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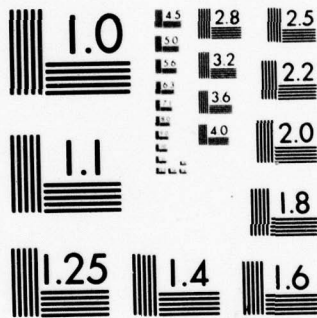
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A COMPUTER STUDY OF THE HYDRODYNAMIC LOADING OF A COMPLIANT TAU--ETC(U)
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ENGINEERING DESIGN AND ANALYSIS LABORATORY

University of New Hampshire
Durham, New Hampshire

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A COMPUTER STUDY
OF THE HYDRODYNAMIC LOADING
OF A COMPLIANT TAUT-WIRE MOORING

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Technical Report No. 109
by

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Stephen E. Demos,
Gary A. Stewart
Robert W. Corell

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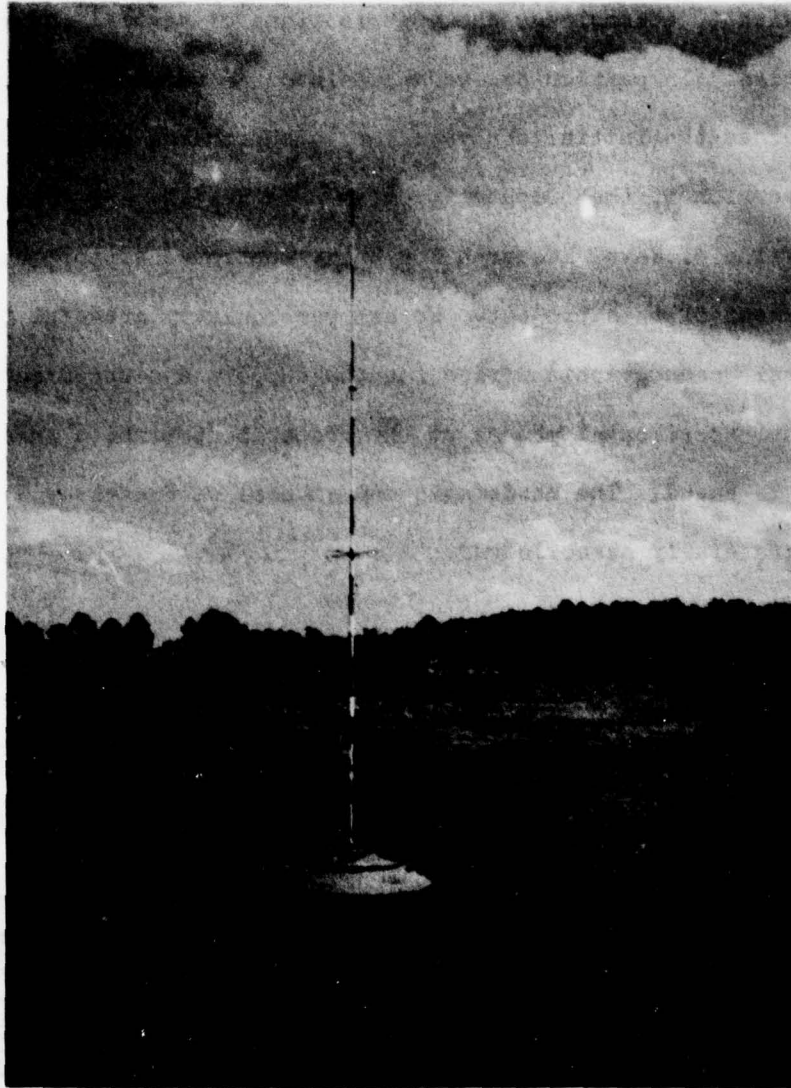
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The prototype buoy system which stimulated this project is shown above. This buoy, part of the Hysurch Program of the U. S. Naval Oceanographic Office, served as the model for the analysis reported herein.

A COMPUTER STUDY OF THE HYDRODYNAMIC LOADINGS
OF A COMPLIANT TAUT-WIRE MOORING

ABSTRACT

↙ This report presents the results of a computer study to investigate, primarily, the effects of hydrodynamic loadings on a highly compliant taut-wire buoy mooring system. A computer simulation of a prototype buoy system was used to study the influence of ocean currents (0 to 2.8 knots), wind loads (0 to 30 knots), water depth (down to 486 ft.), and mooring compliance on the behavior of a highly elastic mooring. Prototype experiments on the buoy studied herein have been conducted and reported elsewhere.³

³Superscript notation is used to denote references listed in Appendix I.

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I. INTRODUCTION

A. BACKGROUND

In February 1967, the Experimental Astronomy Laboratory of the Massachusetts Institute of Technology commenced a systems analysis and feasibility study of a new generation hydrographic survey and charting system for the U. S. Naval Oceanographic Office. As a consequence of that study, published in February 1968¹, a new approach for hydrographic surveys of coastal regions was proposed. The proposed system, known as HYSURCH (Hydrographic Survey and Charting System) includes all aspects of a hydrographic survey, ranging from high speed navigation and bathymetric data collection to rapid production of completed charts of the surveyed areas. One of the basic purposes of the HYSURCH System is to decrease the time required to survey a new area and to produce and publish charts. (For a detailed description of this new system, the reader is referred to Reference 1.)

The HYSURCH System uses radio-navigation buoys, of the range-range or hyperbolic type, for the navigation network. Bathymetric data is acquired aboard high speed (up to 40 knots) survey vessels. An error analysis ² of positional accuracy of bathymetric data indicates that navigation buoy locations must be known within specific limits. Hence, the "watch" circle specifications for the navigation buoys have been set. To determine the performance characteristics of

navigation buoys, an engineering design study was conducted by the University of New Hampshire. Various buoy configurations were analyzed, and a particular design approach was chosen for full-scale prototype evaluation tests. The results of this study, conducted in various ocean current and sea states, and in several water depths are published.³

Concurrent with the field studies, analytical models were developed to predict "watch" circle performance as a function of ocean currents, wind, water depth, and basic design parameters. In July 1969, an internal report⁴ was submitted to the University of New Hampshire in which a computer analysis of the buoy system was conducted and the results compared to field measurements. This computer program, written by Pladars, is based upon the work of Skop, O'Hara and Kaplan.^{5,6}

The buoy configuration studied in the full-scale prototype experience³ and in the computer model of Pladars,⁴ utilizes a stabilized parabolic surface buoy (see frontispiece) and highly compliant or elastic mooring system. A detailed description of this approach is contained in Reference 3.

The elastic mooring technique is not a new approach to buoy technology. The elastic characteristics of non-metallic mooring lines have long been considered important to mooring performance. One of the early uses of elastic mooring lines (actually rubber stock cord), was in the surface marker buoys in the Mohole Project - Phase I, in 1961.⁷ The rubber strands have been tested in a buoy installation in Los Angeles harbor by D. E. Maddux of Marine Advisors Inc., during 1963-1964.

The rubber links in the Marine Advisors Inc. installation evidenced little deterioration during 14 months of exposure to sea water.* G. H. Savage and J. B. Hersey, in the umbilical cord design for the Seaspider Buoy System,⁸ used four 1" diameter 35 ft. solid rubber strands that form a compliant connection between surface and subsurface buoys. John Issacs, of the Scripps Institution of Oceanography, has employed compliant mooring to deep-ocean systems.^{9,10,11} The basic principle in all these moorings is the use of elastic materials with high compliance to reduce the changes in mooring tensions due to relative displacements in the moorings' lines, i. e. waves, tides, and lateral movement by currents.

Out of the in situ experience of these compliant mooring designs, it became increasingly obvious that some mathematical modelling of the approach should be conducted. As an initial step in modelling such systems, Pladars⁴ studied the performance of a specific design configuration to steady state ocean currents and winds. The effect of wave action per se was neglected, because the particular buoy system specification¹ included substantial ocean currents but only modest sea conditions (up through Sea State 4). As a result of Pladars' study, a computer model existed. Therefore, it was deemed desirable to continue to utilize it to study the effects of changing certain environmental conditions and design parameters. This report is concerned with reporting the results of this latter study.

*No reference appears to be available. Statements reported herein came from informal communications.

B. OBJECTIVES OF THIS REPORT

This report presents the result of a computer study of the performance characteristics of the HYSURCH Navigation Buoy discussed in Reference 3. The computer program (listed in Appendix III), written by Pladars³ in Fortran IV for an IBM 360/40 system, is used to study the relation between steady state displacements and configurations when variables such as ocean current, wind velocity, depth, rubber link tension and compliance were altered from a given design³ configuration of a taut-wire surface moored parabolic buoy. The results reported herein are limited to a parabolic buoy system employing an elastic link as part of the mooring design. The problem is considered to be two-dimensional. The study should be considered as preliminary, for many more variables still need to be considered. It does , however, present some trends in the behavior of compliant moorings.

The report is divided in parts, as follows:

- Section I - Introduction
- Section II - A brief discussion of the assumptions used in the computer program
- Section III - A discussion of the results of the computer simulation.
- Section IV - Summary and Recommendations

II. BACKGROUND AND ASSUMPTIONS USED IN COMPUTER MODEL

A relatively simple computer model was developed, based on these types of assumptions:

- 1) Hydrodynamic forces are modelled using lumped parameter techniques.
- 2) Wind induced forces on the buoy structures above water are simulated using the "fifth power law" for the velocity profile and by lumped parameter representation.
- 3) All aero/hydrodynamic forces acting on the buoy system are viewed as coplanar.
- 4) Wave generated forces are neglected.

This section of the report describes the various aspects of the computer model, including a summary of the mathematical assumptions made. The specific design parameters are listed in Appendix II, with a schematic diagram shown in Figure 1.

A. CABLE

For the cable analysis, a lumped parameter representation of the cable was employed, similar to that used by Paquette and Henderson.¹² In a lumped parameter representation the cable is modelled as a series of stations or nodes, connected by straight-line segments of cable (see Figure 2). All forces due to current, weight, and buoyancy of

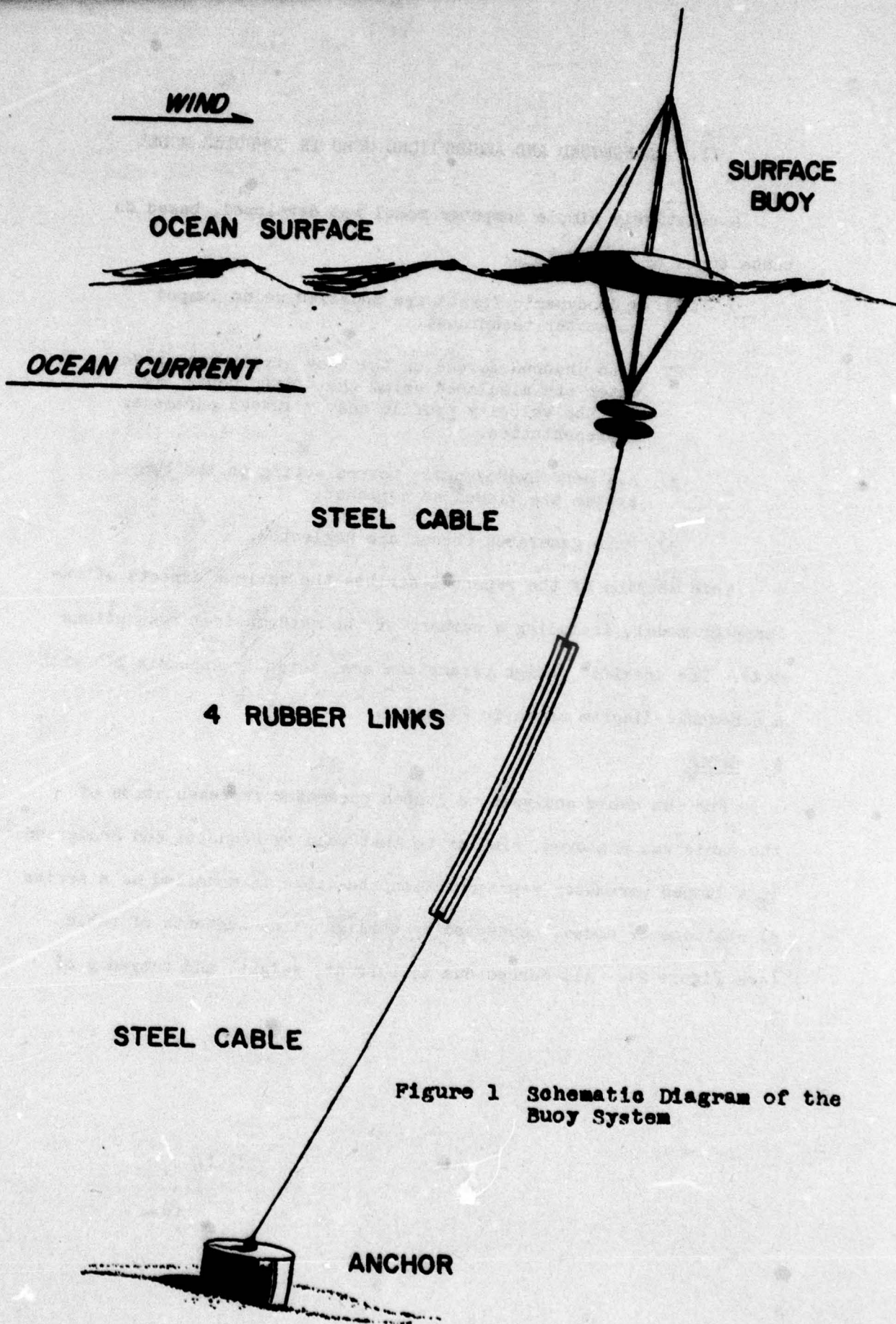


Figure 1 Schematic Diagram of the Buoy System

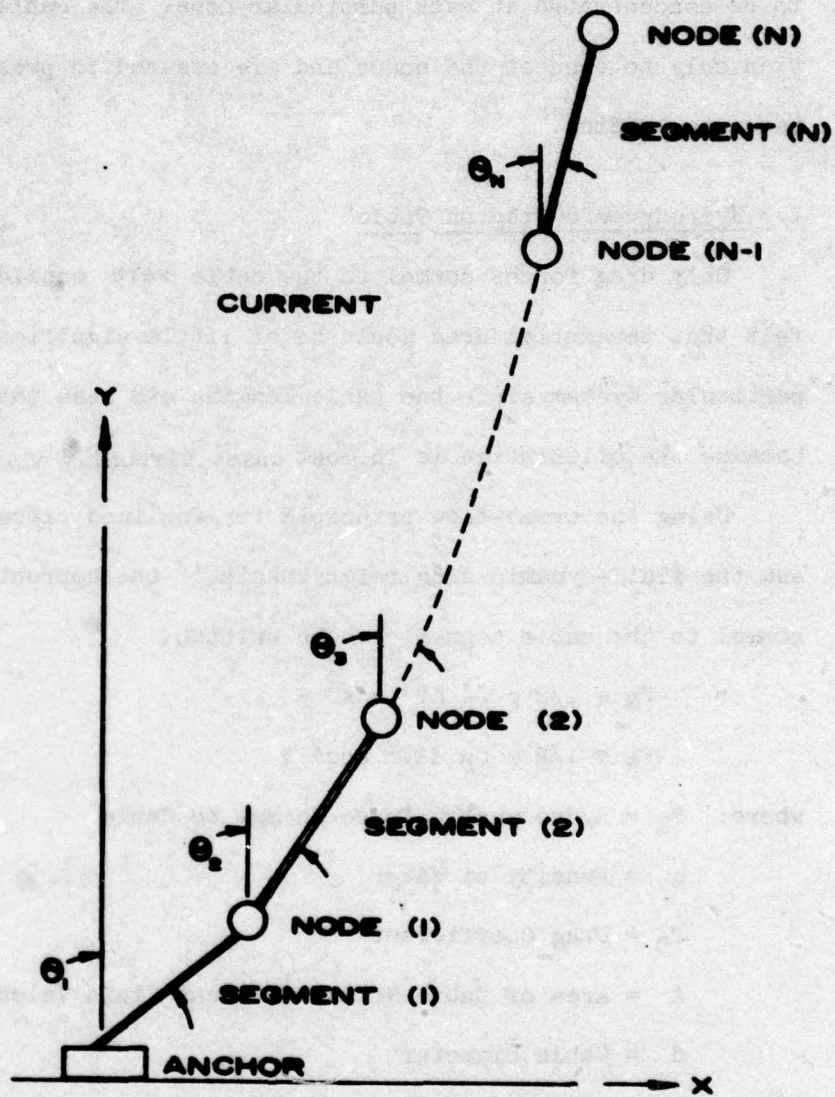


FIGURE 2

Lumped Parameter Representation of a Cable

the cable half-segment adjacent above and below the node are assumed to be concentrated at each particular node. The cable segments function only to connect the nodes and are assumed to present no resistance to bending.

