A TRIDENT SCHOLAR
PROJECT REPORT

NO. 83

"A STUDY TO DETERMINE AN OPTIMAL CONTROL
STRATEGY FOR A MARINE VEHICLE SUBJECTED
TO RANDOM DISTURBANCES"

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"A STUDY TO DETERMINE AN OPTIMAL

CONTROL STRATEGY FOR A MARINE VEHICLE

SUBJECTED TO RANDOM DISTURBANCES"

A Trident Scholar Project Report

by

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ABSTRACT

The specific problem investigated during this project, involved the determination of the near-optimal trajectory, with respect to speed through the water, of a sailcraft subjected to steady-state and random wind and wave forces. The results of the project surpassed existing empirical techniques in that a method was developed for preparing, beforehand, using a set of digital computer programs, an accurate near-optimal performance package for any yacht possessing a valid International Offshore Racing(IOR) certificate. This package can be utilized to accurately predict the yacht's performance for any reasonable set of wind and wave conditions. Theoretical static and dynamic vessel stability was investigated for varying driving forces, wind forces, heeling and righting forces, and varying env' tal conditions. A package of FORTRAN computer programs was developed to: (1) solve the static optimization problem; (2) determine optimum sailing angles to windward for given vessel dimensions, and wind and sea conditions; (3) calculate and plot complete true and apparent wind polar plots of vessel speed through the water for given vessel dimensions, sea state, and wind velocity; and (4) provide a real-time computer-generated video simulation of the vessel motion through the water and in three-dimensions for any arbitrary wind and sea history. Initial experimental verification of the performance package for the U. S. Naval Academy's fifty-eight foot Sparkman & Stevens sloop SYREN indicated extremely close agreement between predicted and actual performance.

PREFACE

As an undergraduate at the United States Naval Academy, my primary responsibility has been to avail myself of every opportunity in order that I might be fully prepared to be commissioned an officer in the United States Navy upon graduation. The mission of the Naval Academy establishes that preparation along three lines: mentally, morally, and physically. I chose to apply for a Trident Research Project in my First Class Year because I saw it as the best means by which I might most fully utilize the facilities here at the Naval Academy in the first of the three areas listed above -- mental preparation.

The Trident Program is one by which a midshipman can augment his major's curriculum, and should be approached in that manner. It has been my perception that too often this program has been used by well-meaning and intelligent persons to provide a substitution or sidetrack. Thus, I was determined to design this project around my major's course of study. In this way, I hoped to avoid such side-tracks, while at the same time greatly enhancing my course of study.

One of the most attractive things about Systems Engineering is its broad application. Almost any physical system can be analyzed using Systems Engineering techniques. The most logical approach, then, was to take a system which

interests me greatly and analyze it. It was in the fall of 1975 when I hit upon that system. Each fall, the Tred Avon Yacht Club of Oxford, Maryland, and the Naval Academy Sailing Squadron co-sponsor an Annapolis to Oxford and return yacht race. While in a thirty foot Shields class keelboat during the fall 1975 race, crashing through three foot seas and driven by twenty to twenty-five knot winds in the middle of the Chesapeake Bay, I suddenly became aware of the complex environment that surrounded me. It was all there: random wave and wind inputs, damping forces, displacement forces, and lift/drag forces. At the time, I had a third year course in Systems Engineering for which I needed to complete a term project. For it, I modeled the lateral dynamics of a system similar to the one represented by the Shields class keelboat. It was from the encouraging results of that project that I decided I would attempt to adopt a Trident Project in my First Class Year. The second chapter of this report is actually an extension of that study made in 1975.

What follows then, is my attempt to mesh together Systems Engineering, Trident Research, and a love for sailing, and in so doing, more completely fulfill the requirements of the major I chose four years ago, gain experience and confidence in independent research, and gain a better understanding of marine vehicles, both sail and

power. In addition, various diverse paths such as the areas
of statistics and ship design were pursued. I am deeply
indebted to my advisor, Assistant Professor Kenneth A.
Knowles, for his assistance and insistance in all matters.
Dr. Hugo Myers of Vienna, Virginia, deserves much of the
credit for the results of this project and certainly my
many heartfelt thanks for the generous loan of his program,
"Theory of Sailing Applied to Ocean Racing Yachts." Dr.
David F. Rogers, Steve Satterfield, and others in the Com-
puter Aided Design and Interactive Graphics Division were
invaluable in helping me display the hardcopy results generated
by my programs. And lastly, to all those who bore the many
frustrating days and nights with me, especially in the last
few weeks of the semester, I am ever grateful. In retrospect,
the Trident Program was for me the means by which I could
most fully carry out the responsibility I have to the Navy
to most effectively utilize the four years at Annapolis.

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CHAPTER ONE

"An Approach to Simulation"

The high seas have provided man with both challenging
occupations as well as fascinating pastimes for generation
upon generation. This combination of occupation and fascination
has led to the continual development of ships over the years,
first in sail and then in power. Ship design has been
aided greatly in the last few decades by the advent of the
h   speed digital computers and interactive graphics tech-
    , yet it still remains very much an art. This is true
in many other related fields as well. One of these areas is
ship simulation, the object of this project.

As the title of the project indicates, a rather broad
subject was chosen to pursue. The first step, then, was to
define the limits of investigation. A specific type of
marine vehicle was needed to center the work around, and due
to the Naval Academy's rapidly growing and nationally
acclaimed sailing team, the simulation of a sailboat under
sail was chosen. Sailing craft are extremely complex
systems affected by countless and continuously varying
forces. The same forces that play havoc with the stability
of merchant and Naval vessels are at work on sailboats, but
the latter have the additional consideration of the forces
generated by the wind on the sails and the optimal use of
that wind. Simulation of this stability and performance
optimization problem for sailboats has been sadly lacking.

Currently there are three major projects under funding in
this area. These projects are headed by, respectively:
Dr. Justin E. Kerwin of the Ocean Engineering Department of
the Massachusetts Institute of Technology; Diana Russell of
Sparkmen and Stephens design firm in New York City; and Dr.
Hugo Myers of I.B.M. Federal Systems Division in Gaithersburg,
Maryland. Dr. Myer's simulation is discussed in Chapter
Three and used extensively in the completion of this project.
Before complex simulations can be studied, however, an
understanding of the problem and the techniques of solving
it is needed. This is the subject of the remainder of this
chapter and Chapter Two.

Simulation usually requires that the physical object
or thought process to be imitated be reduced to a set of
mathematical equations which describe the system's history
and can be used to predict its future status. Whether
dealing with a steady state or a dynamic model of per-
formance, the simulation is often built around simultaneous
equations. In the case of a sailboat, three primary force
equations must be solved. Additionally, the triangle defined
by the apparent wind, true wind, and boat speed must be
satisfied. The three equations deal with the driving and
frictional forces acting on the vessel, the lateral forces
including the hydrodynamic lift of the hull, and the heeling
and righting moment equations. Corresponding to these three
equations are three primary variables:

V_B - speed of the boat in knots

λ - angle of leeway (the angle between the course steered and the course actually sailed) in degrees

θ - angle of heel in degrees

Several other variables are of secondary importance being derived from the above three:

β - angle in degrees between the apparent wind and the boat's actual course

V_A - the apparent wind speed

HEAD - ship's heading

Sketches illustrating these variables and the equations that utilize them can be found in Figures 1 through 4.

Using these variables and equations, a complete simulation model can be built. Ideally, a dynamic model is desired as it will give a continuous display of the motion and attitudes of the craft under study. The steady-state model is analogous to stop-action photography wherein a specific point in time and space is chosen and the model is subjected to the steady conditions existing at the point. After its response is noted, a second point is chosen and the corresponding state of the craft is noted again. In this manner one can observe any specific state he desires. The dynamic model is at an obvious advantage in real-time simulation, just as a movie is a far better representation of reality than a book of snapshots. A trade-off is required, however, because the closer we come to reality with our simulation,

the more complex it becomes.   In the following chapters
the initial simulation of the heeling and righting moment
equations will be dealt with on a dynamic basis, while the
overall model will be dealt with on a steady-state basis.
The heeling and righting moment equation is the simplest
of the three and lends itself well to the initial investi-
gation of the problem of stability.   It also provides the
opportunity to work with a dynamic model on analog and
hybrid computers.   Simulation of the complete system is done
on a steady-state, and in one instance quasi-dynamic, basis
on the digital computer.

CHAPTER TWO

Heeling and Righting Moments

The most pronounced of the three types of motions
exhibited by marine vehicles is that of rolling about
the longitudinal axis. This chapter will deal exclusively
with an analog simulation of that motion as it occurs on
a small boat. The other two motions, pitching and yawing,
are in many ways more important to the optimization of the
speed of the craft through the water. They are also a bit
more complex and will be taken up later.

Studies of heeling and righting moments in the time
domain, or in a dynamic sense, are not generally pursued.
Rather, most authors concentrate on static situations.
Although this is useful in determining the forces on the
craft at any given moment, a model depicting how the
angle of heel changes in time is useful in helping the sailor
understand how quickly his craft will respond and what
kind of actions he will have to take to gain a desired
response. To fill this gap, a model of the lateral movement
about the center of lateral pressure of an "average" sail-
boat is determined as a function of time. The model is
developed for one particular craft, but by the simple
redetermination of the several constants, it is applicable
to any sailboat of similar design.

The design studied is that of a centerboard equipped,
small displacement sailboat. To apply this model to larger

displacement keel boats would require considerable revision, but the same general outline could be followed.

A sailboat's motion of heeling, or the lateral stability, is essentially a matter of rotational dynamics, if consideration in the time domain is desired. It is a very simple matter to solve a problem of statics to determine, given a certain angle of heel and the craft's dimensions, what the required wind velocity was to produce that heel. This was done quite well by Mr. E. C. Seibert in his book on the design of small sailboats.[1] The problem here is to work in the opposite direction: given any wind or gust function, a solution is desired that will give the angle of heel as a function of time. A boat similar in design to the one used in Mr. Seibert's steady-state model is used in this dynamic model.

The problem, being defined as one of rotational dynamics, becomes a matter of first, identifying a point about which to reference the rotation of the boat; secondly, to identify all the various forces which cause a rotation about the longitudinal axis along with their points of application; and lastly, to determine a moment of inertia so that the following equation can be utilized.

$$I_A \ddot{\theta} = \sum_i M_A \mathbf{)} + \qquad (1)$$

where,

I_A = moment of inertia of the sailboat about the point A

M_i = the moment caused by force F_i

Taking these three steps one by one, the first problem
is resolved by designating the center of lateral pressure
(CLP) as the point about which to reference the rotation of
the sailboat. This is the point which most closely approx-
imated the center of rotation, a point which in practice
shifts constantly. Mr. Seibert shows that the difference
between using this point and the actual center of rotation,
wherever it may be, is negligible.[2]

The next step is to identify all the major forces
acting to produce the rotation being studied. Systems
Engineering, like most engineering, requires that approx-
imations be made. When real-life systems are reduced to
equations, some minor considerations must be dropped, while
the major forces must be estimated as closely as possible.
Six forces which produce moments of a large enough magnitude
to be considered have been identified. These are shown
on the sketch of the sailboat in Figure 5. By name they are:
(1) Combined weight of sail and mast; (2) Force of bouyancy;
(3) Weight of the crew; (4) Weight of the hull and equip-
ment; (5) Wind force on the sail; and (6) Damping forces cf
both the sail and the centerboard.

The first force is simply the mass of the sail, mast,
and rigging, multiplied by the acceleration due to gravity,
or in other words, the weight of the sail, mast, and rigging.
As seen in Figure 5, this distributed weight can be
represented by a single force of 38 pounds located 10.54

feet from the CLP and acting vertically downward. The
moment arm when the boat is upright is, of course, zero,
but as the boat heels, becomes 10.54 * sin(θ). The first
moment, then, is:

$$M_1 = 38 * 10.54 * \sin(\theta) \tag{2}$$

The second force is that of the bouyancy. This is
the largest single righting force of almost any craft.
The force of bouyancy is equal to the total displacement of
the craft, which in this case is 850#. When the boat is
upright, it acts through the CLP. Though the force always
acts vertically upward, determination of the point of applica-
tion is very difficult. In practice, the most practical
way to determine how this point varies with the angle of
heel is to empirically collect such data. Thus, an approx-
imation is needed. Using the following reasoning, a
parabolic curve was arrived at. The boundary values that
must be satisfied are: as the angle of heel, θ, goes from
0 to 1.5 radians, or 0 to 90 degrees, the moment arm from
the CLP to the center of bouyancy, x, varies from 0 to a
maximum of 2.25 feet at .75 radians of heel to 0 again at
1.5 radians of heel. Thus:

$$f(\theta) = a\theta^2 + b\theta + c \tag{3}$$

$$2a(.75) + b = 0 \tag{4}$$

$$a(\theta)^2 + b(\theta) + c = 0 \tag{5}$$

$$a(1.5)^2 + b(1.5) + c = 0 \qquad (6)$$

$$a(.75)^2 + b(.75) + c = 2.25 \qquad (7)$$

From these equations:

$$a = -4; \; b = +6; \; c = 0$$

Thus, the equation needed is:

$$x = f(\theta) = -4\theta^2 + 6\theta = 4\theta(1.5-\theta) \qquad (8)$$

The second moment equation, then, is:

$$M_2 = 850 * 4\theta(1.5-\theta) \qquad (9)$$

Two other methods for approximating the point of application for the force of bouyancy have been proposed. These curves are plotted alongside the curve described by equation (8) in Figure 6. Close agreement is seen in all three cases up through fifty to sixty degrees. In order to say which curve is the best one must know what type of boat is being simulated as all three curves are good in their own right.

Thirdly, the force the crew weight exerts must be considered. This is the most readily movable force on the boat and will be varied in the initial modeling by changing the distance from the CLP to the point on the perpendicular from the centerline of the mast through which the 300 pound force of the crew weight acts when the boat is upright, as shown in Figure 7.   The hull is 2.5 feet thick, so the moment arm corresponding to the first position is 3.2 feet long and the angle is .896 radians (multi-digit accuracy is meaningless past three significant figures because of the limits on the accuracy of the analog computer).

Thus, the third moment acting on the boat becomes:

$$M_3 = 300 * 3.202 * \cos(\theta + .896) \tag{10}$$

The fourth force considered is that of the weight of the hull and other equipment. This force acts through the center of gravity, which is not normally the same as the CLP, and in a vertically downward direction. On this particular boat the hull weight is 512 pounds and the center of gravity is 1.2 feet from the CLP. Thus the fourth moment considered becomes:

$$M_4 = 512 * 1.2 * \sin(0) \tag{11}$$

Perhaps the most important force is that of the wind on the sails, for this is the force that causes the boat to heel and, if unchecked, to go unstable. This force is essentially an aerodynamic force and is governed by the elementary lift force equation for an airfoil (a sail is actually an airfoil). This equation is:

$$\text{Lift} = f_a = (1/2) \rho V_A^2 S_A C_L \tag{12}$$

where:

$(1/2)\rho$ = dynamic pressure coefficient

C_L = aerodynamic lift force coefficient

S_A = sail area in square feet

V_A = apparent wind velocity in knots

For this particular model, the values are as follows:

$1/2 \rho$ = 0.0034

C_L = 1.5

S_A = 133

V_A = input to model

Thus, the total lift force in the leeward direction is:

$$f_a = 0.0034 * 1.5 * 133 * V_A^2 = .6783 * V_A^2 \quad (13)$$

This force is assumed to always act in a direction perpendicular to the centerline of the boat and to the mast. A mass of air has no directional orientation. As such, the angle of heel does not determine the angle of attack, nor does the force act in any direction other than perpendicular to the sail. A dihedral effect is present as the boat heels, but for the purposes of this model we will consider it negligible. The resultant force acts through the center of effort of the sail which can easily be calculated using geometric techniques. The height of the center of effort was found to be 10.54 feet. The fore-aft position is only of importance when considering the overall balance of the boat, which we are not doing here. The vertical moment, then, can be expressed as:

$$M_5 = .6783 * 10.54 * V_A^2 \quad (14)$$

The final moment which must be determined is that caused by the damping force of the centerboard moving through the water and the sails moving through the air. Fluid mechanics tells one that a damping force on such objects is given by:

$$F = \frac{C_D \rho A V^2}{2} \quad (15)$$

where:

C$_D$ = coefficient of damping

ρ = density of fluid

A = area opposing fluid

V = velocity through the fluid

For this model:

C$_D$ = 1.2

ρ = 0.08 for air
= 62.37 for water

A = 3 for centerboard
= 108 for mainsail
= 25 for jib

The units have been intentionally left off in order to reduce confusion.

Since a sailboat will never reach large rotational velocities, an important change must be made in equation (15). This change involves the replacement of V^2 with V, a standard procedure for damping equations operating in regions of low Reynolds numbers as we are here. To determine the damping forces, integrals must be used because of the way both the velocity and sail shape vary with the distance from the CLP. These integrals are:

$$F_{board} = \int_0^3 \frac{(1.2)(62.37)(1)(\dot{\theta}x)}{2} dx = 168.4\,\dot{\theta} \quad (16)$$

$$F_{main} = \int_0^{18} \frac{(1.2)(0.08)(18-x)(12)(\dot{\theta}x)}{2 \cdot 18} dx = 31.104\,\dot{\theta} \quad (17)$$

$$F_{jib} = \int_0^{10} \frac{(1.2)(0.08)(10-x)(5)(\dot{\theta}x)}{2 \cdot 10} dx = 4.0\,\dot{\theta} \quad (18)$$

The total moment due to damping is determined by multiplying each of these forces by their moment arms:

$$M_6 = 168(1)\dot{\theta} + 31.304(10)\dot{\theta} + 4(4.3)\dot{\theta} \qquad (19)$$
$$= 496.8 * \dot{\theta}$$

It remains to accomplish step three now: the moment of inertia must be determined.

The sailboat was broken into easily worked sections. The first is that of the mast and rigging, which was approximated by a slender rod. Second, the hull was approximated by a rectangular block and lastly, the centerboard by a rectangular plate:

$$I_{mast \atop CLP} = \left[\frac{38}{(12)(32)} 22^2 + \frac{38}{32} 11^2\right] \qquad (20)$$

$$I_{hull \atop CLP} = \left[\frac{512}{(12)(32)} (5^2 + 2^2) + \frac{512}{32} (0.75)^2\right] \qquad (21)$$

$$I_{board \atop CLP} = \left[\frac{75}{(12)(32)} 3^2 + \frac{75}{32} (0.5)^2\right] \qquad (22)$$

$$I_{CLP} = \sum I_i \qquad (23)$$
$$= 241.6 \quad slug\text{-}ft^2$$

Using this value, and placing all the moments into equation (1), the following programmable equation was arrived at for the heeling and righting moment equation:

$$\ddot{\theta} = 1.658 * \sin(\theta) - 21.109 * \theta$$
$$+ 2.543 * \sin(\theta) - 3.202 * \cos(\theta + .896)$$
$$+ 0.02959 * V_A^2 - 2.056 * \dot{\theta} + 14.073 * \theta^2 \qquad (24)$$

Analog computers were used to model this system. The Naval Academy's EAI-360 MINIAC computers were employed as they are simple to operate and have a sufficient capacity for such a problem as this one. The limit of the machine was reached, however, and future, more complex dynamic simulations must be done on the PDP-15/Hybrid equipment. The analog program for the above equation can be found in Figure 8. The graphs of the various angles of heel versus time which were generated by the MINIAC by using a Hewlett-Packard X - Y plotter are shown in Figures 9 through 16. These graphs will be referenced in the following discussion.

By the mere fact that stable results were achieved with the method and theory used, one could claim a great deal of validity in the model constructed. But the data was taken in order to show the value of this model.

As is readily apparent, three different situations, each involving a different placement of the crew weight, were modeled. Looking at each separately (see Figures 9, 10, and 11), several things are evident. First, the boat heels further with an increase in the wind velocity, all other things remaining constant. This is as it should be, obviously. The angles of heel given are very realistic. An angle of 22 degrees seems to be the "break-point." That is, no stable solution exists beyond this, though at times the heel reached up to 30 degrees in the transient solution.

This so called "break-point" is primarily determined by the physical configuration of the boat, especially the placement of the crew. If the boat had been flatter so that the crew weight would have been almost perpendicular from the centerline of the mast to the CLP, large angles of heel could be reached. Also, if the center of gravity of the hull were closer to the CLP, higher angles would be achieved. It is for this reason that one adds extra weight as close to the CLP as possible when it is necessary to add weight to meet racing class restrictions if the boat is too light. As it is, the angles reported are quite acceptable for this particular model. A different design of sailboat would have different maximum angles of heel.

