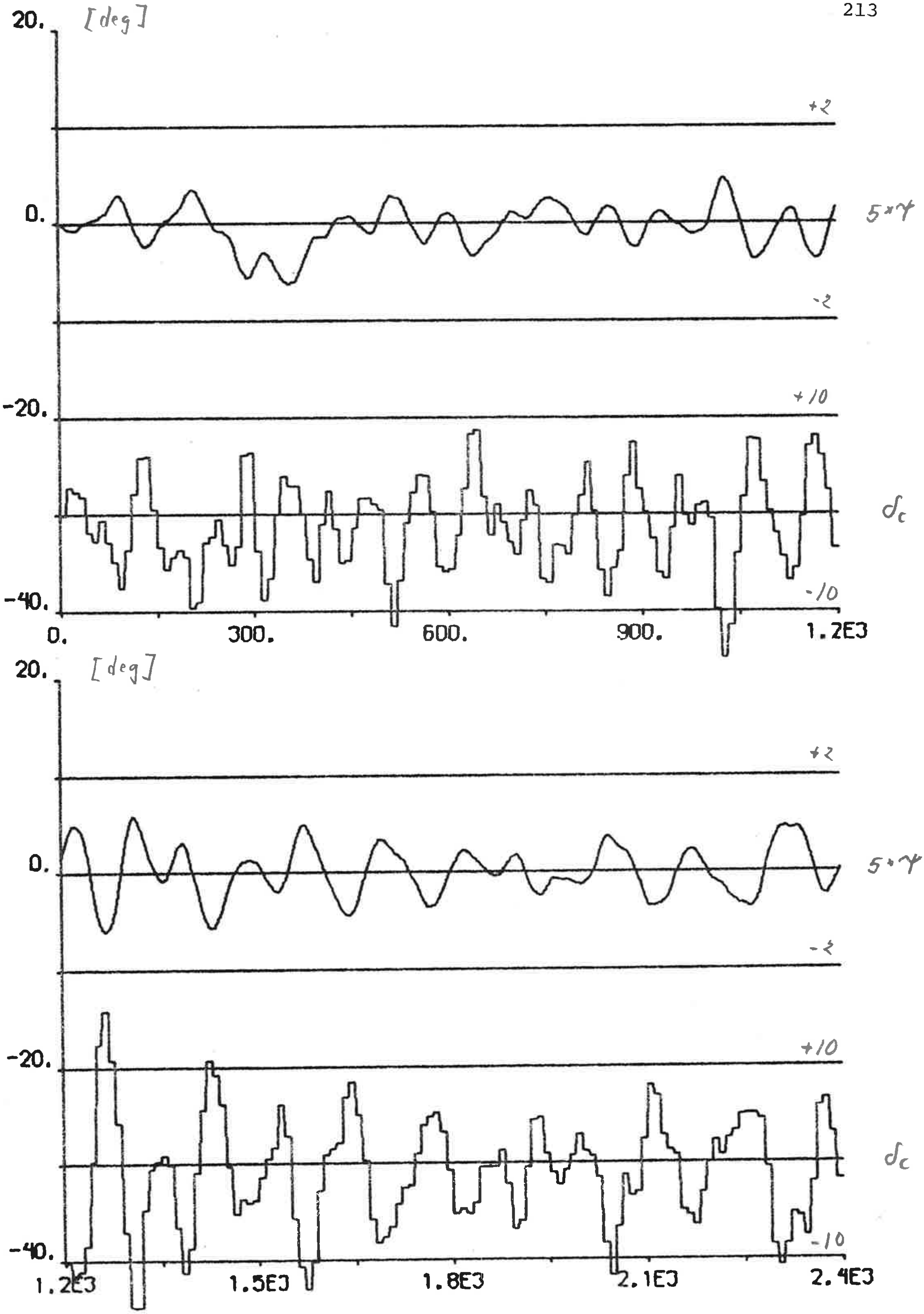
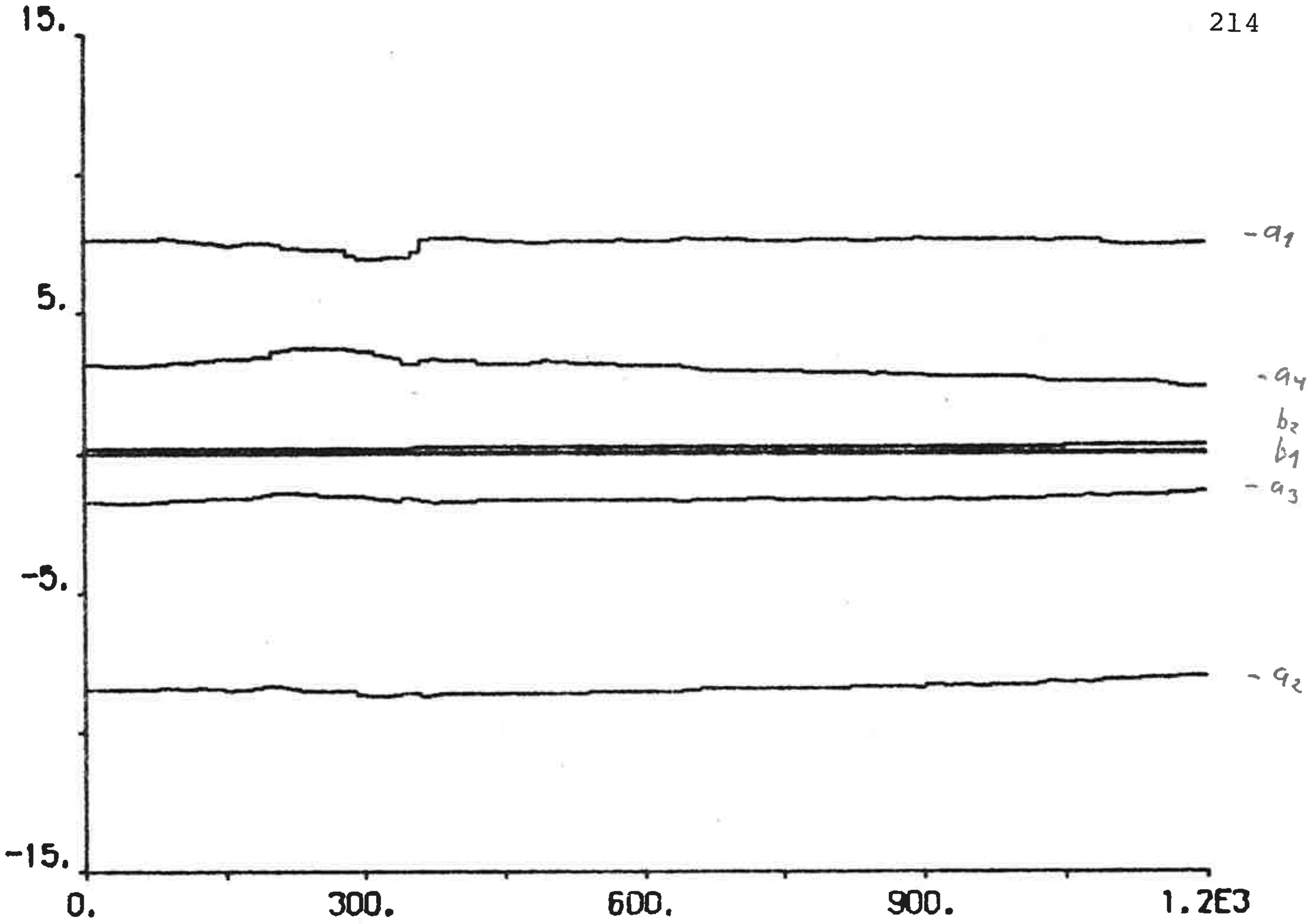


Fig. 4.40 a - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, self-tuning regulator using non-filtered measurements.


15.
5.
-5.
-15.
0.
300.
600.
900.
1.2E3
- a1
- a4
b2
b1
- a3
- a2

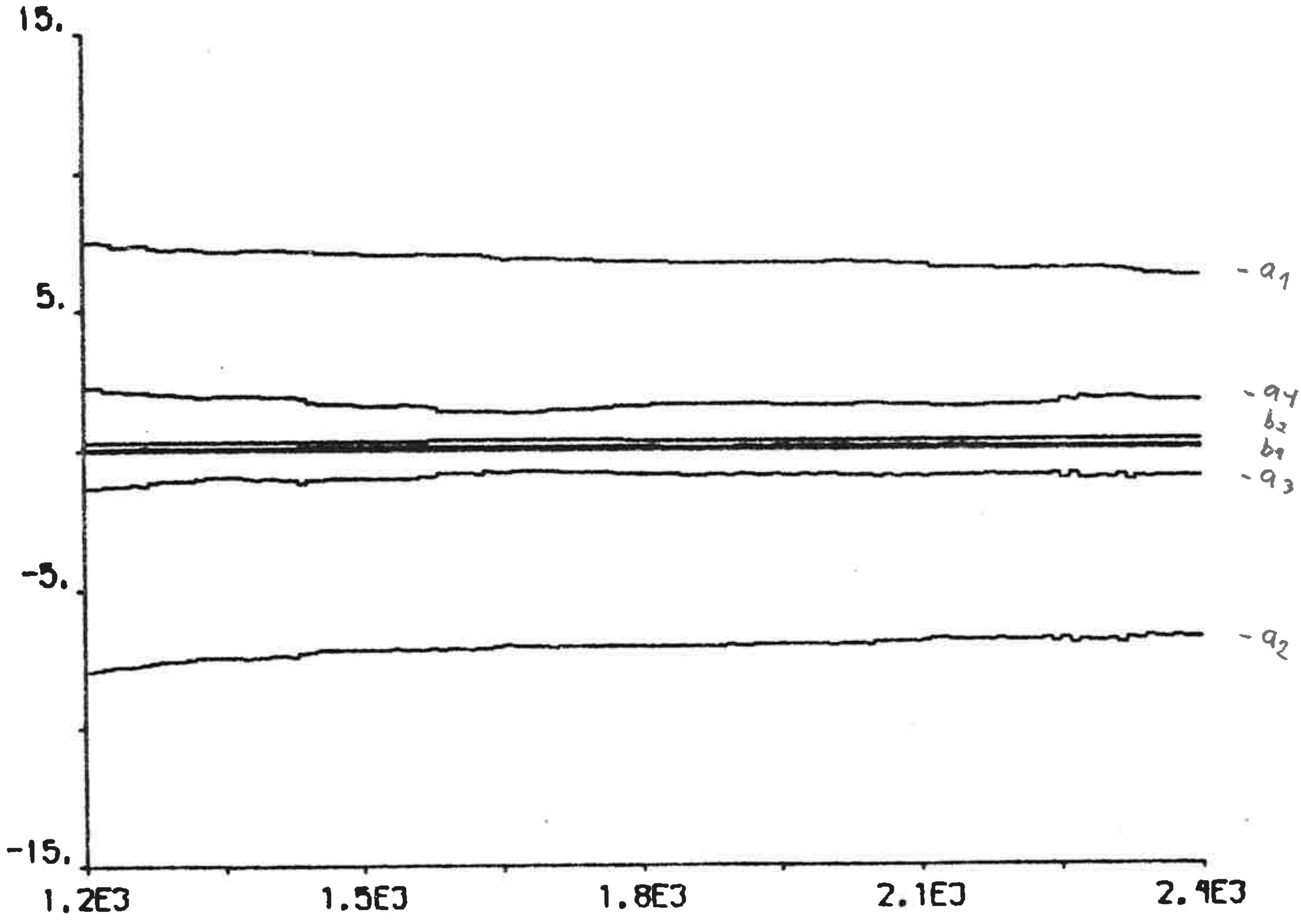

15.
5.
-5.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
- a1
- a4
b2
b1
- a3
- a2

Fig. 4.40 b

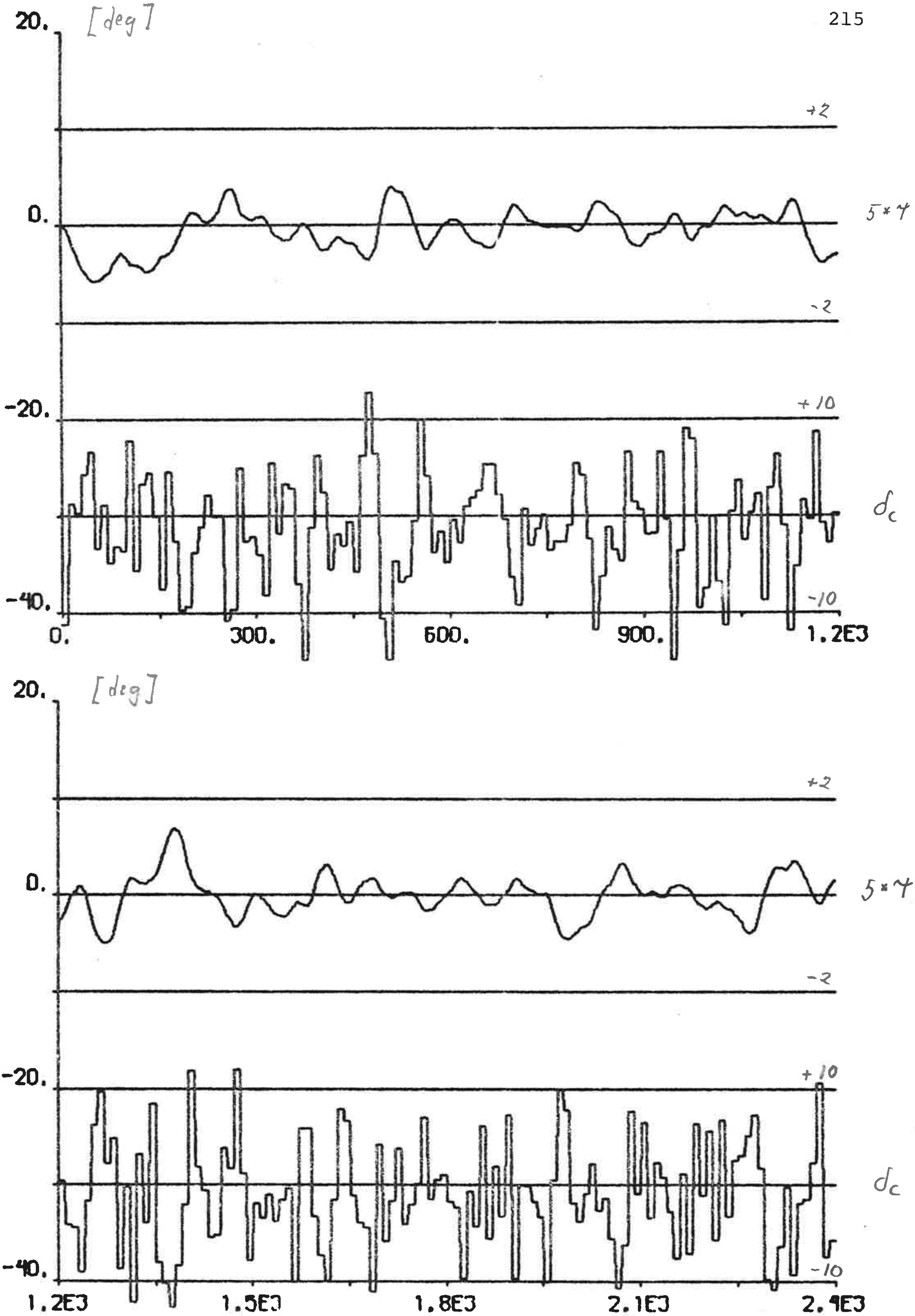
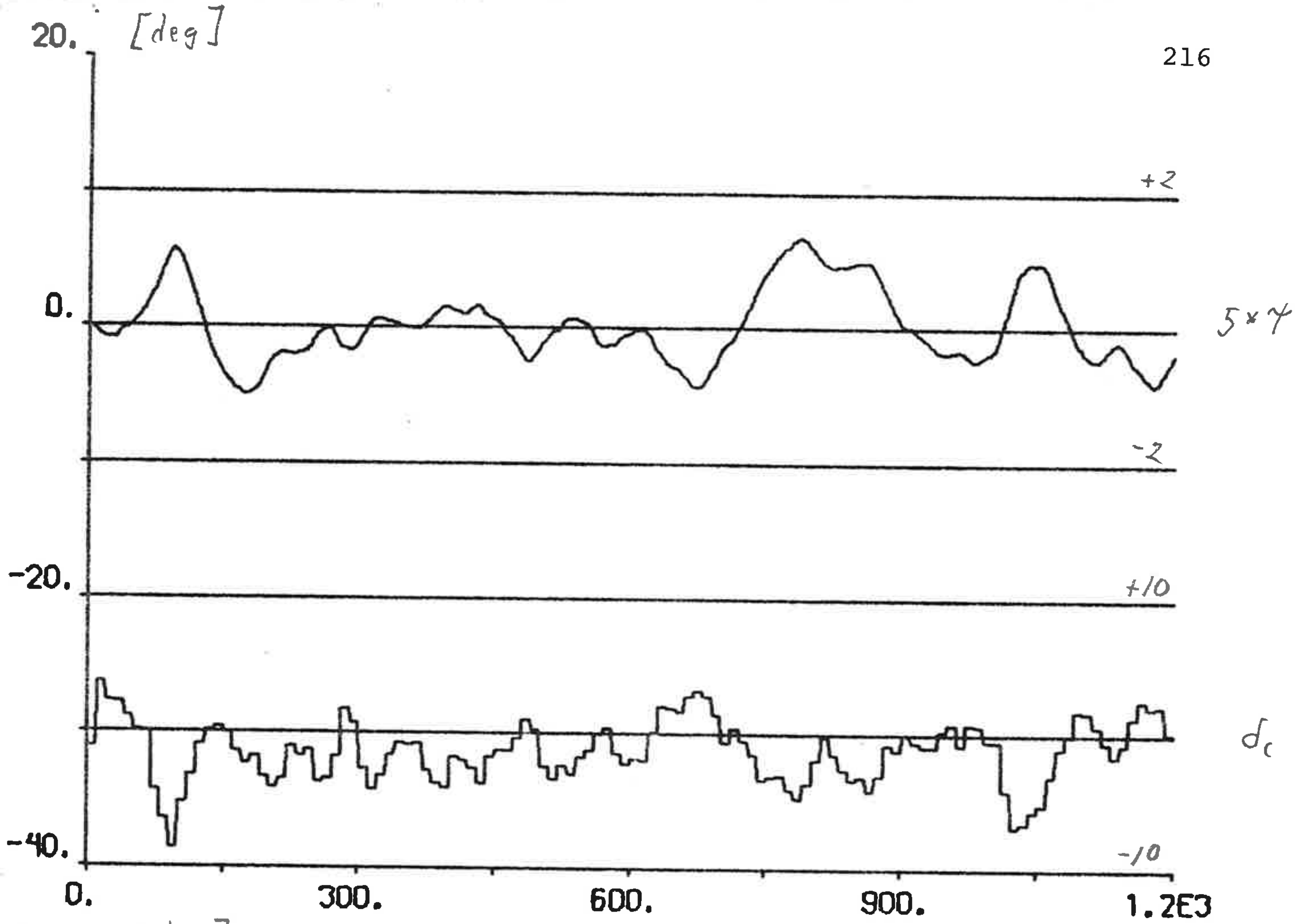


Fig. 4.41 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, PID-regulator using non-filtered measurements.



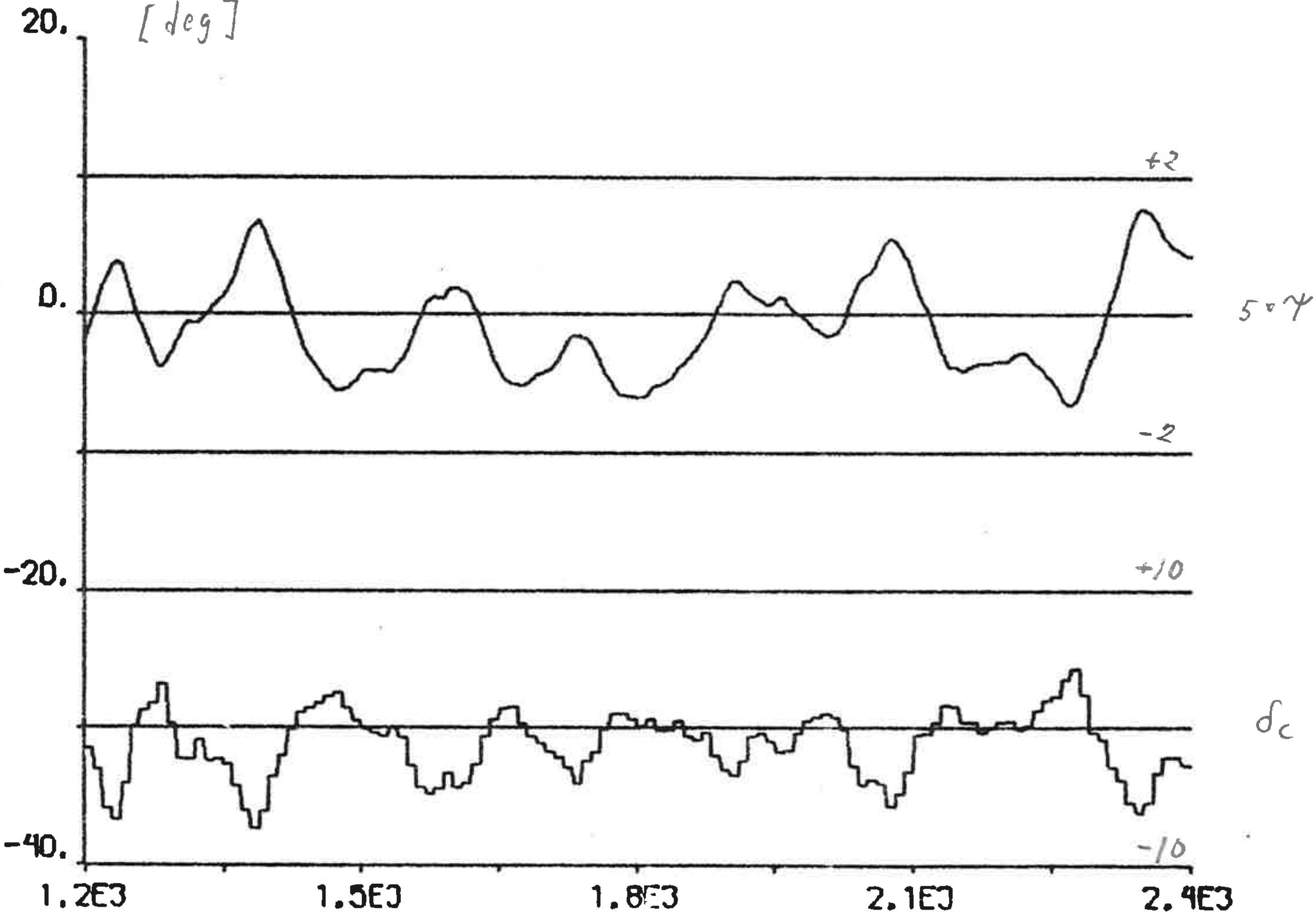
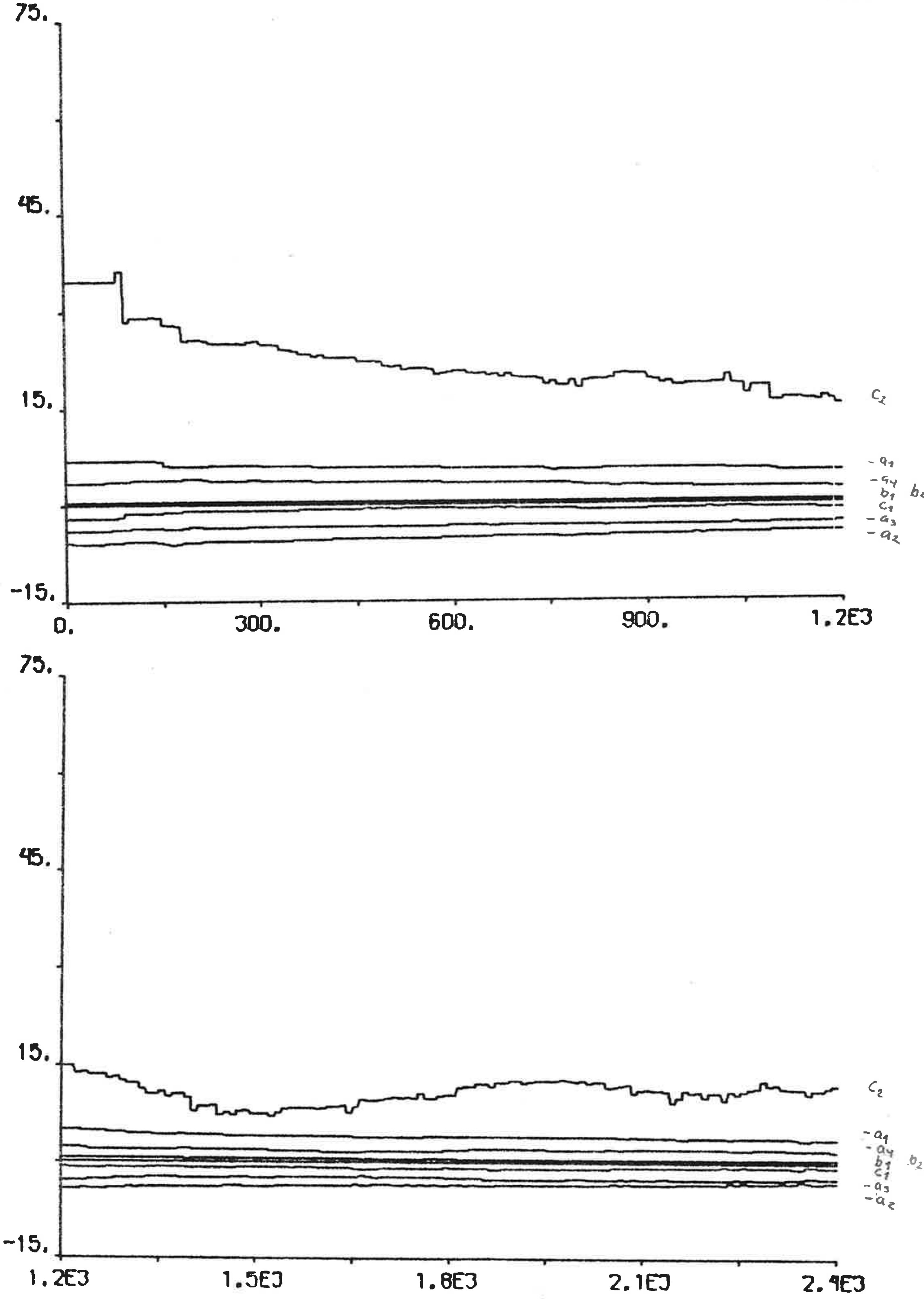
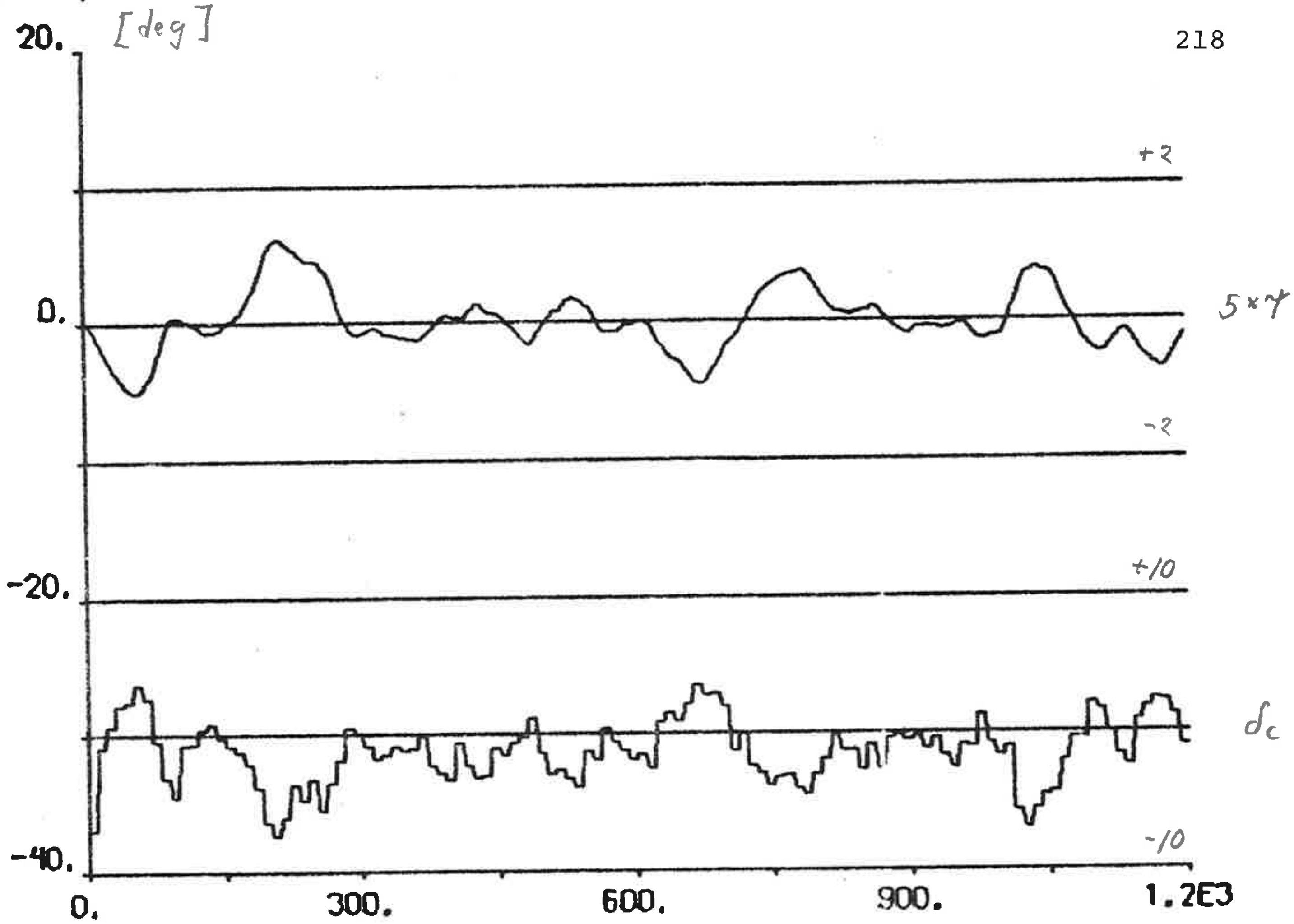


Fig. 4.42 a - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, self-tuning regulator using estimates from the Kalman filter ($q_2^* = 0.6$).



75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$
b_1
b_2
c_1
$-a_3$
$-a_2$

Fig. 4.42 b



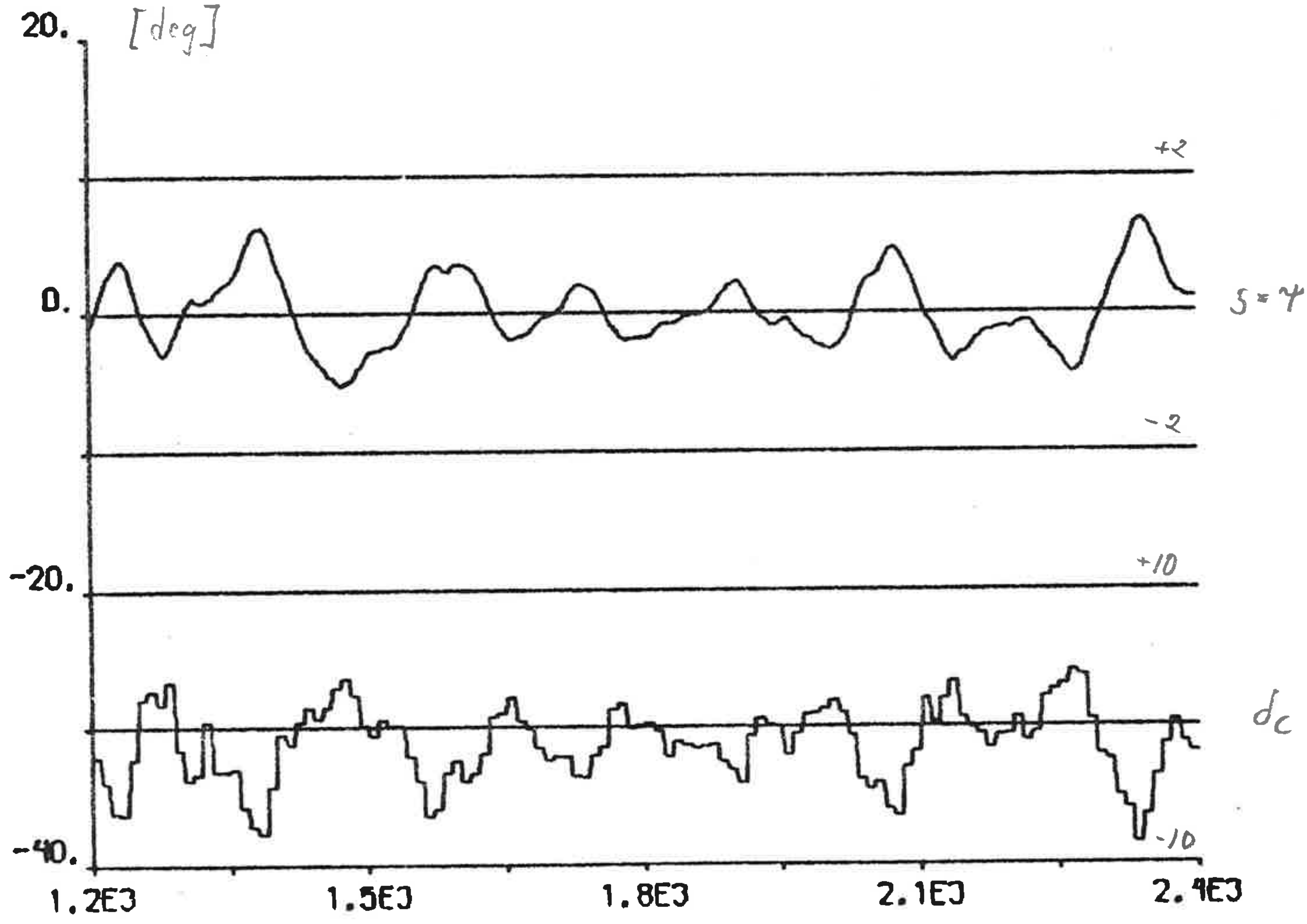


Fig. 4.43 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, δ_ℓ = 35 deg, PID-regulator using estimates from the Kalman filter (V_0 = 6.3 m/s).

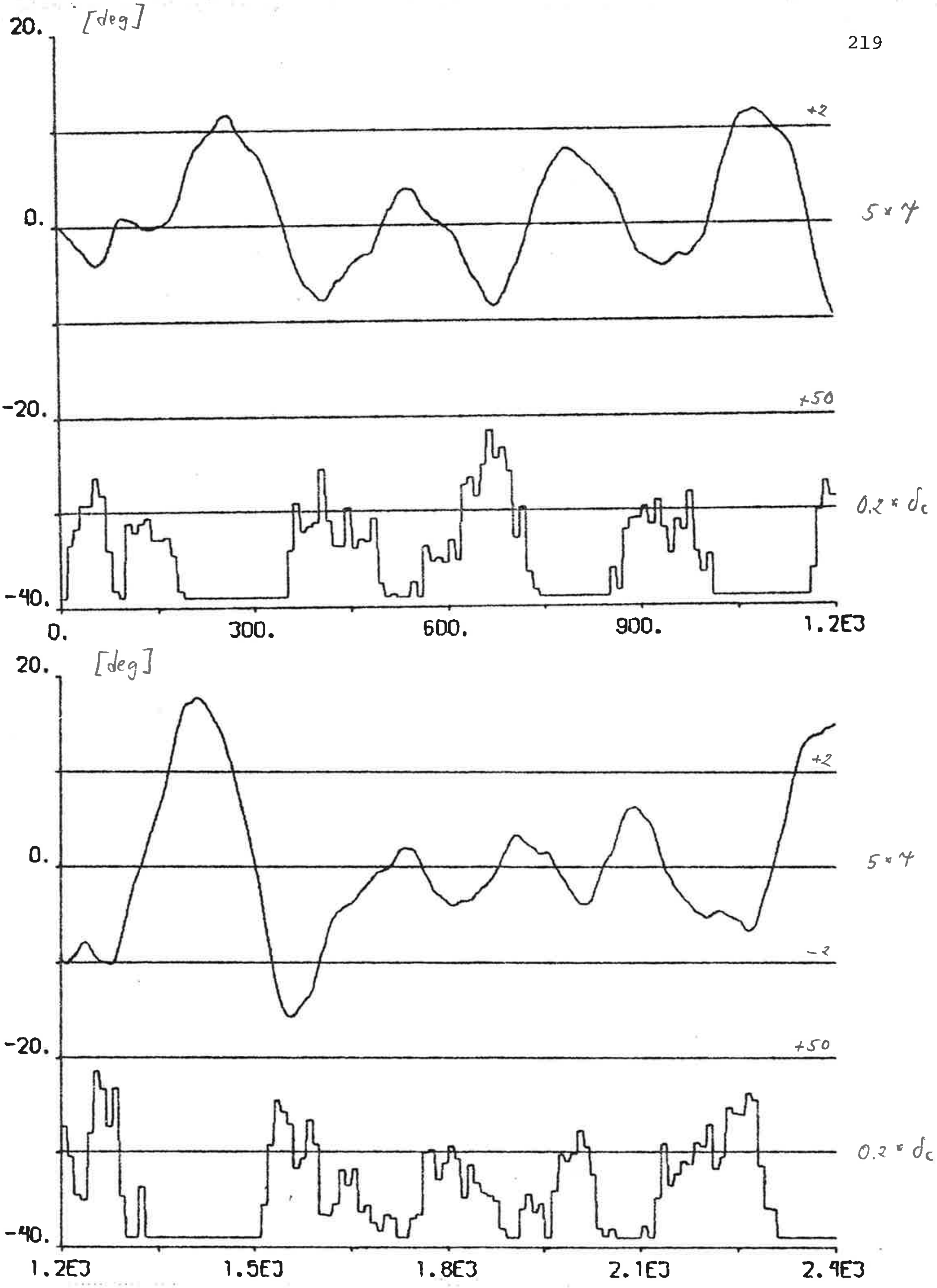


Fig. 4.44 – T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, PID-regulator using estimates from the Kalman filter.

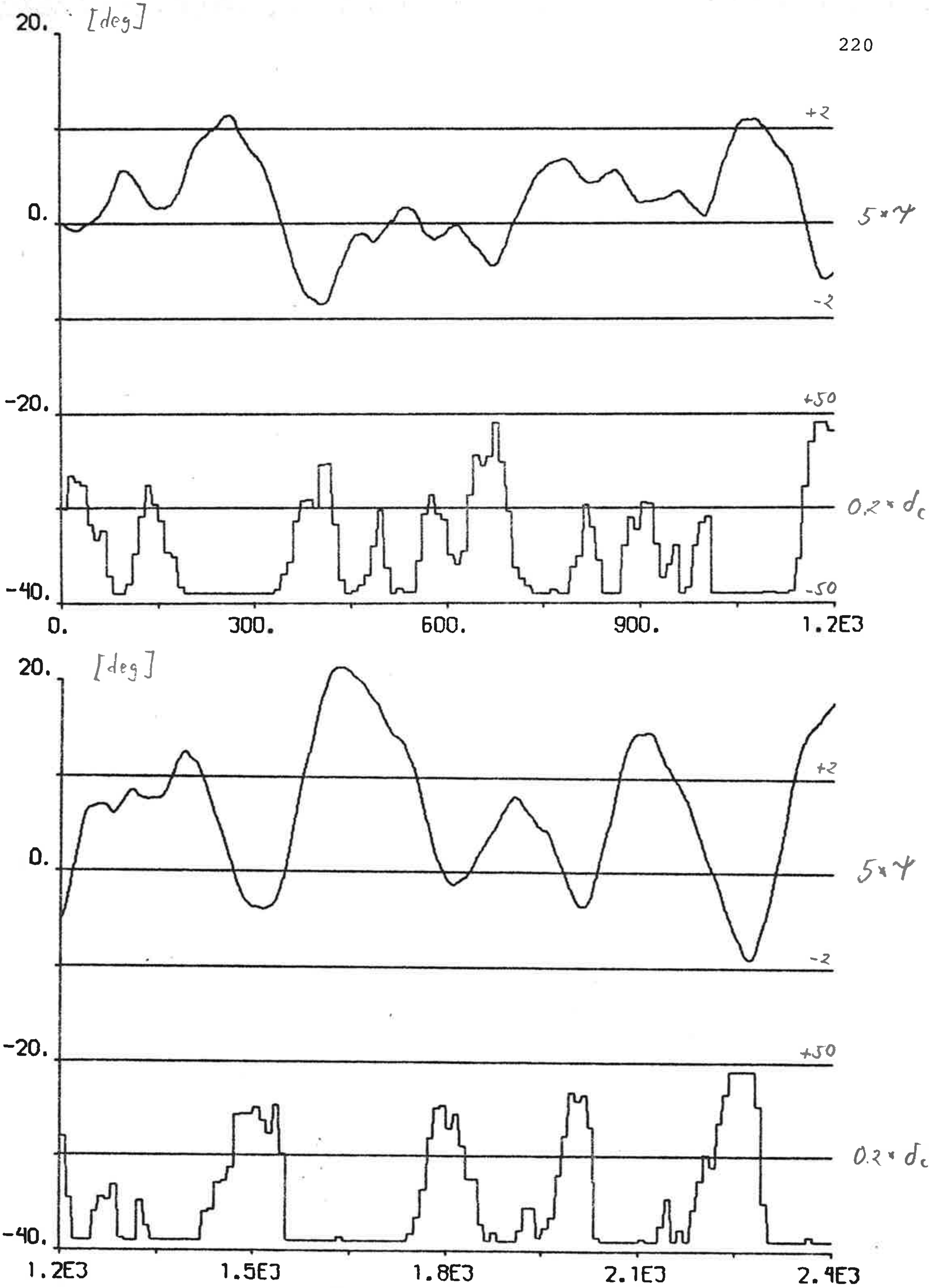
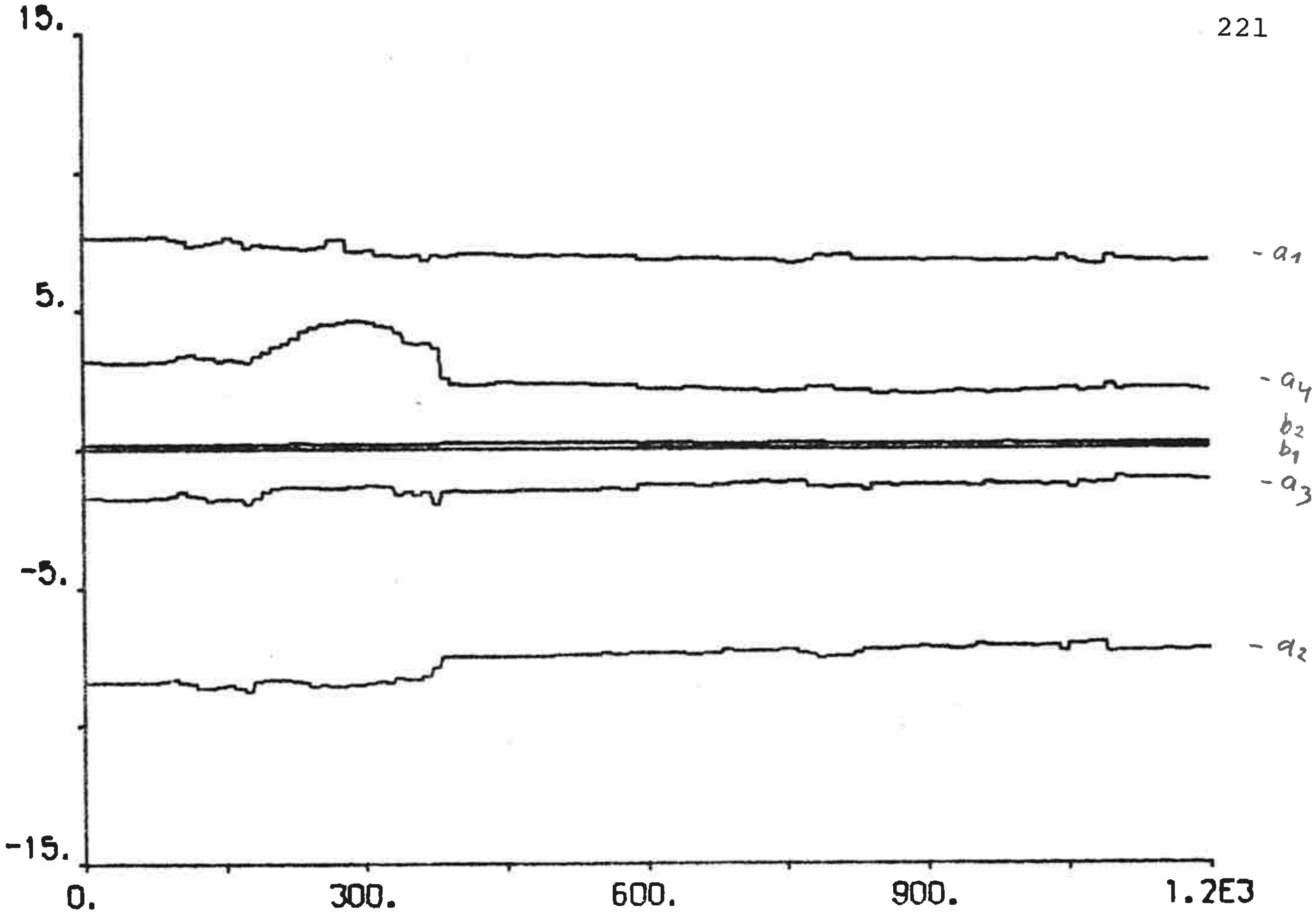


Fig. 4.45 a - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using non-filtered measurements.


15.
5.
-5.
-15.
0.
300.
600.
900.
1.2E3
- a1
- a4
b2
b1
- a3
- a2

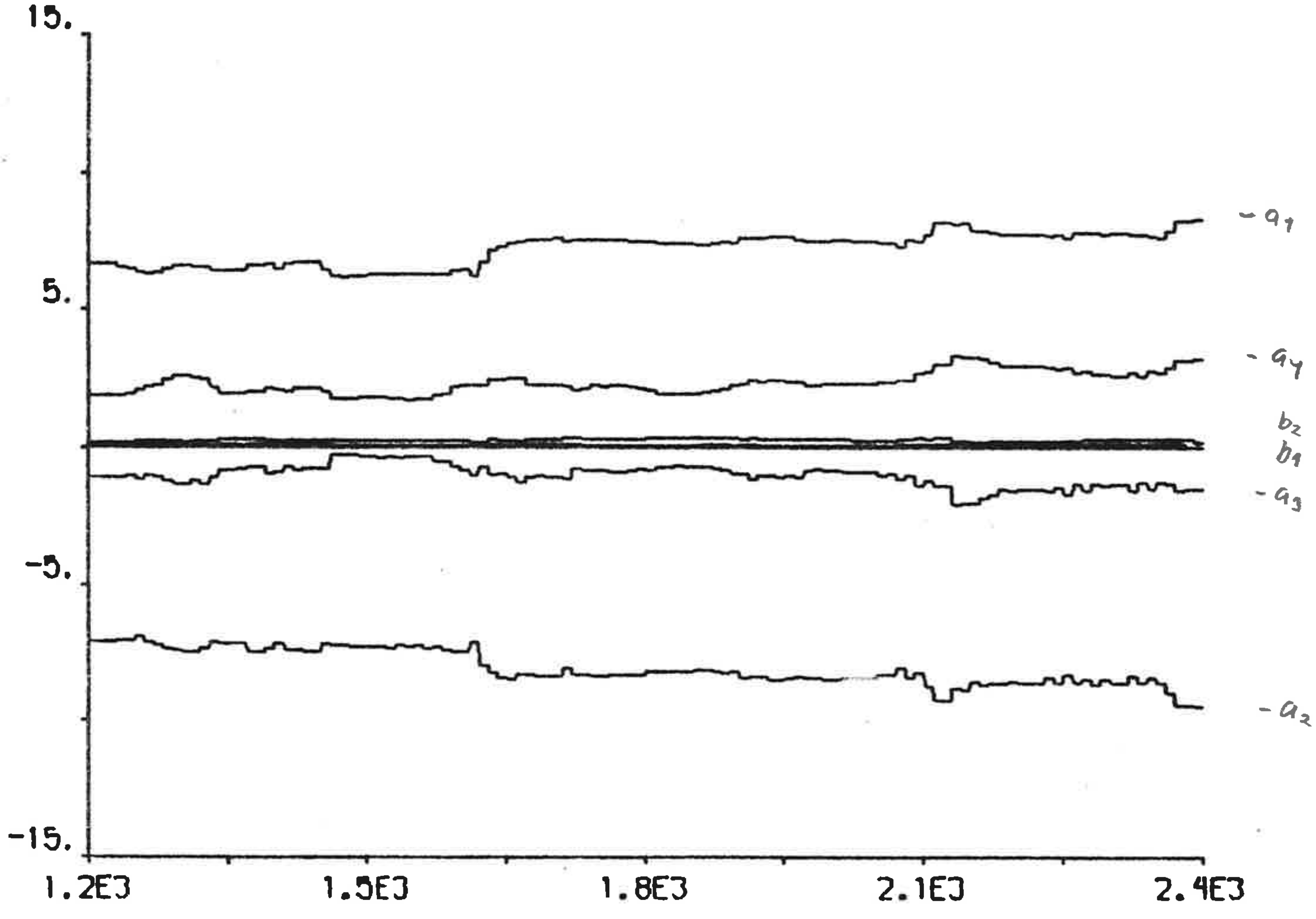

15.
5.
-5.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
- a1
- a4
b2
b1
- a3
- a2

Fig. 4.45 b

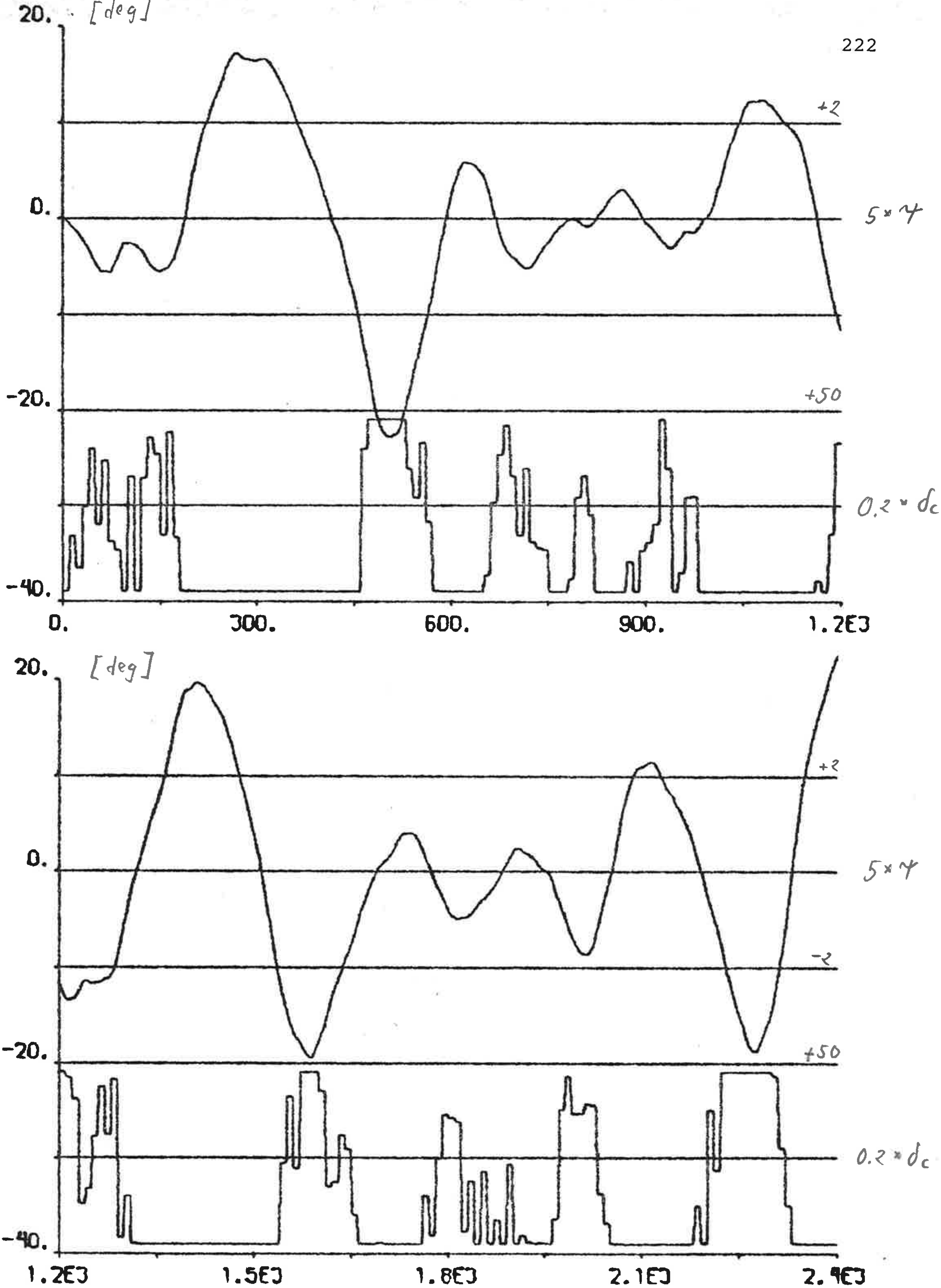


Fig. 4.46 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, PID-regulator using non-filtered measurements.

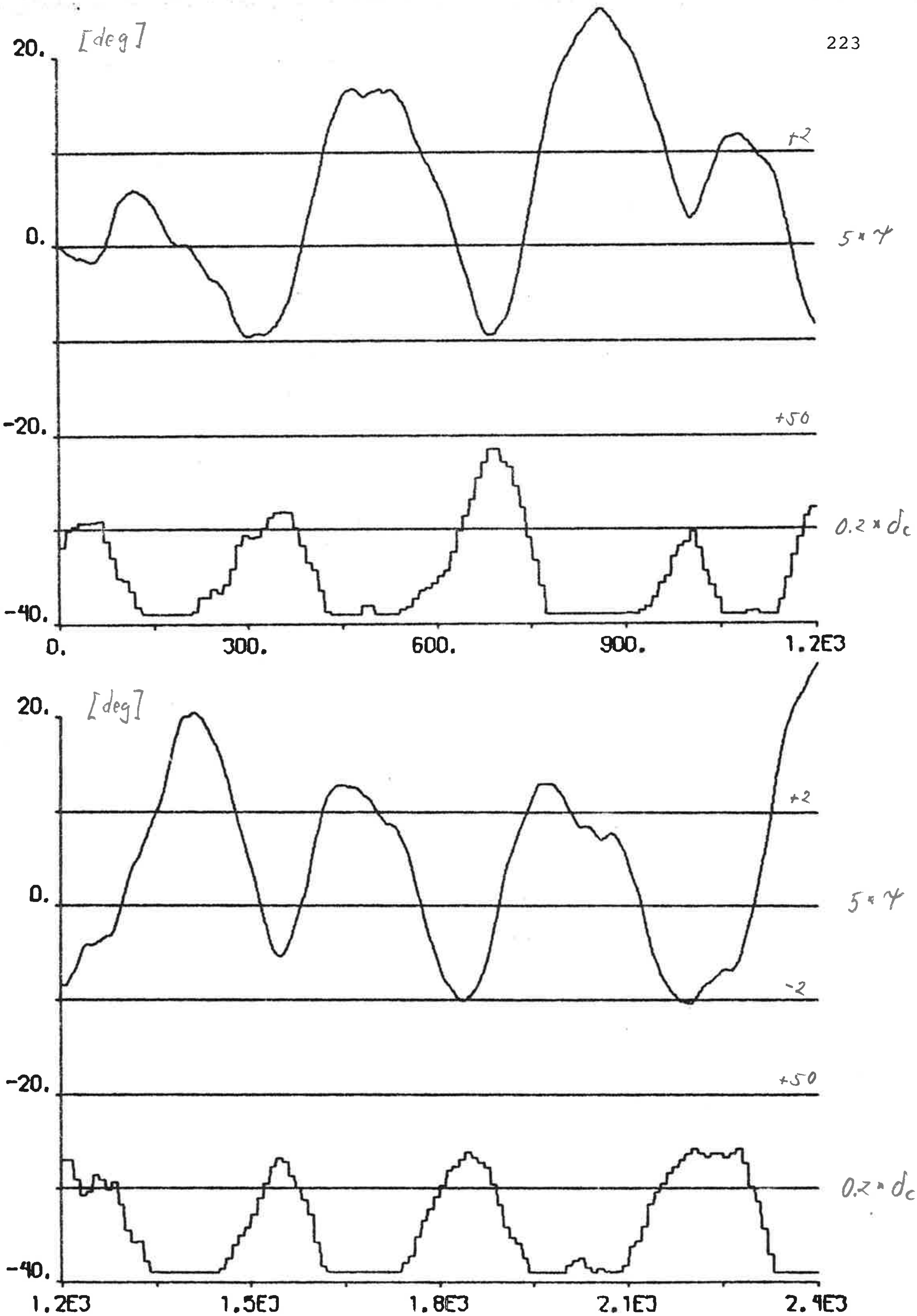


Fig. 4.47 a - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using estimates from the Kalman filter ($q_2^* = 3$).

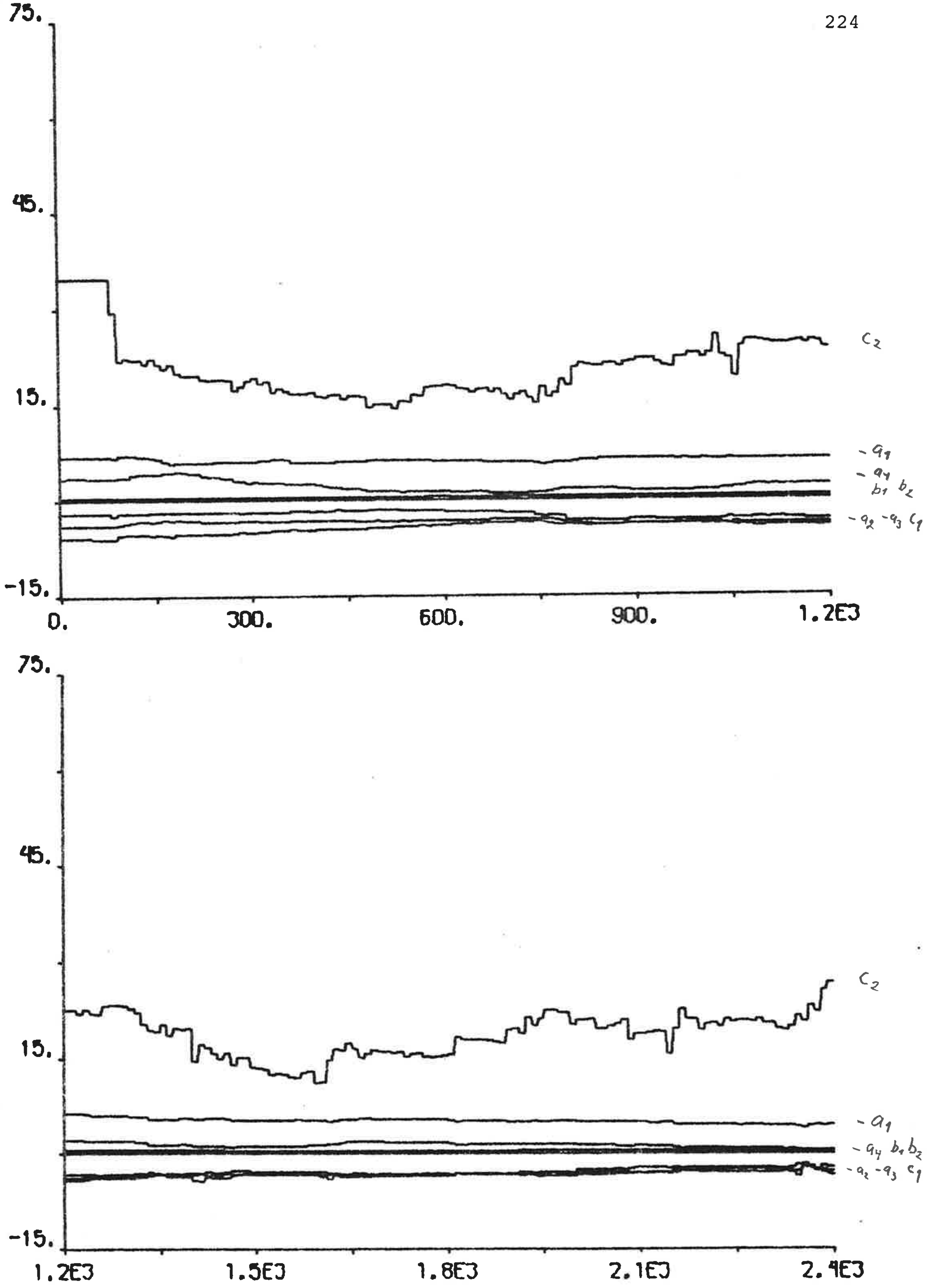

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$ b_1 b_2
$-a_2$ $-a_3$ c_1
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c_2
$-a_1$
$-a_4$ b_1 b_2
$-a_2$ $-a_3$ c_1

Fig. 4.47 b

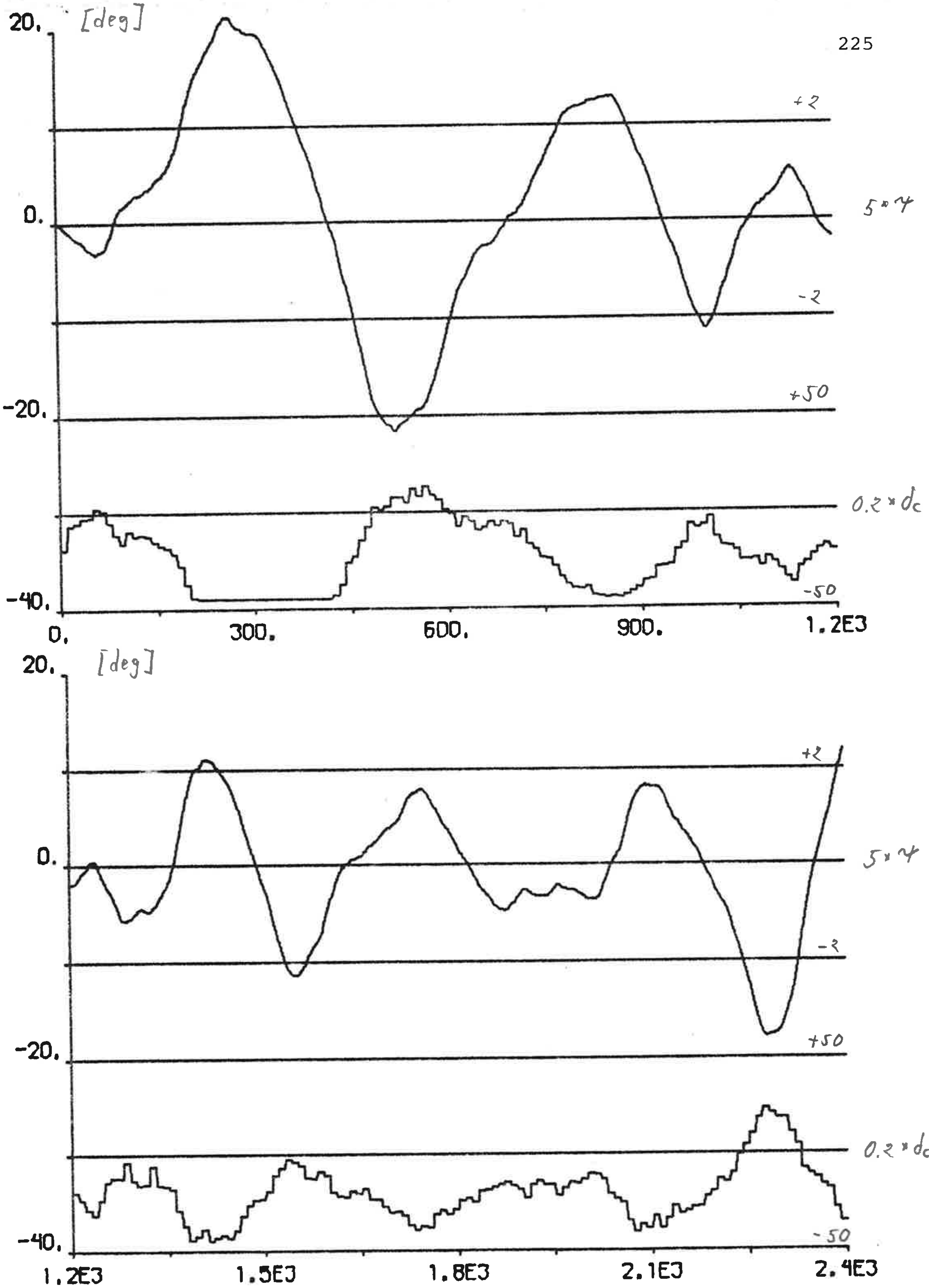


Fig. 4.48 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, PID-regulator using estimates from the Kalman filter (V_0 = 4 m/s).

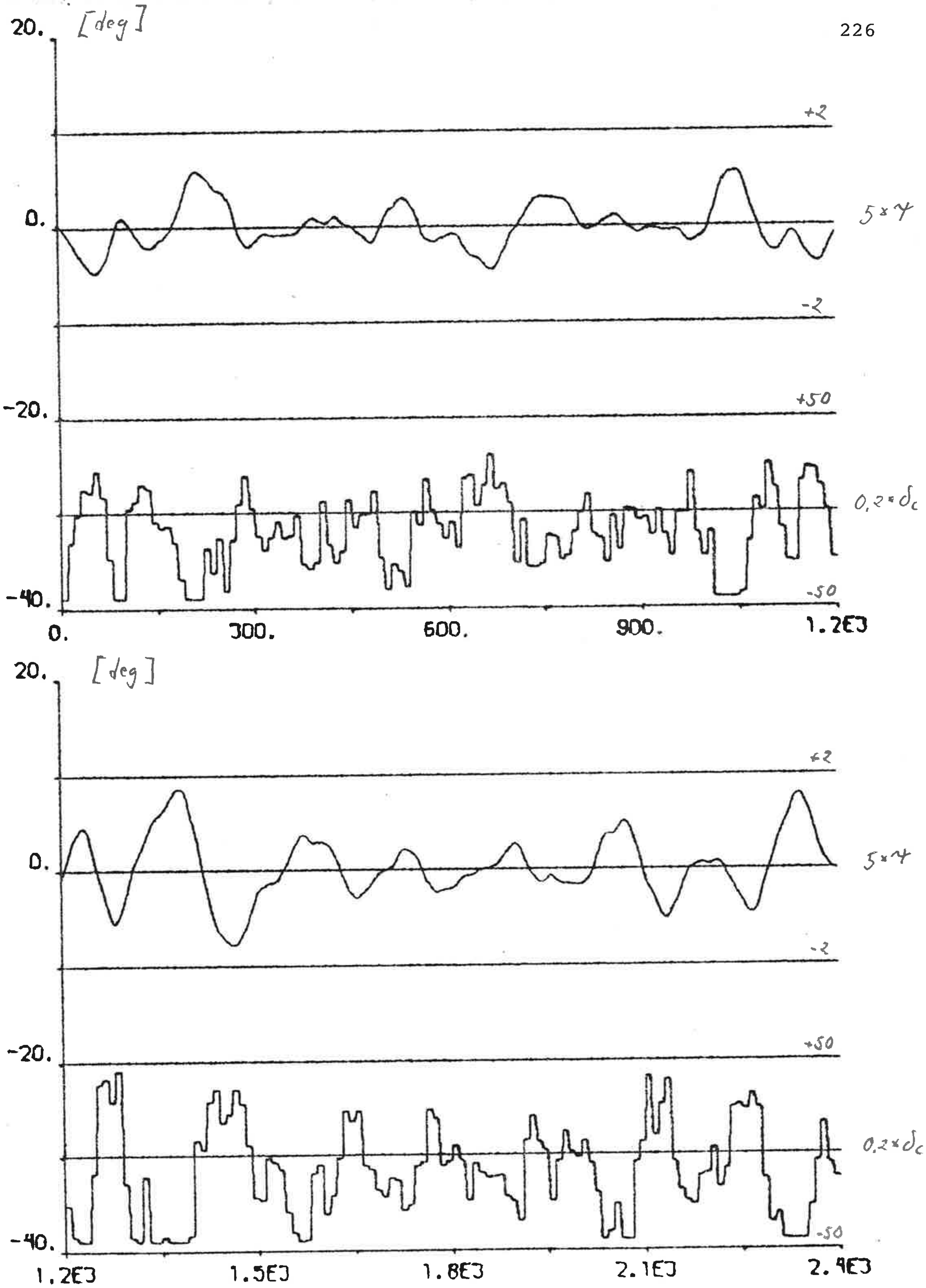


Fig. 4.49 - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, PID-regulator using estimates from the Kalman filter.