1. Hydrodynamic Drag on Cable

Only drag forces normal to the cable were considered. It was felt that tangential drag would be of little significance for this particular system since the cable lengths are less than 500 feet and because the orientation is in most cases virtually vertical.

Using the cross-flow principle for inclined circular cylinders and the fluid-dynamic drag relationship,¹³ the current drag force normal to the cable segment can be written,

$$F_N = 1/2 \rho C_D AV^2 \cos^2 \theta \quad \text{Eq. (1)}$$

$$F_N = 1/2 \rho C_D d l V^2 \cos^2 \theta \quad \text{Eq. (2)}$$

where: F_N = Hydrodynamic Force Normal to Cable

ρ = Density of Water

C_D = Drag Coefficient

A = Area of Cable Normal to Local Fluid Velocity

d = Cable Diameter

l = Length of Cable Over Which F_N Acts

V = Local Fluid Velocity

θ = Angle between Cable and Local Fluid Velocity

This force can be further resolved in horizontal and vertical directions respectively

$$F_X = 1/2 \rho C_D d l V^2 \cos^3 \theta \quad \text{Eq. (3)}$$

$$F_Y = 1/2 \rho C_D d l V^2 \cos^2 \theta \sin \theta \quad \text{Eq. (4)}$$

Where a cable segment was comprised of more than one link in parallel, no interference flow was considered. The drag force for each individual link was added to arrive at a total drag force for the segment. This assumption introduces some error, since, even where the distance between two bodies is fixed and constant, the calculation of interference drag or shielding effect, according to Hoerner,¹³ would be quite complicated, and specific methods to solve such problems have not been fully developed. Thus, to simplify the approach, the interaction between links is disregarded, and the unknown error is accepted in the analysis.

To arrive at a diameter of the rubber links under tension, it was assumed that there was no change in the total volume of the links. The Goodyear Tire and Rubber Company¹⁴ notes that changes in volume of rubber under tension can be neglected. For the steel section of cable the changes after pretensioning in cable segment dimensions are of such small magnitude that they are neglected.

2. Cable Weight and Buoyancy Forces

Due to the constant volume assumption for the rubber links, the cable weight and buoyancy forces can be computed on the basis of the original unstressed dimensions:

$$F_W = W_{CAB} l_0 \quad \text{Eq. (5)}$$

$$F_B = \rho_g \pi d^2 l / 4 \quad \text{Eq. (6)}$$

B. SURFACE BUOY

1. Buoy Volume and Projected Area Normal to Current

An 8-foot parabolic buoy was used in the prototype studies. It is constructed essentially of two paraboloids of revolution. Since the actual paraboloid formula was not available from the manufacturer, $r^2 = 12h$ was determined to provide an approximation of the projected area normal to the current, where r (major radius) and h (minor radius) are in feet. Thus, the volume and cross-sectional area of one parabolic half can be computed as:

$$\text{Vol} = 1/8 \pi h (2r)^2 \quad \text{Eq. (7)}$$

$$= 1/8 \pi h (48h)$$

$$= 6 \pi h^2$$

$$\text{Area} = 4/3 \pi r h \quad \text{Eq. (8)}$$

$$= 8/3 \sqrt{3} \pi h^{3/2}$$

2. Hydrodynamic Forces on the Buoy

Assuming that the drag on the buoy is proportional to the submerged cross-sectional area of the buoy normal to the current and neglecting any wave forces and small inclinations of the buoy (measured in prototype studies to be less than 8°), the drag force could be written as

$$F_D = 1/2 \rho C_D A_S V^2 \quad \text{Eq. (9)}$$

Since the tensions of the cable are such that more than half of the buoy is submerged at all times, the submerged cross-sectional area is simply the total cross-sectional area minus the cross-sectional area above the surface.

The lift force on the buoy was disregarded because the lift was estimated to be insignificant compared to buoyancy force changes due to high buoy volume concentration at the waterline for this buoy shape.

3. Buoy Weight and Buoyancy Forces

Weight of the buoy was not determined separately but incorporated into the total weight of the system.

Buoyancy force on the buoy is given by the following expression

$$F_B = \rho g V_S \quad \text{Eq. (10)}$$

where: F_B = Buoyancy Force

ρ = Mass Density of Water

g = Gravitational Constant

V_S = Submerged Volume

where the submerged volume is obtained by subtracting the volume above the waterline from the total volume of the buoy.

C. PARABOLIC WEIGHTS

The parabolic damper weights (see disks - shaped elements at base of buoy in Figure 1) attached at the base of the bridle or tripod are shaped similarly to the buoy. The determination of forces due to these weights follows the same procedure as for the buoy. The only difference is that the parabolic weights are fully submerged at all times.

D. THE TRIPOD

1. Tripod Drag due to Current

Vertical forces due to current have been disregarded because they are small compared to other forces at the buoy.

Leg 1 of the tripod (see Figure 3) can be handled in exactly the same manner as a cable segment, thus giving

$$F_X = 1/2 \rho C_D dl v^2 \cos^3 \alpha \quad \text{Eq. (11)}$$

where: F_X = Hydrodynamic Force on the Tripod

α = Angle between Local Fluid Velocity and the Tripod Legs

Note: other terms similarly defined as in Equations 1 & 2

For legs 2 and 3, from symmetry basic hydrodynamic stability of the orientation, and forces perpendicular to the x-y plane will cancel. Taking, say, leg 2 and resolving the current into vector components, $|\vec{v}_1| = |\vec{v}| \sin 30^\circ$ and $|\vec{v}_2| = |\vec{v}| \sin 30^\circ$, each component can be handled separately as an effective current. The

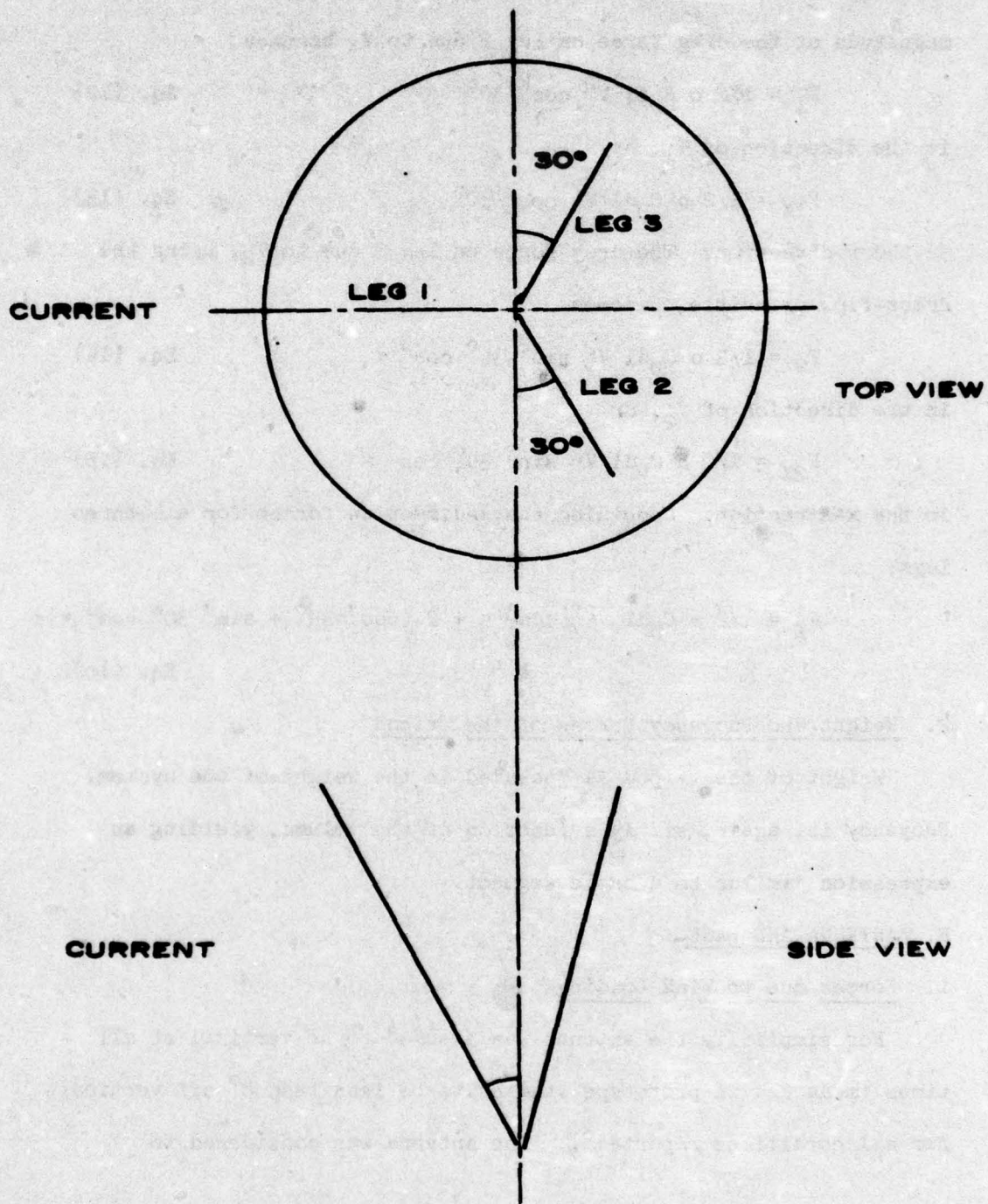


FIGURE 3
Configuration of the Tripod

magnitude of the drag force on leg 2 due to V , becomes

$$F_1 = 1/2 \rho C_D d l V^2 \cos^2 30^\circ \quad \text{Eq. (12)}$$

in the direction of V_1 , or

$$F_{1X} = 1/2 \rho C_D d l V^2 \cos^3 30^\circ \quad \text{Eq. (13)}$$

in the x-direction. The drag force on leg 2 due to V_2 , using the cross-flow principle, becomes

$$F_2 = 1/2 \rho C_D d l V^2 \sin^2 30^\circ \cos^3 \alpha \quad \text{Eq. (14)}$$

in the direction of V_2 , or

$$F_{2X} = 1/2 \rho C_D d l V^2 \sin^3 30^\circ \cos^3 \alpha \quad \text{Eq. (15)}$$

in the x-direction. Combining the x-direction forces for all three legs:

$$F_X = 1/2 \rho C_D d l V^2 [\cos^3 \alpha + 2 (\cos^3 30^\circ + \sin^3 30^\circ \cos^3 \alpha)] \quad \text{Eq. (16)}$$

2. Weight and Buoyancy Forces of the Tripod

Weight of the tripod is included in the weight of the system. Buoyancy is, again, simply a function of the volume, yielding an expression similar to a cable segment.

E. ANTENNA AND BASE

1. Forces due to Wind Loading

For simplicity the antenna was assumed to be vertical at all times (measured in prototype studies to be less than 8° off vertical for all conditions reported³). The antenna was considered to

be a vertical rod without any guy wires or other protuberances. The wind was assumed to vary with height, according to the Fifth Power Law, as given by Saunders,¹⁵ although the logarithmic distribution could have equally as well been used.

$$V_h = V_6 \left(\frac{h}{6}\right)^{1/5} \quad \text{Eq. (17)}$$

where: V_h is the wind velocity at any height (h)

V_6 is the velocity of wind observed at 6 feet

Using the fluid-dynamic drag relationship,

$$F_C = 1/2 \rho C_D A V^2 \quad \text{Eq. (18)}$$

and $\rho = 0.00238$, $C = 1.2$, an empirical formula for antenna drag was calculated to be

$$F_{DA} = 0.011221 V^2 \quad \text{Eq. (19)}$$

and for the antenna base

$$F_{DB} = 0.00171 V^2 \quad \text{Eq. (20)}$$

giving a combined total drag of

$$F_D = 0.012931 V^2 \quad \text{Eq. (21)}$$

2. Weight Force of the Antenna

Weight of the antenna and attached equipment was included in the total weight of the system.

F. COMPUTER PROGRAM

1. General Procedure

Initially, all forces acting on the antenna, the buoy, the tripod, the parabolic weights, and the top half-segment of the cable

are summed up and applied to the top end of the cable. Starting from this top end of the cable and proceeding towards the anchor end, the resultant forces, tensions, new dimensions, and orientations of each cable segment are determined. This, in turn, locates the new position of each station or node. When the boundary conditions for the top end of the cable are satisfied, all forces acting on the top and along the cable are recomputed. This iteration process continues until the node coordinates between successive computations change less than the specified value. The computation is then considered complete and desired output is printed.