A second rather obvious observation can be made from Figure 12. For a given wind velocity, the further out the crew weight is placed (and hence the longer the moment arm) the less heel the boat experiences. The difference is quite significant and indicates quite clearly the need for hiking straps and trapezes on small boats in order that the crew may move their weight out as far as possible.

The third observation was found in looking at the effects of a gust on the boat. For purposes of this simulation, a 13.5 knot steady breeze was assumed, with gusts of 5.3 additional knots occuring on occasion. (It is interesting to note that the magnitude of the steady wind has no affect on the amount of damping experienced.)

The gust was of the general form as shown in Figures 13, 14, 15, and 16, but by simply resetting three potentiometers on the analog computer, the length of the gust can be varied. Several things will be noted upon studying these gusts. Up until a point where the gust function becomes so long as to damp out all oscillation, the gust is responsible for the maximum angle of heel reached, with the longer gusts giving greater angles. In all cases, the longer gusts, and hence more energy, resulted in a greater average angle of heel, which is an indication of greater potential energy. Both of these results coincide with actual observation. Two more observations were made. First the longer the gust, the more damping imparted on the system. After considering this fact, it becomes apparent why this increase should occur. Damping is, as the development of the model showed, related to velocity of the movement of the sails through the air mass. The greater winds and longer gusts thus have more damping. And finally, since all the gusts do eventually go back to zero, no matter what the magnitude or duration of the gust, the steady-state position of the boat will be the same, assuming the gust wasn't so strong as to topple the boat over.

This, then, concludes the preliminary study of the lateral stability of a sailboat. The results seem to indicate an acceptable model has been proposed. Already several insights have been made. In a later chapter, this

model will be incorporated, with the necessary modifications, into an overall model of a sailboat.

CHAPTER THREE

"Theory of Sailing Applied to Ocean Racing Yachts"[3]

In the previous chapter, a simulation of the heeling
and righting moment equation was derived for a small
centerboard-design sailboat. Although this work yielded
some interesting results, it had its shortcoming. The
model was built for one particular sailboat and can be
applied to other craft only with a considerable amount of
revision. Also lacking was any mathematical correlation
of the heeling equation to the forward boat speed. Much
was learned from the simulation, though, and the techniques
used are exactly the same as those used in the more high-
powered models which are described in this chapter.

On January 15, 1977, the Third Chesapeake Sailing
Yacht Symposium was held at St. Johns College in Annapolis,
Maryland. The symposium is co-sponsored by three organ-
izations, one of which is the U.S. Naval Academy Sailing
Squadron. Eight papers were presented, all of great interest,
but none directly applicable to the work at hand. However,
in the course of the day, I met Dr. Hugo Myers of Vienna,
Virginia, a catamaran designer and systems analyst. Dr.
Myers had built a rather complete program several years
earlier in an attempt to derive an engineering mathematical
simulation of a boat's performance. Due to the lack of
funding, the project was dropped in 1975, although it was

essentially complete at this time anyway. This simulation
was exactly along the lines of my earlier simulation,
although much more complete and thorough. In the interest
of reactivating his program, Dr. Myers offered to transfer
his program over to the USNA/DTSS Honeywell computer system
at the Naval Academy where it could be worked on and further
refined. In regards to this project, a program such as
his was exactly what was needed. With a few refinements,
the program could be used directly to begin the true intent
of this project: optimization of sailcraft performance.

The original intention of Dr. Myers' program, "Theory
of Sailing Applied to Ocean Racing Yachts," was to develop
a new, more equitable way of rating ocean racing yachts
than the present I.O.R. Mark III system. In order to do
this, the I.O.R. (International Offshore Rule) measurements
were utilized to define the specific yacht. By building
the simulation around these measured values, it is possible
to write a general program applicable to any boat with a
valid I.O.R. measurement certificate. Thus, one of the
primary weaknesses of the initial simulation described in
the last chapter was overcome. A computer program thus
became available for analyzing all yachts of the ocean
racing classes. Dr. Myers' program utilizes the four
basic simultaneous equations described in Chapter One.
In addition, a separate equation is needed to identify
the apparent wind angle. Thus, we have five equations and

five unknowns. Each of these equations are derived in much
the same way as the heeling and righting moment equation
of Chapter Two. A determination is made as to what forces
and variables must be considered, and the appropriate
relationship between them is expressed mathematically.
When each equation has been properly formulated it is
integrated with the others in an iterative solution routine.
Using the inputs, a first cut estimation is made of the
outputs. Successive interations improve on the balance
of the equations until all equations are satisfied within
set error bounds.

The inputs to the program are the true wind speed
and course sailed (which defines the true wind angle)
while the outputs are leeway angle, apparent wind angle,
apparent wind speed, boat speed, and heading. These
values rather completely describe the physical states of
the sailboat. Close inspection of Dr. Myers' paper is
necessary and sufficient to understand how the simulation
is set up and as such, the specifics of his program will
not be dealt with here. The reader is referred to Dr.
Myers' paper, "Theory of Sailing Applied to Ocean Racing
Yachts" (see reference 2).

The first step in refining this program, called "Sails,"
was to get it working on our system. Originally written
in IBM APL (A Programming Language), the program transferred
over to USNA/DTSS APL without much difficulty. Initial
runs of the program indicated that though it gave good

results, some of them were not in close agreement with experimental results. In particular, the apparent wind direction given by the program seemed to be a bit low. Two modifications were made in order to bring this value up in line with observed values. These modifications were ones that were originally left out because they were thought to be negligible. For the intended purpose of the program this was true, but they had to be taken into account if the program was to be used for optimization purposes.

The first of these modifications corrects the error introduced by assuming the wind at the masthead is the same as the wind at the center of effort of the sails. This error becomes quite significant, especially in the high-aspect rigs of many of the offshore yachts. Figure 17 from C.A. Marchaj's Sailing Theory and Practice (reference 3) shows how the wind varies with the height above the water. This variation is due to boundary layer effects between the relatively stationary water mass and the moving air mass. If the assumption is made that the true wind speed inputed to the computer program is the wind speed at the masthead, the equivalent wind speed at the center of effort must be determined and used as the input to the program since the program is designed to operate at the center of effort of the sails. After the solution has been attained, the wind speeds at the center of effort must be translated back into wind speeds at the masthead where the actual

instuments that measure the wind speed are located.
Using Marchaj's curves, the first step is to choose the
curve which most accurately describes the prevailing wind
conditions. The curve is then entered with the masthead
height and the wind velocity is read off as a percent of
the wind velocity at one hundred feet, which will be called
VMHPER (velocity at masthead in percent). Next, enter
the curves with the height of the center of effort and
again the wind velocity is read off, this time termed
VCEPER (velocity at the center of effort in percent.)
Thus, by definition:

$$VMHPER = \frac{\text{velocity at masthead (VMH)}}{\text{velocity at 100 feet (VT)}} \quad (25)$$

$$VCEPER = \frac{\text{velocity at center of effort (VCE)}}{\text{velocity at 100 feet (VT)}} \quad (26)$$

Rearranging these equations:

$$VCE = \frac{(VMH)\ (VCEPER)}{(VMHPER)} \quad (27)$$

$$VMH = \frac{(VCE)\ (VMHPER)}{(VCEPER)} \quad (28)$$

The necessary change was made in the apparent and true wind
triangle to accommodate this modification. Differences
of as much as several degrees were noticed when the new
program was executed.

The second modification to Dr. Myers' original program
involves primarily changes in the direction of the apparent
wind. Initially, no account was taken for the effect that
heeling has on the apparent wind, which is read from the
instrumentation at the masthead. Although heeling does not

significantly alter the height of the center of effort
above the water such that we need to take into account
Marchaj's curve, the error between the actual direction
of the apparent wind and the direction indicated by the
wind vane at the masthead does change significantly.
Assume the apparent wind is acting such that it is des-
cribed by the vector:

$$\vec{V}_A = (\cos\beta\,\hat{i} + \sin\beta\,\hat{j} + \emptyset\,\hat{k})\,V_A \qquad (29)$$

where B is the angle between the apparent wind and the
course actually steered. As the boat heels, the wind
vane continues to point towards the apparent wind, but the
boat rotates about the longitudinal axis underneath it.
In the new coordinate system oriented on the ship's axis,
the apparent wind is described by the vector:

$$\vec{V}_A = \frac{(\cos\beta\,\hat{i} + \sin\beta\,\hat{j} + \tan\theta\sin\beta\,\hat{k})}{\sqrt{\cos^2\beta + \sin^2\beta + \tan^2\theta\,\sin^2\beta}}\,V_A \qquad (30)$$

where θ is the angle of heel. Putting these two equations
together, the new angle, β^1, which is actually measured by
the wind vane at the masthead, is related to the actual
angle β by:

$$\beta^1 = \tan^{-1}\left[\frac{\tan\beta}{\cos\theta}\right] \qquad (31)$$

This modification is not quite as dramatic as the last,
but at large angles of heel it will produce a noticeable
change in the results.

Together these two changes to the basic program have
brought the results closer to what is actually measured by

the instrumentation at the masthead of ocean racing yachts.
Dr. Myers' program was perfectly correct for considerations
at the center of effort, but unfortunately the performance
indicators are not located there but at the masthead.

One more alteration was made to Dr. Myers' program:
it was translated into FORTRAN programming language. This
is perhaps the most important single change as it will
hopefully open the program up to a wider range of users.
APL was an excellent language in which to write this program
due to its versatility and ease in handling long arithmetic
calculations. FORTRAN language, however, is a much more
widely utilized language and the one that most engineers
are familiar with. Thus, it was quite important to trans-
late Dr. Myers' program with the above alterations into
the FORTRAN language. The new program is called TRISAIL
(Trident Sail Optimization Program). This translation
resulted in a twenty-fold decrease in the necessary computer
run-time for lengthy run of the program due to the higher
stage of development in the current FORTRAN system over
APL on the USNA/DTSS computer. But more importantly, the
FORTRAN program is more accessible to most users and
certainly allows more interface with other systems due to
the versatility of the FORTRAN format.

The adoption of Dr. Myers' program to the USNA/DTSS
system with the subsequent modifications described above
was a very important step in the furtherment of this

project. As will be seen on the remaining chapter, the
FORTRAN program was modified to suit specific needs,
serving well to generate some very important and useful
sail optimization packages.

CHAPTER FOUR

"Simulation and Optimization of Sailcraft Performance"

In the last three chapters we have looked at the general simulation problem, and initial simulation of one portion of the overall problem, and at the changes made to Dr. Myers' "Theory of Sailing Applied to Ocean Racing Yachts." From here on, two related tracks will be pursued: one along the lines of simulation; and the other along optimization lines. Simulation, although interesting in itself, primarily serves to support the optimization process. Once a system has been fairly accurately modeled, the engineer can study the system through simulation, optimize it, and then apply those optimization techniques to the real system.

TRISAIL, a full listing of which is included in Appendix A, is the basic simulation program in this project. In order to run this program, the first step is to construct a file which contains the necessary information about the size and shape of the vehicle to be simulated. As can be seen in Figure 18, this is accomplished by commanding the computer to build a file using inputs typed in from the terminal. The inputs needed are:

      DSPL - Displacement of the boat

      LWL - Length at the waterline

      BWL - Beam waterline

CMD	– Center mid-depth
FMD	– Freeboard at mid-depth station
LOA	– Length overall
P	– Height of the mainsail hoist
E	– Length of the mainsail foot
I	– Height of the foretriangle
J	– Length of the base of the foretriangle
LPG	– Longest perpendicular of the jib
SL	– Spinnaker luff/leech length
SMW	– Spinnaker maximum width
BMAX	– Maximum beam
CK	– Chord of the keel (average)
HK	– Height of the keel
DM	– Measured draft
CR	– Chord of the rudder (average)
HR	– Height of the rudder
RM	– Righting moment

All inputs must be real numbers (including a decimal point),
and they must be made in the order established above as
this is the order in which they are read into the program.
An example of a completed file is shown in Figure 18.
Four of the above inputs must be measured directly on the
boat or taken from scale drawings: CK; HK; CR; HR. The
remaining values are all found on a complete I.O.R.
certificate and can be taken directly from the certificate.
If such a certificate is not available or if more informa-

tion is desired, the reader is directed to reference (4) which contains detailed instructions on how to measure a boat.

After building this file, the program TRISAIL is ready to be executed. Upon typing "RUN," the first question the user must respond to is answered either "YES" or "NO." If "YES" is typed, the program continues. If "NO" is typed, the program halts immediately, allowing the user to type "LIST" and read the first fourty lines of the program which contain instructions similar to these. Assuming the program has continued, the next input will be the true wind velocity. Although almost any number may be used, for sake of realism the recommended limits are five to thirty knots. The program is not set up to change any sails on the basis of wind strength (although it does automatically set a spinnaker when the wind comes aft far enough). Wind speeds outside the range above would require special light or heavy air sails. The next two inputs from the user are the true wind direction bounds between which the simulation should occur. Once again, for the sake of realism, these bounds should be set greater than twenty degrees and less than one-hundred-eighty degrees. And finally, the last input needed specifies the increment at which the boat's states will be printed out as the true wind changes direction. A sample run is shown in Figure 19 for the yacht SYREN in a fifteen knot breeze sailing

between the angle of thirty-five and thirty-nine degrees.

This simulation is a steady-state model, as defined previously, and can be used to find the state of the boat in any given wind. Near the end of the program is a block entitled "CONSTANTS" in which several other variables can be found. These include: the number of square feet of cabin exposed above the deck; lift/drag angle of the sails, mast, rigging, and hull, "GAMMA"; the angles of attack of the rudder and keel, "ALPHAR" and "ALPHAK"; the coefficient for roughness of the air, "RAC"; the wave drag coefficient, an experimentally determined constant, "WAC"; and the rough water coefficient, "RWC". They are initially set up for what was deemed to be "average" sea and sailing conditions, but may be changed at any time by simply entering the program and retyping that line with the desired coefficient in it.

Although quite valuable in determining the stability and response of the system at any given time, static simulations lack the captivating qualities of continuous simulations. In this case, however, a continuous, dynamic model of a sailboat under sail in all three dimensions was too complex to model on our hybrid facilities in the time allotted. Instead, a "quasi-dynamic" simulation using TRISAIL was made. Executed every quarter of a second over a period of two minutes of changing wind and sea conditions, TRISAIL yielded four-hundred-eighty different

static solutions which, when linked together, represented
a quasi-dynamic simulation. This approximation of the
continuous simulation through the use of a rapid succession
of static solutions achieves a satisfactory degree of accuracy
for several reasons. First, personal experience on the water
indicates that the inertial effects of the boat are less
than the direct wind response for small incremental changes
of wind. Sailboats respond immediately to changes in
wind velocity and as such we can ignore the effects of
inertia and damping. In addition, the accuracy of the
constants used and the engineering approximations made in
formulation of the original simulation do not justify a
more sophisticated approach at this stage. And finally,
the resulting quasi-dynamic simulation appears to be quite
realistic and more than satisfactory.

The program FORWIND is shown in Appendix C. This
program was used to generate the wind/gust function shown
in Figure 20. The velocity of the wind was calculated
and inputed into the program TRISAIL at each quarter of a
second. With minor changes to FORWIND, any arbitrary wind/
gust function could be generated. Also included in this
simulation, which was not present in the original simulation,
is a random sinusoidal wave input. As the states for each
quarter of a second were generated they were placed in a
file.

At this point the Computer Aided Design and Inter-
active Graphics Division at the U.S. Naval Academy
provided invaluable assistance. They had a static model
of a sailboat which could be displayed on their picture
system in conjunction with a PDP-11 computer. A few
minor changes were needed to allow this system to accept
data from the file generated above and to display a new
picture every quarter of a second, real-time. In this
manner we were able to actually watch a model of a
sailboat pitching, rolling, and yawing as the wind and
sea conditions varied. The resulting presentation was
quite effective and was utilized in the presentation of
the project at the Naval Academy Officers' and Faculty
Club on May 3, 1977. Two of the four-hundred-eighty
static situations that make up this simulation are
shown in Figures 21 and 22.

The remaining two users of the program TRISAIL attack
the heart of the project - optimization. Ocean racing
yachts are very complex machines which are difficult and
challenging to sail. Not contending for a moment that
a sailor should ignore his intuitive feel for the boat,
the optimization suggestions described here are meant not
to replace experience in the long run, but rather to give
an immediate guide to the inexperienced and a consistant
reference to the experienced.

The first optimization plan is called MAXSAIL.
Using this version of TRISAIL, the optimum angle of ap-
parent wind for a boat moving to windward is determined.
Sailboats cannot sail directly into the wind. As they are
borne away from dead to weather, they gradually pick up
speed. Although they are no longer going in the intended
direction (to weather), there is component of the velocity
in that direction. This component continues to increase
until the angle off the wind becomes large enough that the
boat is at near maximum speed and the increase in speed
from coming off the wind further no longer contributes to
an increase in the speed in the desired direction. The
extreme is when the yacht sails at a true wind angle of
ninety degrees, in which case there is no component of
velocity to weather at all. Thus the component of velocity
starts at zero when the boat is dead to weather, increases
to some optimum speed, and then returns to zero when the
boat reaches a true wind angle of ninety degrees off the
wind. MAXSAIL is configured to find that optimum speed
and the angle at which one should sail to realize it.
Figures 23 and 24 show optimum true and apparent wind
angles as a function of wind speed. Experience would
indicate that in lighter air, the boat should be sailed
somewhat on the heavy side (further off the wind) in
order to keep the sails full. Also in heavier air the
wind angle should be slightly greater to give the boat

drive through the waves. Somewhere in the middle of the
moderate breezes should be a minimum wind angle. Looking
at Figures 23 and 24 we see this is exactly the case.

The same results, and much more, can be obtained
from a second optimization program called POLSAIL. Once
again utilizing TRISAIL, several minor changes were made
to produce the program POLSAIL. The output this time is
a complete true or apparent wind polar plot of the boat
speed as a function of the true wind speed and the
apparent true wind direction. Figures 25 and 26 are examples
of the type of plot which is produced. These plots can be
very valuable to the sailor, both experienced and inex-
perienced. As already mentioned, the optimum angle to sail
to windward can be obtained using this method as well as
the previous method. This is done by simply constructing
a tangent to the top of the polar curve perpendicular to
the vertical (0° - 180°) axis. The angle between 0° and
the point of tangency is the maximum angle to sail to wind-
ward, while the speed indicated at the intersection of
the perpendicular line and the vertical axis is the maximum
speed the boat is capable of sailing to windward. A
construction of this sort is shown in Figure 27. Along
these same lines, the true wind polar plots can be used to
determine at what angle a yacht should sail to most quickly
cross a finish line. If the line is to weather, he will,
of course, sail the fastest course to weather possible.

However if the line is not to weather, the orientation of the line is picked off a chart and transferred to the proper side (port or starboard) of the true wind polar. It is then moved in or out until it is just tangent to the proper curve depending on the wind velocity. The angle at this point of tangency is the one that should be sailed to reach the line quickest (see Figure 28).

These two specific techniques are really offshoots of the primary reason for drawing such polar plots. Polar plots are a concise way of tabulating the maximum speed the boat is capable of making at any heading and any wind velocity. As such they can be extremely valuable to the novice as well as the experienced sailor. For the novice, or new boat owner, these plots can help over-come the lack of knowledge about the boat. Envision a boat being delivered with a set of such polar plots for various wind strengths. Until the new owner gained enough experience on his new boat to know how fast he should be able to go at any point of sail and to insure that he is indeed going that fast, these curves are invaluable. The owner has an immediate optimum boat speed to strive for. For the experienced sailor, curves such as these can do two additional things. First, they can confirm his beliefs as to what "feels good." If both the computer and the "seat of his pants" tell him that the boat sails best at an apparent wind angle of twenty-two degrees, he can be

that much more sure of himself. And secondly, during
long races when the crew begins to slack off late at night
or several days out, the navigator or any crew member can
look at these computer generated, experimentally verified
curves and know what the boat should be doing. The owner
and crew have a consistent reminder of what they should
be able to make good through the water.