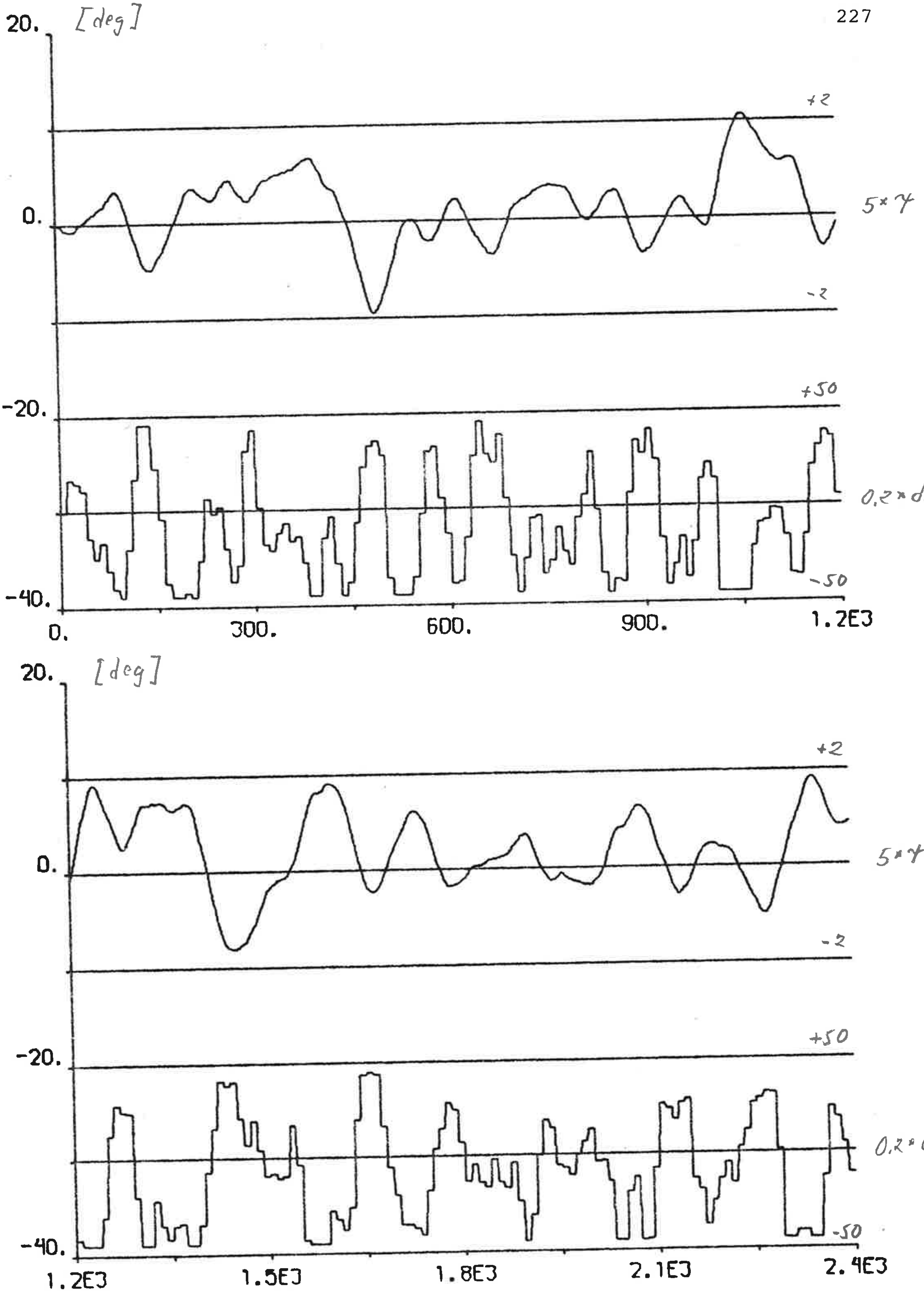


Fig. 4.50 a - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg
self-tuning regulator using non-filtered measurements.

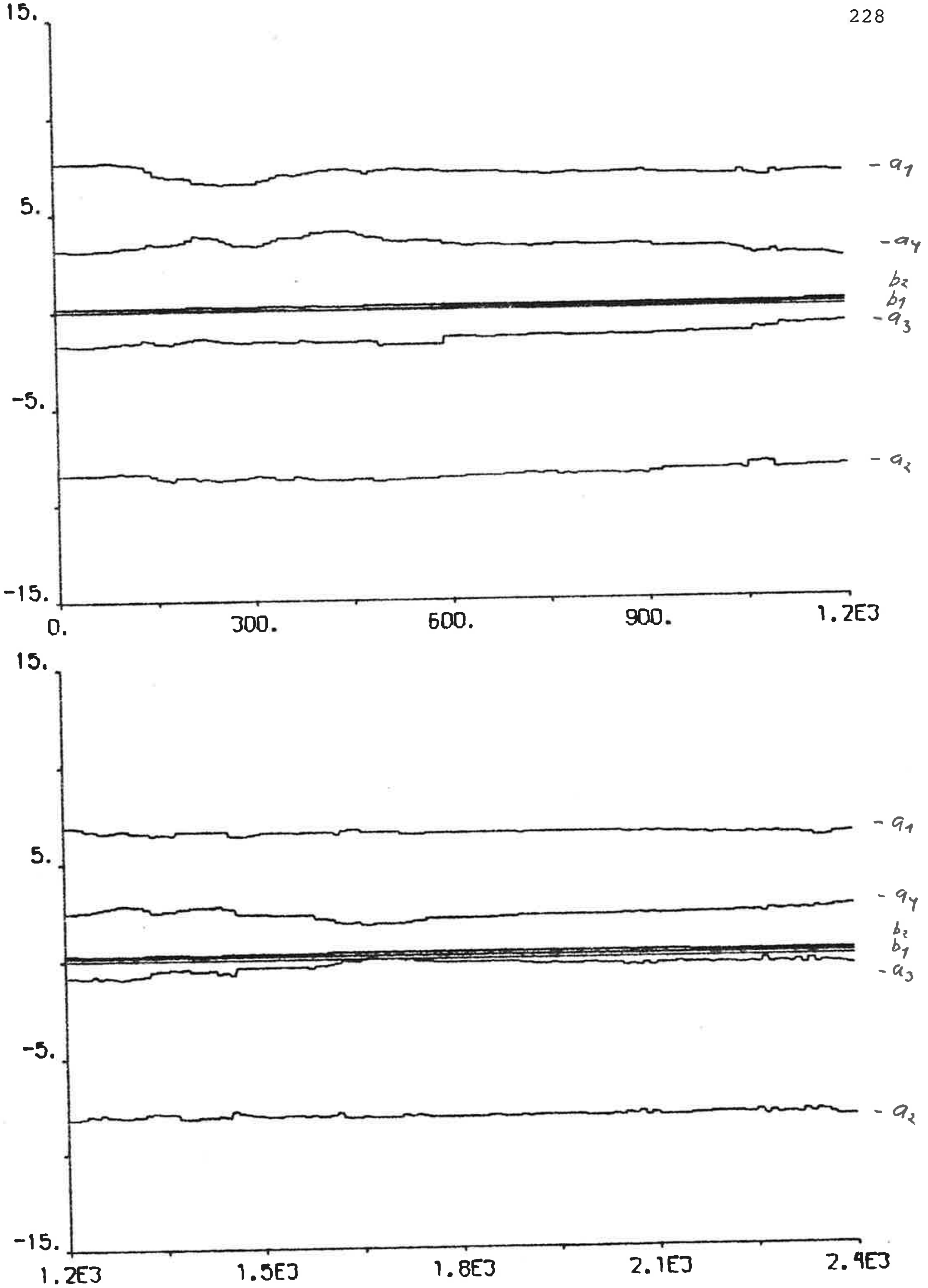
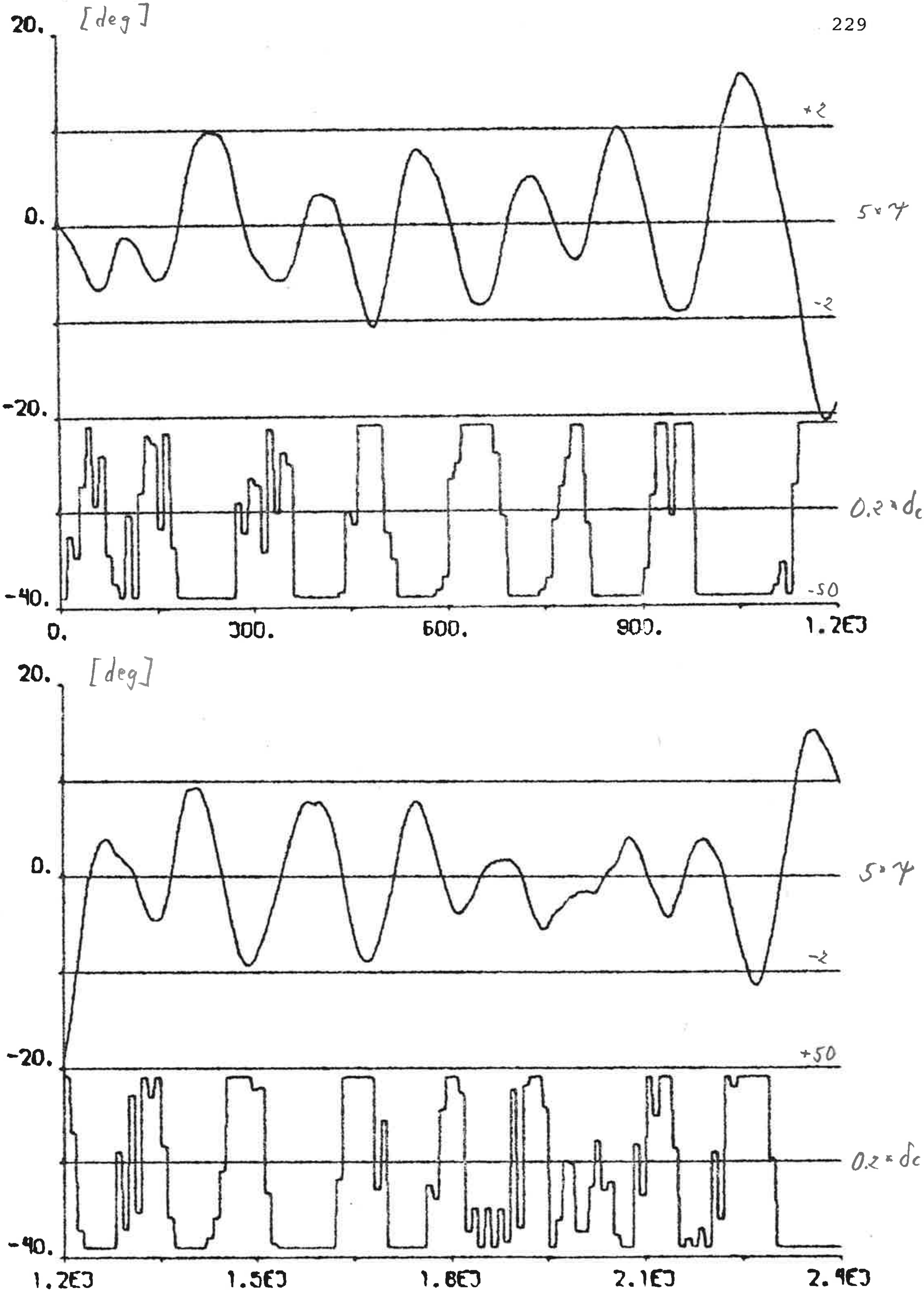

15.
5.
-5.
-15.
0.
300.
600.
900.
1.2E3
- a_1
- a_4
b_2
b_1
- a_3
- a_2
15.
5.
-5.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
- a_1
- a_4
b_2
b_1
- a_3
- a_2

Fig. 4.50 b



<u>Fig. 4.51</u> - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg,
PID-regulator using non-filtered measurements.

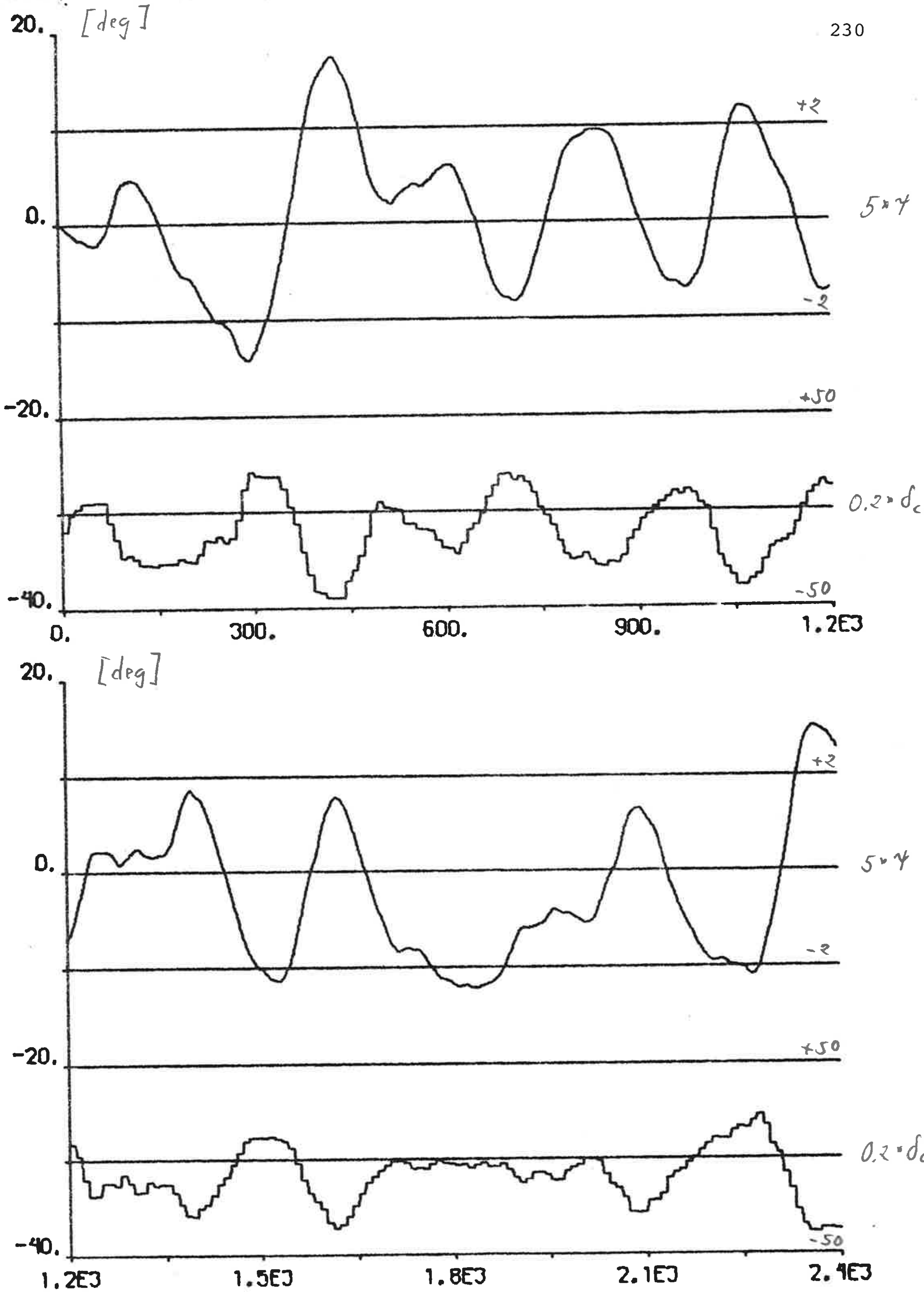


Fig. 4.52 a - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, self-tuning regulator using estimates from the Kalman filter (q_2^* = 3).

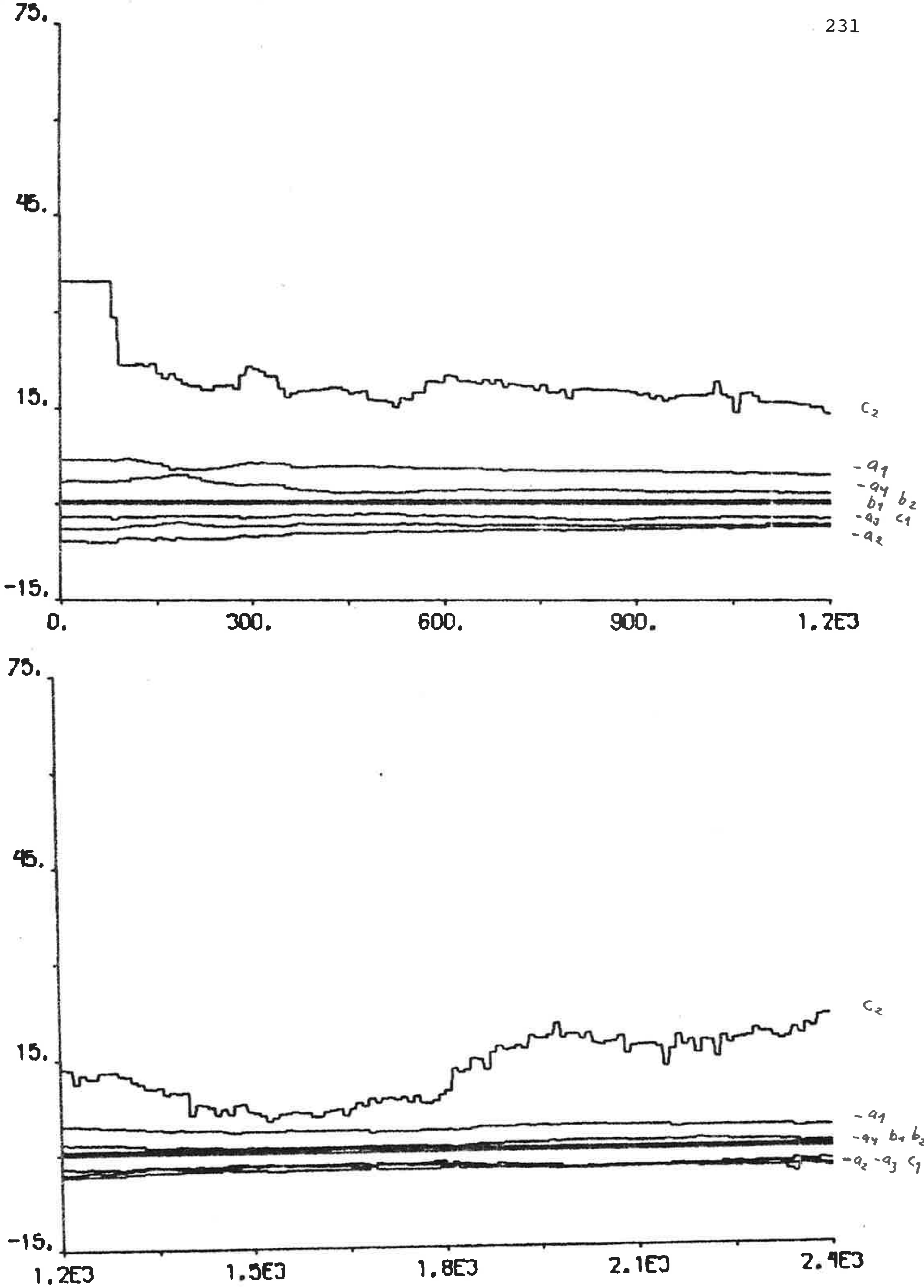

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c2
-a1
-a4 b2
b1
-a3 c1
-a2
75.
45.
15.
-15.
1.2E3
1.5E3
1.8E3
2.1E3
2.4E3
c2
-a1
-a4 b1 b2
-a2 -a3 c1

Fig. 4.52 b

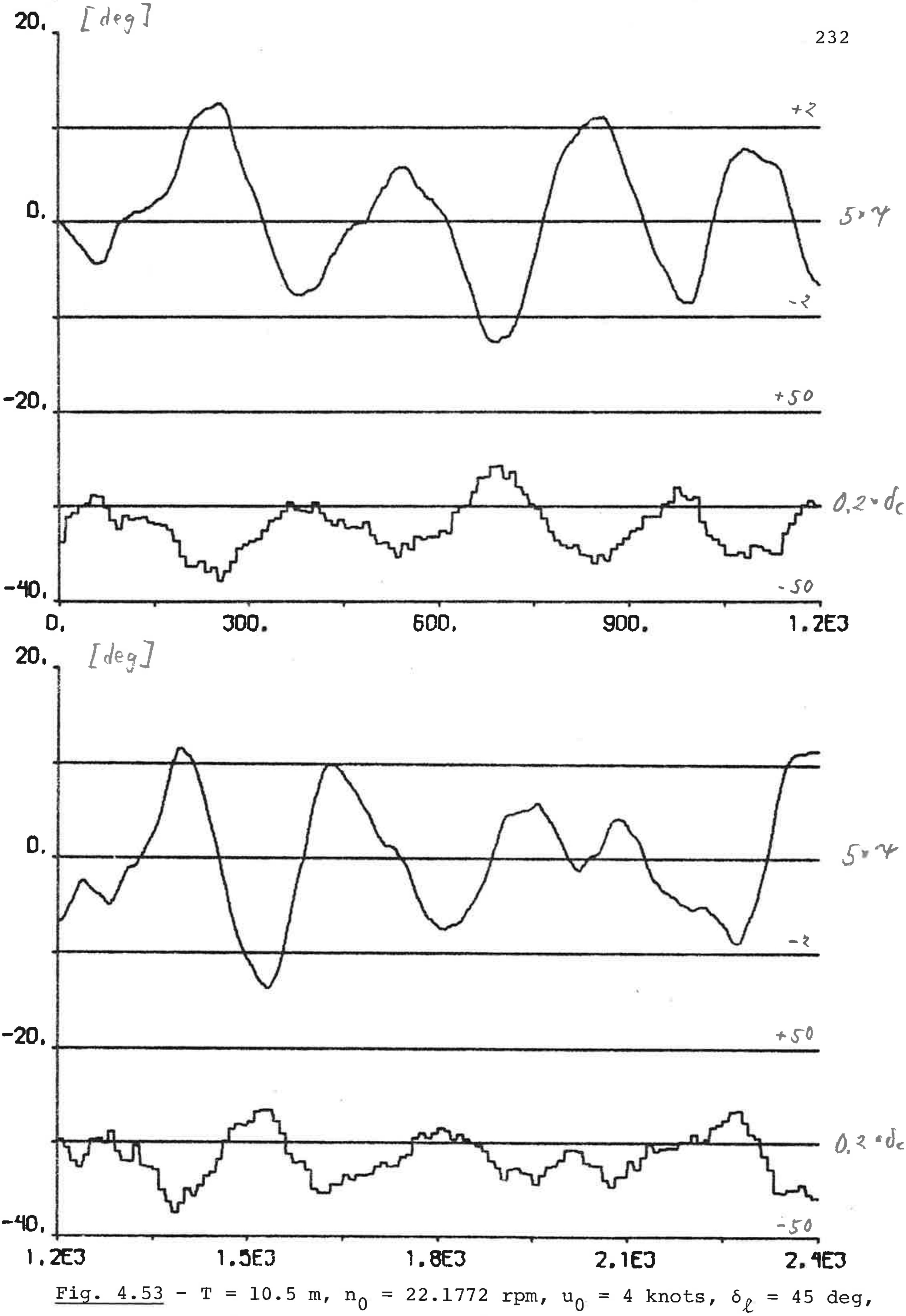


Fig. 4.53 - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, δ_ℓ = 45 deg, PID-regulator using estimates from the Kalman filter (V_0 = 4 m/s).

4.3 Yawing

Yawing simulations with the yaw regulator, using either the Kalman filter estimates or the non-filtered measurements, are shown in Figs 4.54 - 4.95. The initial speed u_0 is equal to 15.8, 10 or 4 knots and the mean draught T is equal to 22.3 or 10.5 m. Course changes $\Delta\psi_{ref}$ of 2, 4, 45 and 120 deg are requested and the reference yaw rate r_{ref} is equal to 0, 0.1 or 0.3 deg/s. The rudder limit δ_ℓ is always equal to 45 deg. Examples of Kalman filter estimates during yaws are shown in Figs 4.57, 4.58, 4.65, 4.66, 4.88 and 4.93. A summary of the simulations is given in Table 4.8.

It can be concluded that the performance of the Kalman filter, when the draught and the initial speed are varied, is approximately of the same quality during yawing as during straight course keeping (cf Section 4.1). Notice, however, that the estimates $\hat{\delta}_0$, $\hat{d}_v$, $\hat{d}_r$ and $\hat{d}_\delta$ are disturbed rather much during yaws. This implies that the correct yaw rate is not always kept when the yaw regulator uses the Kalman filter estimates. Of course, an incorrect yaw rate is always kept when non-filtered measurements are used, since the yaw rate measurement is biased in the simulations. A straightforward way to improve the Kalman filter is to skip the updating of $\hat{\delta}_0$, $\hat{d}_v$, $\hat{d}_r$ and $\hat{d}_\delta$ during yaws.

The only parameter of the yaw regulator, that is changed when the speed is changed, is $\bar{c}_2$. The following relation is found empirically:

$$\bar{c}_2 = \sqrt{\frac{V_0}{V_s}}\ c_2^*$$

where V_0 = 8 m/s and c_2^* = 50 s. This relation is used in the simulations of this section.

T [m]	n_0 [rpm]	u_0 [knots]	Self-tuning reg. and yaw reg. using Kalman filter estimates	Self-tuning reg. and yaw reg. using non-filtered measurements	$\bar{c}_2$ [s]	$\Delta\psi_{ref}$ [deg]	r_{ref} [deg/s]	Fig.	Remarks
22.3	87.6	15.8	×		50	2	0	4.54	
22.3	87.6	15.8	×		50	4	0.1	4.55	
22.3	87.6	15.8	×		50	4	0.3	4.56	
22.3	87.6	15.8	×		50	45	0.1	4.57	x)
22.3	87.6	15.8	×		50	120	0.3	4.58	x)
22.3	87.6	15.8		×	50	4	0.1	4.59	
22.3	87.6	15.8		×	50	45	0.1	4.60	
22.3	87.6	15.8		×	50	120	0.3	4.61	
10.5	87.6	15.8	×		50	2	0	4.62	
10.5	87.6	15.8	×		50	4	0.1	4.63	
10.5	87.6	15.8	×		50	4	0.3	4.64	
10.5	87.6	15.8	×		50	45	0.1	4.65	x)
10.5	87.6	15.8	×		50	120	0.3	4.66	x)
10.5	87.6	15.8		×	50	4	0.1	4.67	
10.5	87.6	15.8		×	50	45	0.1	4.68	
10.5	87.6	15.8		×	50	120	0.3	4.69	
22.3	55.443	10	×		63.25	2	0	4.70	
22.3	55.443	10	×		63.25	4	0.1	4.71	
22.3	55.443	10	×		63.25	4	0.3	4.72	
22.3	55.443	10	×		63.25	45	0.1	4.73	
22.3	55.443	10	×		63.25	120	0.3	4.74	
22.3	55.443	10		×	63.25	4	0.1	4.75	
22.3	55.443	10		×	63.25	45	0.1	4.76	
22.3	55.443	10		×	63.25	120	0.3	4.77	
10.5	55.443	10	×		63.25	2	0	4.78	
10.5	55.443	10	×		63.25	4	0.1	4.79	
10.5	55.443	10	×		63.25	4	0.3	4.80	
10.5	55.443	10	×		63.25	45	0.1	4.81	
10.5	55.443	10	×		63.25	120	0.3	4.82	
10.5	55.443	10		×	63.25	4	0.1	4.83	
10.5	55.443	10		×	63.25	45	0.1	4.84	
10.5	55.443	10		×	63.25	120	0.3	4.85	
22.3	22.1772	4	×		100	2	0	4.86	
22.3	22.1772	4	×		100	4	0.1	4.87	
22.3	22.1772	4	×		100	45	0.1	4.88	x)
22.3	22.1772	4		×	100	4	0.1	4.89	
22.3	22.1772	4		×	100	45	0.1	4.90	
10.5	22.1772	4	×		100	2	0	4.91	
10.5	22.1772	4	×		100	4	0.1	4.92	
10.5	22.1772	4	×		100	45	0.1	4.93	x)
10.5	22.1772	4		×	100	4	0.1	4.94	
10.5	22.1772	4		×	100	45	0.1	4.95	

x) The Kalman filter estimates are shown.

Table 4.8 - Summary of yawing simulations. The initial reference course ψ_{ref} is equal to 0 deg and the course change $\Delta\psi_{ref}$ is requested after 100 s. The rudder limit δ_ℓ is equal to 45 deg.

It can be concluded from the simulations that the performance of the yaw regulator, when Kalman filter estimates are used, is very good for different load conditions and speeds, with one exception: the performance when T = 22.3 m and u_0 = 4 knots is rather bad (cf Figs 4.86 - 4.88). Maybe it is possible to increase the yawing quality in this case by introducing more speed dependent parameters of the yaw regulator. Notice, however, that the forward speed u_m is decreased to the approximate value 1 knot, when T = 22.3 m, u_0 = 4 knots, $\Delta\psi_{ref}$ = 45 deg and r_{ref} = 0.1 deg/s (cf Fig. 4.88 e). It is, of course, rather difficult to obtain a good performance in such an extremely small speed. When the initial speed u_0 is equal to 10 knots, rather large rudder deviations are required compared to the case when u_0 = 15.8 knots. This is necessary, however, to obtain a good performance.

The performance of the yaw regulator, when non-filtered measurements are used, is not at all as good as the case when Kalman filter estimates are used. The rudder deviations are in general very large due to the noisy yaw rate measurements. It is probably possible to improve the performance by decreasing the values of the gain factors of the yaw regulator. See Källström (1976b). It can also be concluded that it is highly desired to filter the yaw rate in some way, if the measurements are very noisy. If the resolution of the heading measurements is good, it is also possible to perform a difference approximation to obtain a yaw rate estimate.

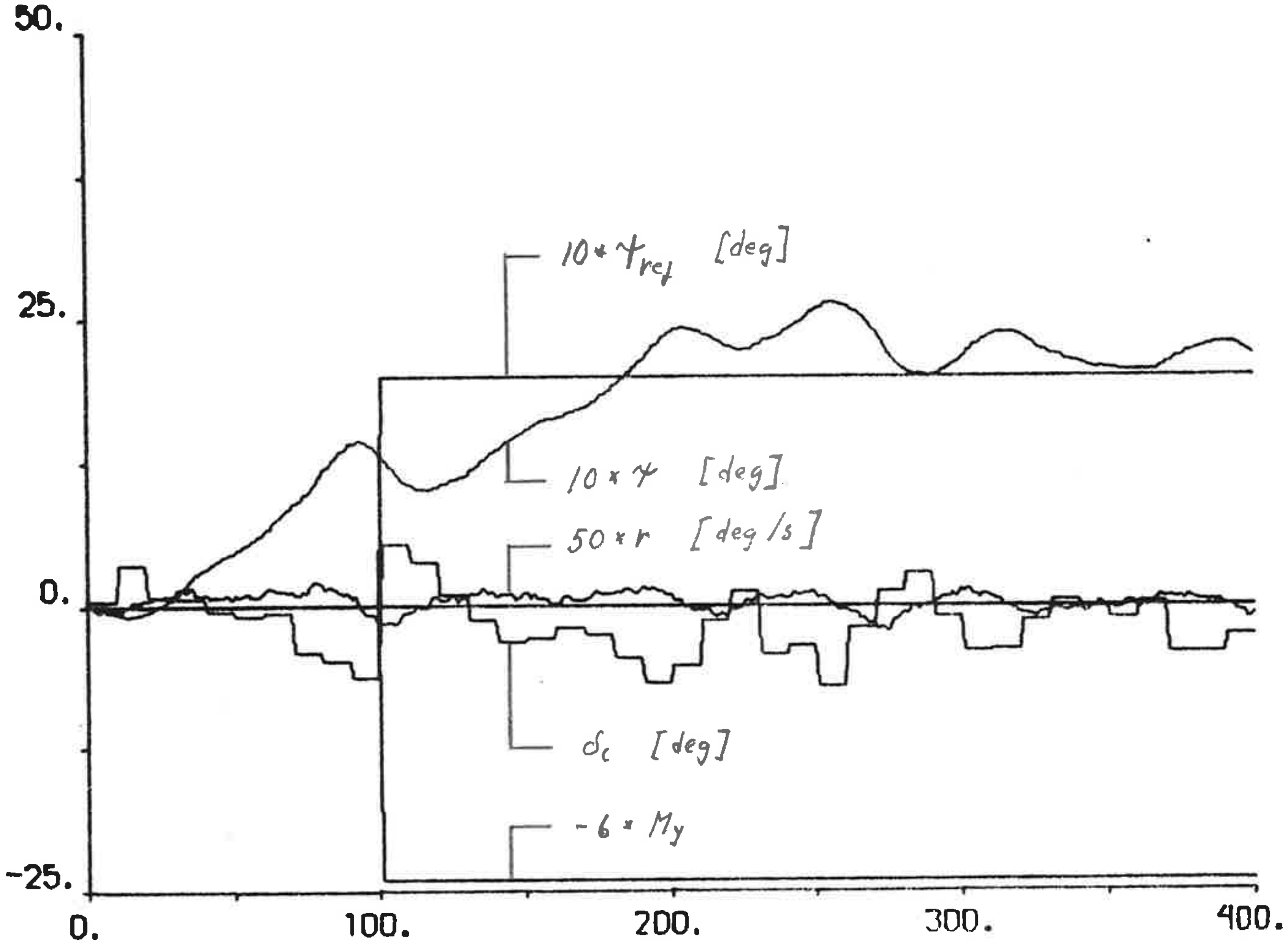


Fig. 4.54 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 2 deg, r_{ref} = 0 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 50 s).

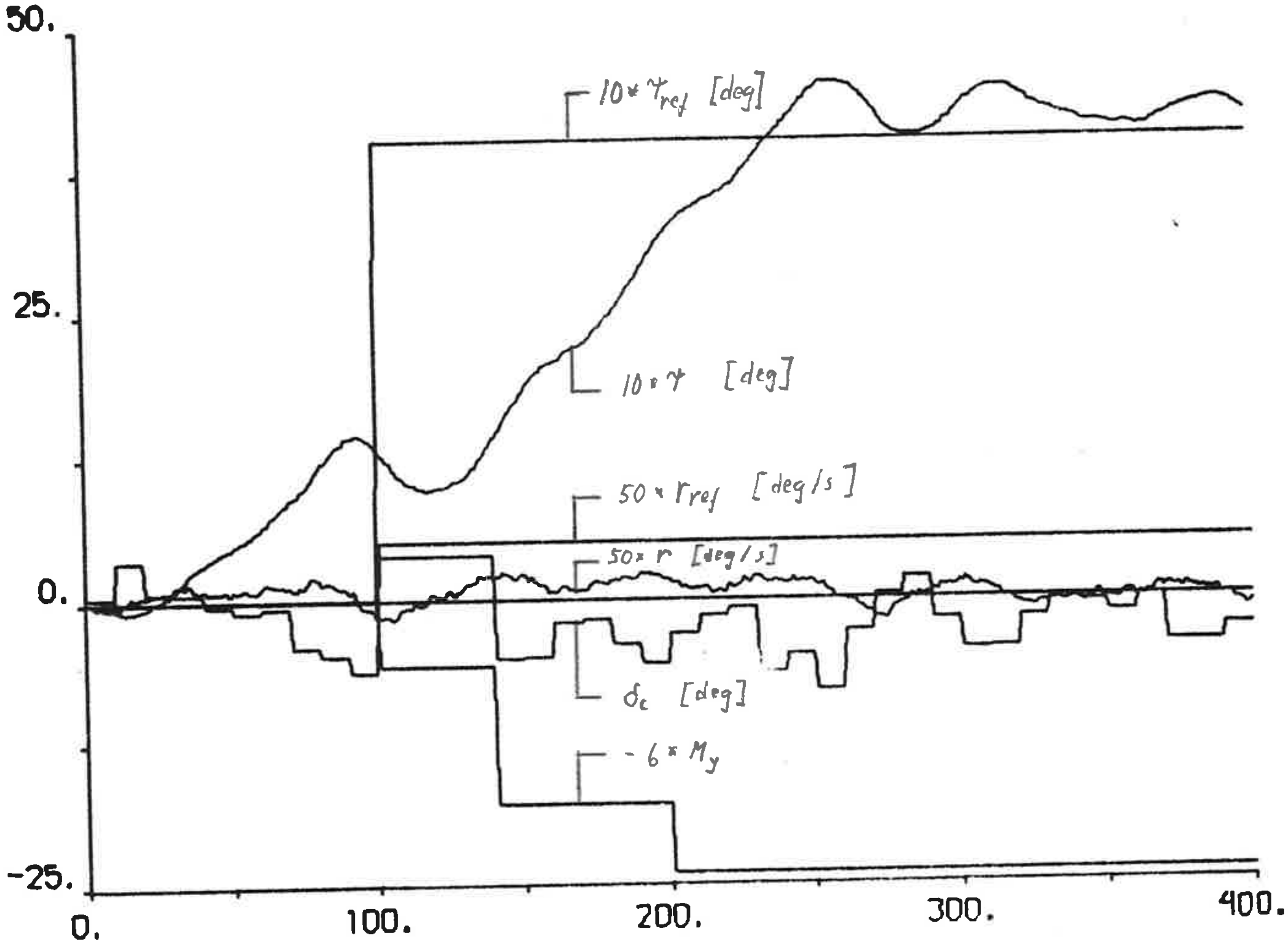


Fig. 4.55 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 50 s).

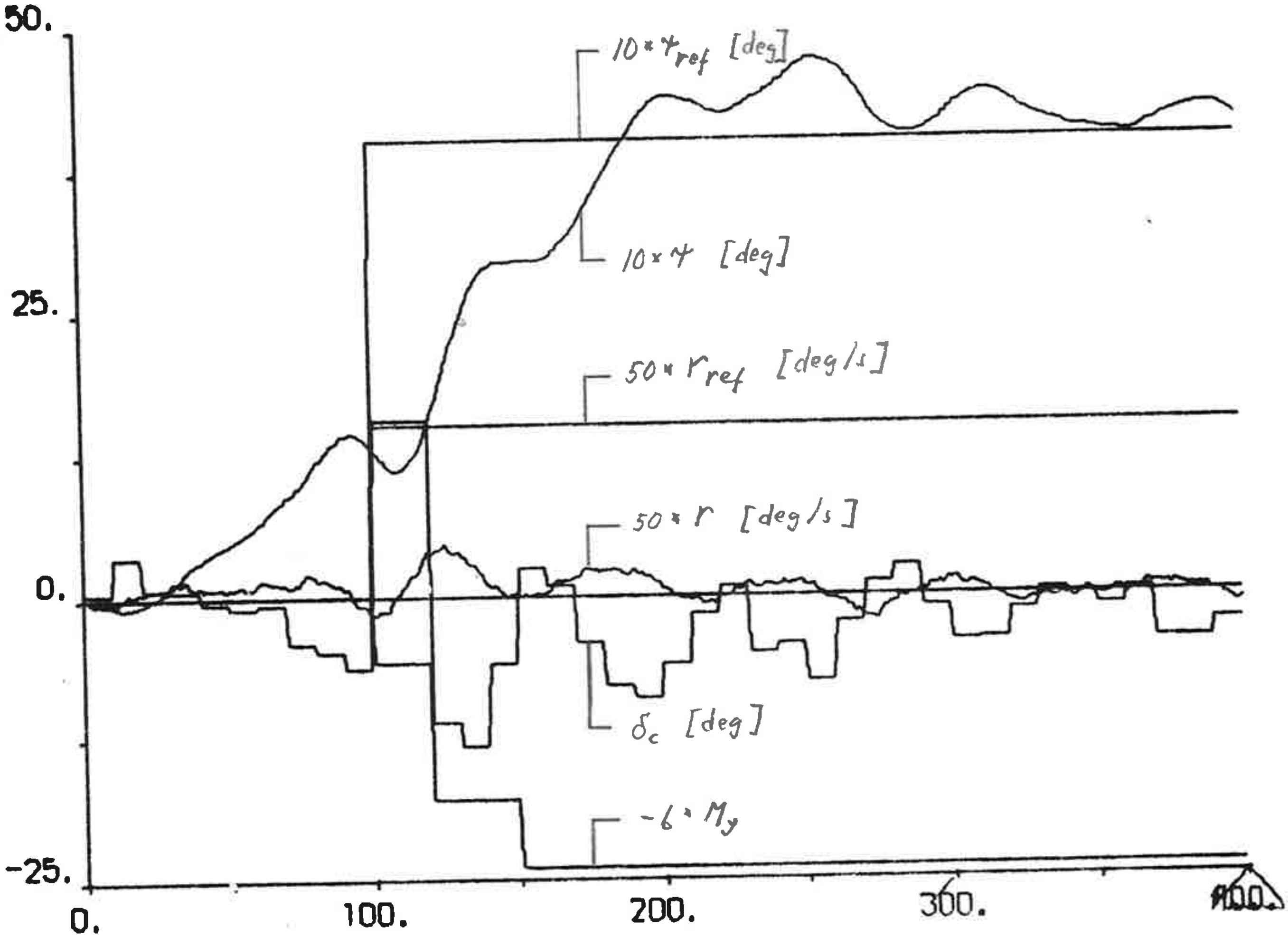


Fig. 4.56 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 50 s).

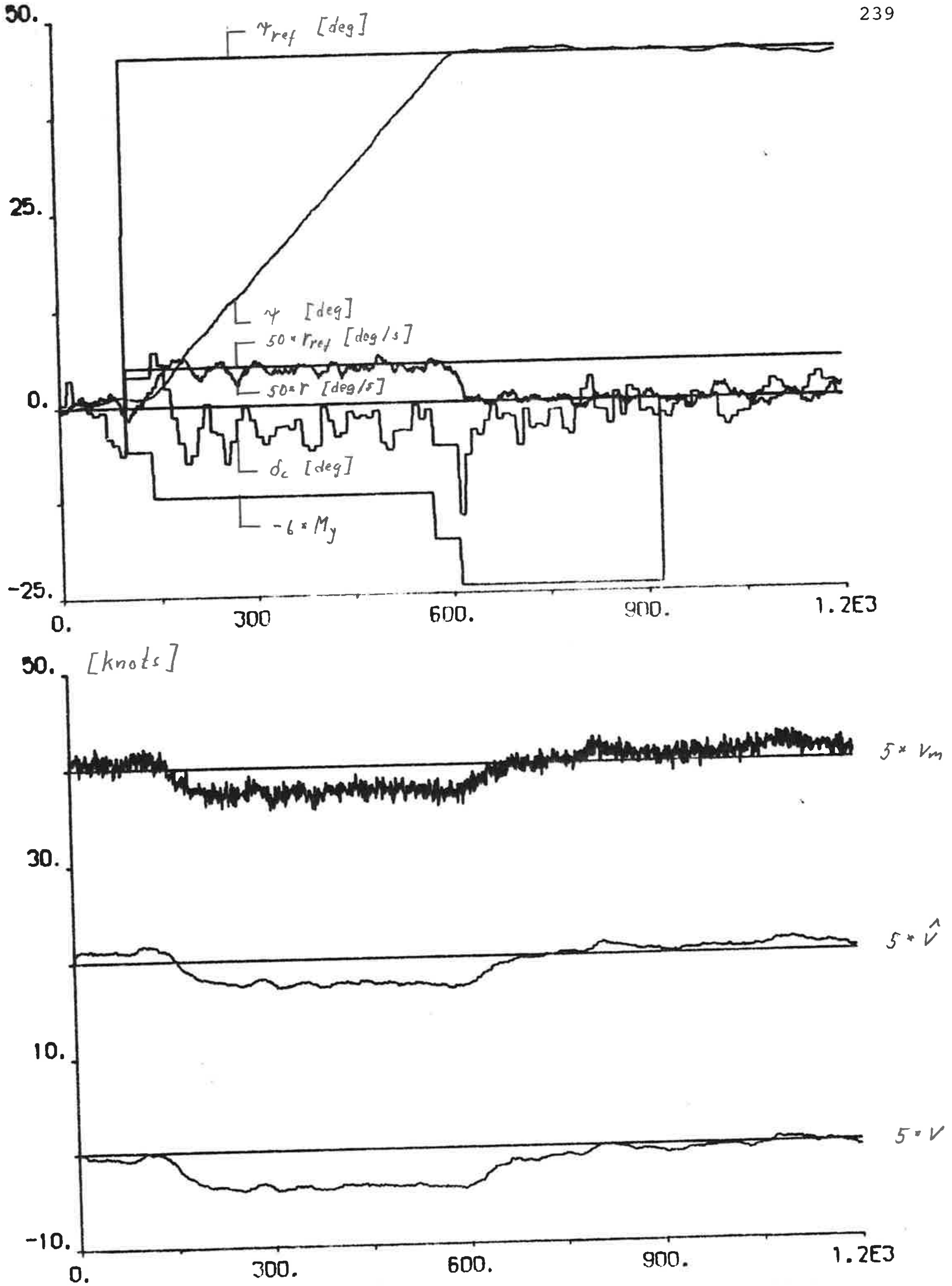
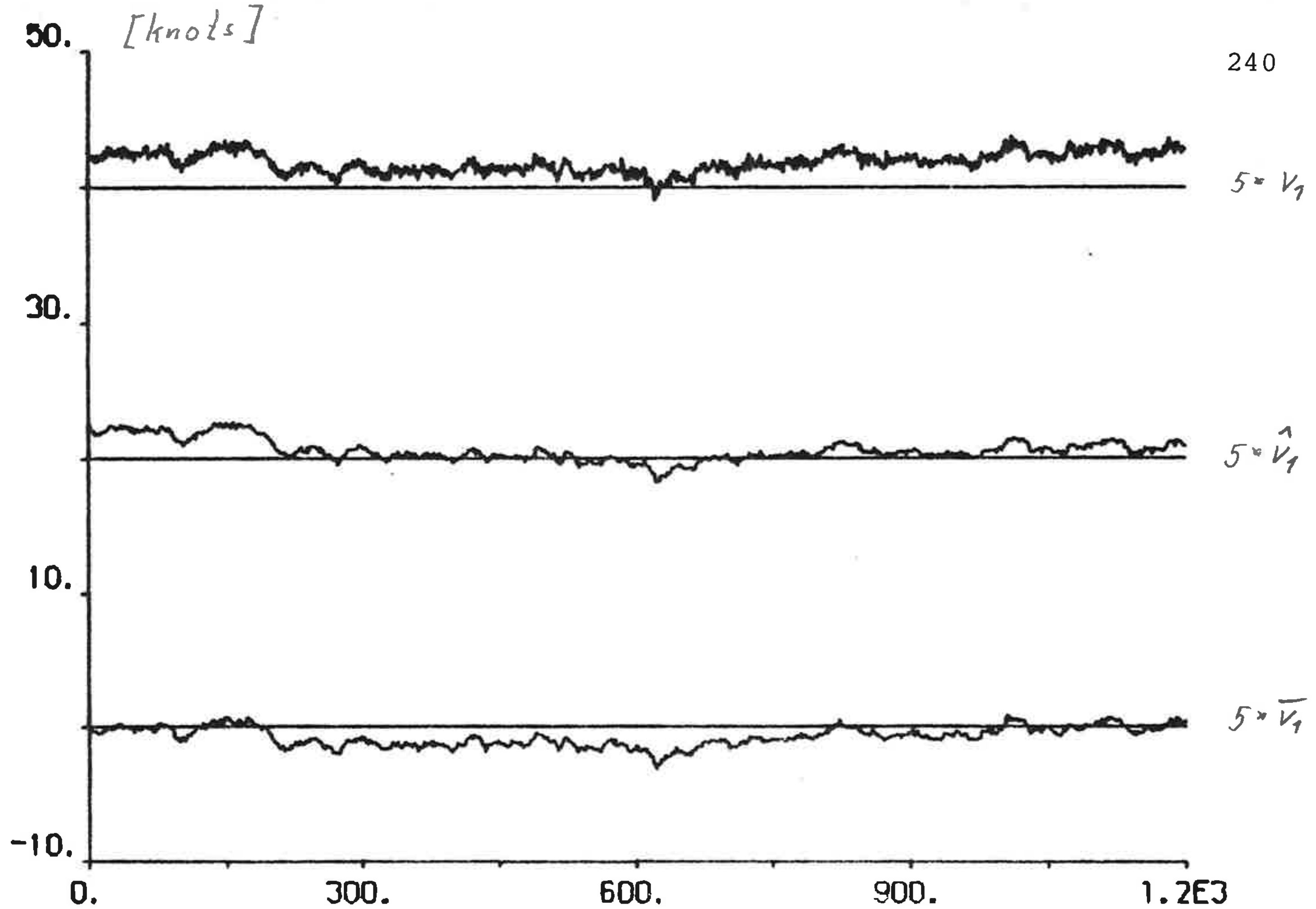
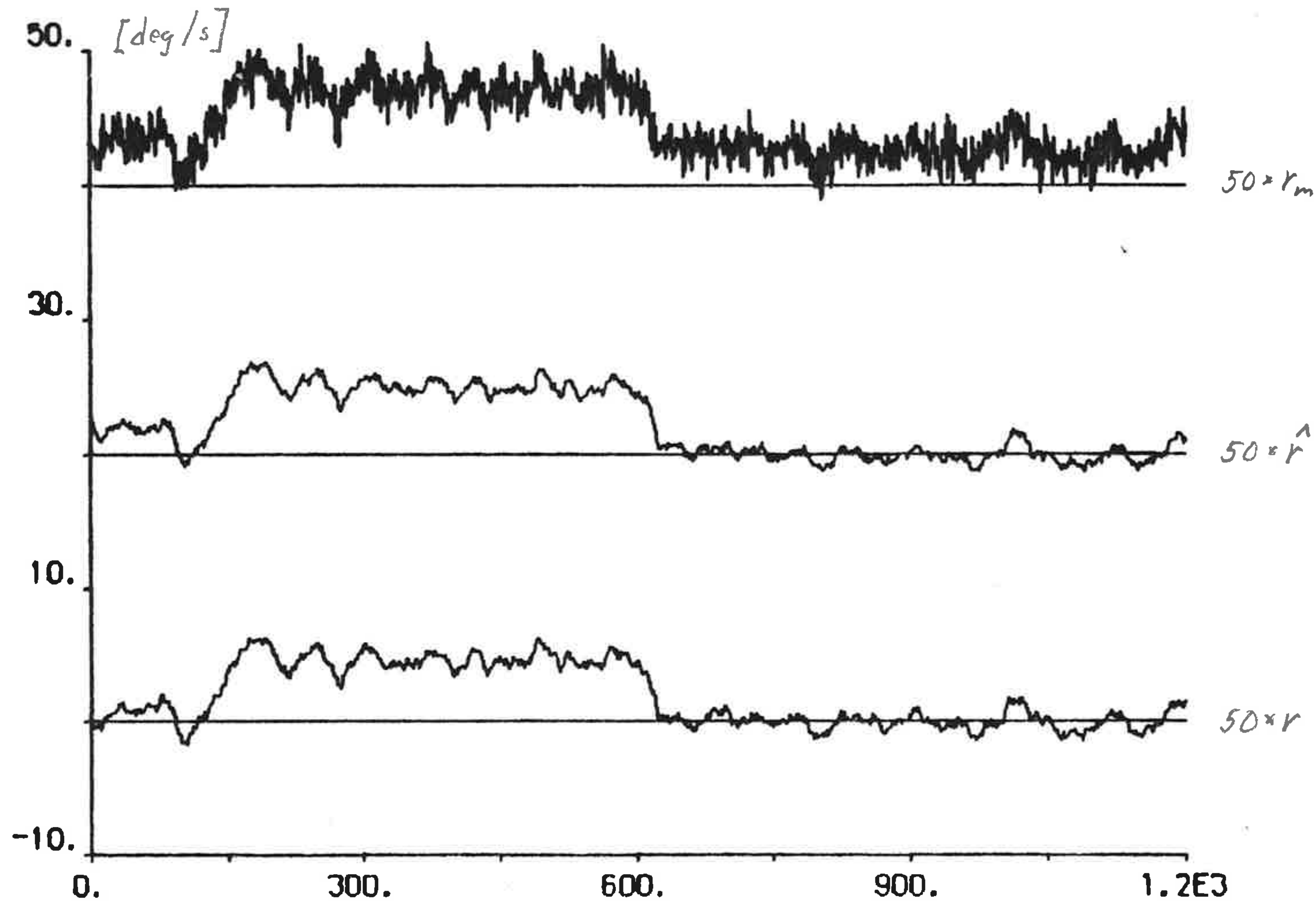


Fig. 4.57 a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter (c_2 = 50 s).

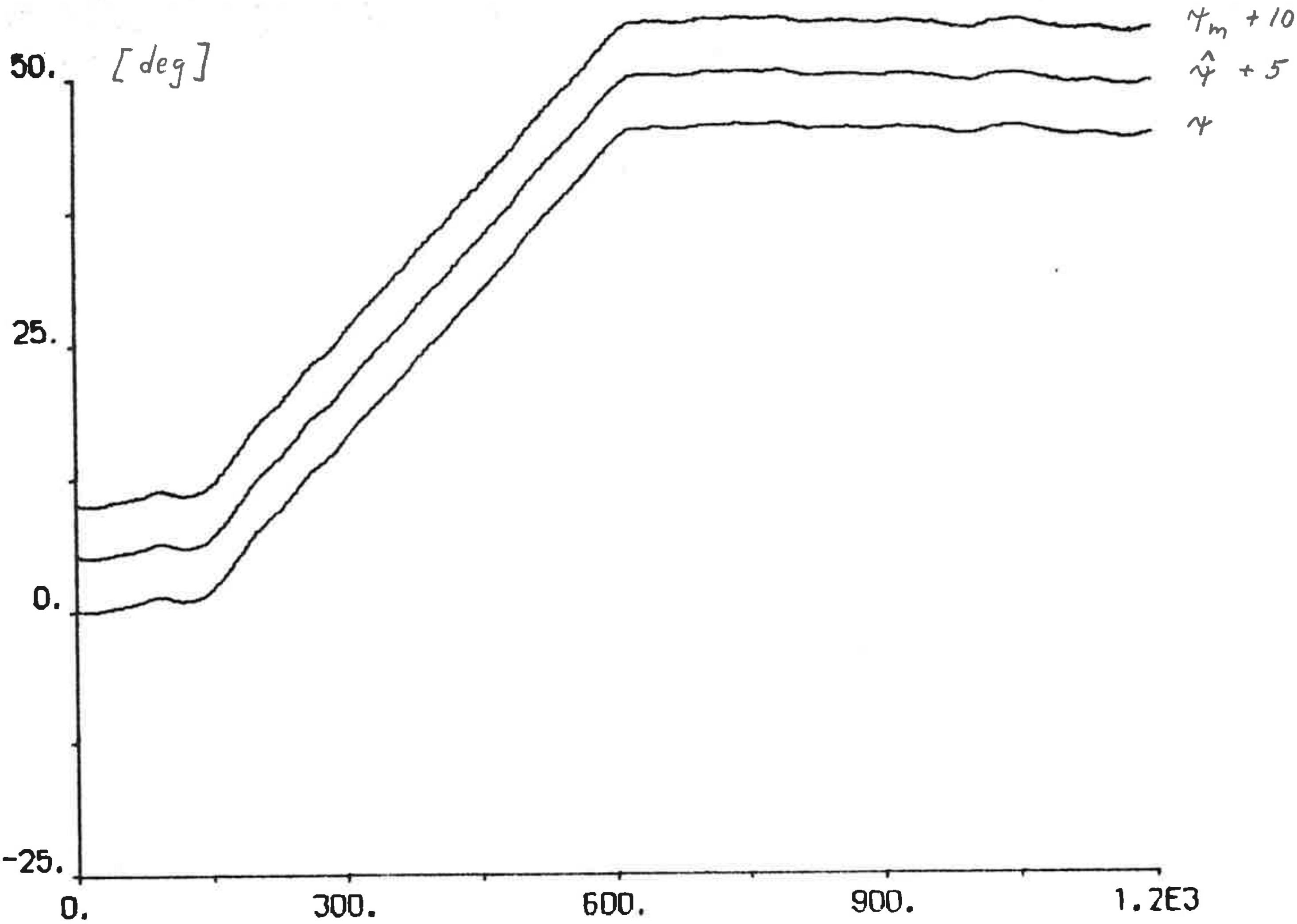


[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$5*V_1$
$5*\hat{V}_1$
$5*\tilde{V}_1$

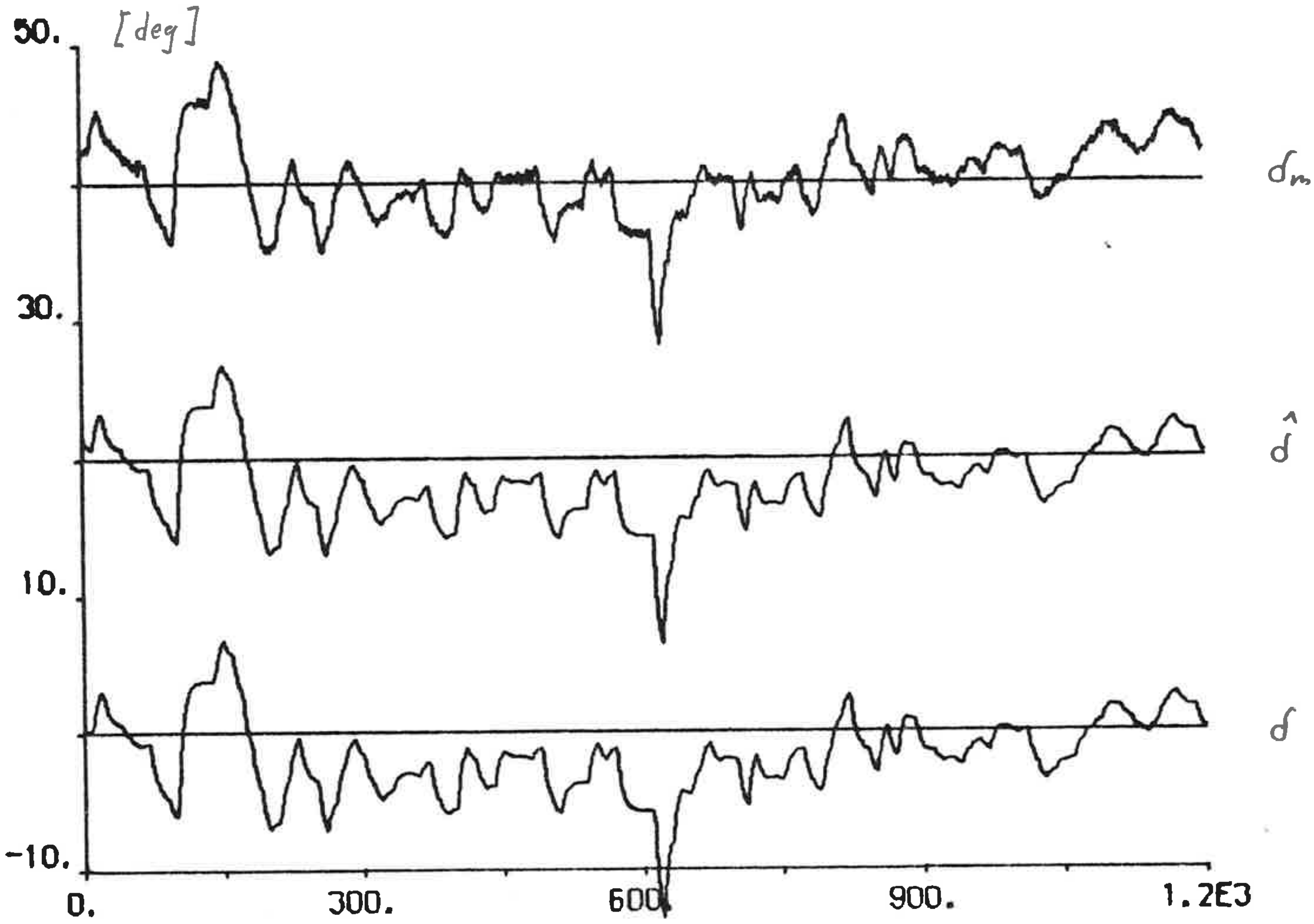


[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$50*r_m$
$50*\hat{r}$
$50*r$

Fig. 4.57 b

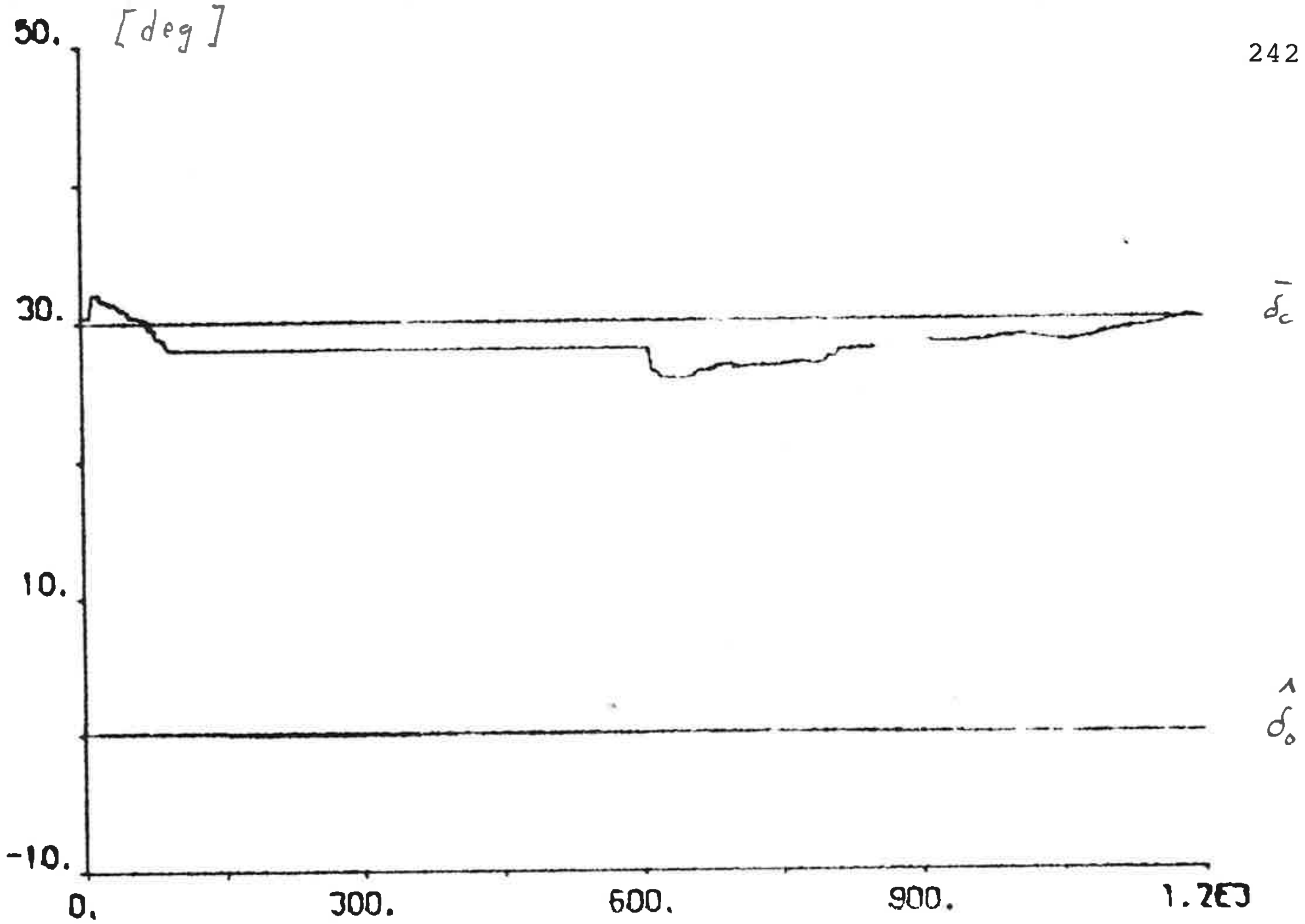


50.
[deg]
25.
0.
-25.
0.
300.
600.
900.
1.2E3
ψ_m + 10
$\hat{\psi}$ + 5
ψ

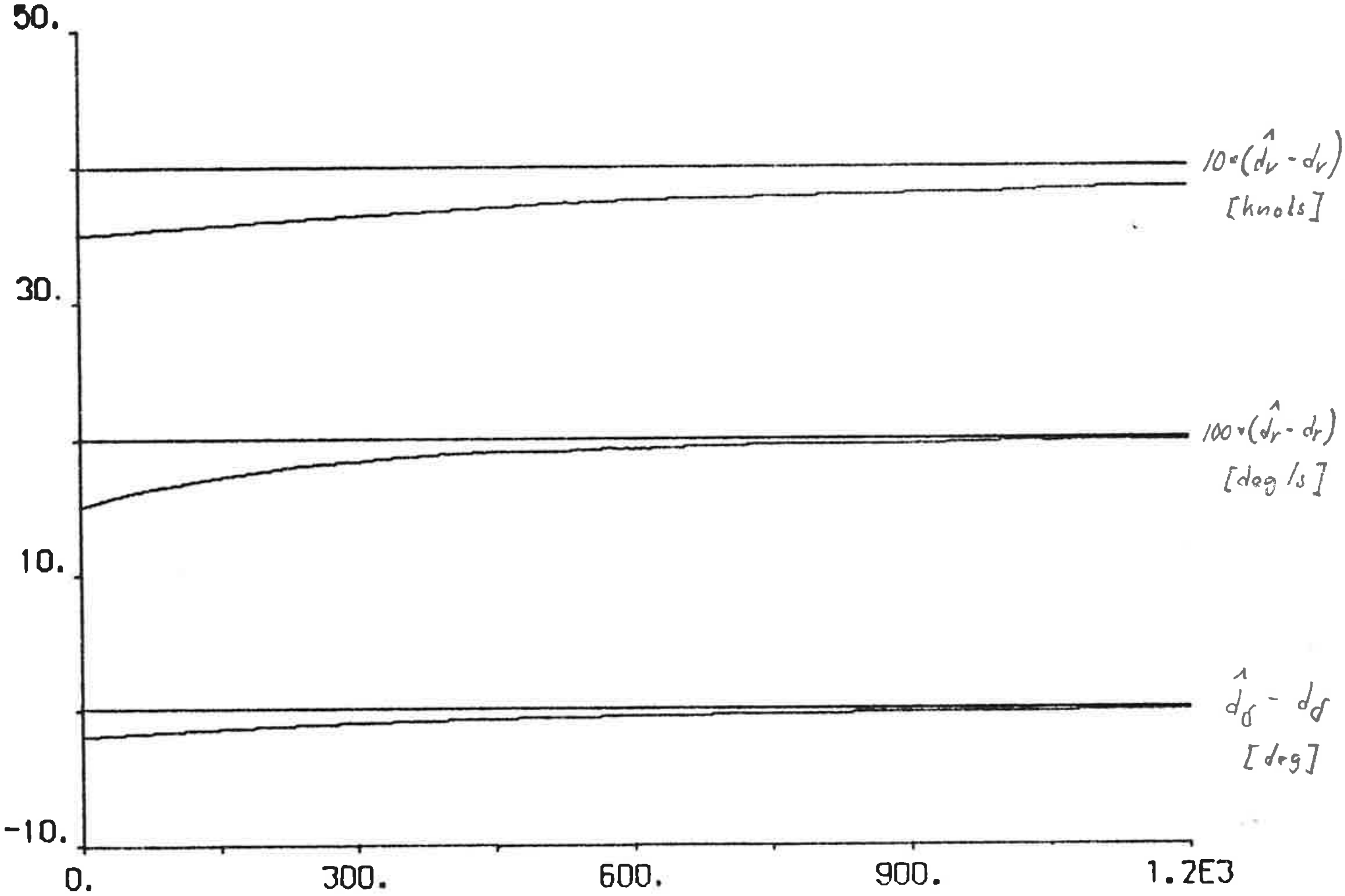


50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
δ_m
$\hat{\delta}$
δ

Fig. 4.57 c

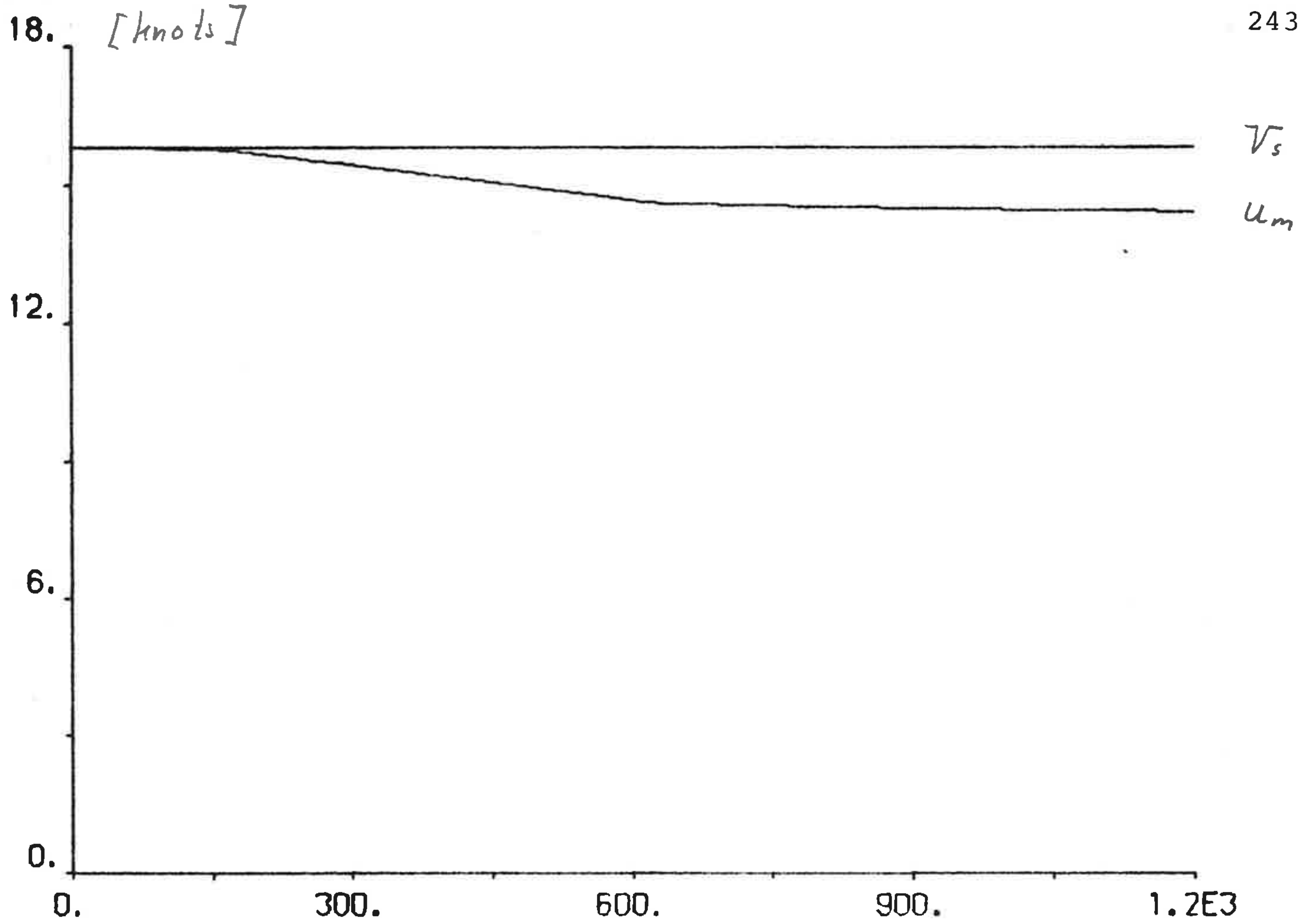


50. [deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$\bar{\delta}_c$
$\hat{\delta}_0$