2. Node and Segment Length Selection

In the selection of segment lengths some consideration must be given to the expected radius of curvature of the cable: a small radius of curvature should have nodes closer together than a large radius of curvature. A node should also be located at every point where a property of the cable changes or an external element is present. A study of the effects of numbers of nodes was made. The number of nodes selected is a function of the particular situation being studied, although, 15 nodes were used in all the calculations. The effect of increasing the number of nodes from 15 to 22, for example, is noted on Figure 4 (which indicates that the maximum difference in the horizontal displacement of any nodal point is 0.01% of these two cases). Other studies were conducted to determine effects of node selection.

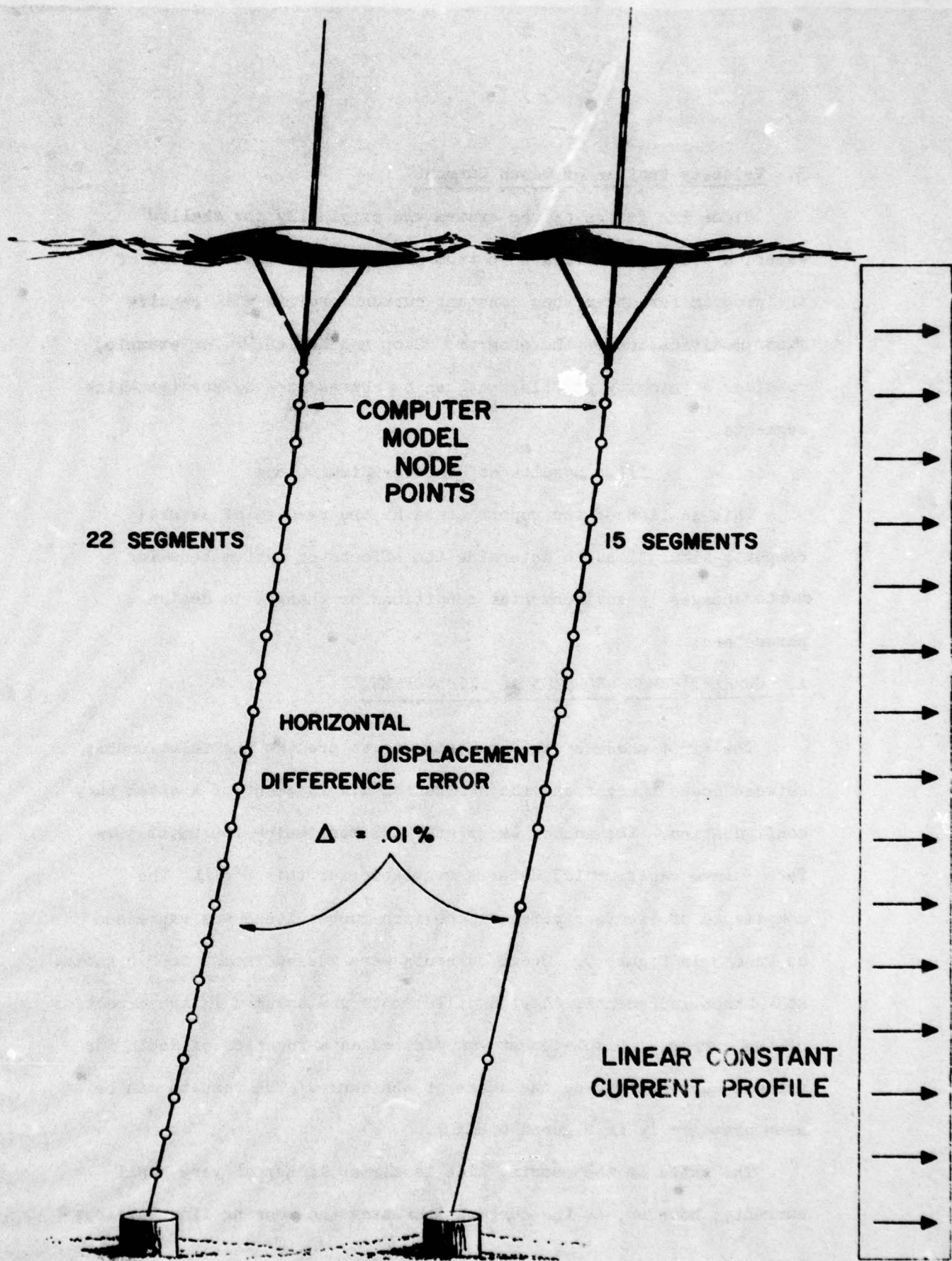


Figure 4 Cross Sectional View of Surface Buoy and Anchor with Nodal Point Comparisons

3. Velocity Profile of Ocean Current

Since the design of the system was originally for shallow water, a constant surface to bottom profile was selected. Use of the program for other than constant current profile will require minor modification of the program. Skop and Kaplan,⁶ for example, consider a velocity profile that can be represented by straight-line segments.

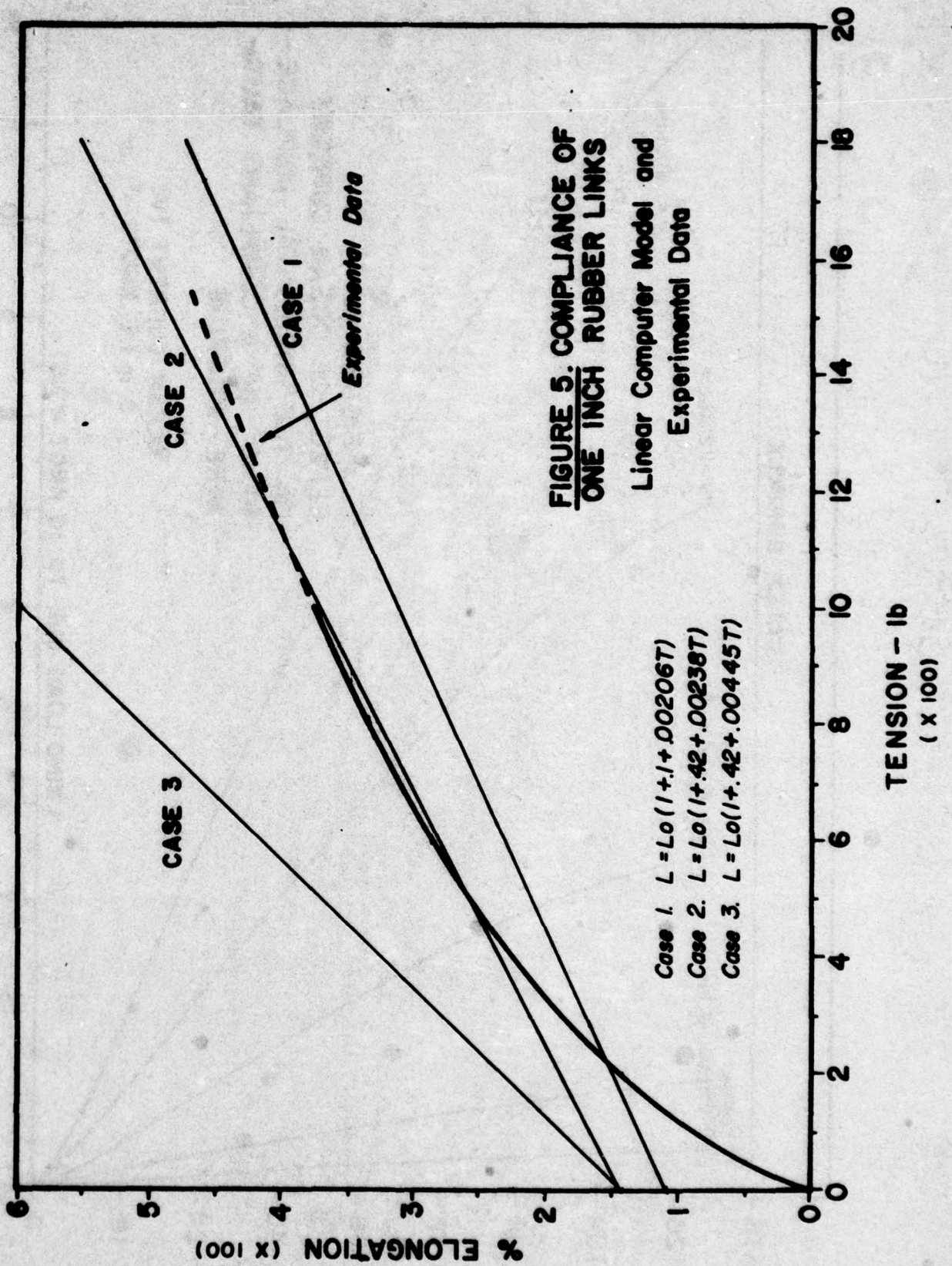
III. Results of Computer Simulations

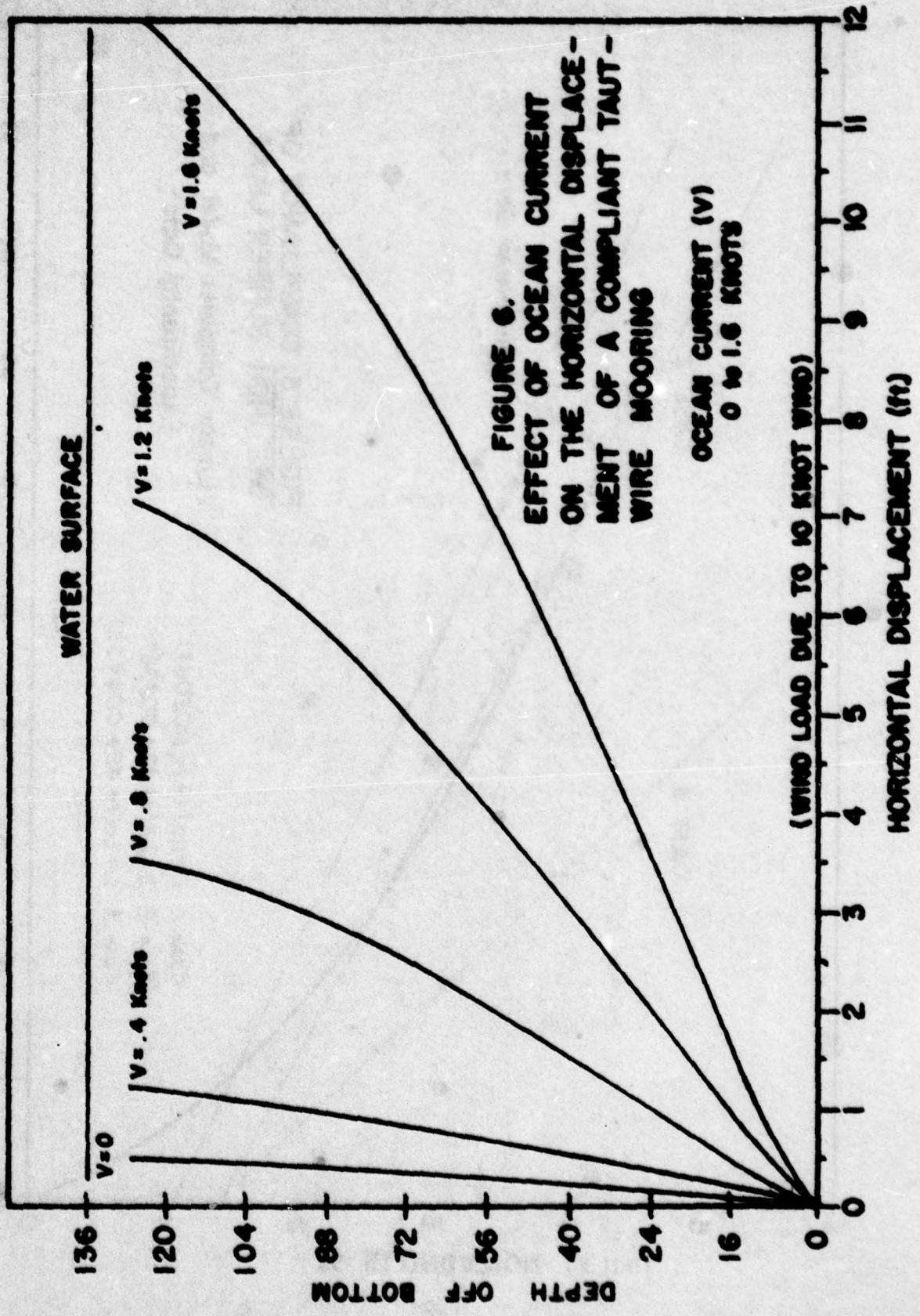
This section of the report contains the results of several computer simulations to determine the effects on system behavior due to changes in environmental conditions or changes in design parameters.

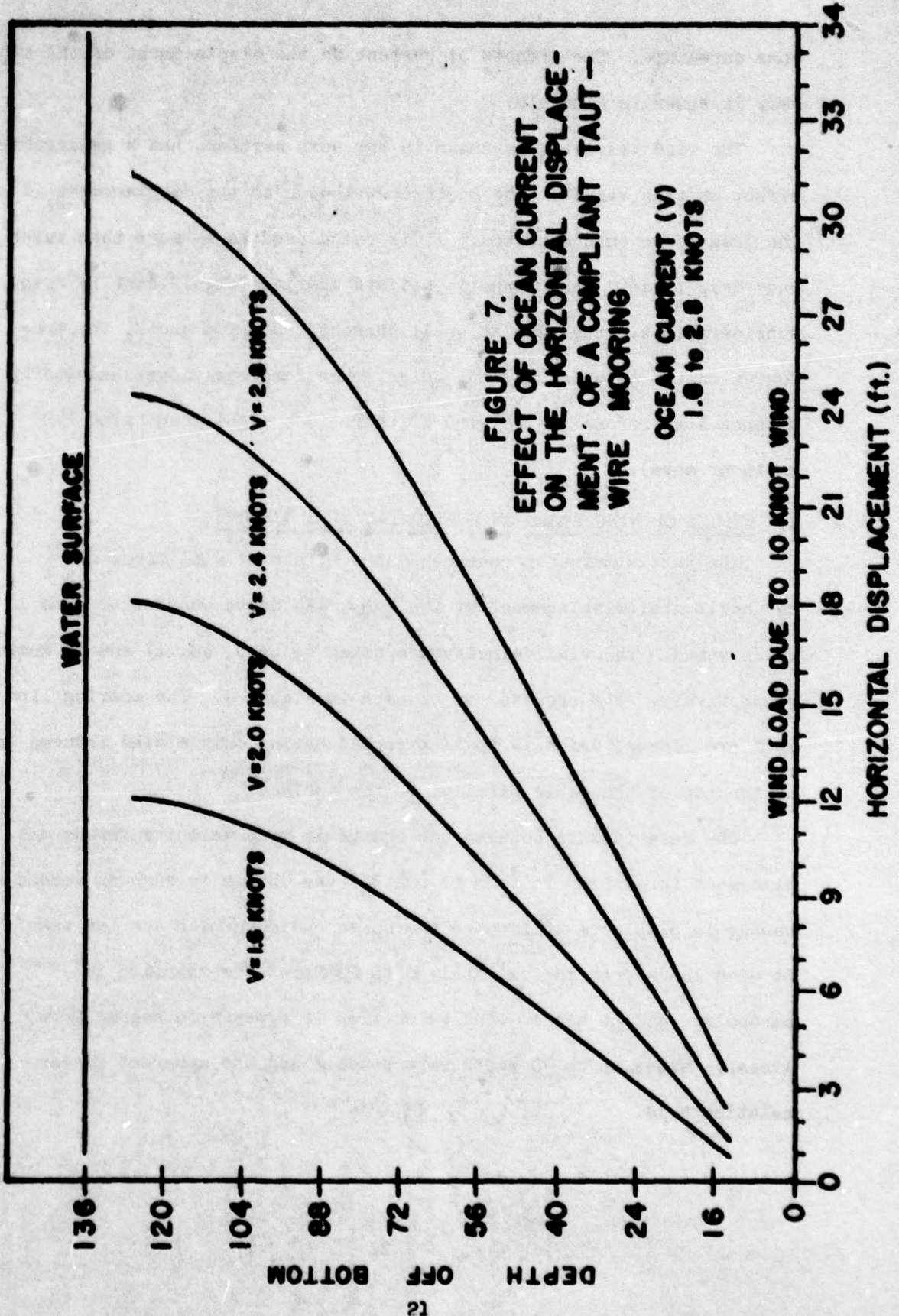
A. CURRENT VERSUS HORIZONTAL DISPLACEMENT

The first phase of the analysis was to predict the relationship between ocean current and the horizontal displacement of a given buoy configuration. The anchor was placed 136 feet below the water surface (since experimental data is available for this depth). The compliance of the four parallel one-inch rubber links was expressed as Case 3 in Figure 5. Ocean currents were varied from 0 to 2.8 knots at 0.4 knot increments. A wind of 10 knots was assumed in the direction of the current. Displacement was plotted as a function of depth for various currents giving the shape of the cable. The results can be seen graphically in Figures 6 and 7.