By placing these two optimization techniques, MAXSAIL
and POLSAIL, together, a performance optimization package
has been developed. Appendix C contains such a package
for the Naval Academy's yacht SYREN. With the present
computer facilities it takes two to four hours to generate
such a package and approximately one thousand seconds of
computer run-time. The Naval Academy's USNA/DTSS computer
was used in conjunction with a Tektronix 4051 terminal to
build this package and packages for the other Class A
yachts owned by the Naval Academy. It is anticipated that
these curves will be utilized by the various crews in both
capacities mentioned above. The value of having such
polar plots on board and available to the crew cannot be
emphasized enough. For the first time, there is a con-
sistent, hard-copy tabulation of data that previously has
been painstakingly collected through empirical means.

drive through the waves. Somewhere in the middle of the
moderate breezes should be a minimum wind angle. Looking
at Figures 23 and 24 we see this is exactly the case.
The same results, and much more, can be obtained
from a second optimization program called POLSAIL. Once
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these same lines, the true wind polar plots can be used to

determine at what angle a yacht should sail to most quickly

cross a finish line. If the line is to weather, he will,

of course, sail the fastest course to weather possible.

CHAPTER FIVE

"The Challenge"

Seldom are true research projects ever completely
finished, for they seem to stir up more questions than
they answer. This one is no exception. Although much
has been done, there is still even more left to do.
Concurrent with the writing of this report, and hence not
included in the report, two important additional steps
are being taken. One involves the Naval Academy's yacht
SYREN. She is at this time being outfitted with stripchart
recorders and special instrumentation to very carefully
record her actual motions so that they might be compared
to the theory. Some verification has already been
completed with very satisfactory results.

A second major on-going effort is to place this
problem, or at least portions of it, on the Naval Academy's
PDP-15/Hybrid facilities. Although the static and quasi-
dynamic simulations described earlier yielded very satis-
factory results, the lure of a completely continuous sim-
ulation is still strong. An analog computer is especially
well suited to solving simultaneous differential and even
algebraic equations. The manner in which this is done is
by compelling the equations to agree in their solutions.
These solutions are, in addition, continuous solutions,
and hence describe actual motion in a much better fashion

than can static models. While the analog portion is doing
the continuous solution, the large volume of algebraic
calculations made in the program TRISAIL could be handled
by the digital portion of the PDP-15/Hybrid system. Thus,
the two working together should be able to handle the
simulation in an efficient manner.

At this time, the heeling/righting moment equation
for the general I.O.R. ocean racing yacht is being set up
on the hybrid computer. Pending its success, the other
portions of the simulation could be added one by one to
the new model. This is indeed a challenging simulation,
but also a very worthwhile one.

One other improvement on the simulation that continued
to be illusive all year was the development of the capa-
bility to input apparent as well as true wind speed and
direction. This would allow completion of the polar plots
described earlier as, in addition to true wind speed
versus apparent and true wind direction plots, the
program would yield apparent wind speed versus apparent and
true wind direction plots.

There is more that could be done, yet much has been
accomplished. Sail optimization packages are now available
for the first time to offshore boat owners. A quasi-
dynamic simulation has been developed that can be used
for studying and exhibiting sailboat behavior. In addition,

countless other bits of knowledge and practical experience
have been gained. Simulation is a fascinating area of
engineering and even more so with a system as beautiful
yet complex as a sailboat. In dealing with projects such
as this one, the engineer is dealing with state of the
art simulation. As such, progress is often slow, but
the results are ever important.

DRIVING FORCE EQUATION
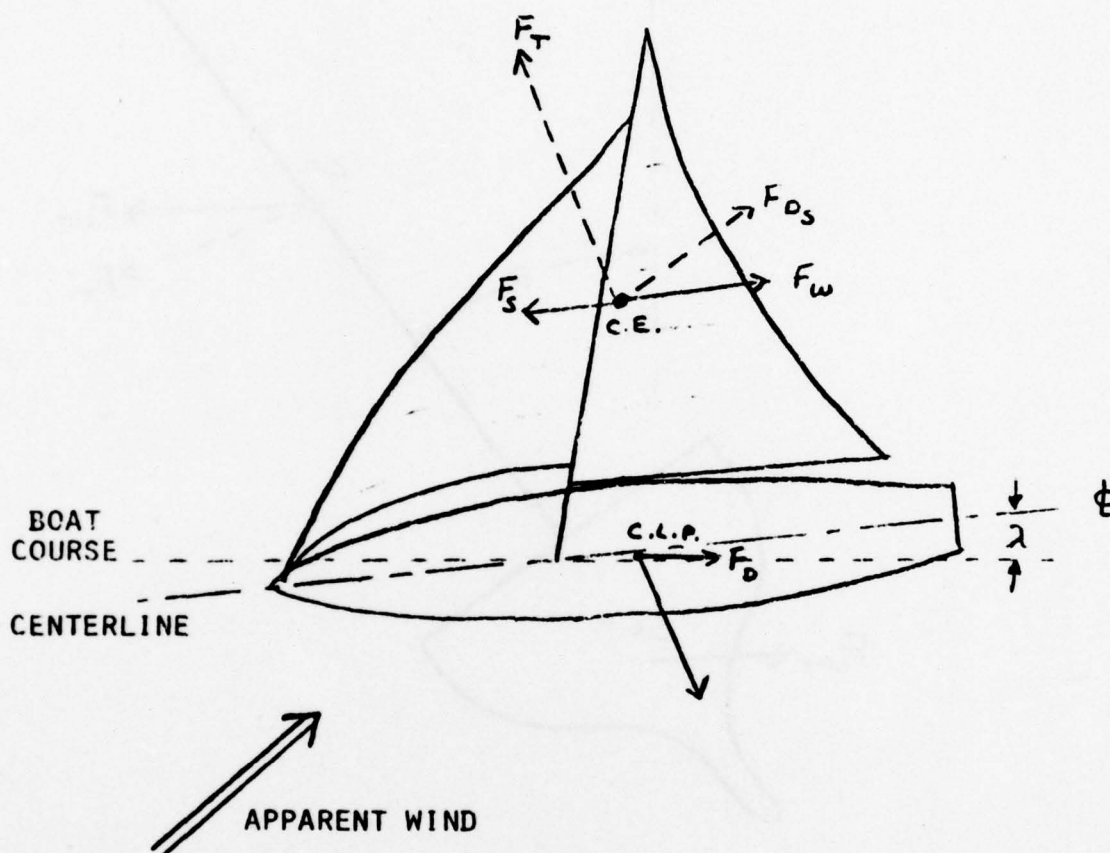
F_S = FORWARD COMPONENT OF SAIL FORCE

F_W = STERNWAY COMPONENT OF WINDAGE DRAG

F_D = HYDRODYNAMIC DRAG FORCES, INCLUDING FRICTION, WAVE, AND ROUGH WATER DRAG, AS WELL AS INDUCED DRAG

λ = LEEWAY ANGLE

C.L.P. = CENTER OF LATERAL PRESSURE

Figure 1

LATERAL FORCE EQUATION
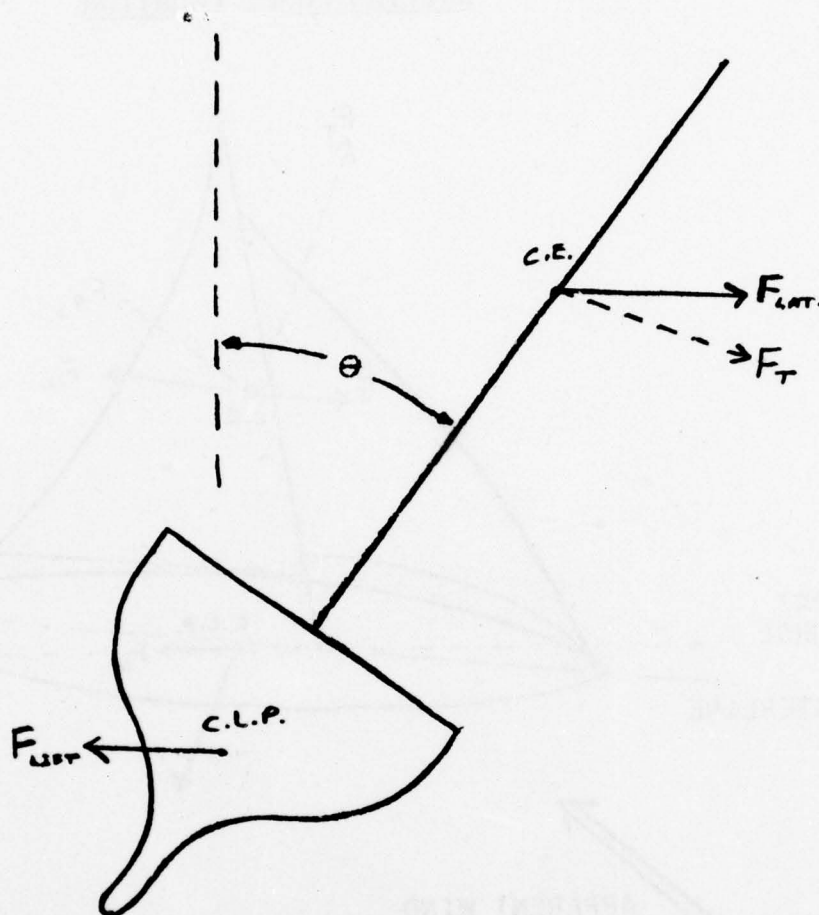
F_{LAT} = LATERAL COMPONENT OF SAIL AND WINDAGE FORCES

F_{LIFT} = LIFT AND LATERAL FORCES DUE TO HULL, RUDDER AND KEEL

Θ = ANGLE OF HEEL

C.E. = CENTER OF EFFORT OF THE SAILS

Figure 2

HEELING/RIGHTING FORCE EQUATION
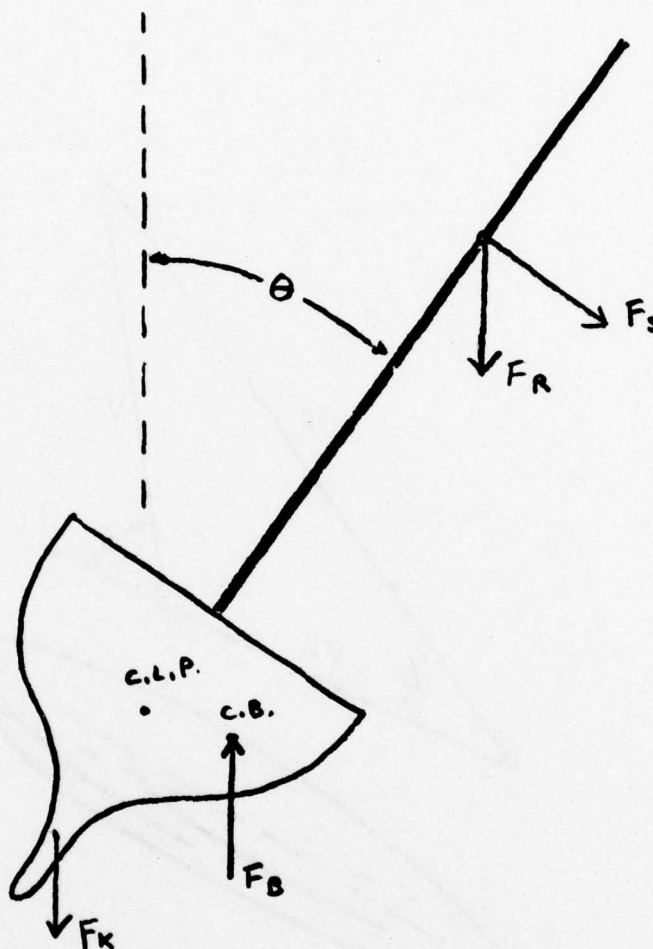
F_S = HEELING FORCE OF WIND ON THE SAILS

F_R = HEELING FORCE OF RIG

F_B = RIGHTING FORCE OF THE HULL BUOYANCY

F_K = RIGHTING FORCE OF THE KEEL

Θ = ANGLE OF HEEL

C.B. = CENTER OF BOUYANCY

Figure 3

APPARENT/TRUE WIND TRIANGLE

VA = APPARENT WIND SPEED

VT = TRUE WIND SPEED

VB = BOAT SPEED

β = ANGLE BETWEEN APPARENT WIND AND BOAT's ACTUAL COURSE

ϕ = ANGLE BETWEEN TRUE WIND AND BOAT COURSE

Figure 4

49
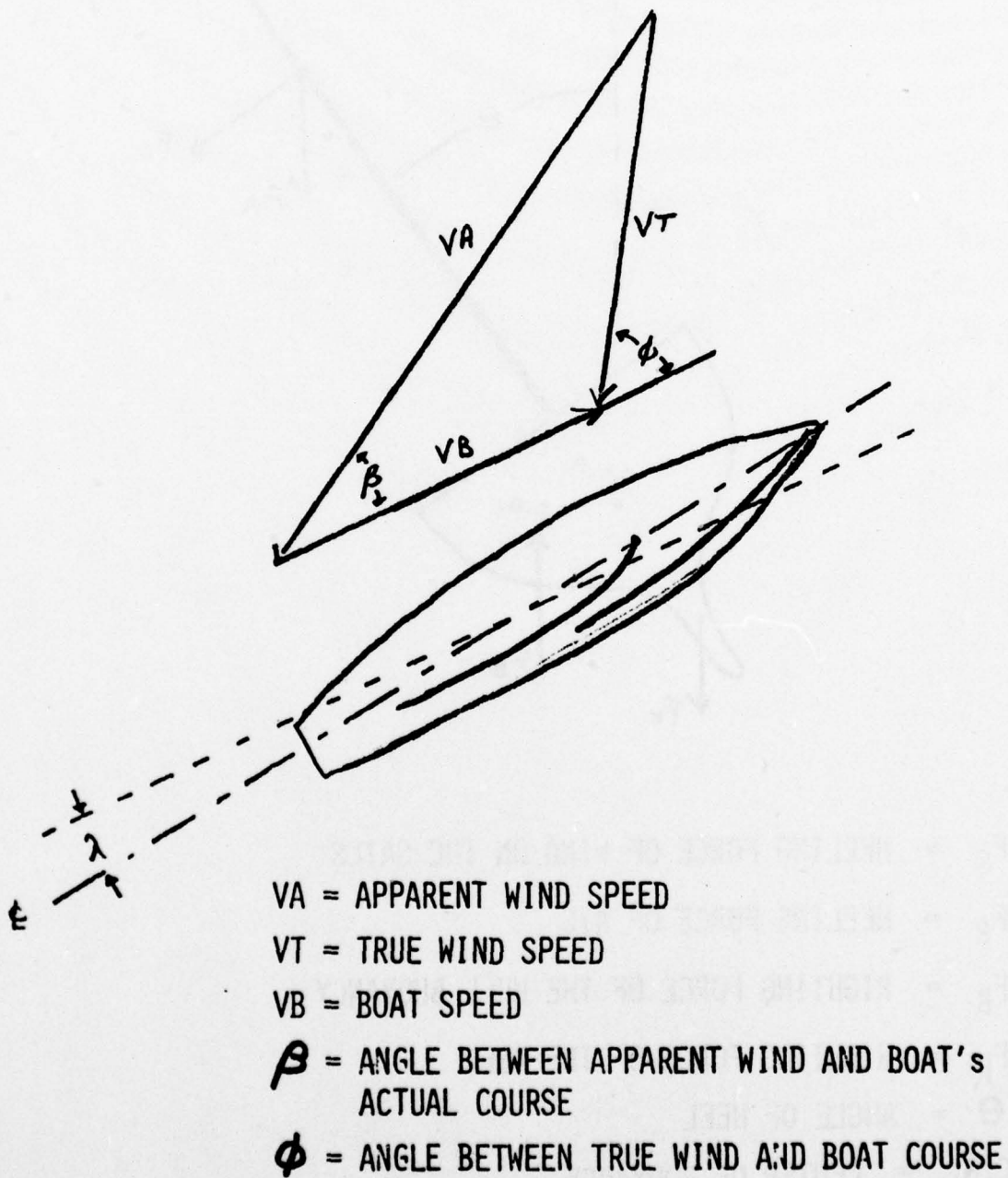
SKETCH OF A SAILBOAT

Figure 5

POINT OF APPLICATION FOR FORCE OF BOUYANCY
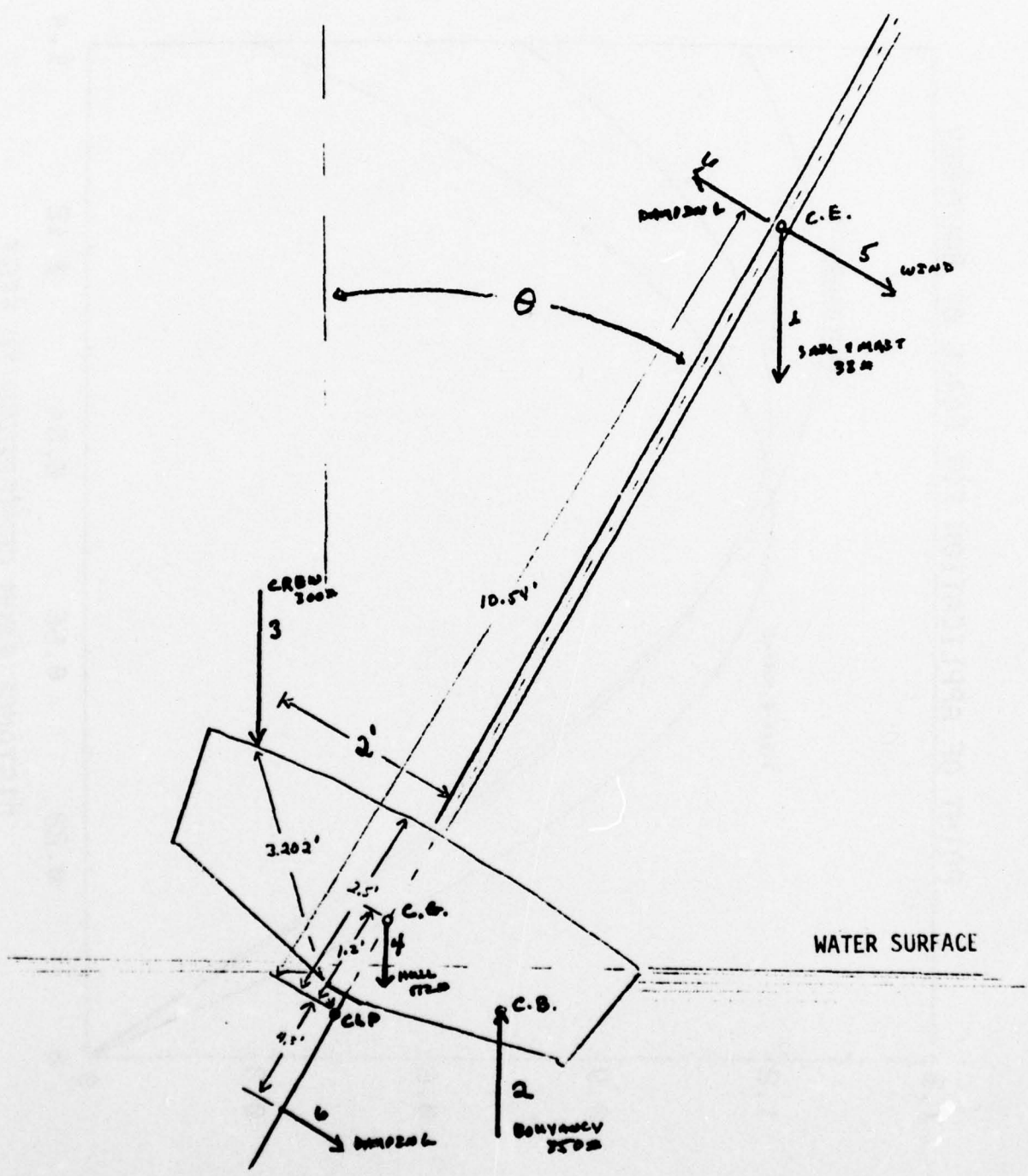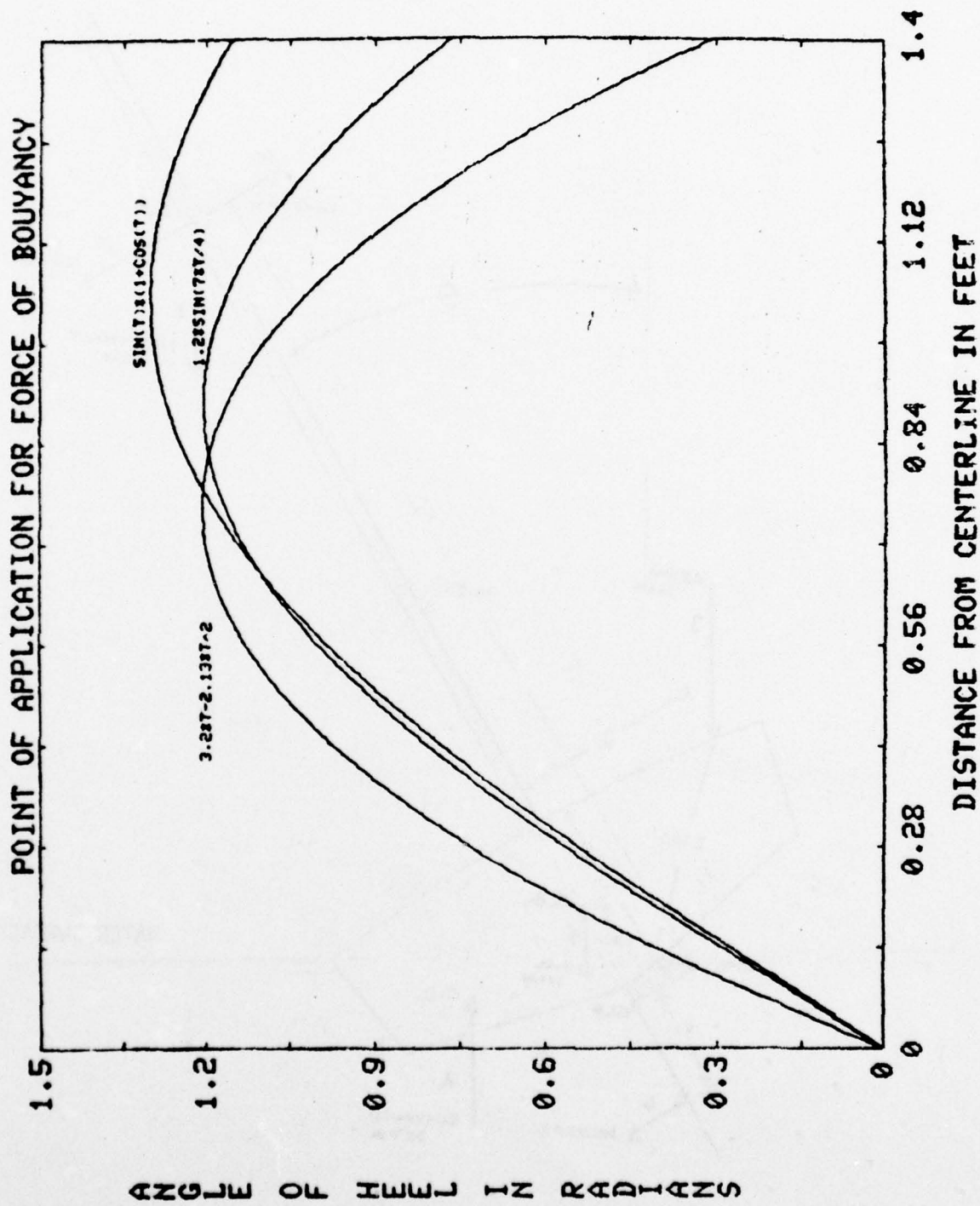
Figure 6