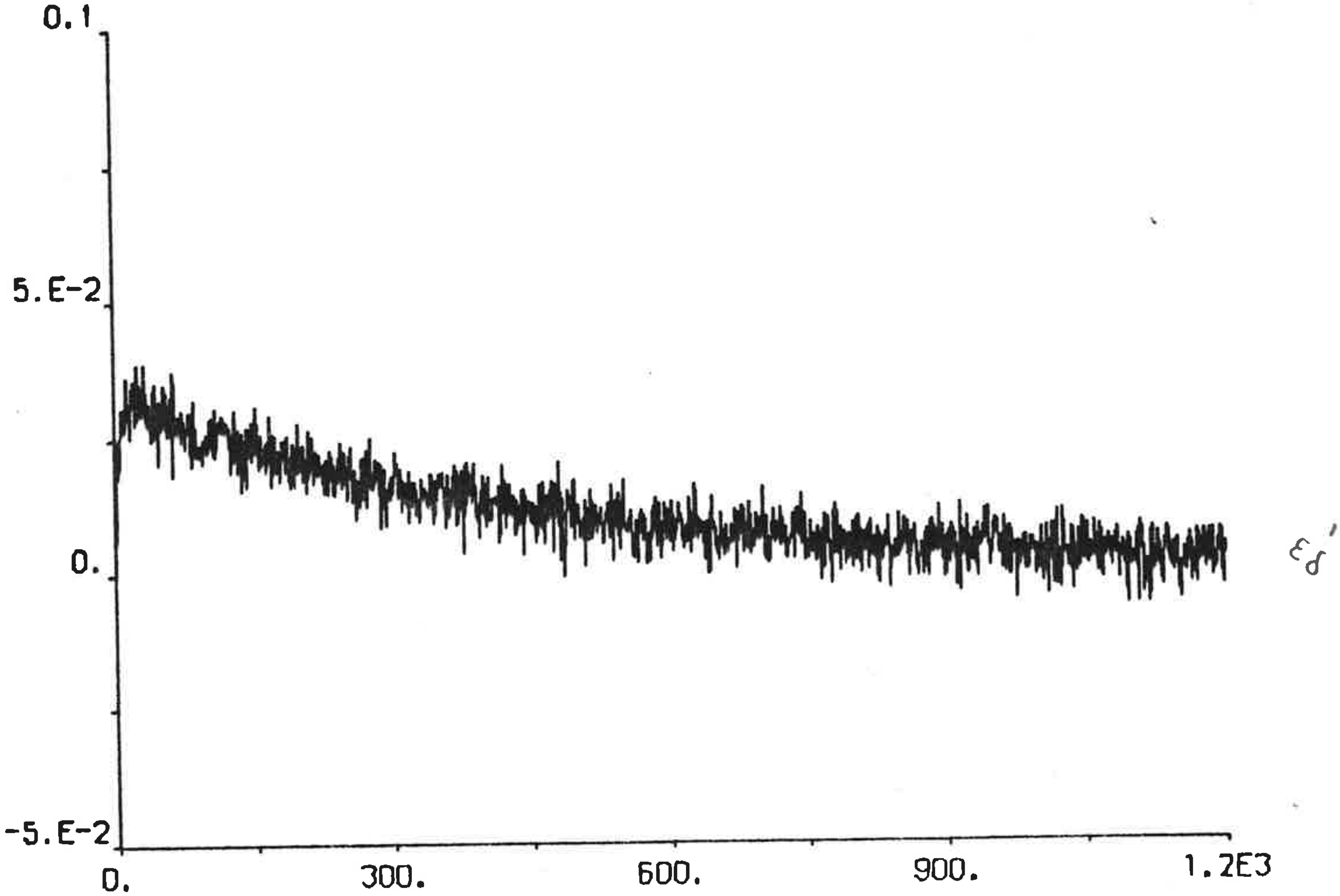


50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
10*($\hat{d}_v$ - d_v)
[knots]
100*($\hat{d}_r$ - d_r)
[deg/s]
$\hat{d}_\delta$ - d_δ
[deg]

Fig. 4.57 d

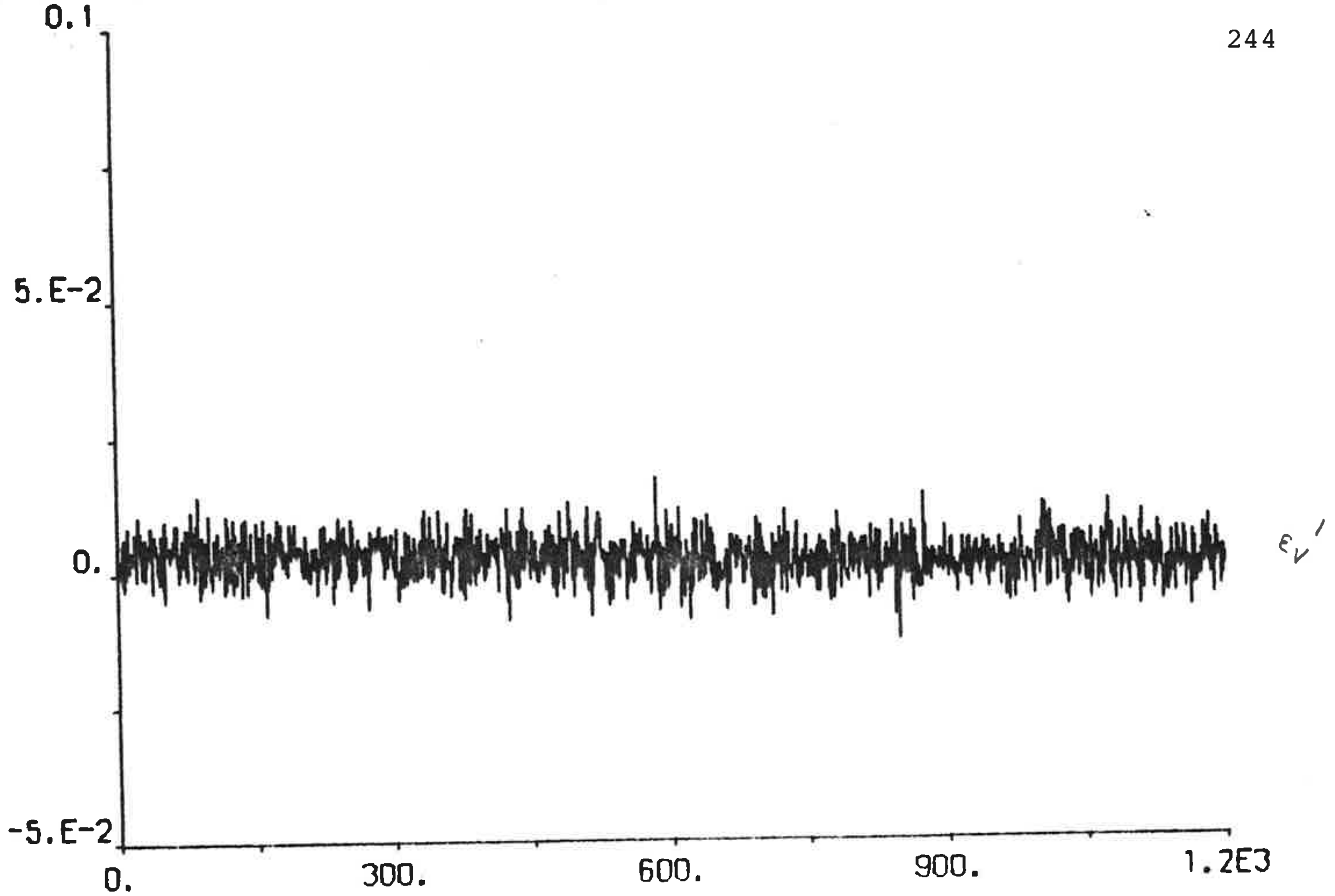


18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
u_m



0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_δ'

Fig. 4.57 e


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_v'

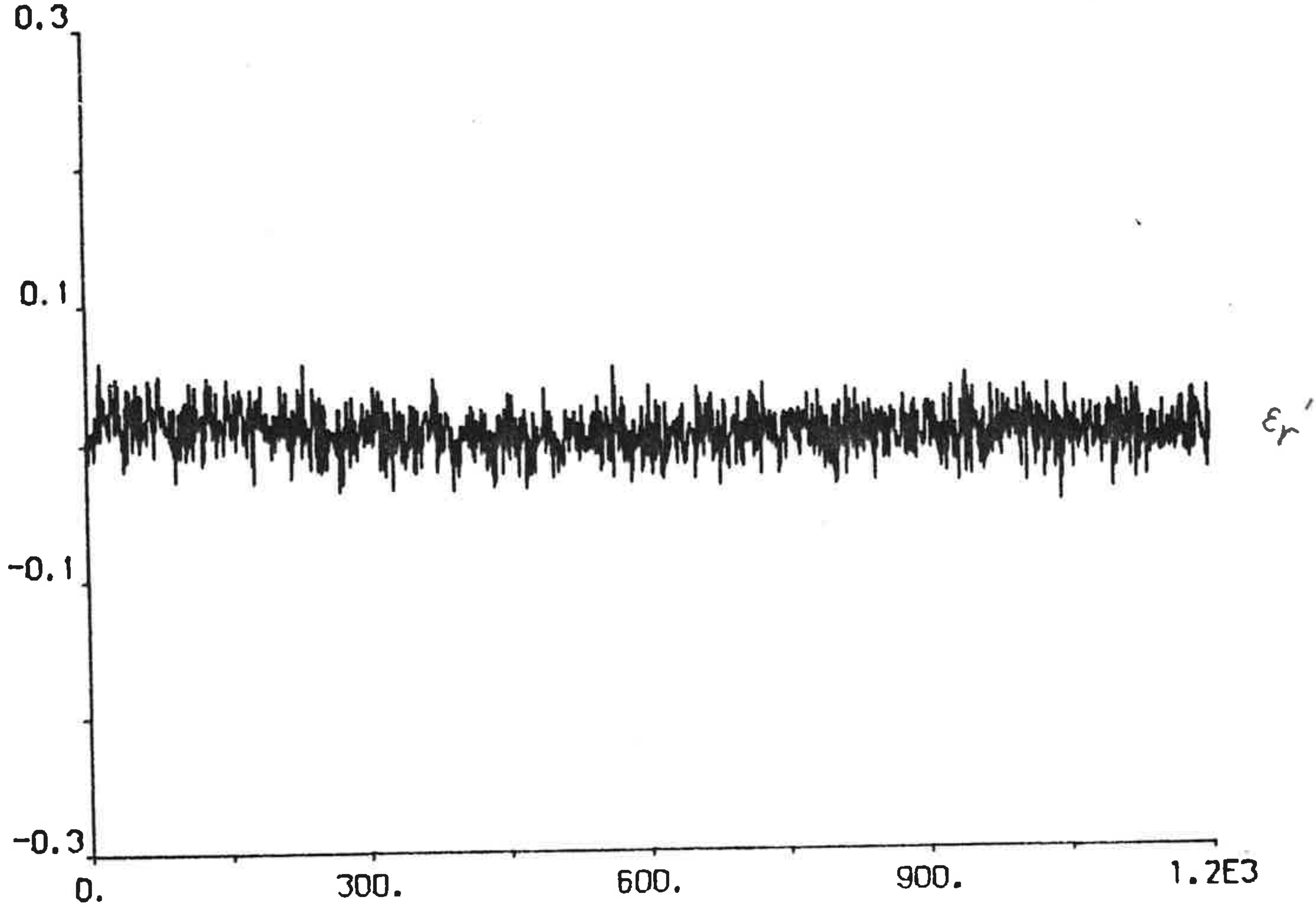

0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
ε_r'

Fig. 4.57 f

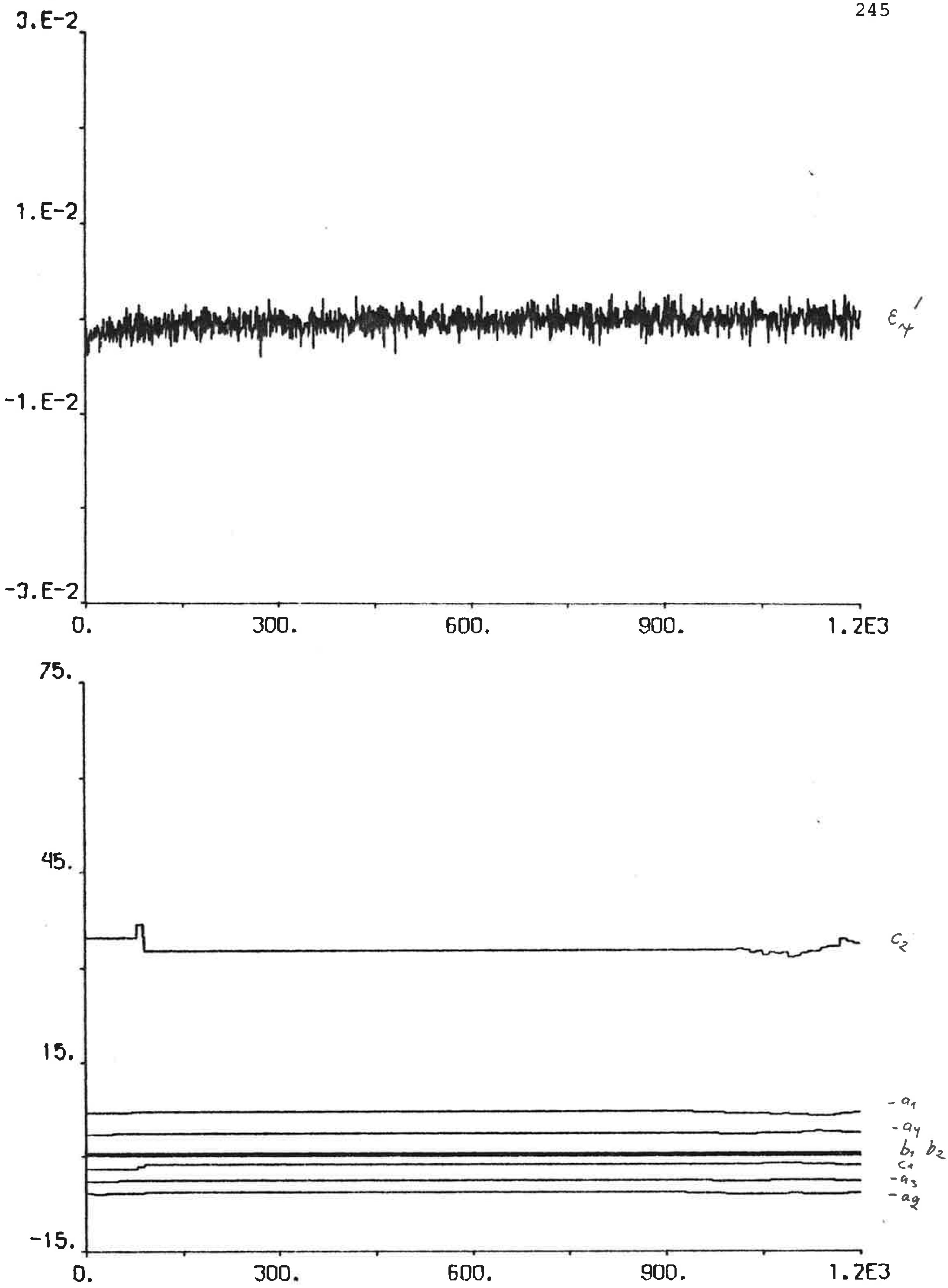


Fig. 4.57 g

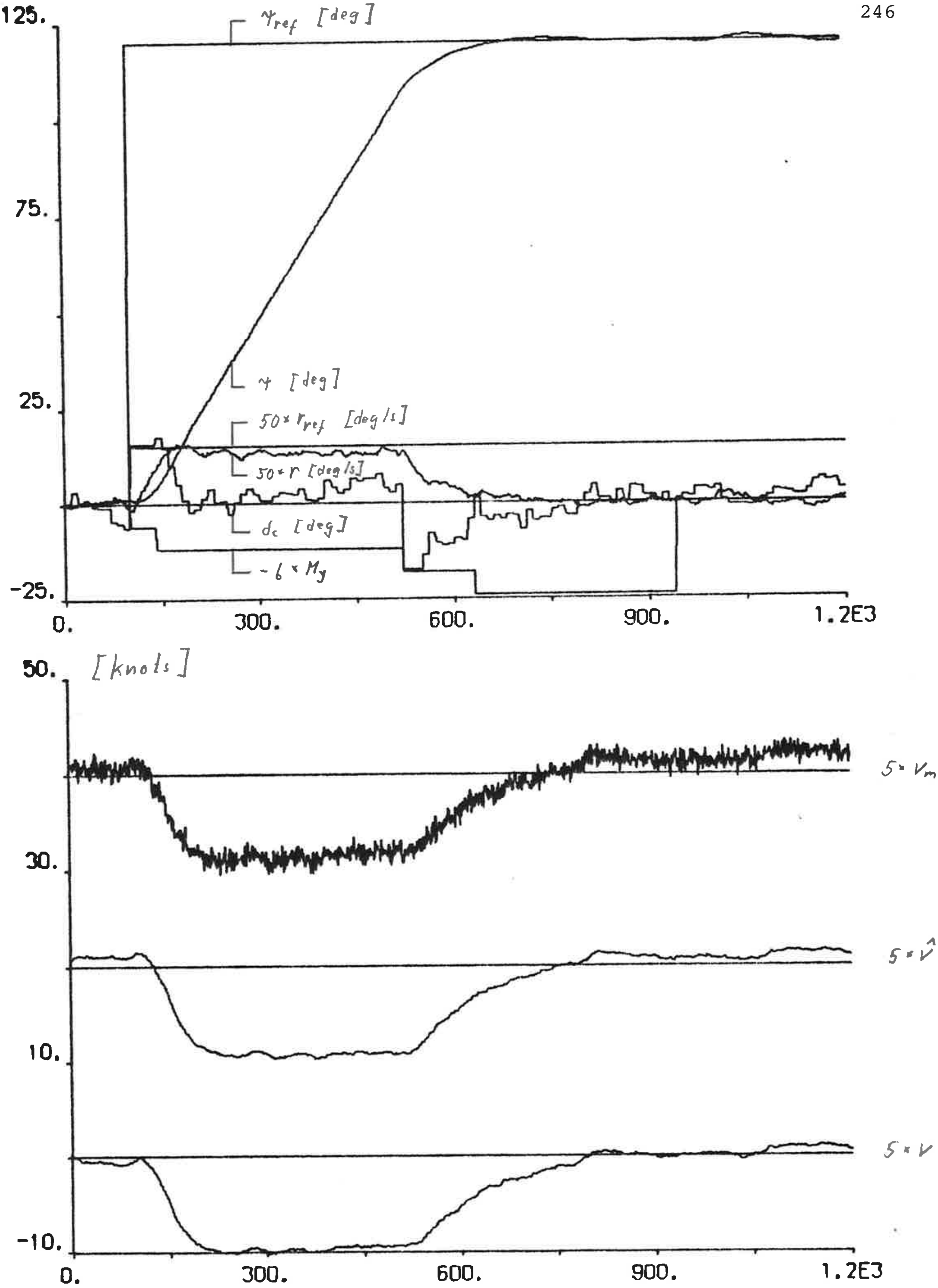
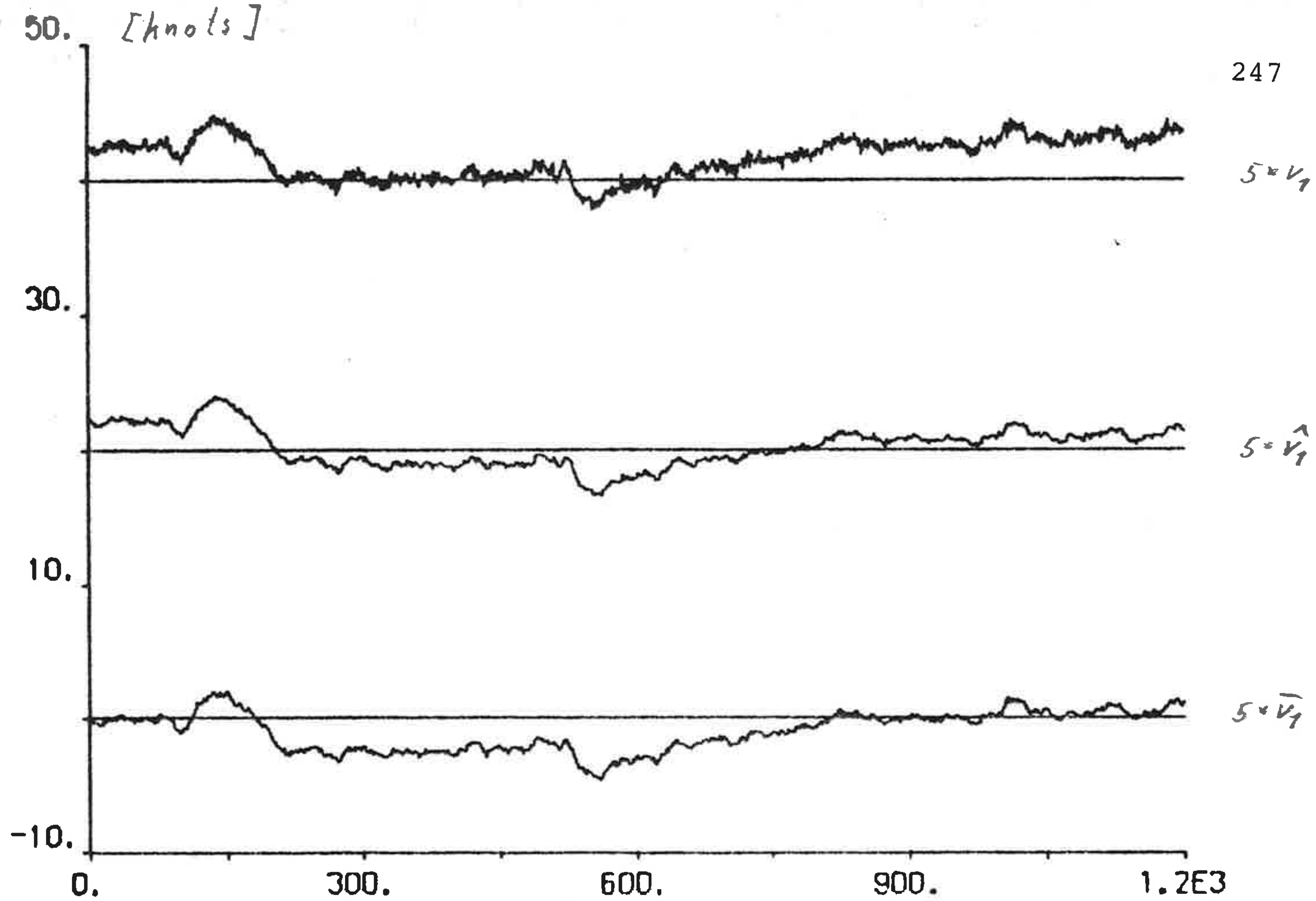


Fig. 4.58 a - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{c}_2$ = 50 s).


50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5×v1
5×v̂1
5×v̄1

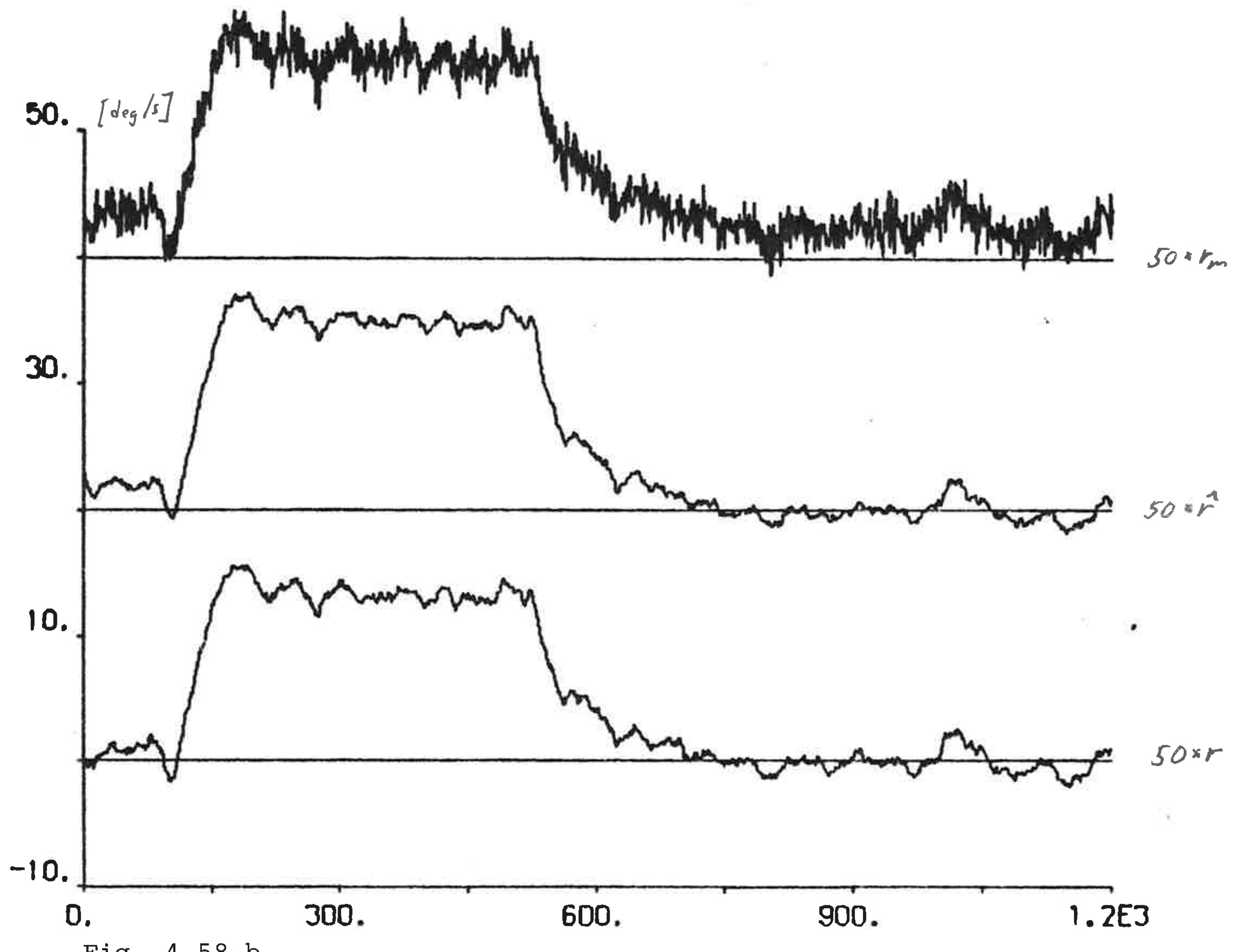
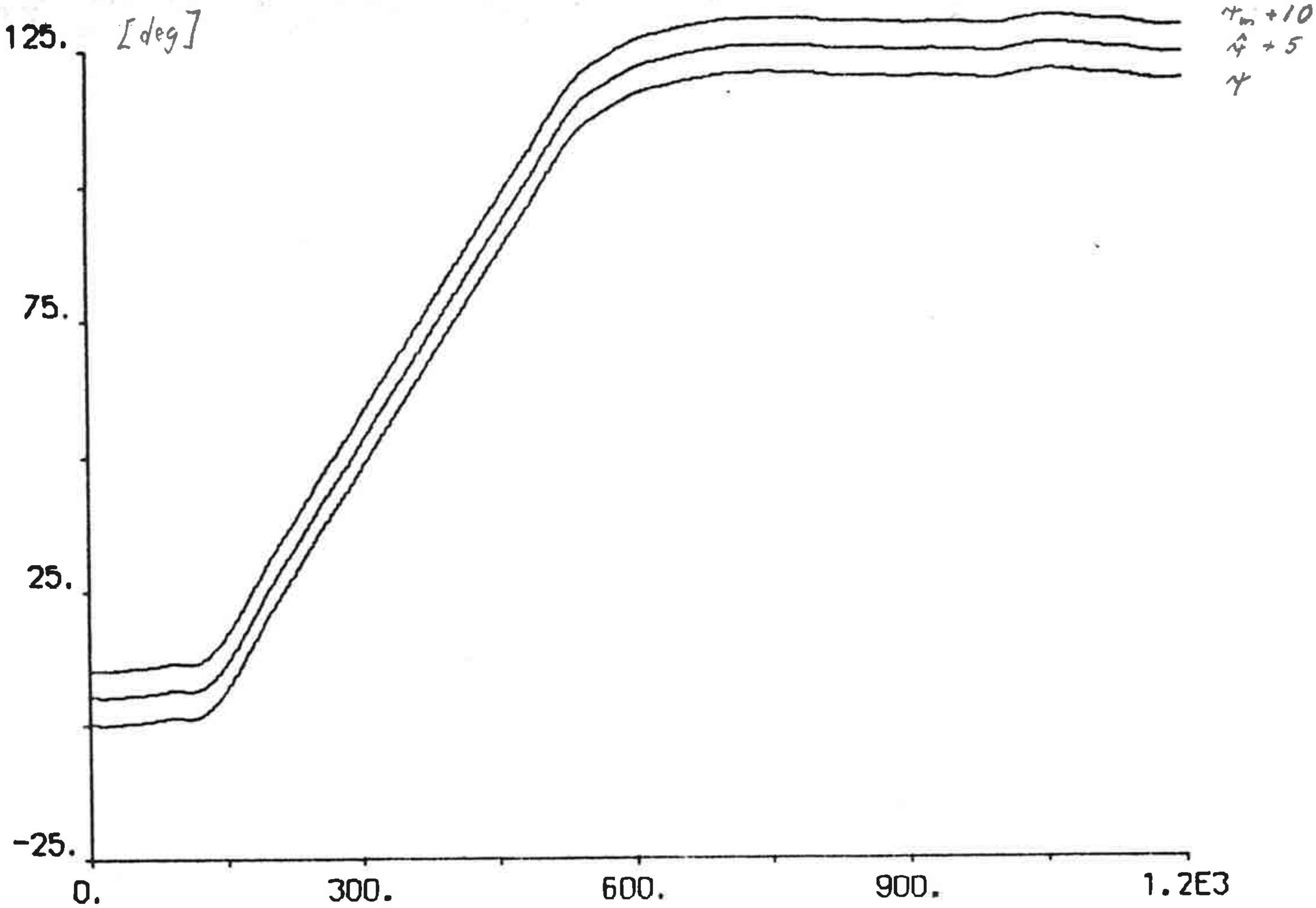
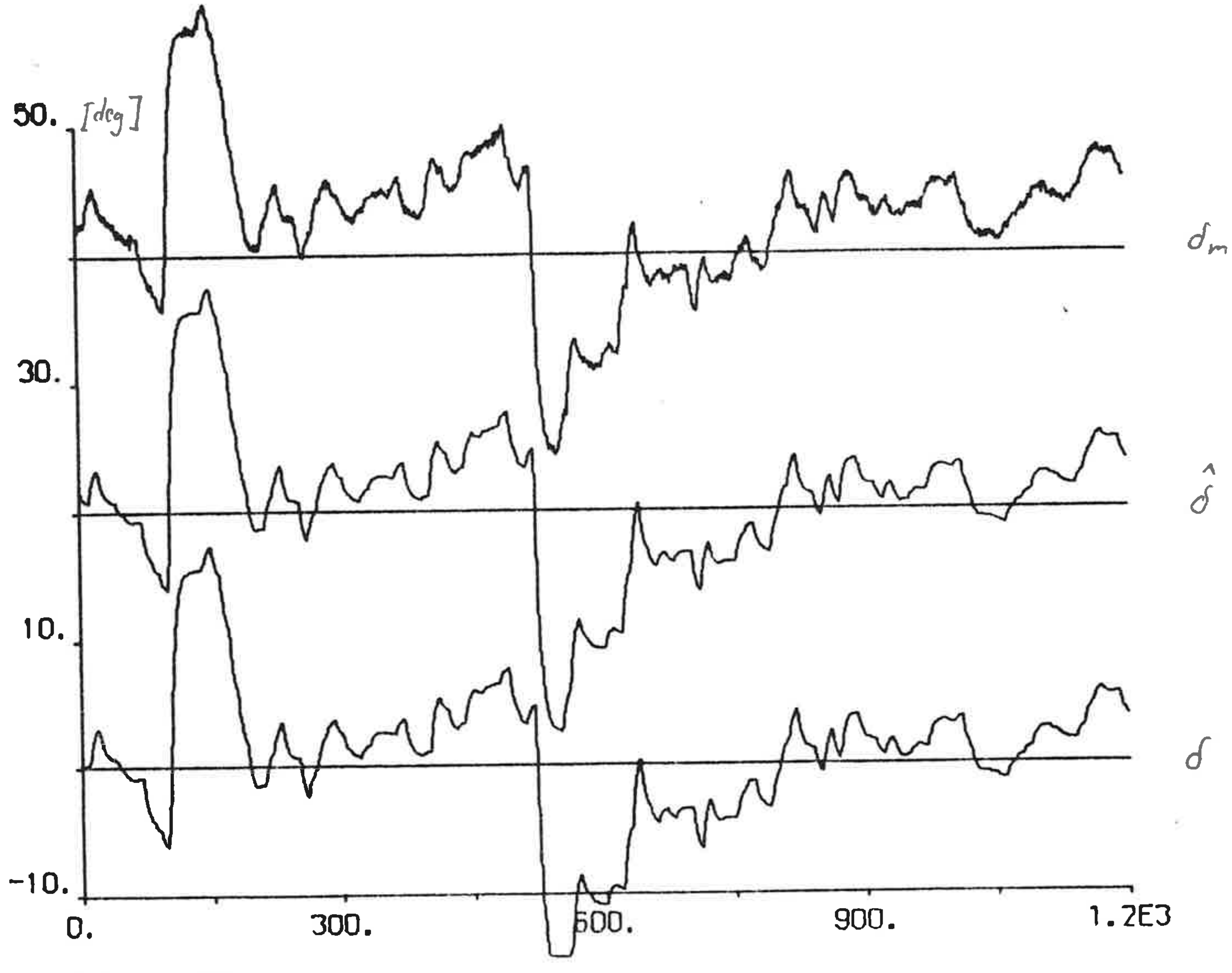

50.
[deg/s]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
50×rm
50×r̂
50×r

Fig. 4.58 b



125.
[deg]
75.
25.
-25.
0.
300.
600.
900.
1.2E3



50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3

Fig. 4.58 c

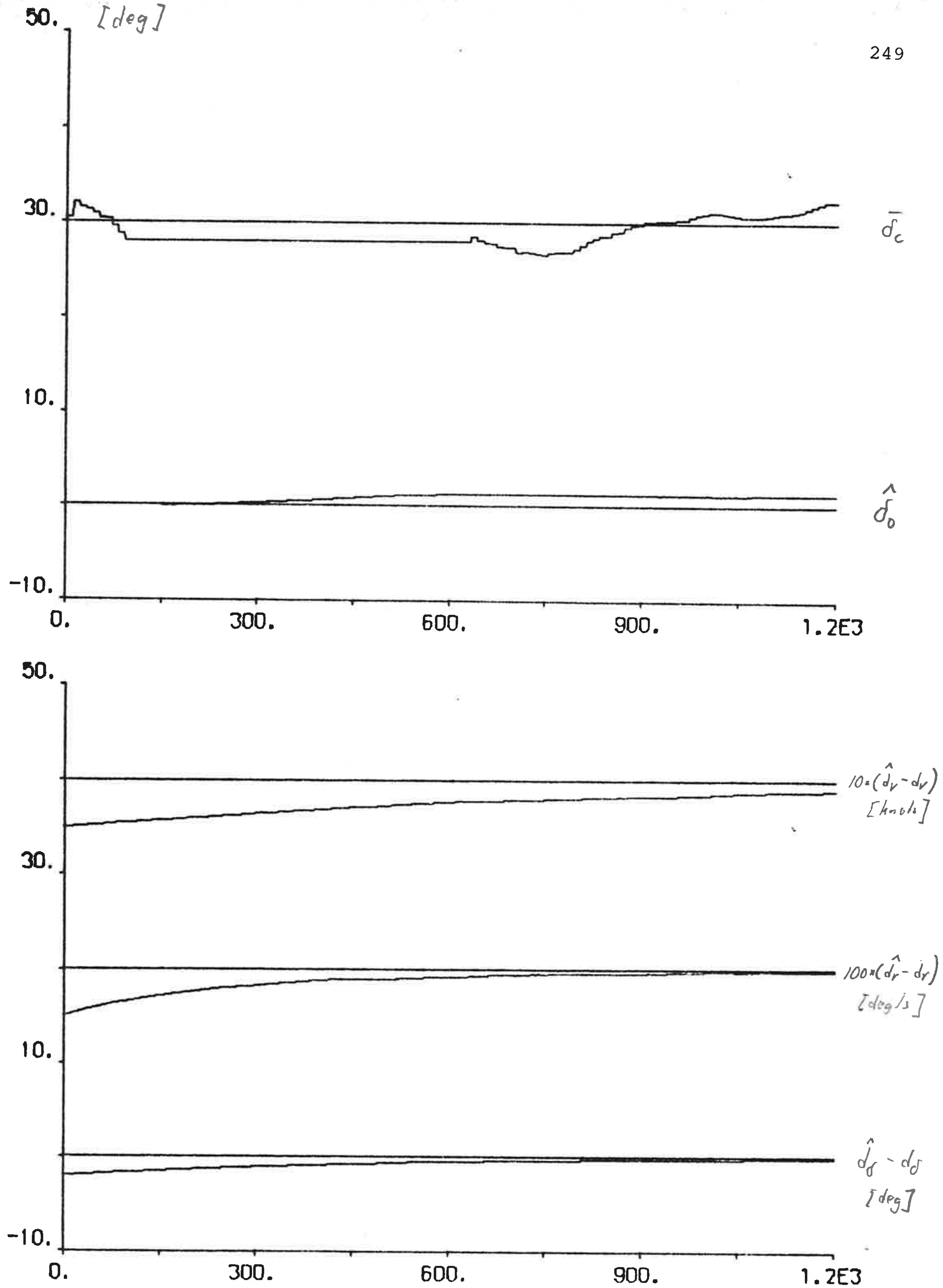
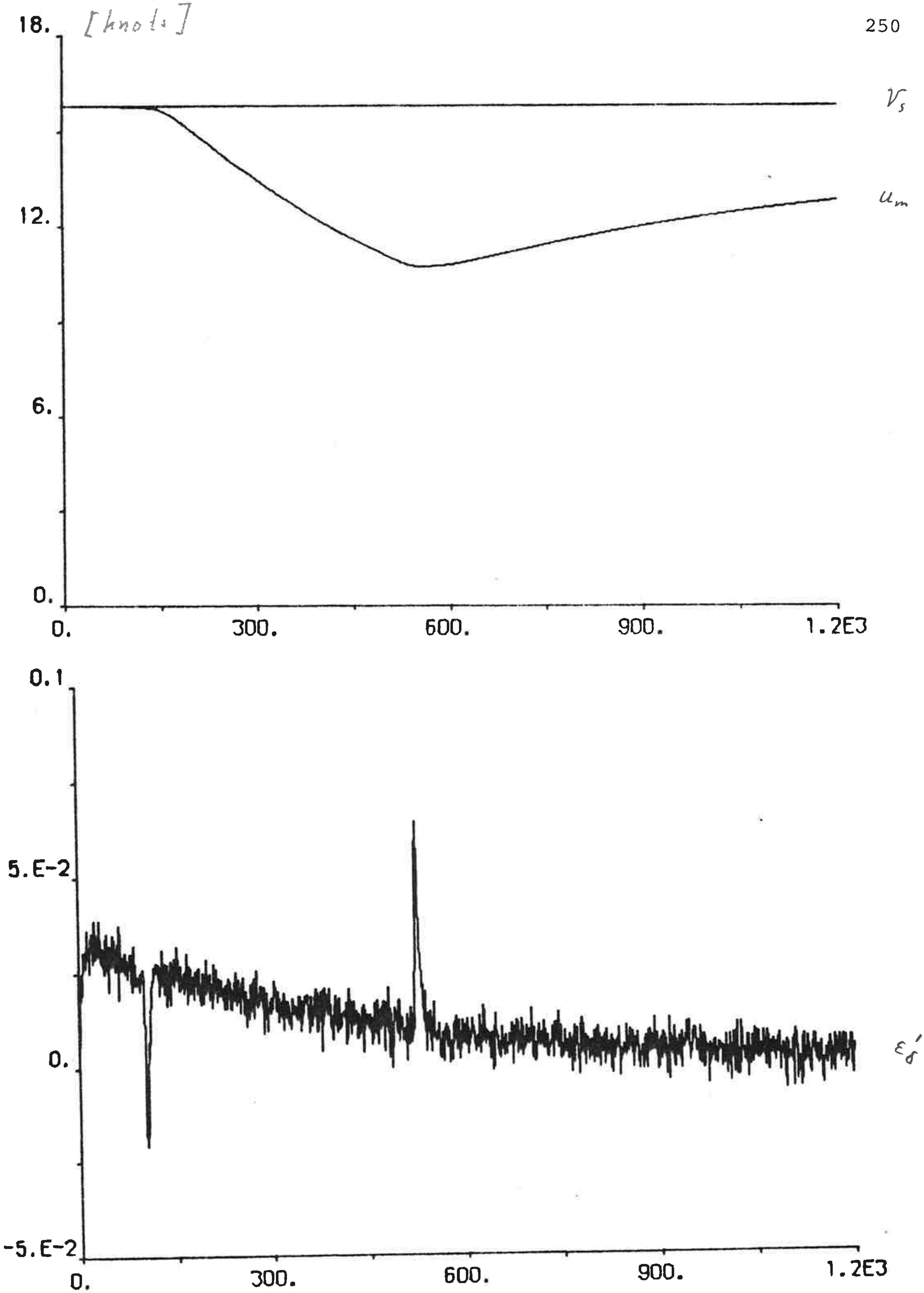
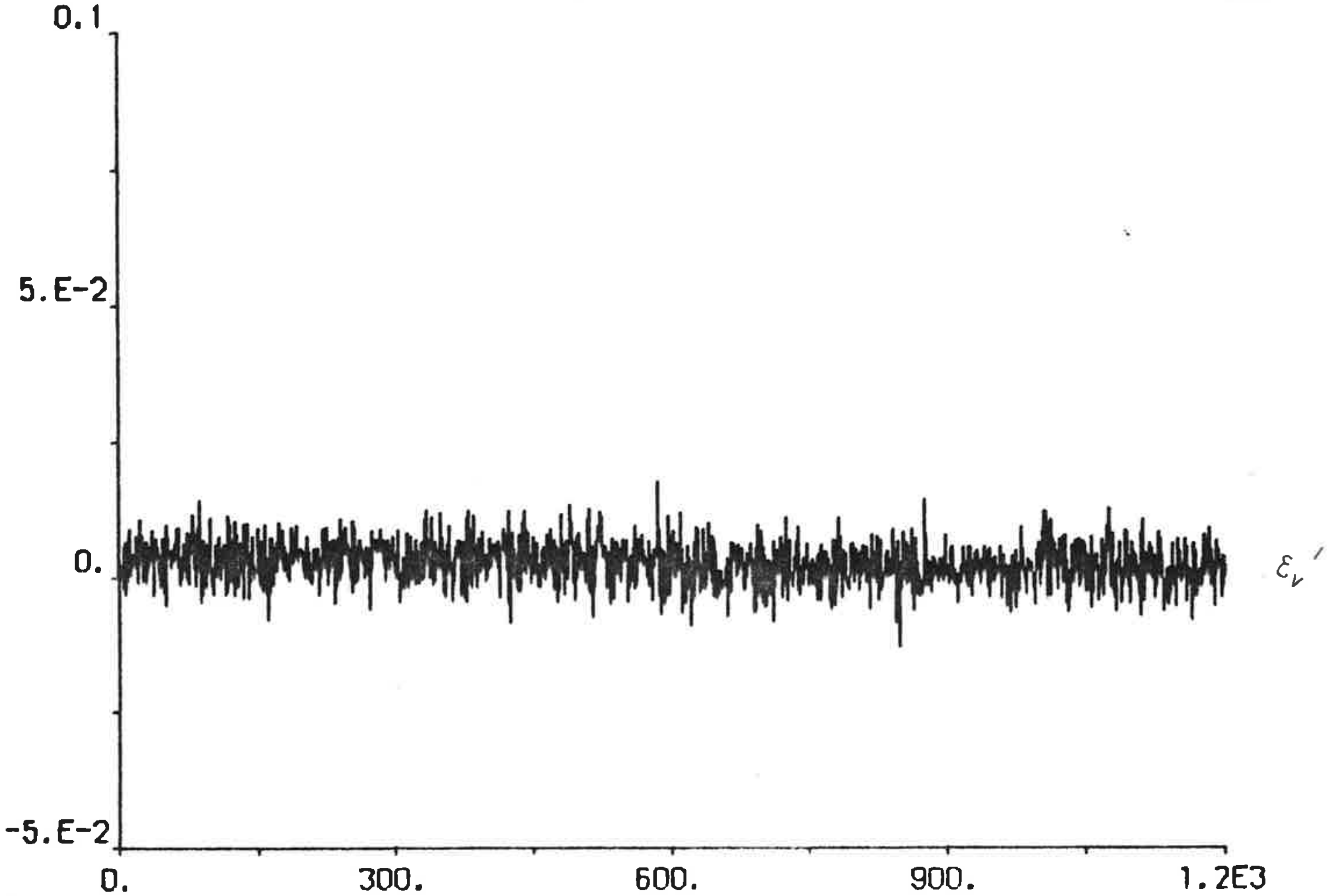

50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$\bar{\delta}_c$
$\hat{\delta}_0$
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$10*(\hat{d}_v - d_v)$
[knots]
$100*(\hat{d}_r - d_r)$
[deg/s]
$\hat{d}_\delta - d_\delta$
[deg]

Fig. 4.58 d



18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
u_m
0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_δ'

Fig. 4.58 e


0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_v'

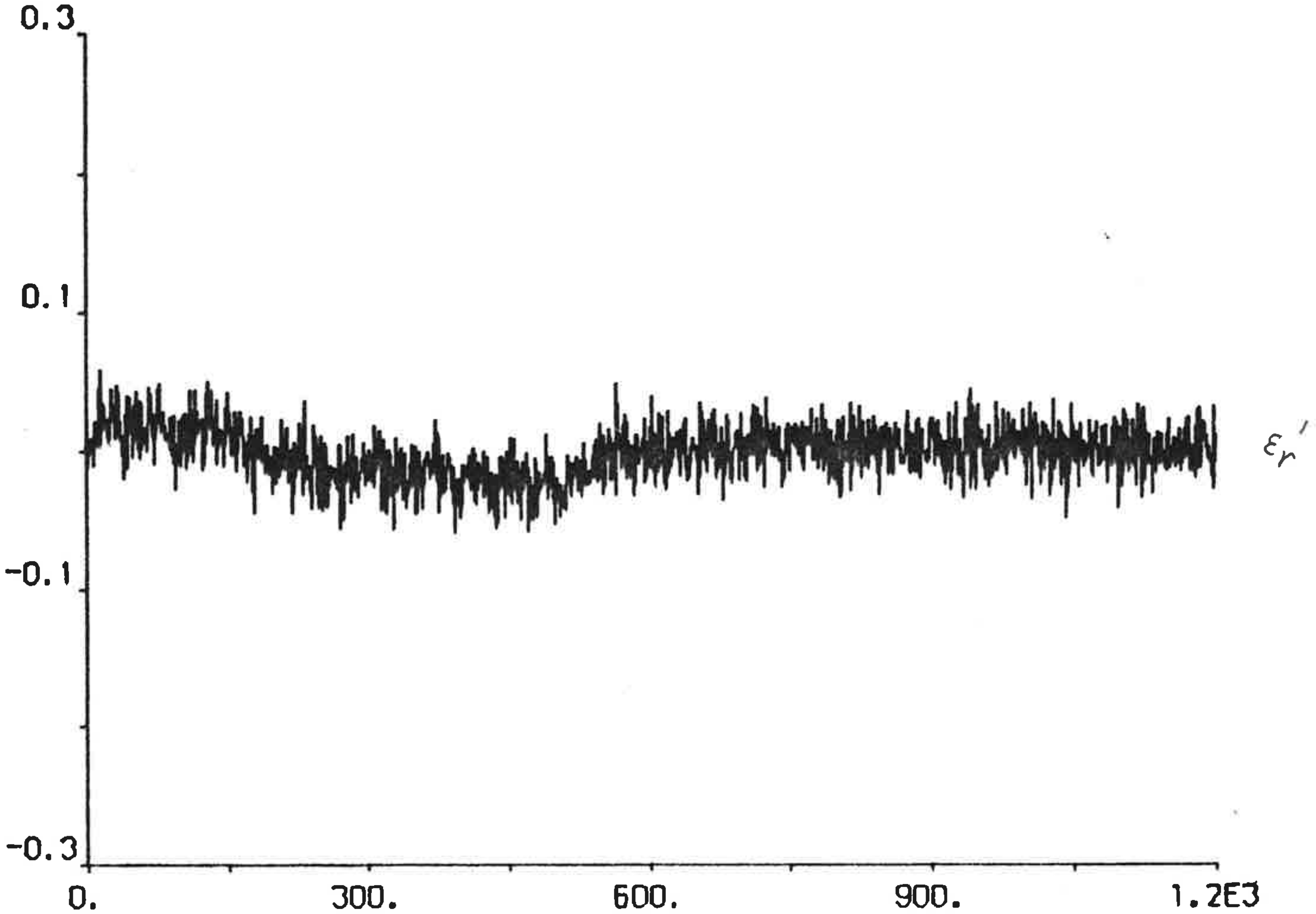
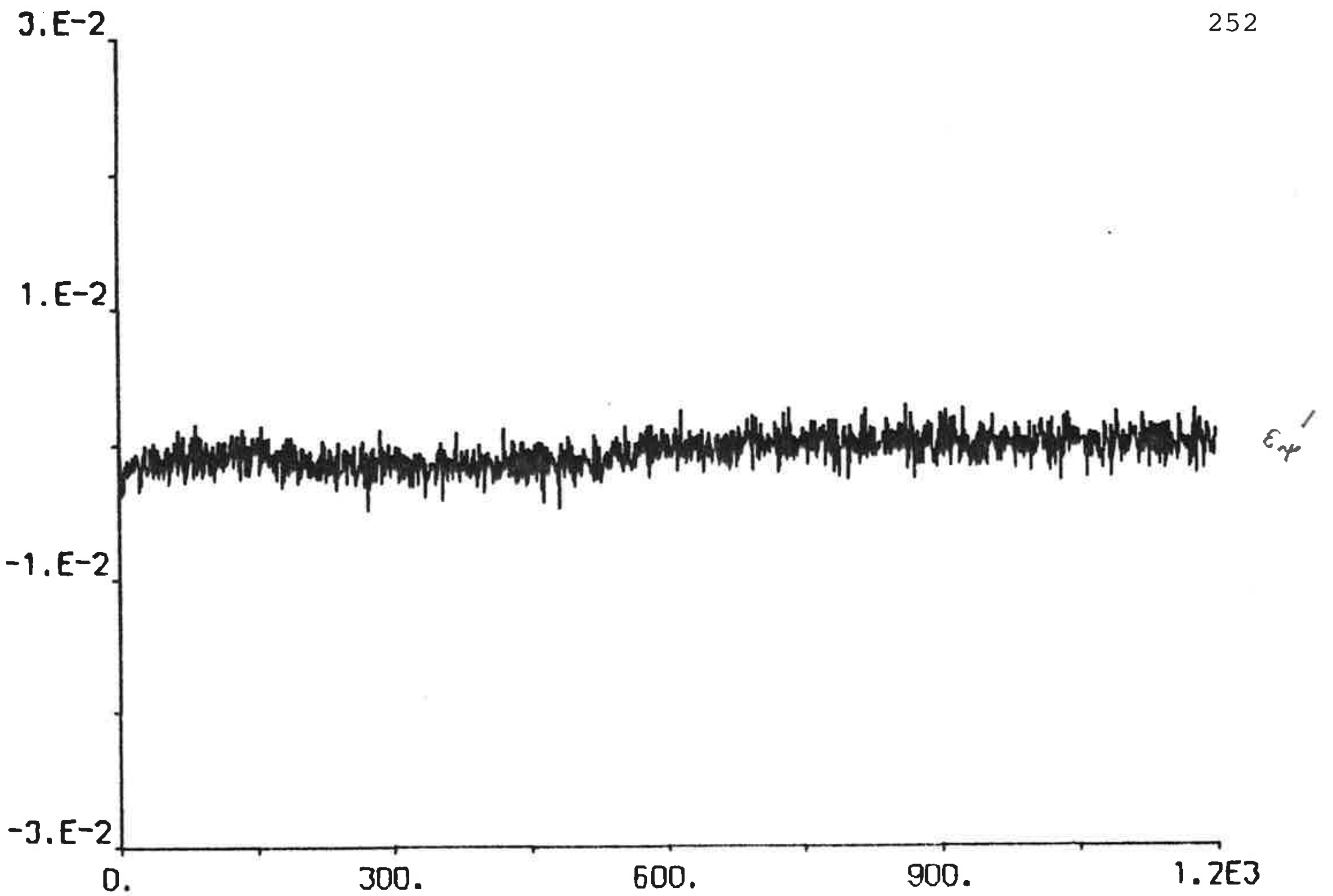

0.3
0.1
-0.1
-0.3
0.
300.
600.
900.
1.2E3
ε_r'

Fig. 4.58 f



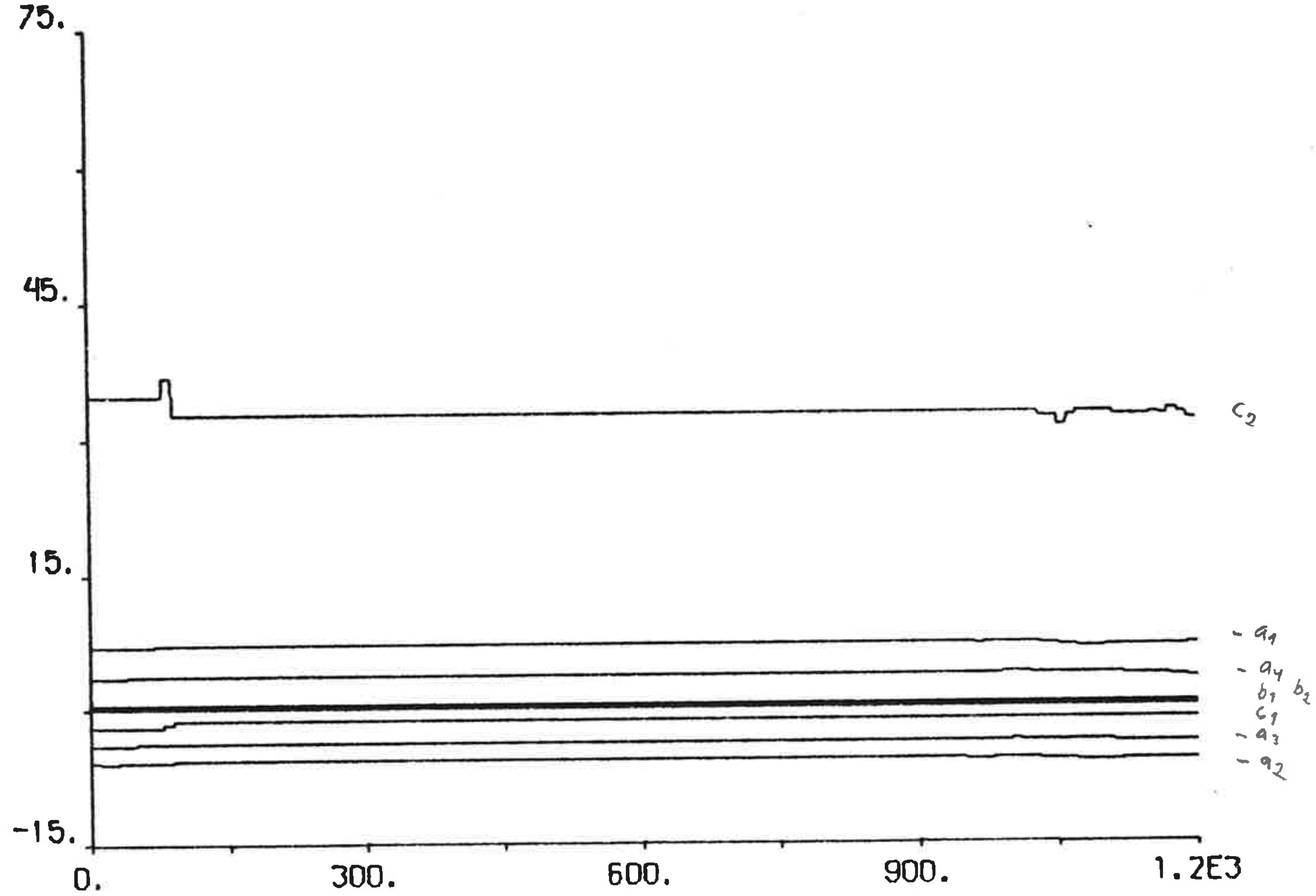


Fig. 4.58 g

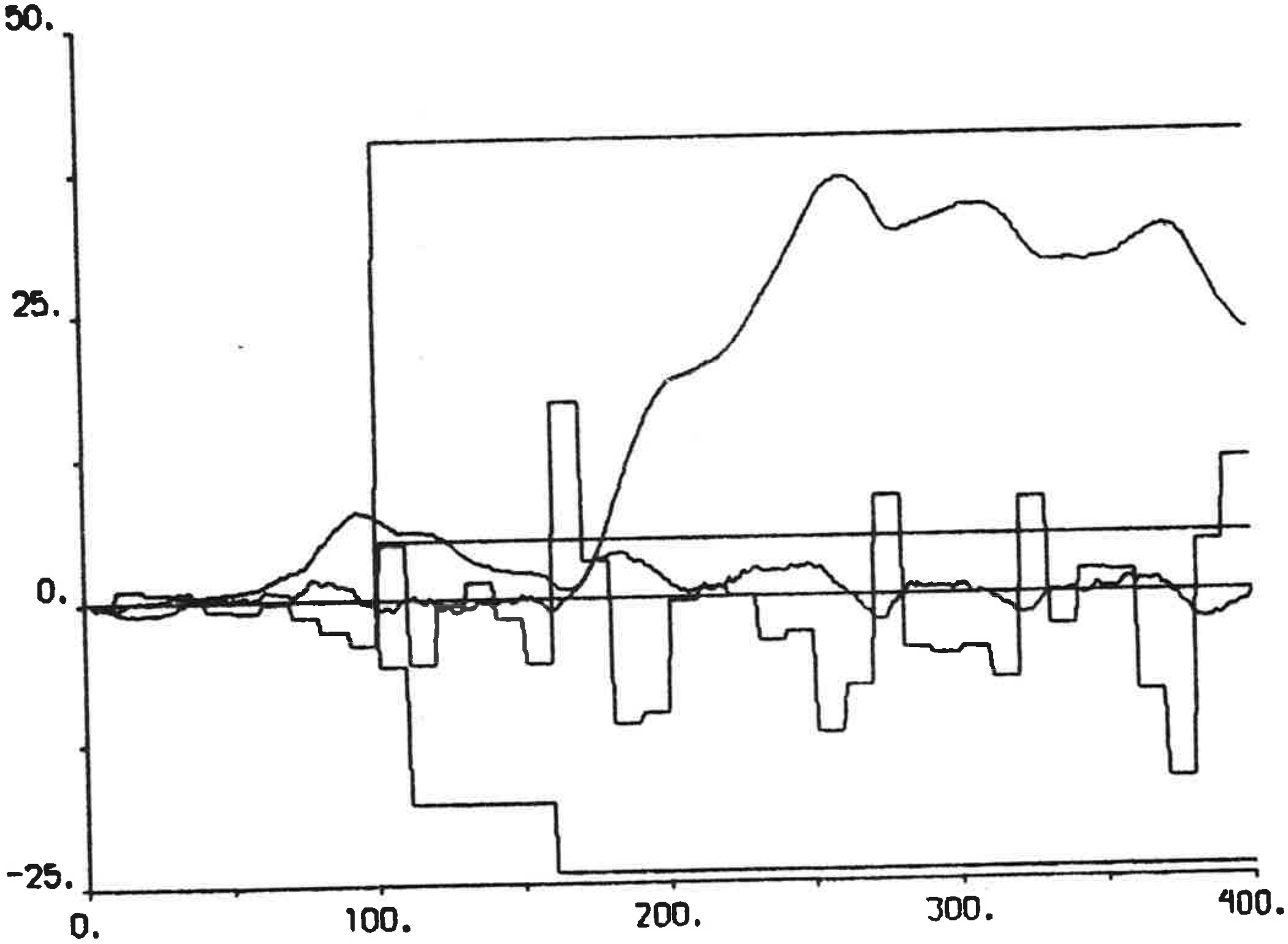
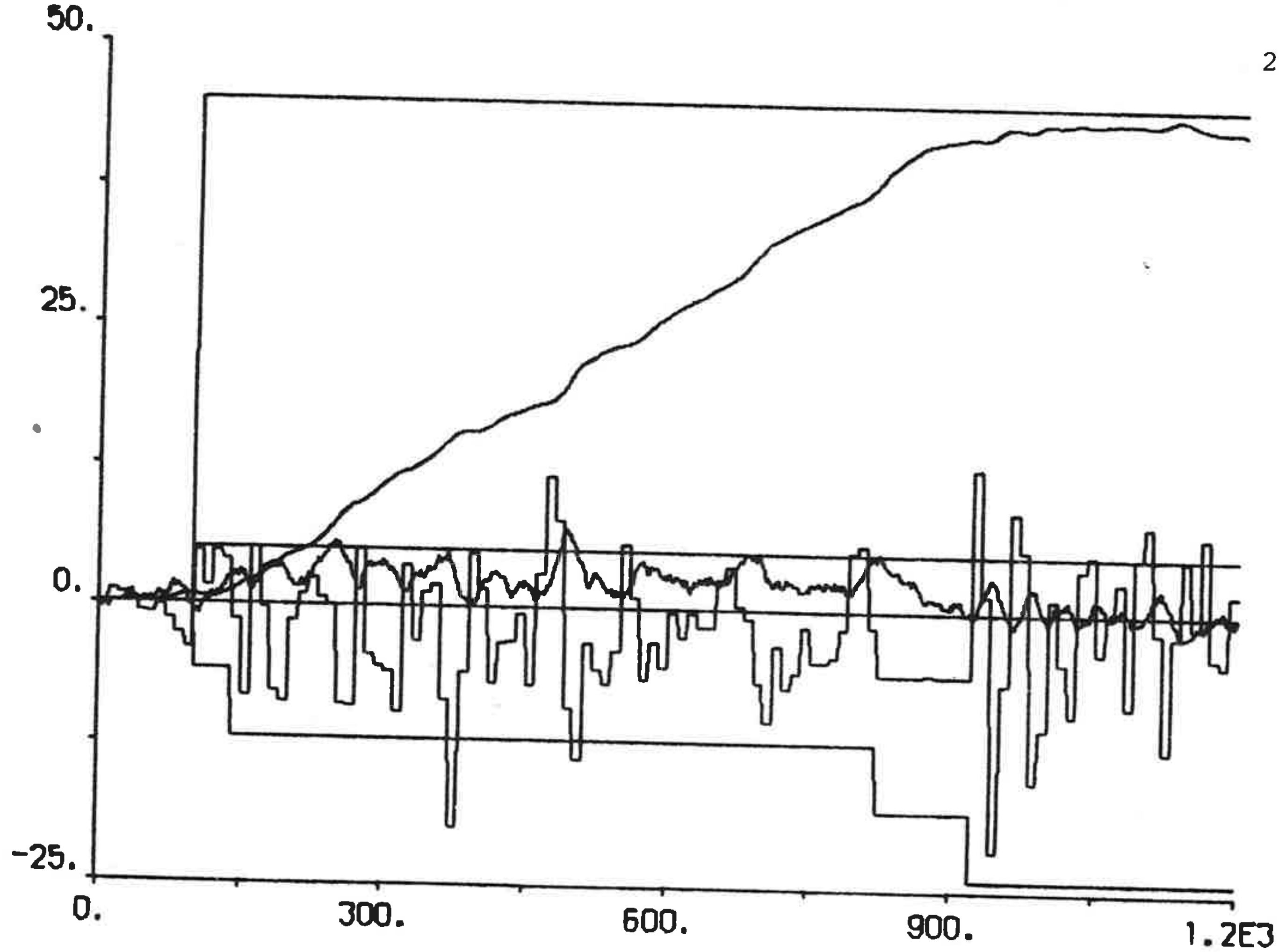


Fig. 4.59 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\bar{c}_2$ = 50 s).



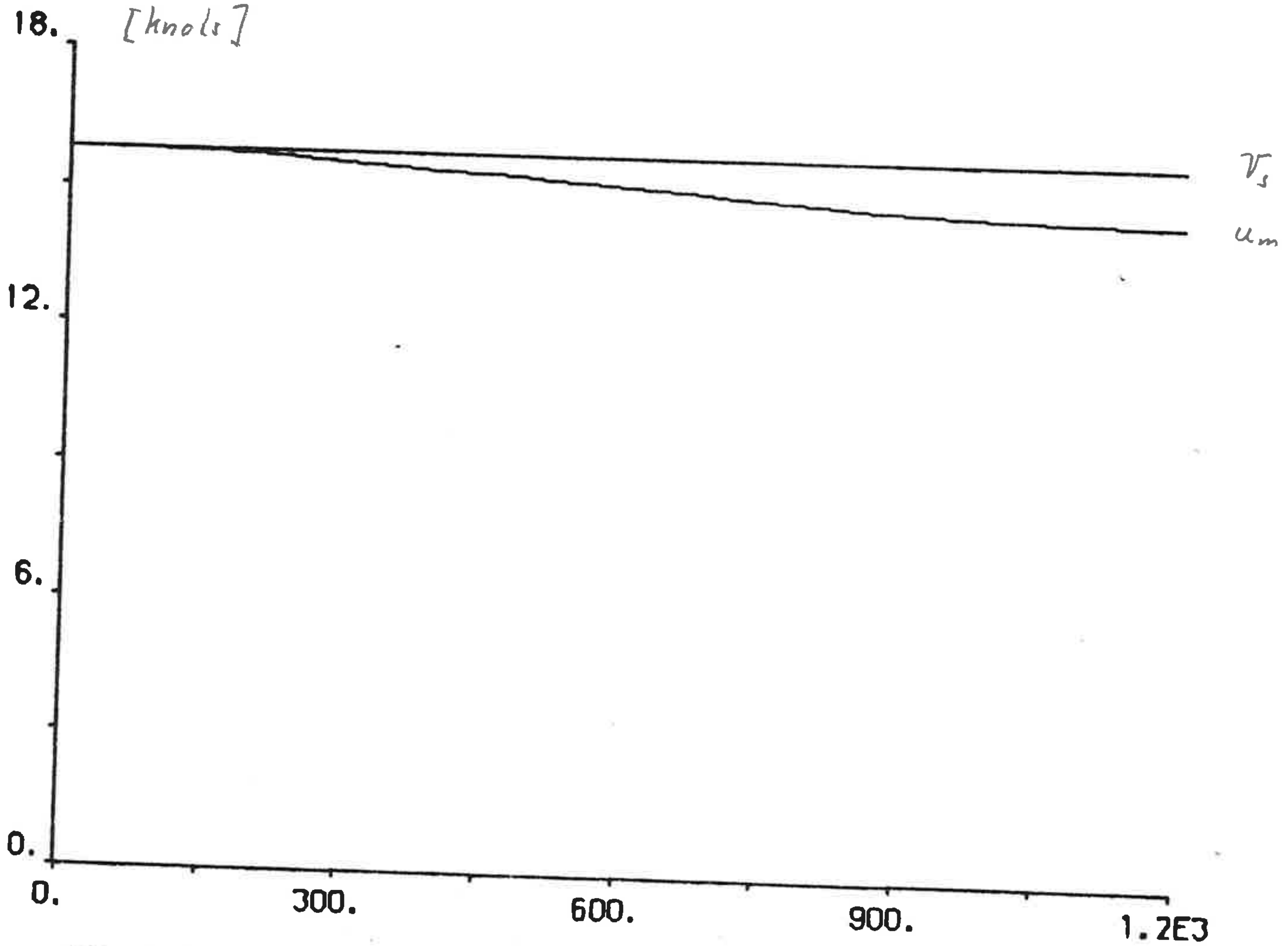
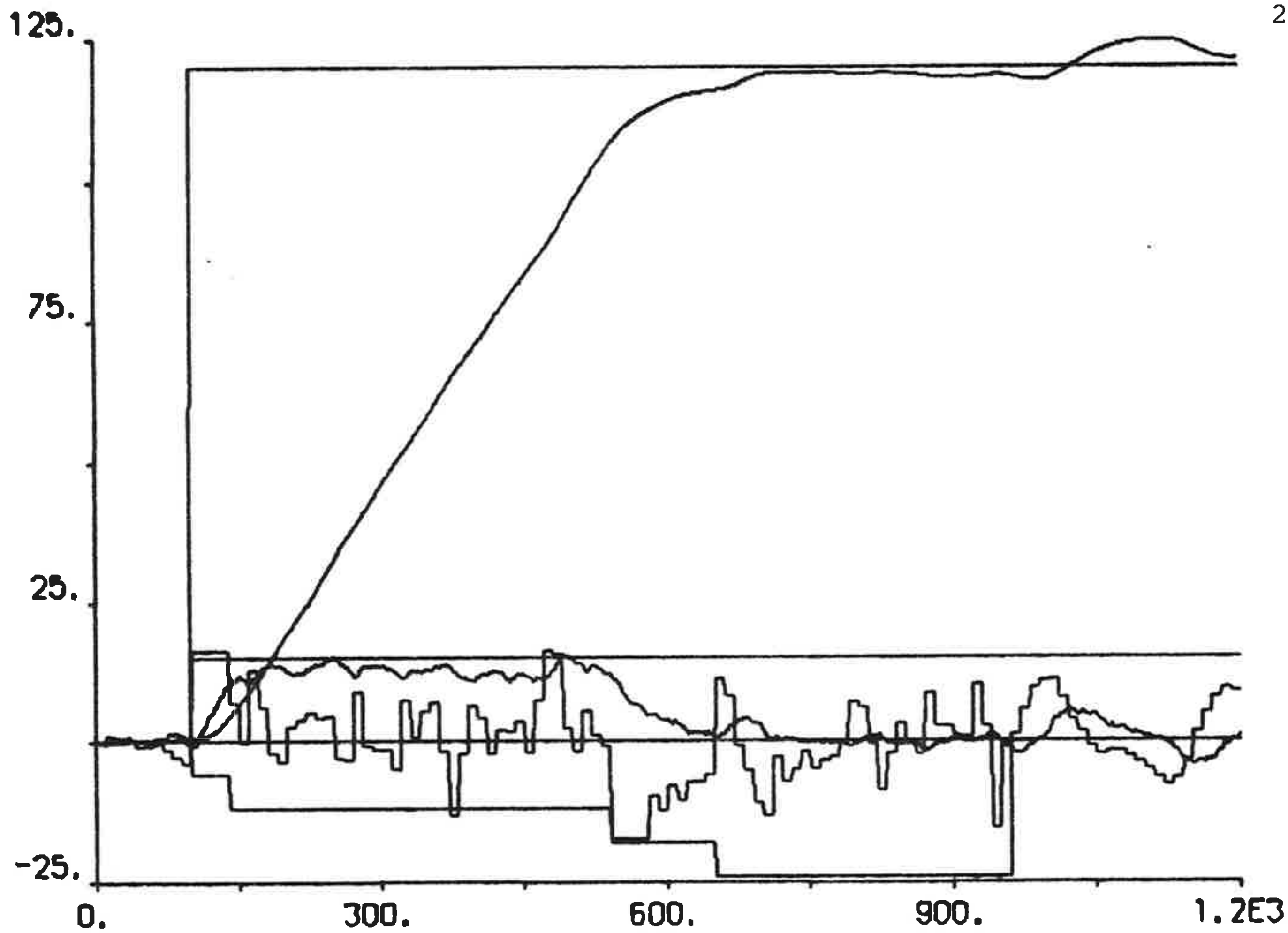


Fig. 4.60 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 50 s).