The shape of the mooring line is almost linear at very small currents; however, as the current increases the mooring line develops







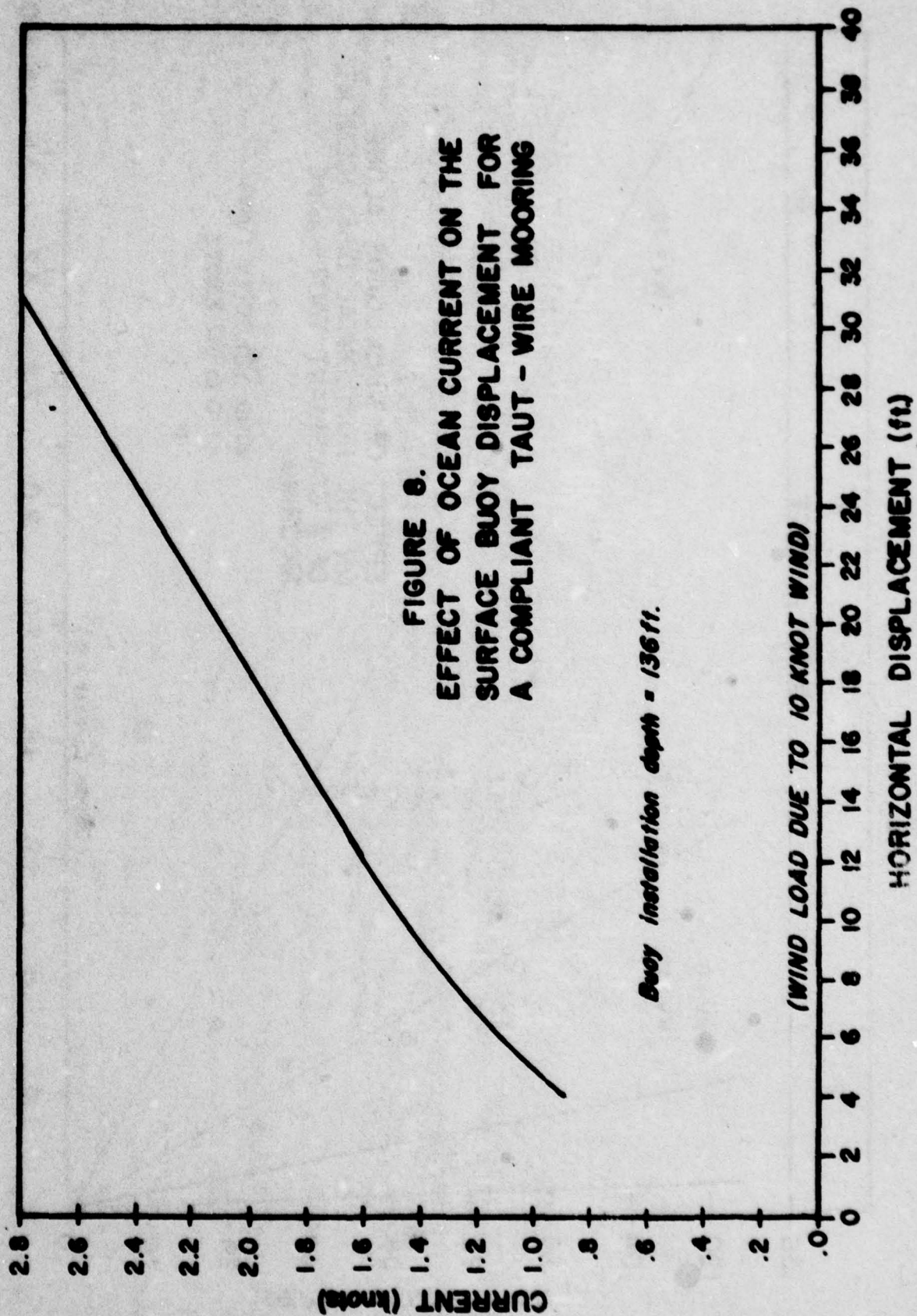
some curvature. The effects of current on the displacement of the surface buoy is shown in Figure 8.

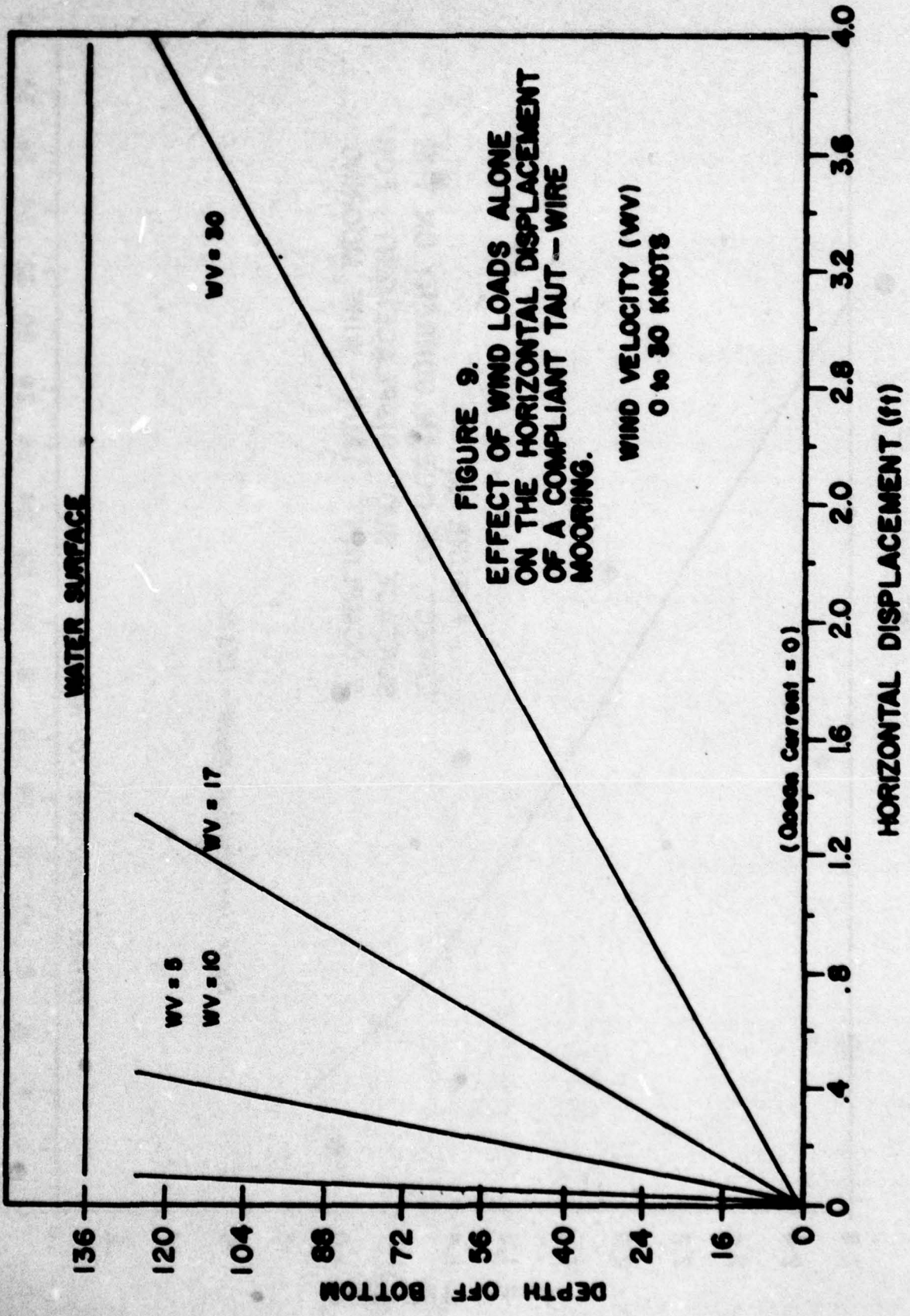
The wind velocity, as shown in the next section, has a negligible effect on this result. The major contributor to the displacement is the drag force on the tripod. It is calculated to be more than twice the buoy drag force. The parabolic weights are less significant in drag considerations. However, at small currents, 0 to 0.4 knots, the drag forces on the tripod, buoy and weights are completely overshadowed by the antenna drag forces due to wind if there is a significant wind (10 knots or more).

B. EFFECT OF WIND LOADS ON HORIZONTAL DISPLACEMENT

The next simulation considered the effect of wind loads on the horizontal displacement of the buoy. An ocean current of zero was assumed. The wind velocity was taken to be 5, 10, 17 and 30 knots respectively. The results can be seen in Figure 9. The mooring line node loci are linear, which is to be expected having only a wind induced force at the top of the cable parallel to the surface.

The relationship between the change in wind velocity versus displacement is similar in form to that of the change in current versus the change in displacement because the basic hydrodynamics are the same. At wind loads from approximately 0 to 20 knots the relation is parabolic, and at higher wind velocities it appears to become more linear. Winds up to 40 knots were studied and the apparent linear relation held.

