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MOORING MOTION

by

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TECHNICAL REPORT

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Mooring Motion

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Introduction:

Mooring motion is the change in the equilibrium position of a moored buoy in response to a change in the direction and speed of the current flowing past the mooring. The motion has a maximum amplitude near the surface and decreases to zero at the bottom. Current measurements are made relative to the mooring so that mooring motion is present as an extraneous signal in the measurements.

The motion is particularly pronounced if the current contains a rotary component exceeding the mean current. The mooring is swept through an irregular orbit with the frequency of the rotary component at speeds that may attain a significant fraction of the measured speeds. Because the mooring tends to move with the current, the amplitude of the rotary component can be considerably attenuated in the relative flow past the mooring. Furthermore, the measured currents at depth can be contaminated with spurious indications of rotary flow by the motion. Because the displacement of a mooring is approximately proportional to the horizontal drag - a nonlinear function of speed - harmonics and intermodulation frequencies are generated in the recorded velocities.

As the presence of mooring motion degrades the quality of the measured currents, the magnitude of the motion has to be estimated to determine the conditions under which it is not negligible. A knowledge of the mechanics of the motion can also provide techniques for minimizing its effects in the measured currents.

Although it is possible to estimate numerically the motion for a given mooring configuration and current profile, the difficulty of specifying the profile continuously in time from measurements at discrete depths and the uncertainty of drag calculations make it desirable to obtain an independent measure of the motion to evaluate the numerical model. It was decided to conduct mooring motion experiments at sea. In November, 1963, a preliminary attempt to detect the motion was conducted from Bermuda using two tracking azimuth telescopes on a three-mile baseline. The telescopes are located about 200 feet above sea level and eight-foot toroidal surface floats could be seen up to 17 miles away under the best conditions. The trial indicated that the floats could be tracked easily during darkness and throughout most of the daylight hours. Tracking was difficult during daylight when the flashing beacons on the floats could not be seen. A slight haze was sufficient to obliterate the buoy from view at 10 miles.

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A more extensive series of measurements were carried out in May, 1964 over a period of one week (Table 1). Two surface floats were tracked for six days. The moorings were instrumented to measure surface wind, currents and cable tension. In addition, three moorings with subsurface floats were set during the same period to measure spatial variation of the velocity field.

The data collected fell short of expectations because of losses to "fishbite" and instrument malfunction so that some of the planned objectives were not attained. However, sufficient measurements were collected to describe several significant aspects of mooring motion.

A Simple Theoretical Model

In deep water, the major contribution to the horizontal drag on a mooring occurs in the upper 10 to 20% of the water column where currents are usually strongest. To a first approximation, the horizontal drag can be represented by a lumped force acting on the mooring float itself. Actually most of the drag is contributed by the upper section of the mooring cable but the motion is not changed significantly in character by assuming the drag force to be concentrated at the float. The resultant simplification of the mooring motion equations makes this assumption extremely useful as a starting point in the analysis. The model can be generalized without difficulty to a multi-level model corresponding to the number of current meters suspended on the mooring. The advantage of the single-level model is that several explicit analytical solutions can be obtained to develop a familiarity with the response characteristics of the mooring.

The drag force F acting on the cross section A of the mooring is estimated from the empirical drag law

$$F = 1/2\ \rho C_D A v^2$$

where ρ is water density (1 gm/cm^3), C_D drag coefficient and v the horizontal speed of flow past the mooring. For explicit calculations, the cross sectional area is calculated from the upper third of the mooring.

For a mooring of length L and cable tension T, the restoring force for small displacements r is given by

$$Tr/L \quad \text{for} \quad r \ll L$$

In equilibrium, the restoring force must equal the drag force so that

$$Tr/L = 1/2\ \rho C_D A v^2$$

or

$$r = \frac{\frac{1}{2}\rho C_D A L}{T} v^2 = K v^2$$

where $K = 1/2\ \rho C_D AL/T$ is a measure of mooring compliance. The displacement is in the direction of the current.

In a changing current, the drag is a function of the relative speed between the mooring and the water, so that the displacement is in the direction of the relative current. It is assumed that the inertia of the mooring is negligible so that equilibrium between the drag and restoring forces holds at all times.

If the float position with respect to a horizontal coordinate system is given by x , y and the current components by u , v , the relative velocity components are

$$u_r = u - \frac{dx}{dt}, \qquad v_r = v - \frac{dy}{dt}$$

The displacement r is equal to $(x^2 + y^2)^{\frac{1}{2}}$ and the displacement components are

$$x = r\, u_r/(u_r^2 + v_r^2)^{\frac{1}{2}}$$

$$y = r\, v_r/(u_r^2 + v_r^2)^{\frac{1}{2}}$$

where

$$r = K\,(u_r^2 + v_r^2) \quad .$$

Hence, by substitution

$$x = (Kr)^{\frac{1}{2}} u_r = (Kr)^{\frac{1}{2}} (u - \frac{dx}{dt})$$

$$y = (Kr)^{\frac{1}{2}} v_r = (Kr)^{\frac{1}{2}} (v - \frac{dy}{dt})$$

These equations yield the mooring response equations

$$\frac{dx}{dt} = u - x/(Kr)^{\frac{1}{2}}$$

$$\frac{dy}{dt} = v - y/(Kr)^{\frac{1}{2}}$$

where u , v are assumed to be known functions of time.

The mooring response equations can be solved explicitly in three important cases. These correspond to a step increase in speed, and a uniformly rotating velocity vector of constant magnitude.

Case I

Assume $x = y = 0$, $u = u_o$, $v = 0$ at $t = 0$
This case corresponds to a step increase in speed at $t = 0$.

The appropriate equation is

$$\frac{dx}{dt} = u_o - (\frac{x}{K})^{\frac{1}{2}}$$

The solution, in implicit form, is

$$t = -2Ku_o \left\{ \ln[1 - (x/Ku_o^2)^{\frac{1}{2}}] - (x/Ku_o^2)^{\frac{1}{2}} \right\}$$

The asymptotic behavior is

$$x \to Ku_o^2 \quad \text{as} \quad t \to \infty .$$

Case II

Assume $x = Ku_o^2$, $y = 0$, $u = v = 0$ at $t = 0$.

This case corresponds to a step decrease in speed at $t = 0$. The appropriate equation is

$$\frac{dx}{dt} = -(x/K)^{\frac{1}{2}}$$

The solution is

$$x = Ku_o^2 (1 - \frac{t}{2Ku_o})^2 , \quad 0 \le t < 2Ku_o$$

$$= 0 \quad , \quad t > 2Ku_o$$

In both cases, the displacement scale (characteristic displacement) is Ku_o^2 , and the time scale is $2Ku_o$. Thus, the compliance constant K is useful in estimating both the time constant and displacement of a mooring to describe its performance. Sample calculations for K are given in Table 2. The compliance constant provides an extremely simple comparative description of the response of different mooring configurations.

Cases I and II are combined in Figure 1 to show the response to a current in the form of a step function. The mooring displacement, speed and relative current are shown to illustrate the effects of the motion.

Case III

Assume $u = u_o \cos \omega t$, $v = u_o \sin \omega t$

This case corresponds to a uniformly rotating current of magnitude u_o .

The rotation period is $2\pi/\omega$.

The mooring is assumed to move through a circular orbit of radius r such that

$$x = r \cos \theta$$

$$y = r \sin \theta$$

where θ is the displacement angle measured from the x axis.