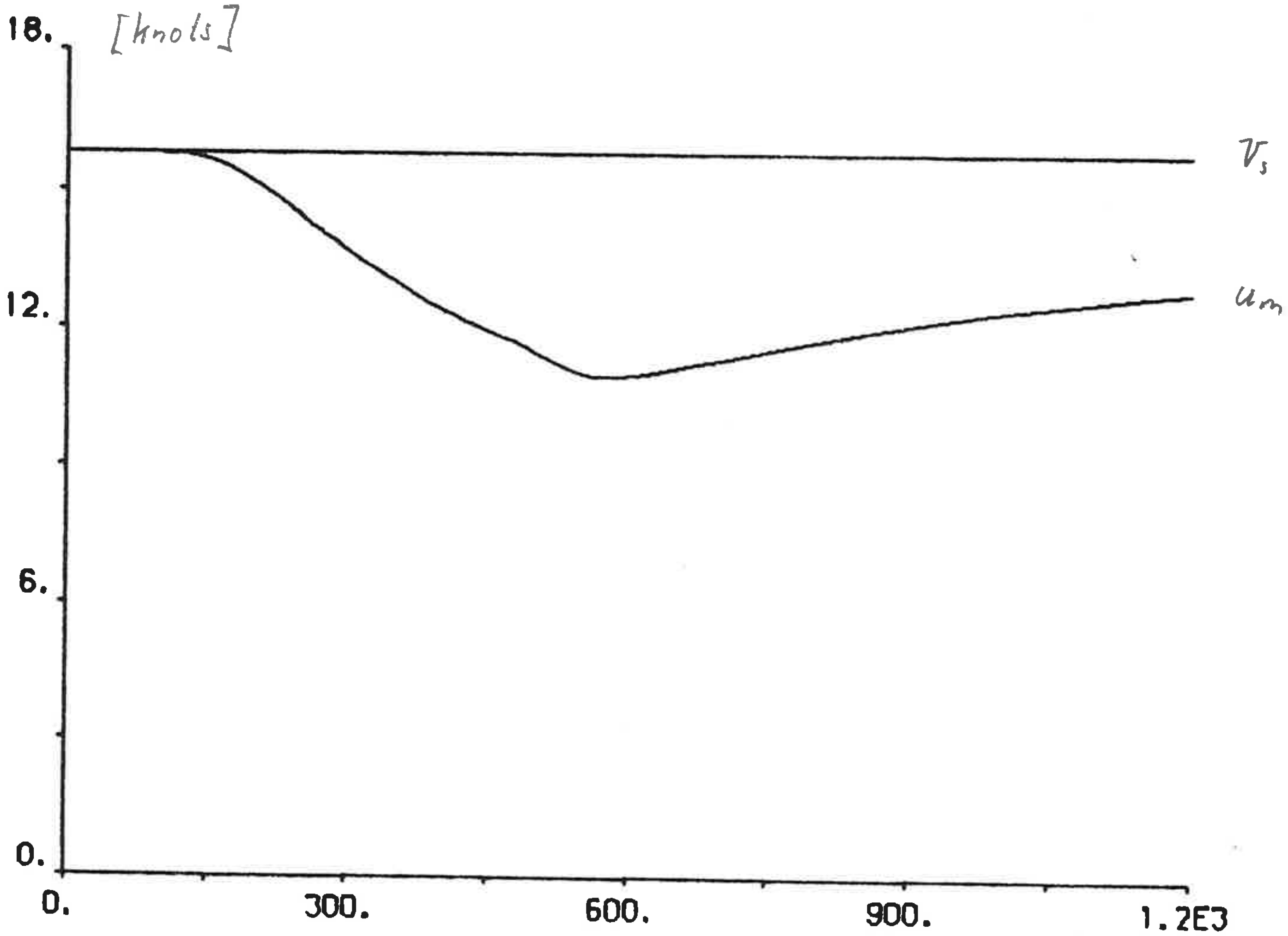


Fig. 4.61 - T = 22.3 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 50 s).

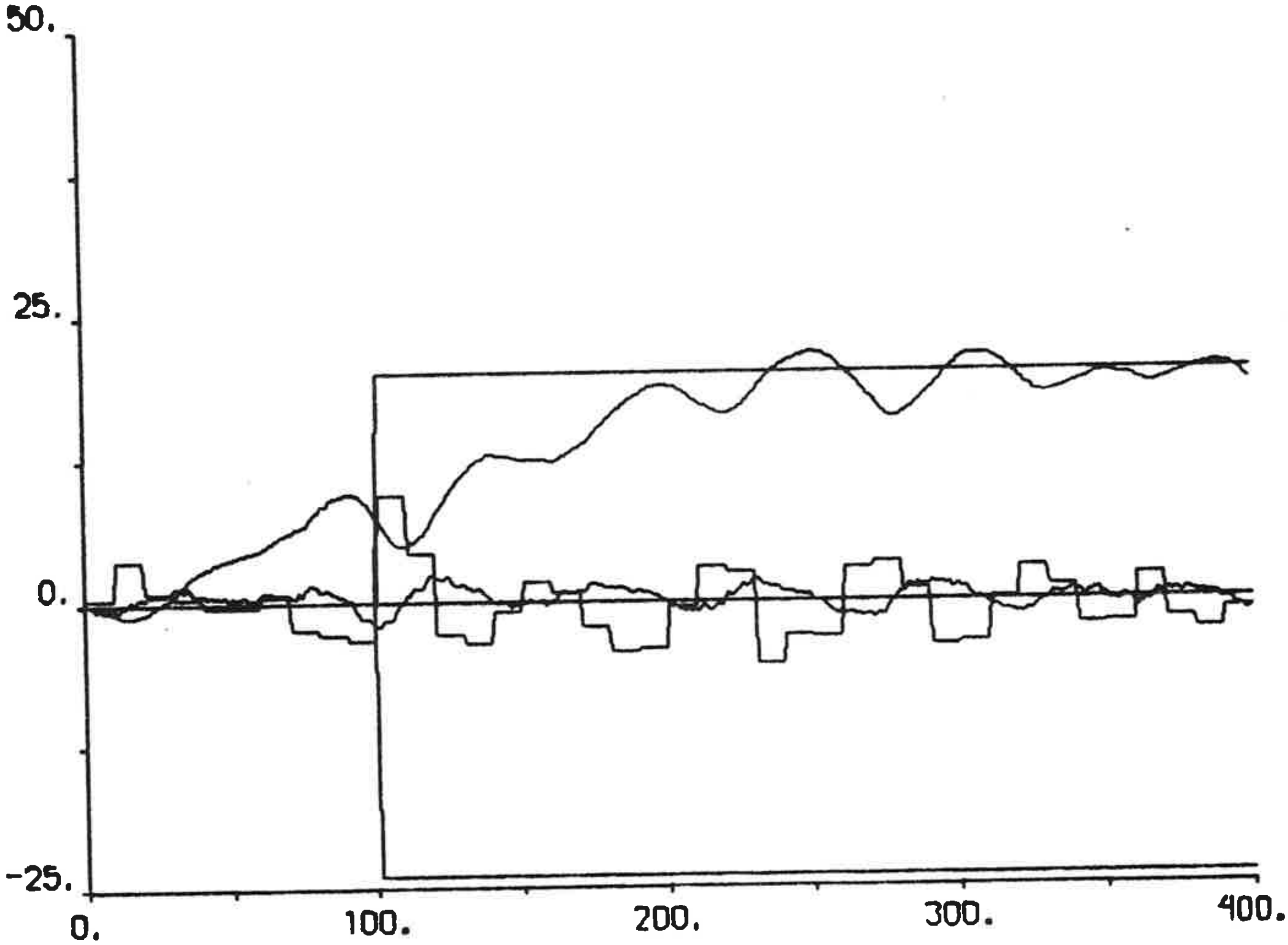


Fig. 4.62 - $T = 10.5$ m, $n_0 = 87.6$ rpm, $u_0 = 15.8$ knots, $\Delta\psi_{ref} = 2$ deg, $r_{ref} = 0$ deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2 = 50$ s).

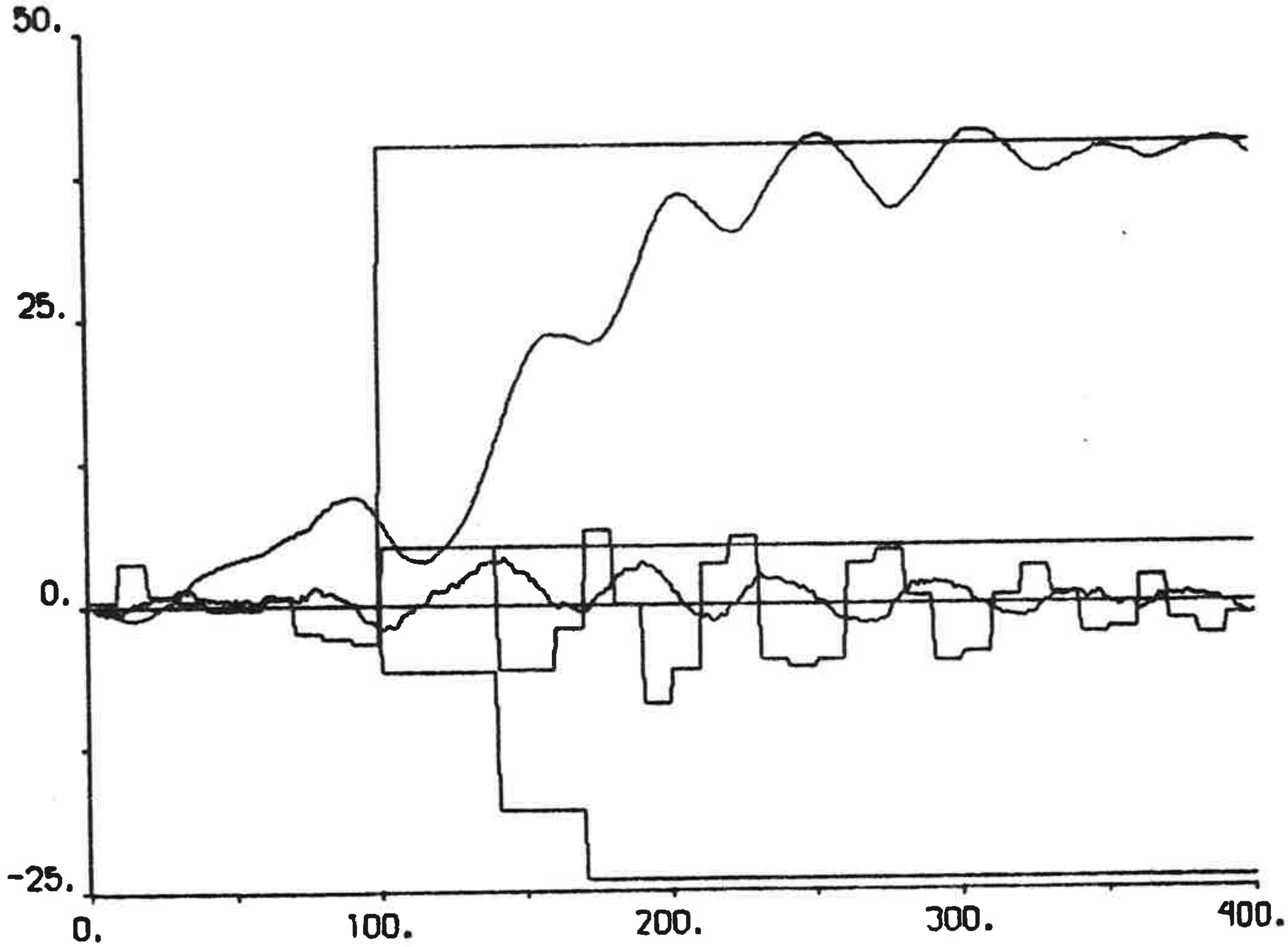


Fig. 4.63 - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 50 s).

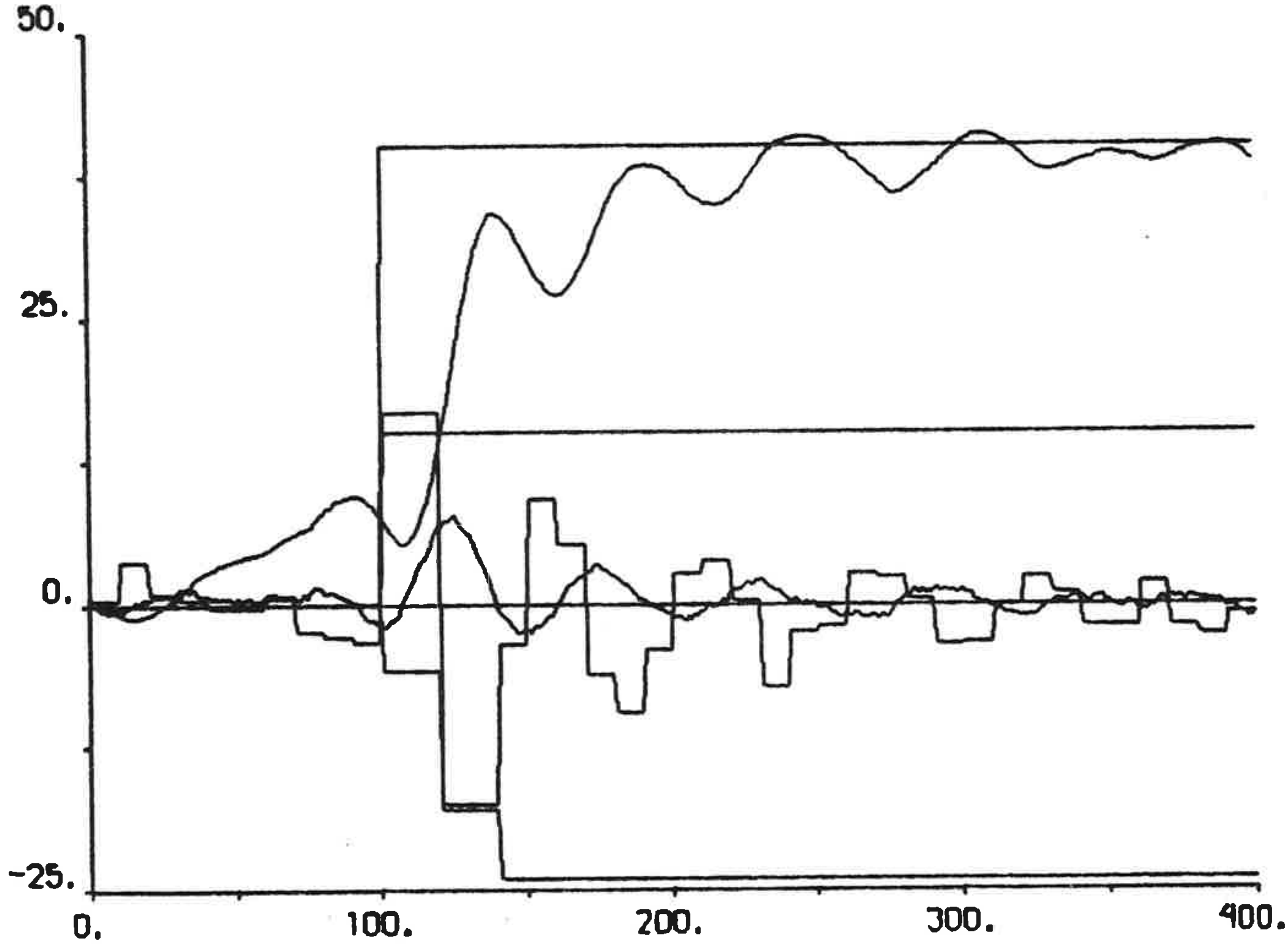


Fig. 4.64 - $T = 10.5$ m, $n_0 = 87.6$ rpm, $u_0 = 15.8$ knots, $\Delta\psi_{ref} = 4$ deg, $r_{ref} = 0.3$ deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2 = 50$ s).

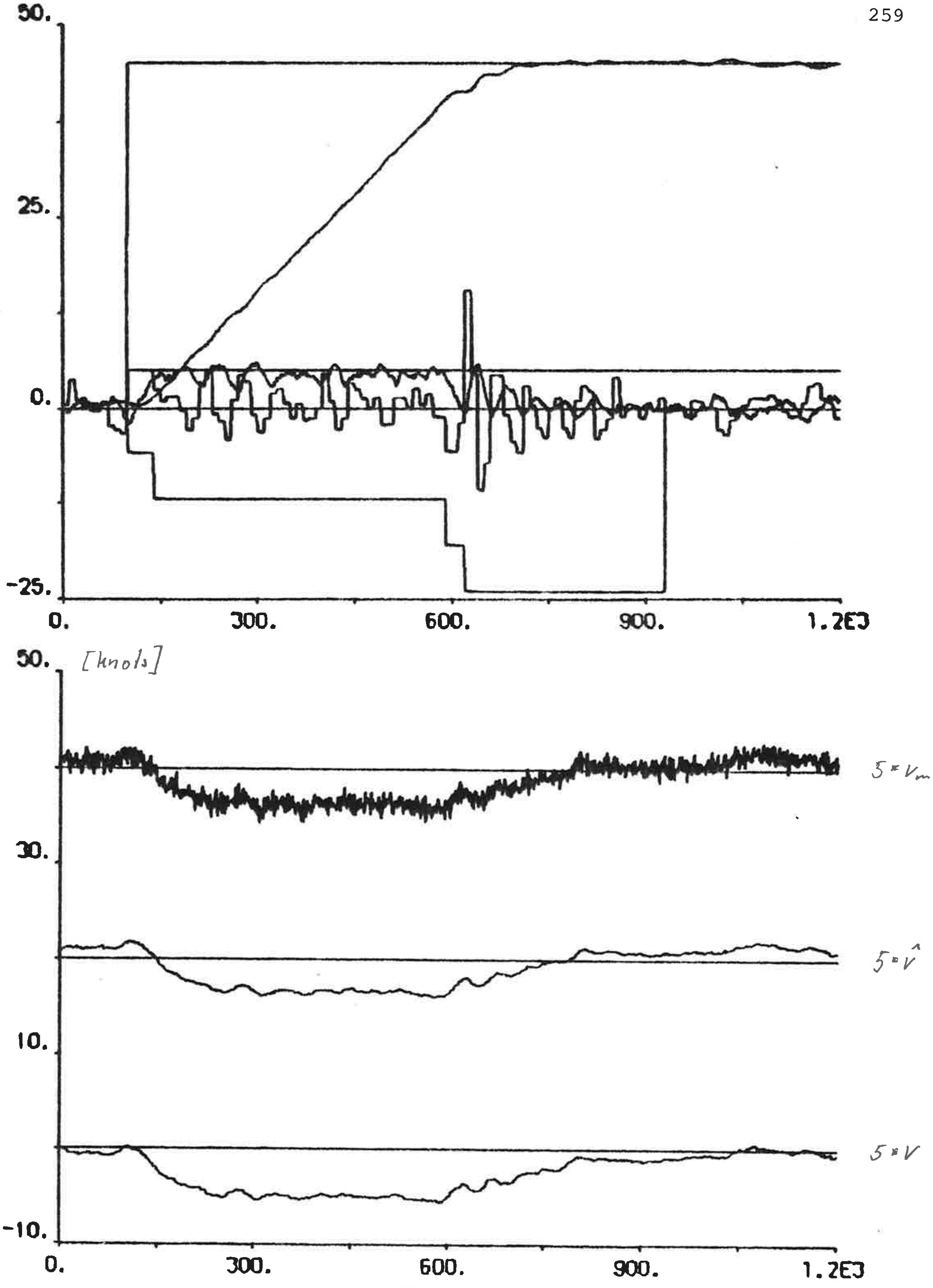
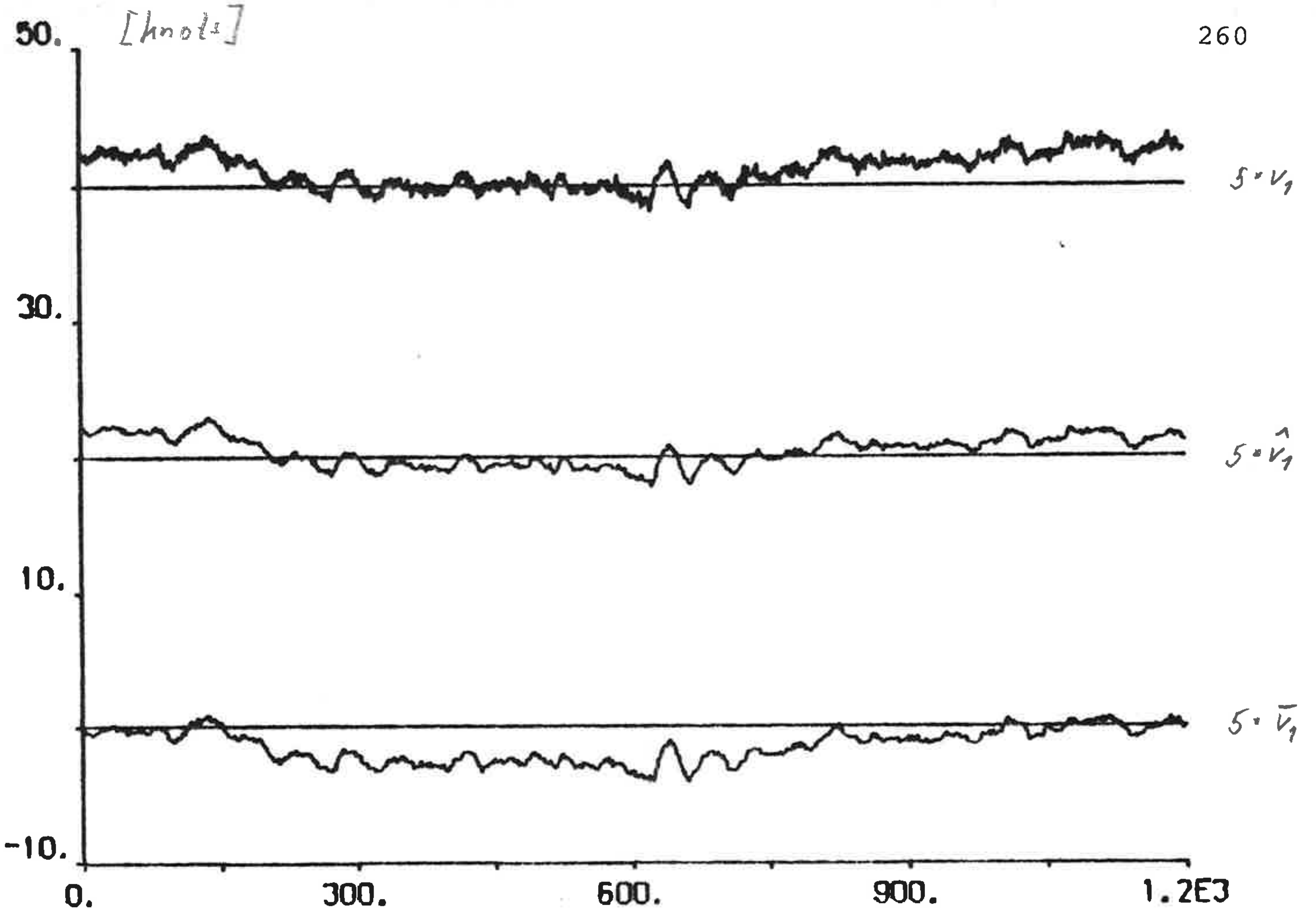


Fig. 4.65 a - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{\tau}_2$ = 50 s).


[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5·v_1
5·$\hat{v}_1$
5·$\bar{v}_1$

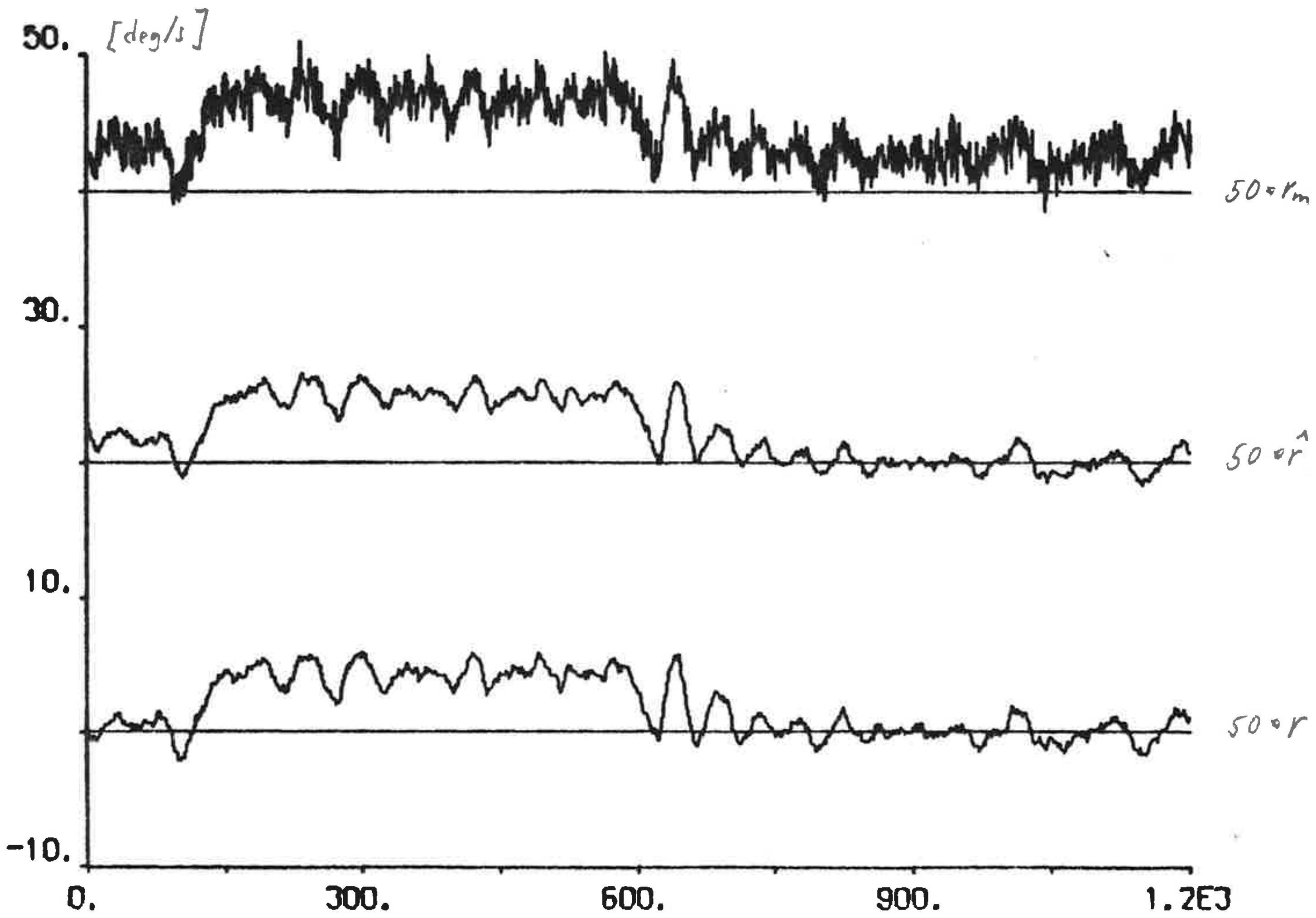

[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
50·r_m
50·$\hat{r}$
50·r

Fig. 4.65 b

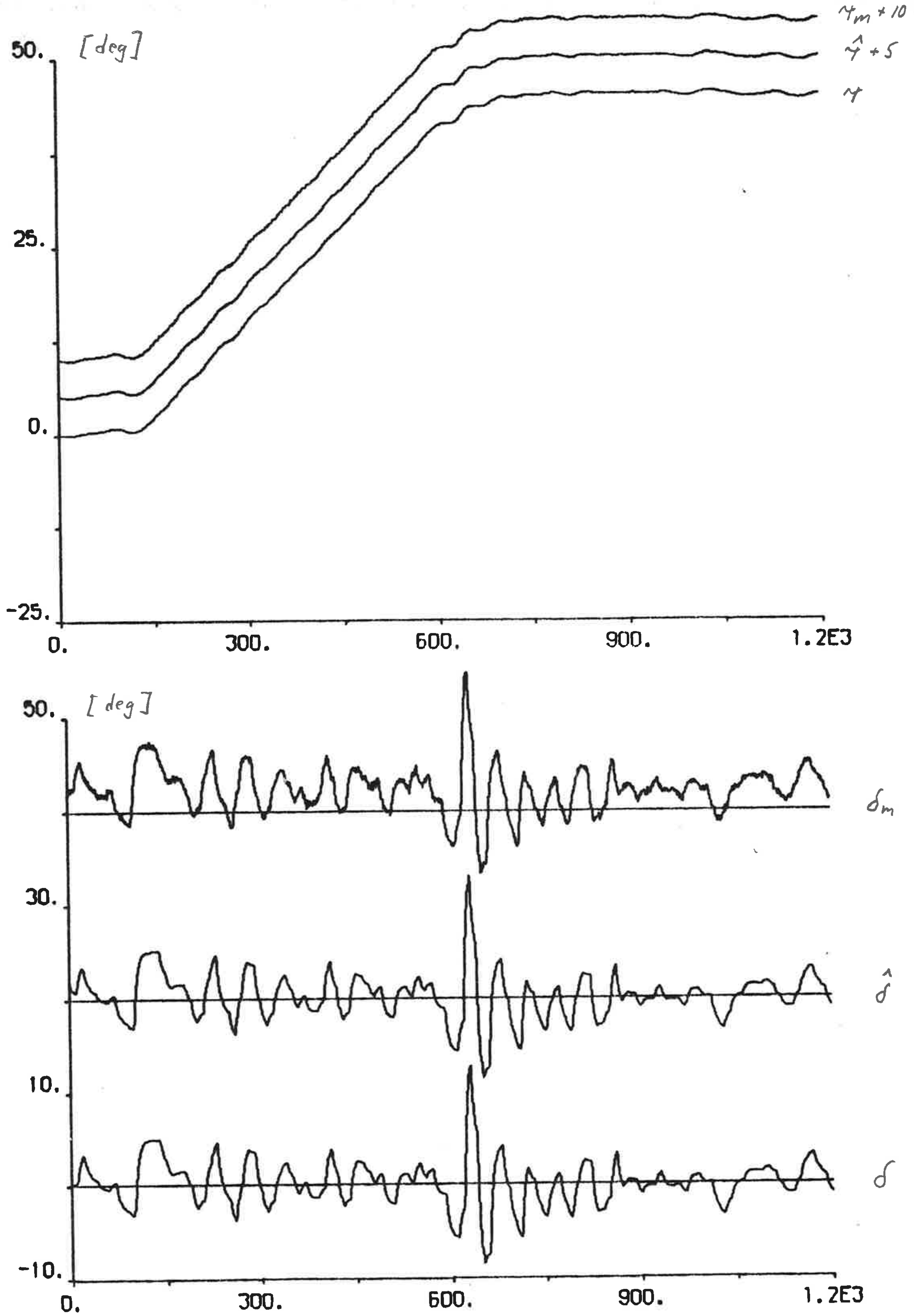
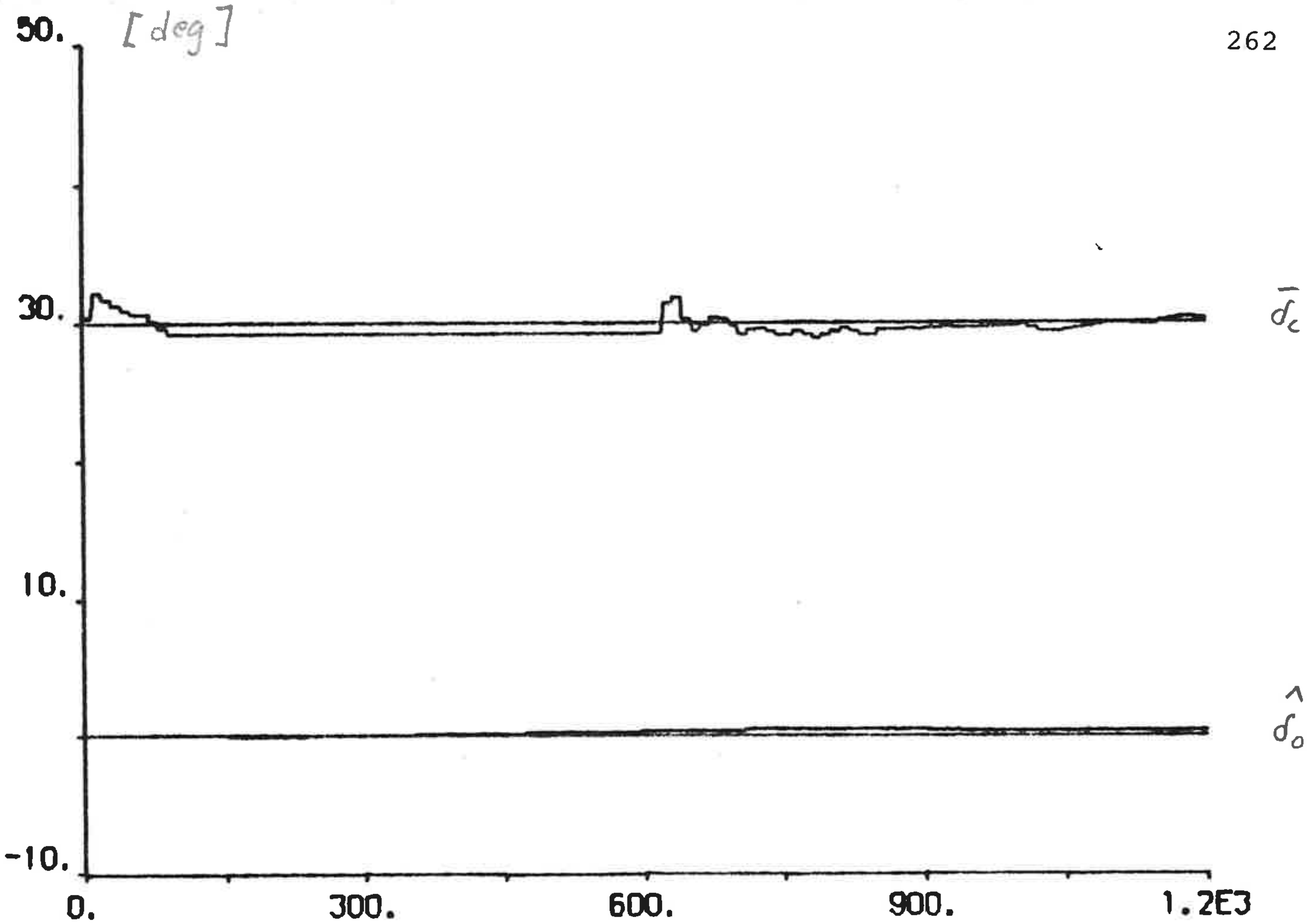


Fig. 4.65 c


[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3

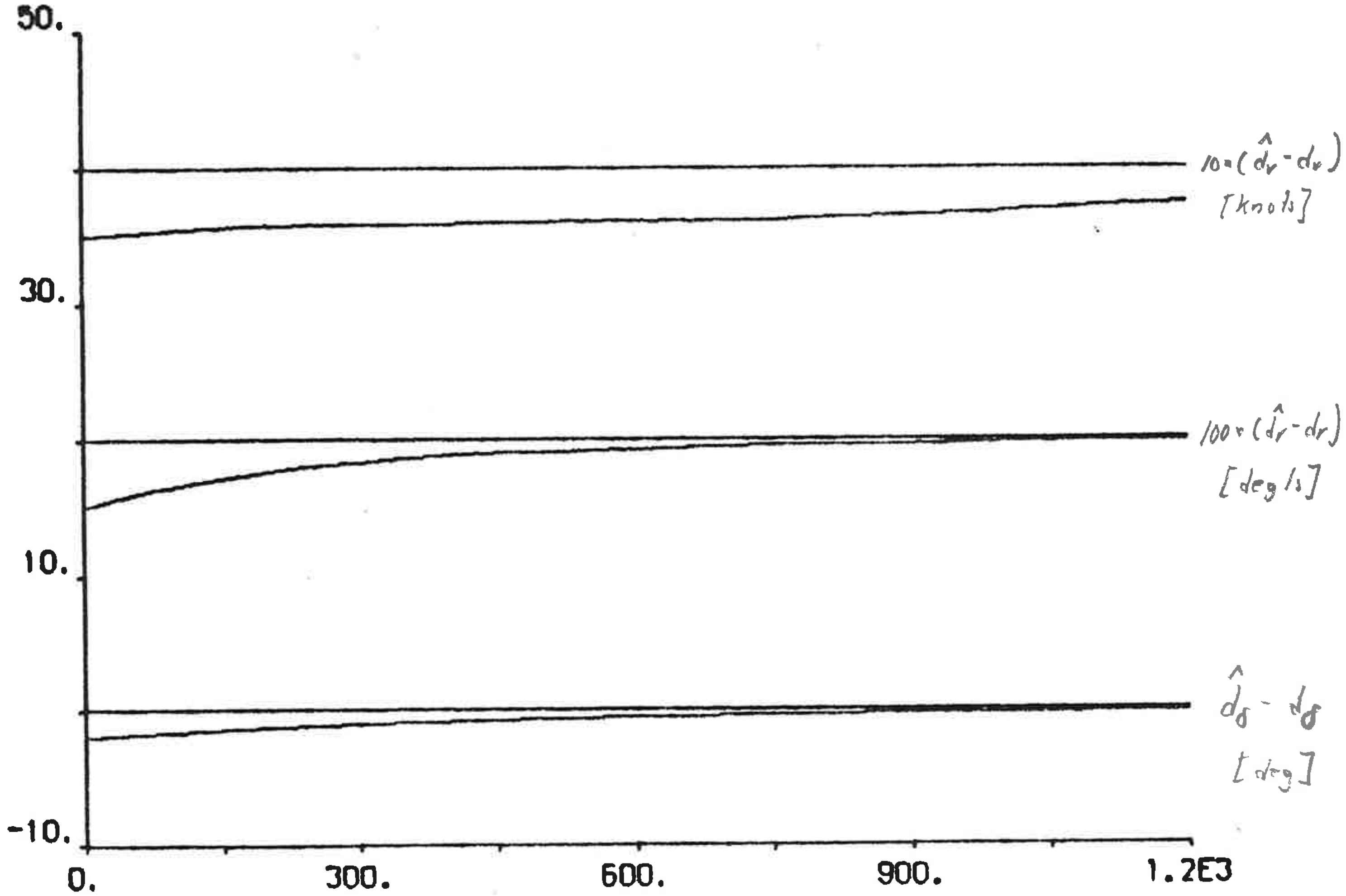
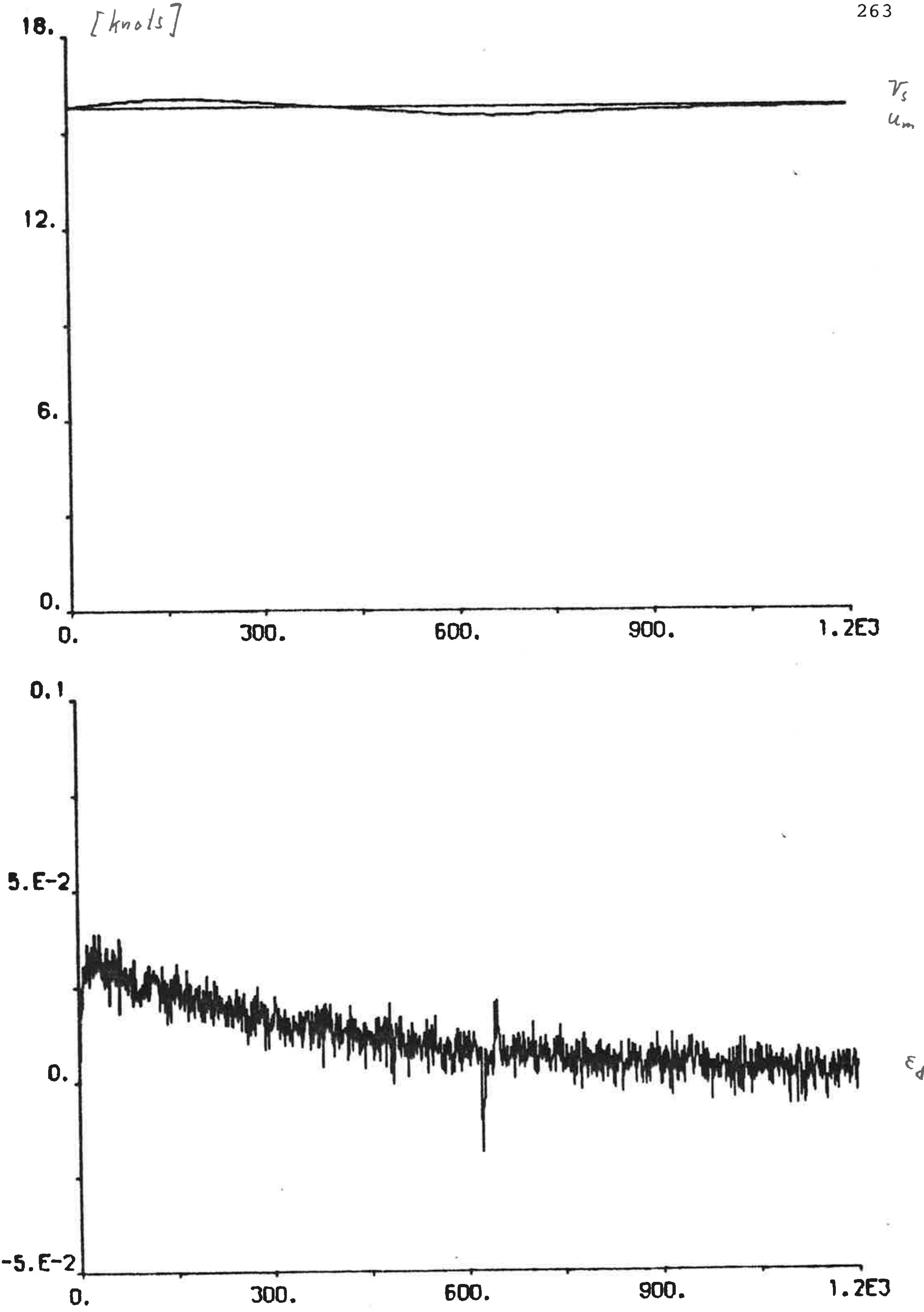
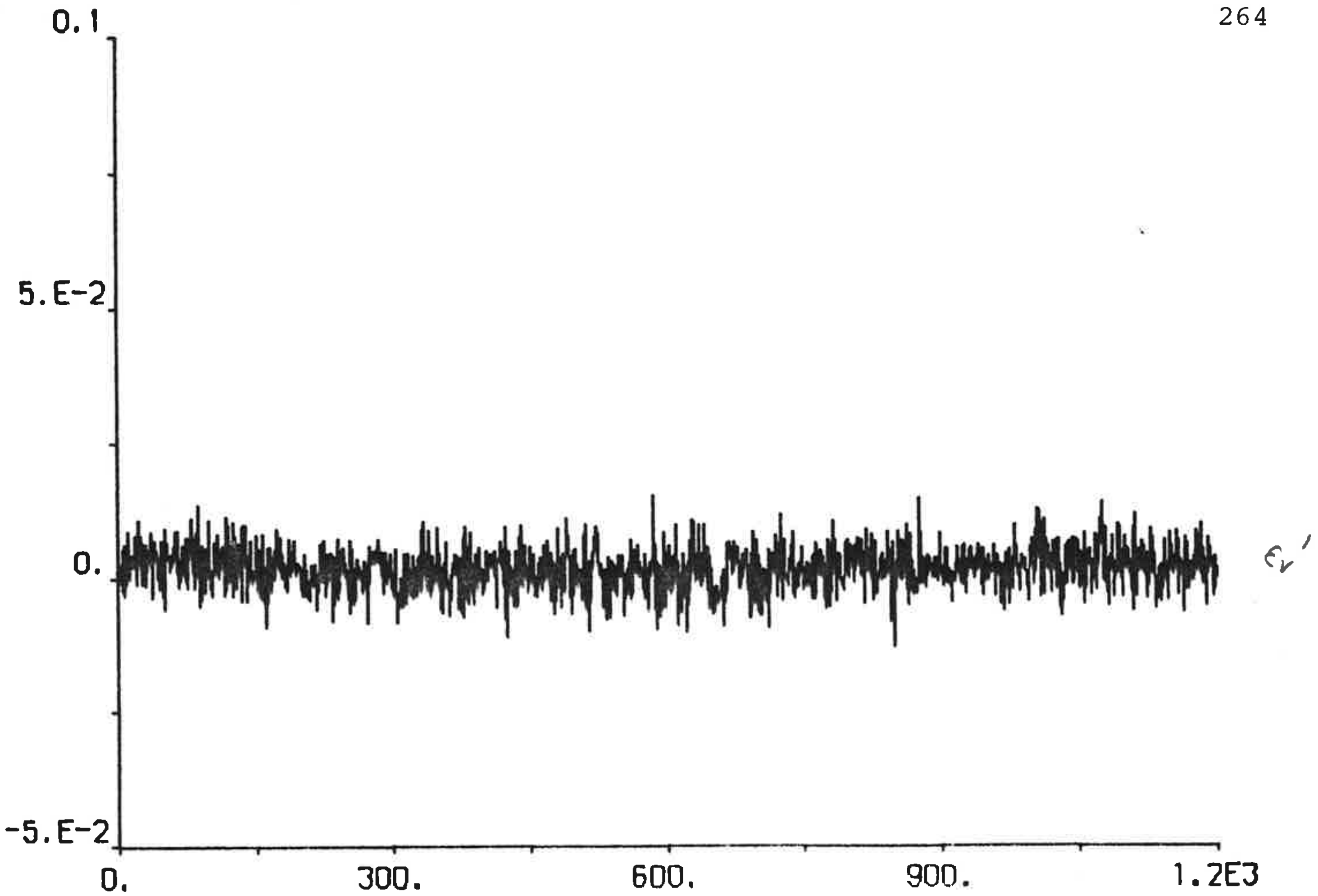

50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[knots]
[deg/s]
[deg]

Fig. 4.65 d



[knots]
18.
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
u_m
0.1
5.E-2
0.
-5.E-2
0.
300.
600.
900.
1.2E3
ε_d'

Fig. 4.65 e



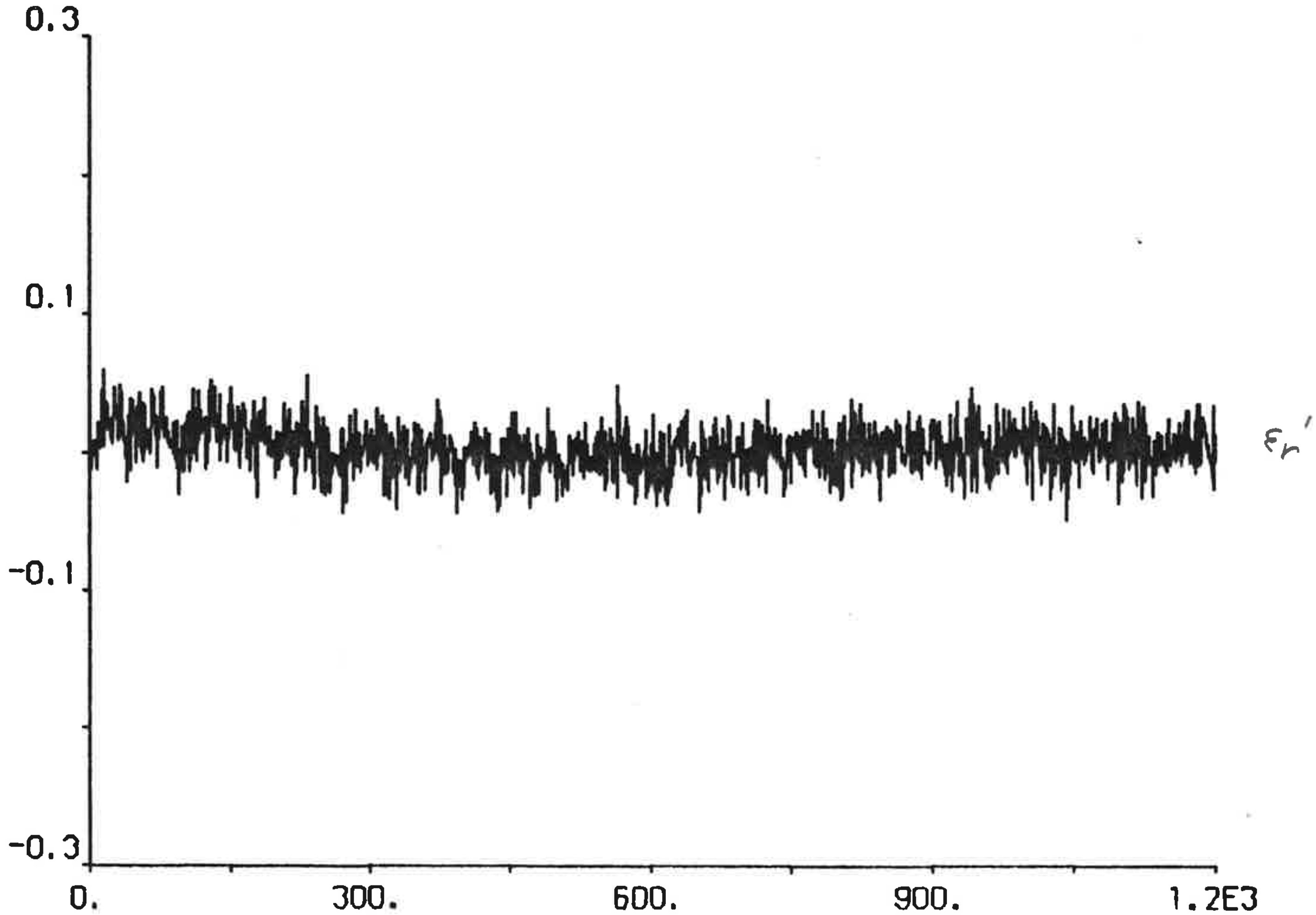
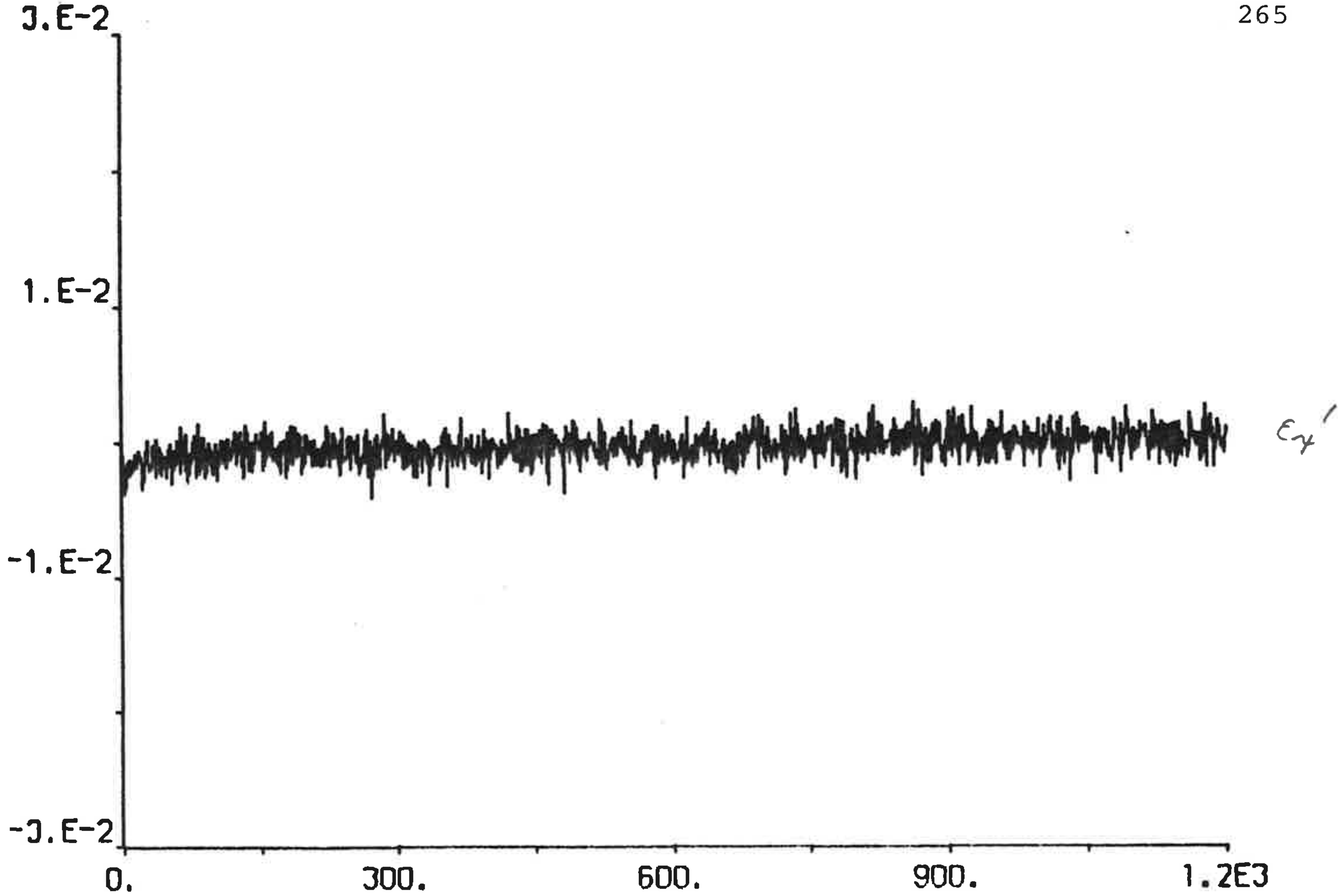


Fig. 4.65 f


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
ε4'

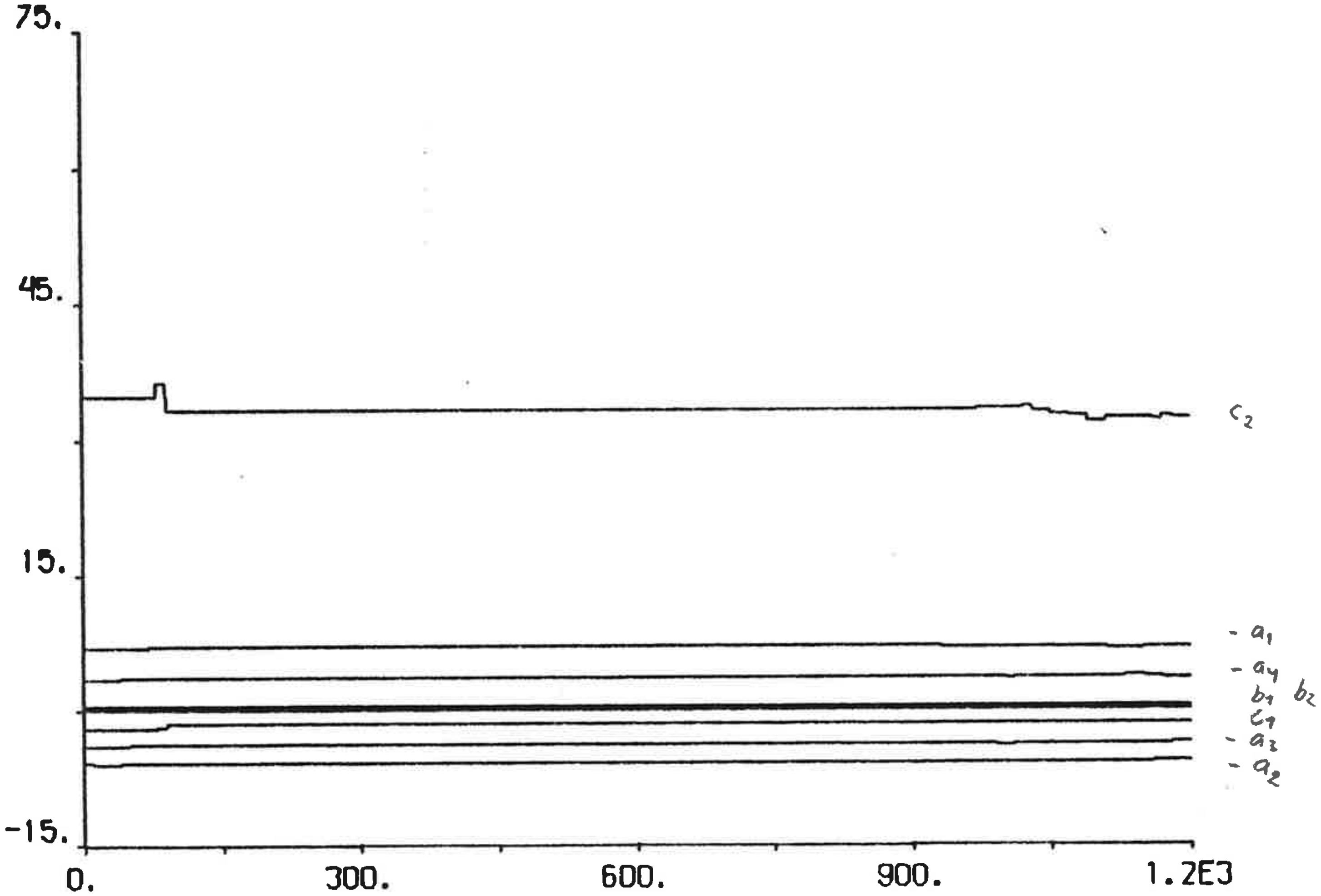

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c2
- a1
- a4
b1
b2
c1
- a3
- a2

Fig. 4.65 q

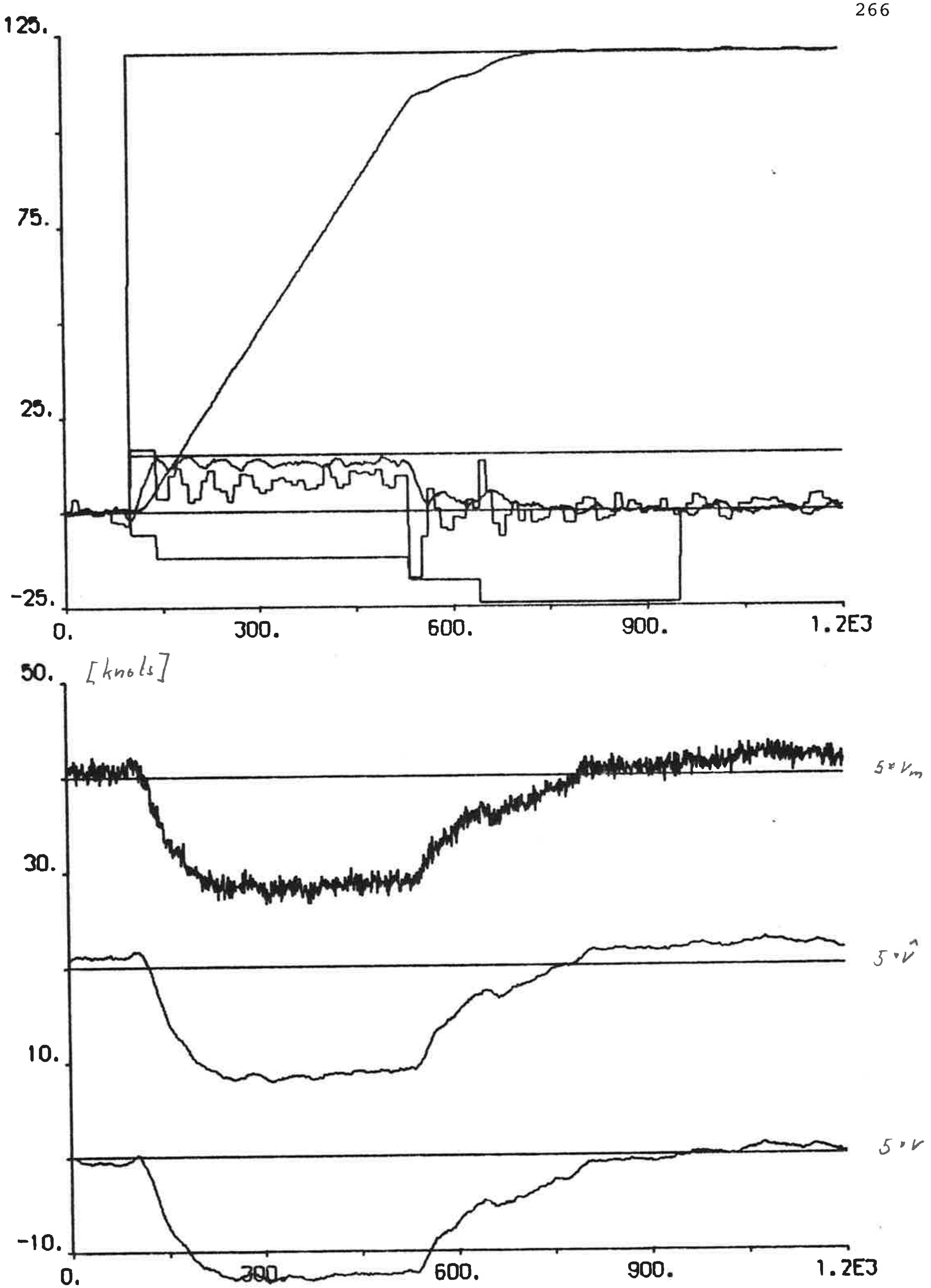
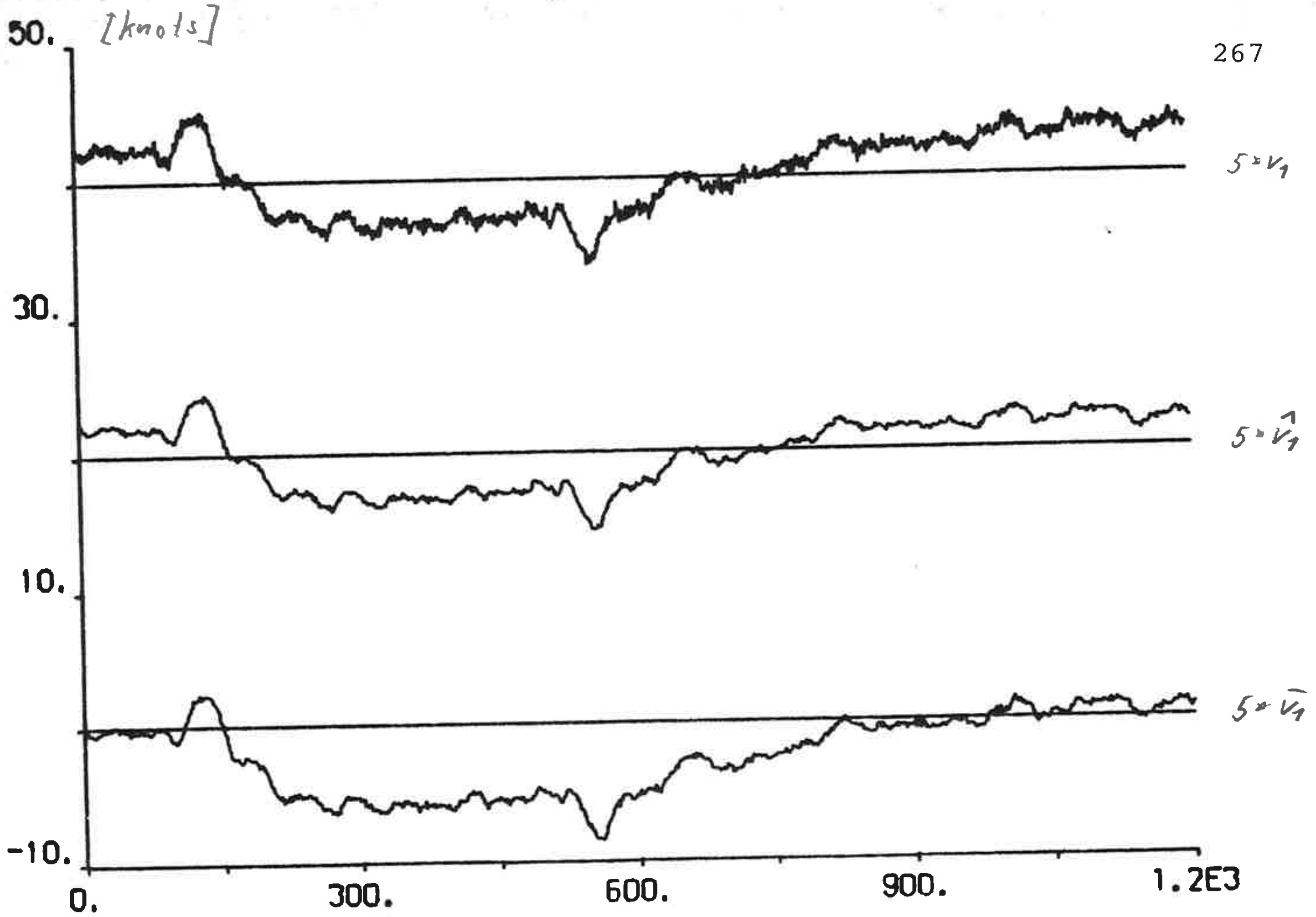


Fig. 4.66 a - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{c}_2$ = 50 s).