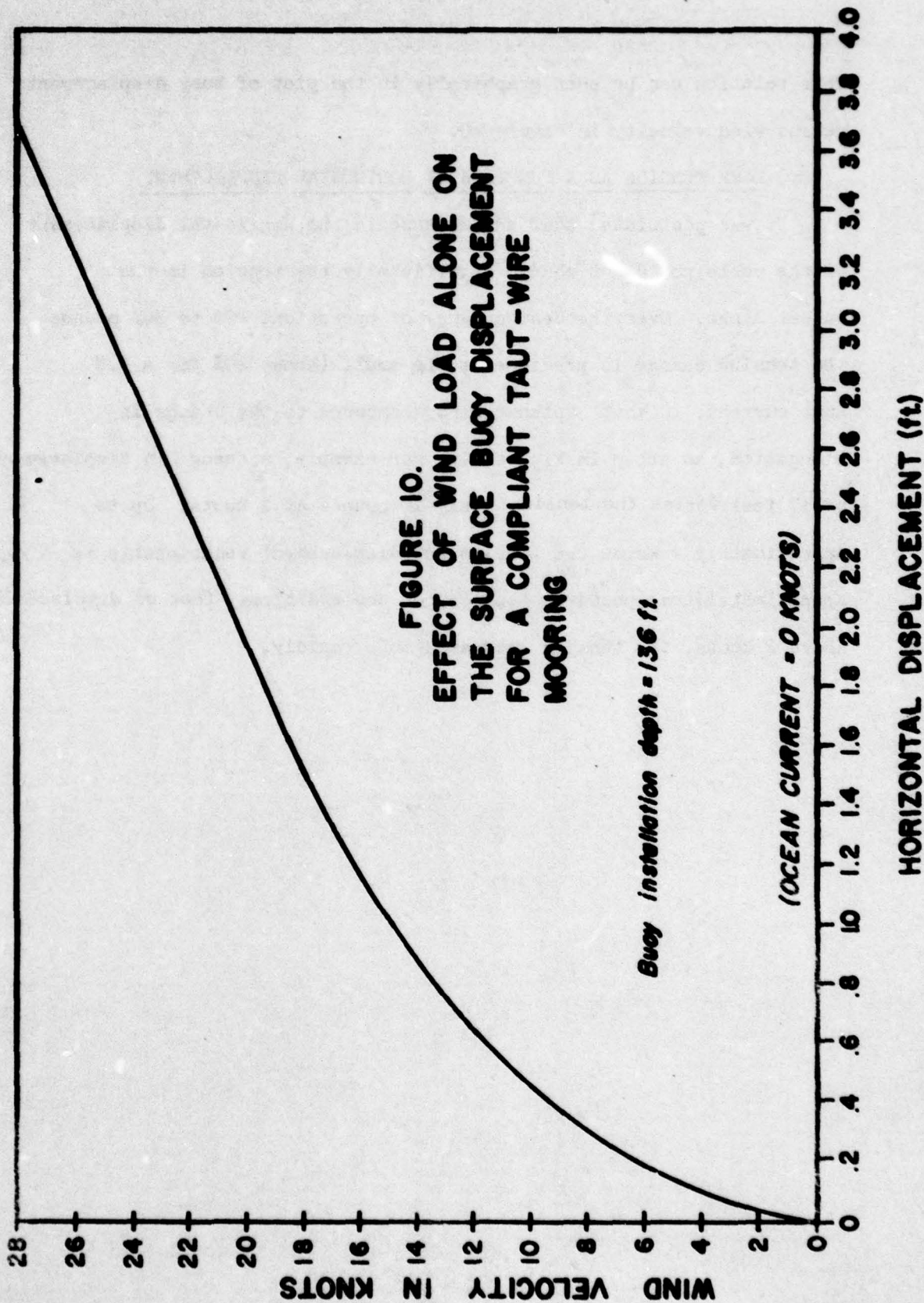


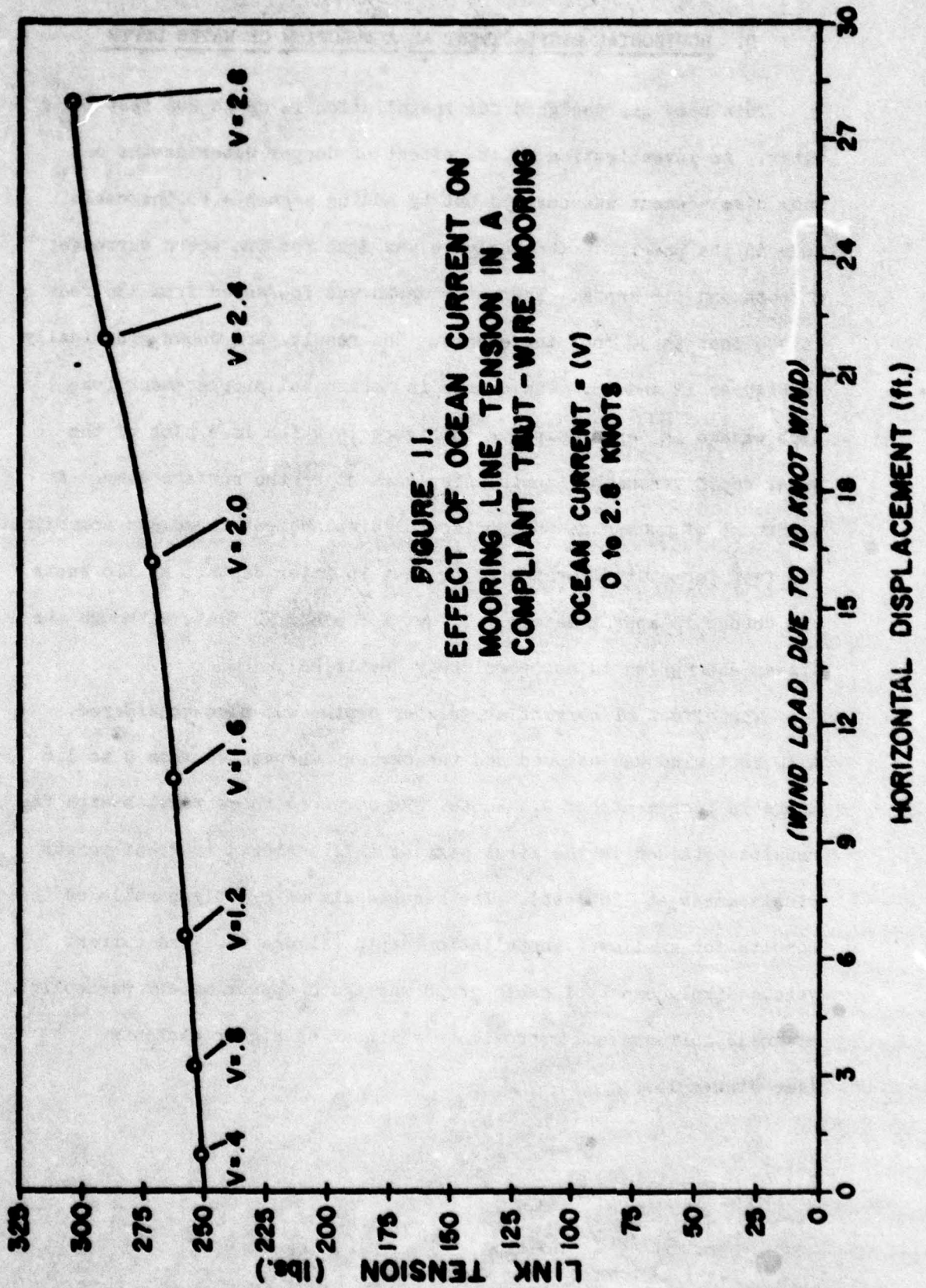


This relation can be seen graphically in the plot of buoy displacement versus wind velocity in Figure 10.

C. LINK TENSION AS A FUNCTION OF HORIZONTAL DISPLACEMENT

It was postulated that an increase in the horizontal displacement of the cable would not change significantly the tension in the rubber links. Over the design range of operation, 250 to 300 pounds, the tension change is predicted to be small (about 20% for a 2.8 knot current; 10 knot coplanar wind) compared to the change in elongation, as shown in Figure 11. For example, a change in displacement of 17 feet varies the tension only 18 pounds at 2 knots. Up to approximately 2 knots the tension and displacement relationship is approximately one pound of tension per one additional foot of displacement. Above 2 knots, the tension increases more rapidly.

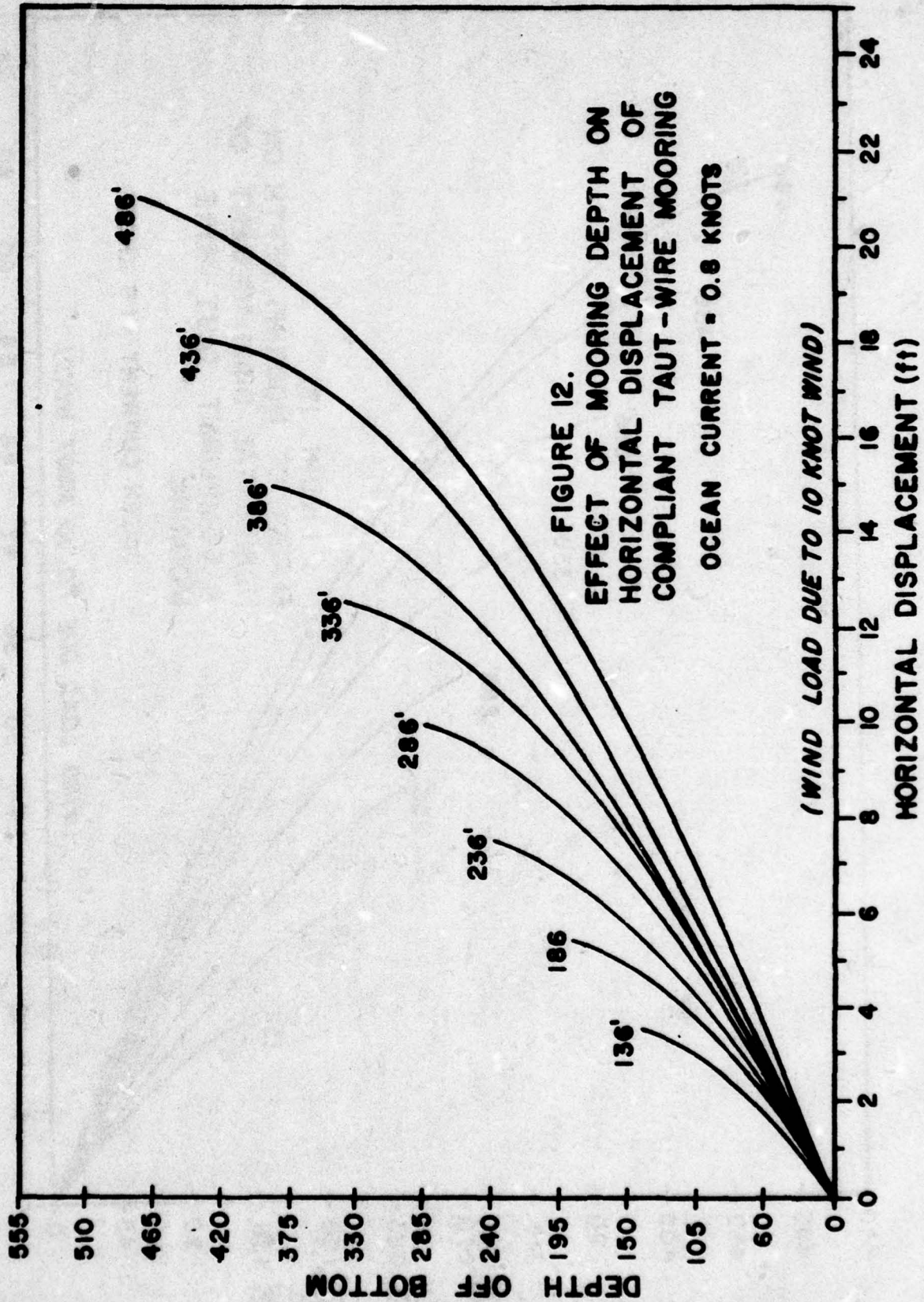


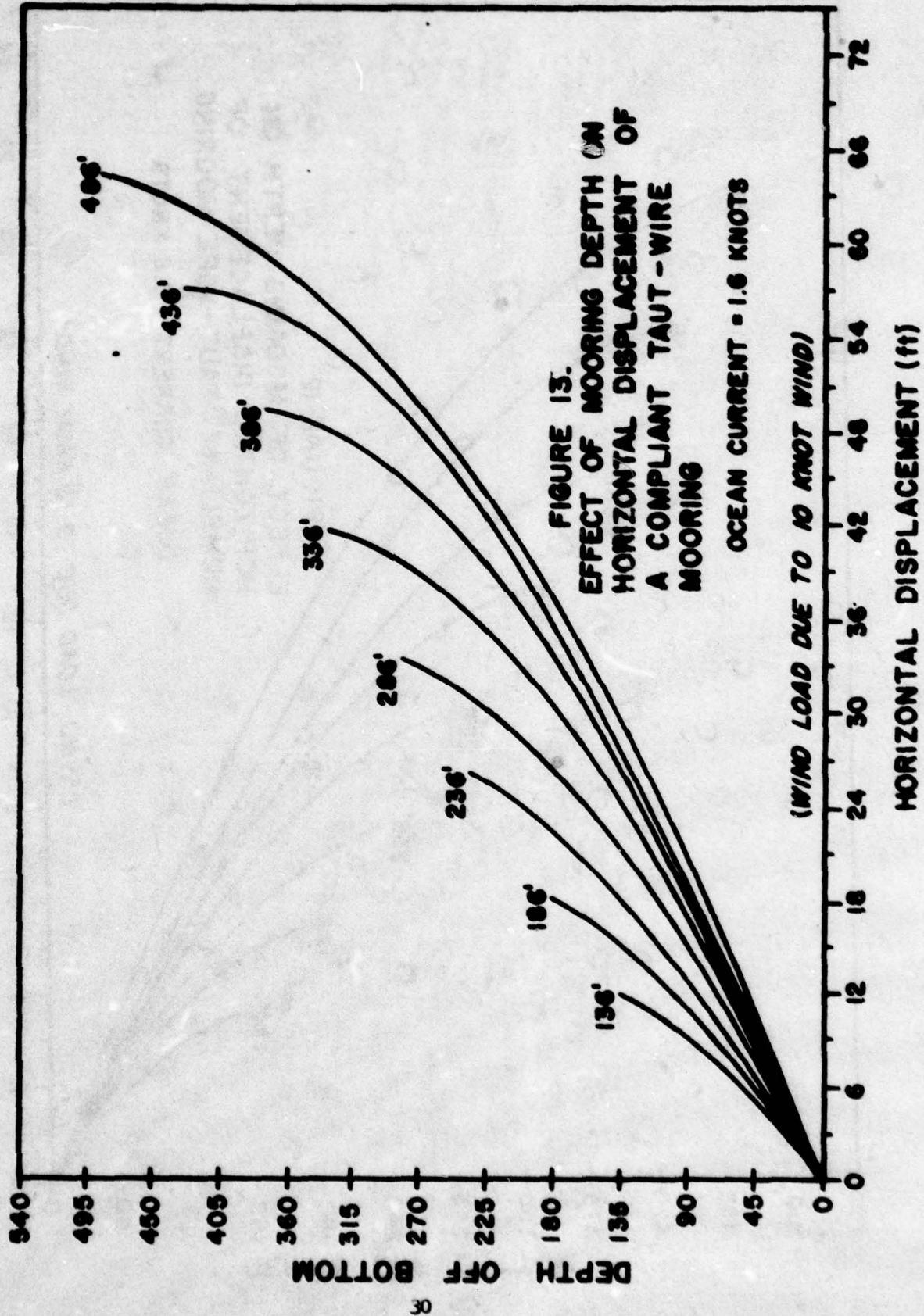


D. HORIZONTAL DISPLACEMENT AS A FUNCTION OF WATER DEPTH

This buoy was designed for installation in up to 200 feet of water. An investigation of the effect of deeper water depths on buoy displacement was carried out by adding segments to the cable node in the program. The analysis was done for two ocean currents: 8 knots and 1.6 knots. The water depth was increased from 136 feet to 486 feet in 50 foot increments. The results are shown graphically in Figures 12 and 13. The change in horizontal displacement for each change in depth is shown in Figure 14 which is a plot of the water depth versus horizontal displacement of the surface buoy. At a current of 0.8 knots, the horizontal displacement increases approximately 2.5 feet for every increase of 50 feet in water depth. At 1.6 knots the change is approximately 7.6 feet for every 50 feet, although the linear assumption is not completely justified.

The effect of current at greater depths was also considered. A 10 knot wind was assumed and the current was varied from 0 to 1.6 knots in increments of 0.4 knots. We compared these results with the results obtained in the first part of this analysis (current versus displacement at 136 feet). The results almost exactly paralleled the results for shallower installation depth (Figure 6). The current versus displacement of cable graph was again approximately parabolic at small currents and approximately linear at higher currents (see Figure 15).