Substitution into the response equations yields

$$- r\theta \sin \theta = u_o \cos \omega t - (r/K)^{\frac{1}{2}} \cos \theta$$

$$r\theta \cos \theta = u_o \sin \omega t - (r/K)^{\frac{1}{2}} \sin \theta$$

Rearranging terms

$$\cos \omega t = \left(\frac{r}{Ku_o^2}\right)^{\frac{1}{2}} \cos \theta - \frac{r\theta}{u_o} \sin \theta = \cos(\theta+\lambda)$$

$$\sin \omega t = \left(\frac{r}{Ku_o^2}\right)^{\frac{1}{2}} \sin \theta + \frac{r\dot{\theta}}{u_o} \cos \theta = \sin(\theta+\lambda)$$

These equations require

$$r = K(u_o^2 - r^2\theta^2) = K(u_o^2 - r^2\omega^2)$$

$$\dot{\theta} = \omega$$

$$\tan \lambda = \omega\sqrt{Kr} .$$

The radius of the displacement circle is

$$r = [(4K^2u_o^2\omega^2 + 1)^{\frac{1}{2}} - 1]/2K\omega^2$$

$$\simeq u_o/\omega \quad \text{for } \omega >> \tfrac{1}{2} Ku_o$$

$$\simeq Ku_o^2 \quad \text{for } \omega << \tfrac{1}{2} Ku_o$$

For rapid rotation, the mooring tends to be advected by the flow ($r\omega = u_o$) so that the relative current is small. For slow rotation, the mooring is near the equilibrium position for a steady current and its motion does not affect the relative current appreciably. The ratio of magnitudes of the relative current to the absolute current is

$$(u_r^2 + v_r^2)^{\frac{1}{2}}/u_o = (r/Ku_o^2)^{\frac{1}{2}} = (u_o^2 - r^2 \;\; ^2)^{\frac{1}{2}}/u_o$$

$$\simeq (1 - (\omega/\omega_o)^2)^{\frac{1}{2}} \text{ for } \omega \ll \omega_o = 1/Ku_o$$

$$\simeq (\omega_o/\omega)^{\frac{1}{2}} \text{ for } \omega \gg \omega_o$$

For subsurface moorings of the type used at WHOI, the time constant Ku_o is about 10 minutes in a 1 knot current. The period, corresponding to ω_o, is $2\pi Ku_o \sim 1$ hour. The attenuation of rotary currents of tidal or inertial period (>12 hours) is less than 2%. Because the mooring motion is nearly at right angles to the current at low frequencies, the contribution to the speed is a small second-order effect.

The relative direction of flow differs from the true direction at low frequencies,

$$\tan \lambda \sim \omega/\omega_o \sim 0.1 \quad \text{for tidal period}$$

so that

$$\lambda \sim 5^\circ .$$

The relative current direction lags behind the absolute current direction.

Launching Transient

Subsurface float moorings are launched buoy first and anchor last. As the anchor drops, the mooring is gradually pulled under toward a vertical position. The anchor reaches bottom while the mooring is still inclined as much as 15° from the vertical. Because of the tilt, the subsurface float exceeds its equilibrium depth. The subsequent recovery toward the vertical is governed by a balance of drag and restoring forces similar to the transient considered in Case II. The transient can be followed by measuring the pressure at the subsurface float. A pressure record from mooring 161 set near Bermuda is shown in Figure 2 . The overshoot of the float is relatively small (15.6 m).

In the absence of strong currents, the mooring response is similar to the example considered in Case II. To the same approximation used in the response equations, the pressure increase, due to the initial dip of the subsurface float, is given by

$$\Delta P = P - P\ eq. = \tfrac{1}{2}\rho g\ r^2/L$$

where $P\ eq$ is the final equilibrium pressure and g is gravity.

Assuming negligible current, the change of pressure with time, found by substituting the transient solution for r , is

$$\Delta P = \tfrac{1}{2}\rho g \frac{R_o^2}{L}(1 - \frac{t}{2Ku_o})^4$$

$$= \Delta P_o (1 - \frac{t}{2Ku_o})^4$$

where $\Delta P_o = \tfrac{1}{2}\rho g\, R_o^2/L$ is the maximum value of the pressure overshoot.

The ratio $(\Delta P/\Delta P_o)^{1/4}$ is a linear function of time and its slope is related to the time constant Ku_o. The variation of this ratio with time and the horizontal displacement r from equilibrium are shown in Figure 3.

The slope corresponds to a time constant

$$T_o = Ku_o \sim 600 \text{ sec (10 minutes)} .$$

The initial displacement corresponding to ΔP_o is 253 m. Thus, the compliance constant is

$$K = T_o^2/R_o = 600^2/25,300 \sim 14.2 \text{ sec}^2/\text{cm}$$

For comparison, the compliance constant estimated in Table 2 from the mooring cross section is $K = 11.4$ sec^2/cm. The agreement is satisfactory.

An independent comparison can be made using speeds measured by a current meter under the subsurface float. Assuming negligible current, the mooring speed is

$$\frac{dx}{dt} = -(u_o - t/2K)$$

The slope of the speed response curve depends only on the compliance constant. The comparison for mooring 161 is made in Figure 4. The sloping line in the figure is the rate of decrease of speed expected from the compliance constant evaluated from the pressure overshoot. The agreement is reasonable. The measured speed was considerably higher than calculated from the simple response equation during the first 5 minutes after the anchor reached bottom. A residual speed of 6 cm/sec produces a deviation from the final portion of the transient. The results obtained indicate that a good estimate of the response characteristics can be made from in situ measurements of the launching transient. The response characteristics, in turn, can be used to evaluate the quality of the recorded velocities.

Buoy Tracking Experiments

Two surface buoys (Table 1) were tracked with azimuth telescopes from two locations in Bermuda as shown in Figure 5. The angles recorded were true bearings of the buoys from the observation sites. These bearings θ_{1m} and θ_{2m}, together with backsights θ_{12} and θ_{21}, as shown in Figure 5, define the buoy location with respect to a rectangular coordinate system with origin at (1) through the equations

$$x = \frac{L \sin(\theta_{21}-\theta_{2m}) \sin \theta_{1m}}{\sin(\theta_{2m}-\theta_{1m})}$$

$$y = \frac{L \sin(\theta_{21}-\theta_{2m}) \cos \theta_{1m}}{\sin(\theta_{2m}-\theta_{1m})} ,$$

where L is the distance between the two observation points (3.0 nautical miles).

Readings were made every five minutes when the buoys were visible. A sample of the bearings recorded at the two stations is shown in Figure 6. The readings were converted to rectangular coordinates for plotting. Hourly positions of moorings 158 and 160 are given in Tables 3 and 4 respectively. The origin of the tabulated positions is chosen relative to the Paynters Hill tracking site. The north and east coordinates of the two moorings are plotted against time in Figures 7 and 8. The positions of floats are replotted in Figures 9 and 10 to show excursions of the moorings. The speed of the floats was quite low. The largest hourly displacement was about 77 meters corresponding to a mean speed of 2.1 cm/sec. The maximum excursions were less than 1 kilometer for both surface moorings.

Tension and current speed were measured near the surface on mooring 160. Some correlation between speed and tension was found (Figure 11) although the scatter was high. Current meters were placed at deeper levels, but the lower portion of the mooring was not recovered. The nylon mooring cable parted as a result of "fish bite" on May 15th and the float was recovered adrift.

More detailed comparisons of mooring motion and measured currents could not be made. Little correlation was found between current records obtained near mooring 160. The velocity field was probably complicated by the presence of the island of Bermuda. The experiment, however, showed that mooring motion was not a major problem for measurement of currents of the type observed near Bermuda.

ACKNOWLEDGEMENT

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The cooperation of personnel at the U.S. Navy Sofar Station in making the tracking facilities available and at the Bermuda Biological Station for logistic support are appreciated.

References

Fofonoff, N.P., 1965 A Technique for analyzing buoy system motion. Geo-Marine Technology, 1 (7) 222-225.

Webster, F. and N.P. Fofonoff, 1966. A compilation of moored current meter observations. Vol. 11. W.H.O.I. Ref. 66-60.