50.
[knots]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5*v1
5*v̂1
5*ṽ1

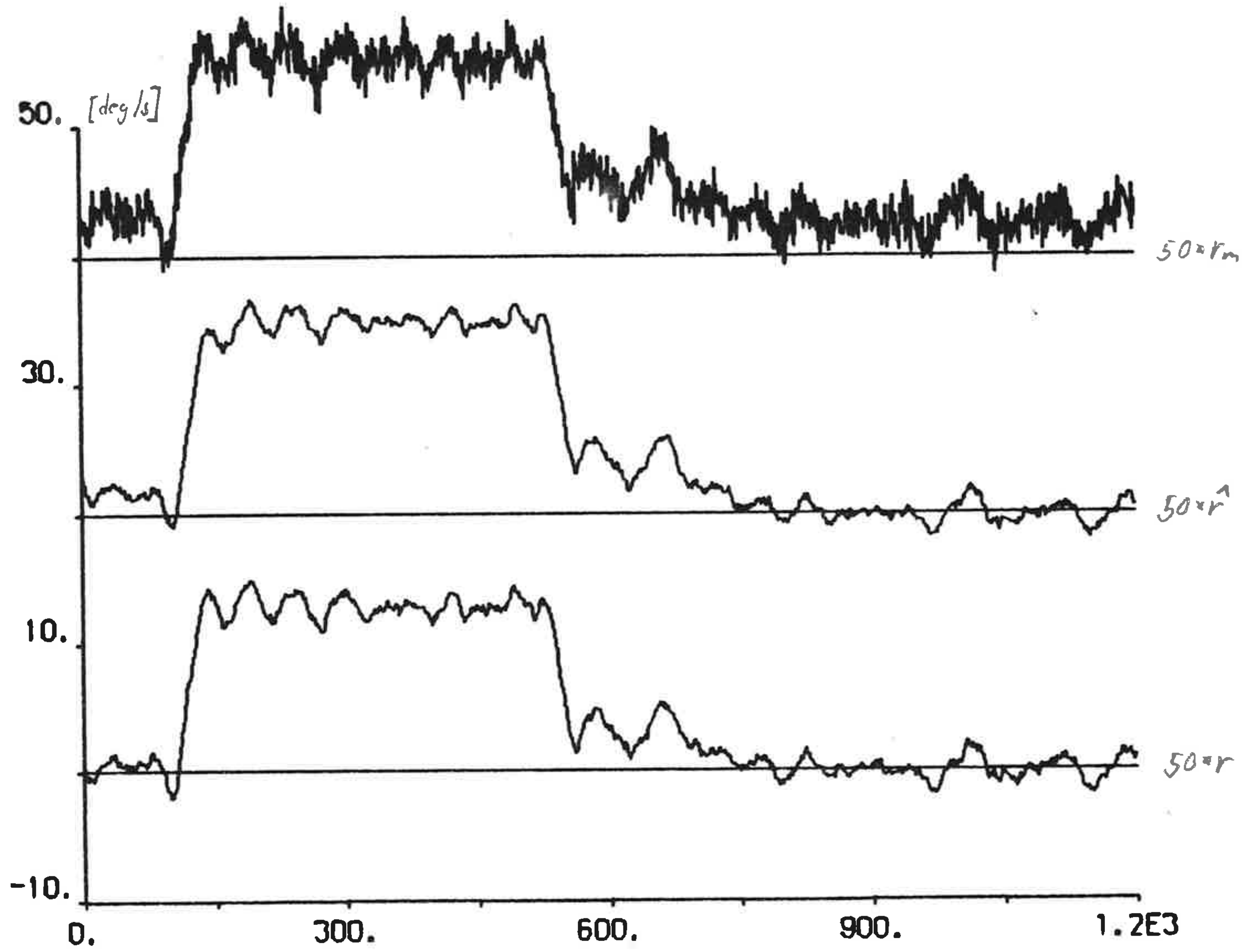
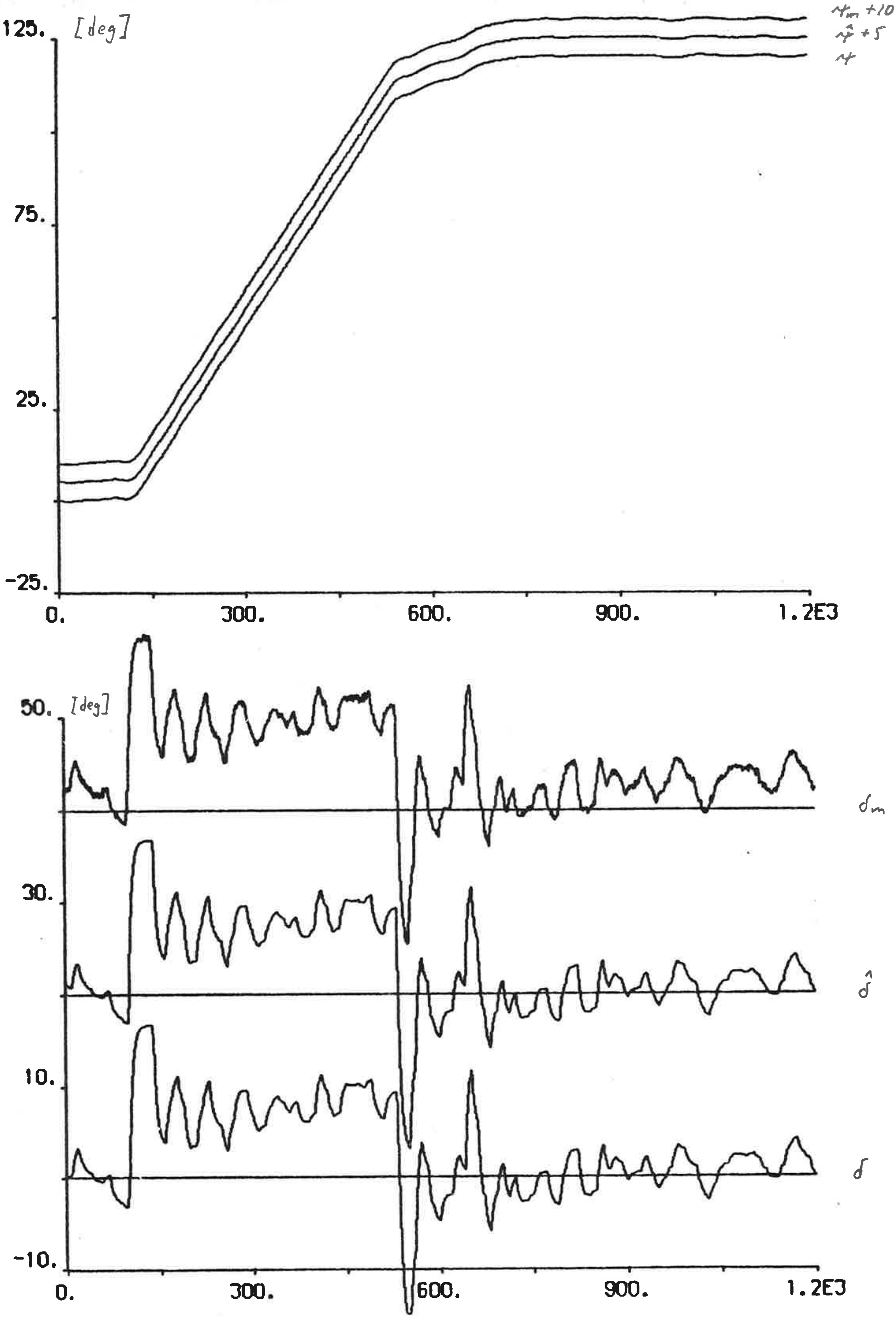

50.
[deg/s]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
50*rm
50*r̂
50*r

Fig. 4.66 b



125.
[deg]
75.
25.
-25.
0.
300.
600.
900.
1.2E3
50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3

Fig. 4.66 c

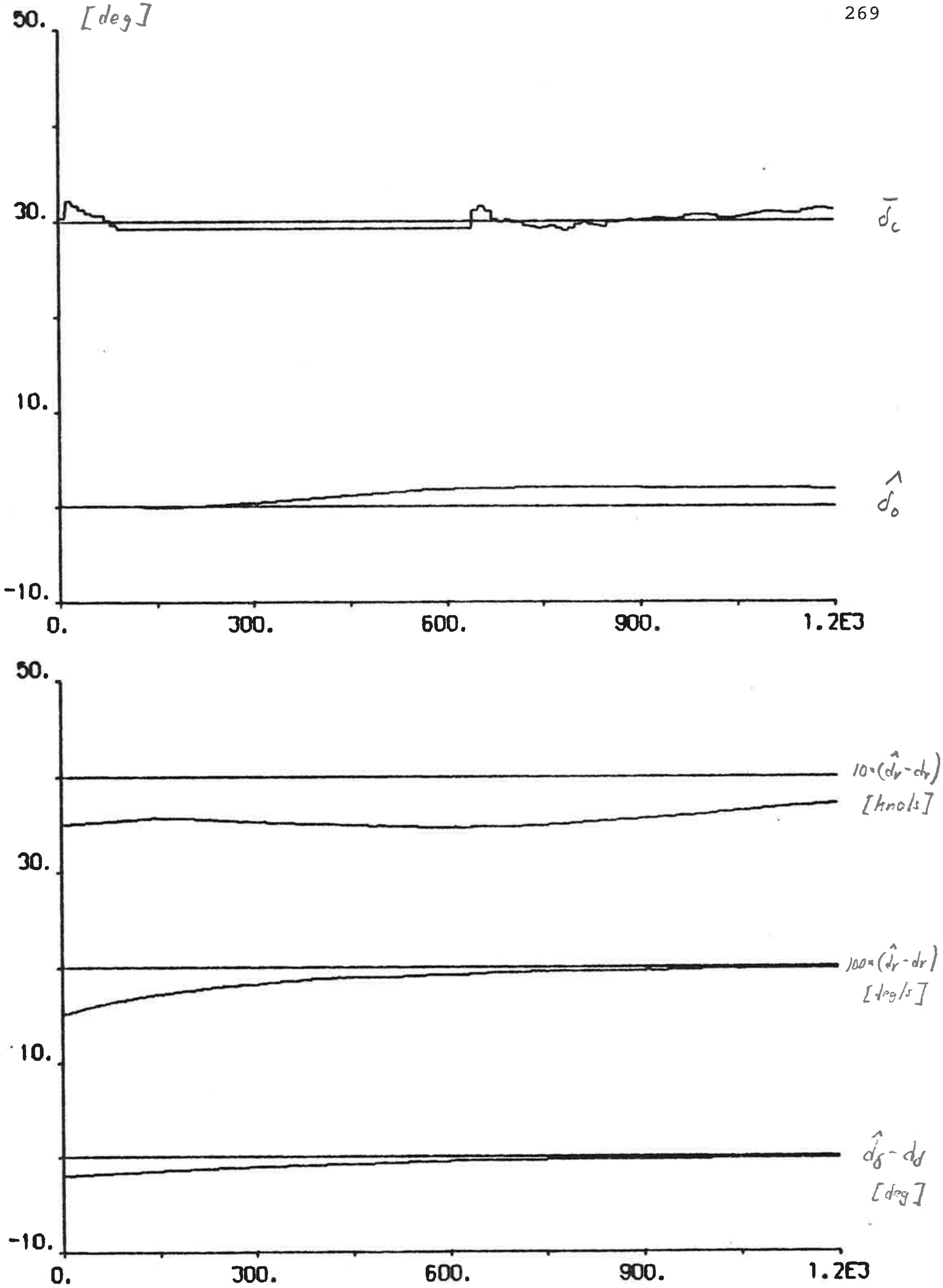
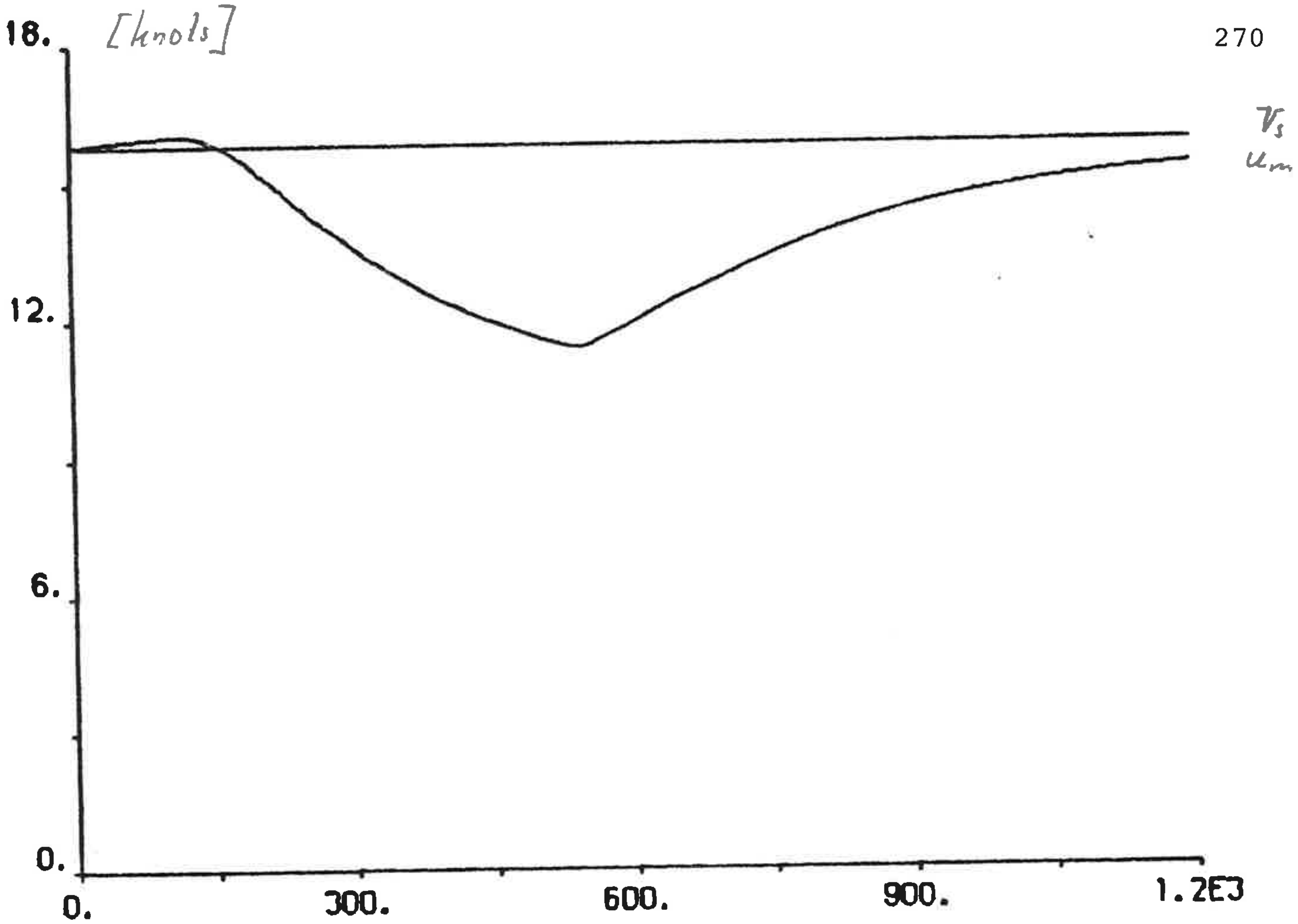

50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[deg]

Fig. 4.66 d



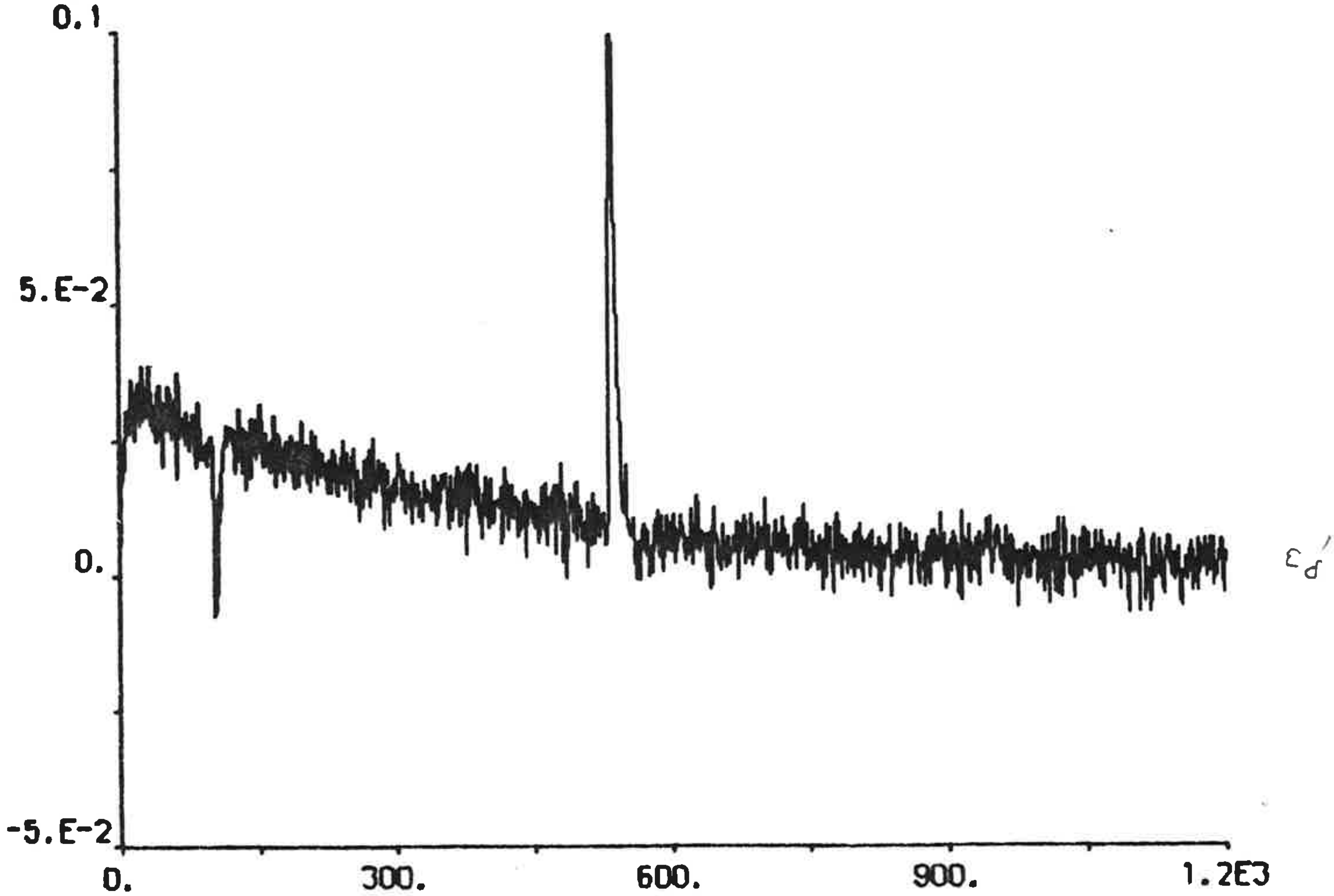


Fig. 4.66 e

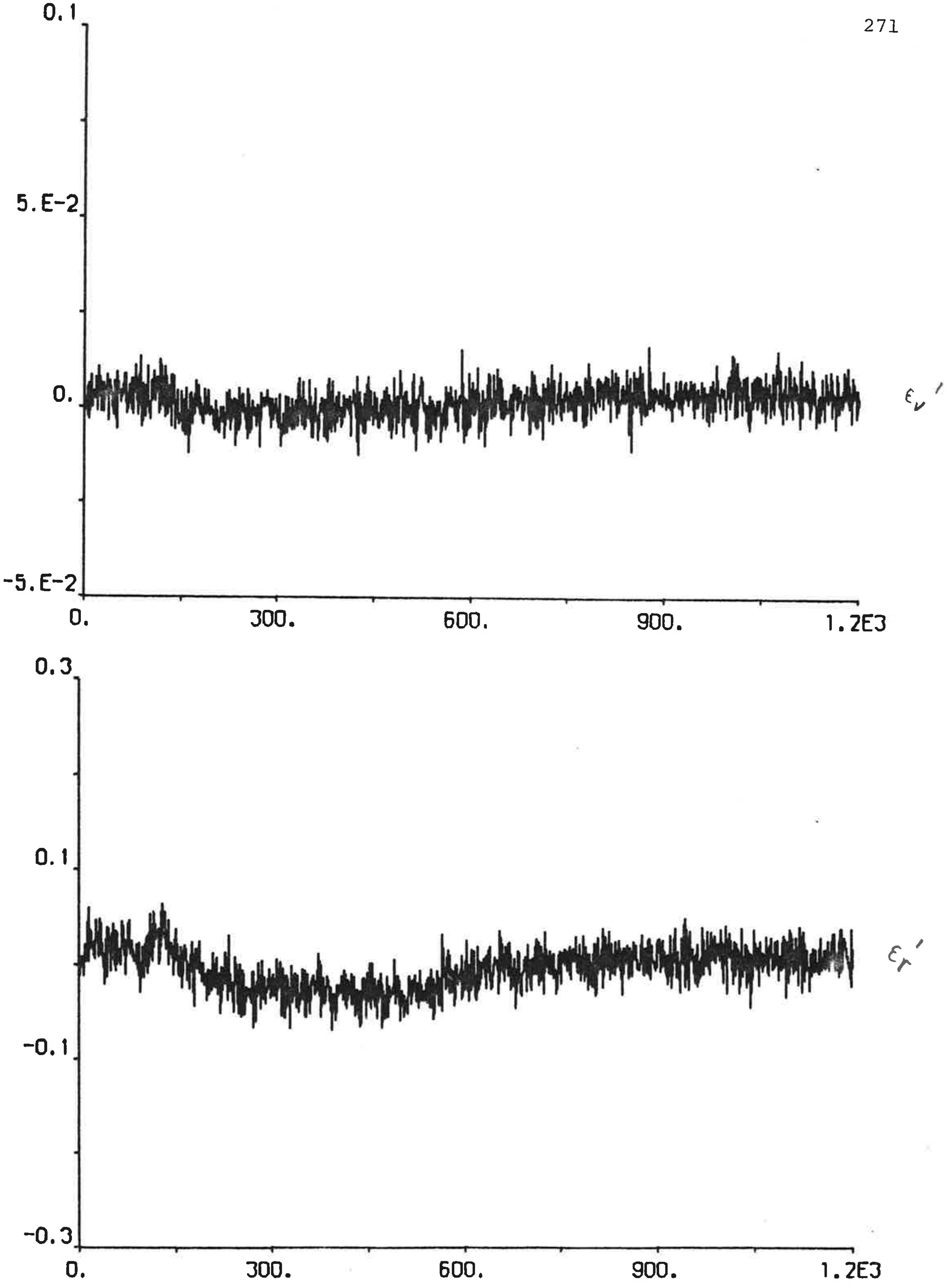
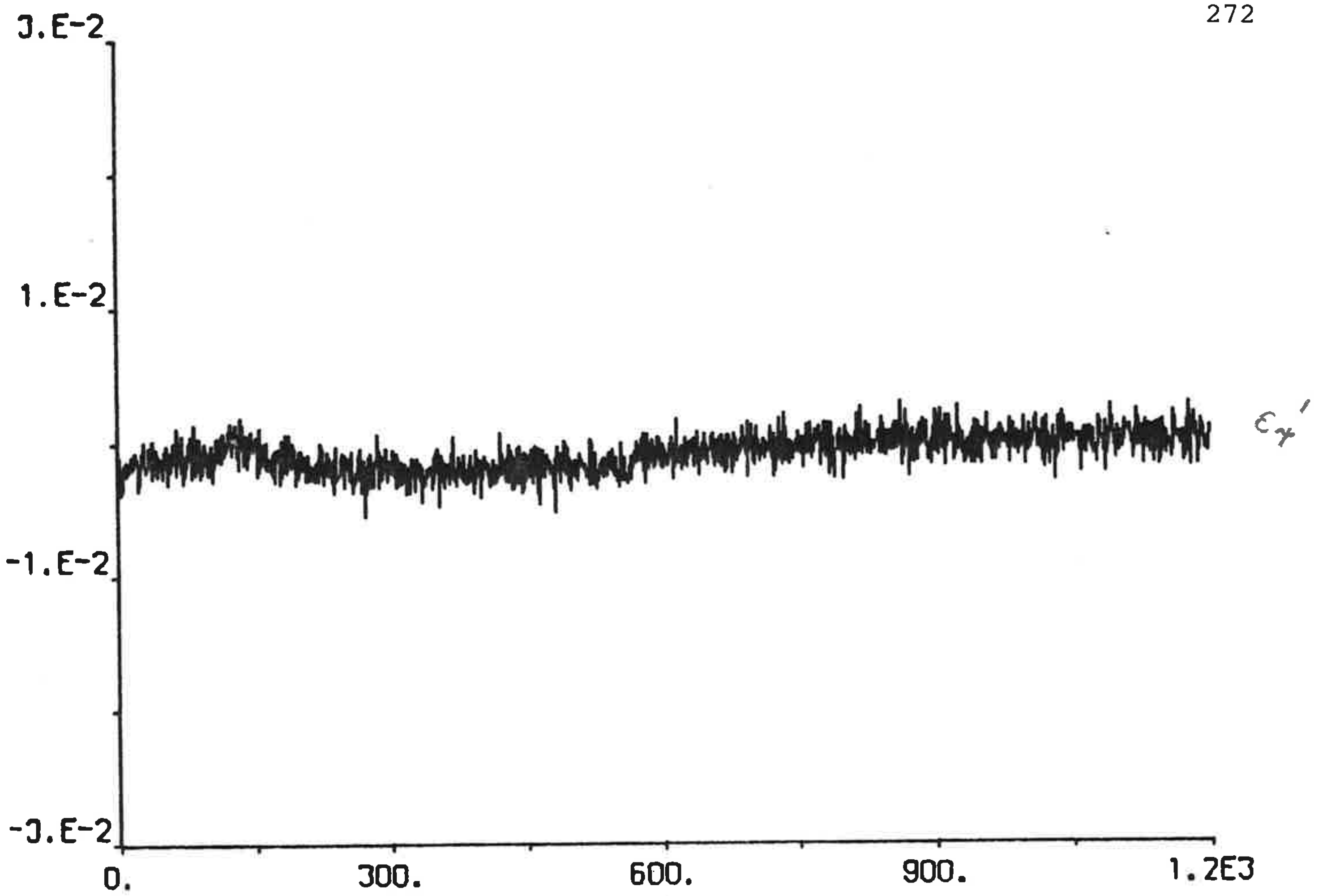


Fig. 4.66 f



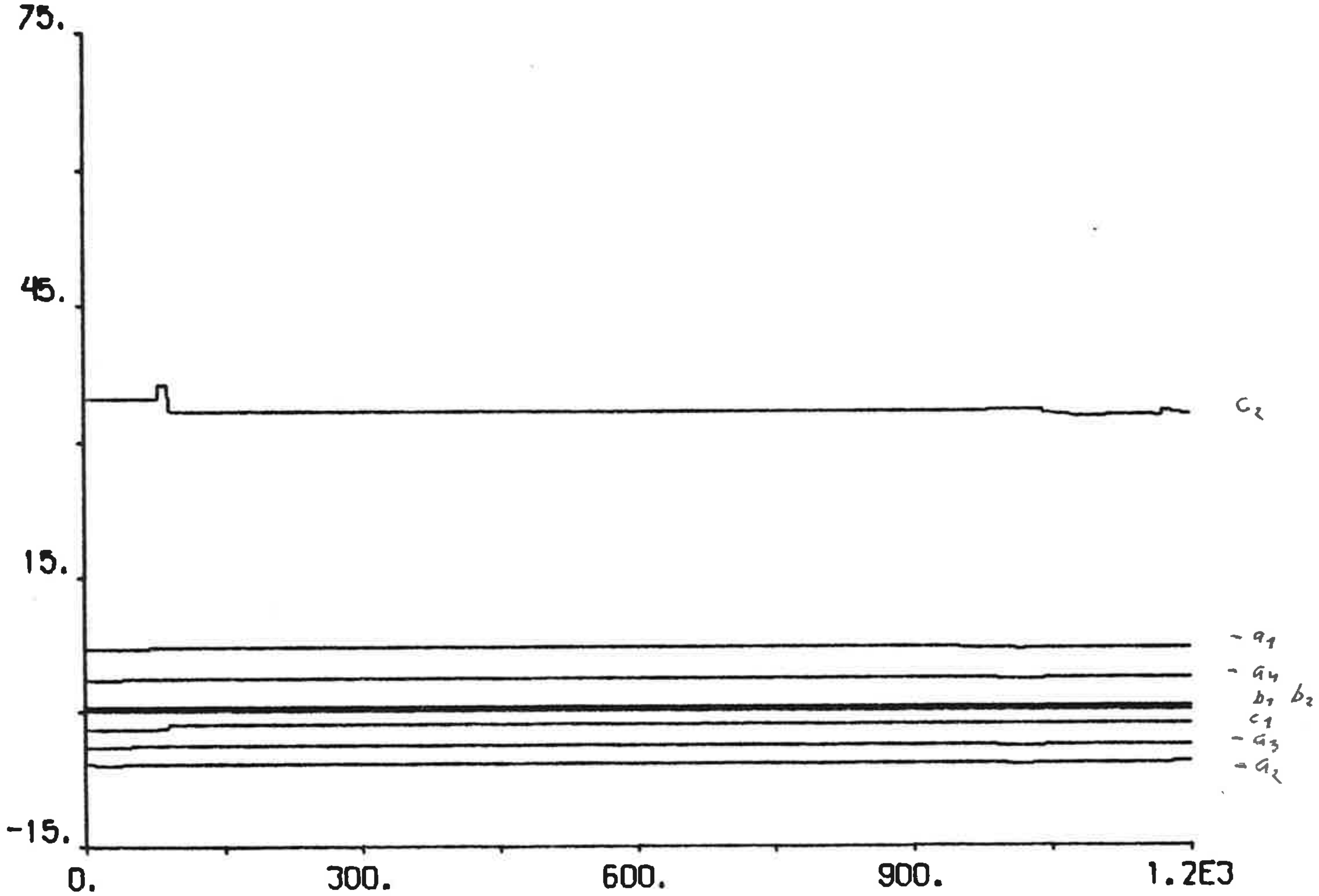


Fig. 4.66 g

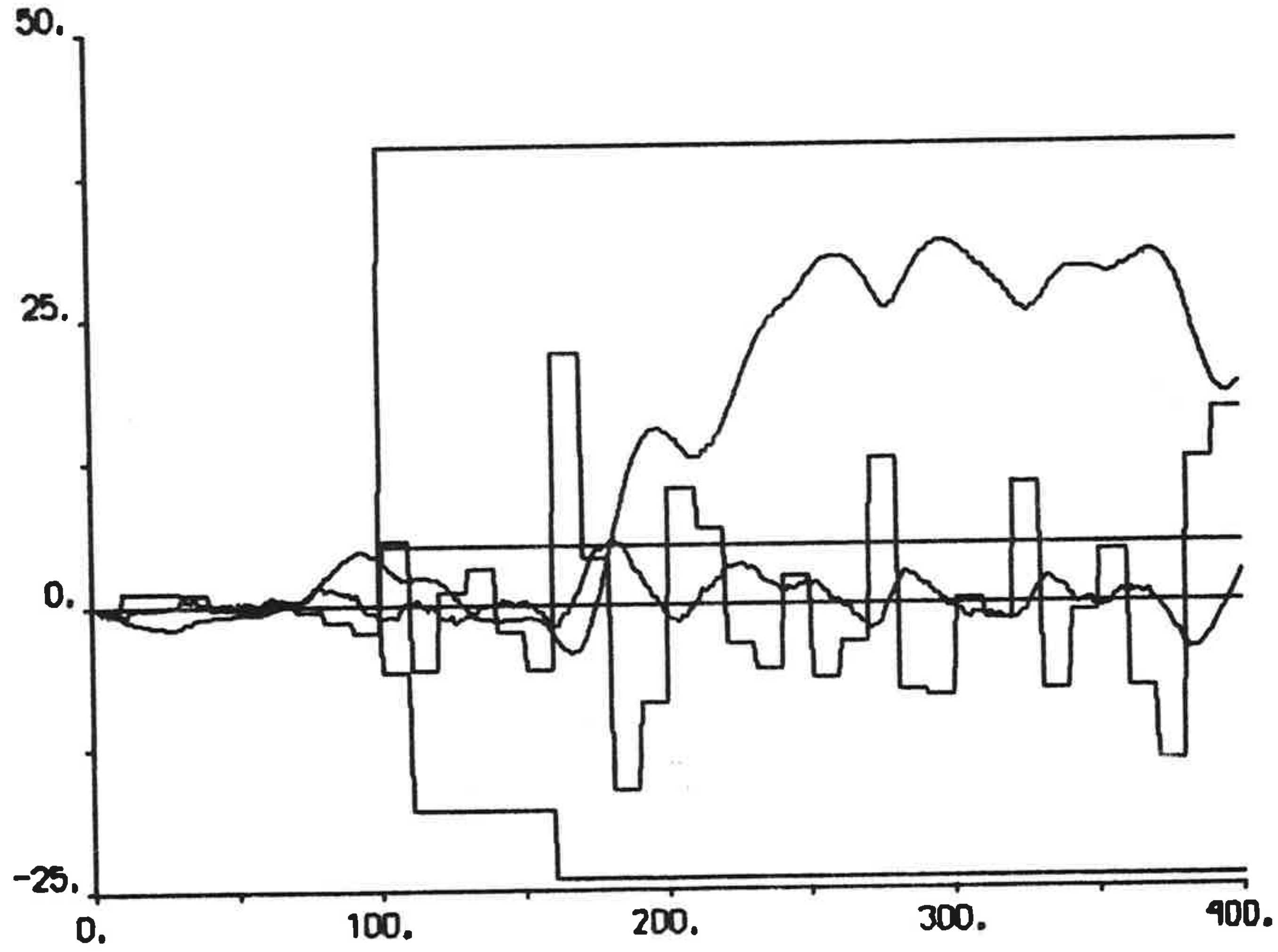
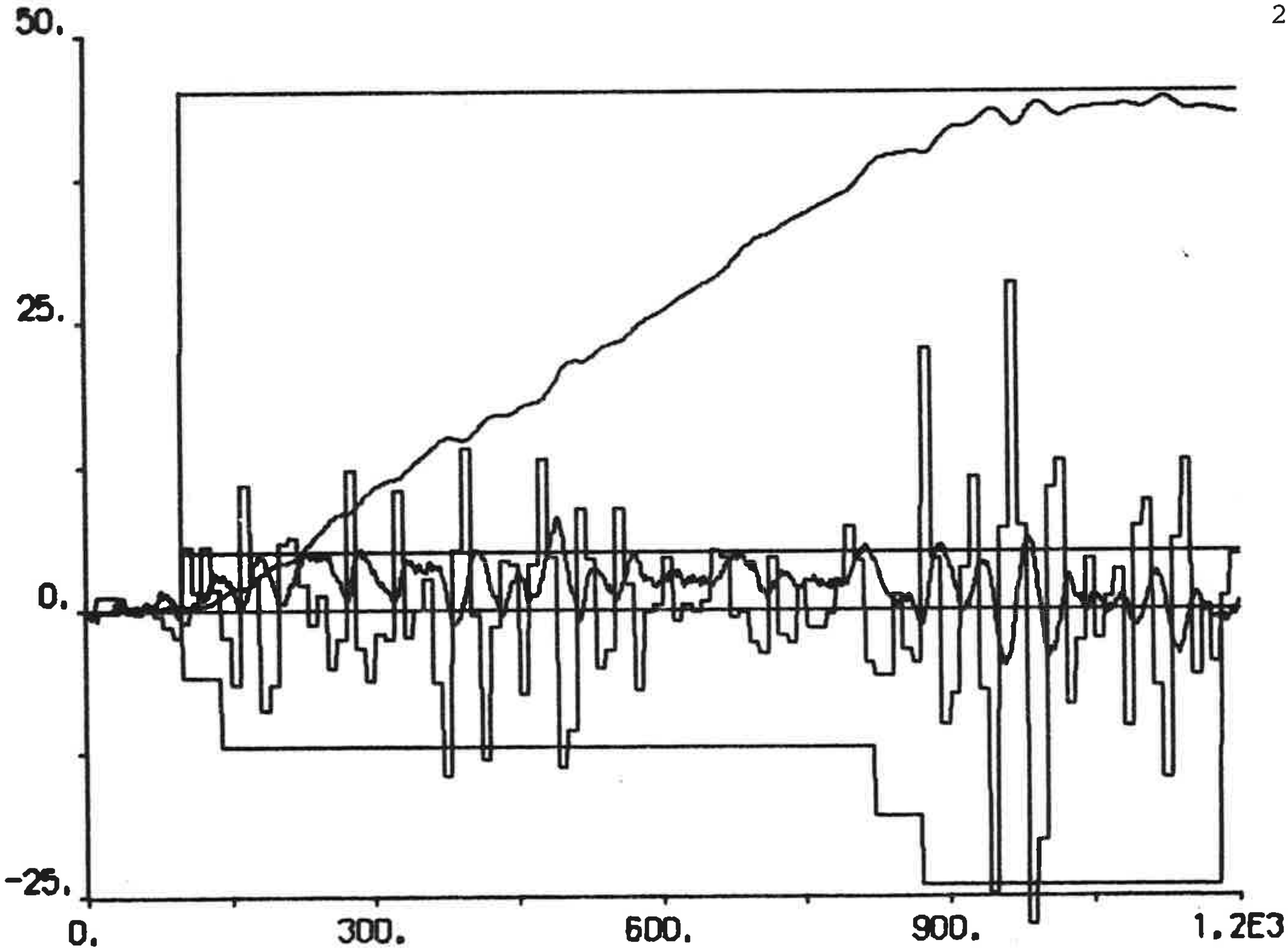


Fig. 4.67 - $T = 10.5$ m, $n_0 = 87.6$ rpm, $u_0 = 15.8$ knots, $\Delta\psi_{ref} = 4$ deg, $r_{ref} = 0.1$ deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\bar{c}_2 = 50$ s).



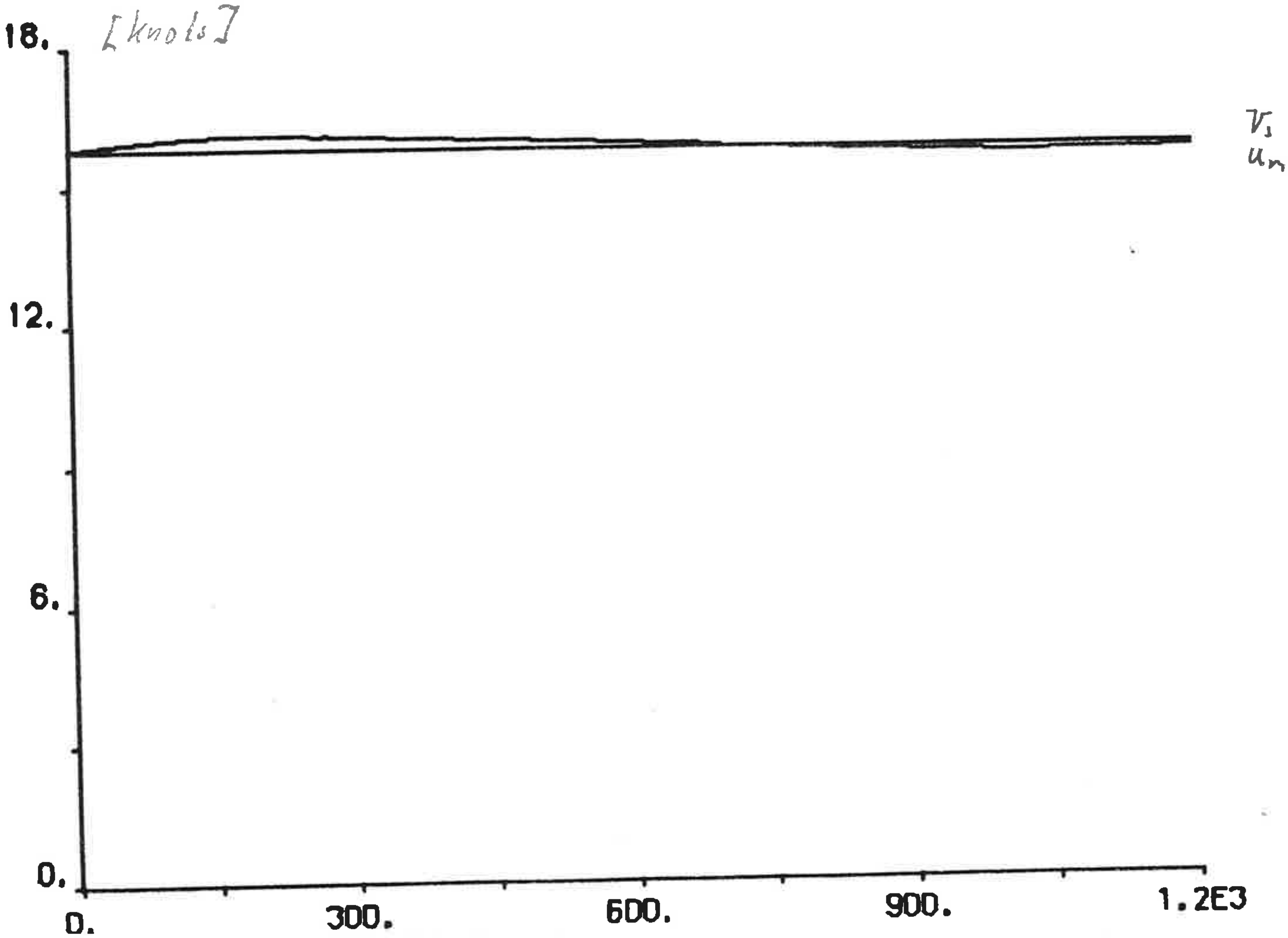
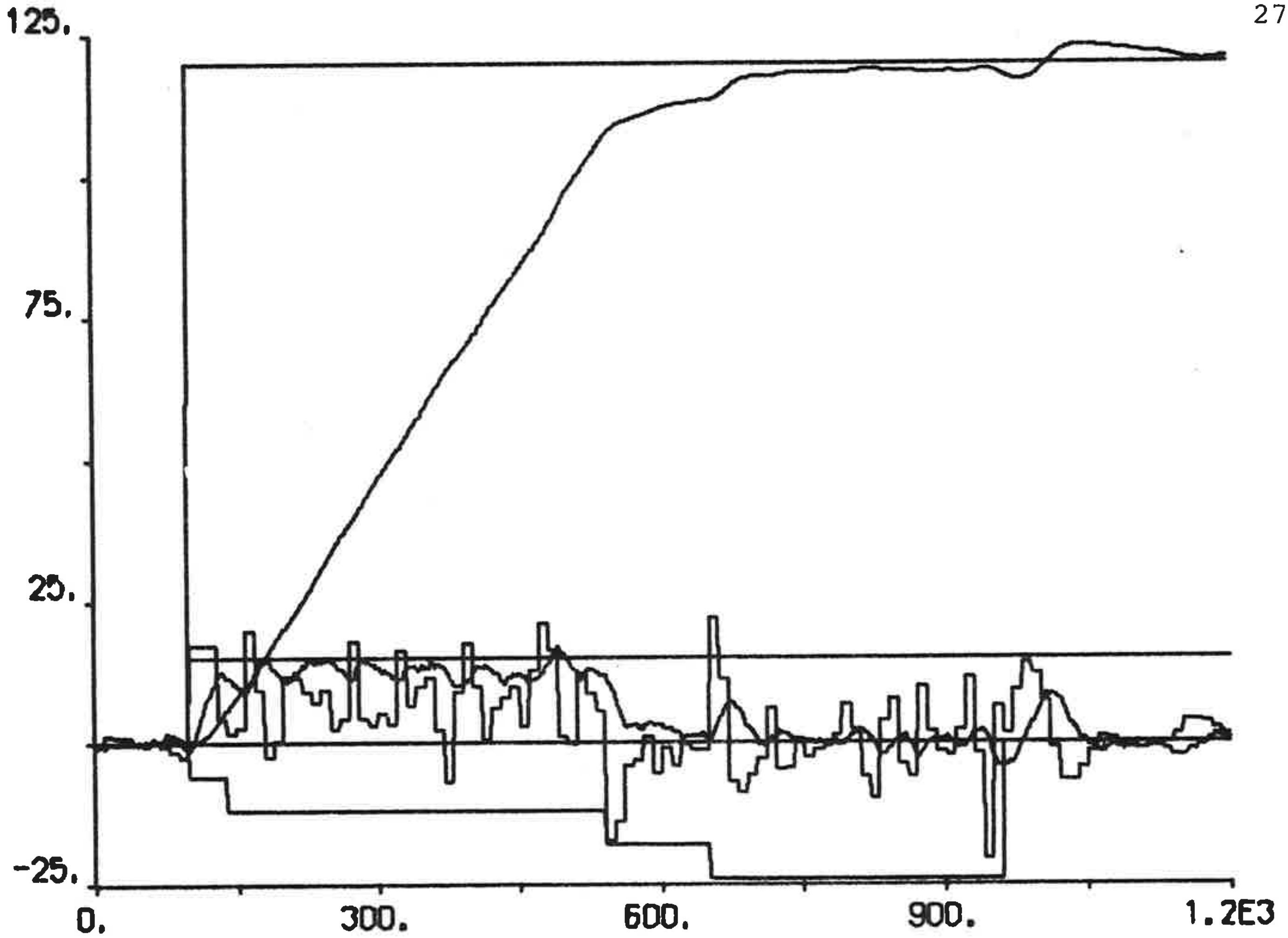


Fig. 4.68 - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 50 s).



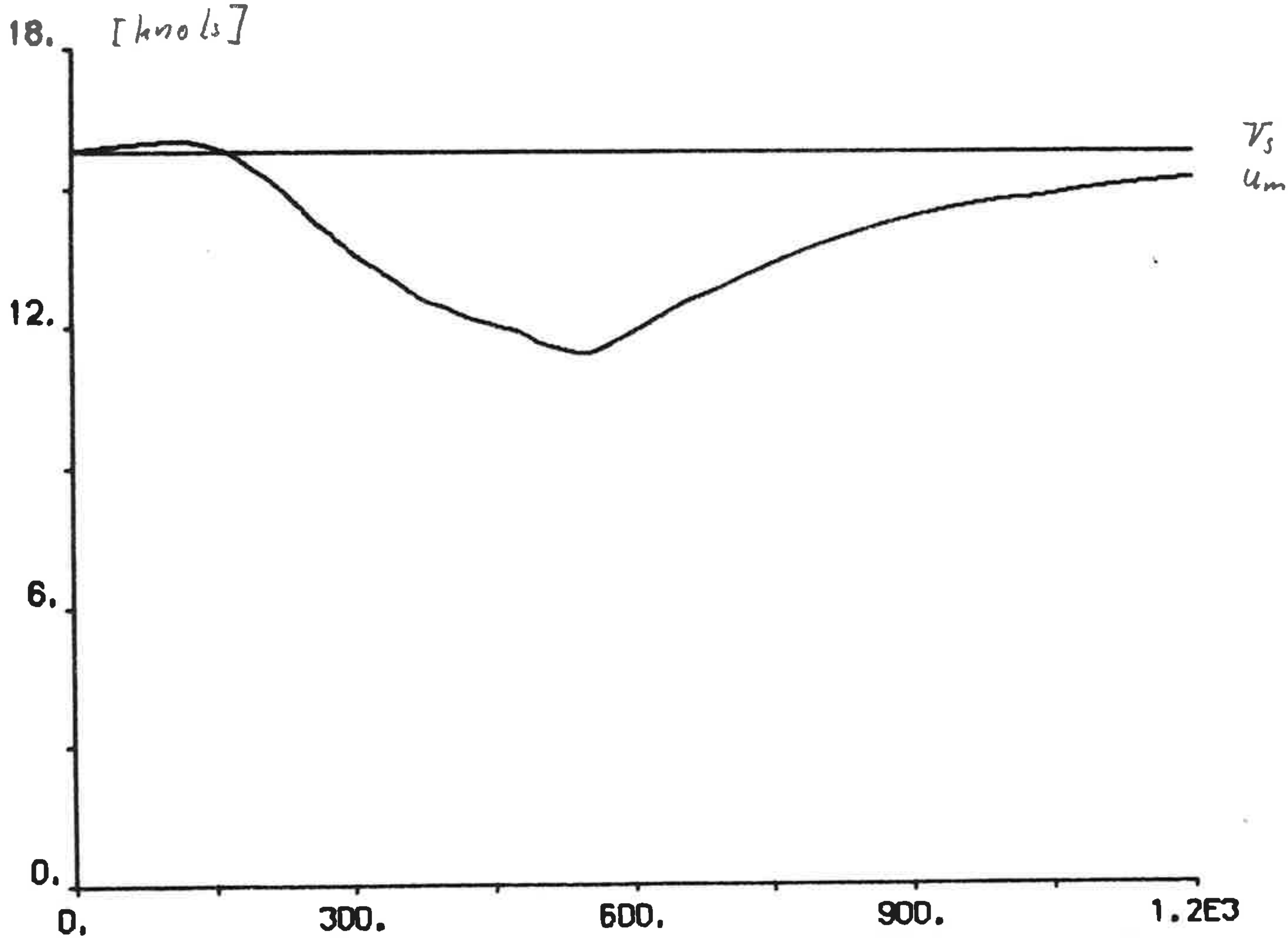


Fig. 4.69 - T = 10.5 m, n_0 = 87.6 rpm, u_0 = 15.8 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 50 s).

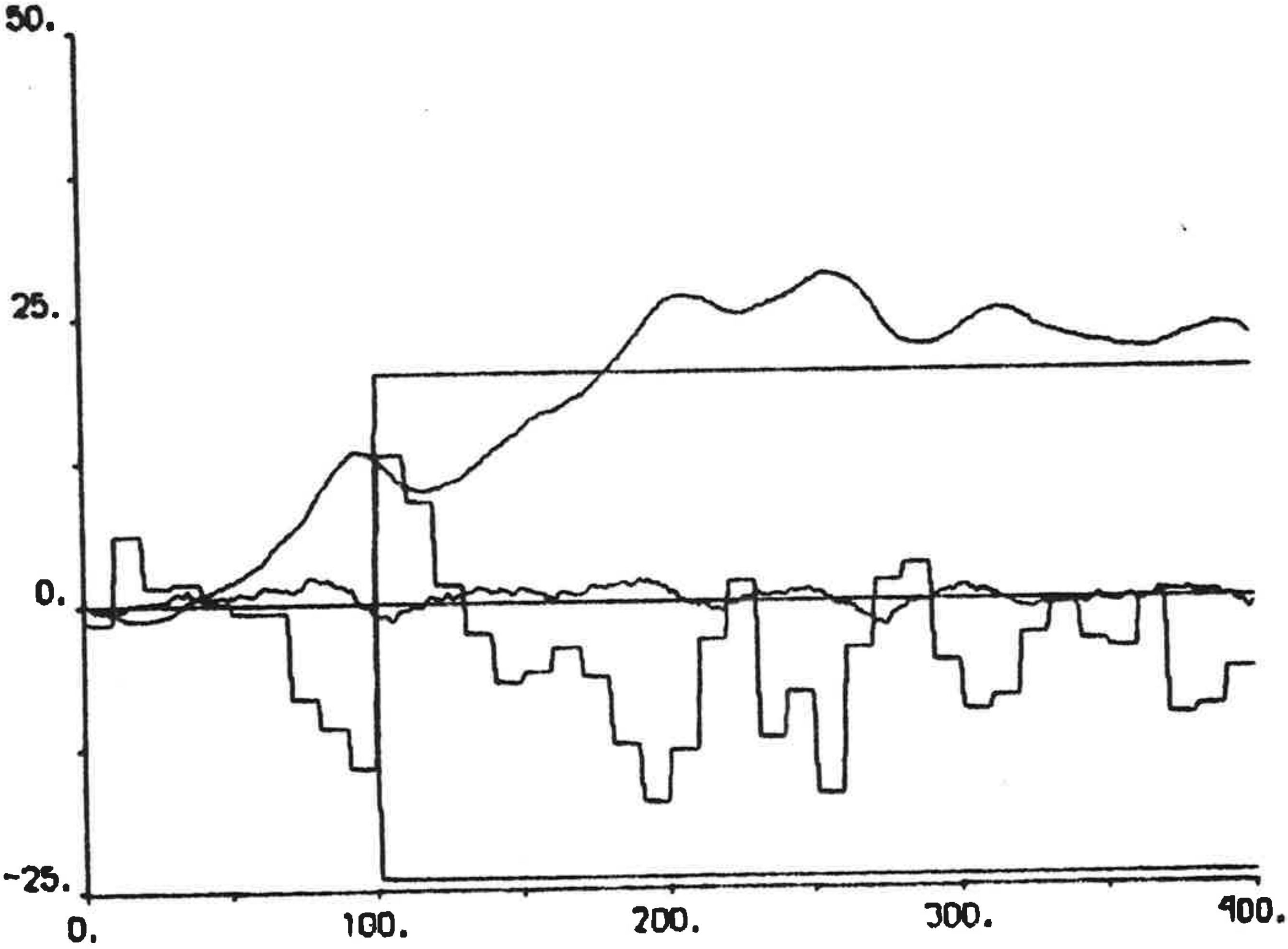


Fig. 4.70 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 2 deg, r_{ref} = 0 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 63.25 s).

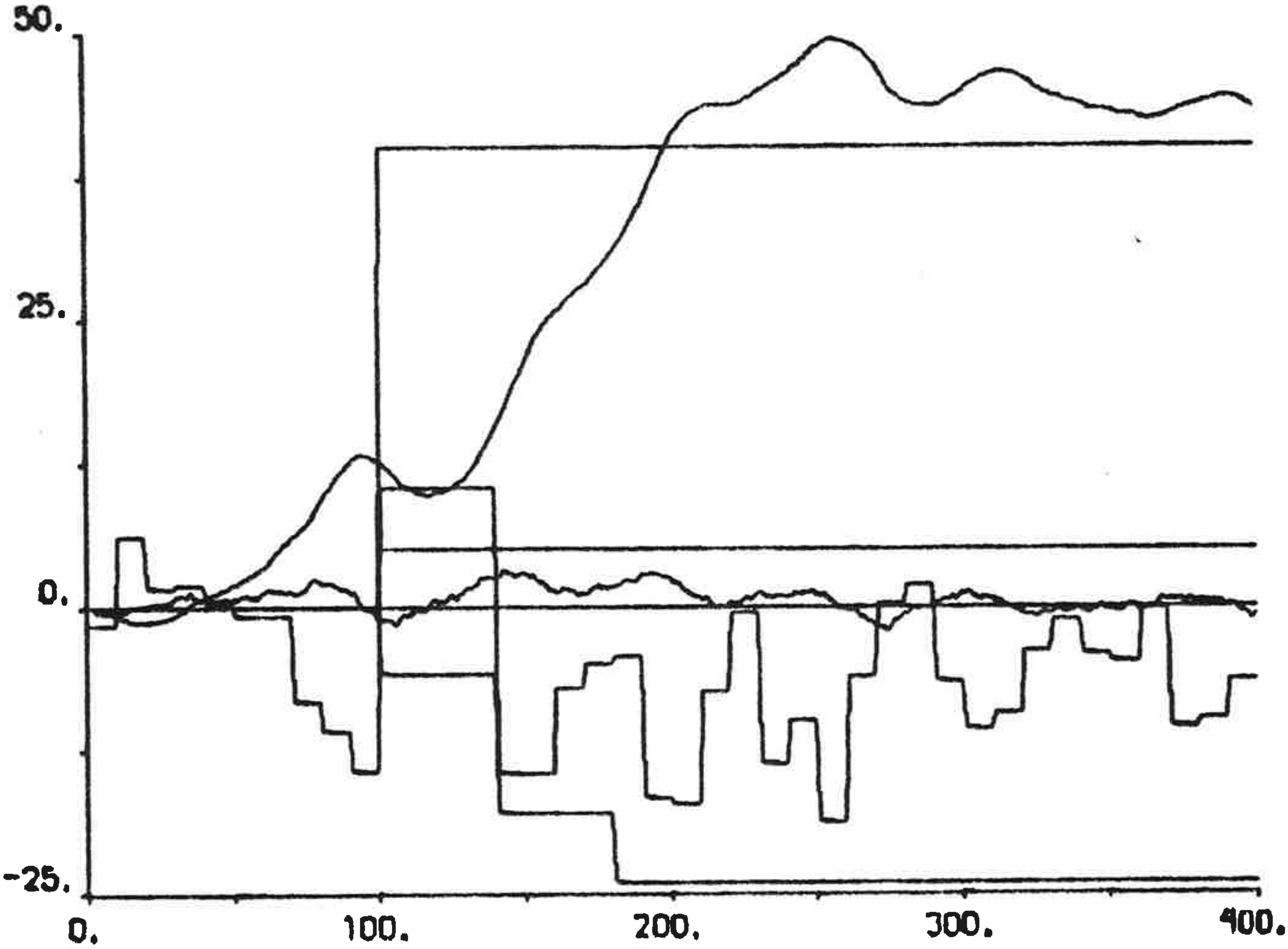


Fig. 4.71 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 63.25 s).

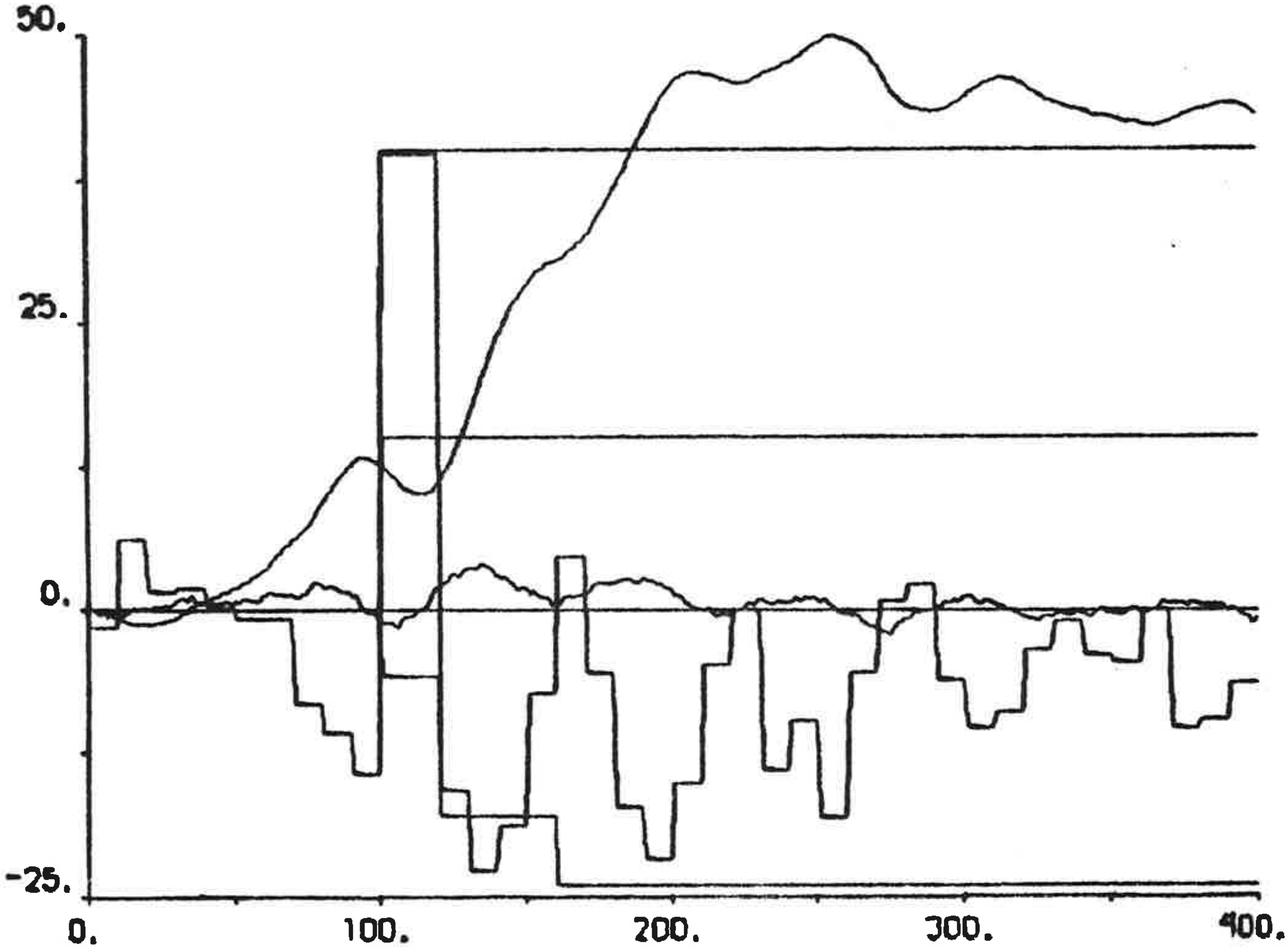
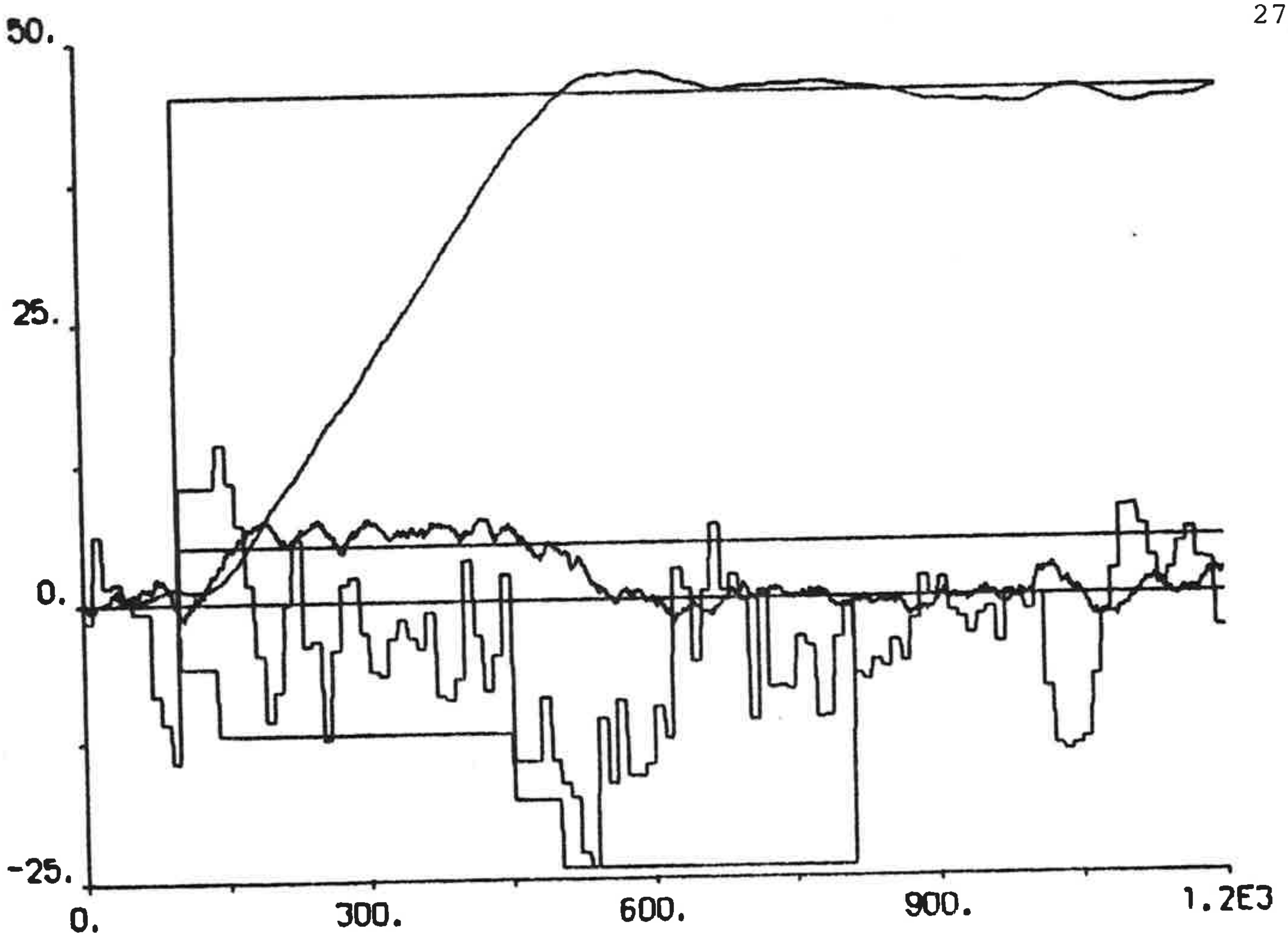


Fig. 4.72 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 63.25 s).



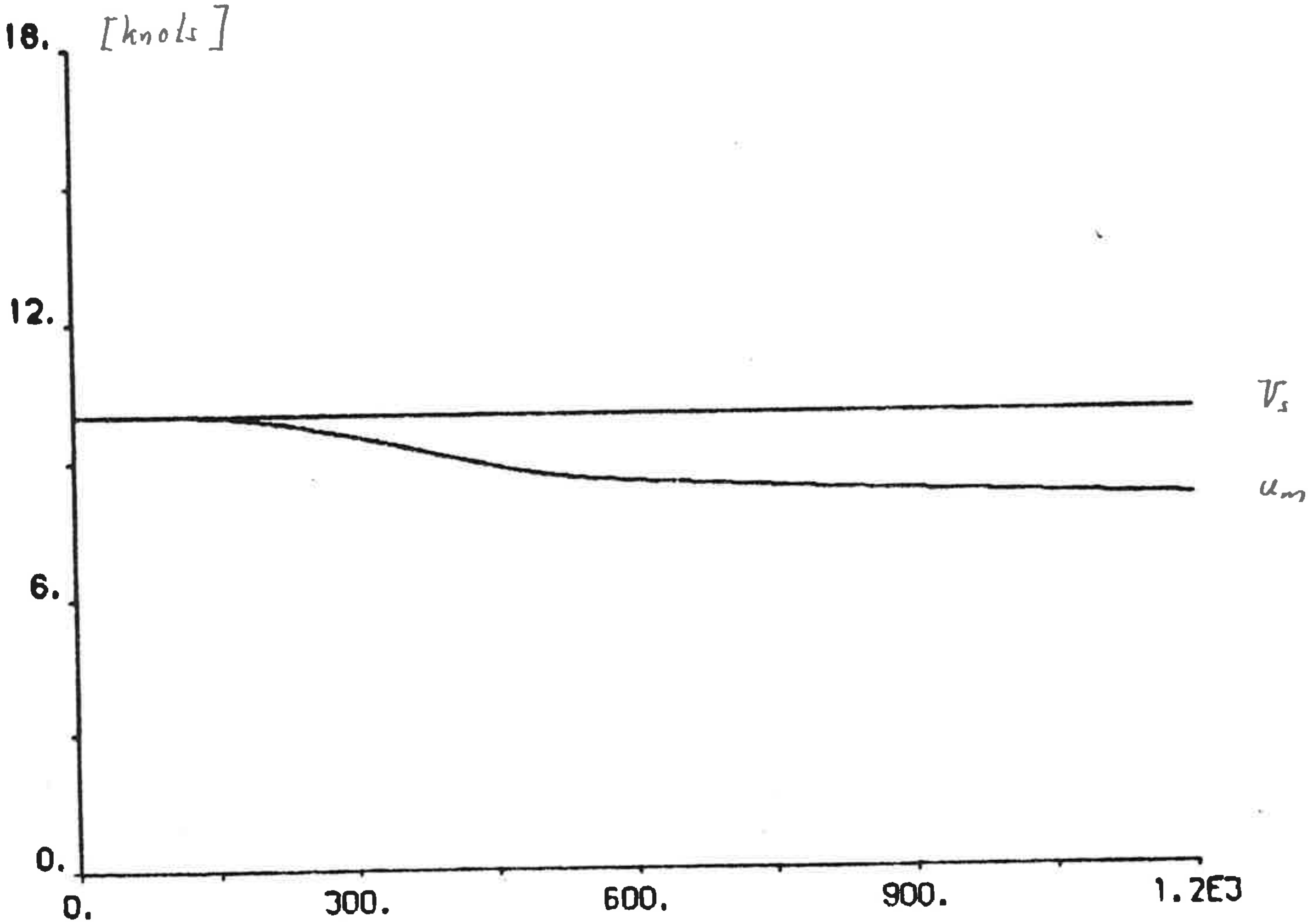


Fig. 4.73 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{c}_2$ = 63.25 s).

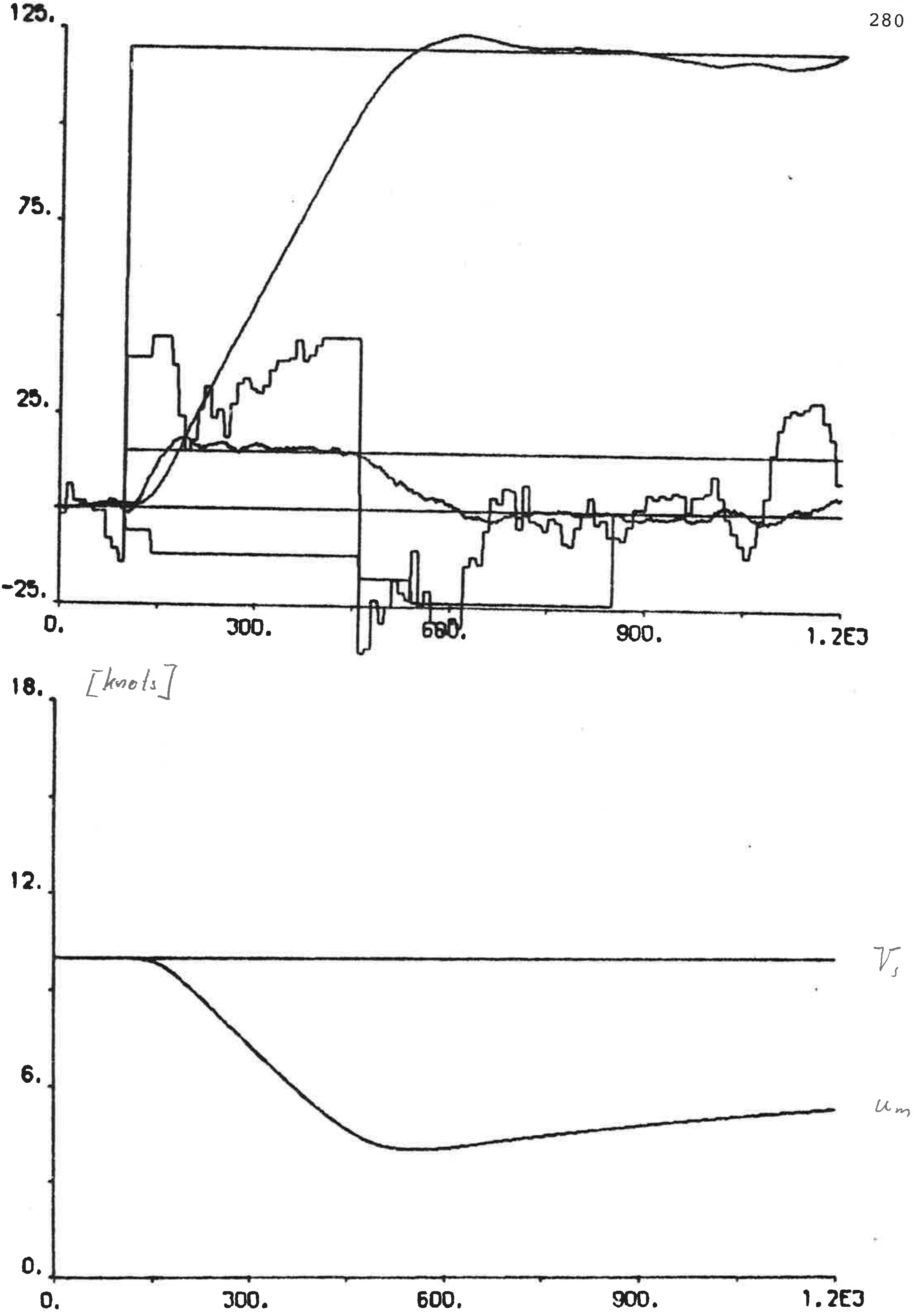


Fig. 4.74 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{c}_2$ = 63.25 s).