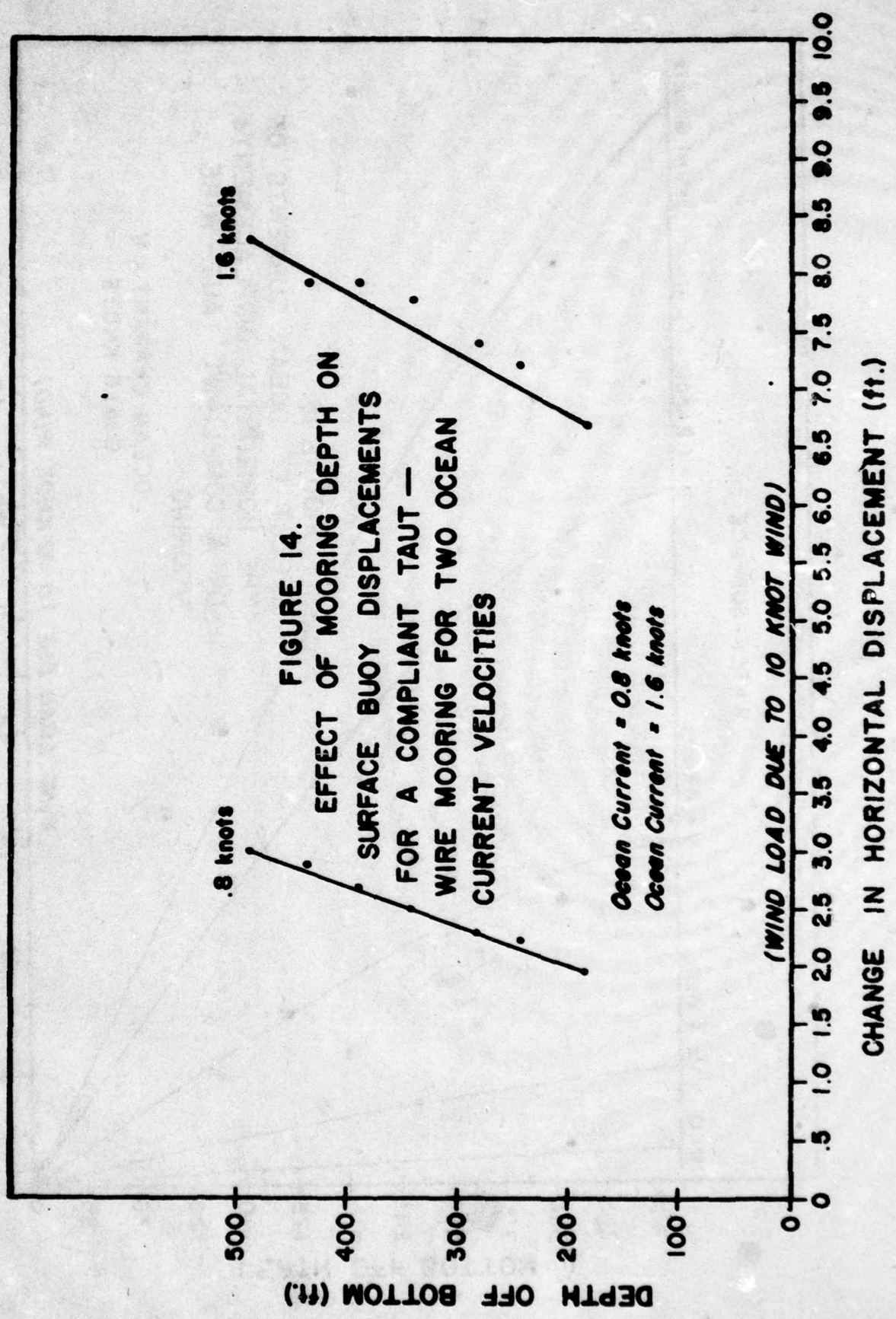
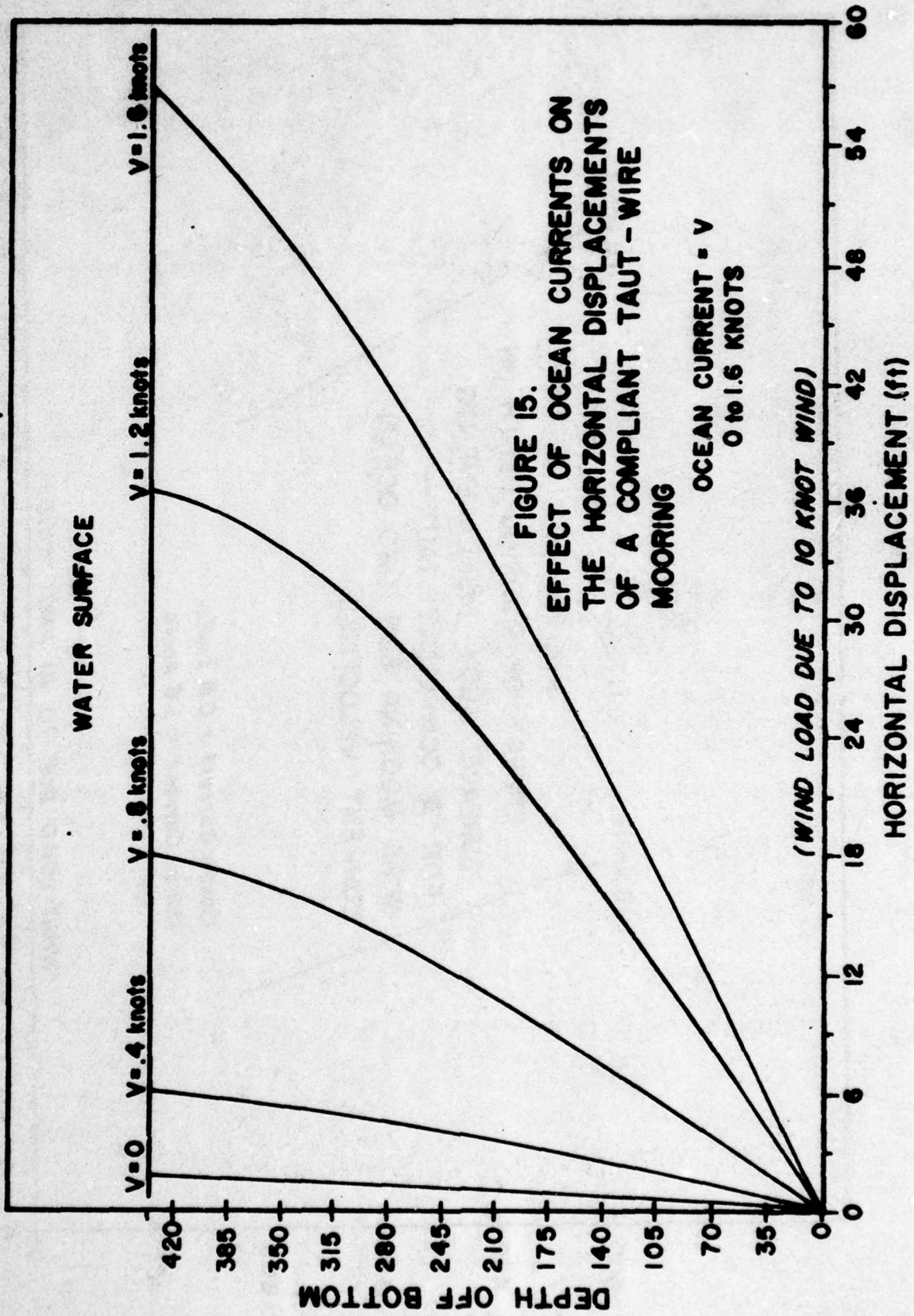


FIGURE 14.
EFFECT OF MOORING DEPTH ON
SURFACE BUOY DISPLACEMENTS
FOR A COMPLIANT TAUT —
WIRE MOORING FOR TWO OCEAN
CURRENT VELOCITIES

Ocean Current = 0.8 knots
Ocean Current = 1.6 knots

(WIND LOAD DUE TO 10 KNOT WIND)

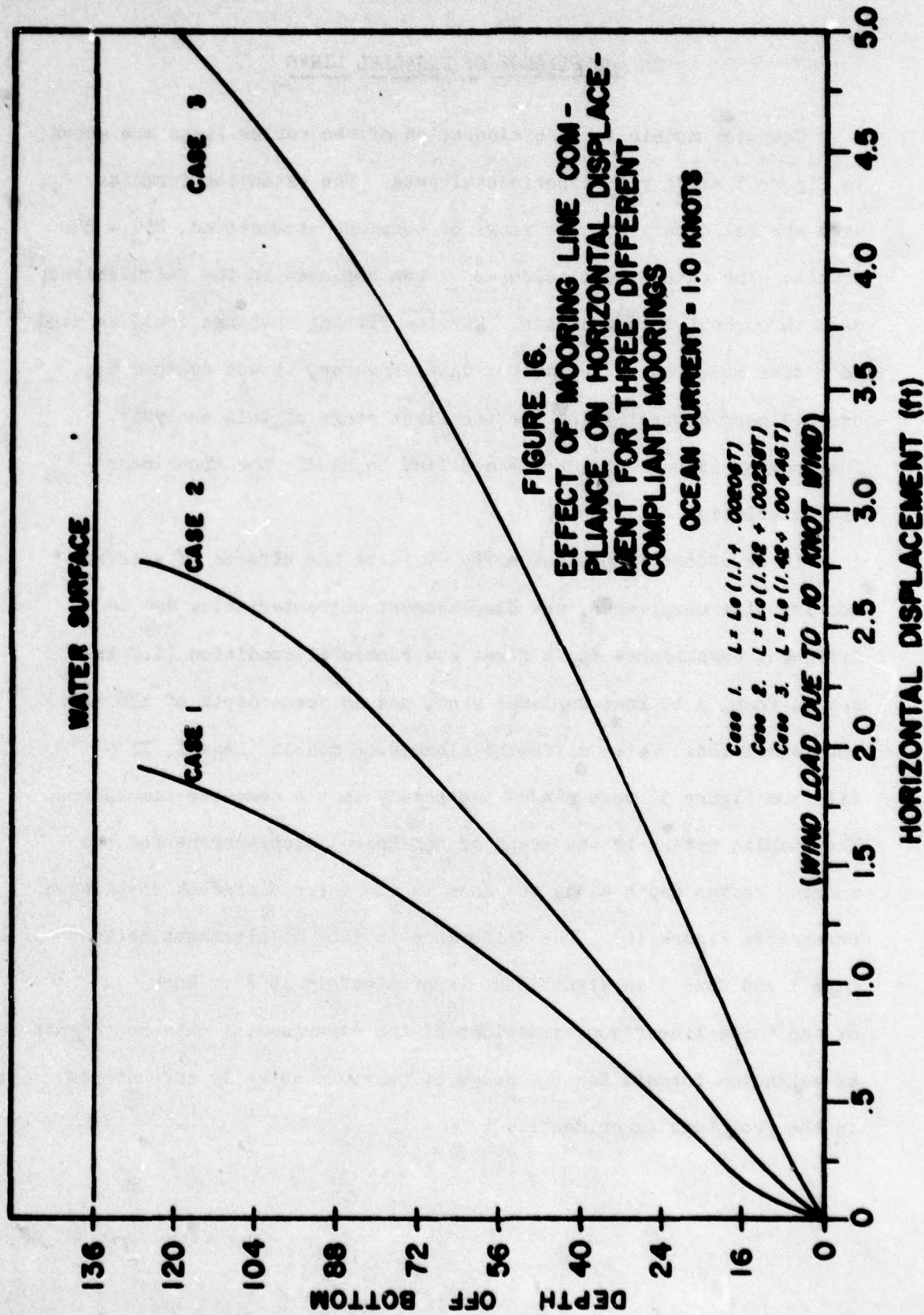
CHANGE IN HORIZONTAL DISPLACEMENT (ft.)



E. COMPLIANCE OF PARALLEL LINKS

Computer models for the elongation of the rubber links are shown in Figure 5 along with experimental data. The extension formulas used are valid only for the range of tensions encountered, 250 - 300 pounds. The case 3 compliance model was employed in the calculations used throughout this analysis. Curving fitting routines could be used to better model the experimental data; however, it was decided to use a linear approximation for the first stage of this analysis. The program is currently being modified to handle the non-linear characteristic.

In an effort to preliminarily evaluate the effects of altered mooring line compliance, the displacement characteristics due to different compliances for a fixed environmental condition (1.0 knot sea current, a 10 knot coplanar wind, and an ocean depth of 136 feet) were simulated. Three different elongation models (Case I, II & III from Figure 5) were placed separately in the computer simulation. The results appear in the graph of horizontal displacement for the mooring versus depth along the moor in the three different compliance cases (see Figure 16). The difference in buoy displacement between Case 1 and Case 3 is significant (approximately 150%). Each of the three linear approximations of the experimental data represents an extension formula for the range of tensions actually encountered in the prototype experiments.



F. Comparison of Simulation with Experiment

In Reference 3, a series of experiments are reported in which a buoy of a design similar to that used in the computer simulation was used. The results of the "Open Sea Tests" are summarized below:

"Open Sea Tests (Isles of Shoals Tests) These tests were conducted in the open ocean with sea conditions up to about state 3-4 seas, with measured winds up to 18 knots, surface currents up to 0.8 knots, and tidal variations of 8.5 feet with a water depth of 140 feet (mean low water). Under these conditions, the 3σ - buoy position error was ± 9.15 feet (calculation based on all data recorded for this site through 10 September - the 12 September data was not used since only one of the four rubber links in the mooring was intact) about the mean position, or a 3σ - buoy position watch circle of 18.3 feet. All recorded data fell within a watch circle of 16.4 feet. The antenna vertical inclination stayed within a cone of $\pm 8^\circ$, while the vertical heave acceleration never exceeded 6 ft./sec.²

In general, the winds were coplanar with the ocean currents (which averaged 0.56 knots during this time with a 3σ of ± 0.32 , or an upper 3σ limit of 0.88 knots).

The results reported in Reference 3 are statistical in form, and hence are not directly comparable to the results from the deterministic computer model. However, using the extreme values of 0.88 knots current, 18 knots of coplanar wind, and a water depth of 136 feet, the computer model predicts a maximum radial displacement of 4.9 feet (using Figures 8 and 9) whereas the experimental maximum excursion for all data was 8.2 feet. Thus the computer simulation prediction is only 60% of the measured value. The comparison, however, is not fully justified since the in situ experiment encountered variability in ocean current direction, wind waves, and wind, and hence the experiment was conducted on a statistical basis using a large number of data points to predict behavior. The comparison between computer simulation and experiment should be considered only as an indication of the possible validity of the model. Controlled experiments should be conducted to more adequately validate the computer simulation.

Pladars⁴, who reanalyzed some of the data reported in Reference 3, found a similar difference between experimental results and computer model.

IV. SUMMARY AND RECOMMENDATIONS

The computer simulation reported herein is not intended to be an exhaustive or general design study. The impetus for the study was a specific buoy system configuration, upon which considerable experimentation had been conducted. The computer simulation was conceived as a way to predict, in a general manner, the behavior of a typical compliant mooring. While a comprehensive study to validate the computer simulation against experiment would be extremely desirable, the data obtained during experiment is not presently in a form that lends itself to such a study. The simple comparison which is made indicates a prediction by computer simulation which is 60% of the value experimentally determined. A carefully designed experiment is still needed to corroborate this computer model.

Since the model has not been adequately validated against experiment, the results contained in this report should be considered only as predicting behavior in a general way. A reanalysis of the in situ data, on a point by point basis, could possibly lead to a more adequate validation of the model, but such is beyond the scope of the work reported herein.