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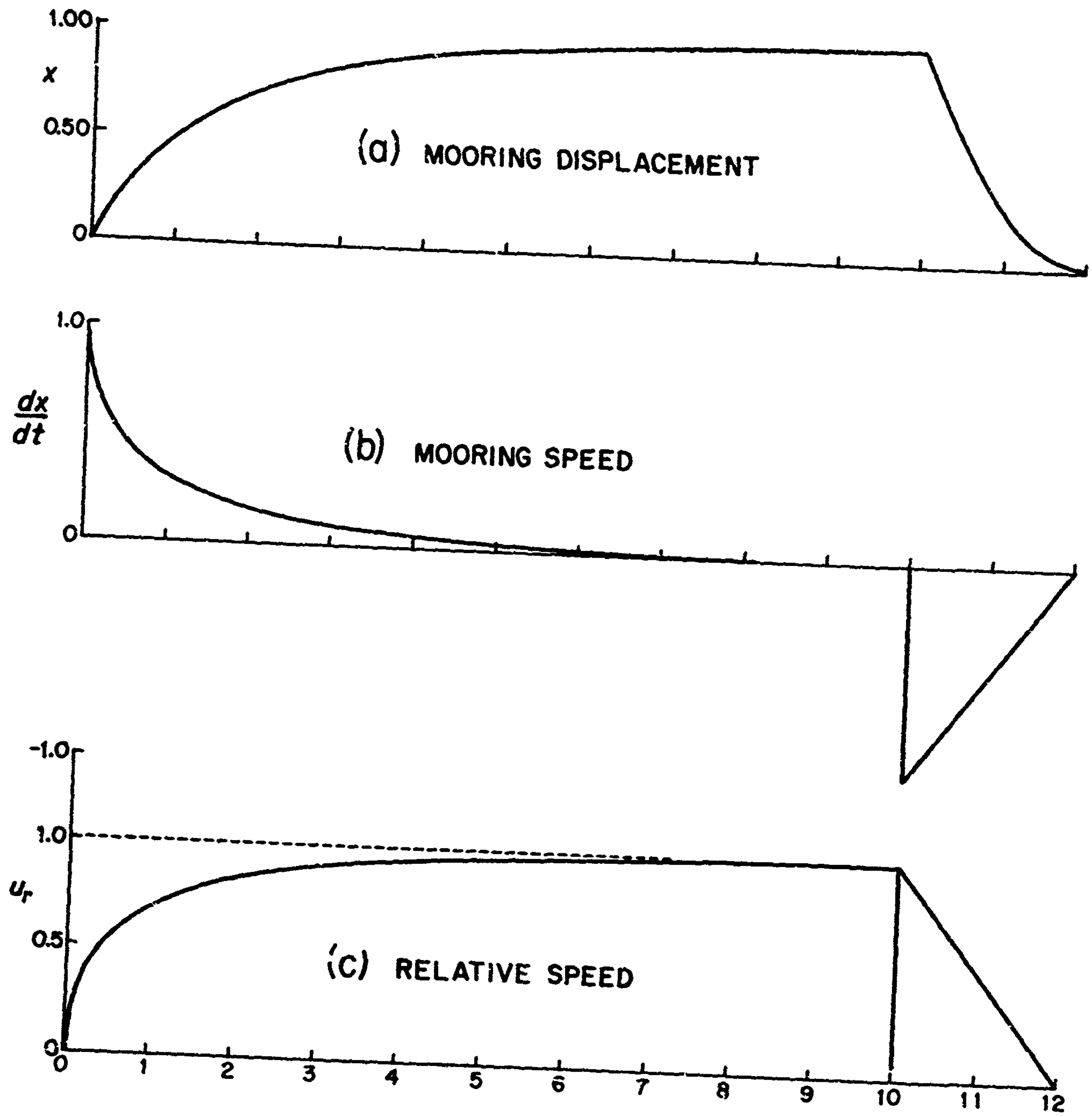

Figure 1. Response of a mooring to a step function current. The displacement unit is Ku_o^2 and the time unit Ku_o. The displacement (a) is shown for a current applied at t = 0 and removed at t = 10 units. The mooring speed (b) scaled by u_o is subtracted from the current to yield the relative speed (c) that would be sensed by a current meter on the mooring.

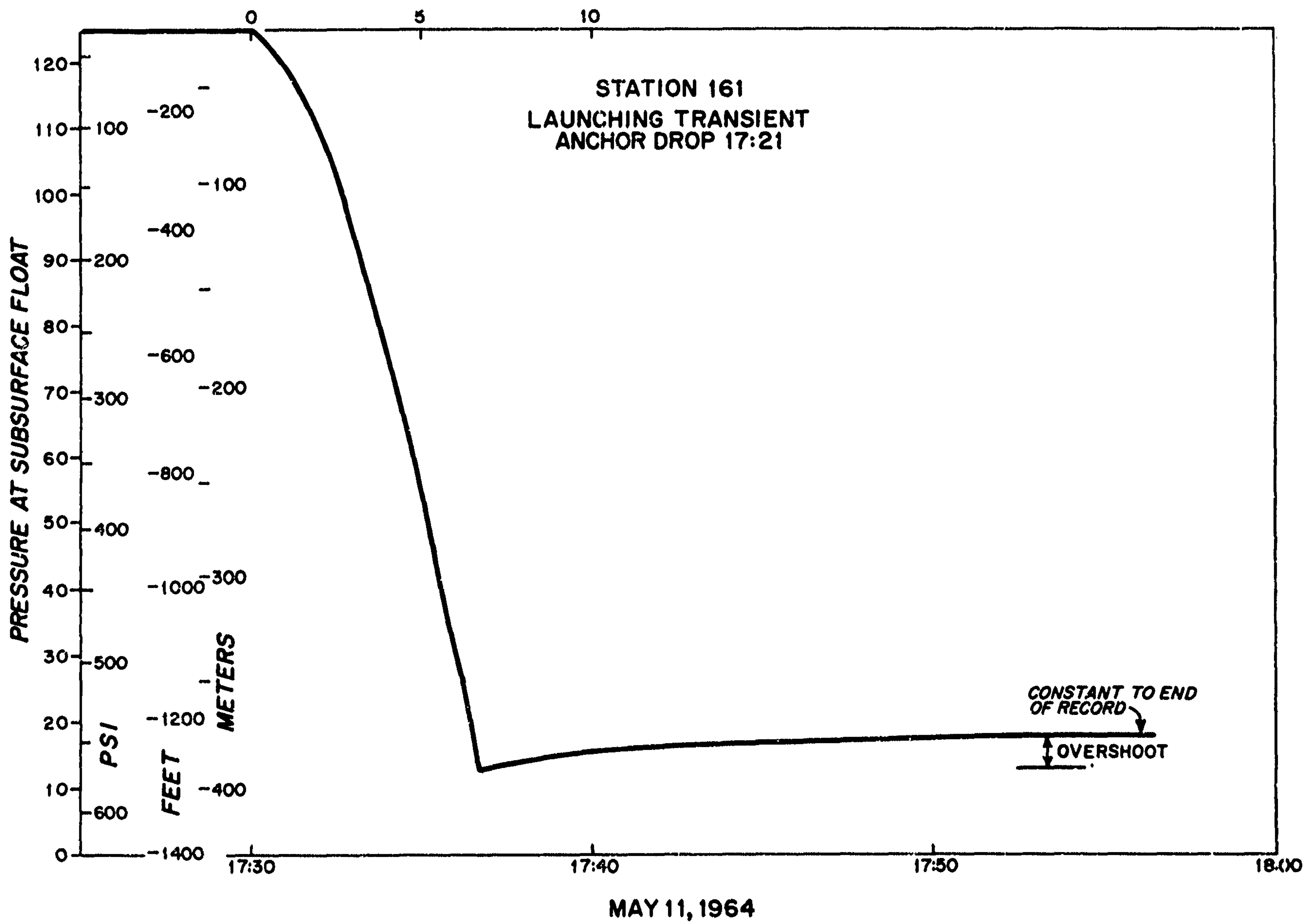

Figure 2. A pressure record from mooring 161 showing the overshoot during the launching transient.