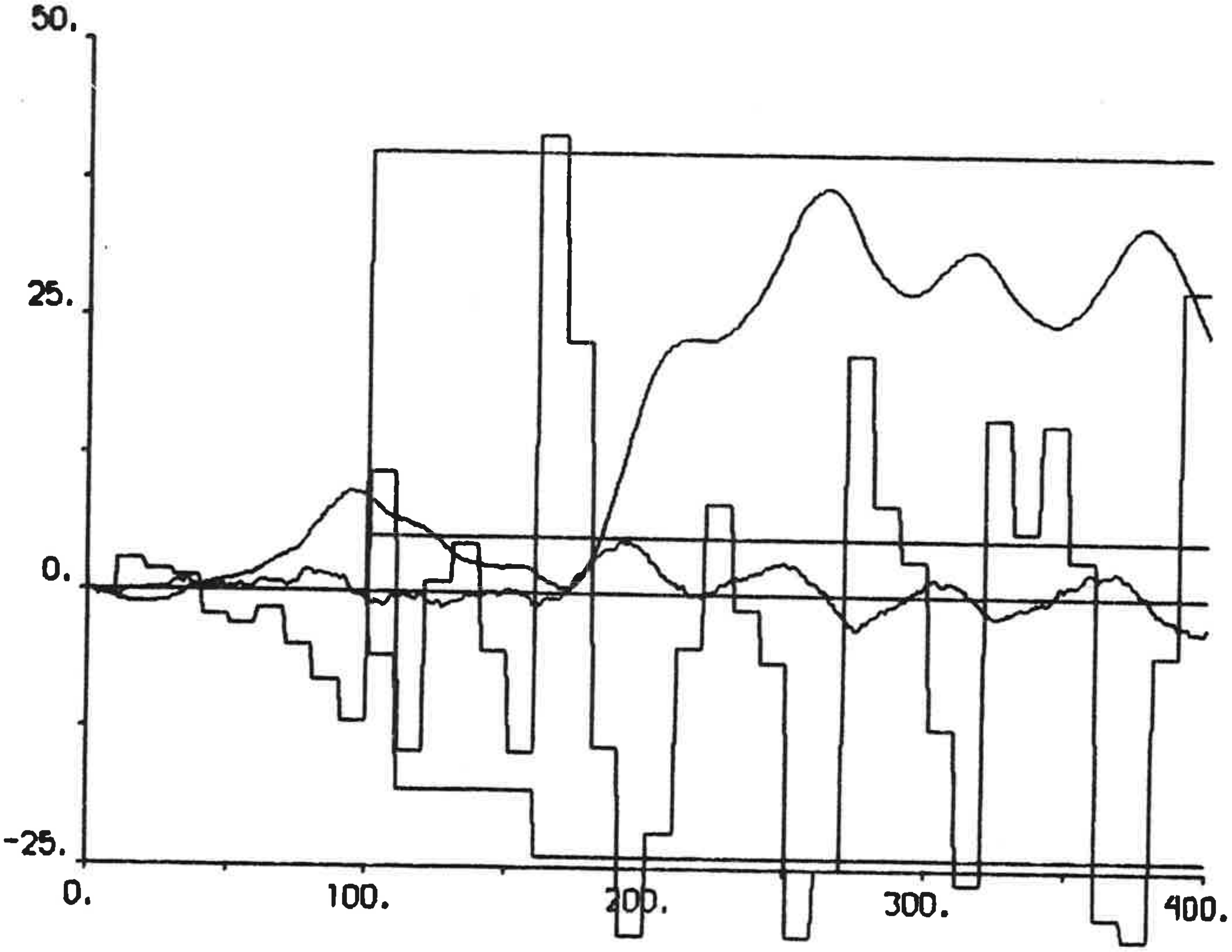


Fig. 4.75 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\bar{c}_2$ = 63.25 s).

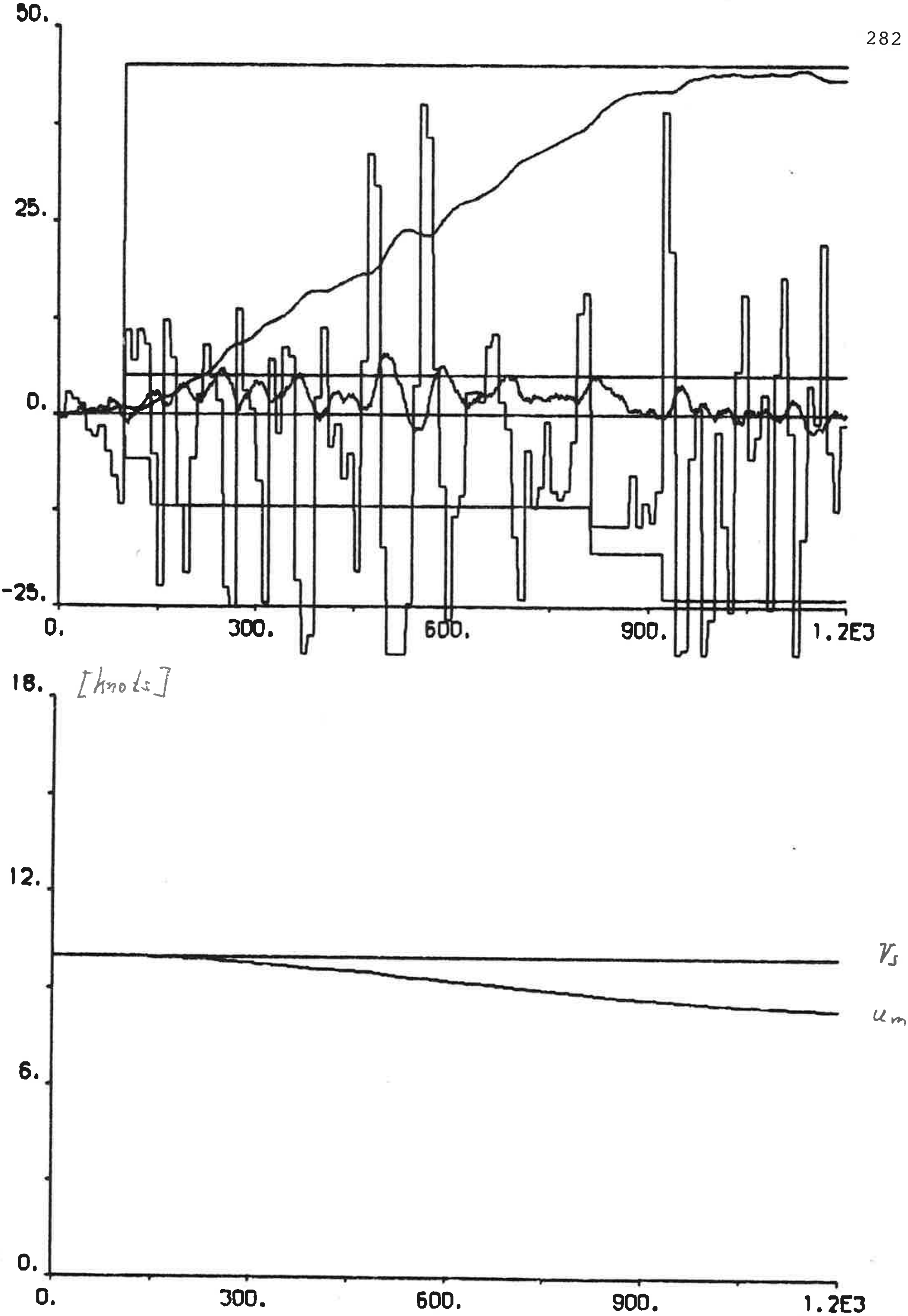


Fig. 4.76 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\bar{c}_2$ = 63.25 s).

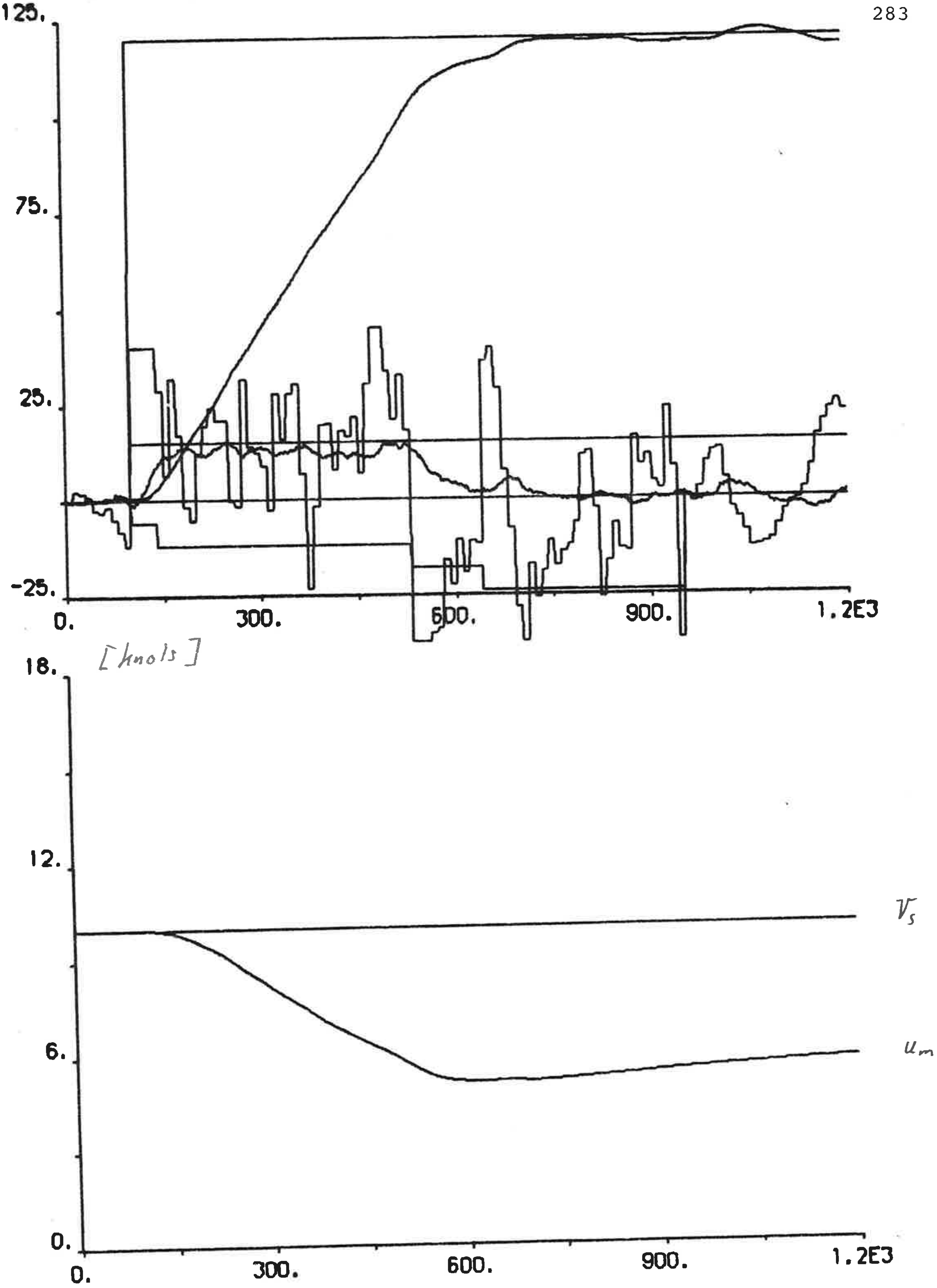


Fig. 4.77 - T = 22.3 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 63.25 s).

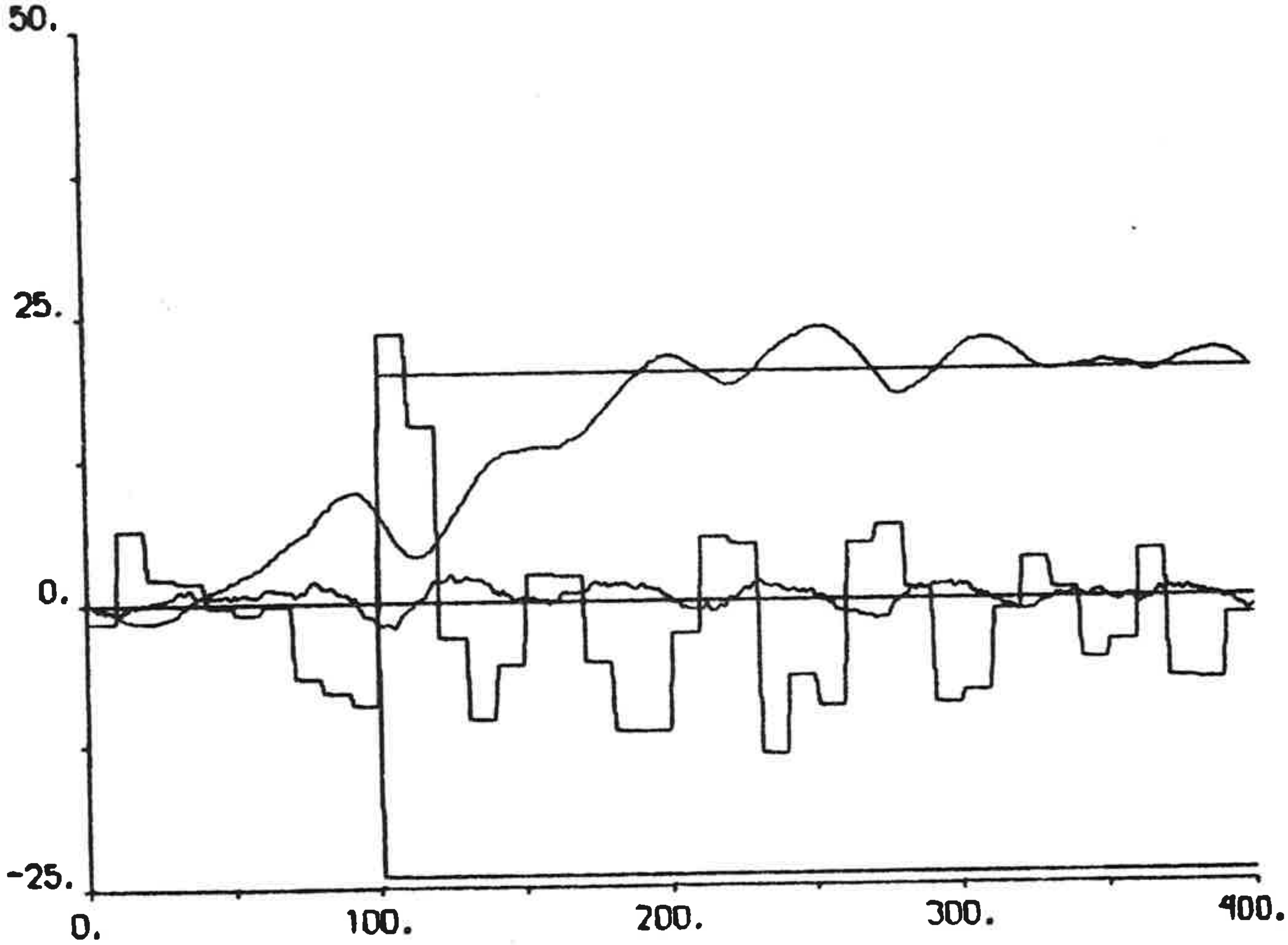


Fig. 4.78 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 2 deg, r_{ref} = 0 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 63.25 s).

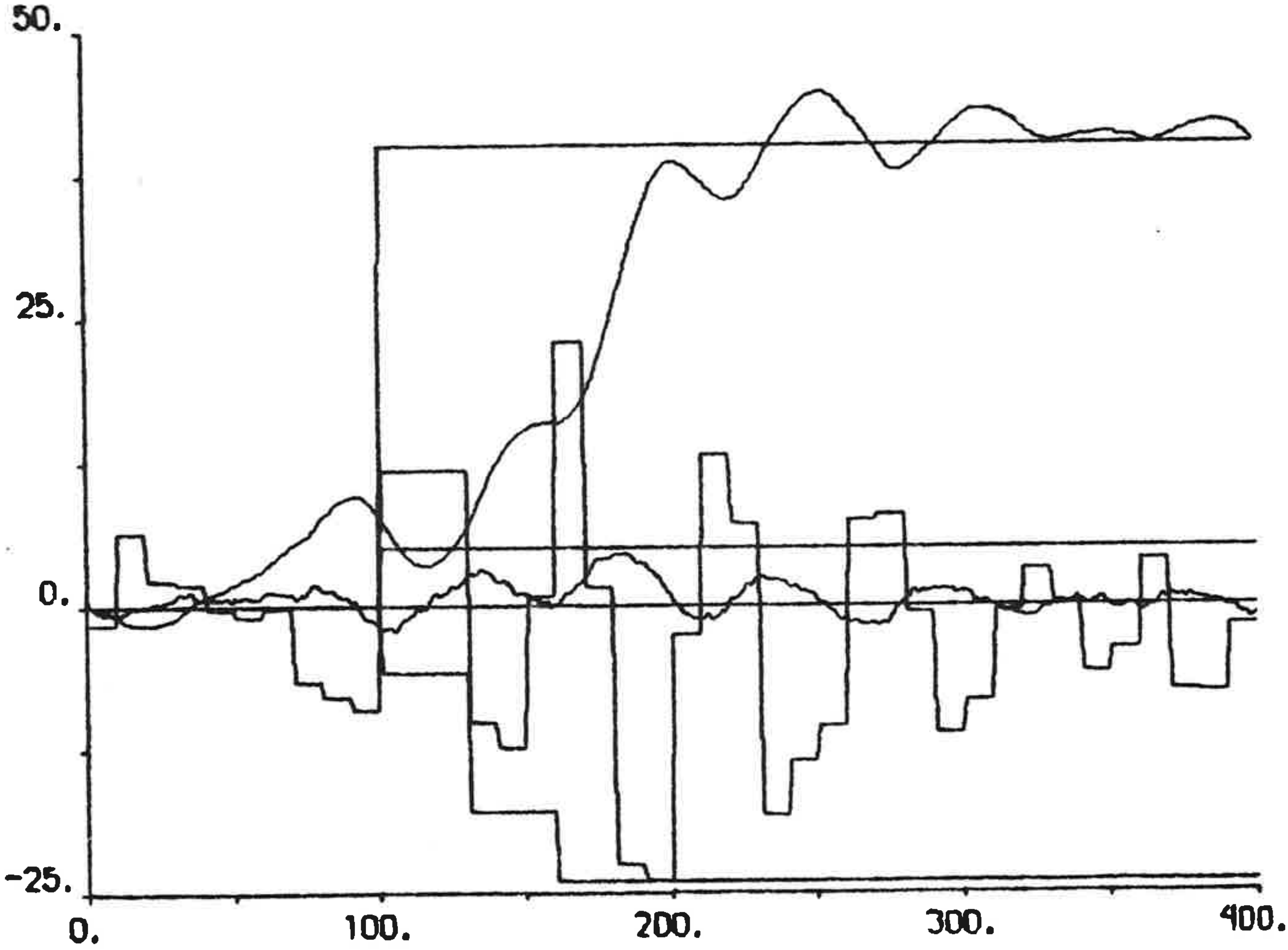


Fig. 4.79 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 63.25 s).

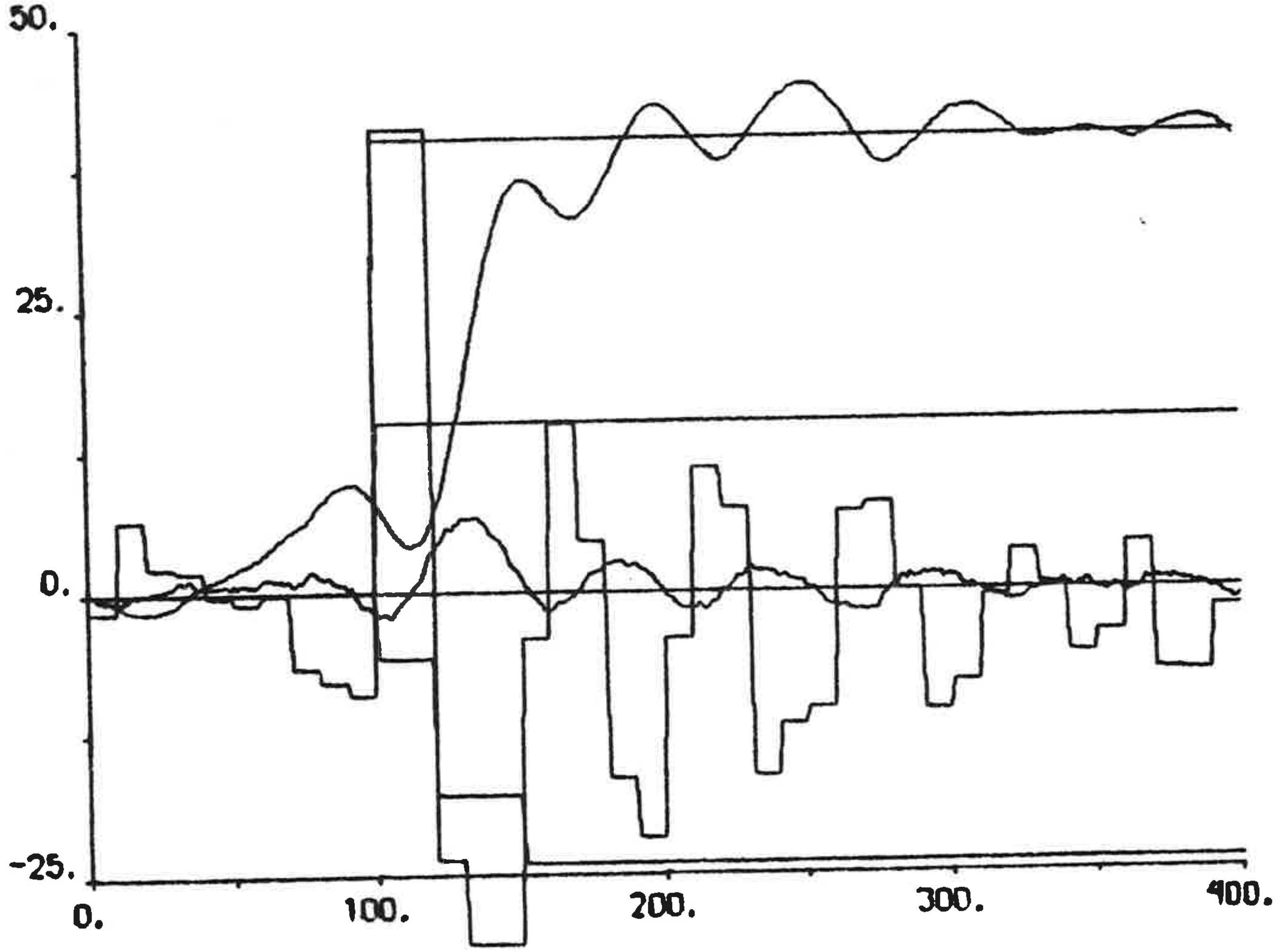
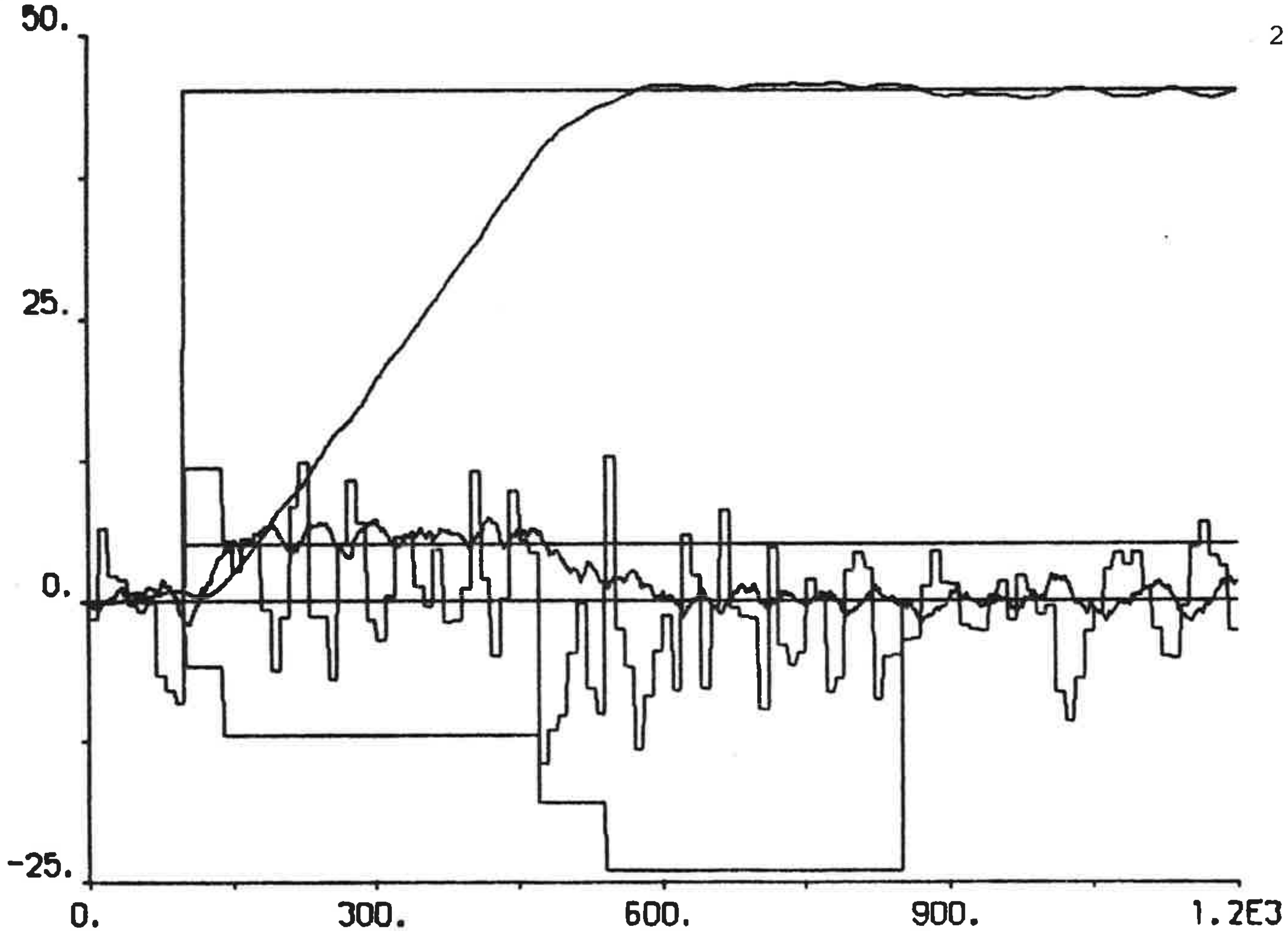


Fig. 4.80 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{\tau}_2$ = 63.25 s).



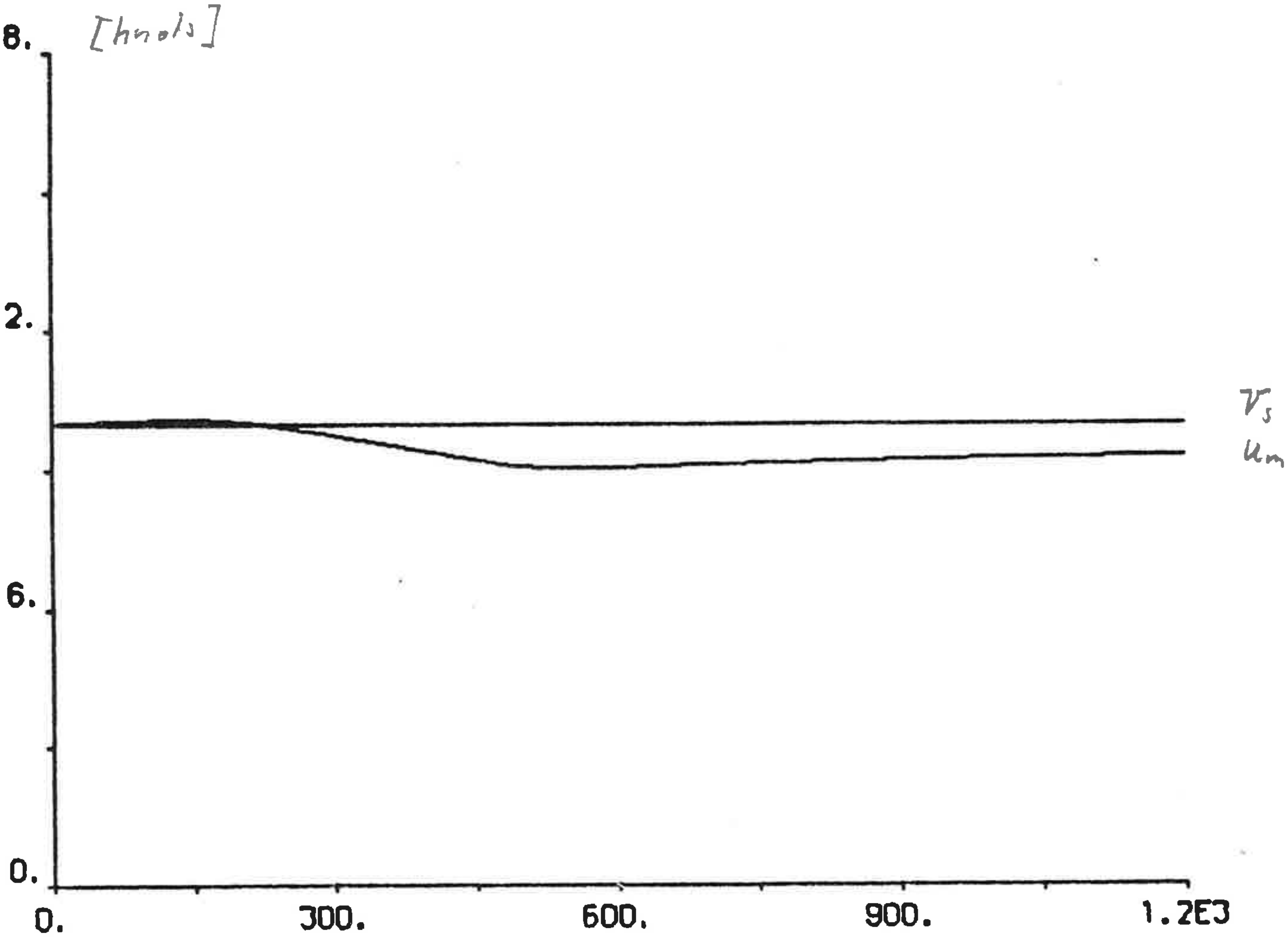


Fig. 4.81 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{c}_2$ = 63.25 s).

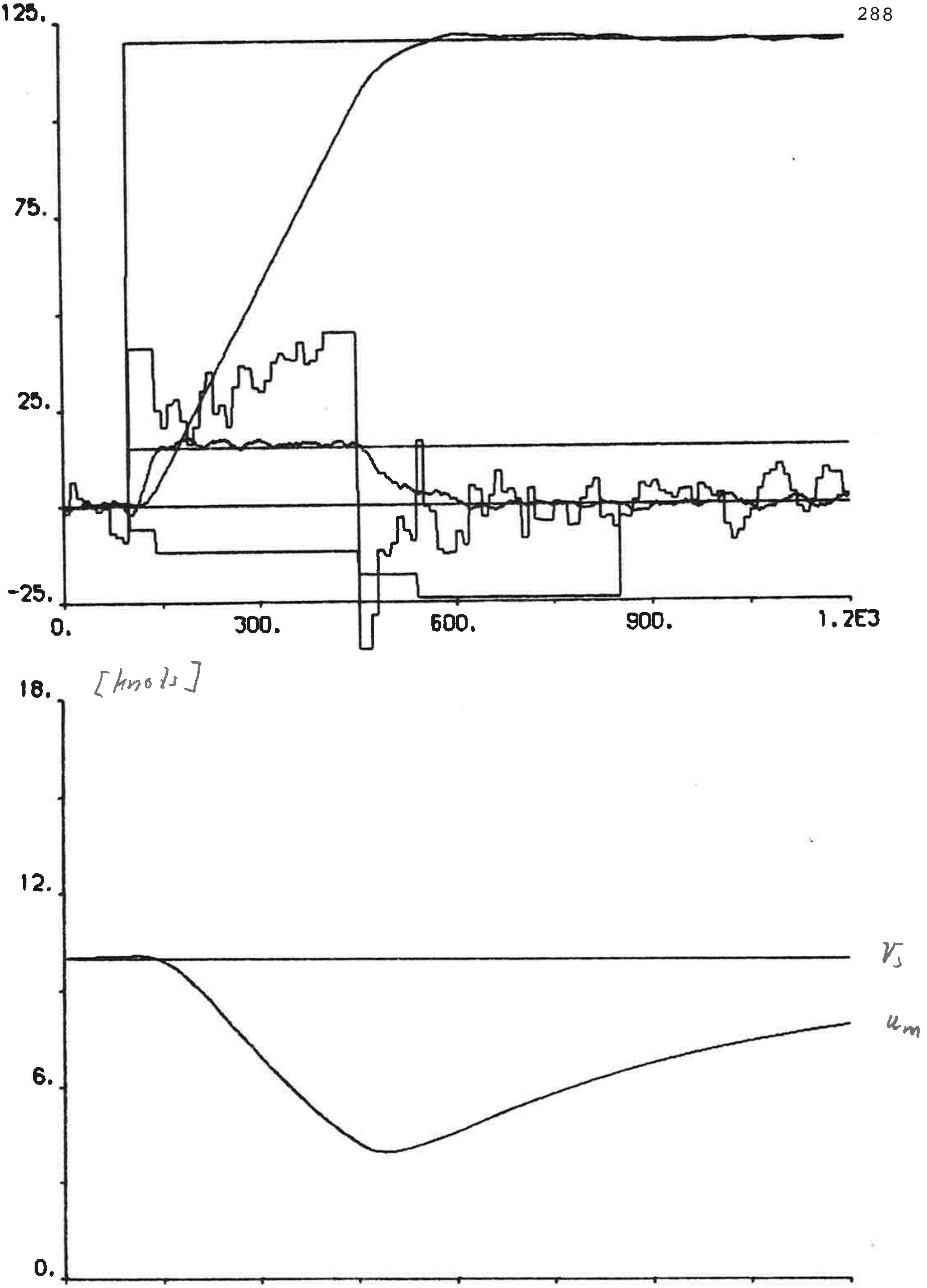


Fig. 4.82 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 63.25 s).

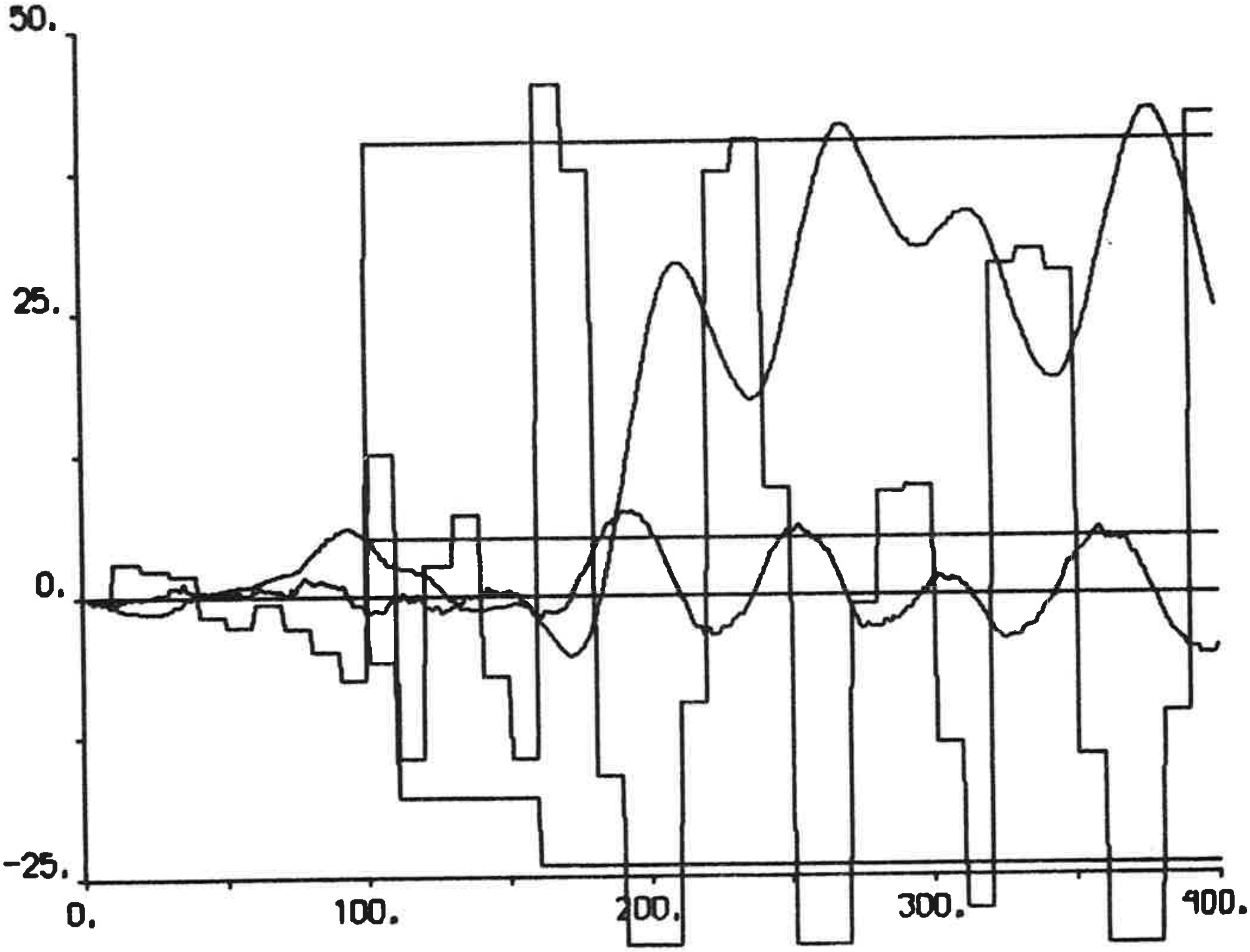
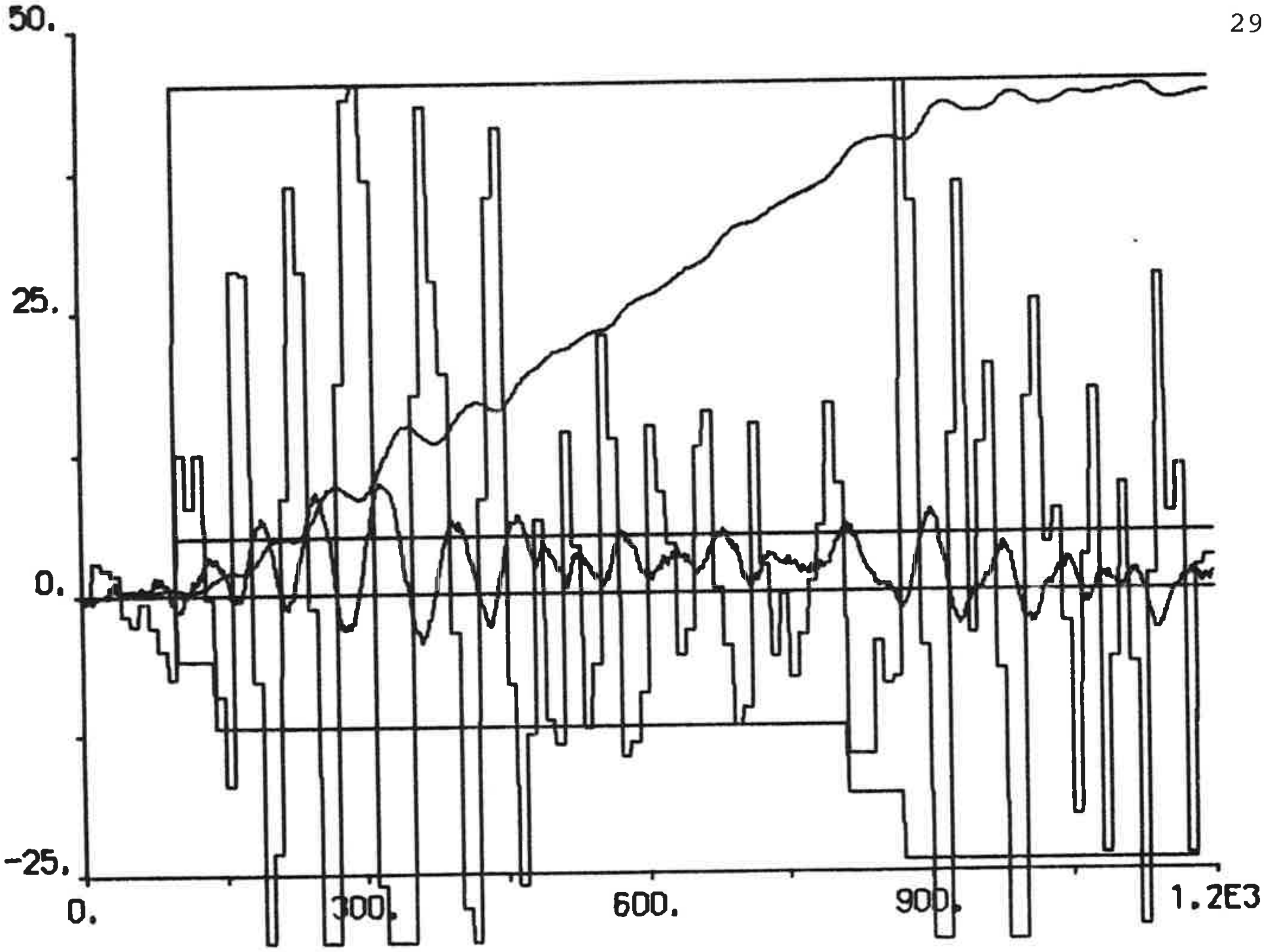


Fig. 4.83 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\bar{c}_2$ = 63.25 s).



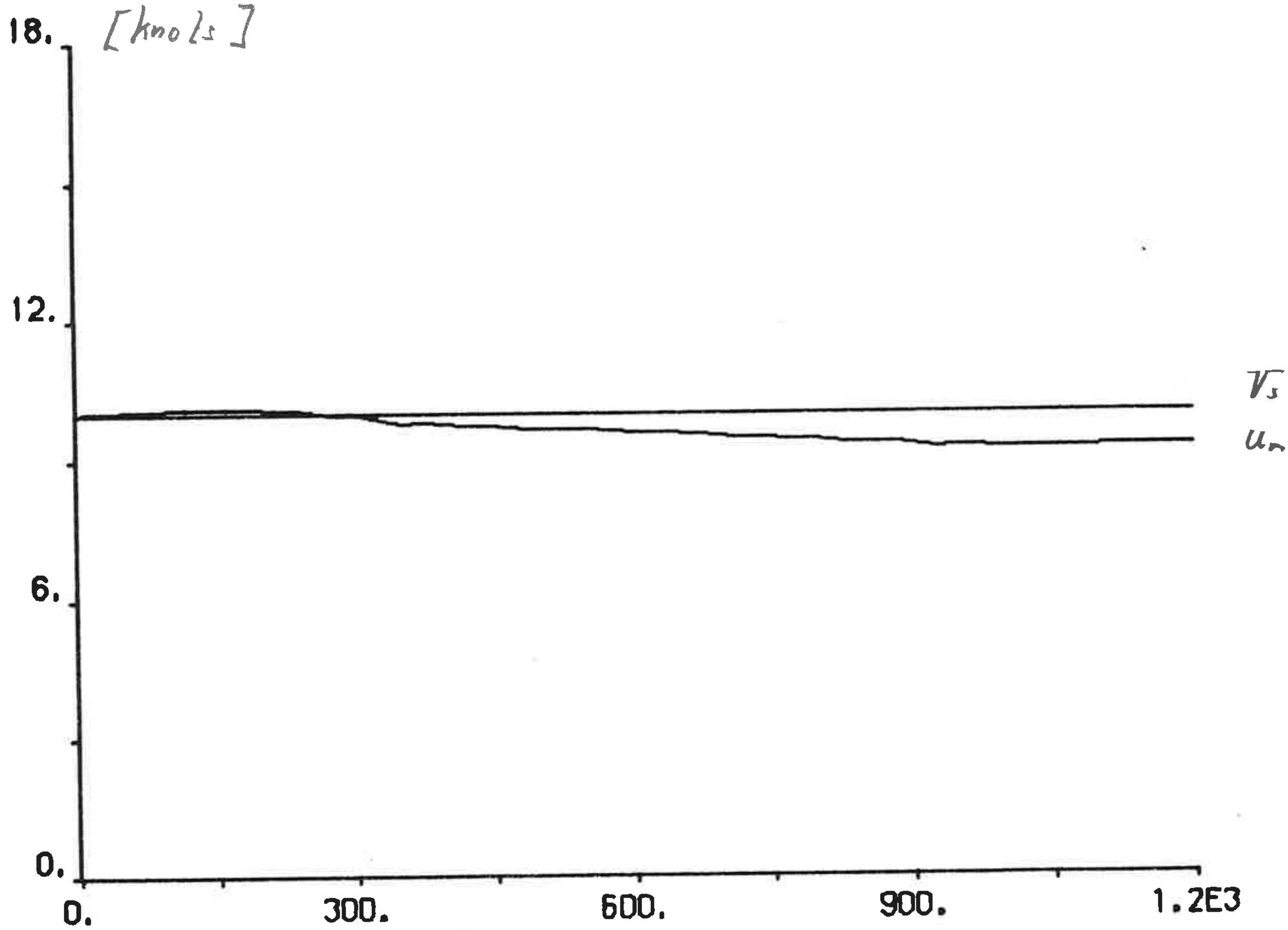
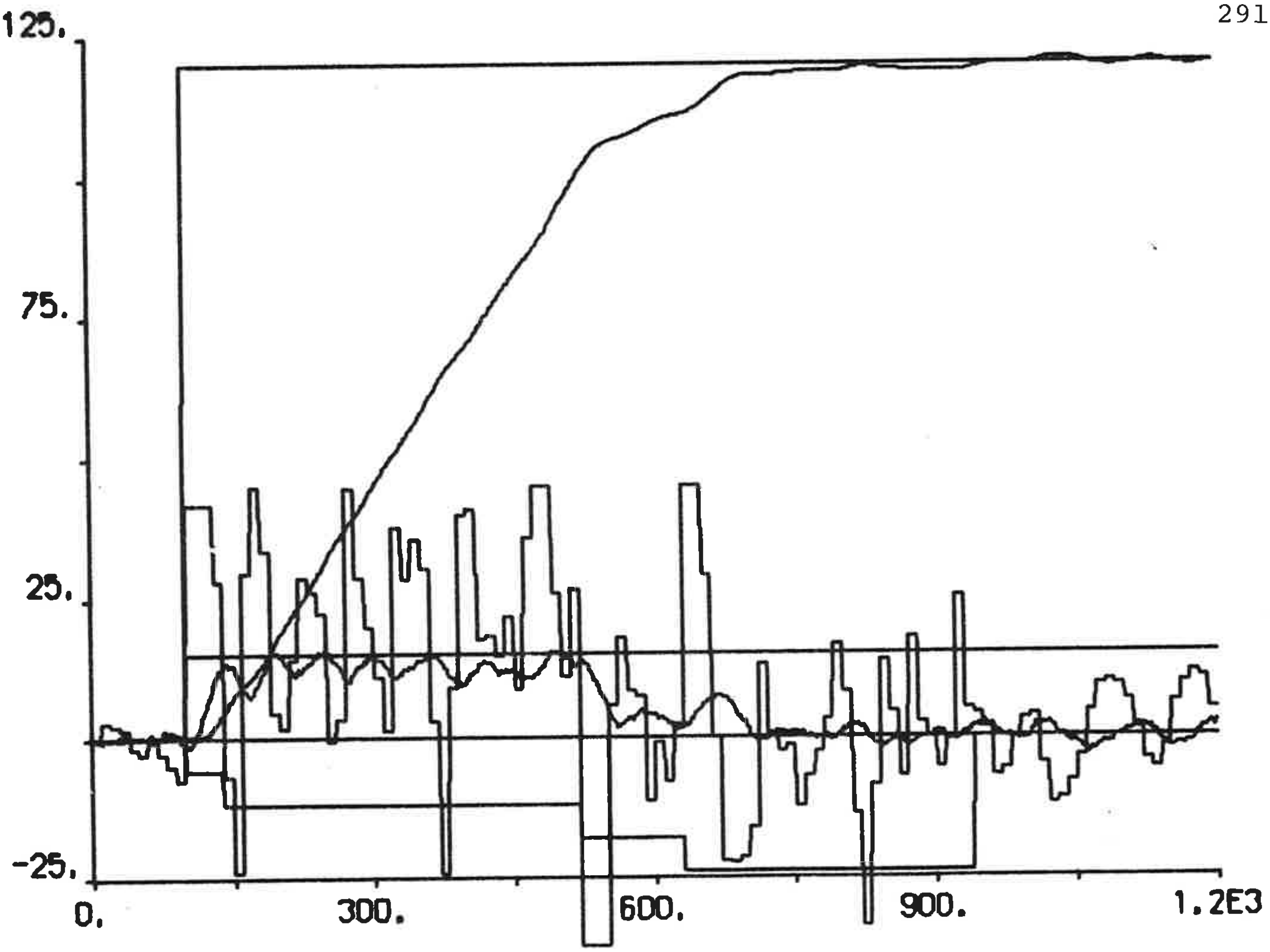


Fig. 4.84 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 63.25 s).



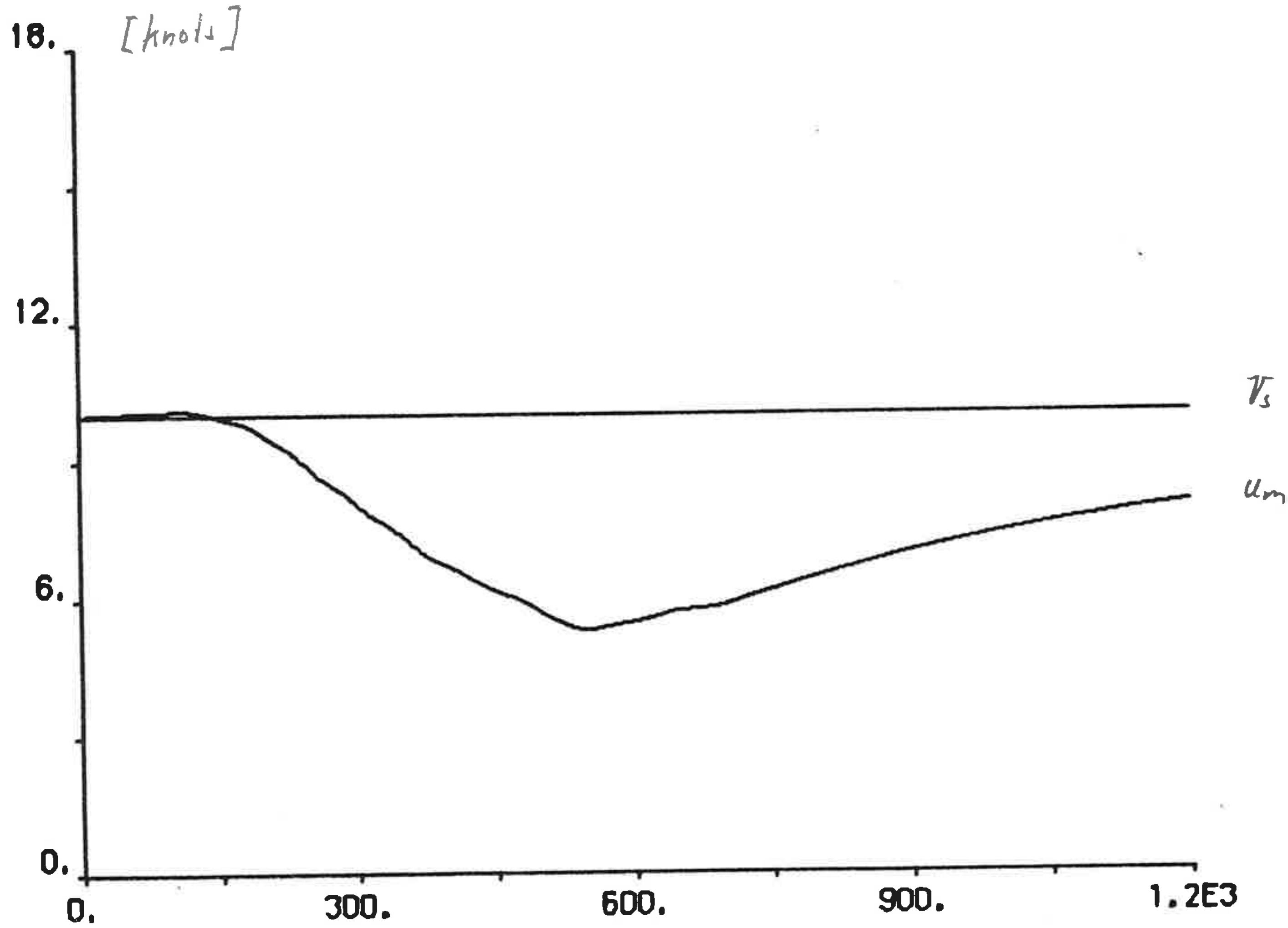


Fig. 4.85 - T = 10.5 m, n_0 = 55.443 rpm, u_0 = 10 knots, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 63.25 s).

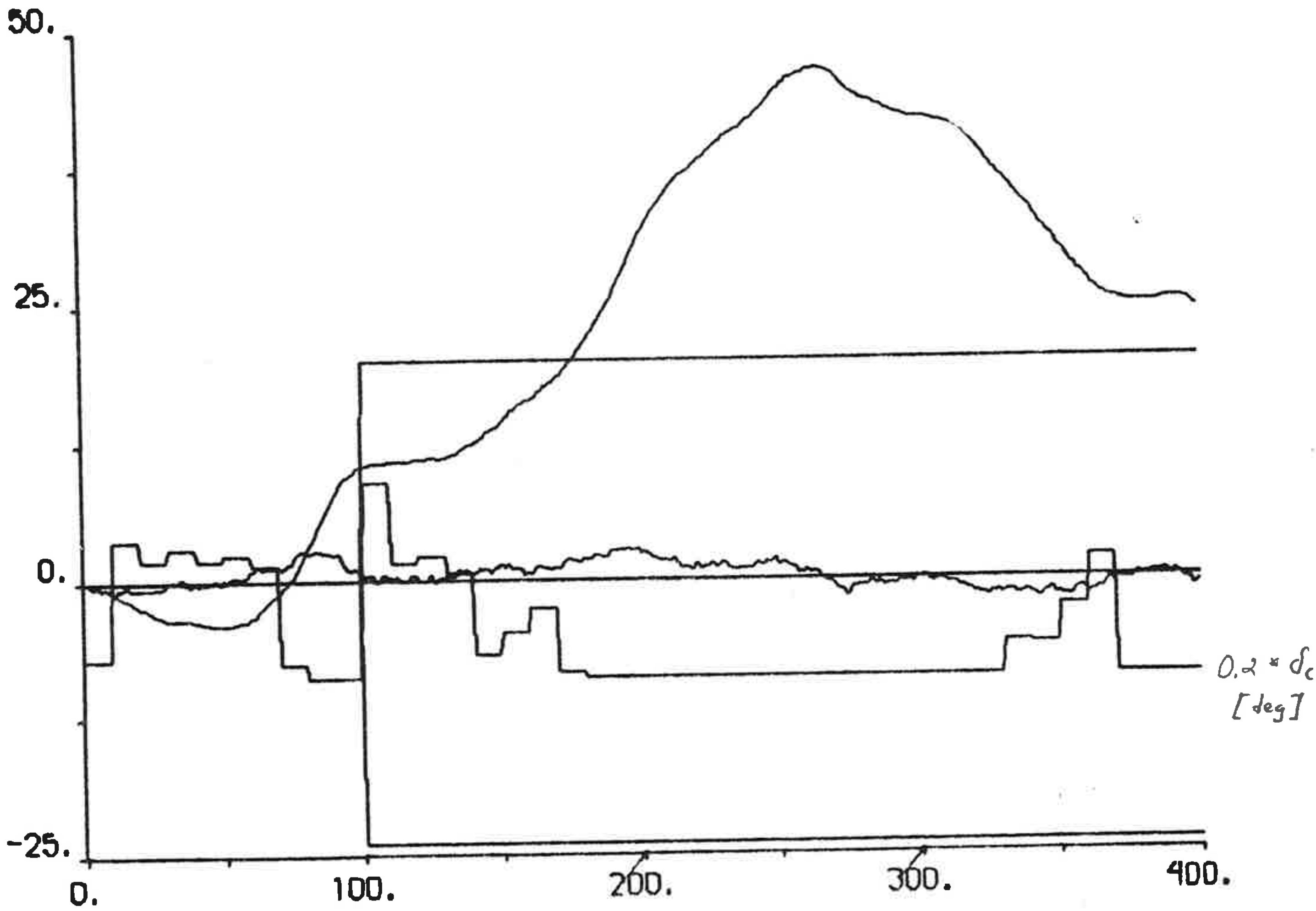


Fig. 4.86 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 2 deg, r_{ref} = 0 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\overline{c}_2$ = 100 s).

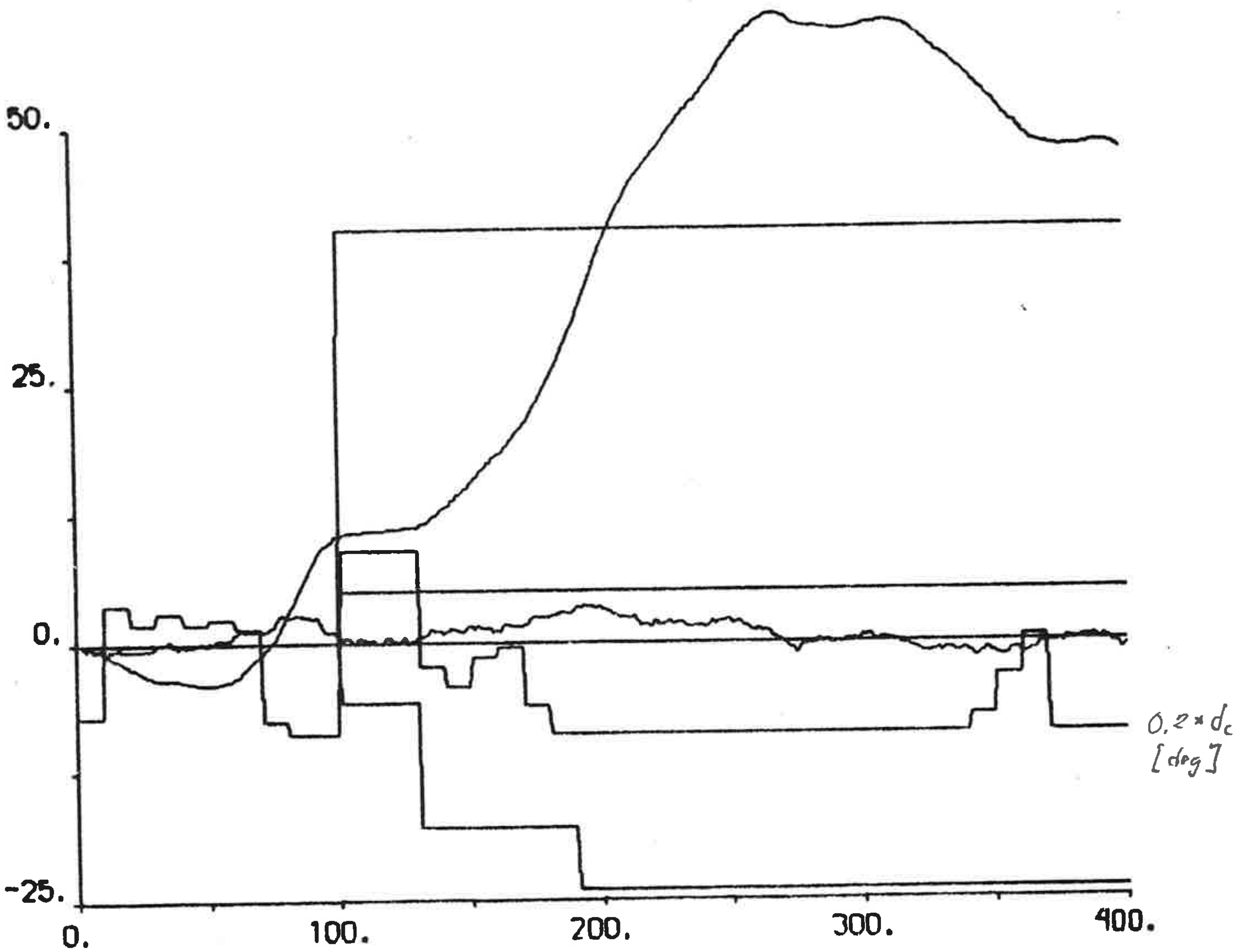


Fig. 4.87 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 100 s).

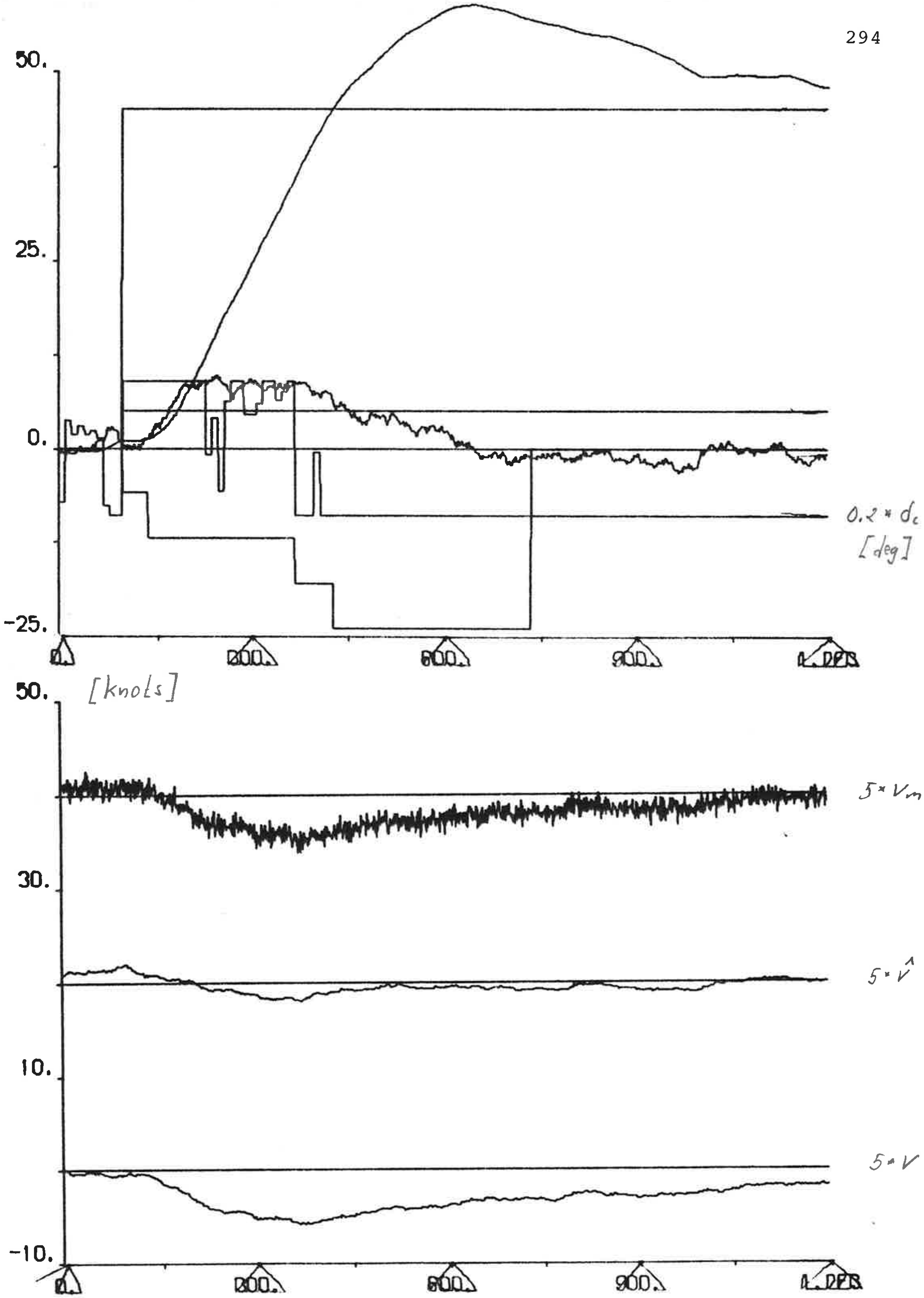
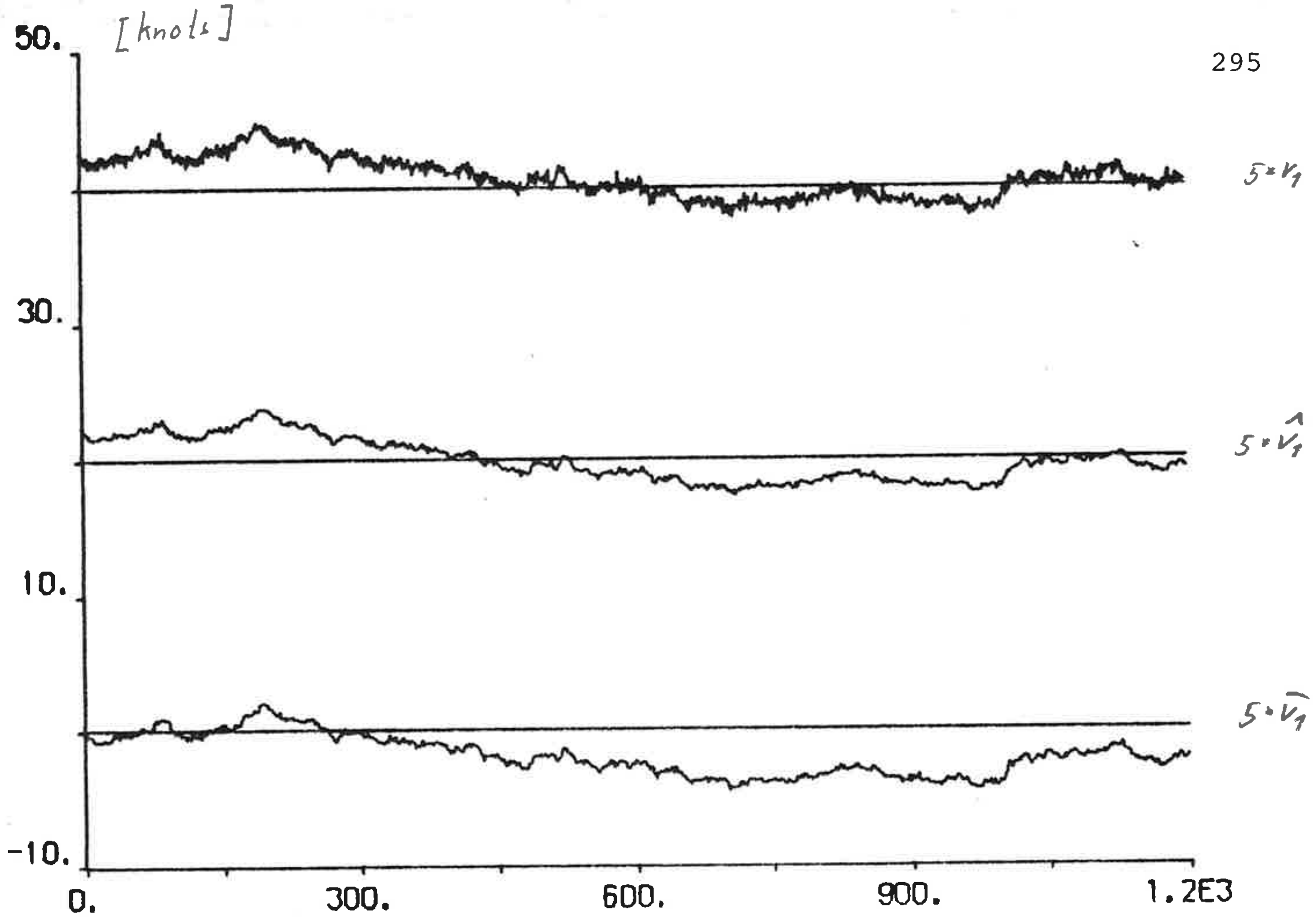


Fig. 4.88 a - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter (c_2 = 100 s).