The essence of this report is contained in Section III. This section discusses the computer simulation of:

- 1) Effects of ocean currents on horizontal displacements
(subsection A)
- 2) Effects of wind loads on horizontal displacements
(subsection B)

- 3) Link tension as function of ocean current (subsection C)
- 4) Horizontal excursions as function of water depth and currents (subsection D)
- 5) Effect of elastic characteristics on horizontal displacements, as function of ocean currents (subsection E)
- 6) Short discussion of the computer simulation as compared to experimental data (subsection F)

It is recommended that serious thought be given to the validation of this and other computer simulations of buoy moorings. There are numerous analytical models; however, very limited experimental corroboration of the analysis. The prototype experiment in Reference 3 was designed for purposes other than validation of this computer model. However, future studies should include instrumentation which will provide data to correlate theoretical prediction with actual behavior. It may be that laboratory experiments are required prior to full-scale studies, since open sea tests do not often provide controlled conditions.

APPENDIX I

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APPENDIX II

DESIGN DATA FOR PROTOTYPE BUOY USED IN THE COMPUTER STUDY

The buoy system selected for this computer study is described in detail in Reference 3. As an aid to understanding the actual buoy system used in this study, some design details are listed below.

The buoy system details, needed to understand the results of the computer study, consist of:

- 1) Surface Buoy
- 2) Antenna
- 3) Mooring Bridle
- 4) Compliant Taut-Wire Mooring
- 5) Anchor

Surface Buoy

The surface buoy consists of a horizontal altitude parabolic configuration,* which is basically eight feet in diameter. To accommodate the instrumentation systems, four 12" dia. x 32" deep instrument compartments were designed into the buoy. The buoy is constructed of aluminum with spun parabolic heads. The welded buoy is polyurethane foam filled to assure buoyancy. The aluminum is treated for corrosion resistance and painted with epoxy paint. The buoy, antenna, and tripod legs are shown in Figure I.

*Model 8-200 Manufactured by Prodelin, Inc., Hightstown, N. J.

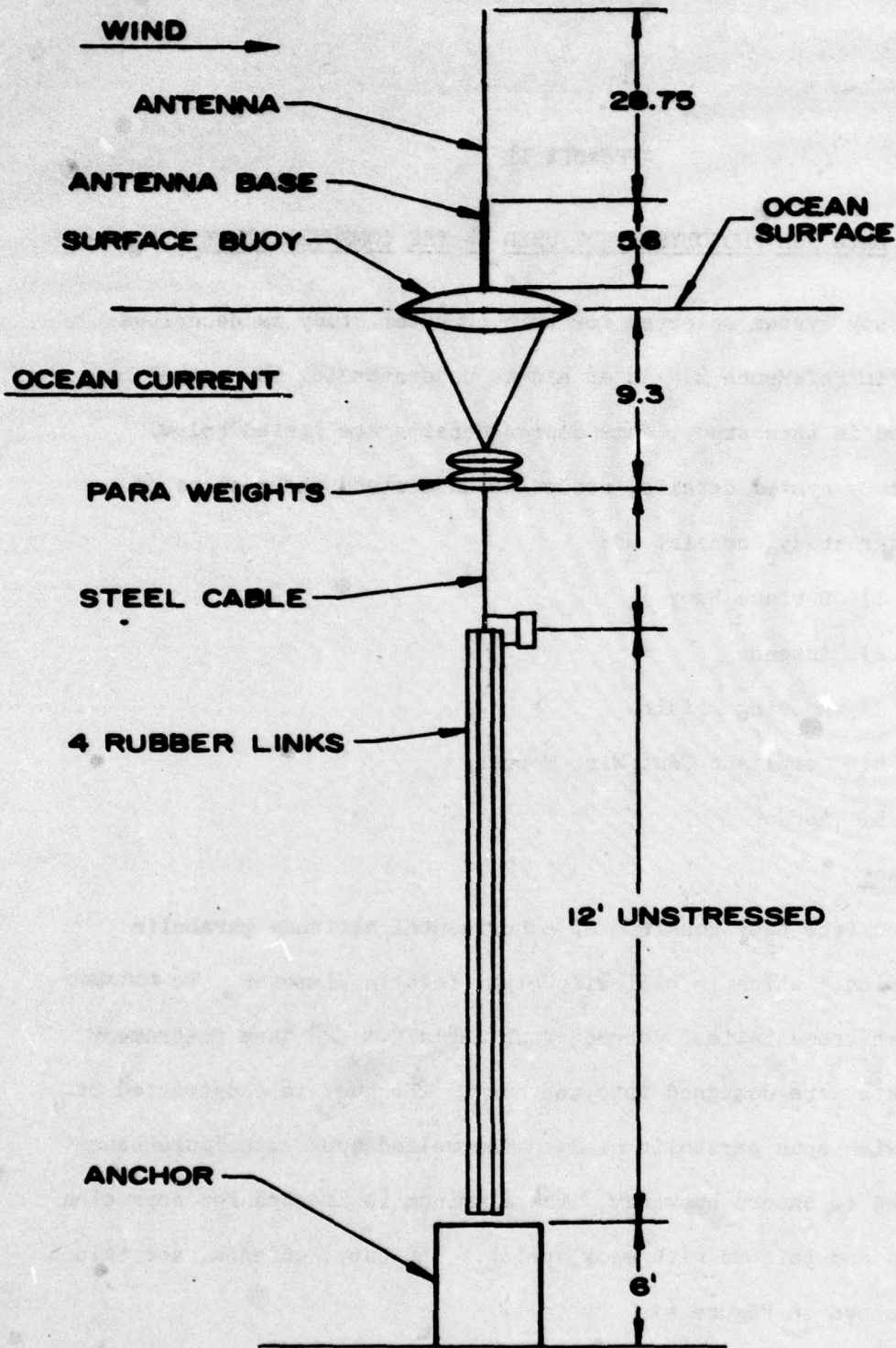


FIGURE I
 Mooring Details for Shallow Water (52') Installation

Antenna

For this study, a Columbia* Model 222 was modified to produce a 30 foot (effective r.f. length) antenna. This fiberglass antenna was mounted on a five-foot (5') aluminum stand-off, which placed the top of the antenna approximately 36' above the ocean surface. The upper 11' of the antenna was not given additional support; however, considerable effort was made to stabilize the lower parts of the antenna. Four diamond spreaders were placed in quadrature between the antenna base and a point 18' above the base which is above a known node on the antenna. These spreaders tended to stabilize the antenna from natural frequency oscillations. The antenna was bolted to the five-foot stand-off, which in turn was bolted to the surface buoy mounting flange.

The mid-point of the diamond spreader stabilizer (9' from antenna base) was supported by three guy wires to the surface buoy (guy wires were, in general, 3/32" stainless stranded wire, terminated with r.f. insulators and "nicopress" fittings). In addition, the five foot antenna stand-off was supported by 3, 3/16" guy wires to the surface buoy.

The antenna stand-off also supported the oceanographic buoy warning light, the radar reflector, and the Sea-Fix antenna loading coil.

Mooring Bridle

The buoy was designed to operate with a tripod mooring bridle,

*Manufactured by Columbia Products, Inc., Columbia, South Carolina.

approximately 8'2" in height. The bridle (see Figure I.) is essential to the operation of the buoy, since it provides the necessary righting moments for the specified vertical stability. The 1 5/6" galvanized tripod legs are bolted to the surface buoy at one end and to an apex yoke at the other. The yoke provides the mooring point as well as a mounting point for the dynamic stabilizing weights (shown in Figure I. as "Para-Weight"). These weights have the effect of substantially increasing the pitch/roll moment of inertia, which is required for dynamic stability.

Mooring

The taut-wire mooring was one of the critical components in the design. Because of the wide range of expected water depths and tidal conditions, the mooring must be capable of accommodating length changes. The study of moorings was focused on methods of overcoming tidal variations while still maintaining mooring tension and essentially a constant buoy waterline. As a part of a research program associated with the Seaspider effort of the Office of Naval Research, the U. N. H. design group had been studying techniques to develop quasi-constant tension taut-wire moorings. The first major application of the quasi-constant tension taut-wire mooring was developed for Seaspider I. The basic principle in these moorings is to use a spring-like material with high compliance compared to the deflections anticipated in a design. This fact can be easily seen from the basic linearized relationship for

a spring-like material: Force (F) = $\frac{\text{displacement (x)}}{\text{compliance } \left(\frac{1}{K}\right)}$

Therefore:

$$\frac{df}{F} = \frac{dx}{x}$$

which indicates that the % change in displacement results in an equal change in force. Therefore, the length of the spring-like material under load must be large compared to tidal variations (say 10 feet), or the material must be highly compliant (note: a constant force spring is infinitely compliant).

There are numerous ways of obtaining this compliance. In an operational buoy system, one can imagine a constant tension winch on the mooring cable, which would serve both for storing of the mooring cables as well as providing the constant tension.

For the prototype evaluation, a relatively simple approach was used. The mooring used four (4) one-inch (1") diameter solid NATSYN rubber rods, configured as shown in Figures I & II. For the load levels used, (approximately 2000 lb.) this rubber produces approximately 2.0 lb. per percent elongation per rubber rod, which for this mooring resulted in a force change of 50 lb/ft of water depth change. For example, a 10-foot tide would change the mooring tension by 500 lb. This tidal effect results in the buoy waterline change of 2 inches which is negligible.

The rubber links were secured to the anchor with self-aligning mounting yokes and shackles. A standard underwater swivel was used to eliminate torsional rotation problems. All shackles were of the seizable type.

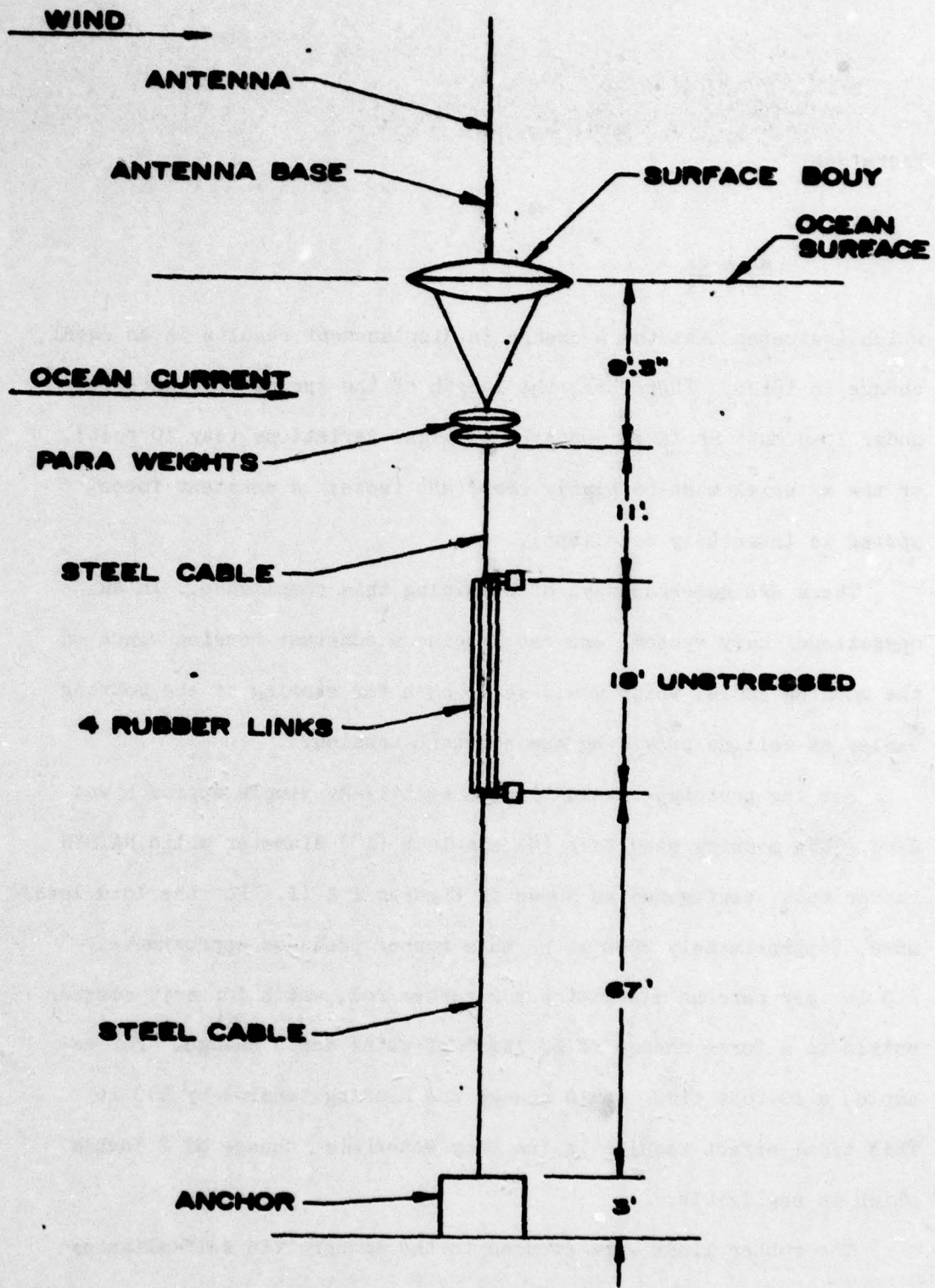


FIGURE II

Mooring Details for Deeper Water (140') Installation

Anchoring

The anchors used were of the dead-weight type and were of a design similar to those reported in Reference 8.