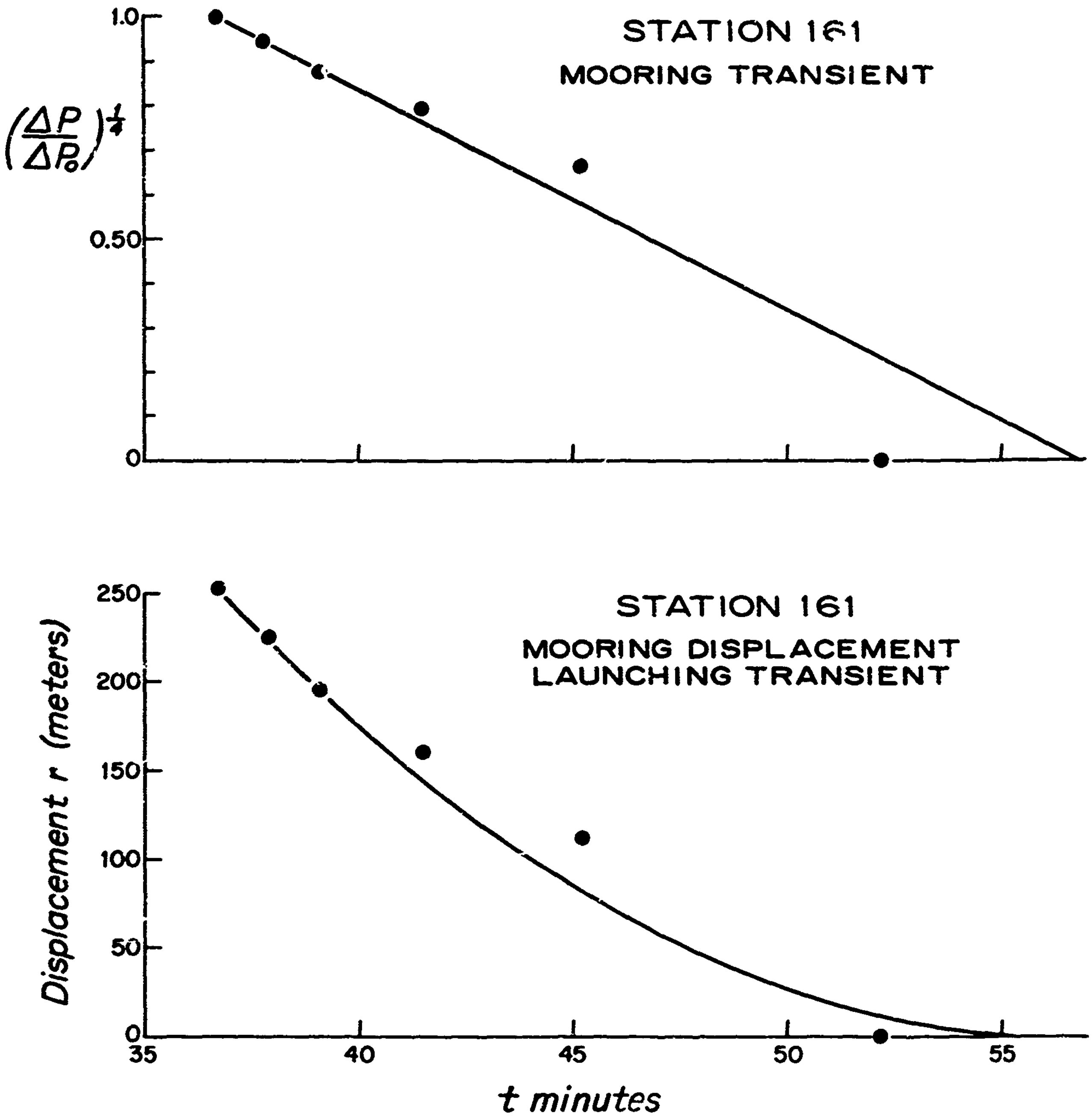

Figure 3. The pressure ratio and horizontal displacement of the mooring during the launching transient.

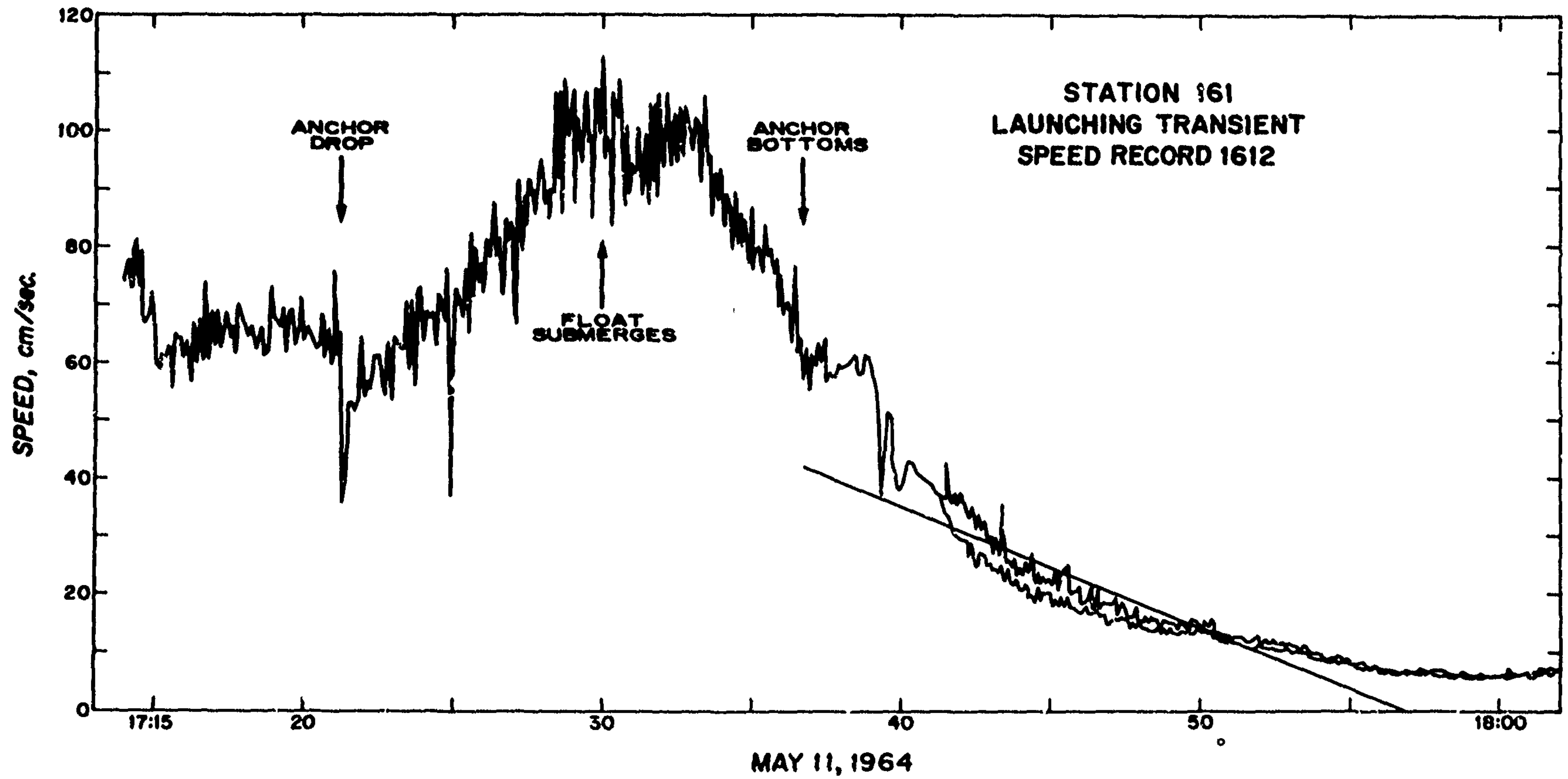

Figure 4. Speed record from a current meter located 150 m below the subsurface float. The straight line shows the speed calculated for a launching transient in still water for K = 14.2 cm^2/sec.