FORCE OF CREW WEIGHT
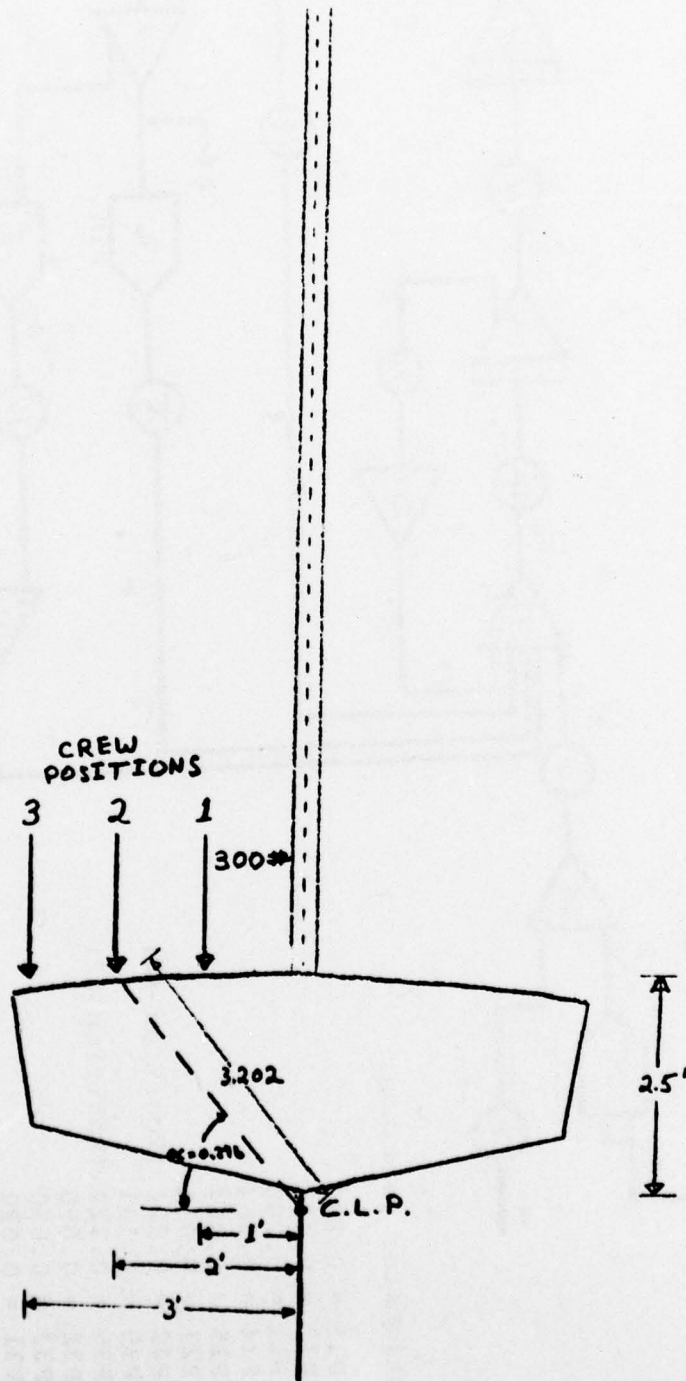
FIGURE 7

EAI-360 MINIAC
ANALOG FLOW DIAGRAM FOR
HEELING AND RIGHTING
MOMENT EQUATION

Gust Function

$-x_\theta$

$\dot{x}_\theta$

$-\ddot{x}_\theta$

x^2_{va}

$-x^2_v$

x_v

sin

cos

mult.

x_θ

$-x^2_\theta$

mult.

Potentiometer settings:

P13 = 0.832
P12 = 0.400
P11 = 0.200
P14 = 0.264
P15 = 0.704
P21 = 0.051
P22 = 0.224 (Position #2)
P35 = 0.131
P36 = 0.124 (Position #2)
P32 = 0.050
P33 = 0.050
P31 = 0.020
P24 = 0.188 (V_A = 13 knots)
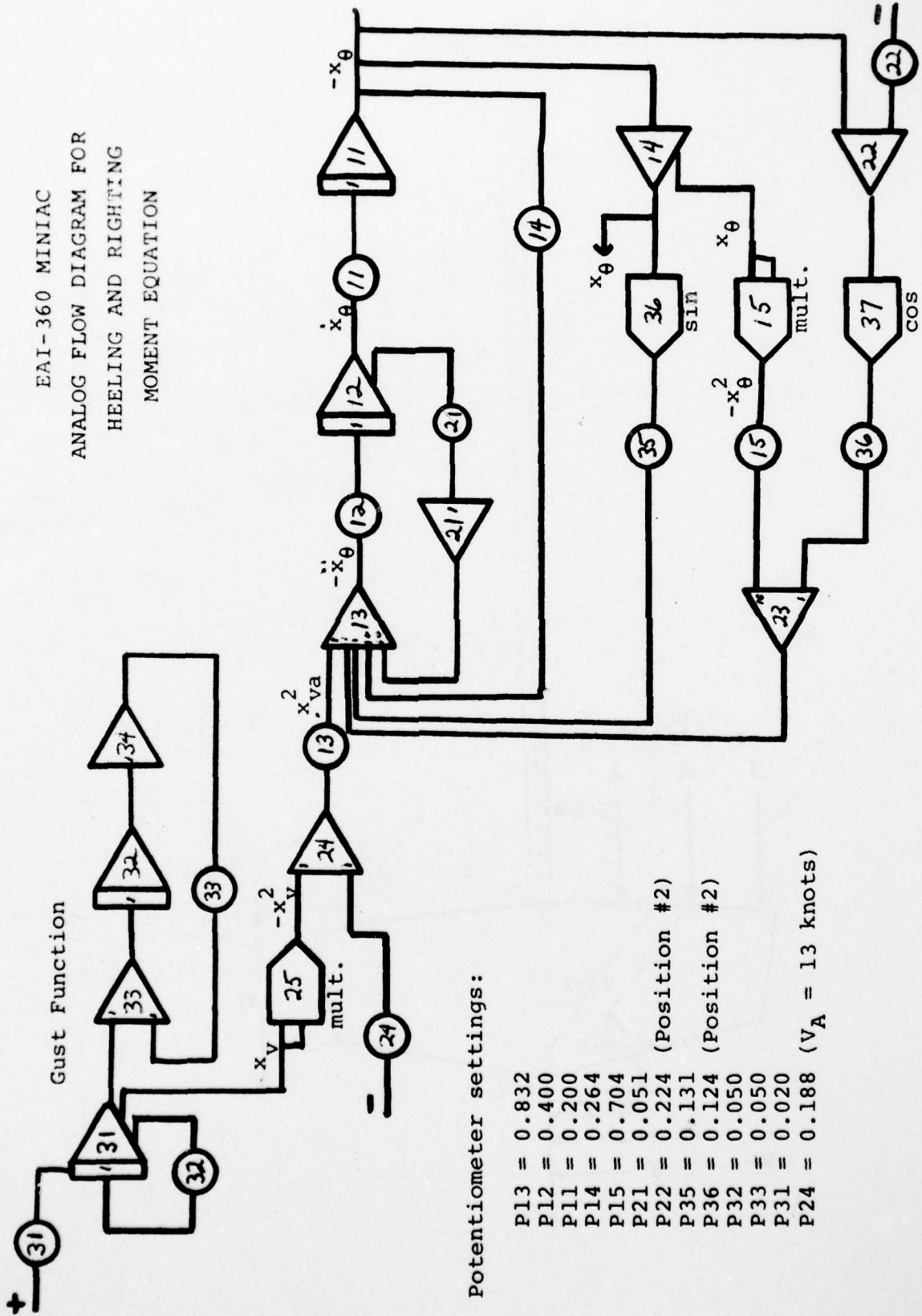
Heeling and Righting Moment Equation