APPENDIX III

COMPUTER PROGRAM LISTING

PAGE 1

// JOB

LOG DRIVE	CART SPEC	CART AVAIL	PHY DRIVE
0000	1DOC	1DOC	0000

V2 M08 ACTUAL 8K CONFIG 8K

// FOR

#LIST SOURCE PROGRAM

C DISPLACEMENT ANALYSIS OF A TAUT WIRE PARABOLIC BUOY

C

C A = ANGLE OF TRIPOD LEG FROM VERTICAL

C ASBUOY = SUBMERGED CROSS-SECTIONAL AREA OF BUOY

C ATBUOY = TOTAL CROSS-SECTIONAL AREA OF BUOY

C

C B = 30-DEGREE ANGLE IN TRIPOD GEOMETRY

C

C CDBUOY = BUOY DRAG COEFFICIENT

C CDCAB(N) = CABLE SEGMENT DRAG COEFFICIENT NORMAL TO CABLE

C CDPRBL = PARABOLIC WEIGHT DRAG COEFFICIENT

C CDTRPD = TRIPOD LEG DRAG COEFFICIENT NORMAL TO LEG

C CONST(N) = EXPERIMENTAL ELONGATION CONSTANT FOR CABLE SEGMENT

C COSTH(N) = COSINE OF ANGLE BETWEEN CABLE SEGMENT AND VERTICAL AT

C

THE N-TH NODE

C

C D(N) = DIAMETER OF CABLE SEGMENT UNDER TENSION

C DBUOY = DIAMETER OF BUOY

C DE(N) = (2 * CD * DIA * LENGTH) FOR THE ELEMENT

C DELE = CUT-OFF VALUE FOR ERROR FUNCTION

C DELTA = POSITIVE CONVERGENCE FACTOR

C DELXY = DESIRED ACCURACY FOR COORDINATES

C DEPTH = DEPTH OF WATER

C DIA(N) = ORIGINAL UNSTRESSED DIAMETER OF CABLE SEGMENT

C DPRBL = DIAMETER OF PARABOLIC WEIGHTS

C DTRPD = DIAMETER OF TRIPOD LEGS

C

C E = ERROR FUNCTION

C

C FBBUOY = BUOYANCY FORCE OF BUOY

C FBCAB = BUOYANCY FORCE OF TOP HALF SEGMENT OF CABLE

C FBPRBL = BUOYANCY FORCE OF PARABOLIC WEIGHTS

C FBTRPD = BUOYANCY FORCE OF TRIPOD

C FBY(N) = BUOYANCY FORCE OF CABLE SEGMENT

C FCY(N) = VERTICAL FORCE ON CABLE SEGMENT DUE TO CURRENT

C FCYCAB = VERTICAL FORCE ON TOP HALF SEGMENT OF CABLE DUE TO CURRENT

C FWY(N) = WEIGHT OF CABLE SEGMENT IN AIR

C FX(N) = HORIZONTAL FORCE ON CABLE SEGMENT DUE TO CURRENT

C FXBUOY = HORIZONTAL FORCE ON BUOY DUE TO CURRENT

C FXCAB = HORIZONTAL FORCE ON TOP HALF SEGMENT OF CABLE DUE TO CURRENT

C FXMAST = HORIZONTAL FORCE ON ANTENNA DUE TO WIND

C FXPRBL = HORIZONTAL FORCE ON PARABOLIC WEIGHTS DUE TO CURRENT

C FXTRPD = HORIZONTAL FORCE ON TRIPOD DUE TO CURRENT

C FY(N) = TOTAL VERTICAL FORCE ON CABLE SEGMENT

PAGE 3

C LBS., YA IN FT.

C

31 READ(1,101)RHOWAT,RHOAIR,WTSYST,YA,NS
101 FORMAT(4F10.6,19)

C

C

C

C

DO 16 N=1,NS

16 READ(1,102)LORIG(N),DIA(N),WCAB(N),CDCAB(N),CONST(N),KE(N),NL(N),
1DE(N),WE(N)

102 FORMAT(6F10.5,F5.0,F10.5,F5.2)

READ(1,105)CDBUOY,CDPRBL,CDTRPD

105 FORMAT(3F5.3)

WRITE(3,301)

WRITE(3,302)

302 FORMAT(T11,'PROPERTIES OF THE CABLE'////)

DO 10 N=1,NS

WRITE(3,303)N

303 FORMAT(T11,'CABLE SEGMENT',I2/)

10 WRITE(3,304)LORIG(N),DIA(N),WCAB(N),CDCAB(N),CONST(N),KE(N),NL(N)

304 FORMAT(T16,'ORIGINAL LENGTH',F10.5,' FEET'/T16,'ORIGINAL DIAMETER'

1,F10.5,' INCHES'/T16,'WEIGHT',F10.5,' POUNDS PER FOOT'/T16,'DRAG C

2OEFFICIENT',F10.5/T16,'ELONGATION CONSTANT',F10.5/T16,'INVERSE ELA

3STIC MODULUS',F10.5/T16,'NUMBER OF PARALLEL LINKS',F4.0//)

J=NS-1

DO 17 N=1,NS

LT(N)=LORIG(N)

DIA(N)=DIA(N)/12.

17 D(N)=DIA(N)

C

C

C

INITIALIZE SYSTEM DIMENSIONS

TBUOY=32./12.

DBUOY=96./12.

DTRPD=1.31/12.

LTRPD=98./12.

TPRBL=4.6875/12.

DPRBL=1.

WRITE(3,301)

301 FORMAT(1H1)

WRITE(3,312)

312 FORMAT(T11,'PROPERTIES OF THE BUOY'////)

WRITE(3,313)TBUOY,DBUOY,TPRBL,DPRBL,DTRPD,LTRPD,WTSYST

313 FORMAT(T16,'BUOY THICKNESS',F10.5,' FEET'/T16,'BUOY DIAMETER',F10.

15,' FEET'/T16,'PARABOLIC WEIGHT THICKNESS',F10.5,' FEET'/T16,'PARA

2BOLIC WEIGHT DIAMETER',F10.5,' FEET'/T16,'DIAMETER OF TRIPOD LEGS'

3,F10.5,' FEET'/T16,'LENGTH OF TRIPOD LEGS',F10.5,' FEET'/T16,'WEIG

4HT OF CABLELESS BUOY SYSTEM',F10.4,' POUNDS',1X)

C

C

C

COMPUTE TOTAL VOLUME AND CROSS-SECTIONAL AREA OF BUOY

VTBUOY=3.*PI*TBUOY**2

PAGE 4

ATBUOY=2.*TBUOY*DBUOY/3.
A=ARSIN(97./98.)
B=0.5235988

C
C
C

READ IN DEPTH IN FEET, VELOCITY OF CURRENT AND WIND IN KNOTS

104 READ(1,103)DEPTH,VWAT,VAIR
103 FORMAT(3F10.2)

C
C
C
C

NEGATIVE NUMBER FOR DEPTH ALLOWS FOR COMPLETE RECYCLE OF INPUTS,
BLANK CARD TERMINATES PROGRAM

IF(DEPTH)31,100,21
21 VWAT=1.68894*VWAT
VAIR=1.68894*VAIR
VWATSQ=VWAT**2
VSBUOY=VTBUOY/2.
ASBUOY=ATBUOY/2.
YCAB=DEPTH - 9.3
LOOPE=0
LOOPA=0
MUWAT=RHOWAT * VWATSQ / 4.

C
C
C

COMPUTE CONSTANT FORCES (POSITION INDEPENDENT)

FXMAST=0.012931*ABS(VAIR)*VAIR
FXTRPD=0.5*CDTRPD*RHOWAT*DTRPD*LTRPD*(COS(A)**3+2*(COS(B)**3+SIN(B)**3)*COS(A)**3)*VWATSQ
FXPRBL=2.*0.5*RHOWAT*CDPRBL*2.*TPRBL*DPRBL*VWATSQ/3.
FBTRPD=3.*RHOWAT*32.174*PI*DTRPD**2*LTRPD/4.
FBPRBL=2.*RHOWAT*32.174*PI*TPRBL*DPRBL**2/16.
FBCAB=RHOWAT*32.174*PI*DIA(NS)**2*LORIG(NS)*NL(NS)/4.
DO 13 N=1,J
FWY(N)=(LORIG(N)*WCAB(N)*NL(N)+LORIG(N+1)*WCAB(N+1)*NL(N+1))/2.+
1WE(N)
13 FBY(N)=RHOWAT*32.174*PI*(DIA(N)**2*LORIG(N)*NL(N)+DIA(N+1)**2*
1LORIG(N+1)*NL(N+1))/8.

C
C
C

COMPUTE POSITION DEPENDENT FORCES

FCYCAB=MUWAT*CDCAB(NS)*D(NS)*LT(NS)*SINTH(NS)*COSTH(NS)**2*NL(NS)
18 LEAP=1
FXBUOY=0.5*RHOWAT*CDBUOY*ASBUOY*VWATSQ
FXCAB=MUWAT*CDCAB(NS)*D(NS)*LT(NS)*COSTH(NS)**3*NL(NS)
FX(NS)=FXMAST+FXBUOY+FXTRPD+FXPRBL+FXCAB
FBBUOY=RHOWAT*32.174*VSBUOY
FY(NS)=FBBUOY+FBPRBL+FBTRPD+FBCAB-WTSYST-FCYCAB
DO 11 N=1,J
FX(N)=MUWAT*(CDCAB(N)*D(N)*LT(N)*COSTH(N)**3*NL(N)+(CDCAB(N+1)*D(N+1)*
1LT(N+1)*NL(N+1)+DE(N))*COSTH(N+1)**3)
FCY(N)=MUWAT*(CDCAB(N)*D(N)*LT(N)*SINTH(N)*COSTH(N)**2*NL(N)+CDCAB
1(N+1)*D(N+1)*LT(N+1)*SINTH(N+1)*COSTH(N+1)**2*NL(N+1))
11 FY(N)=FBY(N)-FWY(N)-FCY(N)

PAGE 5

```
C
C   COMPUTE RESULTANT FORCES
C
3  RX(NS)=FX(NS)
   RY(NS)=FY(NS)
   DO 9 M=1,J
     N=J-M+1
     RX(N)=FX(N) + RX(N+1)
9  RY(N)=FY(N) + RY(N+1)

C
C   COMPUTE SEGMENT TENSIONS AND LENGTHS UNDER TENSION
C
DO 7 N=1,NS
T(N)=SQRT(RX(N)**2+RY(N)**2)
LT(N)=LORIG(N)*(1.0+CONST(N)+T(N)*KE(N)/NL(N))
IF(LT(N)/LORIG(N).LT. 1.1) GO TO 8
D(N)=DIA(N)*SQRT(LORIG(N)/LT(N))
8  SINTH(N)=RX(N)/T(N)
   COSTH(N)=RY(N)/T(N)

C
C   COMPUTE NODE COORDINATES
C
GO TO (4,5),N
5  X(N)=LT(N)*SINTH(N)+X(N-1)
   Y(N)=LT(N)*COSTH(N)+Y(N-1)
GO TO 7
4  X(N)=LT(N)*SINTH(N)+XA
   Y(N)=LT(N)*COSTH(N)+YA
7  CONTINUE
   LOOPE=LOOPE+1

C
C   COMPUTE AND COMPARE ERROR FUNCTION
C
E=(YCAB-Y(NS))**2
IF(E.GT.DELE) GO TO (19,50,15),LEAP
DO 55 N=1,J
IF(ABS(X(N)-XO(N)).GT.DELXY.OR.ABS(Y(N)-YO(N)).GT.DELXY) GO TO 57
55 CONTINUE

C
C   COORDINATE ACCURACY SATISFIED - WRITE RESULTS
C
WRITE(3,301)
WRITE(3,305)
305 FORMAT(T11,'BUOY AND CABLE CONFIGURATION UNDER CURRENT AND WIND'/T
135,'CONDITIONS'///)
WRITE(3,306)X(NS),DEPTH,VWAT,RHOWAT,VAIR,RHOAIR
306 FORMAT(T16,'BUOY HORIZONTAL DISPLACEMENT IS',F10.3,' FEET'/T16,'DE
1PTH OF WATER IS',F10.3,' FEET'/T16,'VELOCITY OF WATER IS',F10.5,'
2FEET PER SECOND'/T16,'DENSITY OF WATER IS',F10.5,' SLUGS PER CU.FT
3.'/T16,'VELOCITY OF AIR IS',F10.5,' FEET PER SECOND'/T16,'DENSITY
4OF AIR IS',F10.5,' SLUGS PER CU.FT. '/')
H=12.*H
WRITE(3,314)FXMAST,FXBUOY,FXTRPD,FXPRBL,H
```

PAGE 6

314 FORMAT(T16,'ANTENNA DRAG IS',F10.5,' POUNDS'/T16,'BUOY DRAG IS',F10.5,' POUNDS'/T16,'TRIPOD DRAG IS',F10.5,' POUNDS'/T16,'PARABOLIC 2WEIGHT DRAG IS',F10.5,' POUNDS'/T16,'WATERLINE IS',F5.2,' INCHES FROM TOP OF BUOY'////)

DO 39 N=1,NS
T(N)=T(N)/NL(N)

39 WRITE(3,311)N,X(N),Y(N),N,T(N),N,FX(N)

311 FORMAT(T16,'COORDINATES FOR NODE ('I2.')

ARE X=',F10.5,' FEET, Y=',F10.5,' FEET'/T21,'TENSION IN SEGMENT ('I2.')

IS',F10.3,' POUNDS'/T21,'HORIZONTAL FORCE AT NODE ('I2.')

DUE TO CURRENT IS',F10.3,' POUNDS'//)

WRITE(3,308)LOOPE,LOOPA,E,DELTA

308 FORMAT(T11,'NUMBER OF ERROR LOOPS =',I5,T45,'NUMBER OF ITERATION L
LOOPS =',I5//T11,'ERRCR FUNCTION =',E14.7/T11,'DELTA =',E14.7)
GO TO 104

C
C COORDINATES NOT WITHIN DESIRED ACCURACY - RECORD NODE COORDINATES
C FOR COMPARISON
C

37 DO 37 N=1,J

XO(N)=X(N)

37 YO(N)=Y(N)

C
C RECOMPUTE SUBMERGED BUOY VOLUME AND CROSS-SECTIONAL AREA
C

FCYCAB=MUWAT*CDCAB(NS)*D(NS)*LT(NS)*SINTH(NS)*COSTH(NS)**2*NL(NS)

FBBUOY=FY(NS)+WTSYST+FCYCAB-FBPRBL-FBTRPD-FBCAB

VSBUOY=FBBUOY/(RHOWAT*32.174)

H=SQRT((VTBUOY-VSBUOY)/(6.*PI))

ASBUOY=ATBUOY-8.*H*SQRT(3.*H)/3.

DELTA=FY(NS)

LOOPA=LOOPA + 1

C
C RECOMPUTE POSITION DEPENDENT FORCES
C

GO TO 18

C
C CHECK IF ERROR FUNCTION HAS DECREASED
C

50 IF(E.LT.EP) GO TO 20

C
C IF ERROR FUNCTION HAS NOT DECREASED, DECREASE CONVERGENCE FACTOR
C

DELTA=DELTA/2.

12 DELT=DELTA/SQRT(EP)

C
C CHANGE VERTICAL FORCE TO MOVE END COORDINATE TO DESIRED VERTICAL
C POSITION
C

FY(NS)=FYP+(YCAB-YP)*DELT

IF(FY(NS).NE.FYP) GO TO 3

C
C NO CHANGE IN FORCES - TERMINATE PROGRAM
C

C

```
LEAP=3  
GO TO 3  
15 WRITE(9,301)  
WRITE(9,307)  
307 FORMAT(T11,'PROBLEM IS NOT COMPLETE, DELTA HAS BECOME TOO SMALL TO  
1CHANGE THE IMAGINARY REACTIONS')  
GO TO 100  
19 GO TO (22,23),LOOPE
```

C

C

C

SAVE NODE COORDINATES FOR COMPARISON

```
22 DO 14 N=1,J  
XO(N)=X(N)  
14 YO(N)=Y(N)  
23 LEAP=2
```

C

C

C

SAVE ERROR FUNCTION, CABLE END COORDINATE AND FORCE

```
20 EP=E  
YP=Y(NS)  
FYP=FY(NS)  
GO TO 12  
100 CALL EXIT  
END
```