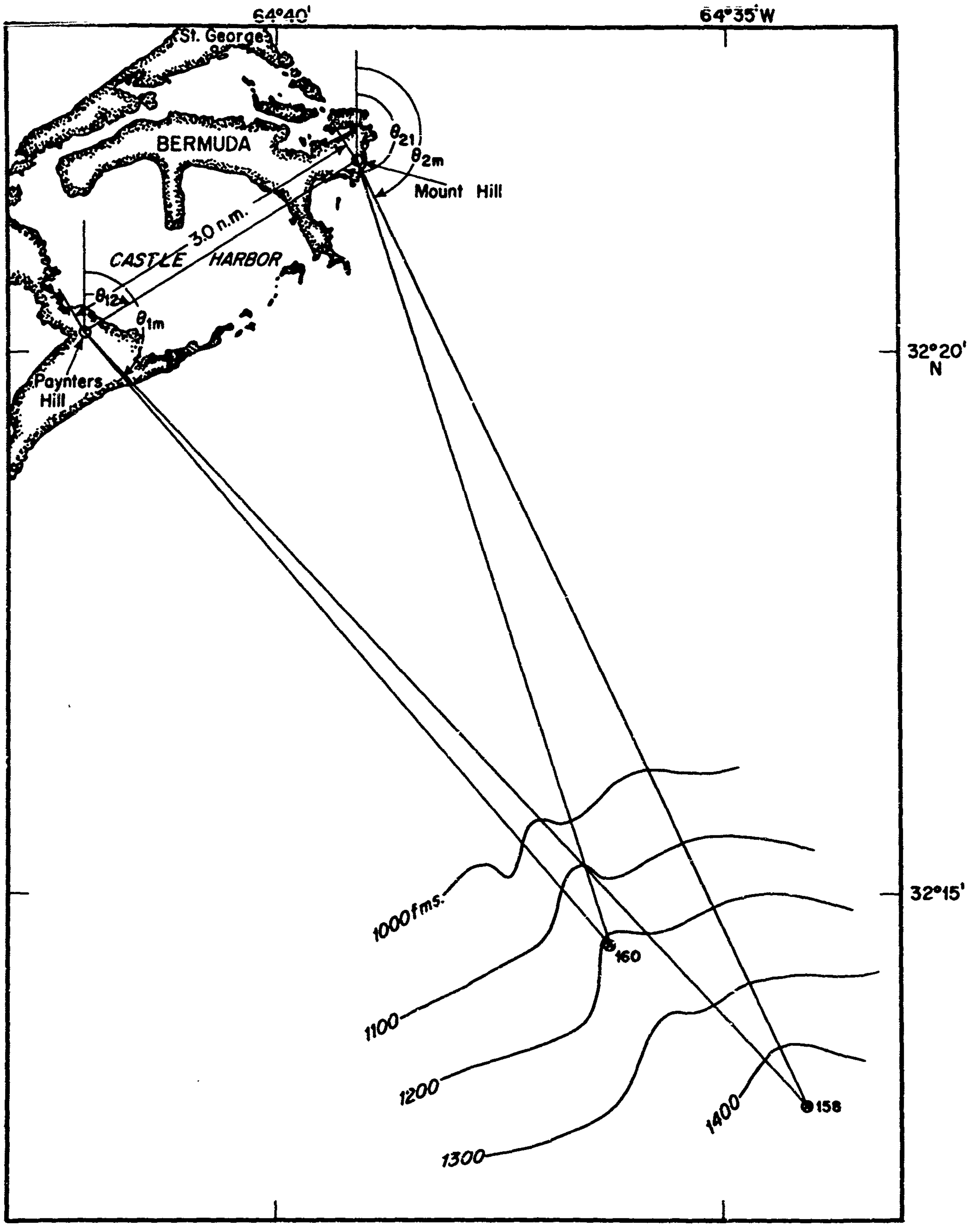

Figure 5. Location of tracking stations and surface float moorings 158 and 160 used for the tracking experiments.

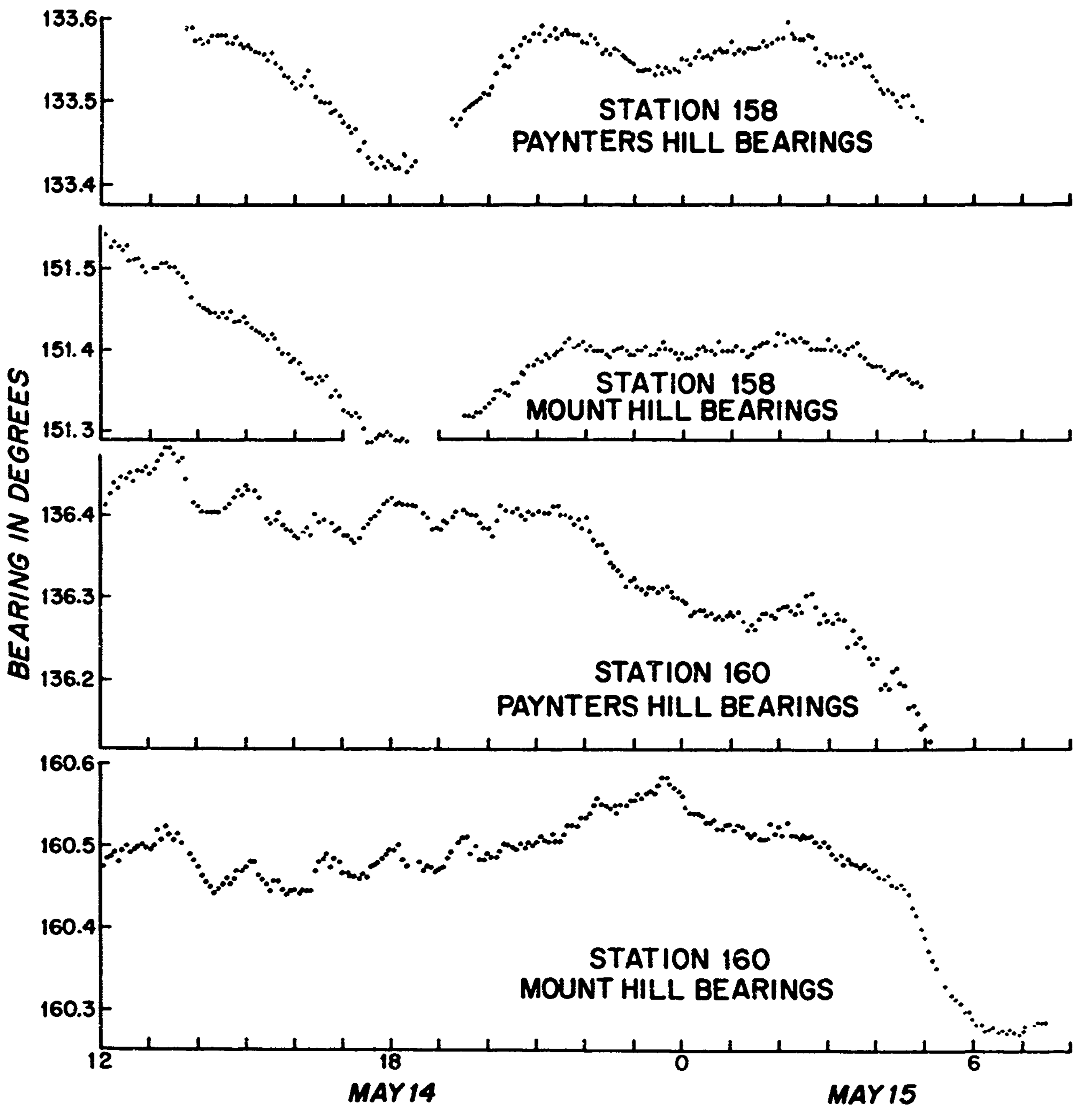

Figure 6. Examples of bearings recorded at 5-minute intervals at the two tracking stations. Some short period fluctuations can be seen. These are not explained.

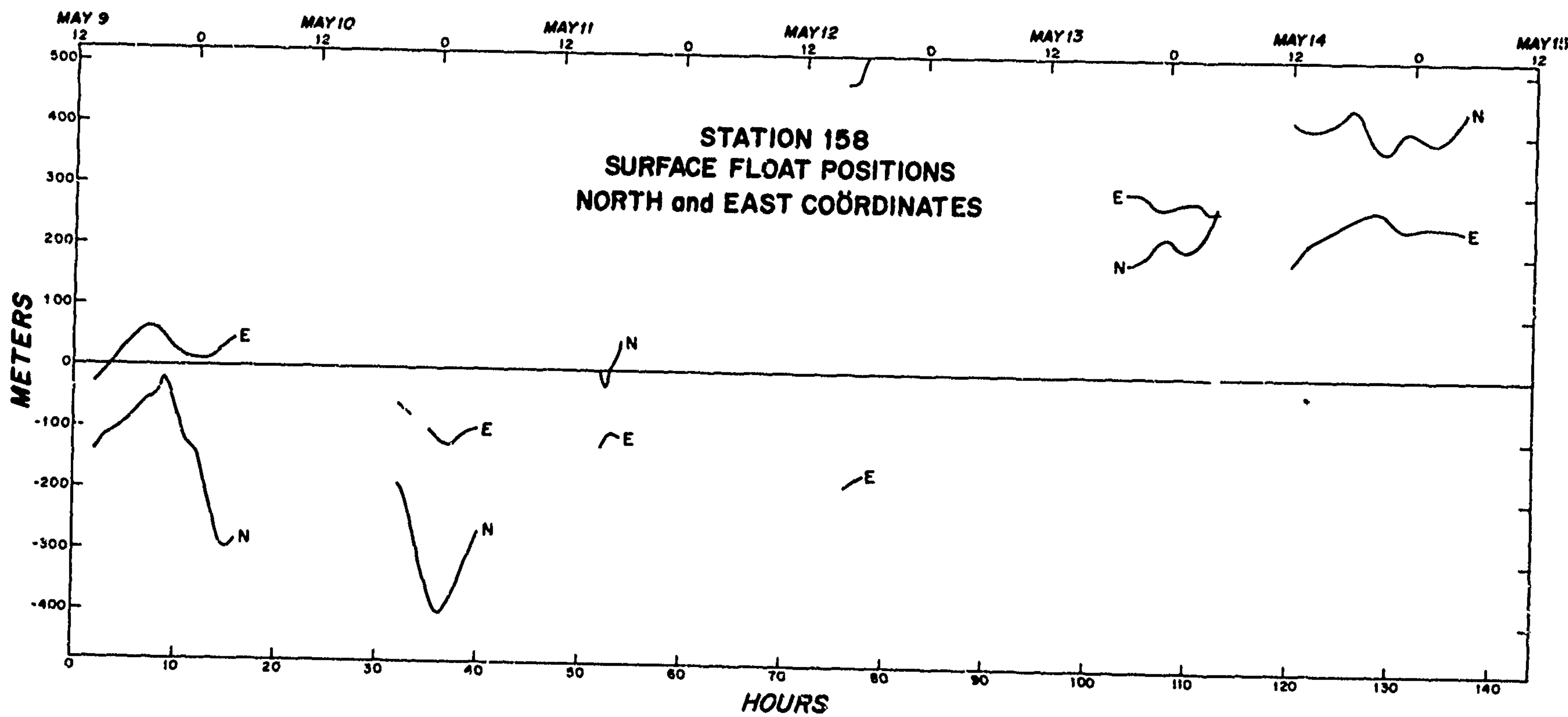

Figure 7. North and east components of mooring 158 plotted against time. The moorings were not visible from sunrise to noon because of adverse sun angle.