Figure 8

ANGLE OF HEEL VS. TIME FOR CREW POSITION #1

V_A = 13 knots

V_A = 12 knots

V_A = 11 knots

V_A = 10 knots

ANGLE OF HEEL IN DEGREES

27.50

22.92

18.33

13.75

9.17

4.58

1.0   2.0   3.0   4.0   5.0   6.0   7.0   8.0

TIME IN SECONDS

53
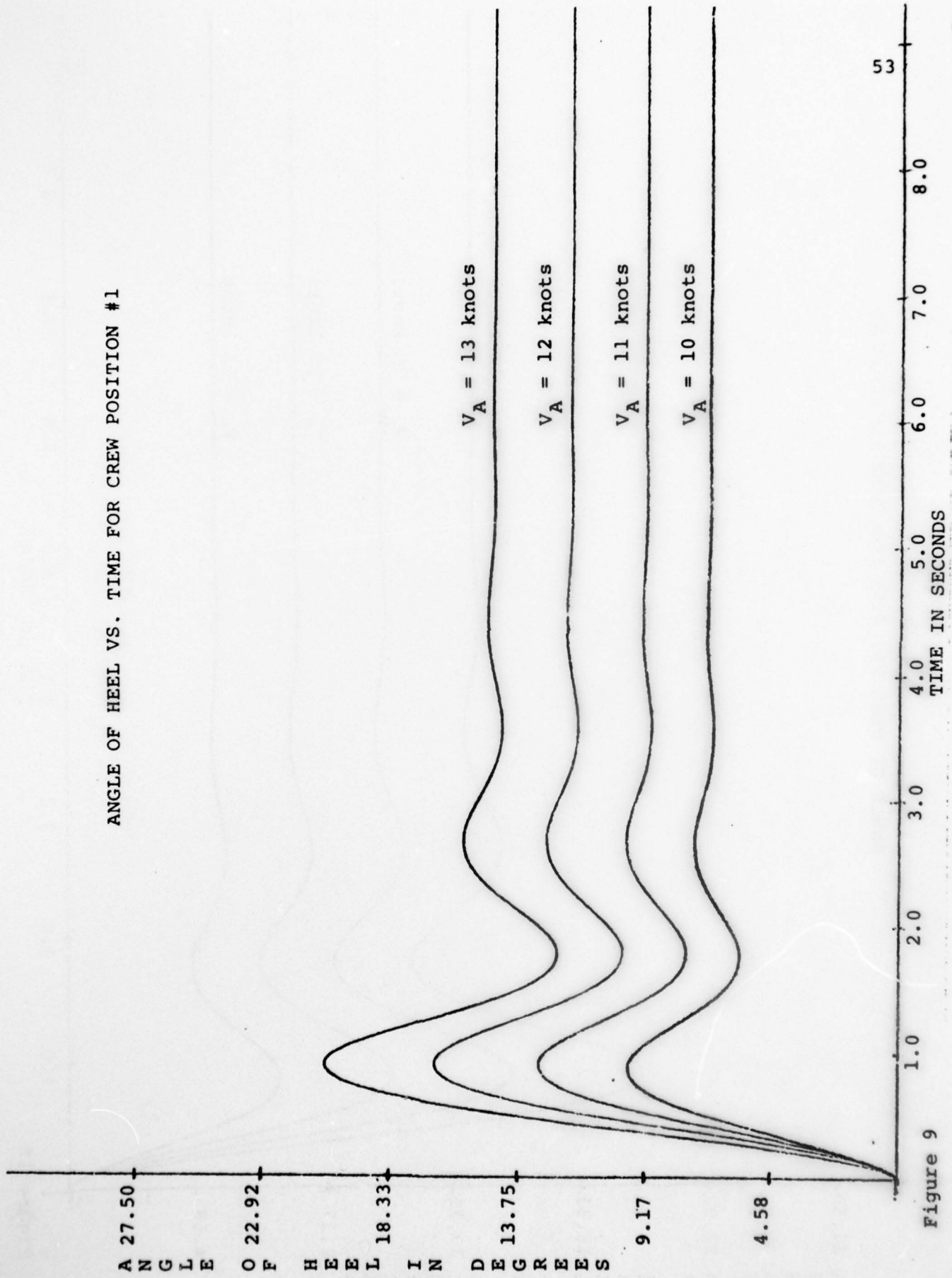
Figure 9

ANGLE OF HEEL VS. TIME FOR CREW POSITION #2

V_A = 14 knots

V_A = 13 knots

V_A = 12 knots

V_A = 11 knots
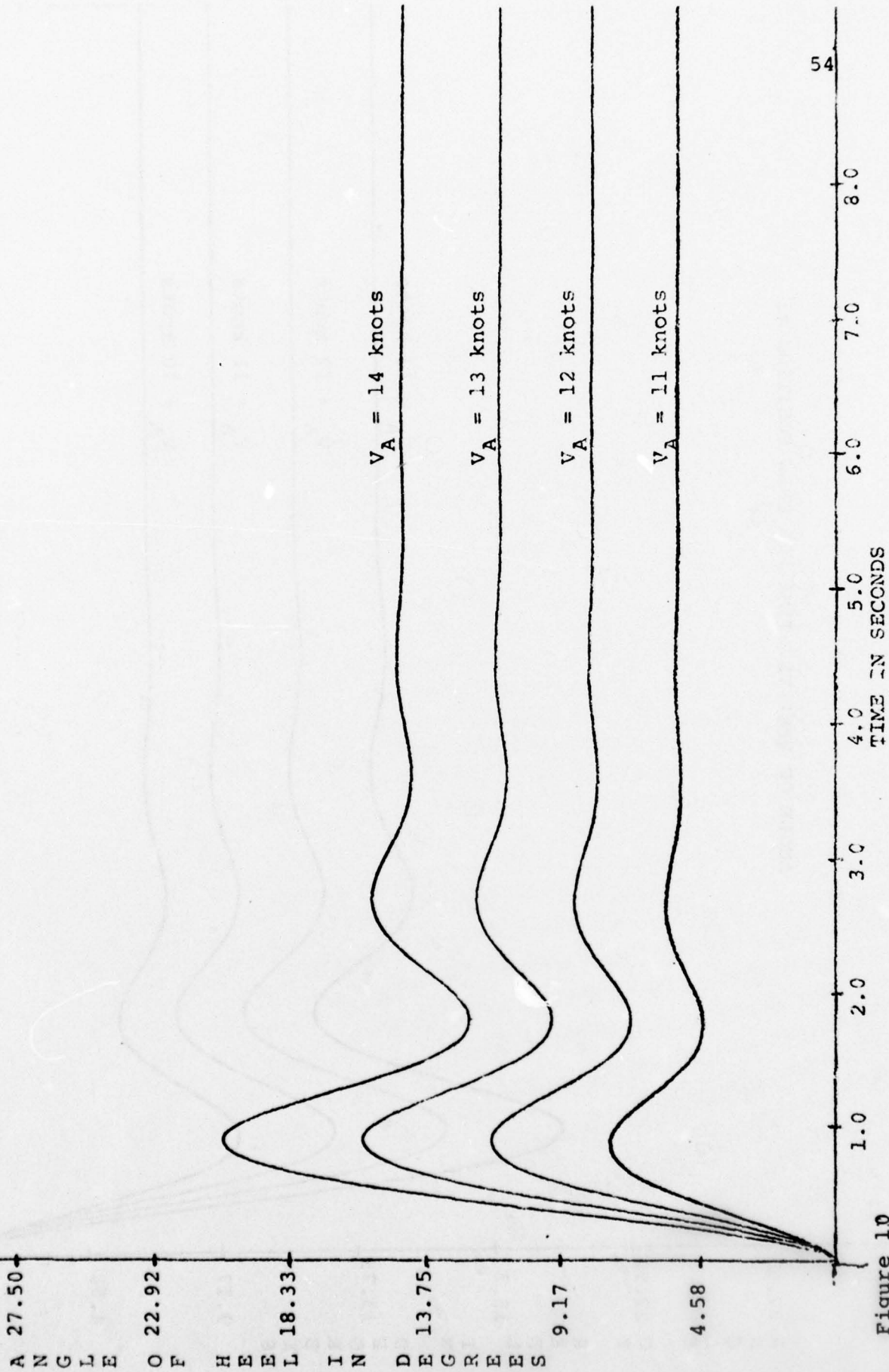
Figure 10

ANGLE OF HEEL VS. TIME FOR CREW POSITION #3

Figure 11

55
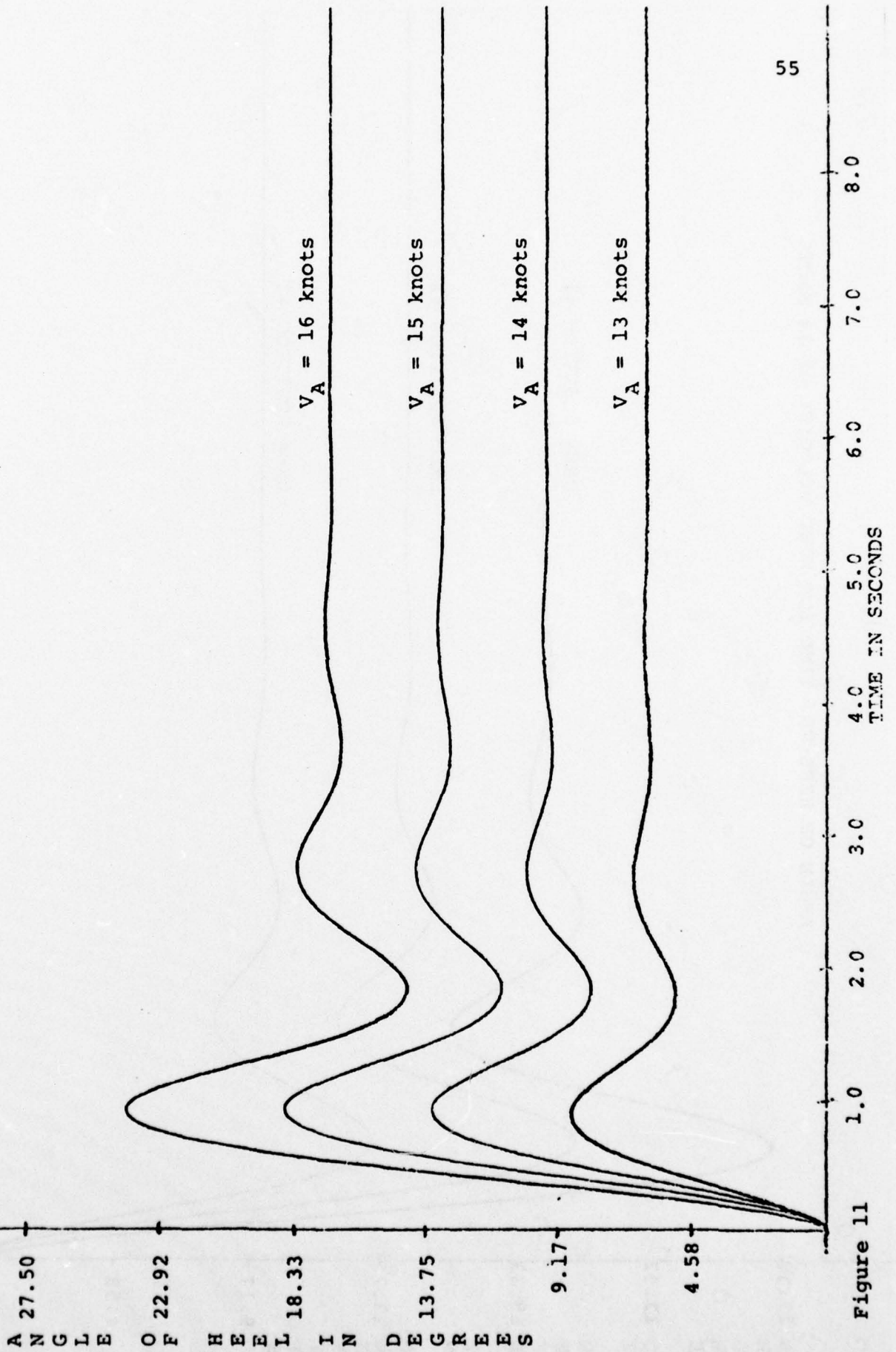
ANGLE OF HEEL VS. TIME FOR WIND VELOCITY OF 14 KNOTS
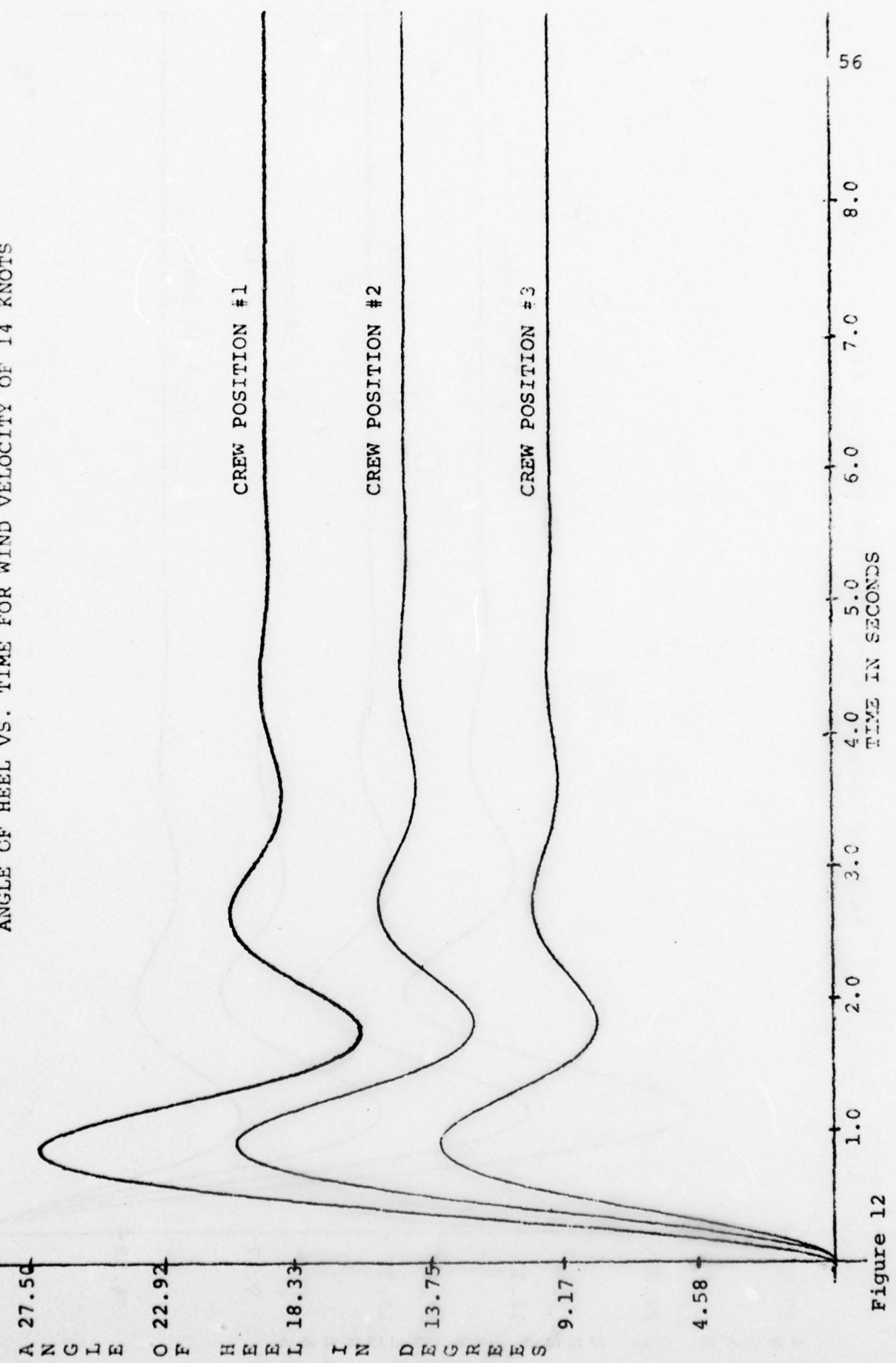
Figure 12

RESPONSE TO A SHORT GUST FUNCTION

ANGLE OF HEEL VS. TIME IN SECONDS
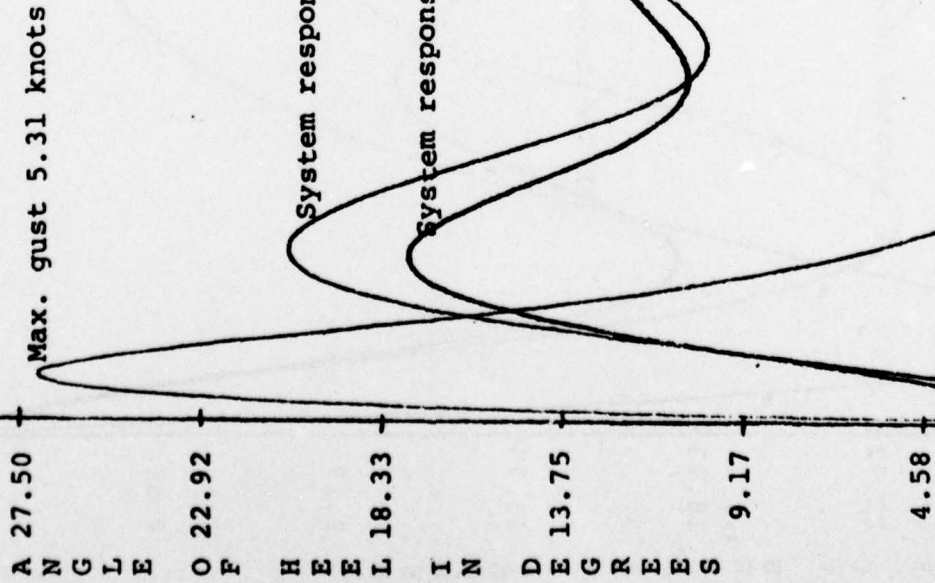
Figure 13

RESPONSE TO A MEDIUM GUST FUNCTION

ANGLE OF HEEL VS. TIME

Max. gust 5.31 knots

System response to gust

System response without gust

A	27.50
N	
G	
L	
E	22.92
O	
F	
H	18.33
E	
E	
L	
I	
N	13.75
D	
E	
G	9.17
R	
E	
E	
S	4.58

1.0   2.0   3.0   4.0   5.0   7.0   8.0

TIME IN SECONDS

58
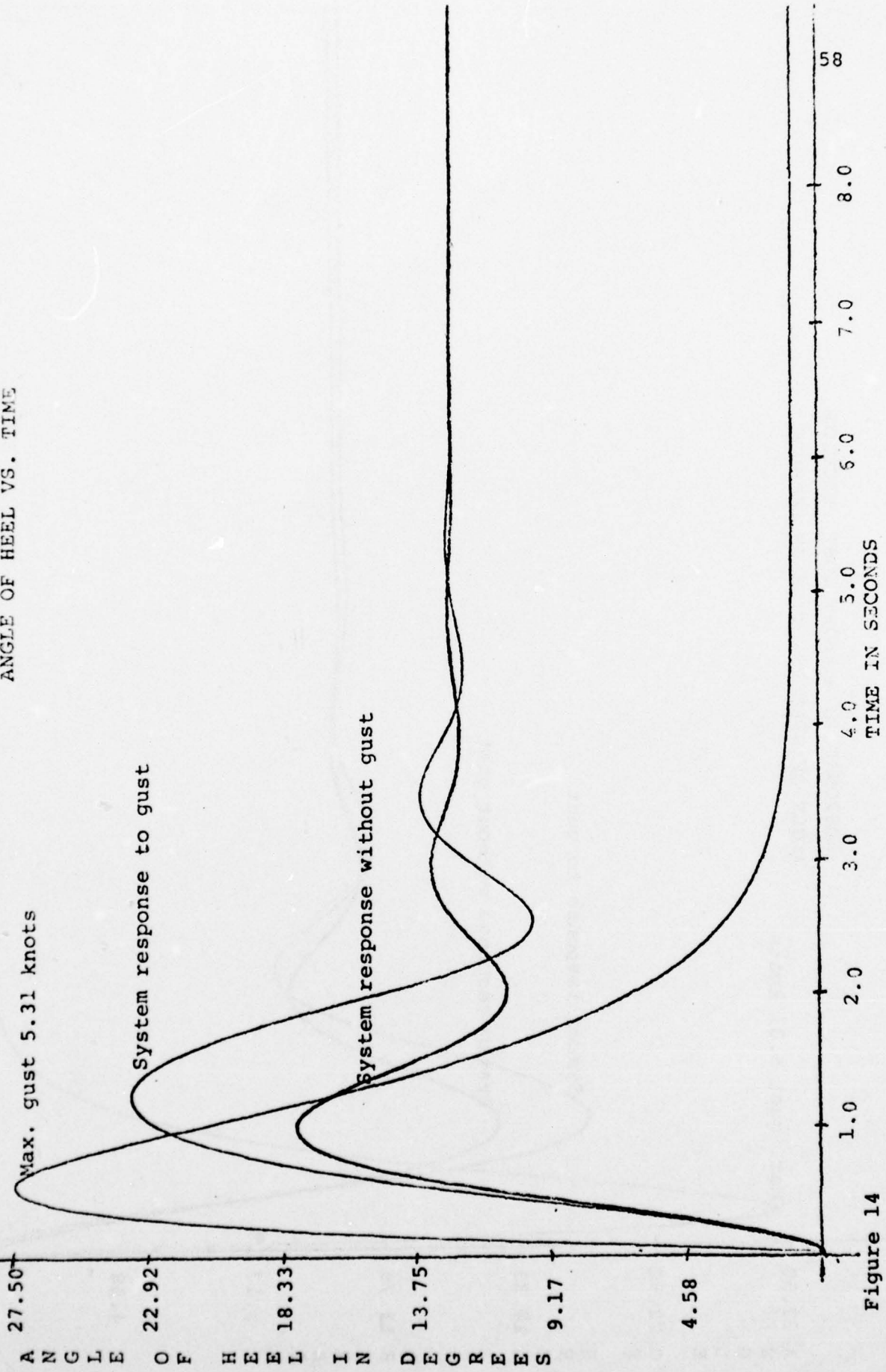
Figure 14

RESPONSE TO A LONG GUST FUNCTION

ANGLE OF HEEL VS. TIME

Figure 15

59
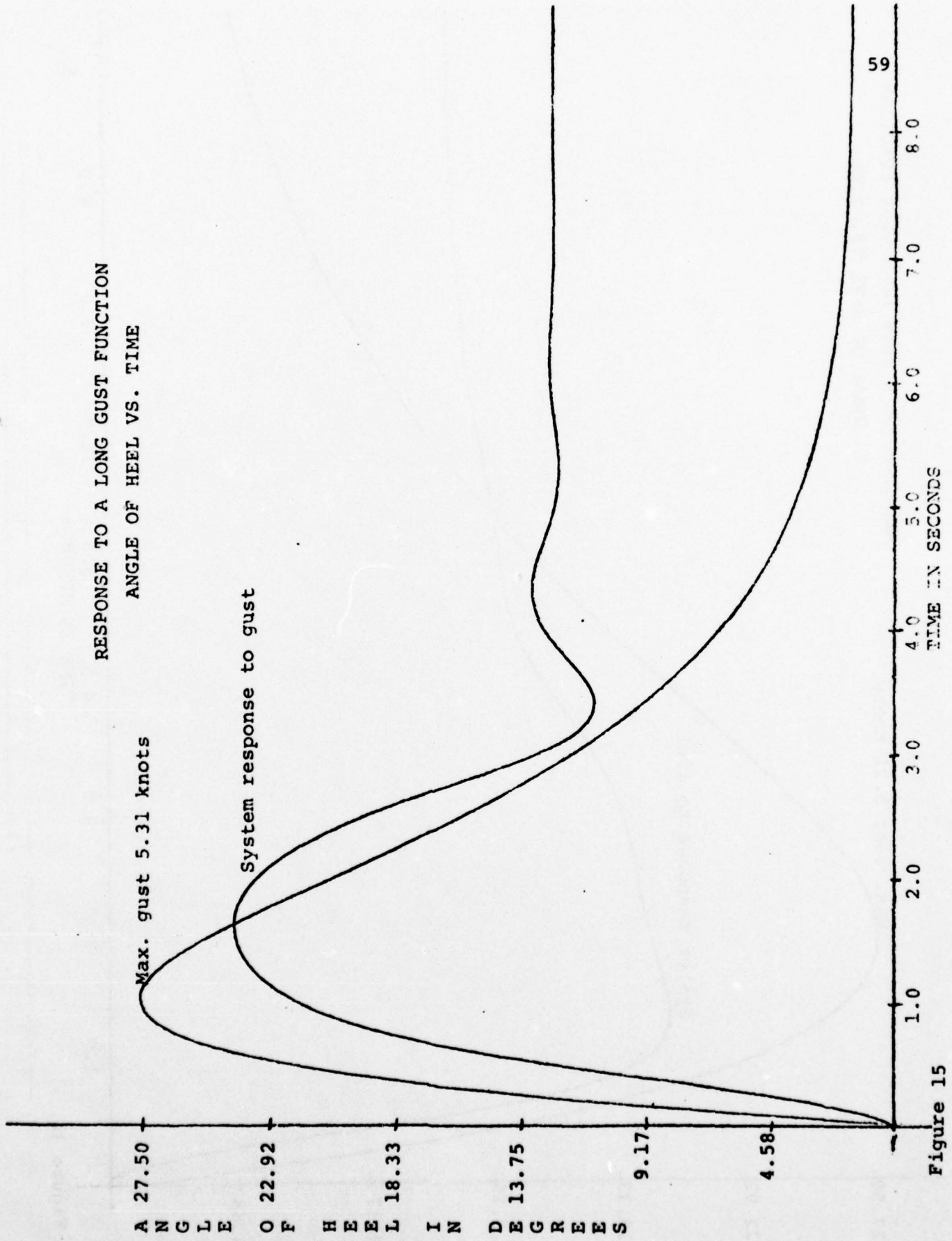
RESPONSE TO A VERY LONG GUST FUNCTION
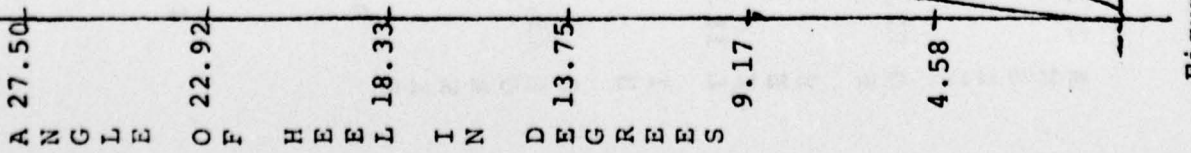
ANGLE OF HEEL VS. TIME

Max. gust 5.31 knots

System response to gust

A N G L E

O F

H E E L

I N

D E G R E E S

27.50

22.92

18.33

13.75

9.17

4.58

1.0   2.0   3.0   4.0   5.0   6.0   7.0   8.0   60

TIME IN SECONDS
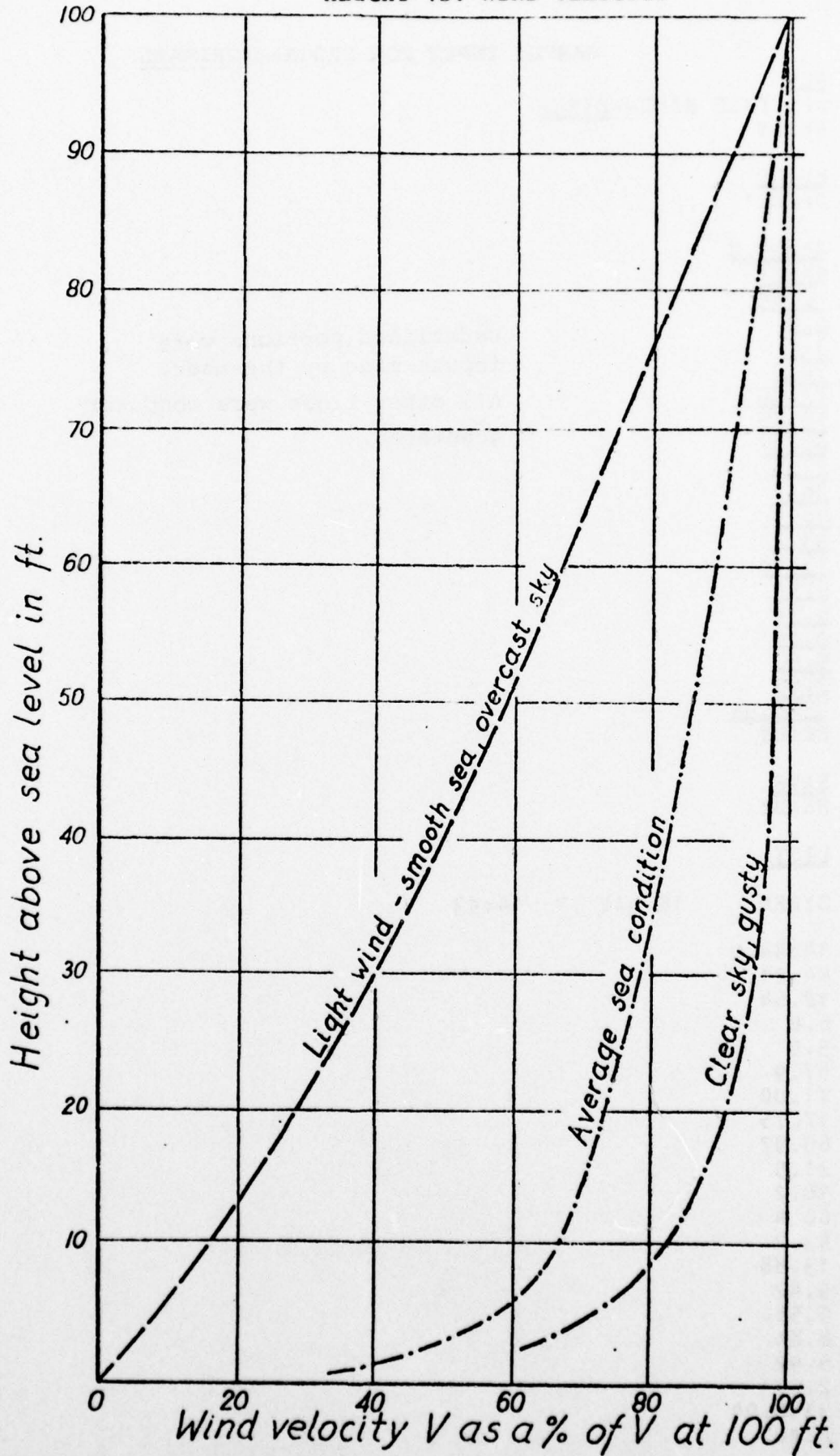
Figure 16

Figure 17

```
NEW
NEW FILE NAME--SYREN
READY

BUILD
SPEAK!

34844.0
44.21
12.64
6.6
3.9
57.9
71.00
17.75
65.97
21.5
36.2
66.4
43.2
13.88
9.42
5.58
8.84
5.92
2.67
3340.94
READY

SAVE
READY

LIST
```