[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5*v_1
5*$\hat{v}_1$
5*$\tilde{v}_1$

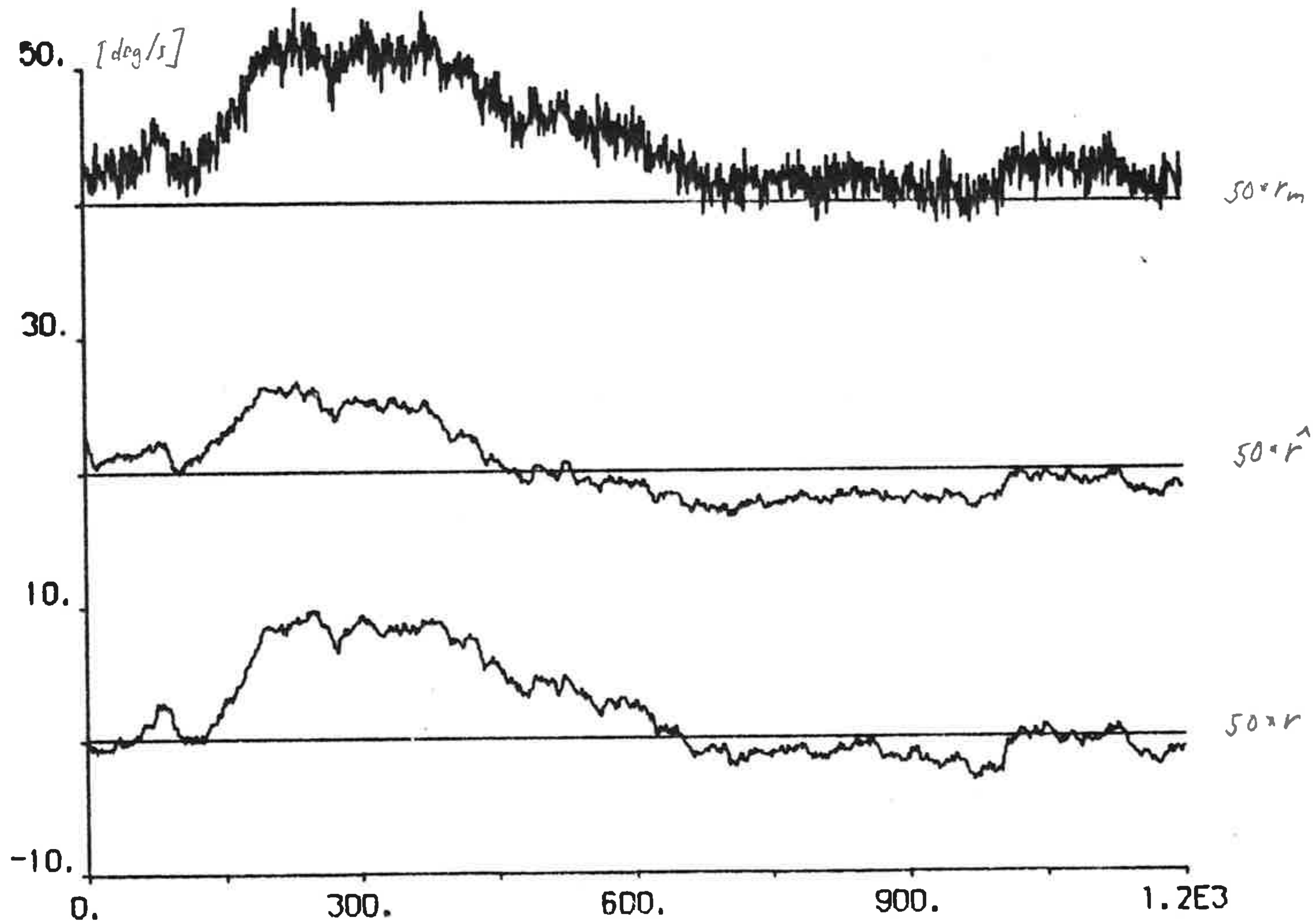

[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
50*r_m
50*$\hat{r}$
50*r

Fig. 4.88 b

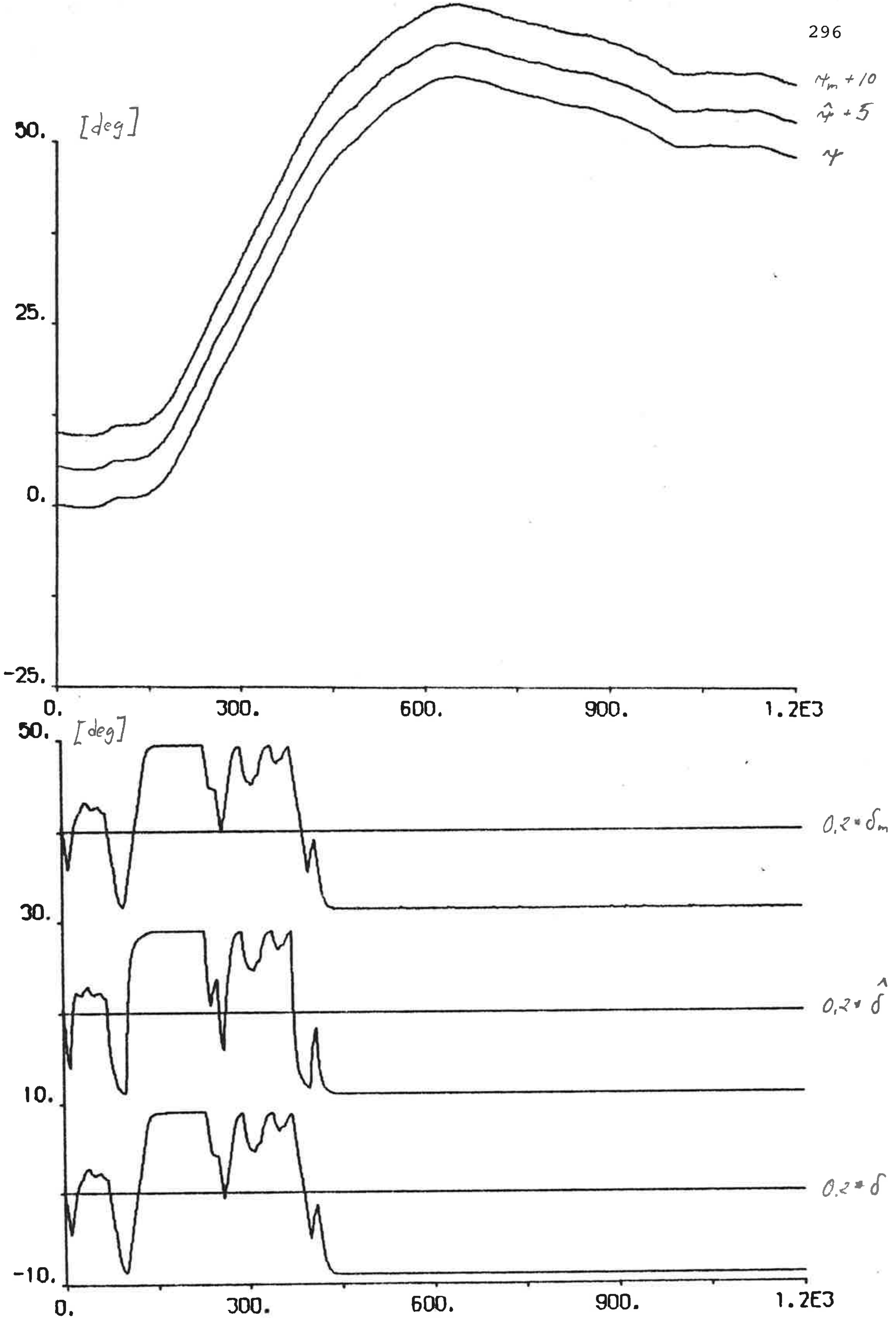

[deg]
50.
25.
0.
-25.
0.
300.
600.
900.
1.2E3
$\psi_m + 10$
$\hat{\psi} + 5$
ψ
[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
$0.2 * \delta_m$
$0.2 * \hat{\delta}$
$0.2 * \delta$

Fig. 4.88 c

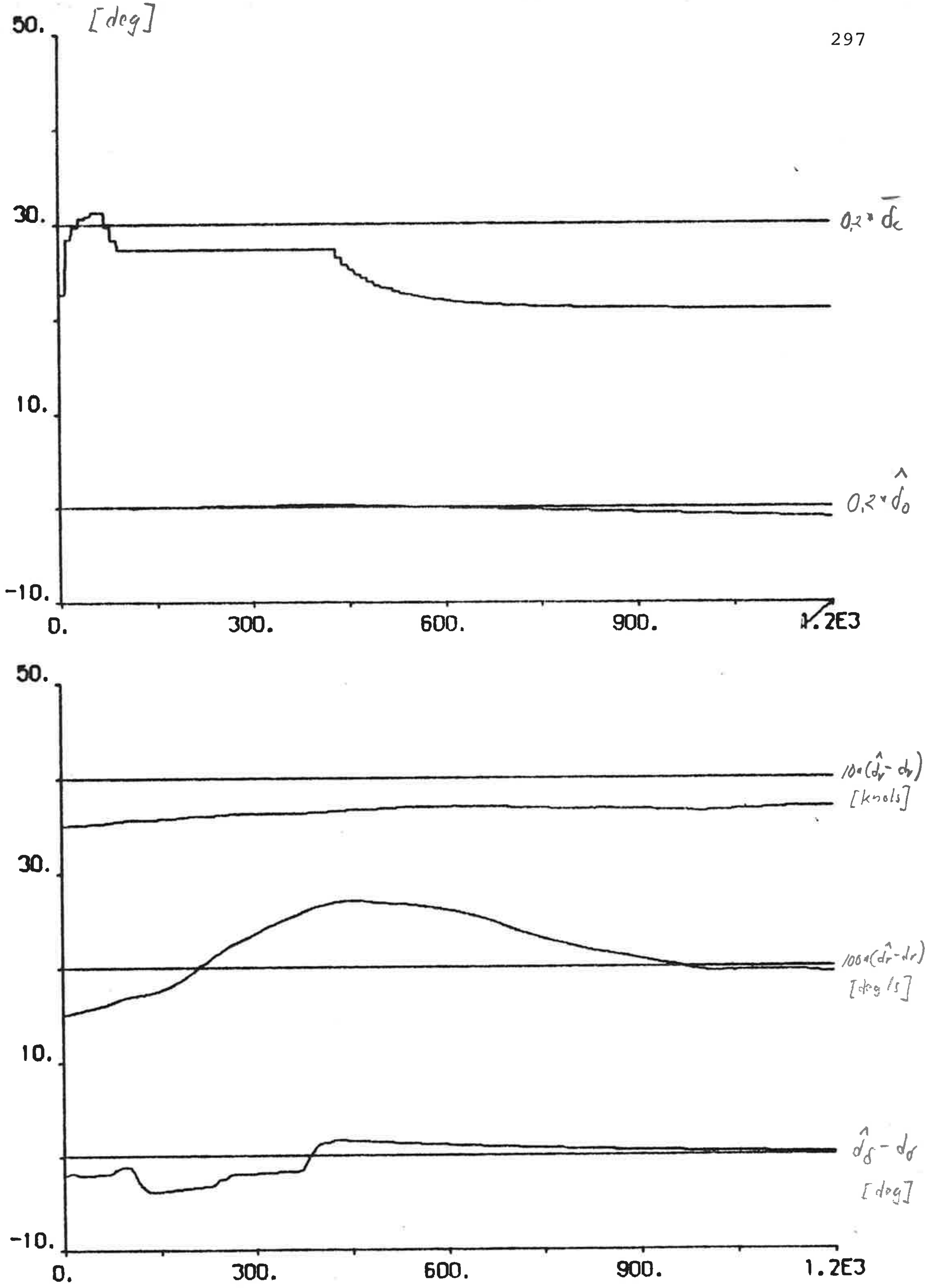
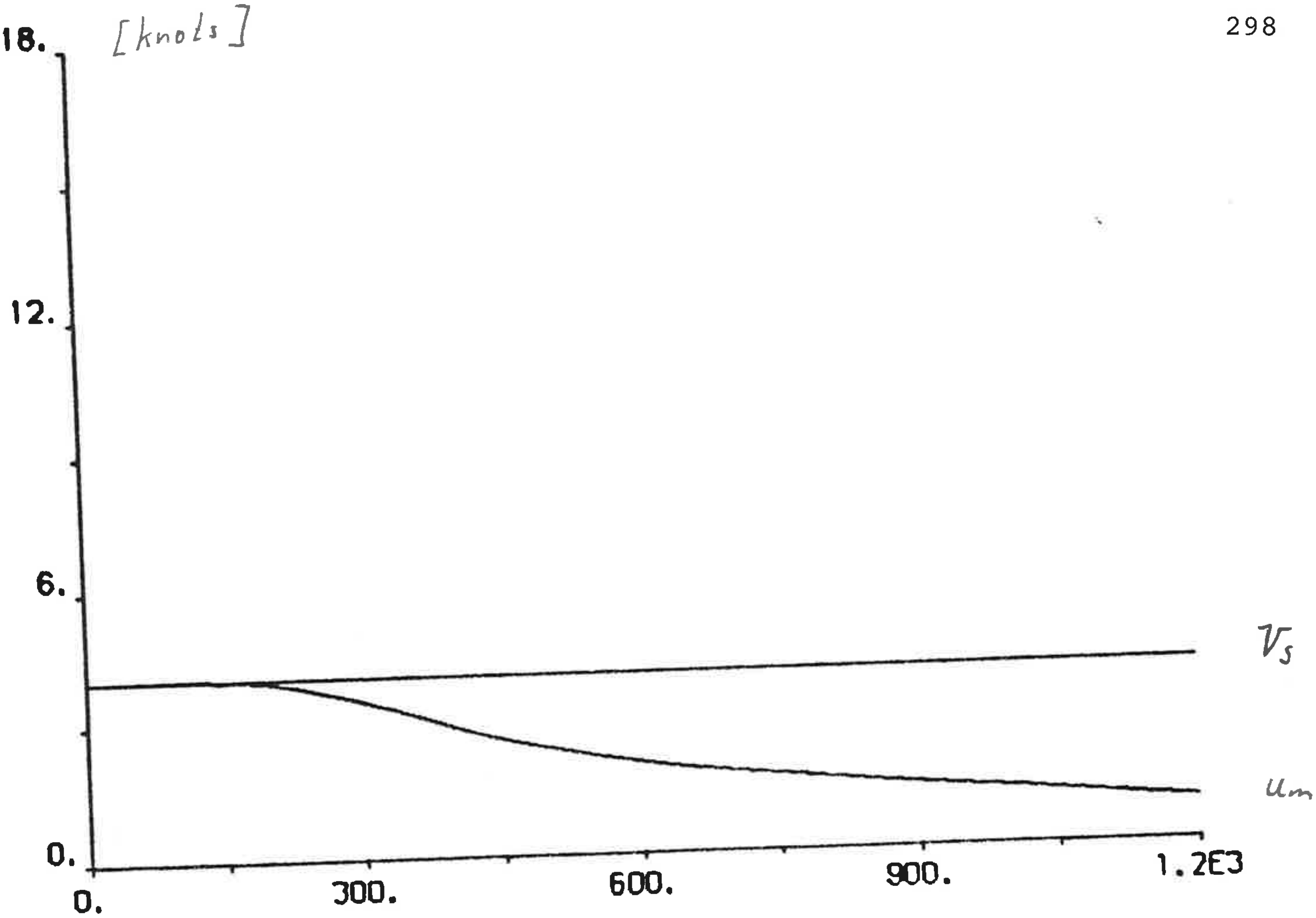

[deg]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
0,2 * $\bar{d}_c$
0,2 * $\hat{d}_0$
10 * ($\hat{d}_v$ - d_v)
[knots]
100 * ($\hat{d}_r$ - d_r)
[deg/s]
$\hat{d}_\delta$ - d_δ
[deg]

Fig. 4.88 d


18.
[knots]
12.
6.
0.
0.
300.
600.
900.
1.2E3
V_s
u_m

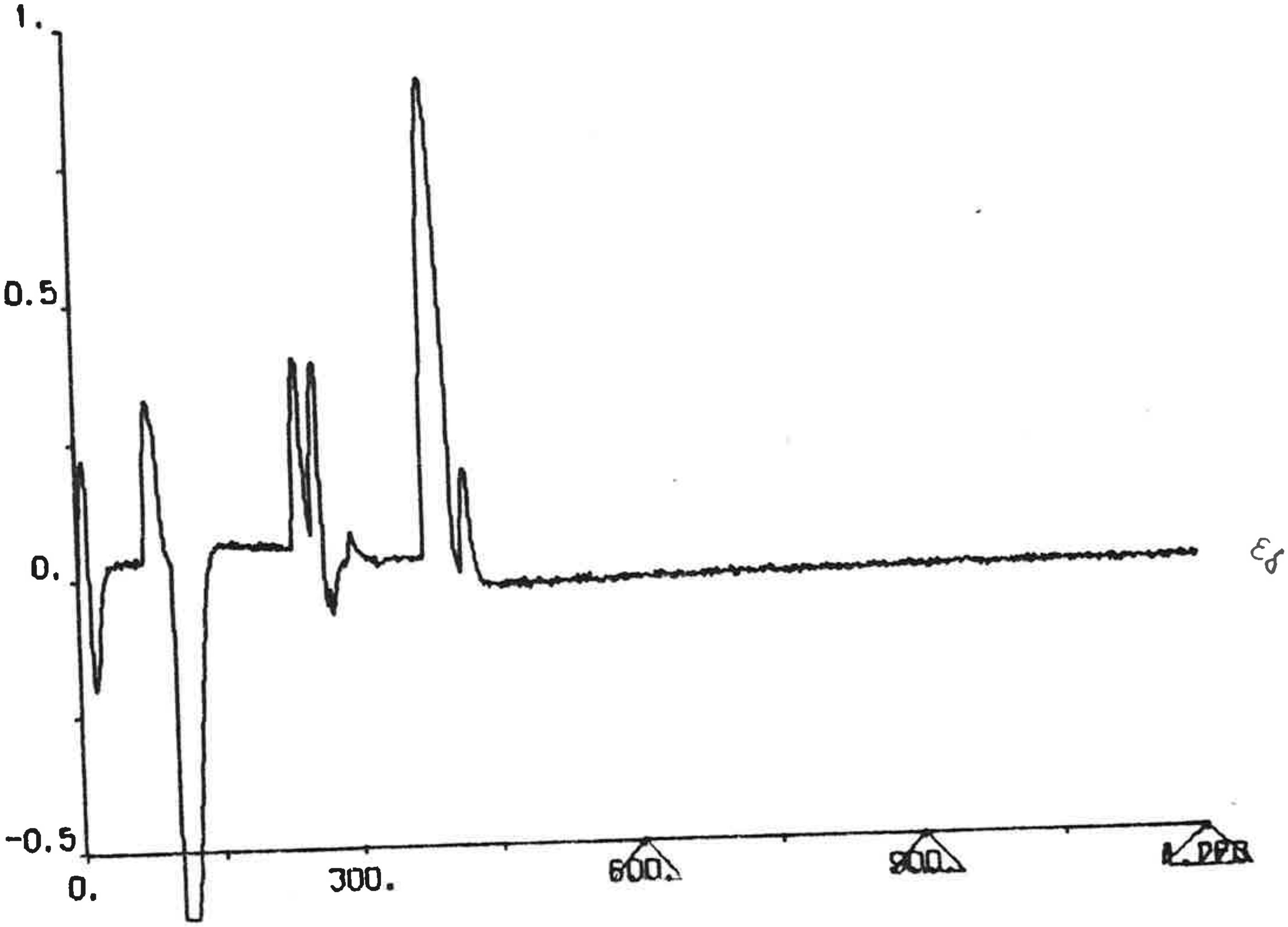

1.
0.5
0.
-0.5
0.
300.
600.
900.
ε_δ'

Fig. 4.88 e

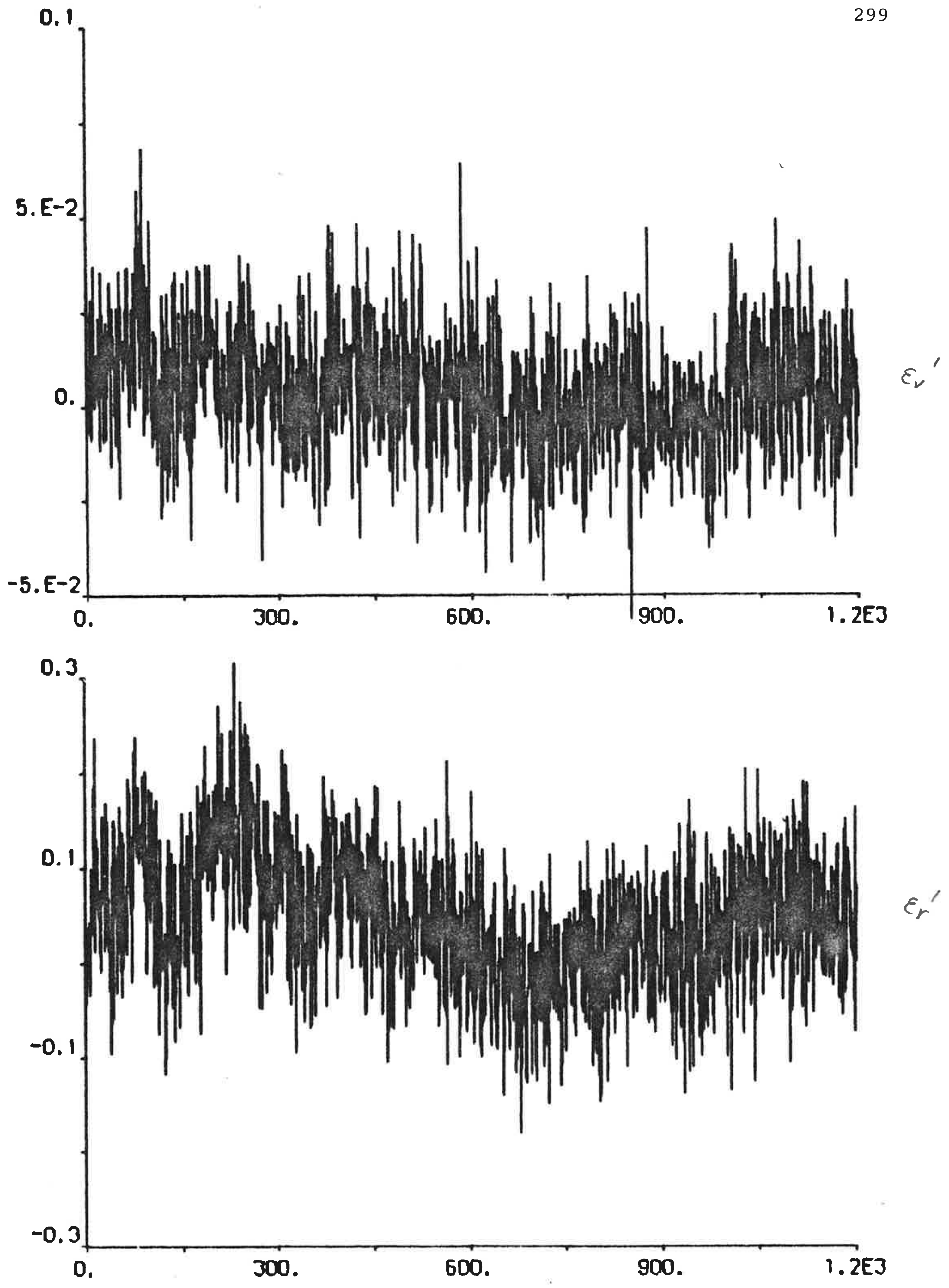
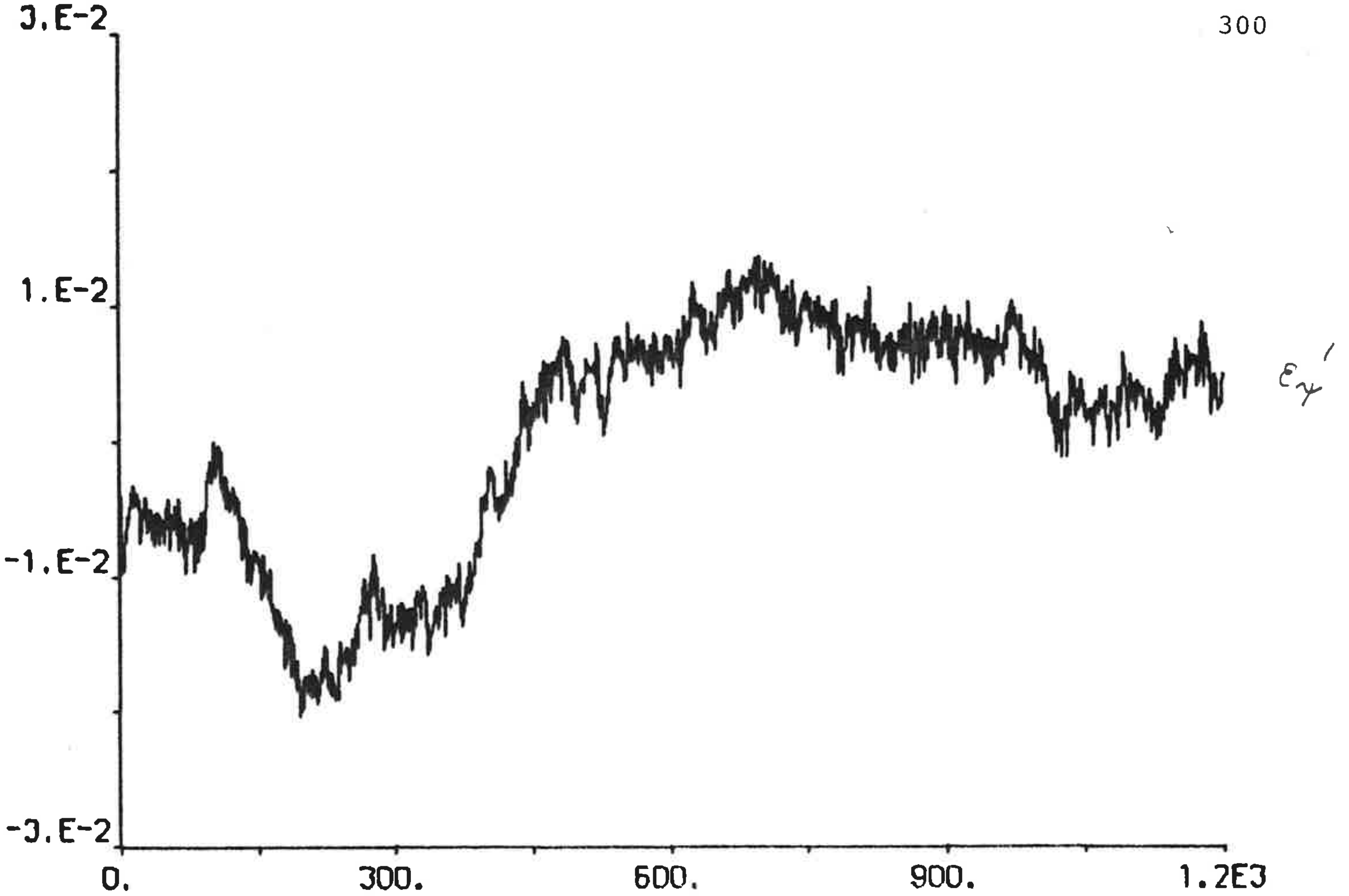


Fig. 4.88 f


3.E-2
1.E-2
-1.E-2
-3.E-2
0.
300.
600.
900.
1.2E3
ε_γ'

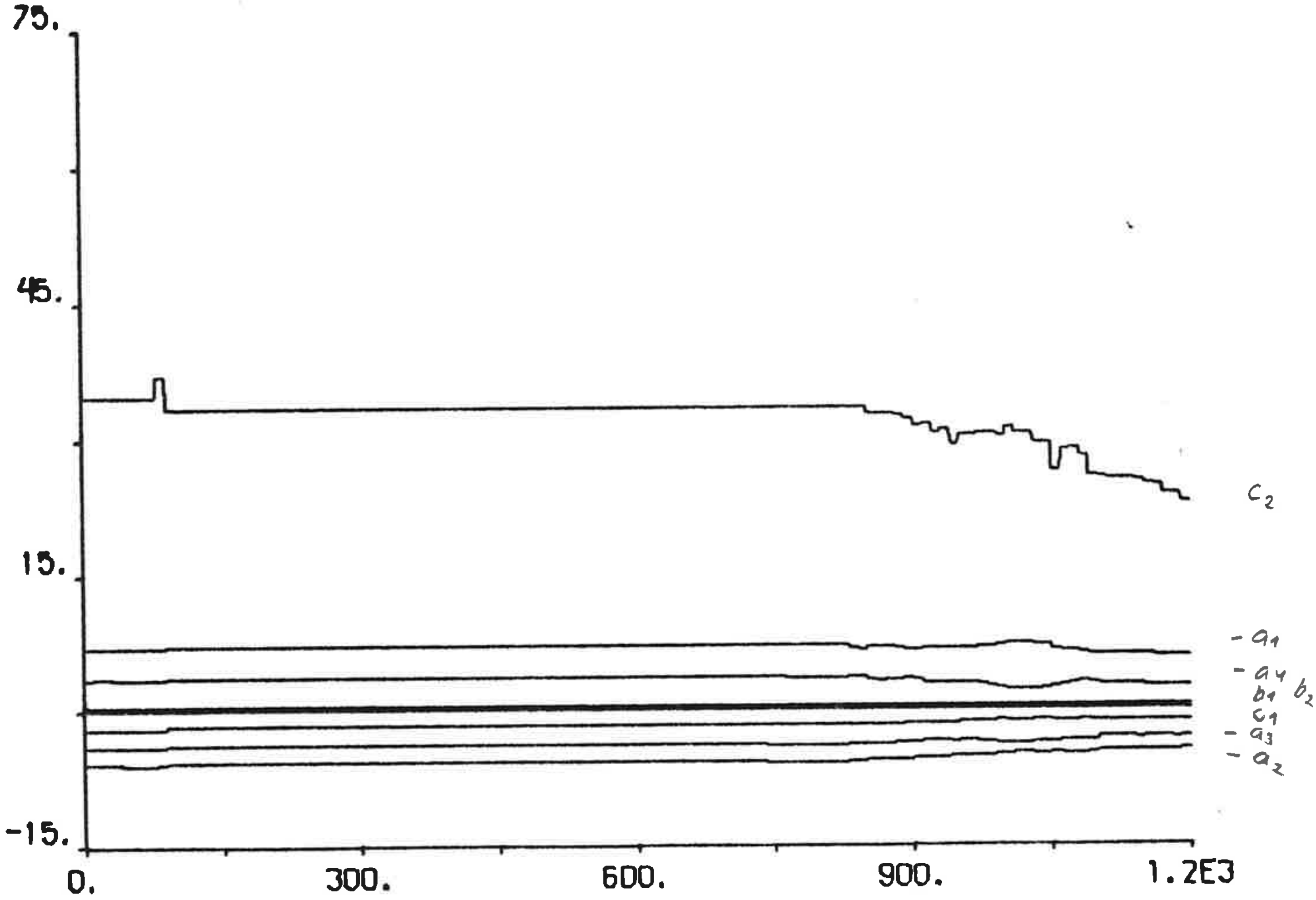

75.
45.
15.
-15.
0.
300.
600.
900.
1.2E3
c_2
$-a_1$
$-a_4$ b_2
b_1
c_1
$-a_3$
$-a_2$

Fig. 4.88 g

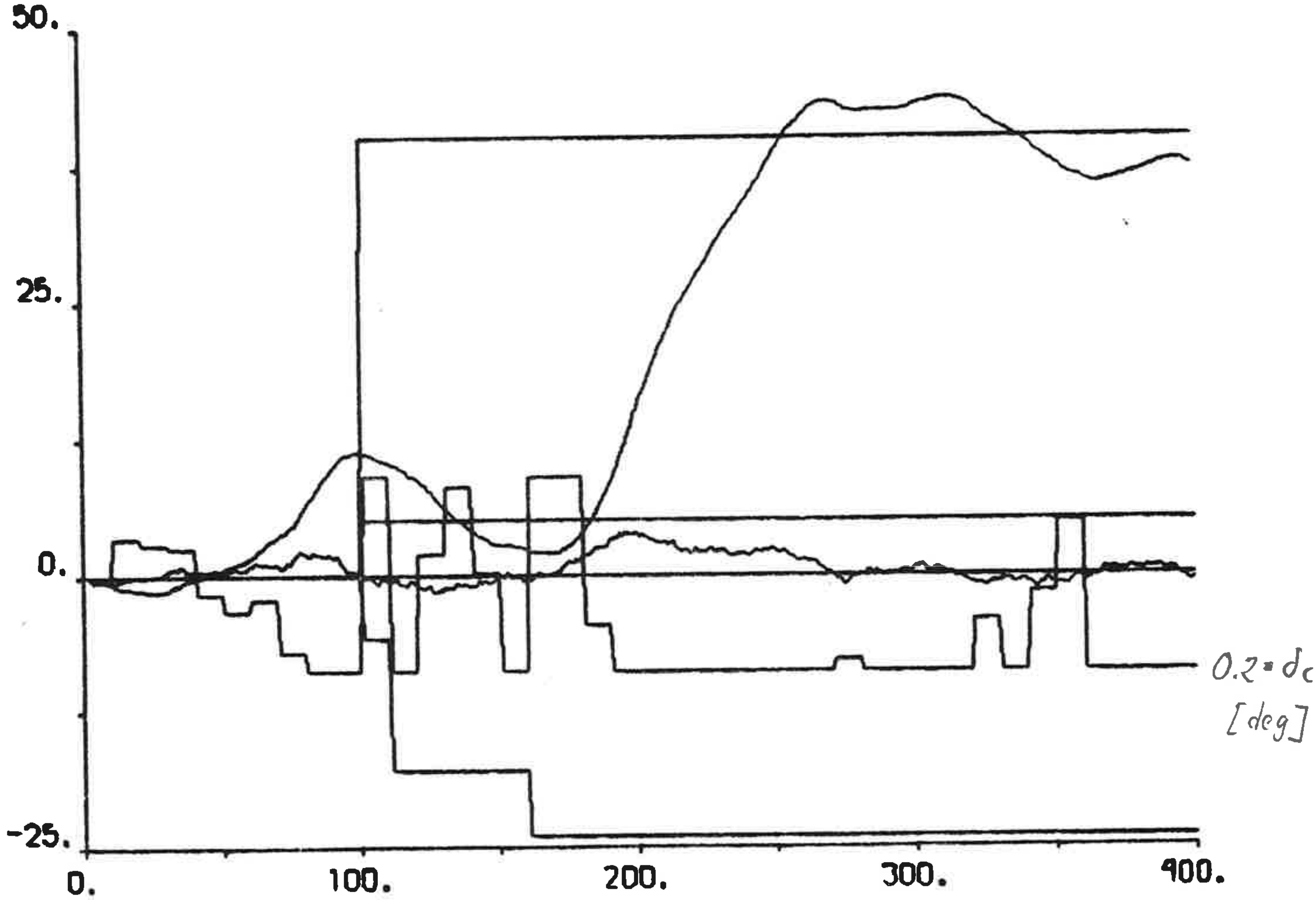
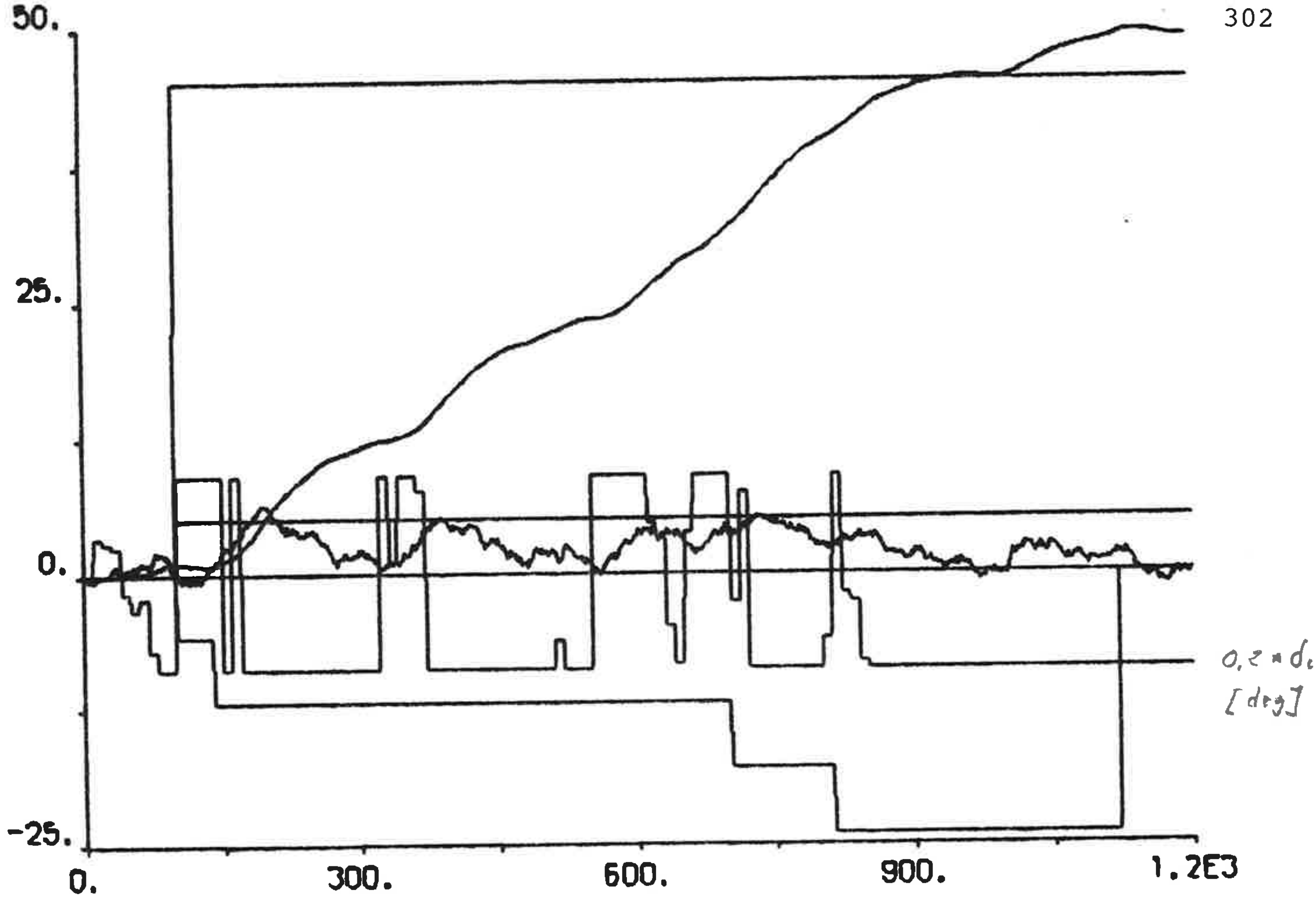


Fig. 4.89 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\bar{c}_2$ = 100 s).



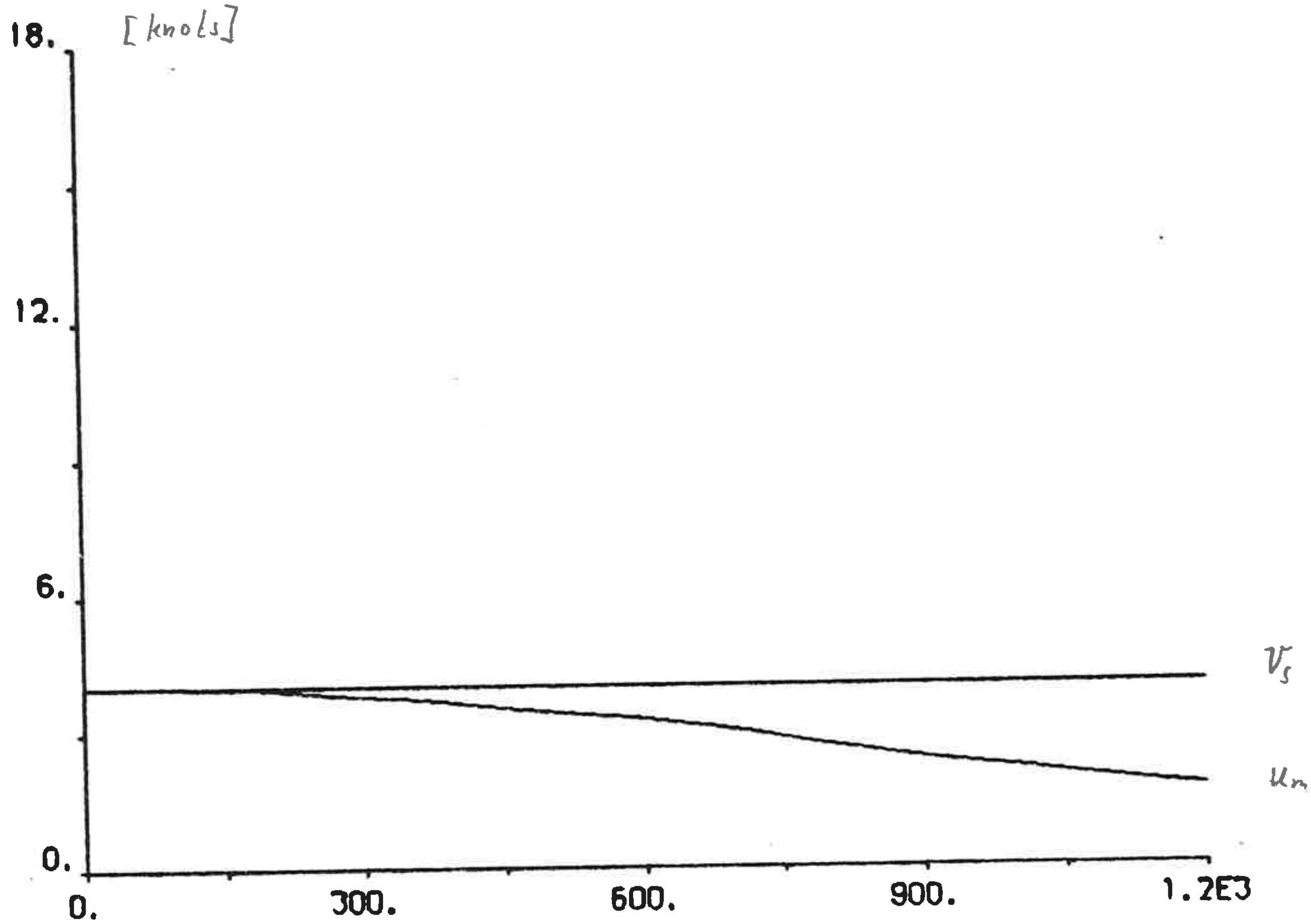


Fig. 4.90 - T = 22.3 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 100 s).

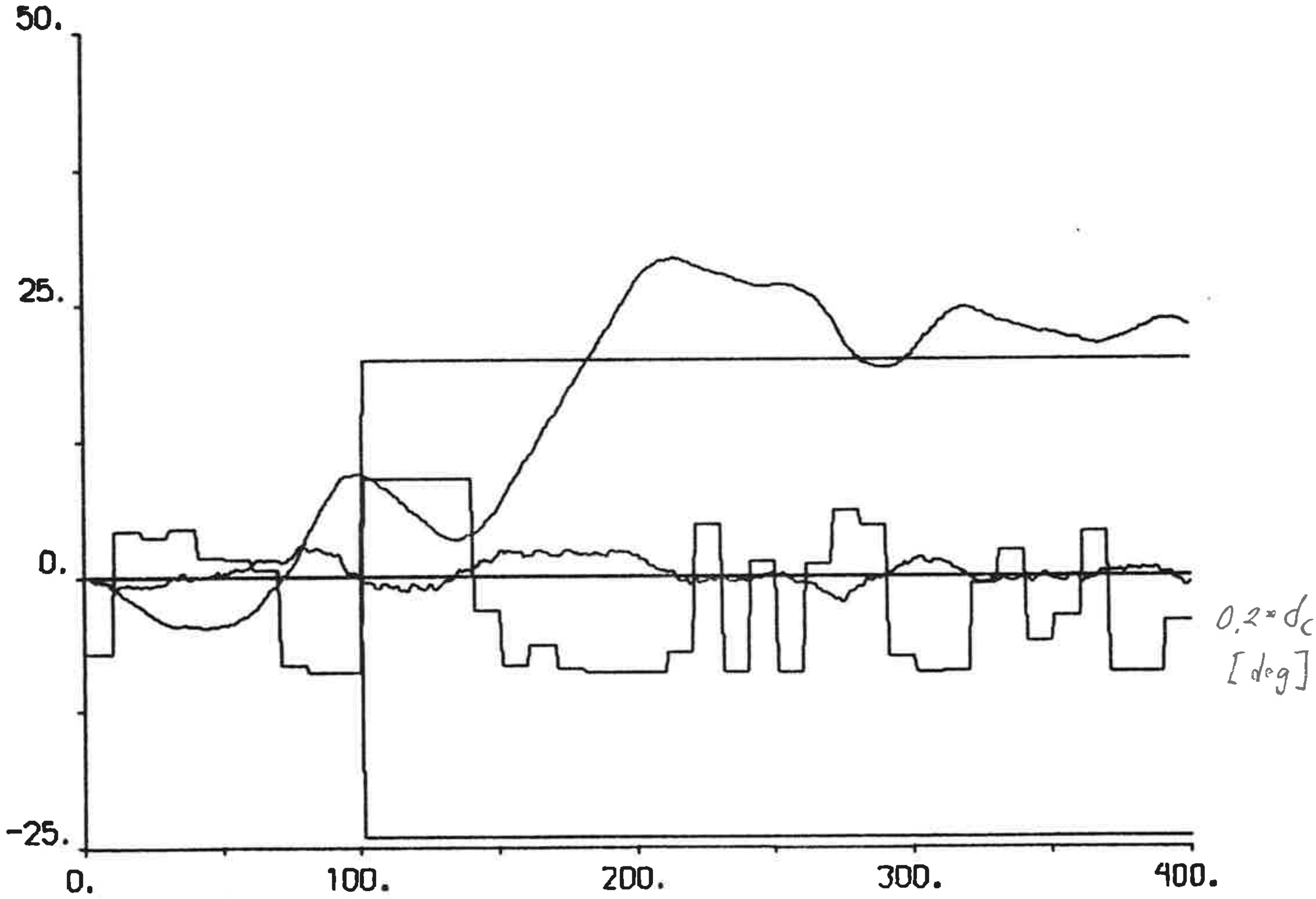


Fig. 4.91 - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 2 deg, r_{ref} = 0 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 100 s).

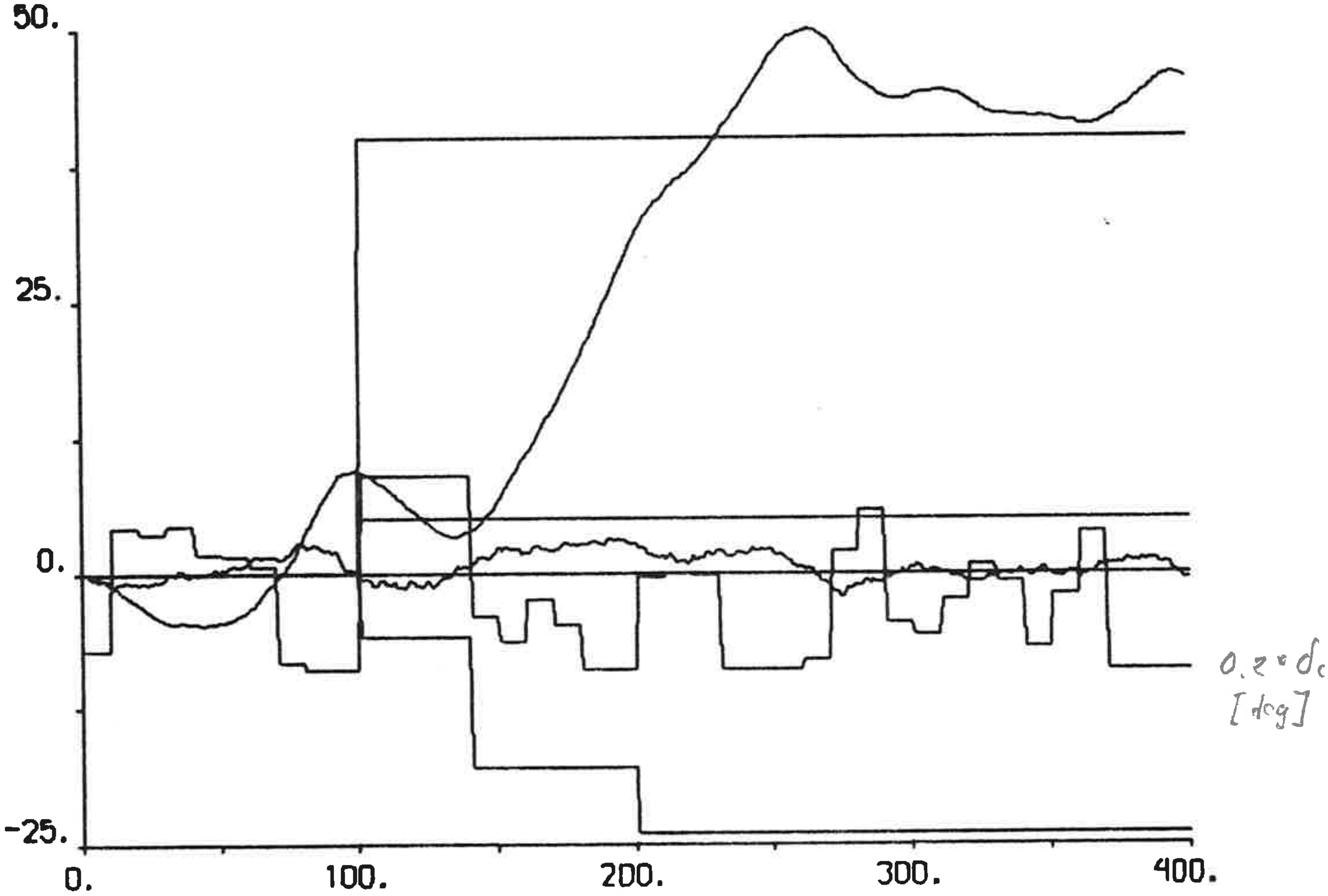


Fig. 4.92 - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 100 s).

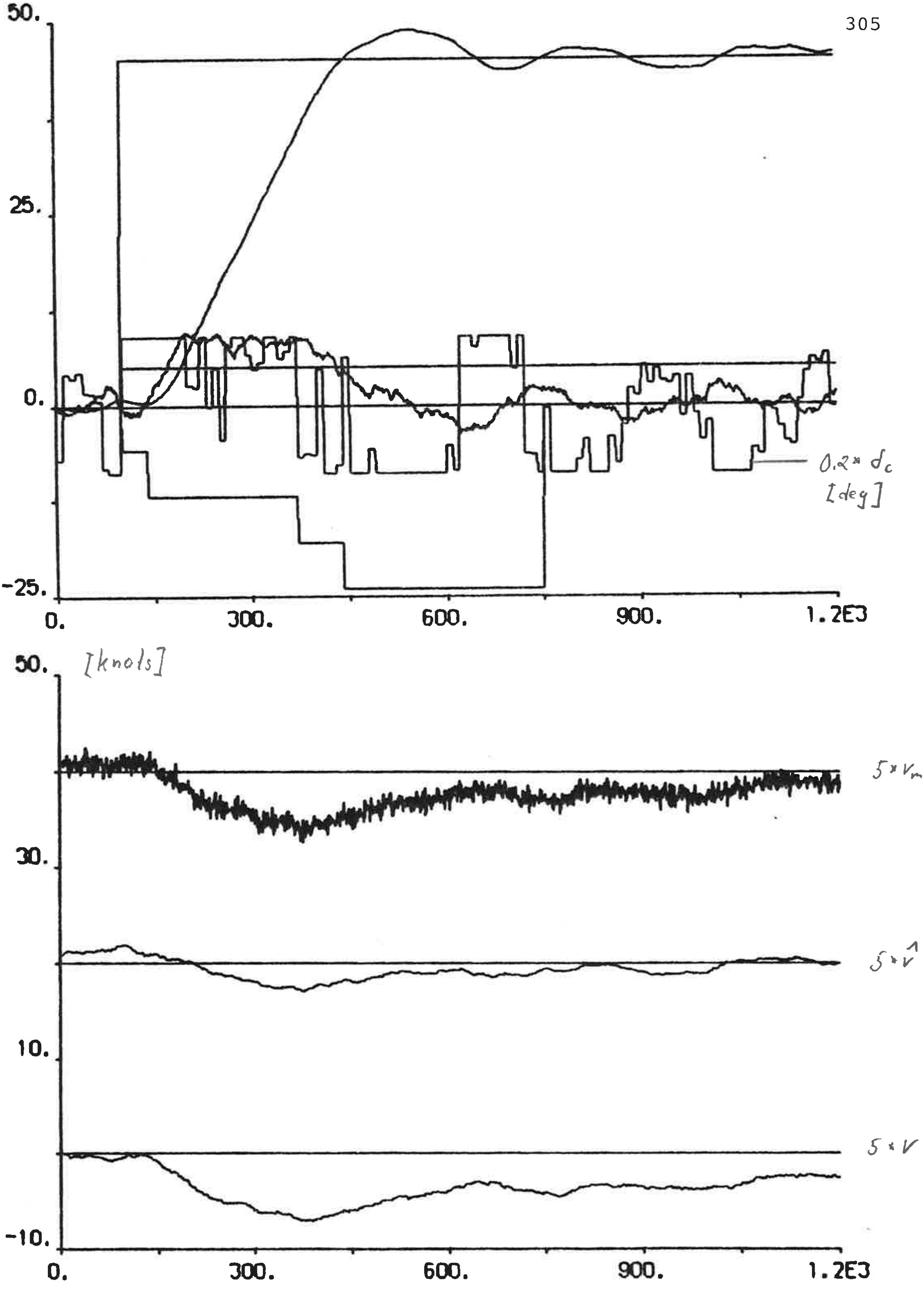


Fig. 4.93 a - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using estimates from the Kalman filter ($\bar{c}_2$ = 100 s).

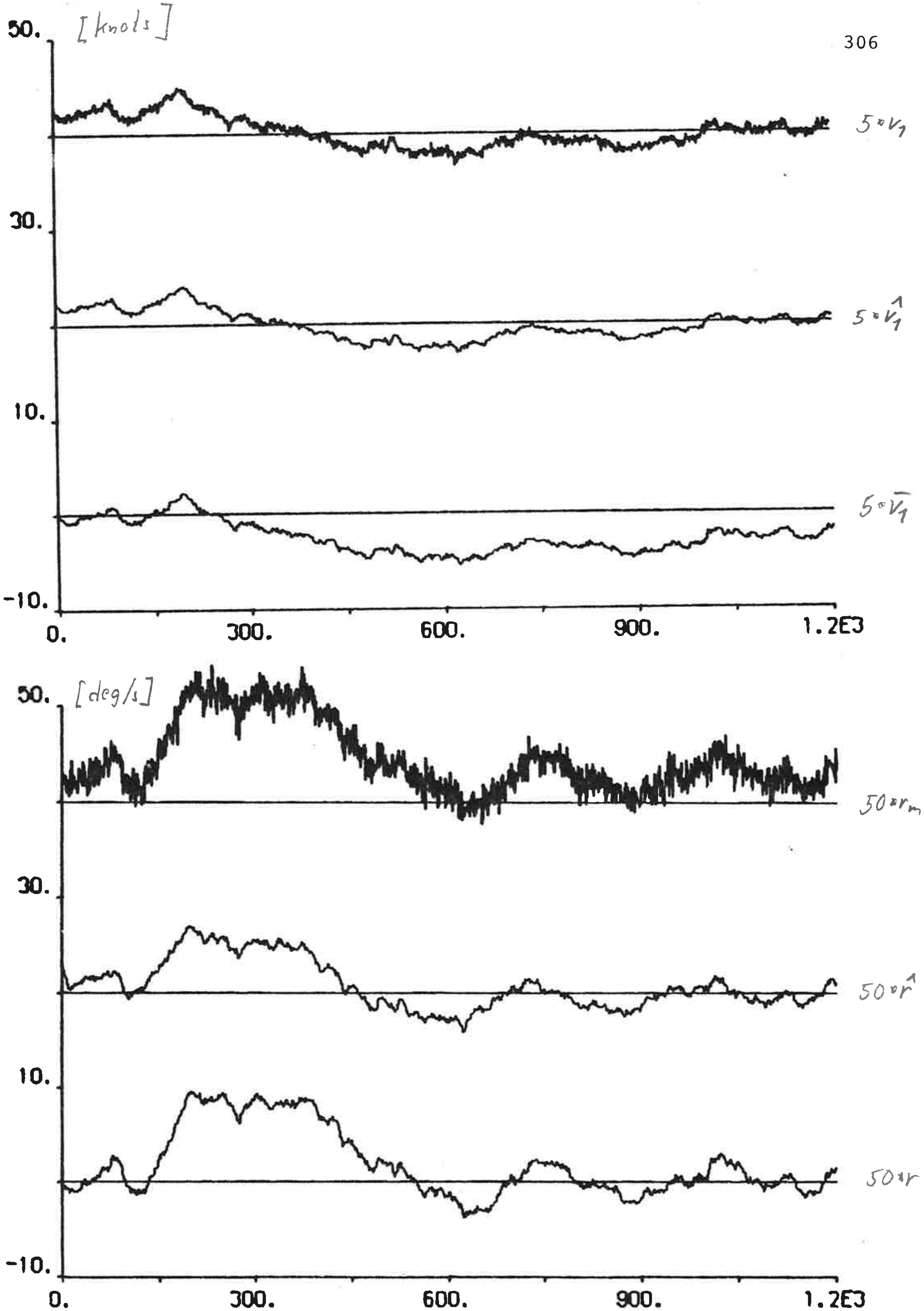

[knots]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
5*v1
5*v̂1
5*v̄1
[deg/s]
50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
50*rm
50*r̂
50*r

Fig. 4.93 b

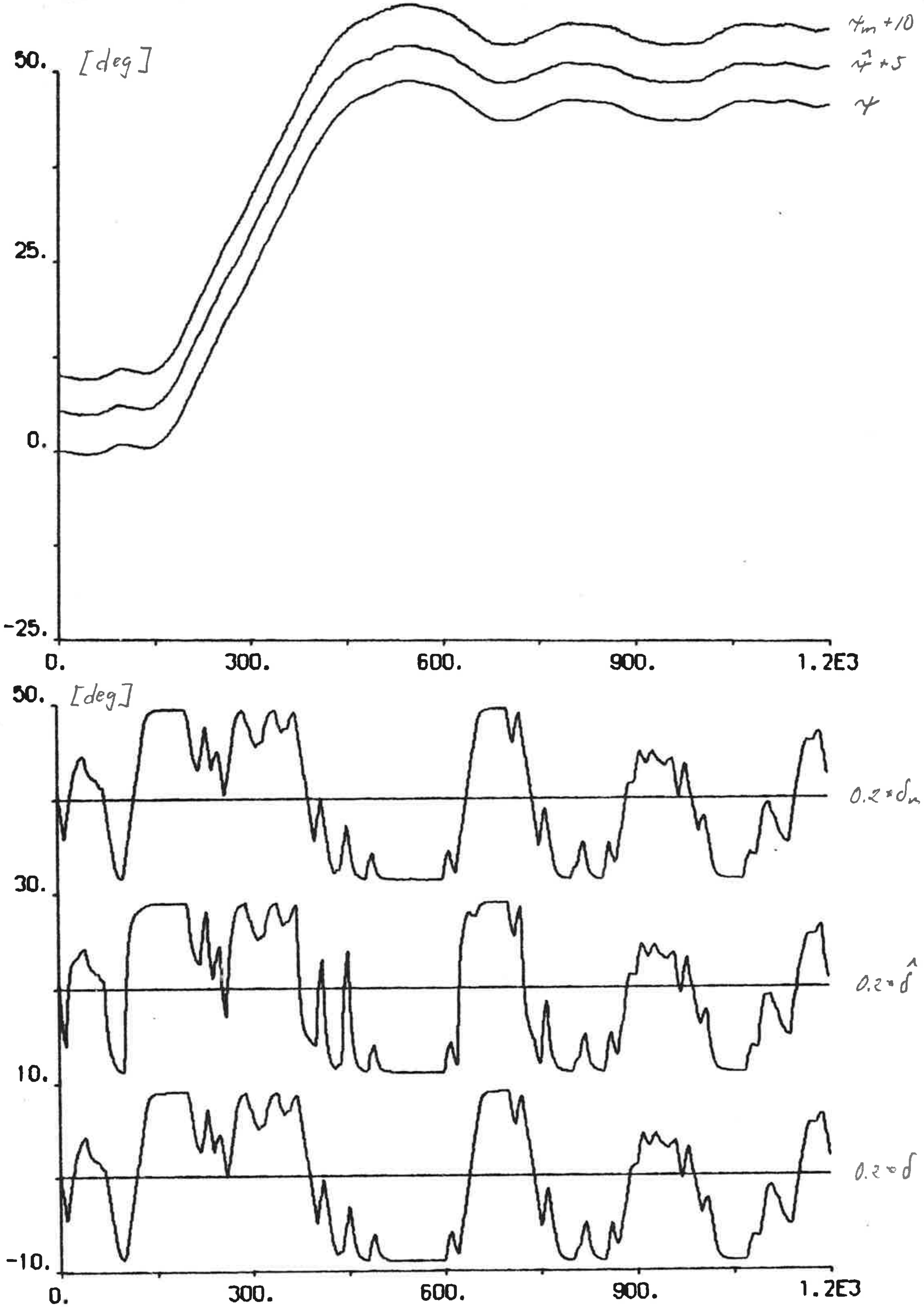
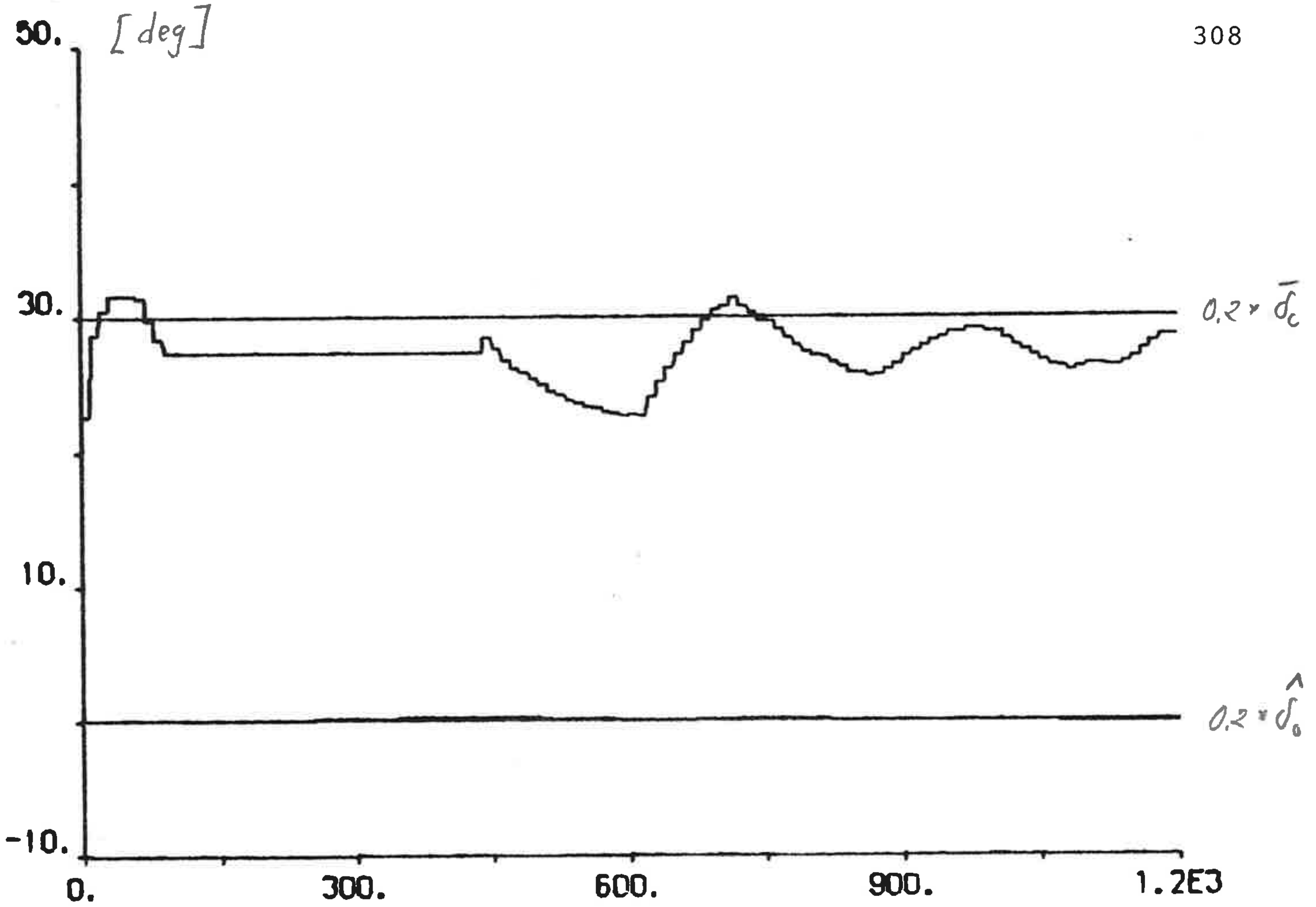


Fig. 4.93 c


50.
[deg]
30.
10.
-10.
0.
300.
600.
900.
1.2E3

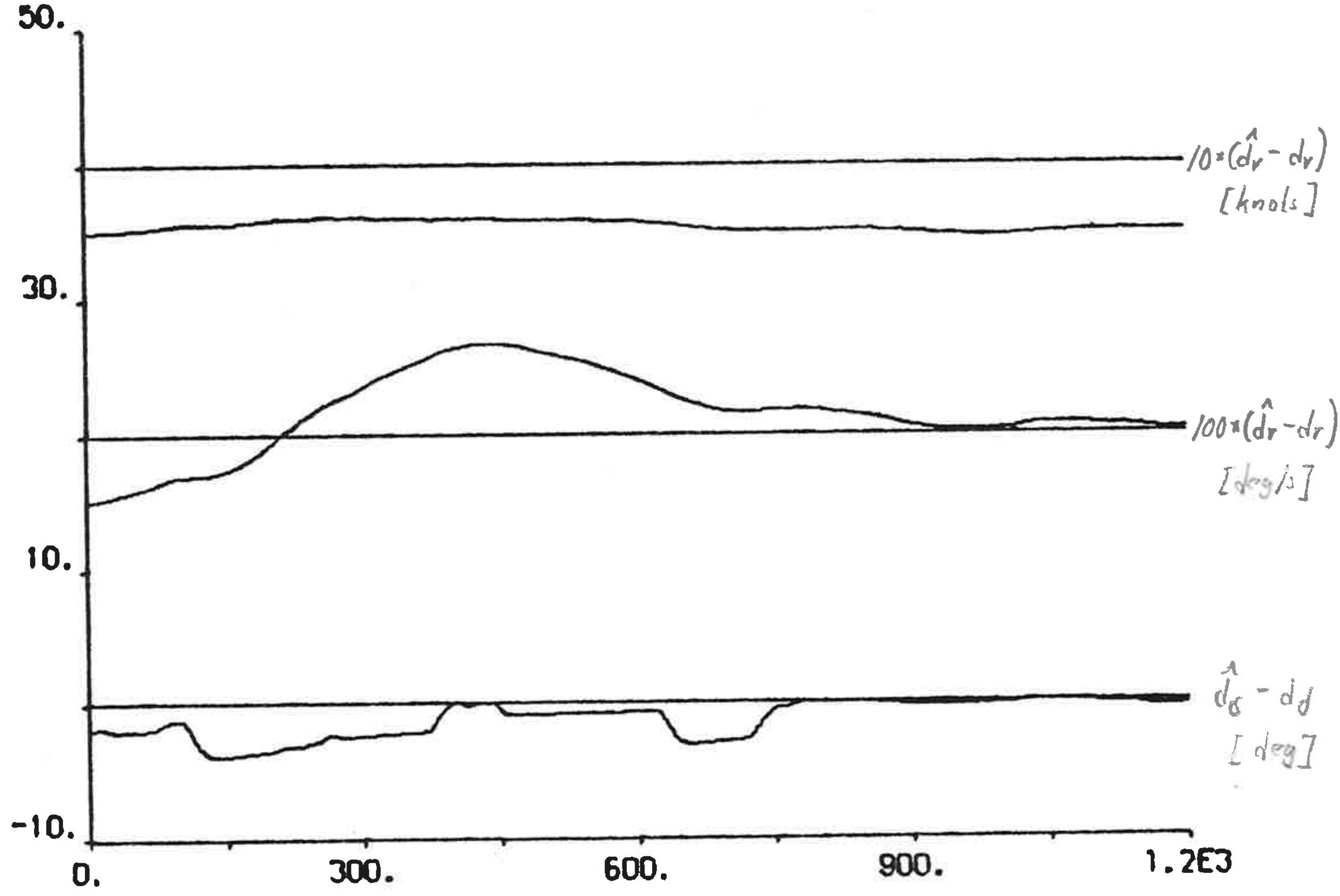

50.
30.
10.
-10.
0.
300.
600.
900.
1.2E3
[knots]
[deg/s]
[deg]

Fig. 4.93 d

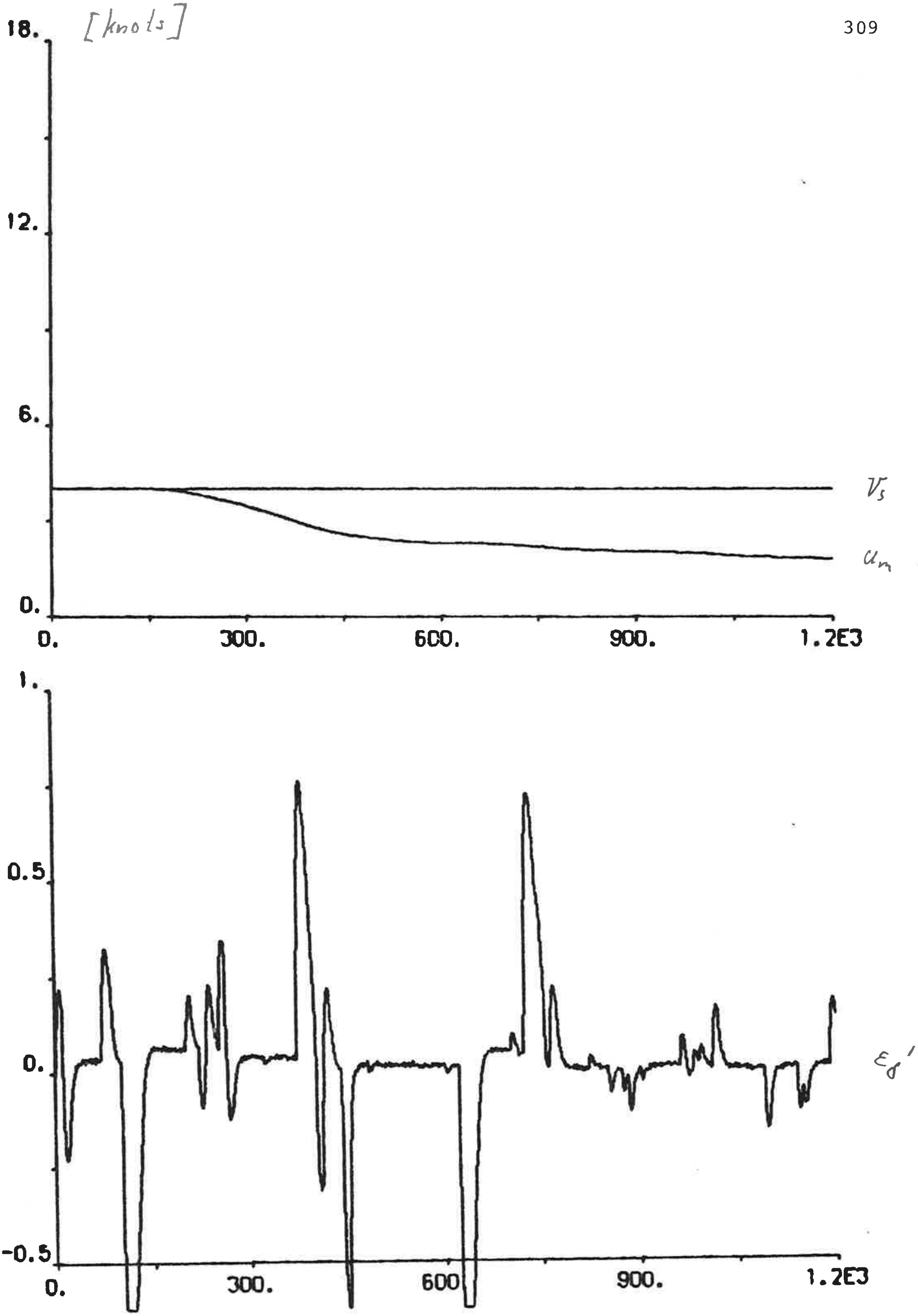

18.
[knots]
12.
6.
0.
V_s
u_m
0.
300.
600.
900.
1.2E3
1.
0.5
0.
-0.5
ε_δ'
0.
300.
600
900.
1.2E3