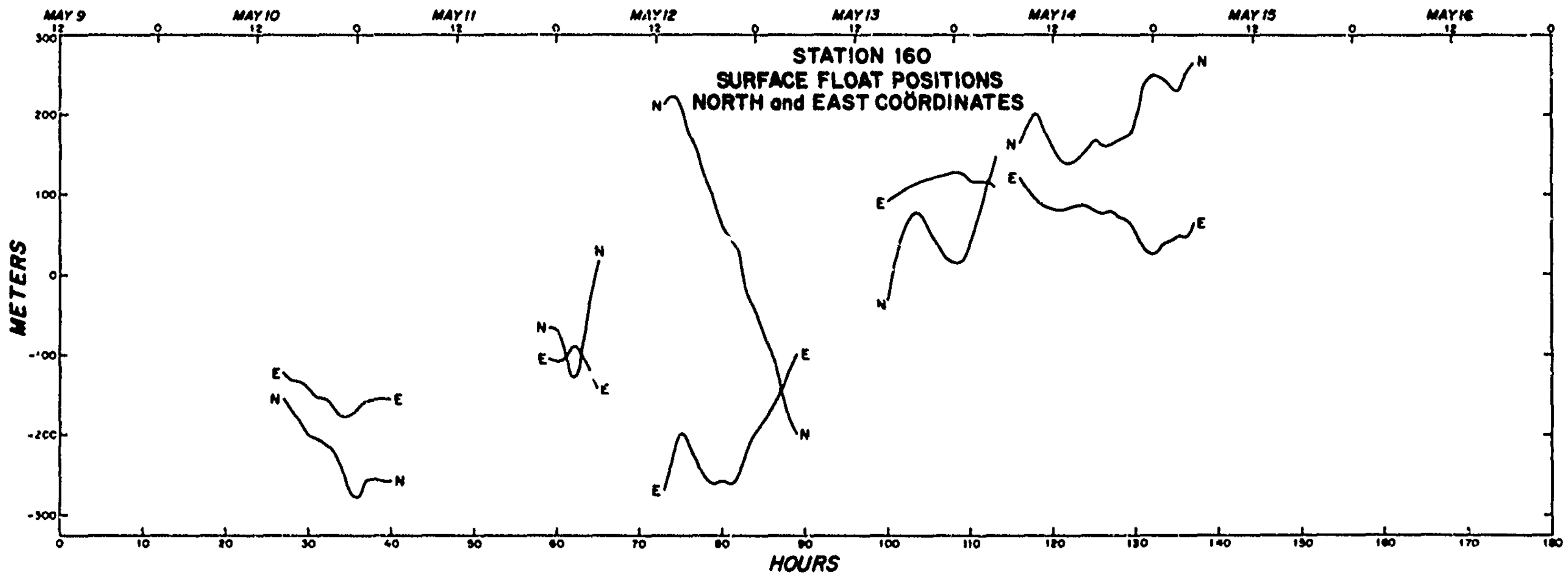

Figure 8. North and east components of mooring 160 plotted against time.

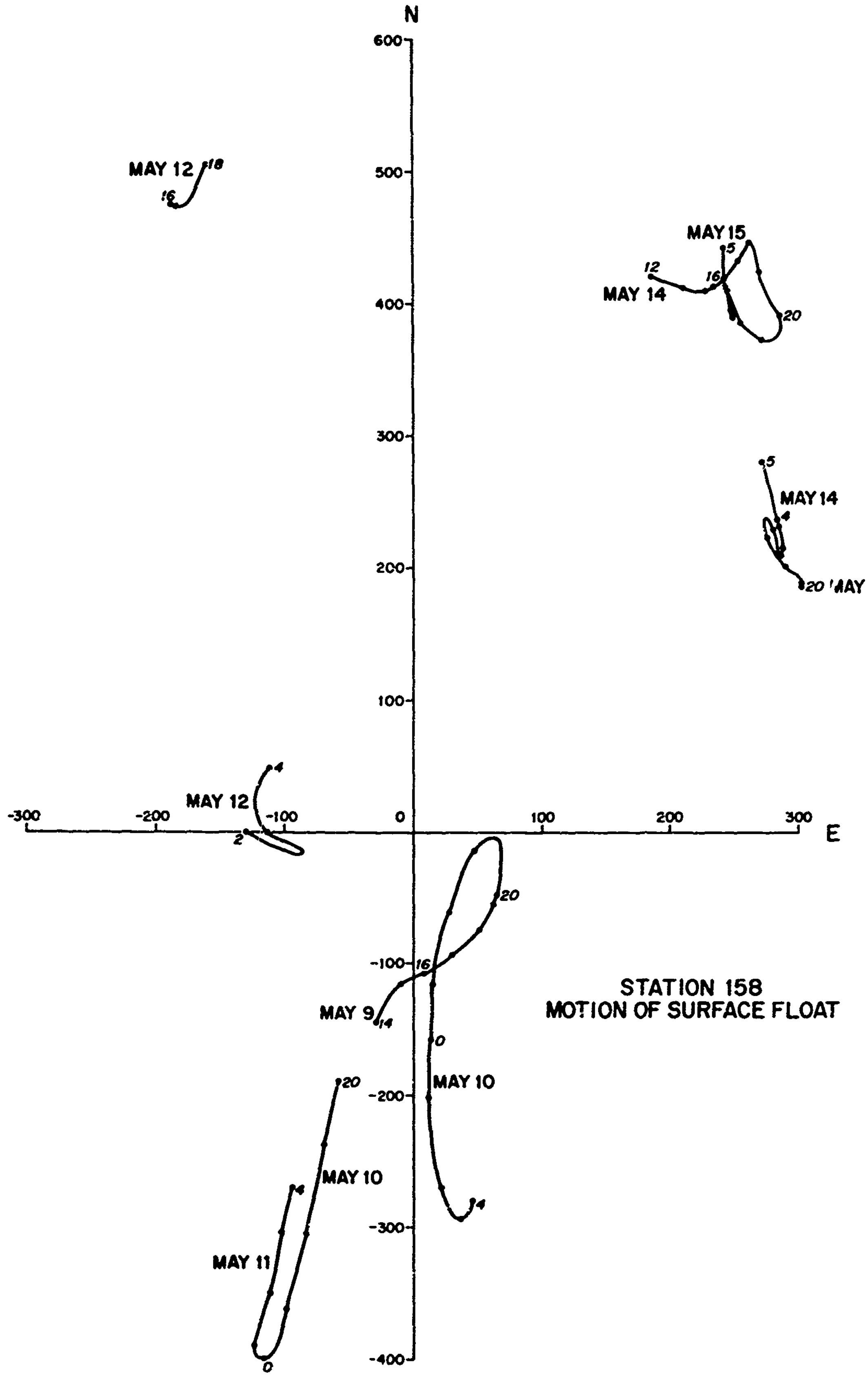

Figure 9. Excursions of mooring 158 during tracking.