                           Underlined portions were
                           inputs made by the user.
                           All other lines were computer
                           generated.

```
SYREN          15 MAY 77   14:43

34844.0
44.21
12.64
6.6
3.9
57.9
71.00
17.75
65.97
21.5
36.2
66.4
43.2
13.88
9.42
5.58
8.84
5.92
2.67
3340.94
READY
```

Figure 18

RUN

TRISAIL   15 MAY 77   14:39

LIST PROGRAM FOR GENERAL INSTRUCTIONS.   CONTINUE? <u>YES</u>
INPUT BOAT NAME? <u>SYREN</u>
INPUT TRUE WIND SPEED IN KNOTS? <u>15</u>
INPUT INITIAL TRUE WIND DIRECTION? <u>35</u>
INPUT FINAL TRUE WIND DIRECTION? <u>39</u>
INPUT INCREMENT TRUE WIND DESIRED AT
(IF ONLY ONE DIRECTION DESIRED, INPUT 0.)? <u>2</u>

TRUE WIND (DEG.)=   35.00
LWY. ANGLE (DEG)=   3.95
APP. WIND (DEG.)=   20.73
HEEL ANGLE (DEG)=   15.23
TRUE WIND (KTS.)=   15.00
APP. WIND (KTS.)=   21.16
BOAT SPEED (KTS)=   7.04
BOAT HEAD (DEG.)=   31.05
SPD TO WIND (KT)=   3.42

TRUE WIND (DEG.)=   37.00
LWY. ANGLE (DEG)=   3.79
APP. WIND (DEG.)=   22.09
HEEL ANGLE (DEG)=   15.45
TRUE WIND (KTS.)=   15.00
APP. WIND (KTS.)=   21.25
BOAT SPEED (KTS)=   7.26
BOAT HEAD (DEG.)=   33.21
SPD TO WIND (KT)=   3.43

TRUE WIND (DEG.)=   39.00
LWY. ANGLE (DEG)=   3.65
APP. WIND (DEG.)=   23.44
HEEL ANGLE (DEG)=   15.60
TRUE WIND (KTS.)=   15.00
APP. WIND (KTS.)=   21.31
BOAT SPEED (KTS)=   7.45
BOAT HEAD (DEG.)=   35.35
SPD TO WIND (KT)=   3.43

4.019 SEC.   69 I/O
READY

Figure 19

64

WIND GUST FUNCTION

TIME IN SECONDS

WIND IN KNOTS
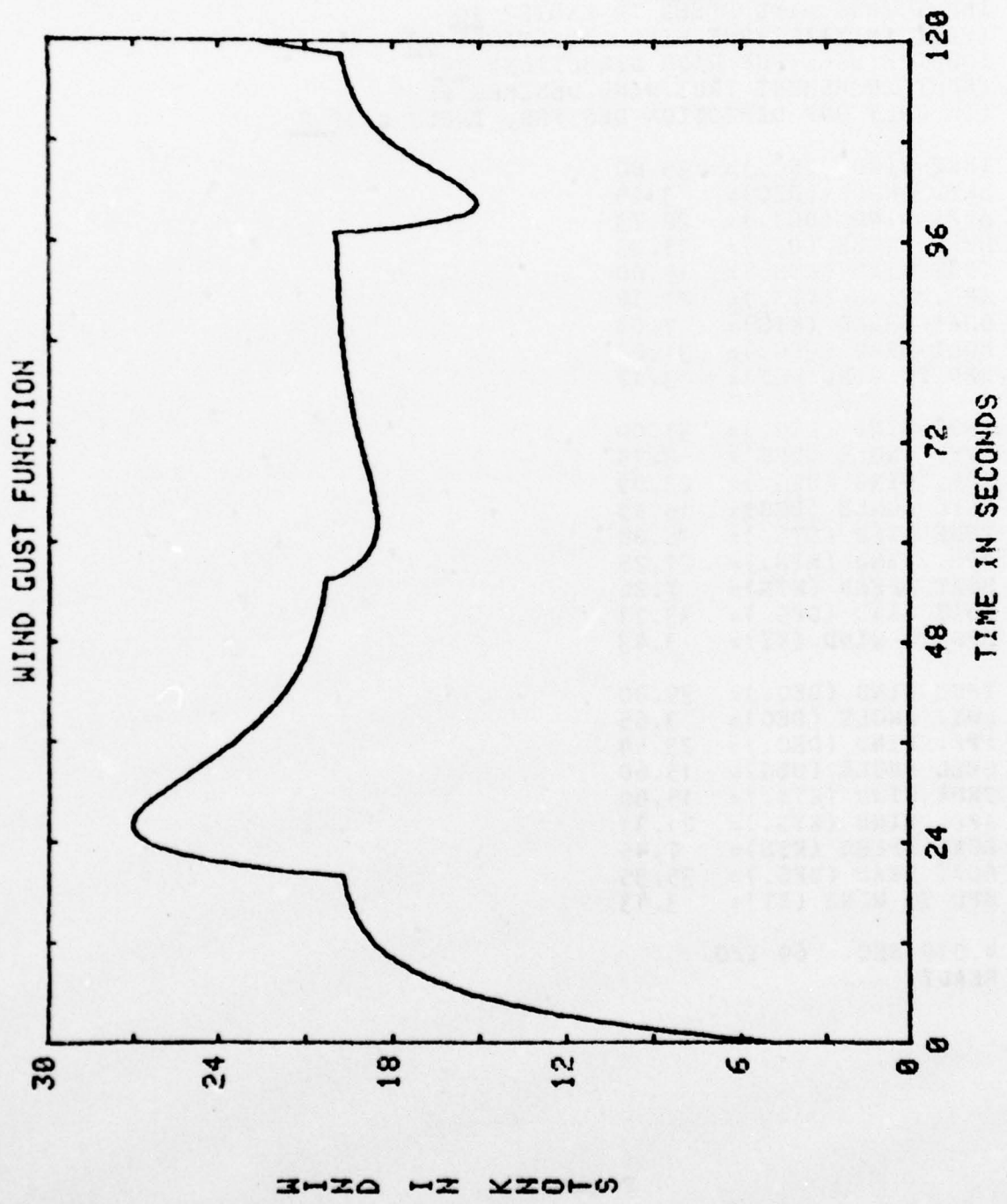
Figure 20

SEC. = 25.50
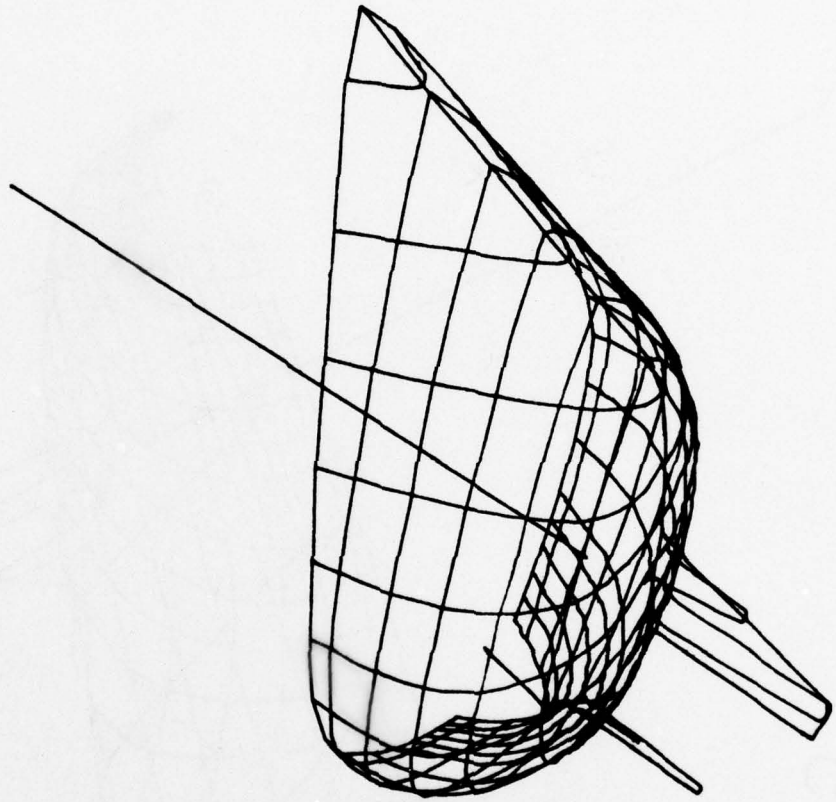
Figure 21

SEC. = 48.75

Figure 22

TRUE WIND ANGLE VERSUS TRUE WIND SPEED

TRUE WIND SPEED IN KNOTS

TRUE WIND ANGLE IN DEGREES

Figure 23

APPARENT WIND ANGLE VS. TRUE WIND SPEED

Figure 24

TRUE WIND POLARS

STED

PORT

YACHT SYREN

Figure 25

Figure 26

71

APPARENT WIND POLARS

STBD

PORT

At V_A = 18 knots,
desired angle = 28
boat speed = 7.4 knots
            to windward