Fig. 4.93 e

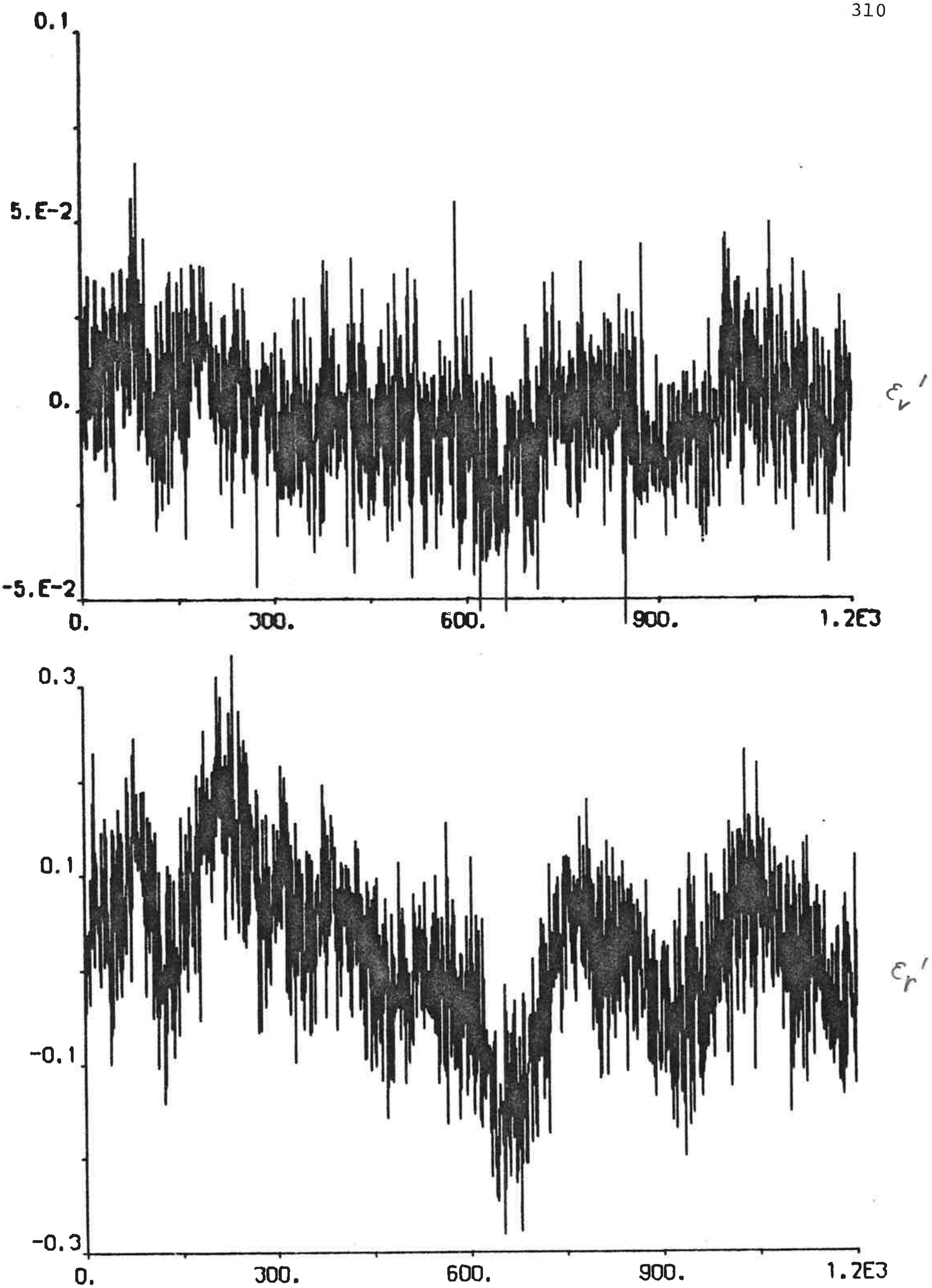


Fig. 4.93 f

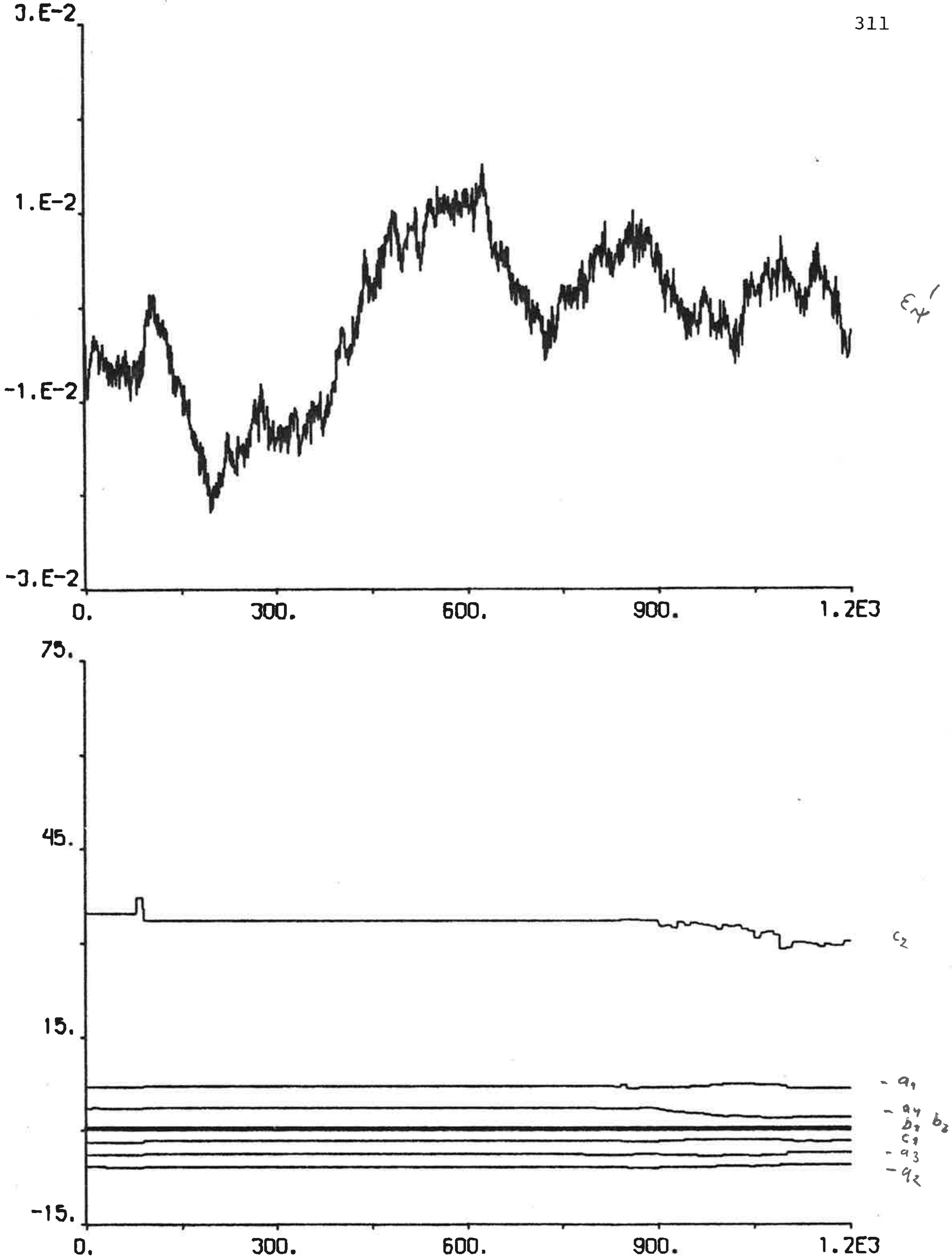


Fig. 4.93 g

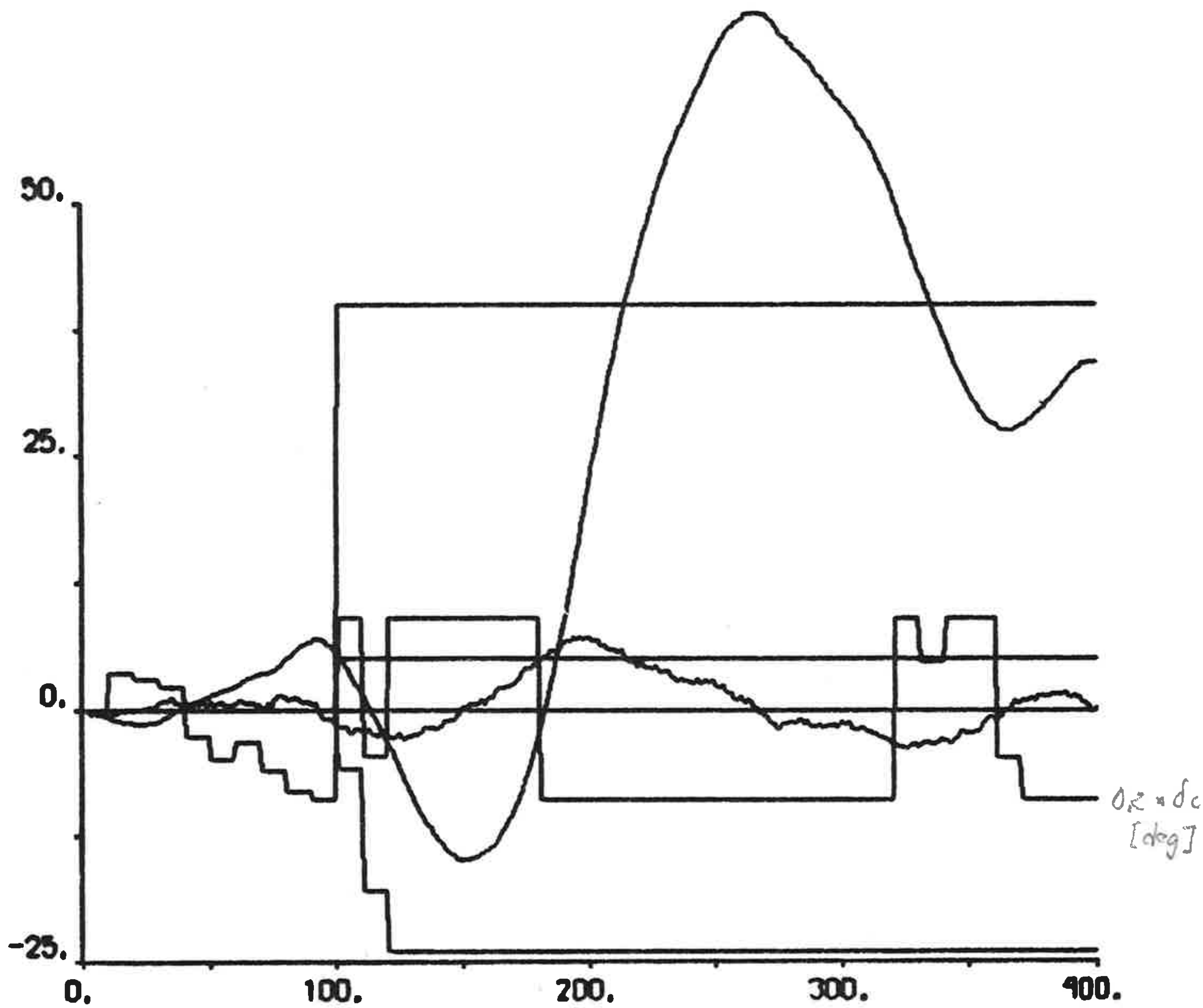
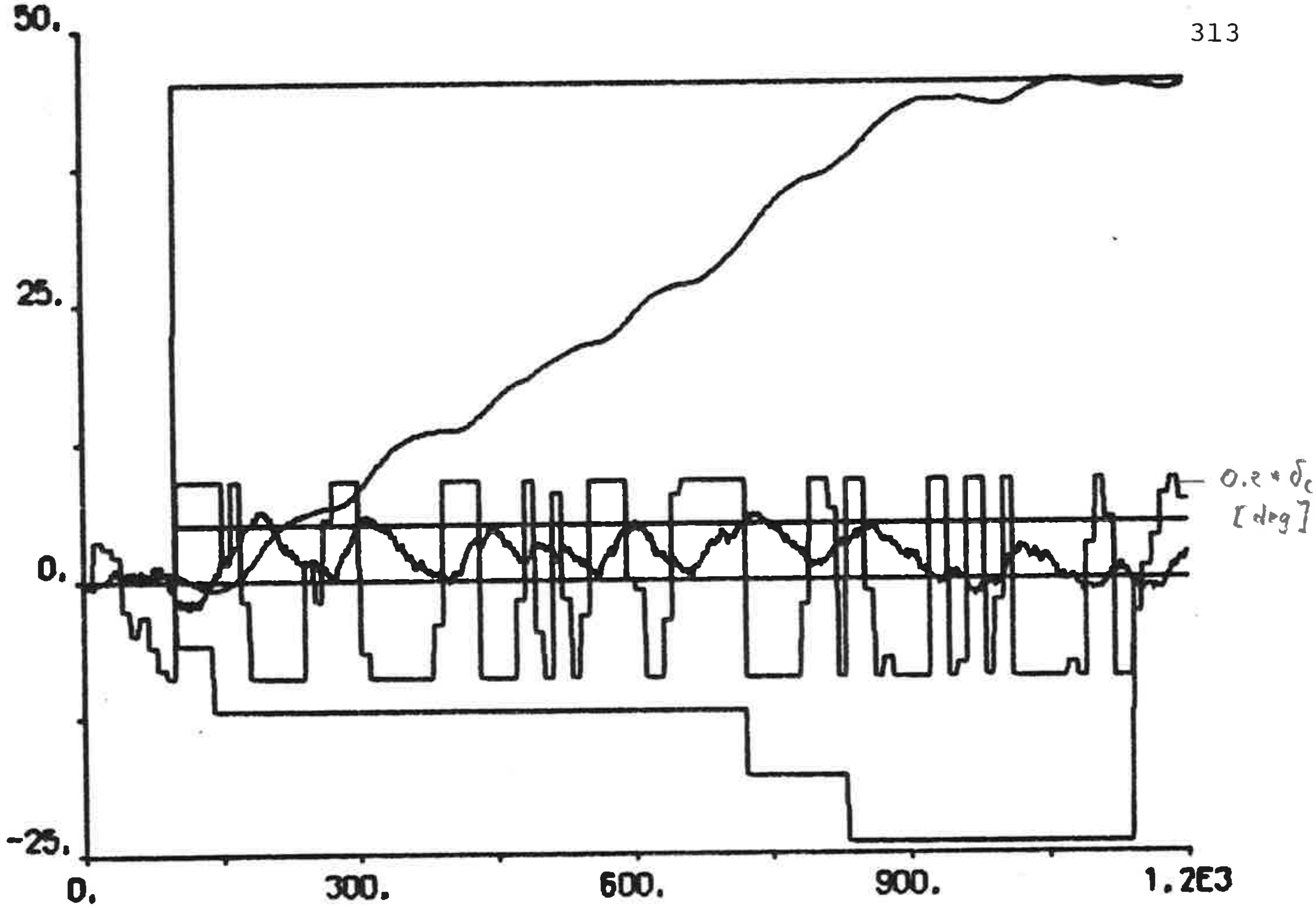


Fig. 4.94 - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\bar{c}_2$ = 100 s).



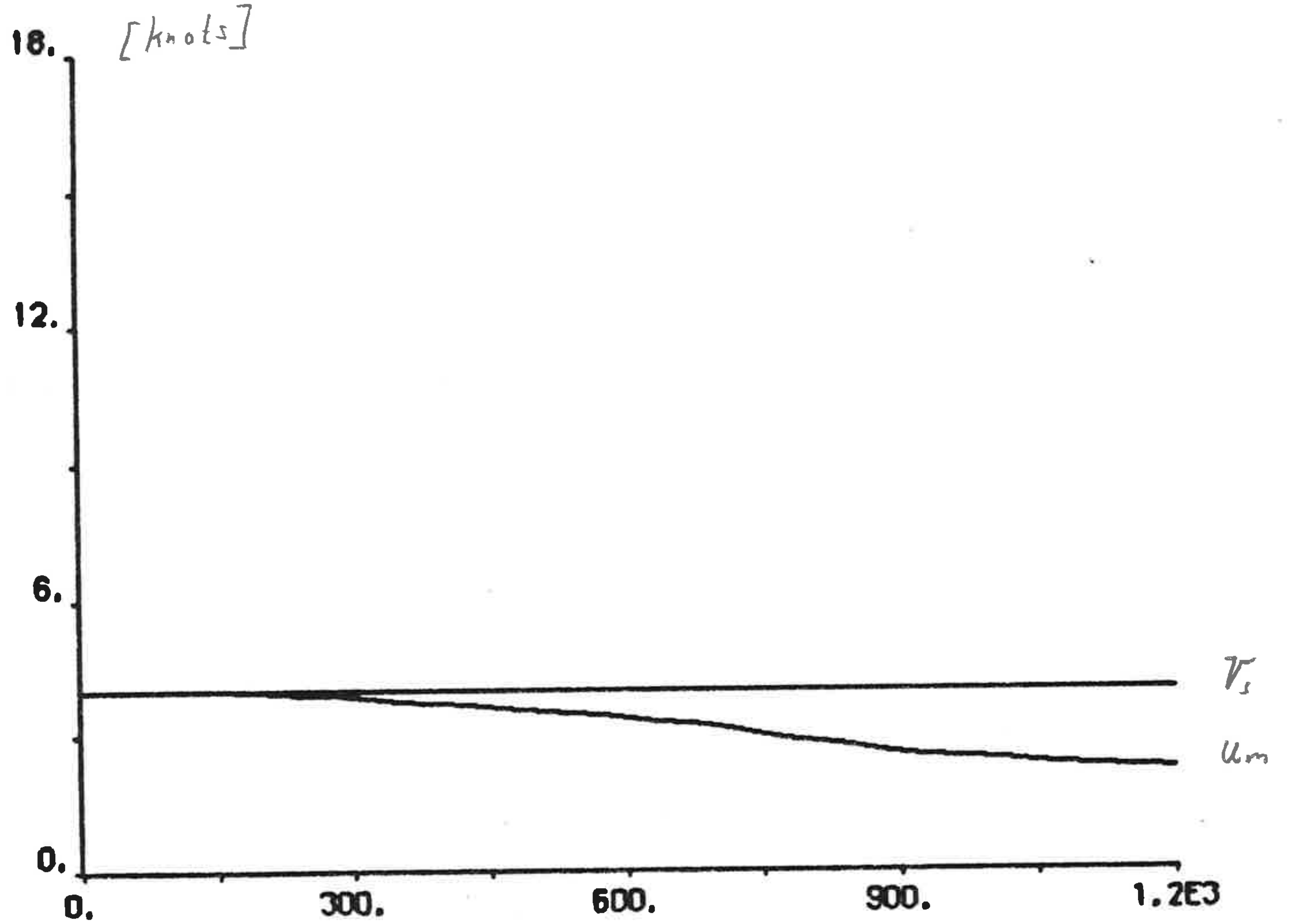


Fig. 4.95 - T = 10.5 m, n_0 = 22.1772 rpm, u_0 = 4 knots, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s, self-tuning regulator and yaw regulator using non-filtered measurements ($\overline{c}_2$ = 100 s).

5. CONCLUSIONS

Simulations of straight course keeping and yawing of a 350 000 tdw tanker in full load condition as well as in ballast condition and with three different initial speeds (15.8, 10 and 4 knots) are presented in this report. The disturbances applied are equivalent to a rather rough weather condition to obtain decisive comparisons. The steering is performed by an autopilot, which consists of a Kalman filter, a self-tuning regulator and a yaw regulator. A PID-regulator is also implemented for comparison. It is possible to use either the Kalman filter estimates or the non-filtered measurements in the different regulators.

The performance of the Kalman filter is very good in full load condition as well as in ballast condition, when the initial speed is 15.8 or 10 knots. The quality of the filter estimates is decreased, although quite acceptable, when the initial speed is 4 knots. A difficulty is that the limited rudder turning rate has not been considered in the Kalman filter. This means rather poor estimates of the rudder angle when large rudder deviations are requested, which is the case quite often when the speed is low. The performance of the Kalman filter is approximately of the same quality during yawing as during straight course keeping. Notice, however, that it is suitable to skip the updating of the bias estimates of the filter during yaws.

The simulations show that 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 significantly better than the performance of the PID-regulator, if the ship is full-loaded. However, the difference between the two regulators is hardly noticable in ballast condition. It is not possible to make any conclusions when non-filtered measurements are used by the self-tuning regulator and the PID-regulator, since the simulation results are rather confusing. However, the self-tuning regulator using Kalman filter estimates is always significantly better than the PID-regulator using non-filtered measurements, and the PID-regulator using Kalman filter estimates is always significantly better than the self-tuning regulator using non-filtered measurements.

The performance of the yaw regulator, when Kalman filter estimates are used, is very good for different load conditions and speeds, with one exception: the performance is rather bad when the ship is full-loaded and the initial speed is 4 knots. One explanation is that the actual forward speed is increased to the extreme value 1 knot during one of the simulations. When non-filtered measurements are used instead of Kalman filter estimates, the performance quality of the yaw regulator is significantly decreased. The reason is, of course, that the yaw rate measurements are very noisy. In such a case, it is highly desired to filter the yaw rate signal in some way, to obtain a better performance. Another possibility is to perform a difference approximation of the heading angle measurement to obtain a yaw rate estimate. This requires, however, a rather good resolution of the heading measurement.

6. REFERENCES

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```
CONNECTING SYSTEM CON1
₣
₣AUTHOR, C.KALLSTROM 1976-03-24
₣
TIME T
₣
W1ÄTANK3Å=E1ÄNOIS1Å*NOI1
W2ÄTANK3Å=E2ÄNOIS1Å*NOI2
EE1ÄTANK3Å=E3ÄNOIS1Å
EE2ÄTANK3Å=E4ÄNOIS1Å
EE3ÄTANK3Å=E5ÄNOIS1Å
EE4ÄTANK3Å=E6ÄNOIS1Å
DELMÄAUTÅ=DELMÄTANK3Å
DELTAÄAUTÅ=DELMNÄTANK3Å
V1ÄAUTÅ=V1MNÄTANK3Å
RÄAUTÅ=RMNÄTANK3Å
PSIMÄAUTÅ=PSIMÄTANK3Å
PSIÄAUTÅ=PSIMNÄTANK3Å
UÄAUTÅ=UMÄTANK3Å
ANÄAUTÅ=NMÄTANK3Å
DELCÄTANK3Å=DELCOÄAUTÅ
₣
SCC1:0.
SCC2:0.
SCC3:0.
SCC4:0.
NOI1:1.E-5
NOI2:1.E-5
₣
END
```

```
CONTINUOUS SYSTEM TANK3

₣AUTHOR, C.KALLSTROM 1976-03-17
₣
₣KOCKUMS CONVENTION OF THE RUDDER SIGN
₣
INPUT DELC W1 W2 EE1 EE2 EE3 EE4

₣DELC = RUDDER COMMAND ÄDEGÅ
₣W1   = STATE NOISE ÄM/(S*S)Å
₣W2   = STATE NOISE Ä1/(S*S)Å
₣EE1  = MEASUREMENT NOISE ÄDEGÅ
₣EE2  = MEASUREMENT NOISE ÄKNOTSÅ
₣EE3  = MEASUREMENT NOISE ÄDEG/SÅ
₣EE4  = MEASUREMENT NOISE ÄDEGÅ

OUTPUT DELM DELMN V1MN RMN PSIM PSIMN UM NM
₣
₣DELM = RUDDER ANGLE ÄDEGÅ
₣DELMN= RUDDER ANGLE MEASUREMENT ÄDEGÅ
₣V1MN = BOW SWAY VELOCITY MEASUREMENT ÄKNOTSÅ
₣RMN  = YAW RATE MEASUREMENT ÄDEG/SÅ
₣PSIM = HEADING ÄDEGÅ
₣PSIMN= HEADING MEASUREMENT ÄDEGÅ
₣UM   = FORWARD SPEED ÄKNOTSÅ
₣NM   = NUMBER OF PROPELLER REVOLUTIONS ÄRPMÅ

STATE DEL U V R PSI

₣DEL  = RUDDER ANGLE ÄRADÅ
₣U    = FORWARD VELOCITY ÄM/SÅ
₣V    = SWAY VELOCITY ÄM/SÅ
₣R    = YAW RATE Ä1/SÅ*100
₣PSI  = HEADING ÄRADÅ

DER DDEL DU DV DR DPSI

INITIAL

U=U0/CMK
SGL=SQRT(G*L)

F1=(22.3-TT)/11.8
F2=(TT-10.5)/11.8
N=N0/60.
U01=N*(17.25*F1+15.8*F2)/(1.46*CMK)

TS1 = 1/TS
TS2 = TS1/CRG
DL1 = DL/CRG

XUD=XUD1*F1+XUD2*F2
XUDL=XUD*L
XUU=(XUU1*F1+XUU2*F2)/XUDL
XVR=(XVR1*F1+XVR2*F2)/XUD
XRR=(XRR1*F1+XRR2*F2)*L/XUD
XUV=XUVVV/(G*L*XUDL)
XUUDD=(XUDD1*F1+XUDD2*F2)/XUDL
XT=X1T/XUD

YVD=YVD1*F1+YVD2*F2
YVDL=YVD*L
YRU1=YRU/YVD
```

```
YRUU1=YRUU/(SGL*YVD)
YUV=(YUV1*F1+YUV2*F2)/YVDL
YUUV=(YUUV1*F1+YUUV2*F2)/(SGL*YVDL)
YVV=(YVV1*F1+YVV2*F2)/YVDL
YRAV=(YRAV1*F1+YRAV2*F2)/YVD
YARV=(YARV1*F1+YARV2*F2)/YVD
YUUD=(YUUD1*F1+YUUD2*F2)/YVDL
YTD1=YTD/YVD
KTY1=KTY/YVD

NRDL=NRD*L
NRDLL=NRDL*L
NRU=(NRU1*F1+NRU2*F2)/NRDL
NRUU=(NRUU1*F1+NRUU2*F2)/(SGL*NRDL)
NUV=(NUV1*F1+NUV2*F2)/NRDLL
NUUV=(NUUV1*F1+NUUV2*F2)/(SGL*NRDLL)
NVV=(NVV1*F1+NVV2*F2)/NRDLL
NRR=(NRR1*F1+NRR2*F2)/NRD
NRAV=(NRAV1*F1+NRAV2*F2)/NRDL
NARV=(NARV1*F1+NARV2*F2)/NRDL
NUUD=(NUUD1*F1+NUUD2*F2)/NRDLL
NTD1=NTD/NRDL
KTN1=KTN/NRDL

XF=FW/XUD
YF=FW/YVD
NF=FW*LV/NRDLL

JJ1=(1-W)/(N*D)
DISPL=DISP1*F1+DISP2*F2
TT1=N*N*D*D*D/DISPL
JJ=U01*JJ1
JJP=JJ/SQRT(1+JJ*JJ)
KKT=-0.33*JJP*JJP-0.38*JJP+0.35
TMO=KKT*(1+JJ*JJ)*TT1
LL1=CMK*L1
ALF1=ALFA/CRG

OUTPUT

DELM=CRG*DEL
DELMS=SC35*DELM+SC36
DELMN=DELM+D3+EE1
DMNS=SC37*DELMN+SC38
D3S=SC39*D3+SC40
VM=CMK*V
VMS=SC41*VM+SC42
V1M=LL1*R/100.+VM
V1MS=SC43*V1M+SC44
V1MN=V1M+D1+EE2
V1MNS=SC45*V1MN+SC46
D1S=SC47*D1+SC48
RM=CRG*R/100.
RMS=SC49*RM+SC50
RMN=RM+D2+EE3
RMNS=SC51*RMN+SC52
D2S=SC53*D2+SC54
PSIM=CRG*PSI
PSIMS=SC55*PSIM+SC56
PSIMN=PSIM+EE4
PSMNS=SC57*PSIMN+SC58
UM=CMK*U
UMS=SC59*UM+SC60
NM=NO
```

```
DYNAMICS

RR=R/100.
APSI=ALF1-PSI
SINW=SIN(APSI)
J=U*JJ1
JP=J/SQRT(1+J*J)
KT=-0.33*JP*JP-0.38*JP+0.35
TM=KT*(1+J*J)*TT1
TM1=IF TM<TMO THEN TM ELSE TMO
TMD =TM1*DEL
U2=U*U
AV=ABS(V)
AR=ABS(RR)
RU=RR*U
RU2=RU*U
UV=U*V
U2V=U*UV
VAV=V*AV
RAV=RR*AV
ARV=AR*V
U2D=U2*DEL
DDEL1=-TS1*DEL+TS2*DELC
DDEL=IF DDEL1<-DL1 THEN -DL1 ELSE IF DDEL1>DL1 THEN DL1 ELSE DDEL1

DU=XUU*U2+XVR*V*RR+XRR*RR*RR+XUV*UV*VAV+XUUDD*U2D*DEL+XT*TM-XF*COS(APSI)

SL=YRU1*RU+YRUU1*RU2+YUV*UV+YUUV*U2V+YVV*VAV+YRAV*RAV
DV=YARV*ARV-YUUD*U2D-YTD1*TMD+KTY1*TM-YF*SINW+W1/YVD+SL
SL1=NRU*RU+NRUU*RU2+NUV*UV+NUUV*U2V+NVV*VAV+NRR*RR*AR
DR=(SL1+NRAV*RAV+NARV*ARV-NUUD*U2D-NTD1*TMD+KTN1*TM+NF*SINW+W2/NRD)*100.

DPSI=RR
G:9.80665
CMK:1.943844
CRG:57.2958
L:350.
U0:15.8
TT:22.3
TS:5.0
DL:2.32    E2 PUMPS
XUD1:
XUD2:
XUU1:
XUU2:
XVR1:
XVR2:
XRR1:
XRR2:
XUVVV:
XUDD1:
XUDD2:
X1T:
YVD1:
YVD2:
YRU:
YRUU:
YUV1:
YUV2:
YUUV1:
YUUV2:
YVV1:
YVV2:
```

YRAV1:
YRAV2:
YARV1:
YARV2:
YUUD1:
YUUD2:
YTD:
KTY:
NRD:
NRU1:
NRU2:
NRUU1:
NRUU2:
NUV1:
NUV2:
NUUV1:
NUUV2:
NVV1:
NVV2:
NRR1:
NRR2:
NRAV1:
NRAV2:
NARV1:
NARV2:
NUUD1:
NUUD2:
NTD:
KTN:

FW:0.
LV:25.
W:
D:
DISP1:
DISP2:
L1:164.35
ALFA:0.
NO:87.6
D1:1.
D2:0.1
D3:2.
SC35:1.
SC36:0.
SC37:1.
SC38:0.
SC39:1.
SC40:0.
SC41:1.
SC42:0.
SC43:1.
SC44:0.
SC45:1.
SC46:0.
SC47:1.
SC48:0.
SC49:1.
SC50:0.
SC51:1.
SC52:0.
SC53:1.
SC54:0.
SC55:1.
SC56:0.

```
SC57:1.
SC58:0.
SC59:1.
SC60:0.

END
```

```
C
C     SIMNON -
C
C     AN INTERACTIVE SIMULATION PROGRAM
C     FOR NONLINEAR SYSTEMS
C
C     MAIN PROGRAM
C
C     AUTHOR  HILDING ELMQVIST
C     REVISED, C.KALLSTROM 1976-03-24.
C
C     REFERENCE
C     ---------
C
C     H. ELMQVIST: SIMNON - AN INTERACTIVE SIMULATION
C                  PROGRAM FOR NONLINEAR SYSTEMS -
C                  USER'S MANUAL
C
C
C     DATA BASE
C     ---------
C
C     /PSCODE/ IPSEUD( )
C             IPSEUD- PSEUDO CODE AREA
C
C     /VARTAB/ VARS( ),IPNTS( ),ITYPES( )
C             VARS  - IDENTIFIER TABLE
C             IPNTS - ADDRESS TABLE
C             ITYPES- TYPE TABLE
C                     1: TIME
C                     2: STATE
C                     3: INPUT
C                     4: OUTPUT
C                     5: INIT
C                     6: DER
C                     7: NEW
C                     8: TSAMP
C                     9: PAR
C                    10: VAR
C
C     /VALUES/ VALUE( )
C             VALUE - VALUE TABLE AND LITTERAL TABLE
C
C     /SYSINF/ NASYST,ASYSTS( ),IVARS( ,2),INFSYS( ),LENTRY( ,3)
C             NASYST- NUMBER OF ACTIVE SYSTEMS
C             ASYSTS- SYSTEM IDENTIFIERS FOR ACTIVE SYSTEMS
C             IVARS - DEFINING THE POSITION OF THE VARIABLE
C                     TABLE FOR EACH SYSTEM
C             INFSYS- SYSTEM TYPE
C                     1: CONNECTING
C                     2: CONTINUOUS
C                     3: DISCRETE
C                     4: CONTINUOUS (FORTRAN)
C                     5: DISCRETE (FORTRAN)
C             LENTRY- ENTRY POINTS FOR EACH ACTIVE SYSTEM
C                     ( ,1): INITIAL-SECTION
C                            OR THE NUMBER OF A FORTRAN-SYSTEM
C                     ( ,2): OUTPUT- OR CONNECT-SECTION
C                     ( ,3): DYNAMICS-SECTION
C
C     /EXTCOM/ IEVAL,IERR,TYPE,SYSID,NEXTSY,NS
C             IEVAL - POINTER IN VARIABLE TABLE
C             IERR  - ERROR INDICATOR
C             TYPE  - SYSTEM TYPE FROM SUBROUTINE IDENT
```

```
C                 'CONT' OR 'DISCR'
C           SYSID  - SYSTEM IDENTIFIER FROM SUBROUTINE IDENT
C           NEXTSY- NUMBER OF EXTERNAL SYSTEMS
C           NS     - NUMBER OF ELEMENTS IN THE ALLOCATION AREA
C     /ENTRYS/ NTRINT,NTRDER,NTRSMP
C           NTRINT- ENTRY POINT FOR INITIAL COMPUTATIONS
C           NTRDER- ENTRY POINT FOR COMPUTATIONS OF DERIVATIVES
C           NTRSMP- ENTRY POINT FOR SAMPLING
C
C     /ENTRY/ LENTRY
C           LENTRY- ACTUAL ENTRY POINT FOR CALCUL
C
C     /PNTS/ NXC,NXD,KX( ),KDX( ),KXI( ),KTSAMP( )
C           NXC    - NUMBER OF STATES IN CONTINUOUS SYSTEMS
C           NXD    - NUMBER OF STATES IN DISCRETE SYSTEMS
C           KX     - POINTERS TO STATE VARIABLES
C           KDX    - POINTERS TO DER- AND NEW-VARIABLES
C           KXI    - POINTERS TO INIT-VARIABLES
C           KTSAMP- POINTERS TO TSAMP-VARIABLES
C
C     /COMINF/ (SEE INTRAC)
C
C     /MACINF/ (SEE INTRAC)
C
C     /MESSS/ MESS
C           MESS   - MESSAGE INDICATOR
C
C     /SIMN/ NOSYST,OVFLO,IPLCOM,IEXIT,IWARN,ICOMPU,LDARK
C          ,NOCONT,LLPCOM,INIDRA
C           NOSYST- TRUE IF NO SYSTEM DEFINED
C           OVFLO - TRUE IF OVERFLOW CHECK PERFORMED
C           IPLCOM- TRUE IF PLOT-COMMAND SHOULD BE WRITTEN
C           IEXIT - TRUE IF THE EDITOR IS TO MAKE
C                   AUTOMATIC EXIT (SYST)
C           IWARN - TRUE IF WARNINGS SHOULD BE WRITTEN
C           ICOMPU- TRUE IF MESSAGE ABOUT COMPUTATIONS
C                   IN OUTPUT-SECTION SHOULD BE GIVEN
C           LDARK - TRUE IF NOT VISABLE LINES AT SAMPLINGS
C           NOCONT- TRUE IF CONTINUATION OF THE SIMULATION
C                   IS NOT POSSIBLE
C           LLPCOM- TRUE IF COMMANDS SHOULD BE ECHOED ON THE LP
C           INIDRA- TRUE IF INITIALIZATION OF DRAW
C
C     /PLT/ NPLT,IVADR( ),IHADR,PLTCOM( )
C           NPLT   - NUMBER OF PLOT-VARIABLES
C           IVADR  - POINTERS TO VERTICAL VARIABLES
C           IHADR  - POINTER TO HORIZONTAL VARIABLE
C           PLTCOM- BUFFER FOR PLOT-COMMAND
C
C     /STOVAR/ NSTV,IVARS( ),ISYSS( )
C           NSTV   - NUMBER OF VARIABLES TO BE STORED
C           IVARS  - POINTERS TO VARIABLE NAMES
C           ISYSS  - POINTERS TO SYSTEM IDENTIFIERS
C
C     /DATCOM/ FILE,DTF
C           FILE   - STORE FILE NAME
C           DTF    - MINIMAL TIME INCREMENT
C
C     /SHOVAR/ NSHVAR
C           NSHVAR- NUMBER OF SHOWED VARIABLES SINCE AXES
C
C     /AX/ HMIN,DH,VMIN,DV
C           HMIN   - HORIZONTAL MINIMUM
C           DH     - HORIZONTAL VALUE PER CENTIMETER
```

```
C               VMIN   - VERTICAL MINIMUM
C               DV     - VERTICAL VALUE PER CENTIMETER
C
C     /ERRWEI/ EPS,WEIGHT( )
C               EPS    - ERROR BOUND
C               WEIGHT- ERROR WEIGHTS
C
C     /ALG/ IALG
C               IALG   - SPECIFIES INTEGRATION ALGORITHM
C                        1: HAMPC
C                        2: RK
C                        3: RKFIX
C
C     /MARKS/ IMARK,MRK,TMRK,DTMRK
C               IMARK  - TRUE IF MARKS WANTED
C               MRK    - SPECIFIES WHICH MARKS
C               TMRK   - TIME FOR NEXT MARKS
C               DTMRK  - TIME DISTANCE BETWEEN MARKS
C
C     /USER/ LSTOP,LDARK,LCALUS,NRESUM,LFIRST,NOPLOT
C               LSTOP  - TRUE IF SIMULATION SHOULD BE STOPPED
C               LDARK  - TRUE IF DARK LINE
C               LCALUS- TRUE IF THE SUBROUTIEN USRSUB SHOULD BE CALLED
C               NRESUM- NUMBER OF DISCRETE SYSTEMS THAT HASN'T
C                        PRODUCED A DISCONTINUITY
C               LFIRST- TRUE IF SYSTS CALLED FIRST TIMES
C               NOPLOT- IF TRUE NO PLOT
C
C     /DESTIN/ ISYST,IPART
C               ISYST  - SYSTEM NUMBER
C               IPART  - PART NUMBER
C
C     /NSYSTS/ NSYST
C               NSYST  - NUMBER OF EXTERNAL SYSTEMS
C
C     /NALLOC/ NALL
C               NALL   - NUMBER OF ELEMENTS IN THE ALLOCATION AREA
C
C     /TIME/ T
C               T      - THE SIMULATION TIME
C
C     /STATES/ X( )
C               X      - STATES OF CONTINUOUS SYSTEMS
C
C     /DERS/ DX( )
C               DX     - DERIVATIVES OF THE STATES
C
C     /CMPVAR/ MODE,IASYST,ISYTYP,IERR,IVAR1,IVAR2,IVAL1,IVAL2
C               L,LENTR1,LENTR2,LENTR3
C               MODE   - COMPILER MODE
C                        1: SYSTEM HEADING
C                        2:
C                        3: DECLARATIONS
C                        4:
C                        5: INITIAL-SECTION
C                        6: OUTPUT-SECTION
C                        7: DYNAMICS-SECTION
C                        8: CONNECT-SECTION
C                        9: END
C               IASYST- INDEX FOR ACTUAL SYSTEM
C               ISYTYP- SYSTEM TYPE
C                        1: CONNECTING
C                        2: CONTINUOUS
C                        3: DISCRETE
```

```
C                IERR   - ERROR FLAG
C                IVAR1  - INDEX FOR LOWER BOUND IN VARIABLE TABLE
C                IVAR2  - INDEX FOR UPPER BOUND IN VARIABLE TABLE
C                IVAL1  - POINTER IN THE VALUE TABLE
C                IVAL2  - POINTER IN THE LITTERAL TABLE
C                L      - POINTER IN THE PSEUDO CODE AREA
C                LENTR1- POINTER TO INITAL-SECTION
C                LENTR2- POINTER TO OUTPUT- OR CONNECT-SECTION
C                LENTR3- POINTER TO DYNAMICS-SECTION
C
C         /NXPNT/ NXP( ,2)
C                NXP    - SPECIFIES WHICH STATES THAT BELONGS
C                         TO EACH DISCRETE SYSTEM
C
C         /COND/ LSAMP,LSAMPS( )
C                LSAMP  - TRUE IF SAMPLING IS TO BE DONE
C                LSAMPS- SPECIFIES WHICH SYSTEMS THAT IS TO BE SAMPLED
C
C         /LIMITS/ MPSC,MVAR,MVAL,MX
C                MPSC   - NUMBER OF ELEMENTS IN PSEUDO CODE AREA
C                MVAR   - NUMBER OF ELEMENTS IN VARIABLE TABLE
C                MVAL   - NUMBER OF ELEMENTS IN VALUE TABLE
C                MX     - MAXIMUM NUMBER OF STATES
C
C         /SIMARG/ T1,T2,DT,LCONT,LMARK
C                T1-      START TIME
C                T2-      STOP TIME
C                DT-      TIME INCREMENT
C                LCONT-   LOGICAL VARIABLE TO INDICATE IF CONTINUATION
C                         OF SIMULATION IS WANTED
C                LMARK-   LOGICAL VARIABLE INDICATING IF MARKS IS WANTED
C                         DURING THE PLOTTING
C
C         /ARGSAV/ H1,H2,V1,V2
C                H1     - LAST HORIZONTAL MINIMUM (AXES)
C                H2     - LAST HORIZONTAL MAXIMUM
C                V1     - LAST VERTICAL MINIMUM
C                V2     - LAST VERTICAL MAXIMUM
C
C         /AXINF/ IX0,IY0,XAX,YAX
C                IX0,IY0 - ORIGO FOR AXES (TEKPOINTS)
C                XAX,YAX - LENGTH OF AXES (CM)
C
C
C
C        SUBROUTINE REQUIRED
C                ISIMN
C                ESIMN
C                SIMNSY
C                SIMU
C
      COMMON/ALLCOM/IDD(3)
      COMMON /PSCODE/ IDUM1(1500)
      COMMON /VARTAB/ IDUM2(1000),DUM2(500)
      COMMON /VALUES/ DUM3(300)
      COMMON /SYSINF/ IDUM4(151),DUM4(25)
      COMMON /EXTCOM/ IDUM5(4),DUM5(2)
      COMMON /ENTRYS/ IDUM6(3)
      COMMON /ENTRY/  IDUM7
      COMMON /PNTS/   IDUM8(177)
      COMMON /COMINF/ IDUM9(33),DUM9(41)
      COMMON /MACINF/ IDUM10(191),DUM10(107)
      COMMON /MESSS/  IDUM11
```

```
      COMMON /SIMN/    IDUM12(10)
      COMMON /PLT/     IDUM13(12),DUM13(16)
      COMMON /STUVAR/ IDU135(101)
      COMMON /DATCOM/ DUM136(2)
      COMMON /SHUVAR/ IDU137
C ***** HCOPY *****
      COMMON/HCPCOM/DUM138(10),IDU138(30)
C ***** HCOPY *****
      COMMON /AX/      DUM14(4)
      COMMON /ERRWEI/ DUM15(51)
      COMMON /ALG/     IDUM16
      COMMON /MARKS/   IDUM17(2),DUM17(2)
      COMMON /USER/    IDUM18(6)
      COMMON /DESTIN/ IDUM19(2)
      COMMON /NSYSTS/ IDM191
      COMMON /NALLOC/ IDM192
      COMMON /TIME/    DUM20
      COMMON /STATES/ DUM21(50)
      COMMON /DERS/    DUM211(50)
      COMMON /CMPVAR/ IDUM23(12)
      COMMON /NXPNT/   IDUM24(50)
      COMMON /COND/    IDUM25(26)
      COMMON /LIMITS/ MPSC,IDM261,MVAL,MX
      COMMON /SIMARG/ IDUM26(2),DUM26(3)
      COMMON /ARGSAV/ DUM0(4)
      COMMON /AXINF/ IDUM27(2),DUM27(2)
C
C
      MPSC=1500
      MVAL=300
      MX=20
      CALL LOGG(0)
      CALL LPHDL(0)
C
      CALL ISIMN
C
      MODE=1
 10   CALL ESIMN(MODE)
C
      GOTO(1,2,3,4),MODE
C
 1    CALL LPHDL(1)
      CALL LOGG(1)
      STOP
C
 2    CALL SIMNSY
      GO TO 10
C
 3    CALL SIMU
      GO TO 10
C
 4    CALL LPHDL(2)
          CALL LOGG(2)
      STOP
      END
```

```
      SUBROUTINE SYSTS
C
C     AUTHOR, C.KALLSTROM 1976-03-24.
C
      DIMENSION S(88)
      COMMON/DESTIN/ISYST,IDUM
      COMMON/NSYSTS/NSYST
      COMMON/NALLOC/NS
      COMMON/SAVEAR/IS(9)
C
      NSYST=2
      NS=88
C
      GO TO (1,2),ISYST
C
 1    CALL SNOISE('NOIS1',IS(1),S)
      RETURN
2     CALL AUT
      RETURN
      END
```

```
      SUBROUTINE AUT
C
C     SYSTEM DEFINITION OF AN AUTOPILOT FOR SHIP.
C
C     AUTHOR, C.KALLSTROM 1976-03-18.
C     REVISED, C.KALLSTROM 1976-04-01.
C
C     SUBROUTINE REQUIRED
C        AUTP3
C           STUR
C        IDENT
C        INPUT
C        OUTPUT
C        TSAMP
C        PAR
C        PARV
C        VAR
C        VARV
C
      DIMENSION AMSO(4),AMEAS(4),AMSUM(4),SC(34),PPD(10)
C
      COMMON /DESTIN/ IDUM,IPART
C
      COMMON /TIME/ T
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),DELTAO,D1,D2,D3,TH(10),
     *   CGR,CKM,PI,PI2,AL,AL1,A11,A12,A14,A15,A21,A22,A24,A25,
     *   A31,A32,A34,A35,A44,A45,B11,B21,B31,B41,AKK(32),
     *   TEST(4),BB,PVO,RLV,AKVO,VCONST,VMIN,VMAX,VO,THO(10),
     *   PPC(10),RL,BO,Q2,AK1,AK2,AK3,PSIMX1,PSIMX2,PSIMX3,
     *   EPS1Y,EPS2Y,EPS3Y,C1Y,C2Y,C3Y,AK1Y,AK2Y,AK3Y,AK4Y,
     *   AK5Y,AK6Y,AK7Y,AK8Y,BD,BV,ALAM,DELAMP,PSIO,AKID,
     *   IREGK,IKAL,IKMX,IMX,IVVC,IVV,IREGV,IAKV,ILOS,IREGYT,IREG,IPID,
     *   IST,NA,NB,NC1,NC2,K,IREGY,IYAW,IT1Y,IT3Y,IT4Y,IPK,IPC,IPR,
     *   EPS(4),VV,PV,PP(55),EPSI1(2),EDEL(2),VLOS1(2),
     *   ENM1(2),CN,EDELTA,EPSI2,VLOS2,ENM2,
     *   MEASUM(4),IVV1,
     *   X(8),PS(4),DD(3),DDOLD,VVV(4),VV2,VOV,VOV2,AKV,
     *   PF01,PF02,DELOLD,VOLD,ROLD,DAT(46),SINT,RRF,AINT2,
     *   AINT4,STD,STV,SL1,SL2,SL3,SL4,SL5,DUM(10),
     *   IRK,IREV,IMEAS(4),IRYT,IR,NC,NAB,NP,K1,NDAT,NDAT1,
     *   NU1,N1,IRY,ITIM1,ITIM3,ITIM4,IP,I,J,L
C
      GO TO (100,200,300,400,500,600,700,800) , IPART
C
C
100   CALL IDENT('DISCR','AUT')
C
      RETURN
C
C
200   CALL INPUT(DELM,'DELM')
      CALL INPUT(DELTA(1),'DELTA')
      CALL INPUT(V1(1),'V1')
      CALL INPUT(R(1),'R')
      CALL INPUT(PSIM,'PSIM')
      CALL INPUT(PSII,'PSI')
      CALL INPUT(U,'U')
      CALL INPUT(AN,'AN')
C
```

```
      CALL OUTPUT(DELCO,'DELCO')
C
      CALL TSAMP(TS,'TS')
C
      CALL PAR(DT,'DT')
      CALL PAR(PREF1,'PREF1')
      CALL PAR(PREF2,'PREF2')
      CALL PAR(R0,'R0')
      CALL PAR(T0,'T0')
      CALL PAR(DLIM,'DLIM')
      CALL PAR(BB,'BB')
      CALL PAR(PV0,'PV0')
      CALL PAR(RLV,'RLV')
      CALL PAR(AKV0,'AKV0')
      CALL PAR(VCONST,'VCONS')
      CALL PAR(VMIN,'VMIN')
      CALL PAR(VMAX,'VMAX')
      CALL PAR(V0,'V0')
      CALL PAR(RL,'RL')
      CALL PAR(B0,'B0')
      CALL PAR(Q2,'Q2')
      CALL PAR(AK1,'AK1')
      CALL PAR(AK2,'AK2')
      CALL PAR(AK3,'AK3')
      CALL PAR(PSIMX1,'PSIX1')
      CALL PAR(PSIMX2,'PSIX2')
      CALL PAR(PSIMX3,'PSIX3')
      CALL PAR(EPS1Y,'EPS1Y')
      CALL PAR(EPS2Y,'EPS2Y')
      CALL PAR(EPS3Y,'EPS3Y')
      CALL PAR(C1Y,'C1Y')
      CALL PAR(C2Y,'C2Y')
      CALL PAR(C3Y,'C3Y')
      CALL PAR(AK1Y,'AK1Y')
      CALL PAR(AK2Y,'AK2Y')
      CALL PAR(AK3Y,'AK3Y')
      CALL PAR(AK4Y,'AK4Y')
      CALL PAR(AK5Y,'AK5Y')
      CALL PAR(AK6Y,'AK6Y')
      CALL PAR(AK7Y,'AK7Y')
      CALL PAR(AK8Y,'AK8Y')
      CALL PAR(BD,'BD')
      CALL PAR(BV,'BV')
      CALL PAR(ALAM,'ALAM')
      CALL PAR(AIREGK,'IREGK')
      CALL PAR(AIKAL,'IKAL')
      CALL PAR(AIKMX,'IKMX')
      CALL PAR(AIMX,'IMX')
      CALL PAR(AIVVC,'IVVC')
      CALL PAR(AIVV,'IVV')
      CALL PAR(AIREGV,'IREGV')
      CALL PAR(AIAKV,'IAKV')
      CALL PAR(AIRYT,'IRYT')
      CALL PAR(AIREG,'IREG')
      CALL PAR(AIPID,'IPID')
      CALL PAR(AIST,'IST')
      CALL PAR(ANA,'NA')
      CALL PAR(ANB,'NB')
      CALL PAR(ANC1,'NC1')
      CALL PAR(ANC2,'NC2')
      CALL PAR(AK,'K')
      CALL PAR(AIREGY,'IREGY')
      CALL PAR(AIYAW,'IYAW')
      CALL PAR(AIT1Y,'IT1Y')
```

```
      CALL PAR(AIT3Y,'IT3Y')
      CALL PAR(AIT4Y,'IT4Y')
      CALL PAR(AILO,'ILO')
C
      CALL PARV(AMSO,4,'MSO')
      CALL PARV(AKK,32,'AKK')
      CALL PARV(TEST,4,'TEST')
      CALL PARV(THO,10,'THO')
      CALL PARV(PPO,10,'PPO')
      CALL PARV(SC,34,'SC')
C
      CALL VAR(DELCS,'DELCS')
      CALL VAR(DELES,'DELES')
      CALL VAR(VCS,'VCS')
      CALL VAR(VES,'VES')
      CALL VAR(V1ES,'V1ES')
      CALL VAR(RES,'RES')
      CALL VAR(PSIES,'PSIES')
      CALL VAR(PREFS,'PREFS')
      CALL VAR(RREFS,'RREFS')
      CALL VAR(VESTS,'VESTS')
      CALL VAR(VVS,'VVS')
      CALL VAR(D0ES,'D0ES')
      CALL VAR(D1ES,'D1ES')
      CALL VAR(D2ES,'D2ES')
      CALL VAR(D3ES,'D3ES')
      CALL VAR(AMODS,'MODY')
      CALL VAR(EDELS,'EDELS')
      CALL VAR(PV,'PV')
      CALL VAR(CN,'CN')
      CALL VAR(EPSI2,'EPSI2')
      CALL VAR(VLOS2,'VLOS2')
      CALL VAR(ENM2,'ENM2')
      CALL VAR(AIVV1,'IVV1')
      CALL VAR(EPSIM,'EPSIM')
      CALL VAR(SPSIM,'SPSIM')
      CALL VAR(EDELT,'EDELT')
      CALL VAR(SDELT,'SDELT')
      CALL VAR(ENM,'ENM')
      CALL VAR(VL1,'VL1')
      CALL VAR(VL2,'VL2')
      CALL VAR(FLL,'FLL')
C
      CALL VARV(AMEAS,4,'MEAS')
      CALL VARV(TH,10,'TH')
      CALL VARV(EPS,4,'EPS')
      CALL VARV(PPD,10,'PPD')
      CALL VARV(EPSI1,2,'EPI1')
      CALL VARV(EDEL,2,'EDEL')
      CALL VARV(VLOS1,2,'VLS1')
      CALL VARV(ENM1,2,'ENM1')
      CALL VARV(AMSUM,4,'MSUM')
C
      RETURN
C
C
300   DT=1.
      PREF1=0.
      PREF2=45.
      RC=0.1
      TC=100000.
      DLIM=35.
      RB=0.806
      PV0=1.
```

```
      RLV=0.995
      AKV0=100.
      VCONST=6.
      VMIN=0.2
      VMAX=12.
      V0=8.
      RL=0.99
      B0=1.
      Q2=0.
      AK1=5.
      AK2=200.
      AK3=0.005
      PSIMX1=0.35
      PSIMX2=2.5
      PSIMX3=2.5
      EPS1Y=0.
      EPS2Y=0.02
      EPS3Y=1.
      C1Y=60.
      C2Y=50.
      C3Y=60.
      AK1Y=5.
      AK2Y=200.
      AK3Y=0.005
      AK4Y=200.
      AK5Y=200.
      AK6Y=8.
      AK7Y=2.
      AK8Y=200.
      BD=0.05
      BV=0.05
      ALAM=0.0833333
      AIREGK=1.
      AIKAL=1.
      AIKMX=300.
      AIMX=10.
      AIVVC=1.
      AIVV=2.
      AIREGV=5.
      AIAKV=0.
      AIRYT=5.
      AIREG=15.
      AIPID=0.
      AIST=2.
      ANA=4.
      ANB=2.
      ANC1=1.
      ANC2=1.
      AK=5.
      AIREGY=10.
      AIYAW=2.
      AIT1Y=30.
      AIT3Y=100.
      AIT4Y=300.
      AIL0=1201.
      DO 302 I=1,4
302   AMS0(I)=0.
      AKK(1)=-1.054E-4
      AKK(2)=5.367E-4
      AKK(3)=1.173E-5
      AKK(4)=1.603E-2
      AKK(5)=-2.172E-5
      AKK(6)=-7.649E-5
      AKK(7)=-2.793E-6
```

```
      AKK(8)=2.542E-3
      AKK(9)=0.2332
      AKK(10)=0.3541
      AKK(11)=4.458E-3
      AKK(12)=9.306E-5
      AKK(13)=-1.173E-5
      AKK(14)=7.462E-3
      AKK(15)=-9.884E-4
      AKK(16)=1.360E-6
      AKK(17)=-3.960E-2
      AKK(18)=0.1157
      AKK(19)=3.849E-3
      AKK(20)=1.717E-3
      AKK(21)=-1.692E-3
      AKK(22)=9.062E-4
      AKK(23)=2.932E-3
      AKK(24)=2.507E-6
      AKK(25)=-0.5298
      AKK(26)=1.237
      AKK(27)=0.3351
      AKK(28)=1.843E-2
      AKK(29)=-1.827E-2
      AKK(30)=9.269E-3
      AKK(31)=-5.871E-2
      AKK(32)=2.599E-5
      TEST(1)=0.0070
      TEST(2)=0.0084
      TEST(3)=0.033
      TEST(4)=0.0022
      THO(1)=10.6
      THO(2)=-12.9
      THO(3)=3.4
      THO(4)=0.
      THO(5)=0.45
      THO(6)=0.30
      THO(7)=-5.3
      THO(8)=42.8
      THO(9)=0.
      THO(10)=0.
      PPO(1)=1000.
      PPO(2)=1000.
      PPO(3)=1000.
      PPO(4)=1000.
      PPO(5)=1.
      PPO(6)=1.
      PPO(7)=1000.
      PPO(8)=1000.
      PPO(9)=0.
      PPO(10)=0.
      DO 310 I=1,33,2
      SC(I)=1.
310   SC(I+1)=0.
C
      RETURN
C
C
400   TS=T
      IREGK=AIREGK+0.1
      IKAL=AIKAL+0.1
      IKMX=AIKMX+0.1
      IMX=AIMX+0.1
      IVVC=AIVVC+0.1
      IVV=AIVV+0.1
      IREGV=AIREGV+0.1
```

```
      IARV=AIARV+0.1
      IREGYT=AIRYT+0.1
      IREG=AIREG+0.1
      IPID=AIPID+0.1
      IST=AIST+0.1
      NA=ANA+0.1
      NB=ANB+0.1
      NC1=ANC1+0.1
      NC2=ANC2+0.1
      K=AK+0.1
      IREGY=AIREGY+0.1
      IYAW=AIYAW+0.1
      IT1Y=AIT1Y+0.1
      IT3Y=AIT3Y+0.1
      IT4Y=AIT4Y+0.1
      ILO=AILO+0.1
      DO 410 I=1,4
410   MEAS(I)=AMSU(I)+0.1
C
      ITIME=-1
      IDEXP=0
      INAUT=1
      TO1=TO-0.01
      FLL=0.
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      SUM5=0.
      CGR=0.0174533
      CKM=0.514444
      PI=3.141593
      PI2=6.283185
      AL=350.
      AL1=164.35
      A11=0.99163
      A12=-0.0100810
      A14=-0.00208207
      A15=0.000212358
      A21=-0.0759537
      A22=0.96485
      A24=0.0164706
      A25=-0.00170991
      A31=-0.000874514
      A32=0.0224515
      A34=0.000195418
      A35=-0.0000132723
      A44=0.81873
      A45=-0.18127
      B11=-0.000212358
      B21=0.00170991
      B31=0.0000132723
      B41=0.18127
      ILOS=1
      IPK=0
      IPC=1
      IPR=0
C
      RETURN
C
C
500   ITIME=ITIME+1
      PSI(1)=PSII
      IF(PSII .LT. 0.) PSI(1)=PSII+360.
```

```
      P=0.341860*AN
      PREF=PREF1
      IF(T .GE. T01) PREF=PREF2
      PSIREF=PREF
      IF(PSIREF .LT. 0.) PSIREF=PSIREF+360.
      RREF=0.
      IF(T .GE. T01) RREF=R0
C
      CALL AUTP3
C
      PSIE=PSI(2)
      IF(PSIE .GT. 180.) PSIE=PSIE-360.
      DO 508 I=1,10
      L=I*(I+1)/2
508   PPD(I)=PP(L)
      IF(ILO) 516,510,510
510   IF(ITIME-ILO) 514,512,514
C
512   FLL=0.
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      SUM5=0.
C
514   FLL=FLL+1.
      SL1=PSIM-PREF
      IF(SL1 .LE. -180.) SL1=SL1+360.
      IF(SL1 .GT. 180.) SL1=SL1-360.
      SUM1=SUM1+SL1
      SUM2=SUM2+SL1*SL1
      SUM3=SUM3+DELM
      SUM4=SUM4+DELM*DELM
      SUM5=SUM5+P/(CKM*U*COS(CGR*SL1))
C
516   DELCS=SC(1)*DELCO+SC(2)
      DELES=SC(3)*DELTA(2)+SC(4)
      VCS=SC(5)*V(1)+SC(6)
      VES=SC(7)*V(2)+SC(8)
      V1ES=SC(9)*V1(2)+SC(10)
      RES=SC(11)*R(2)+SC(12)
      PSIES=SC(13)*PSIE+SC(14)
      PREFS=SC(15)*PREF+SC(16)
      RREFS=SC(17)*RREF+SC(18)
      VESTS=SC(19)*VEST+SC(20)
      VVS=SC(21)*VV/CKM+SC(22)
      D0ES=SC(23)*DELTA0+SC(24)
      D1ES=SC(25)*D1+SC(26)
      D2ES=SC(27)*D2+SC(28)
      D3ES=SC(29)*D3+SC(30)
      AMODS=SC(31)*FLOAT(MODYAW)+SC(32)
      EDELS=SC(33)*EDELTA+SC(34)
C
      DO 520 I=1,4
      AMEAS(I)=MEAS(I)
520   AMSUM(I)=MEASUM(I)
      AIVV1=IVV1
C
      RETURN
C
C
600   TS=T+DT
      RETURN
C
```

```
C
700   RETURN
C
C
800   EPSIM=SUM1/FLL
      VPSIM=SUM2/FLL-EPSIM*EPSIM
      SPSIM=-1.
      IF(VPSIM .GE. 0.) SPSIM=SQRT(VPSIM)
      EDELT=SUM3/FLL
      VDELT=SUM4/FLL-EDELT*EDELT
      SDELT=-1.
      IF(VDELT .GE. 0.) SDELT=SQRT(VDELT)
      ENM=SUM5/FLL
      VL2=SUM2/FLL+ALAM*VDELT
      VL1=VL2+ALAM*EDELT*EDELT
C
      RETURN
C
C
      END
```

```
      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 1976-04-01.
C
C     SUBROUTINE REQUIRED
C          STUR
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),DELTAO,D1,D2,D3,TH(10),
     *   CGR,CKM,PI,PI2,AL,AL1,A11,A12,A14,A15,A21,A22,A24,A25,
     *   A31,A32,A34,A35,A44,A45,B11,B21,B31,B41,AK(8,4),
     *   TEST(4),BB,PVO,RLV,AKVO,VCONST,VMIN,VMAX,VO,THO(10),
     *   PPO(10),RL,BO,Q2,AK1,AK2,AK3,PSIMX1,PSIMX2,PSIMX3,
     *   EPS1Y,EPS2Y,EPS3Y,C1Y,C2Y,C3Y,AK1Y,AK2Y,AK3Y,AK4Y,
     *   AK5Y,AK6Y,AK7Y,AK8Y,BD,BV,ALAM,DELAMP,PSIO,AKID,
     *   IREGK,IKAL,IKMX,IMX,IVVC,IVV,IREGV,IAKV,ILOS,IREGYT,IREG,IPID,
     *   IST,NA,NB,NC1,NC2,K,IREGY,IYAW,IT1Y,IT3Y,IT4Y,IPK,IPC,IPR,
     *   EPS(4),VV,PV,PP(55),EPSI1(2),EDEL(2),VLOS1(2),
     *   ENM1(2),CN,EDELTA,EPSI2,VLOS2,ENM2,
     *   MEASUM(4),IVV1,
     *   X(8),PS(4),DD(3),DDOLD,VVV(4),VV2,VOV,VOV2,AKV,
     *   PFO1,PFO2,DELOLD,VOLD,ROLD,DAT(46),SINT,RRF,AINT2,
     *   AINT4,STD,STV,SL1,SL2,SL3,SL4,SL5,DUM(10),
     *   IRK,IREV,IMEAS(4),IRYT,IR,NC,NAB,NP,K1,NDAT,NDAT1,
     *   NU1,N1,IKY,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
      VV2=VVV(1)*VVV(1)
      VEST=U
      VVV(2)=VVV(1)
      VVV(3)=AN*0.18*CKM
      VVV(4)=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)
      VOV=VO/VV
      VOV2=VOV*VOV
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)*CGR/VV
      GO TO 36
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    DDOLD=0.
      PS(1)=PSI(1)
      PS(2)=PSI(1)
      PS(3)=PSI(1)
      PS(4)=PSI(1)
      DD(1)=0.
      DD(2)=0.
      DD(3)=0.
      PV=PV0
      IREV=IREGV
C
      IRYT=IREGYT
      PFOT=PSI(1)
      NODYAW=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)=THO(I)
        EDELTA=0.
        STD=1.-8D
        EPSI2=0.
        VLOS2=0.
        ENM2=0.
        STV=1.-8V
        ISTBD=0
        IPORT=0
        IP=IPR
        IMAUT=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*DELCOF
        SL1=A11*X(1)+A12*X(2)+A14*X(4)+A15*X(5)+B11*SL5
        SL2=A21*X(1)+A22*X(2)+A24*X(4)+A25*X(5)+B21*SL5
        SL3=A31*X(1)+A32*X(2)+X(3)+A34*X(4)+A35*X(5)+B31*SL5
        SL4=A44*X(4)+A45*X(5)+B41*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
       DELTAD=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    IF(IREGV) 160,160,141
141    IF(IREV-IREGV) 156,142,160
C
142    IREV=1
       PS(1)=PSI(IVV)
       DD(1)=DELTA(IVV)-DDOLD
       DDOLD=DELTA(IVV)
       SL1=FLOAT(IREGK*IREGV)
       SL2=BB*SL1*SL1*DD(2)/(AL*AL)
       SL3=1.+PV*SL2*SL2
       AKV=PV*SL2/SL3
       SL4=PS(1)-PS(4)
       IF(SL4 .LE. -180.) SL4=SL4+360.
       IF(SL4 .GT. 180.) SL4=SL4-360.
       SL5=PS(3)-PS(2)
       IF(SL5 .LE. -180.) SL5=SL5+360.
       IF(SL5 .GT. 180.) SL5=SL5-360.
       SL1=AKV
       IF(IAKV .GT. 0) SL1=AKV0
       VV2=VV2+SL1*(SL4+3.*SL5-SL2*VV2)
       PV=(PV-AKV*AKV*SL3)/RLV
       PS(4)=PS(3)
       PS(3)=PS(2)
       PS(2)=PS(1)
       DD(2)=DD(1)
C
       IF(VV2) 144,143,143
143    VVV(1)=SQRT(VV2)
       GO TO 146
144    VVV(1)=-1.
146    VEST=VVV(1)/CKM
       VVV(2)=U*CKM
       VVV(3)=AN*0.18*CKM
       VVV(4)=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)
       VLV=V0/VV
       VUV2=VUV*VUV
       GO TO 160
C
156    IREV=IREV+1
C
```

```
C       COMPUTE THE LOSS FUNCTIONS.
C
160     IF(ILOS) 170,166,162
162     ILOS=0
        CN=0.
        DO 164 I=1,2
        EPSI1(I)=0.
        EDEL(I)=0.
        VLOS1(I)=0.
164     ENM1(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.
        EPSI1(I)=SL1*EPSI1(I)+SL2/CN
        EDEL(I)=SL1*EDEL(I)+DELTA(I)/CN
        VLOS1(I)=SL1*VLOS1(I)+(SL2*SL2+ALAM*(DELTA(I)-EDEL(I))*
       *    (DELTA(I)-EDEL(I)))/CN
168     ENM1(I)=SL1*ENM1(I)+P/(CKM*U*COS(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)-PSIMX1) 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)-PSIMX3) 320,320,306
306     IF(MODYAW-2) 314,314,308
308     MODYAW=1
309     IF(SL2) 310,310,312
310     RRF=RREF
```

```
      GO TO 320
312   RRF=-RREF
      GO TO 320
314   IF(RRF) 316,315,318
316   IF(SL2) 306,320,320
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)-PSIMX2) 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. -EPS1Y) GO TO 330
      IF(RRF .LT. 0. .AND. SL3 .LT. EPS1Y) GO TO 330
      IF(ITIM1-IT1Y) 332,332,330
C
330   MODYAW=2
      AINT2=0.
332   IF(RRF .GE. 0. .AND. -C2Y*R(IYAW) .LT. SL2) GO TO 334
      IF(RRF .LT. 0. .AND. -C2Y*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. EPS2Y) GO TO 338
      IF(RRF .GE. 0. .AND. SL2 .GT. -EPS3Y) GO TO 338
      IF(RRF .LT. 0. .AND. SL2 .LT. EPS3Y) 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=AK4Y*SL3
      SL5=ABS(C1Y*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*(AK5Y*SL3+AK6Y*AINT2)+EDELTA
      AINT2=AINT2+SL3*FLOAT(IREGY)
      GO TO 380
C
C     YAW PHASE 3.
C
360   SL4=AK7Y*SL2+AK8Y*R(IYAW)
      SL5=ABS(C3Y*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*(AK1Y*SL2+AK2Y*R(IYAW)+AK3Y*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)=BO*(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*COS(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)-PSIO
      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         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-TM(I)*DAT(L)
C
         DO 32 I=2,NDAT
         L=NDAT1-I
32       DAT(L+1)=DAT(L)
         DAT(NU1)=R
C
         RETURN
         END
```