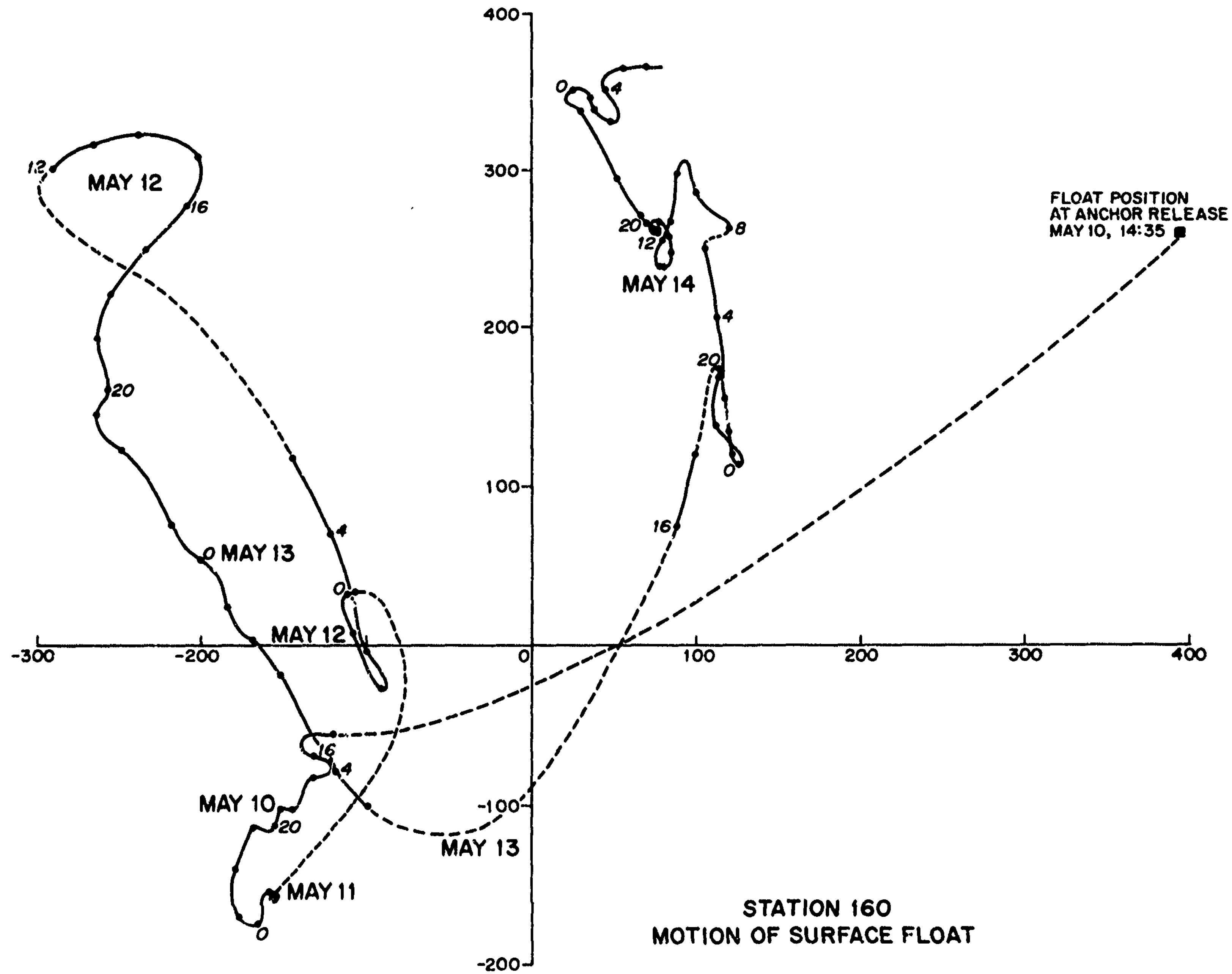

Figure 10. Excursions of mooring 160 during tracking.

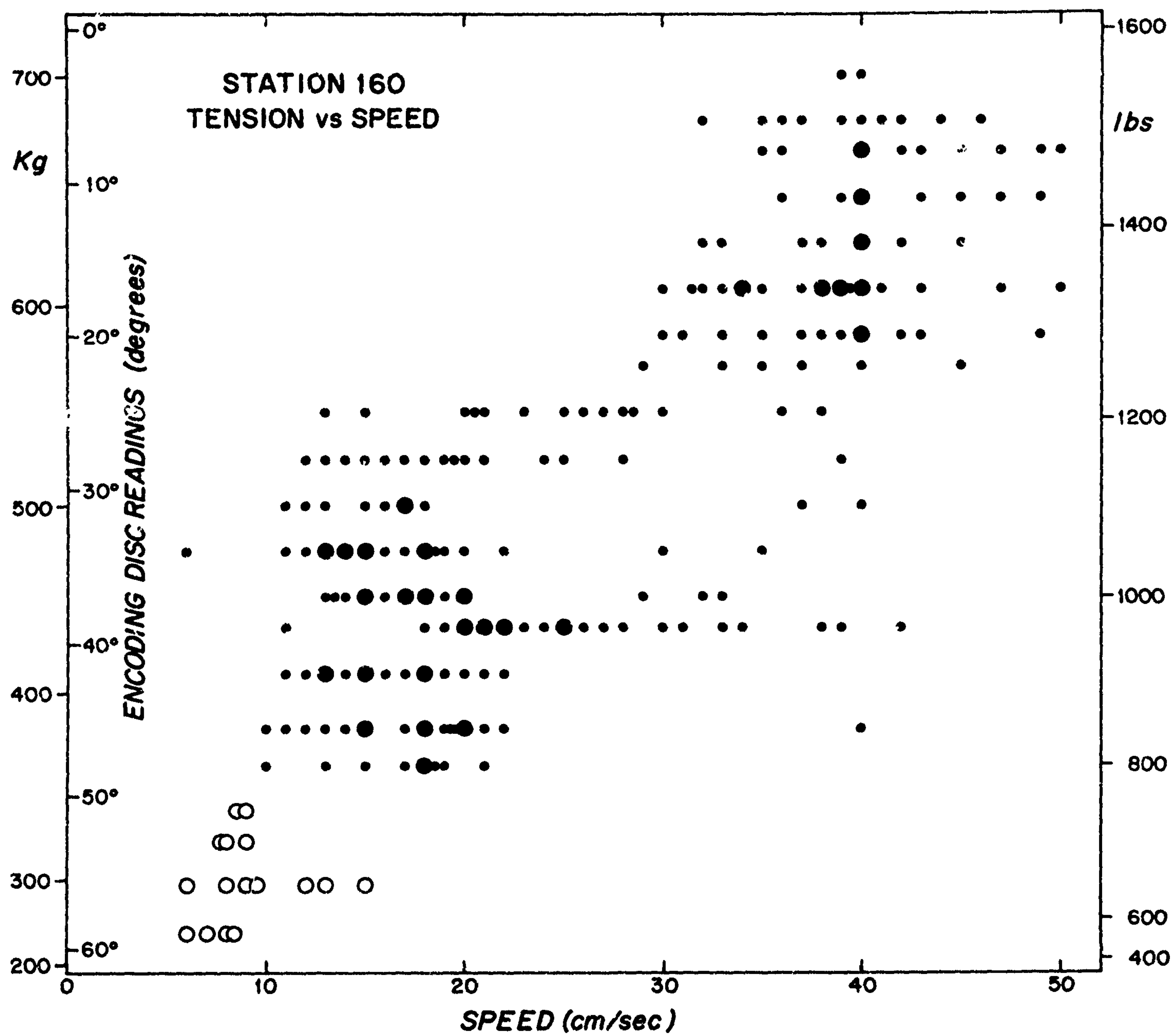

Figure 11. Tension versus speed for mooring 160. Measurements were taken at 60 m depth below the surface float. The circles indicate readings after the mooring went adrift.