At V_A = 10 knots
desired angle = 32
boat speed = 6.3 knots
            to windward
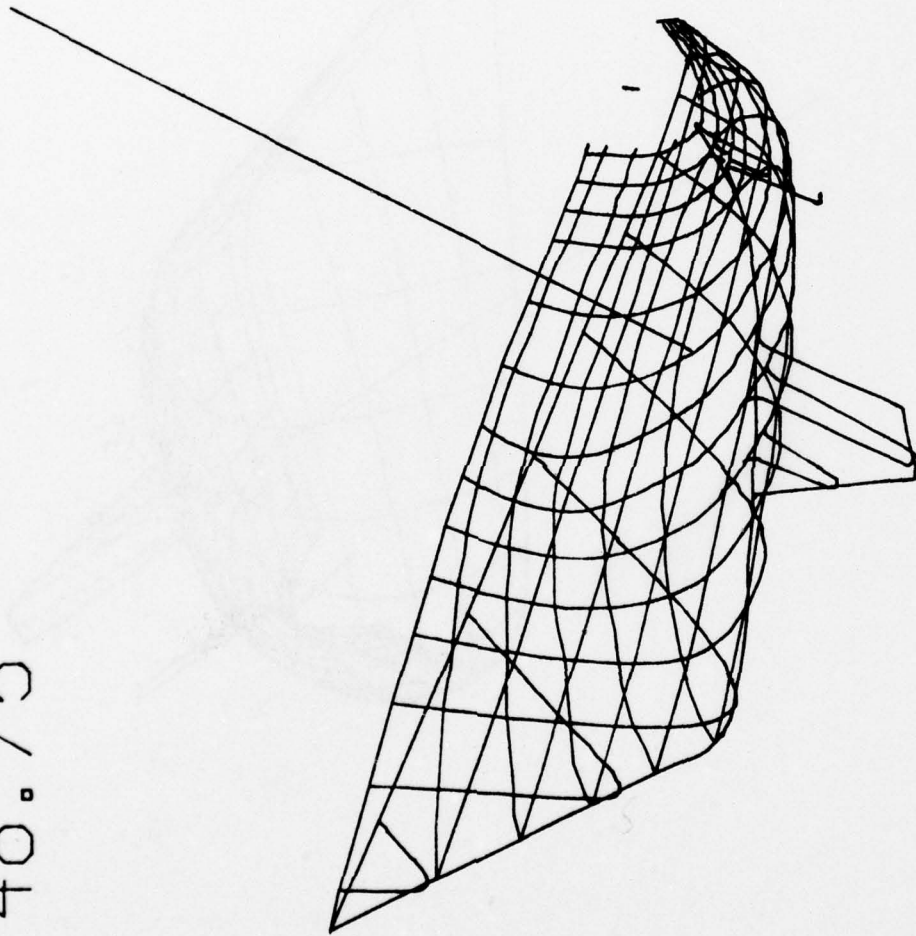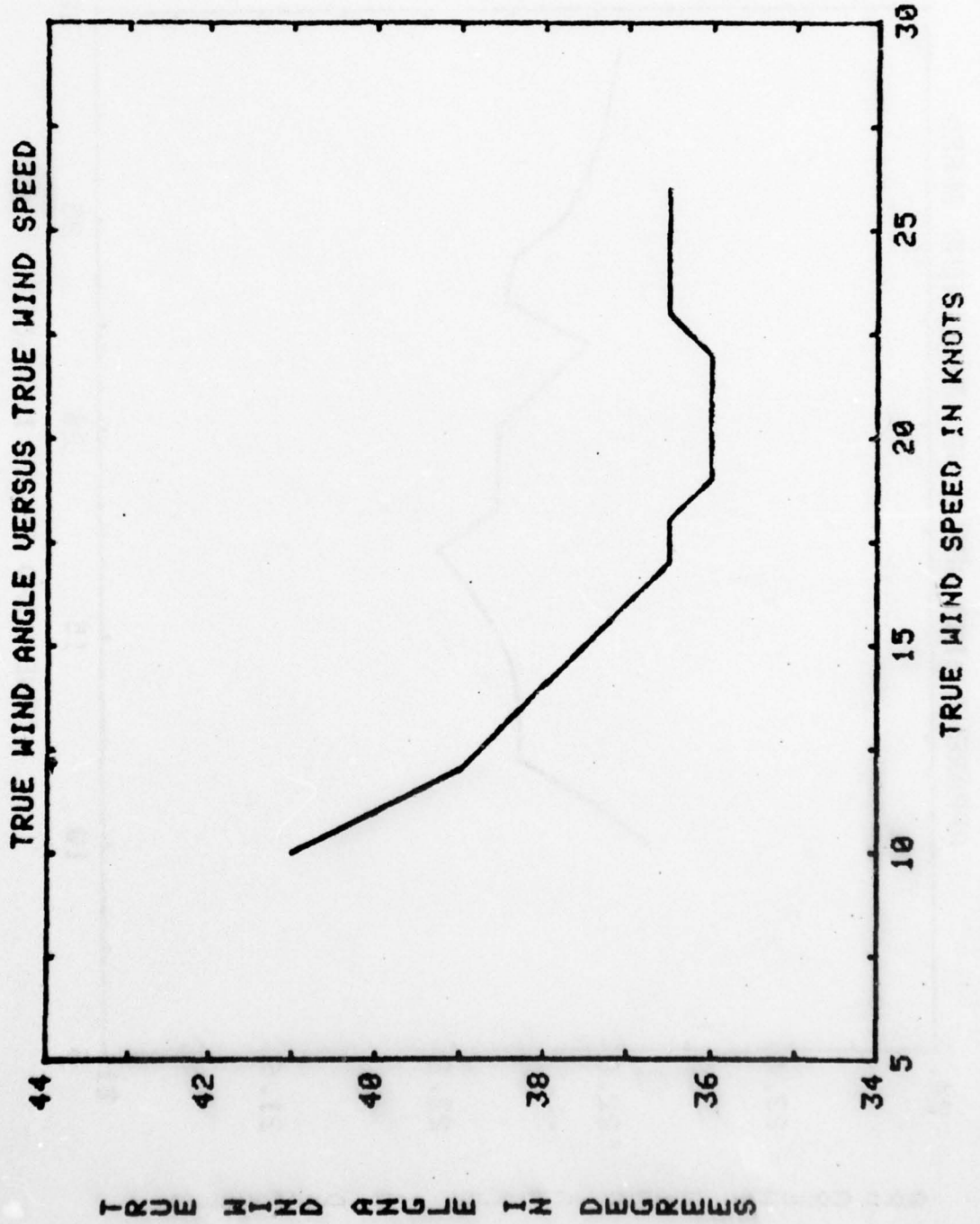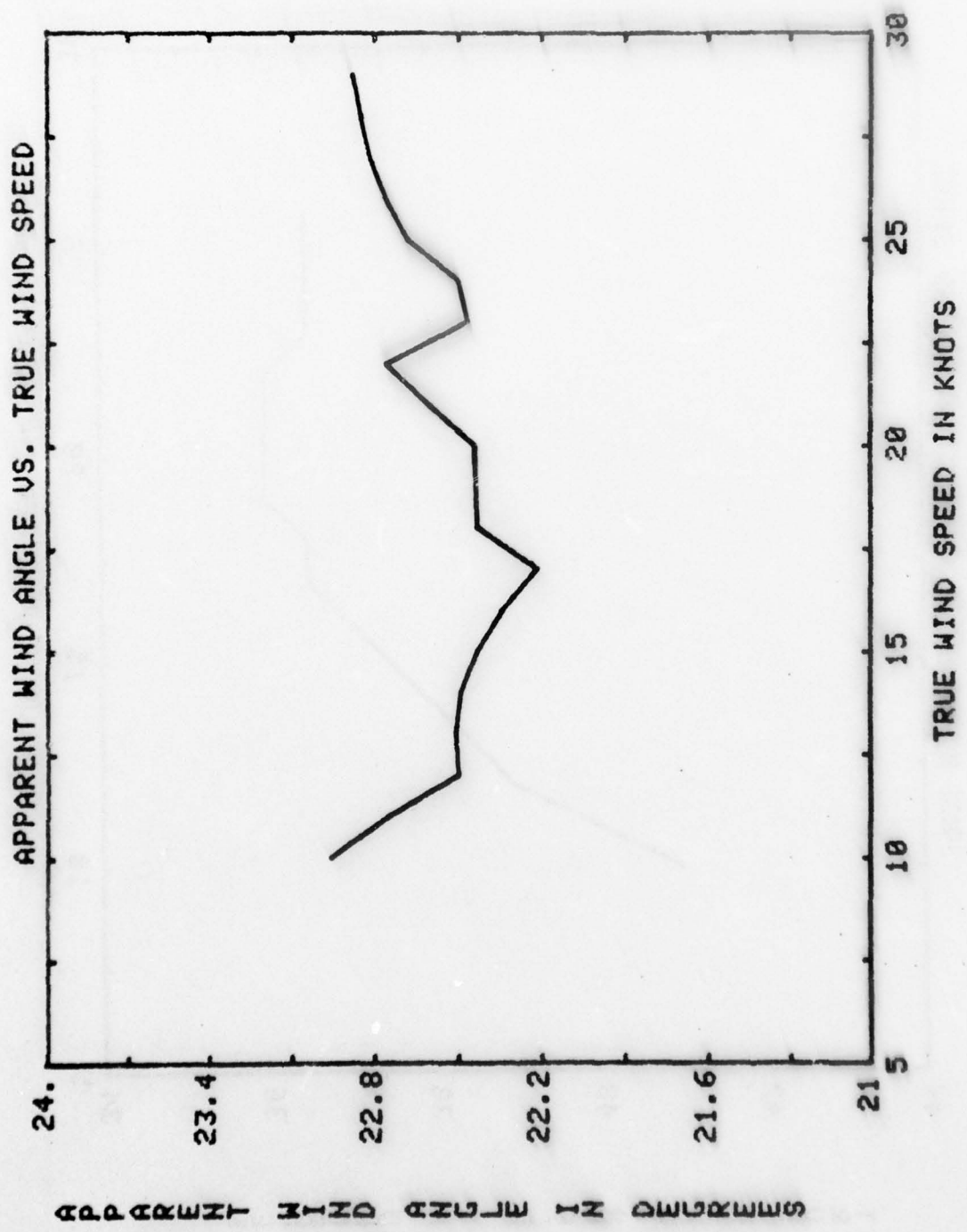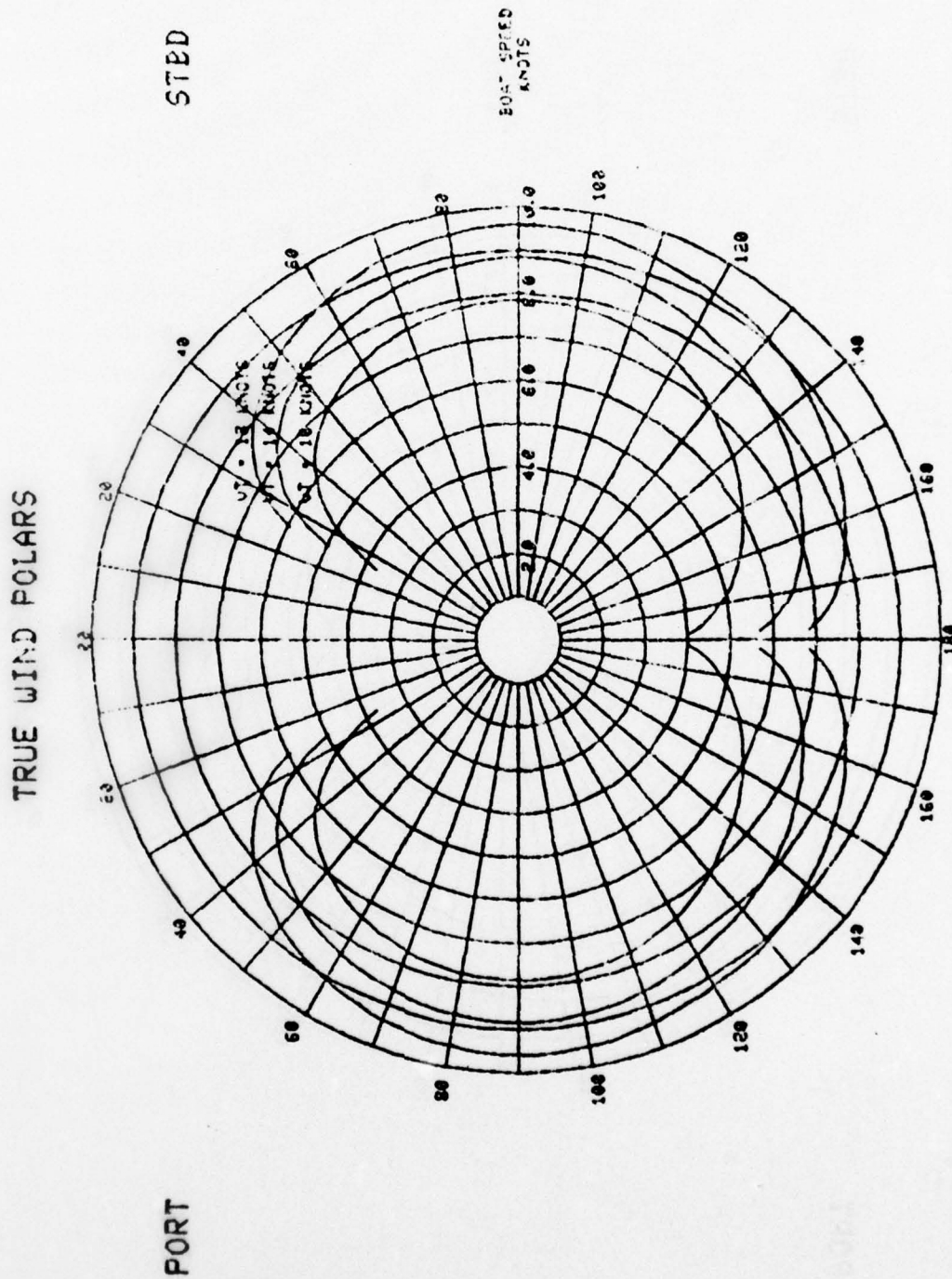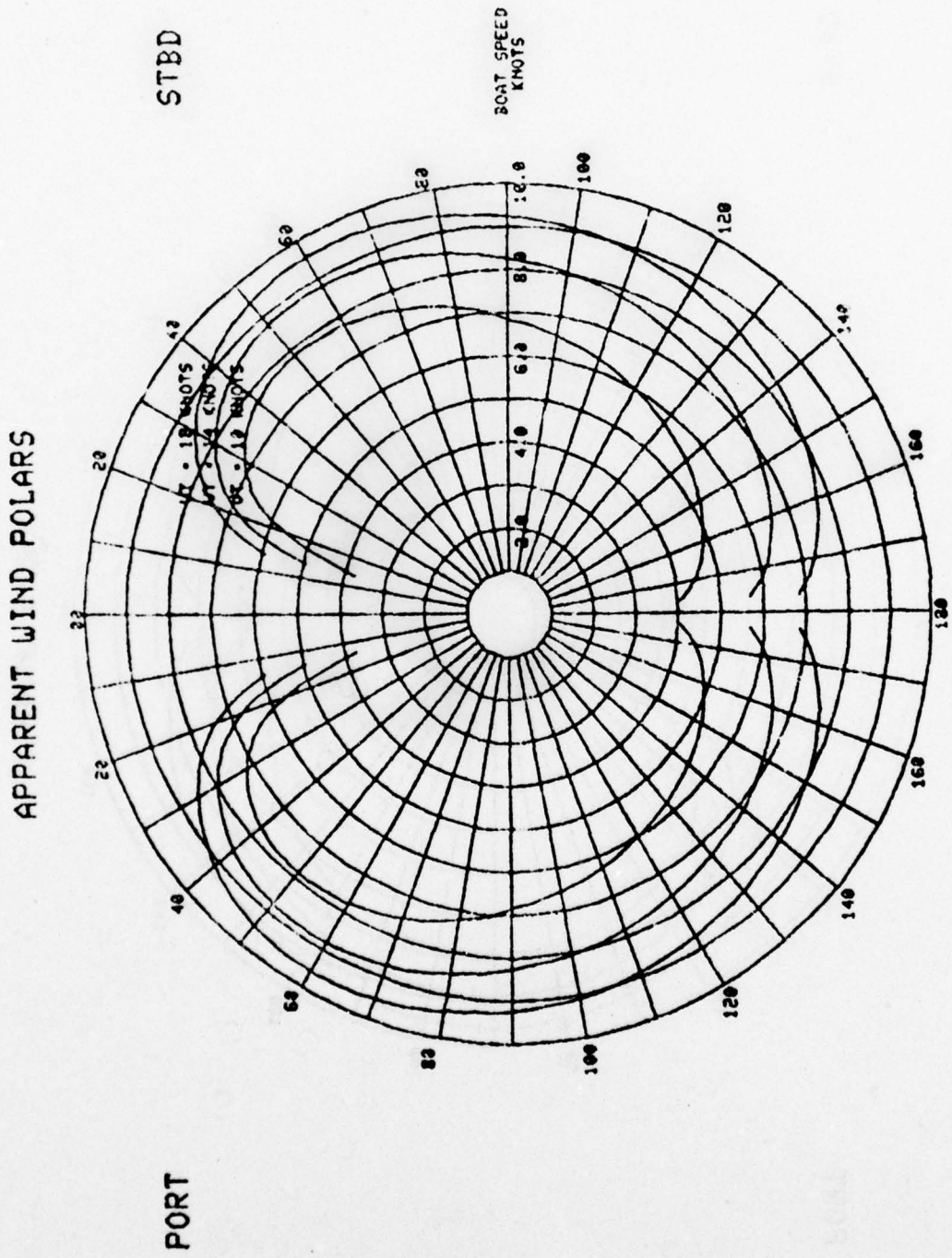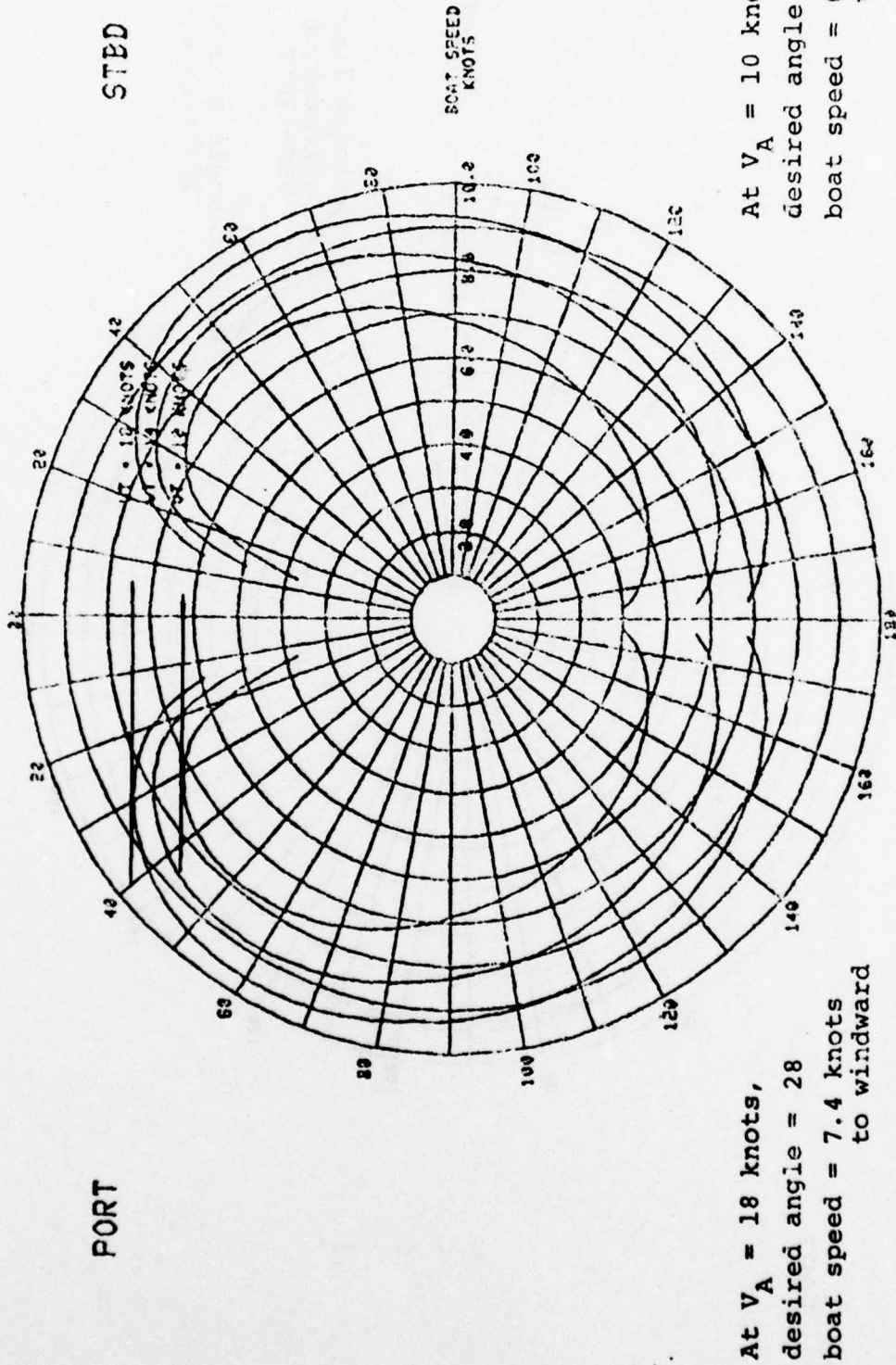
YACHT SYREN
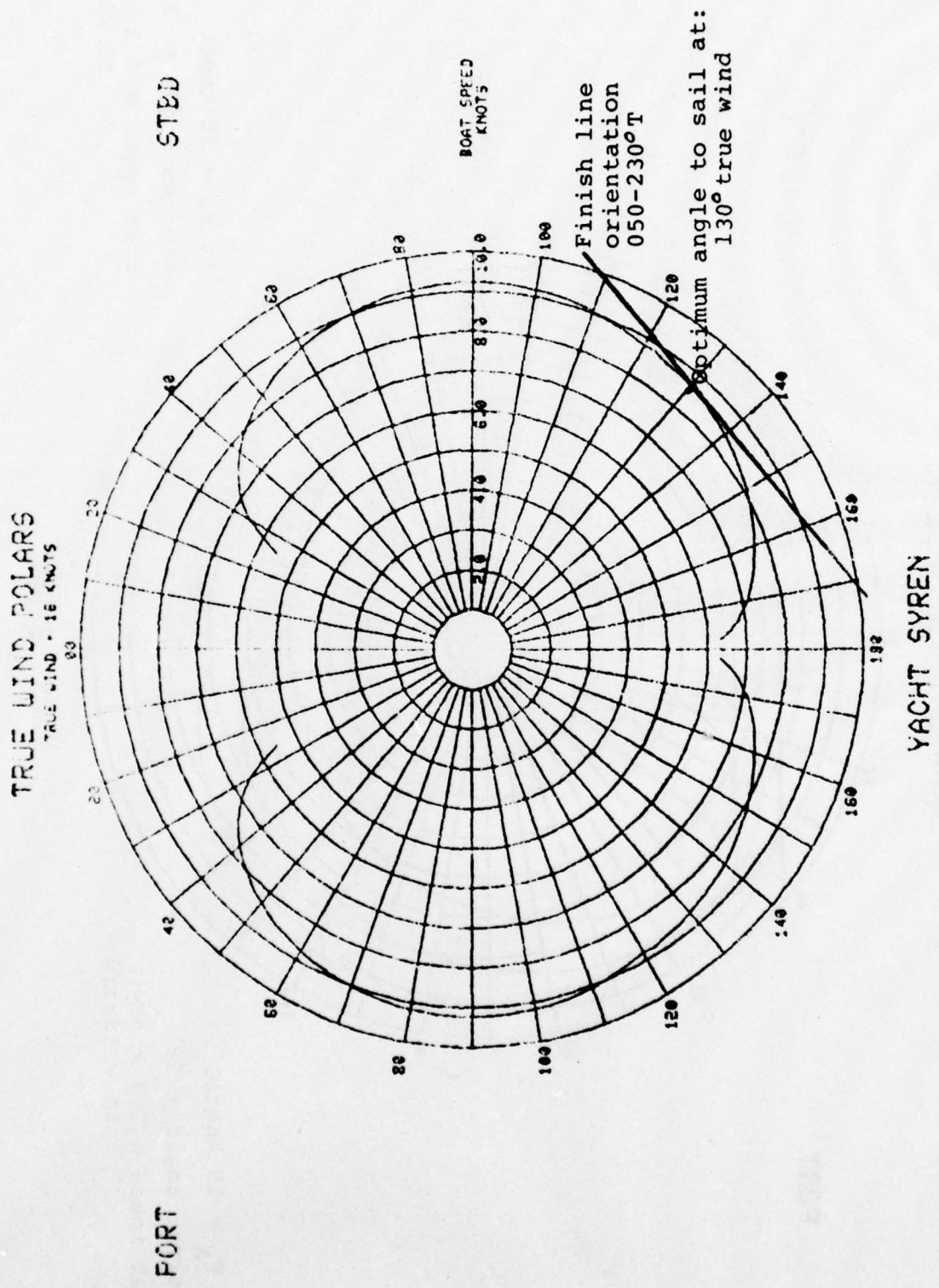
Figure 27

Figure 28

FOOTNOTES

[1]E.C. Seibert, How to Design Small Sailboats (New York: Dodd, Mead and Company, 1947), pp. 30-36.

[2]Seibert, pp. 35-36.

[3]Hugo A. Myers, "Theory of Sailing Applied to Ocean Racing Yachts," SNAME, Chesapeake Sailing Yacht Symposium, Collected Papers, January 1975.

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1. E. C. Seibert, How to Design Small Sailboats, Dodd, Mead and Company, New York, 1947.

2. H. A. Myers, "Theory of Sailing Applied to Ocean Racing Yachts," SNAME, Chesapeake Sailing Yacht Symposium, Collected Papers, January 1975.

3. C. A. Marchay, Sailing Theory and Practice, Dodd, Mead and Company, New York, 1964.

4. The Offshore Rating Council, 19 St. James' Place, London, England, International Offshore Rule I.O.R. Mark III, Liss Printers Limited, Station Road, Liss, Hampshire, 1975.

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Bhattacharyya, R. "Computer Simulation in Ship Dynamics," <u>Proceedings of the Washington-Annapolis-Baltimore Area Symposium on Computers in Education</u>. United States Naval Academy: Academic Computing Center, 3 December 1974.

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Keast, D. M. <u>Measurement in Mechanical Dynamics</u>. New York: McGraw-Hill Book Co., 1967.

Marchaj, C. A. <u>Sailing Theory and Practice</u>. New York: Dodd, Mead and Company, 1964.

Myers, Dr. H. A. "Theory of Sailing Applied to Ocean Racing Yachts," SNAME, Chesapeake Sailing Yacht Symposium, Collected Papers, January 1975.

Seibert, E. C. <u>How to Design Small Sailboats</u>. New York: Dodd, Mead and Company, 1947.

Shepard, D. G. <u>Elements of Fluid Mechanics</u>. New York: Harcourt, Brace and World, Inc., 1965.

APPENDIX A

"Trident Sail Optimization Program"

In this appendix the complete listing of the program TRISAIL can be found. This program was translated into FORTRAN from the APL program written by Dr. Hugo A. Myers entitled "Theory of Sailing Applied to Ocean Racing Yachts." Through minor alterations, the basic program below was made to perform a variety of simulation and optimization techniques. Chapter Four has a complete description of the many uses of this program.

TRISAIL

```
1000  *                   THEORY OF SAILING PROGRAM
1010  *                   FOR OCEAN RACING YACHTS
1020  *
1030  *
1040  * THIS PROGRAM IS DESIGNED TO GIVE AN INDICATION OF A SAILBOAT'S
1050  * PERFORMANCE BASED UPON A KNOWLEDGE OF THE I.O.R. MEASUREMENTS
1060  * FOR THAT BOAT.  THE PROGRAM WAS DEVELOPED IN A.P.L. BY DR. HUGO
1070  * MYERS OF I.B.M. FEDERAL SYSTEMS DIVISION, GAITHERSBURG, MARYLAND.
1080  * IT HAS BEEN AMENDED AND TRANSLATED INTO FORTRAN BY MIDN. DIRK J.
1090  * DEBBINK, CLASS OF 1977, IN CONJUNCTION WITH A TRIDENT PROJECT.
1100  *
1110  * TO RUN THIS PROGRAM, YOU MUST FIRST BUILD A FILE WHOSE NAME IS
1120  * <(BOAT NAME)> (NAME OF BOAT, LESS THAN NINE CHARACTERS LONG).
1130  * THE FILE MUST CONTAIN ONLY ONE REAL NUMBER PER LINE (IE., EACH
1140  * ENTRY MUST HAVE A DECIMAL POINT).  THE CONTENTS OF THE FILE ARE
1150  * THE FOLLOWING CONSTANTS TAKEN FROM THE I.O.R. CERTIFICATE OF
1160  * THE BOAT:  DSPL, LWL, BWL, CMD, FMD, LOA, P, E, I, J, LPG, SL,
1170  * SMW, BMAX, CK, HK, DM, HR, CR, RM.  CK, HK, HR, CR ARE NOT FOUND
1180  * ON THE CERTIFICATE AND MUST BE DIRECTLY MEASURED OR TAKEN FROM
1190  * THE BOAT PLANS.  THEY ARE ALL AVERAGE VALUES AND REPRESENT,
1200  * RESPECTFULLY, THE CHORD OF THE KEEL, HEIGHT OF THE KEEL, HEIGHT
1210  * OF THE RUDDER, AND THE CHORD OF THE RUDDER.
1220  *
1230  *
1240  * PROGRAM BODY FOLLOWS.
1250  *
1260  *
1270  * * * * * * * * * * * * * * *
1280  * SET-UP BLOCK
1290  * READS IN BOAT DATA AND DIRECTS CALCULATION OF YACHT FUNCTIONS.
1300  *
1310      IMPLICIT REAL(A-Y)
1320      CHARACTER Z*12,ZA,ZB
1330  90 FORMAT(F10.3)
1340  91 FORMAT(A17,F7.2)
1350      PRINT,"LIST PROGRAM FOR GENERAL INSTRUCTIONS.  CONTINUE"
1360      INPUT, Z
1370      IF (Z.EQ."YES") GO TO 96
1380      GO TO 82
1390  96 PRINT,"INPUT BOAT NAME"
1400      INPUT, Z
1410      OPENFILE 1, Z
1420      READ (1,90) DSPL,LWL,BWL,CMD,FMD,LOA,P,E,I,J
1430      READ (1,90) LPG,SL,SMW,BMAX,CK,HK,DM,HR,CR,RM
1440      GO TO 75
1450   1 GO TO 70
1460  * * * * * * * * * * * * * * *
1470  * INPUT BLOCK
1480  * INPUTS WIND CONDITIONS
1490  *
```