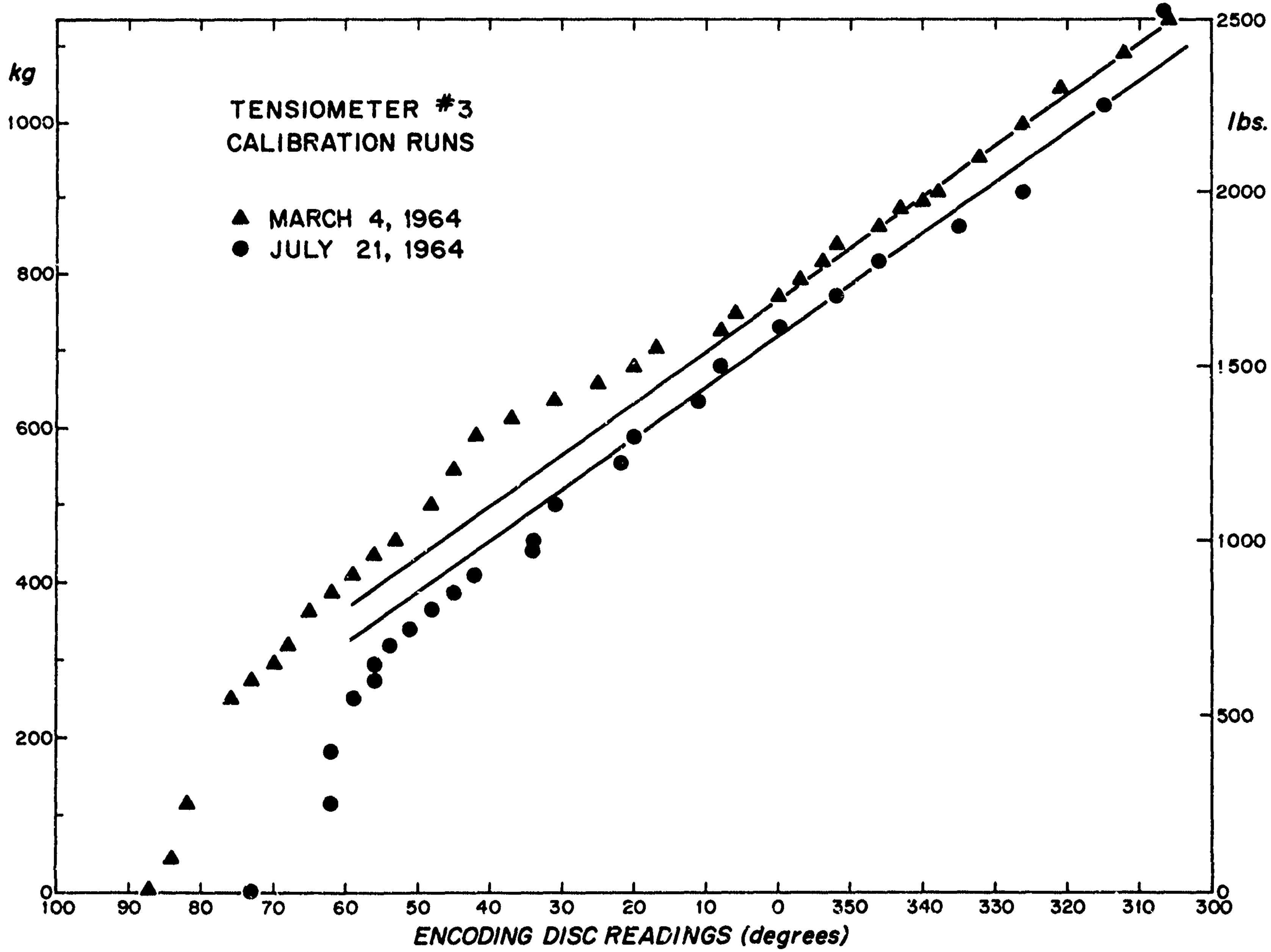

Figure 12. Tension calibration curves before and after exposure.

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TABLE 1

Description of Moorings

May 8—May 16, 1964

Station No.	158	159	160	161	162
Set	8 11:52	10 11:54	10 14:29	11 17:21	12 17:20
Recovered	15	16 11:00	16 14:15	14 11:47	15 10:58
Latitude	32°13.1'N	32°14.8'N	32°14.6'N	32°15.4'N	32°17.0'N
Longitude	64°34.1'W	64°35.1'W	64°36.3'W	64°31.8'W	64°37.2'W
Depth (meters)	2670	2140	2157	2430	2140
Type	Surface float	Subsurface float	Surface float	Subsurface float	Subsurface float
Scope	Approx.100%	---	90%	---	---
Depth to float	---	140 m.	---	344 m.	118 m.
Mooring line	9/16" Polypropylene (jacketed)	Steel cable	9/16" plaited nylon	Steel cable	Steel cable
Special measurements	Surface wind	---	Line tension	Pressure	Pressure

TABLE 2. Calculation of Mooring Compliance Conscant

Compliance Constant for Mooring #161

$K = \frac{1}{2}\rho C_D AL/_T$

ρ	∿	1.0 gm/cm^3,	density of sea water
C_D	∿	1.0	, drag coefficient
A	=	5.44 m^2	, drag cross section of mooring
L	=	2054 m	, length of mooring cable
T	=	500 kg	, cable tension

Drag Cross Section of Upper 500 meters

Cable	500 m	
Float	181 m	(equivalent cable length)
3 Current meters	144 m	" " "
	825 m	

Cable diameter = 0.66 cm

Cross section A = 0.66 X 825 X 10^2 = 54,400 cm^2

Compliance Constant

$$K = \frac{1}{2} \frac{5.44 \times 10^4 \times 2.054 \times 10^5}{.981 \times 10^3 \times 5.0 \times 10^5} = 11.4 \ sec^2/cm$$

For a current of 50 cm/sec (∿ 1 kt)

$R_o = KV_o^2 = 285$ m

$T_o = KV_o = 570$ sec ($9\frac{1}{2}$ min)

TABLE 3

Station 158

Coordinates of Surface Float

(hourly positions in meters)

	May 9		10		11		12		13		14		15	
hour	N	E	N	E	N	E	N	E	N	E	N	E	N	E
0			-158	+13	-400	-117					+228	+280	+408	+246
1			-202	+12	-390	-125					+210	+284	+393	+250
2			(-270)	(+21)	-350	-112	0	-130			+208	+286	+389	+250
3			-294	+36	-304	-103	0	-114			+214	+288	+396	+249
4			-280	+45	(-270)	(- 95)	+48	-112			+236	+283	+412	+245
5											+280	+272	+442	+244
6														END
7														
8														
9														
10			Not	Visible	Not	Visible	Not	Visible	Not	Visible	Not	Visible		
11														
12											+420	+186		
13	START										+411	+210		
14	-145	-30									+409	+228		
15	-116	-10									+412	+234		
16	-108	+ 8					+475	-187			+418	+242		
17	- 94	+30					+474	-173			+432	+253		
18	- 75	+51					+505	-160			+445	+262		
19	- 56	+62									+423	+270		
20	- 48	+65	(-190)	(-58)					+185	+302	+390	+286		
21	- 15	+47	-238	-70					+188	+302	+372	+272		
22	- 62	+27	-305	-83					+200	+290	+385	+356		
23	-116	+15	-362	-100					+222	+276	+409	+246		

( ) estimated

Origin

x_o = 12,900 m

y_o = 12,900 m

TABLE 4

Station 160

Coordinates of Surface Float

(hourly positions in meters)

hour	May 10		11		12		13		14		15	
	N	E	N	E	N	E	N	E	N	E	N	E
0			-176	-166	+ 32	-111	+ 53	-200	+114	+126	+350	+25
1			-156	-159	+ 7	-108	+ 24	-185	+113	+125	+345	+36
2			-156	-157	- 28	- 91	3	-169	+138	+112	+338	+38
3			-158	-155	- 4	-100	- 39	-152	+169	+114	+330	+48
4			-157	-157	+ 70	-122	- 79	-119	+206	+113	+350	+45
5			↑		+117	-145	-101	- 99	+250	+106	+364	+56
6					↑		↑				+364	+70
7											END	
8			Not	Visible	Not	Visible	Not	Visible	+263	+120		
9									+285	+100		
10					↓				+297	+ 89		
11									+269	+ 85		
12					(+300)	-290			+255	+ 80		
13					+314	-265			+239	+ 78		
14					+322	-238			+239	+ 81		
15	- 56	-120			+307	-202	↓		+247	+ 85		
16	- 70	-132			+276	-209	+ 75	+ 88	+257	+ 84		
17	- 83	-132			+248	-234	+120	+ 99	+266	+ 78		
18	-103	-144			+220	-255	↕		+260	+ 75		
19	-105	-153			+192	-263			+262	+ 77		
20	-114	-155			+160	-257	+174	+114	+266	+ 70		
21	-115	-168			+145	-263	+155	+118	+270	+ 67		
22	-141	-179	↓		+122	-248	+134	+120	+294	+ 52		
23	-171	-177	+ 33	-107	+ 75	-218	+120	+122	+337	+ 30		

( ) estimated

Origin

x_o = 9,200 m

y_o = 10,000 m

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Security Classification

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3. REPORT TITLE

MOORING MOTION

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Office of Naval Research Washington, D.C.

13. ABSTRACT

A study of the horizontal displacement of moored buoys in response to currents. A simple theoretical model is used to interpret measured displacements of moorings set near Bermuda.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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