TRISAIL (continued)

```
1500   2 PRINT,"INPUT TRUE WIND SPEED IN KNOTS"
1510     INPUT, VTK
1520     PRINT, "INPUT INITIAL TRUE WIND DIRECTION"
1530     INPUT, PH
1540     PRINT, "INPUT FINAL TRUE WIND DIRECTION"
1550     INPUT, FPH
1560     PHI=180-PH
1570     FPHI=180-FPH
1580     PRINT, "INPUT INCREMENT TRUE WIND DESIRED AT"
1590     PRINT, "(IF ONLY ONE DIRECTION DESIRED, INPUT 0.)"
1600     INPUT, STEP
1610 * * * * * * * * * * * * * * * *
1620   * SOLUTION BLOCK
1630   * THIS IS THE MAIN BODY OF THE PROGRAM WHICH CONTROLS AND
1640   * DIRECTS THE ITERATIVE PROCESS WHICH SOLVES THE FOUR BASIC
1650   * SIMULTANEOUS EQUATIONS.
1660   *
1670  10 PRINT, " "
1680     PRINT 91,"TRUE WIND (DEG.)=",180-PHI
1690     GO TO 65
1700  17 LAMBDA=VTT*PHI/40000
1710     THETA=0.004*VTT*PHI*DTR
1720     VB=0.4*LWL^0.5*VTT^0.3
1730  11 GO TO 49
1740   3 GO TO 48
1750   4 GO TO 50
1760   5 GO TO 47
1770   6 GO TO 20
1780   7 GO TO 25
1790   8 IF ((VTT-VT)^2.LT.1.E-4) GO TO 12
1800     THETA=THETA*(VTT/VT)
1810     VB=VB*(VTT/VT)^0.5
1820     GO TO 11
1830  12 GO TO 60
1840  14 LWY=LAMBDA*RTD
1850     APPW=UPS*RTD
1860     HEEL=THETA*RTD
1870     VT=VT*FPSTK*(VMHPER/VCEPER)
1880     VA=VAM*FPSTK
1890     VB=VB*FPSTK
1900     HEAD=180-PHI-LAMBDA*RTD
1910     SPEED=VB*FPSTK*COS((180-PHI)*DTR)
1920     PHI=PHI-STEP
1930     GO TO 80
1940  16 IF (STEP.EQ.0) GO TO 82
1950     IF (PHI.LT.FPHI) GO TO 82
1960     GO TO 10
1970 * * * * * * * * * * * * * * *
1980   * HEELING EQUATIONS
1990   * THIS BLOCK CONTAINS THE HEELING/RIGHTING MOMENT EQUATIONS.
```

TRISAIL (continued)

```
2000  *
2010 20 L=LWL+THETA*(LOA-LWL)
2020    IF(BETA.GE.1.4) GO TO 21
2030    NUM=COS(GAMMA)*(8*L*BWL^3+3.6*KWR*W*DM-0.067*W*(P+3*FMD))
2040    DEN=(P+3*FMD)*RHOA*AWWD*COS(BETA-GAMMA)
2050    GO TO 22
2060 21 NUM=8*L*BWL^3+3.6*KWR*W*DM-0.067*W*(P+3*FMD)
2070    DEN=(P+3*FMD)*RHOA*ADWDR
2080 22 B=NUM/DEN
2090    ROOTH=(B^2+4*VA^4)^0.5
2100    THETA1=SQRT(4*VA^4-(ROOTH-B)^2)
2110    THETA=ATAN2(ROOTH-B,THETA1)
2120    AH=AHO*(1+0.5*THETA)
2130    IF (NA.EQ.1) GO TO 23
2140    GO TO 7
2150 23 NA=0
2160    GO TO 32
2170 * * * * * * * * * * * * * * *
2180  * ERROR EQUATION BLOCK
2190  * THIS BLOCK CHECKS TO SEE IF FORCES HAVE BEEN BALANCED.
2200  * IF THEY HAVEN'T, VB AND LAMBDA ARE RESET AND ANOTHER
2210  * ITERATION IS STARTED.
2220  *
2230 25 NC=0
2240    GO TO 30
2250 26 IF (NC.GT.7) GO TO 27
2260    NC=NC+1
2270    VB=VB*((SDF-WID)/(FRD+WAD+RWD+RAD+IND))^DDEXP
2280    LAMBDA=LAMBDA*((LSF+LWF)/LOH)^DLEXP
2290    IF ((ABS(DELTAD)+ABS(DELTAL)).GT.6*NC) GO TO 30
2300 27 GO TO 45
2310 28 GO TO 8
2320 * * * * * * * * * * * * * * *
2330  * COEFFICIENTS OF FRICTION DRAG CALCULATED.
2340  *
2350 30 GO TO 46
2360 31 CFH=0.455/(ALOG10(VB*L/NU)^2.58)
2370    CFR=0.455/(ALOG10(VB*CR/NU)^2.58)
2380    CFK=0.455/(ALOG10(VB*CK/NU)^2.58)
2390    GO TO 35
2400 32 GO TO 40
2410 33 GO TO 26
2420 * * * * * * * * * * * * * * *
2430  * DRIVING FORCE EQUATIONS
2440  * CALCULATES DRIVING FORCES AND ERROR PRESENT.
2450  *
2460 35 IF (BETA.GT.1.4) GO TO 36
2470    SDF=0.5*RHOA*VA^2*(AWWD/COS(GAMMA))*SIN(BETA-GAMMA)*COS(THETA)
2480    RAD=RAC*SDF*VB^2/((W*L^2)^0.5*SIN(BETA-GAMMA))
2490    GO TO 37
```

TRISAIL (continued)

```
2500 36 SDF=0.5*RHOA*VA^2*ADWDR*COS(THETA)*SIN(0.5*BETA)
2510    RAD=RAC*SDF*VB^2/((W*L^2)^0.5)
2520 37 FRD=0.5*RHOW*VB^2*(CFH*AH+CFK*AK+CFR*AR)
2530    IF (VB.LE.WAC*L^0.5) GO TO 38
2540    WAD=VB^2*AH*W*((VB-WAC*L^0.5)^2.5)*0.12/(L^4*G*(COS(THETA))^2)
2550    WAD=WAD+10*WAD*((BWL/LWL)-0.25)^2
2560    WAD=WAD*(VB/L^0.5)^0.3
2570    GO TO 39
2580 38 WAD=0
2590 39 RWD=RWC*WAD*PHI*VB^2/((W*LOA)^0.5*LOA)
2600    IND=VB^2*0.5*AK*COS(THETA)*CDIK+0.5*AR*COS(THETA)*CDIR+AHL*CDIH
2610    WID=0.5*RHOA*VA^2*ATW*COS(BETA)
2620    DELTAD=SDF-(FRD+WAD+RAD+RWD+IND+WID)
2630    NA=1
2640    GO TO 20
2650 * * * * * * * * * * * * *
2660 * LATERAL FORCE EQUATIONS
2670 * CALCULATES LATERAL FORCES AND ERROR PRESENT.
2680 *
2690 40 AWWDK=AGR+CLM*AM+AMZ
2700    IF (BETA.GT.1.4) GO TO 41
2710    LSF=0.5*RHOA*VA^2*AWWDK*COS(BETA-GAMMA)*COS(THETA)/COS(GAMMA)
2720    GO TO 42
2730 41 LSF=0.5*RHOA*VA^2*ADWDR*0.3*COS(THETA)
2740 42 LWF=0.5*RHOA*VA^2*ATL*CDW*SIN(BETA)
2750    LOH=VB^2*(AHL*CLH+0.5*AR*CLR*COS(THETA)+0.5*AK*CLK*COS(THETA))
2760    DELTAL=LSF+LWF-LOH
2770    GO TO 33
2780 * * * * * * * * * * * * *
2790 * TRUE WIND SPEED CALCULATION THROUGH LAW OF COSINES.
2800 *
2810 45 VT=(VA^2+VB^2-2*VA*VB*COS(BETA))^0.5
2820    GO TO 28
2830 * * * * * * * * * * * * *
2840 * LIFT AND INDUCED DRAG COEFFICIENTS.
2850 *
2860 46 CLR=6*SIN(LAMBDA+ALPHAR)*HR*COS(THETA)/(CR+HR*COS(THETA))
2870    CLK=6*SIN(LAMBDA+ALPHAK)*HK*COS(THETA)/(CK+HK*COS(THETA))
2880    CLH=0.3*SIN(LAMBDA)
2890    CDIK=6*CK*HK*(SIN(LAMBDA+ALPHAK))^2/(HK+CK)^2
2900    CDIR=6*CR*HR*(SIN(LAMBDA+ALPHAR))^2/(HR+CR)^2
2910    CDIH=0.3*(SIN(LAMBDA))^2
2920    GO TO 31
2930 * * * * * * * * * * * * *
2940 * RATED DOWNWIND SAIL AREA CALCULATION.
2950 *
2960 47 ADWDR=1.2*((AM+AMZ)+1.6*ASP*(0.5*BETA-0.05*BETA^3))
2970    GO TO 6
2980 * * * * * * * * * * * * *
2990 * CALCULATION OF THE ANGLE BETA THROUGH LAW OF COSINES.
```

TRISAIL   (continued)

```
3000  *
3010  48 BETA=(VA^2+VB^2-VTT^2)/(2*VA*VB)
3020     NUM=SIGN(SQRT(1-ABS(BETA)^2),ABS(BETA))
3030     DEN=BETA
3040     BETA=ATAN2(NUM,DEN)
3050     GO TO 4
3060  * * * * * * * * * * * * * *
3070  * CALCULATION OF THE APPARENT WIND SPEED THROUGH LAW OF COSINES.
3080  *
3090  49 VA2=VB^2+VTT^2-2*VB*VTT*COS(PHI*DTR)
3100     VA=VA2^0.5
3110     GO TO 3
3120  * * * * * * * * * * * * * * *
3130  * RATED SAIL AREA TO WINDWARD.
3140  *
3150  50 CLM=-0.741*BETA^2+1.63*BETA+0.37
3160     AMZ=0.5*PY*EY
3170     CLMZ=1.2*SIN(BETA)
3180     AMR=CLM*AM+CLMZ*AMZ
3190     CLG=0.111*BETA^2+0.233*BETA+1.06
3200     AGR=0.75*CLG*AG
3210     AWWD=AMR+AGR
3220     GO TO 5
3230  * * * * * * * * * * * * * * *
3240  * CALCULATION OF THE KEEL TO WEIGHT RATIO.
3250  *
3260  55 FIRST=57.3*RM
3270     SECOND=-1.3*BWL^3*LWL
3280     THIRD=0.011*W*(1+3*FMD)
3290     KWR=(FIRST+SECOND+THIRD)*5/(3*W*DM)
3300     GO TO 2
3310  * * * * * * * * * * * * * *
3320  * ADJUSTMENT OF THE APPARENT WIND DUE TO HEIGHT OF MAST AND
3330  * THE EFFECT OF THE HEEL OF THE BOAT ON THE APPARENT WIND DIRECTION.
3340  *
3350  60 VAM=VB^2+VMH^2-2*VB*VMH*COS(PHI*DTR)
3360     VAM=VAM^0.5
3370     ANGLE=(VAM^2+VB^2-VMH^2)/(2*VB*VAM)
3380     NUM=SIGN(SQRT(1-ABS(ANGLE)^2),ABS(ANGLE))
3390     DEN=ANGLE
3400     OMEGA=ATAN2(NUM,DEN)-LAMBDA
3410     UPS=ATAN2(SIN(OMEGA),COS(OMEGA)*COS(THETA))
3420     IF (UPS.LT.0) UPS=(180*DTR)+UPS
3430     GO TO 14
3440  * * * * * * * * * * * * * * *
3450  * CALCULATION OF THE WIND VELOCITY AT THE CENTER OF EFFORT OF THE
3460  * SAILS FROM THE VELOCITY AT THE MASTHEAD.
3470  *
3480  65 VMH=VTK/FPSTK
3490     CE=FMD+P/3
```

TRISAIL (continued)

```
3500     MH=FMD+P
3510     IF (VTK.LT.10) GO TO 66
3520     IF (VTK.GT.30) GO TO 67
3530     VMHPER=0.3*MH+70-70*EXP(-MH/5)
3540     VCEPER=0.3*CE+70-70*EXP(-CE/5)
3550     GO TO 68
3560 66  VMHPER=0.85*MH+15-15*EXP(-MH/18)
3570     VCEPER=0.85*CE+15-15*EXP(-CE/18)
3580     GO TO 68
3590 67  VMHPER=0.05*MH+95-95*EXP(-MH/5)
3600     VCEPER=0.05*CE+95-95*EXP(-CE/5)
3610 68  VTT=(VCEPER/VMHPER)*VMH
3620     GO TO 17
3630 * * * * * * * * * * * * * * * *
3640  * YACHT FUNCTIONS
3650  * CALCULATION OF CRITICAL YACHT FUNCTIONS.
3660  *
3670 70  W=1.2*DSPL
3680     HD=CMD-FMD
3690     MG1=0.5*BWL+HD
3700     MG2=((0.5*BWL)^2+HD^2)^0.5
3710     MG=MG2*2.2
3720     AHO=0.65*LWL*MG
3730     AMZ=0.5*PY*EY
3740     AM=0.5*P*E
3750     FT=0.5*I*J
3760     AG=0.5*LPG*(J^2+P^2)^0.5
3770     ASP=0.85*SL*SMW
3780     HK=(DM-HD)
3790     AK=2*CK*HK
3800     AR=2*CR*HR
3810     ATL=0.8*(FMD*LOA+P+PY)
3820     ASW=0.005*(P*(P+E)+PY*(PY+EY))
3830     ATW=0.4*FMD*BMAX+ASW+0.5*(CABIN+CREW)
3840     AHL=0.67*LWL*HD
3850     GO TO 55
3860 * * * * * * * * * * * * * * *
3870  * CONSTANTS
3880  *
3890 75  DTR=0.01745
3900     FPSTK=0.5925
3910     CREW=20
3920     CABIN=0
3930     GAMMA=0.15
3940     RHOA=0.00238
3950     ALPHAR=0
3960     ALPHAK=0
3970     NU=1.408E-5
3980     RAC=2
3990     RHOW=1.99
```

TRISAIL (continued)

```
4000    WAC=1.2
4010    RWC=1
4020    CDW=1
4030    G=32.2
4040    RTD=57.3
4050    PY=EY=0
4060    DDEXP=0.2
4070    LLEXP=1.0
4080    GO TO 1
4090 * * * * * * * * * * * * *
4100  * PRINT BLOCK
4110  *
4120 80 PRINT 91,"LWY. ANGLE (DEG)=",LWY
4130    PRINT 91,"APP. WIND (DEG.)=",APPW
4140    PRINT 91,"HEEL ANGLE (DEG)=",HEEL
4150    PRINT 91,"TRUE WIND (KTS.)=",VT
4160    PRINT 91,"APP. WIND (KTS.)=",VA
4170    PRINT 91,"BOAT SPEED (KTS)=",VB
4180    PRINT 91,"BOAT HEAD (DEG.)=",HEAD
4190    PRINT 91,"SPD TO WIND (KT)=",SPEED
4200    GO TO 16
4210 82 CONTINUE
4220    END
```

APPENDIX B

"Fortran Random Wind Generating Program"

The program whose listing is below is entitled <u>FORWIND</u>. By the use of the gust function:

$$f(t)=Ate^{-at}$$

and the random number generator in the computer, random gusts were produced around a steady base wind. A graph of this wind function is shown in Figure 20. The files "WIND1" and "GRAPH" were used to input the data generated by <u>FORWIND</u> into <u>TRISAIL</u> and a plotting program "L.IG*** :TEKGRAF", respectively.

FORWIND

```
100     IMPLICIT REAL(A-Z)
110   7 FORMAT (F8.4)
120   6 FORMAT (F8.4,A1,F8.4)
130   5 FORMAT (A9)
140     OPENFILE 1, "WIND1"
150     OPENFILE 2, "GRAPH"
160     REWIND 1
170     ENDFILE 1
180     REWIND 2
190     ENDFILE 2
200     P=135.0
210     T=0.00
220   4 T1=0.00
230     M=AINT(10.0*(RND(1.0)*20.0-10.0))/10.0
240     M1=AINT(100.0*RND(1.0))/10.0
250     A=M*EXP(1.0)/M1
260     T2=AINT(12.0*M1+0.5)/2.0
270     IF(T.EQ.0.0) T2=20.0
280   3 W=20.0+A*T1*EXP(-T1/M1)
290     IF(T.LE.1) W=20-15.0*EXP(-0.2*T1)
300     WRITE (1,7) W
310     WRITE (1,7) P
320     WRITE (1,7) T+T1
330     WRITE (2,6) T+T1,",",W
340     T1=T1+0.25
350     IF (T+T1.GT.120) GO TO 1
360     IF (T1.GT.T2) GO TO 2
370     GO TO 3
380   2 T=T+T2
390     IF (T.GT.120) GO TO 1
400     GO TO 4
410   1 WRITE (2,5) "1E37,1E37"
420     END
```

APPENDIX C

"Sailing Performance Package"

The final marketable output of this project can be found in this appendix. In the next several pages a sailing performance package consisting of two rectangular graphs and twenty-two polar plots for the Naval Academy's fifty-eight foot sloop SYREN is exhibited exactly as it would have been presented to the owner/skipper of SYREN for his use on board the boat. Being a unique development, this sailing performance package is still under study and could be augmented by additional curves of the same or different type at a later date, depending on user demand.

SAILING PERFORMANCE PACKAGE

DESIGNED ESPECIALLY FOR

NAVAL ACADEMY YACHT <u>SYREN</u>

MAY 1977

The curves enclosed have been developed by Midshipman
Dirk J. Debbink, Class of 1977, United States Naval Academy
under his advisor Assistant Professor Kenneth A. Knowles as
a part of a Trident Research Project. Several programs
have been used, but all were offshoots from the FORTRAN
program TRISAIL, which is a translation and modification
of Dr. Hugo A. Myers' "Theory of Sailing Applied to Ocean
Racing Yachts."

The first two curves are designed to give an indication
of the optimum apparent wind and true wind angles your
sailboat should be sailing at to windward and what sort
of tacking angle you should achieve. Utilizing these curves
you can optimize your windward performance. On the
apparent wind versus true wind speed graph you will notice
that as the wind increases, the apparent wind angle
decreases and then slowly rises again.   The change is
small, however, since we are dealing with smooth water and
moderate to moderately heavy air in which one should expect
little change. Lighter air and/or heavier seas would
require that you open up the apparent wind angle some more,
but in no case should the boat ever be sailed for maximum
speed at an apparent wind angle less than the one shown. The
second rectangular graph gives an indication of the true wind
angles. By doubling the wind angle, the tacking angle can be
found. Notice at ten knots of true wind this angle is around

eight-two degrees while in moderately heavy breeze, your boat should be able to tack through about seventy-two degrees. Heavier winds will actually give you greater tacking angles than the ones shown due to the affect of the leeway angle on the course made good.

Twenty-two polar plots are also included in the package. These polar plots serve primarily to tell you how fast your boat should be able to go under any given conditions. Once again, they are derived on the basis of smooth water and proper sail trim (a spinnaker is automatically set when the wind angle reaches eighty-five degrees relative). Eleven graphs are given in terms of apparent wind angles and eleven more in terms of true wind angles. To use them, simply flip to the desired type of plot and then locate the proper wind speed. All wind speeds are in true knots at the masthead, while wind angles are expressed in both apparent and true degrees. The point of sail is located on the peri-meter of the graph and the boat speed in then read off of the curve. These curves should come in extremely handy in getting the most out of your boat at every point of sail.

Two specific uses of these polar plots are shown on the last two graphs. The first of these is the determina-tion of the optimum wind angle to sail at to windward. This is found on either true or apparent wind angle plots by con-structing a line perpendicular to the 0-180 degrees axis and tangent to the top of the curve in question. An example is

shown on the apparent wind polar. The optimum angle to
sail at is read off the point of tangency while the speed is
read off the 0-180 degrees axis. A second technique involves
the determination of the optimal angle at which to approach
a finish line. The orientation of the finish line with
respect to the true wind direction is transferred from a
chart onto the appropriate true wind polar plot. It is then
moved in or out until it is just tangent with the proper
curve. This point of tangency yields the optimum angle
to sail at to reach that finish line in the shortest amount
of time. Other special techniques are still under develop-
ment, however, with a little imagination, much else can be
derived from these curves on your own.

Feel free to contact the Naval Academy at any time regard-
ing this performance package, especially in such areas as the
accuracy you observe and the usefulness of the curves. In
making such contact the following address should be used:

> Sailing Performance Package
> c/o Assistant Professor Kenneth A. Knowles
> Weapons and Systems Engineering Dept.
> United States Naval Academy
> Annapolis, Maryland   21402

Thank you for your interest in this project and good luck!

APPARENT WIND ANGLE VS. TRUE WIND SPEED

TRUE WIND ANGLE VERSUS TRUE WIND SPEED

APPARENT WIND POLARS
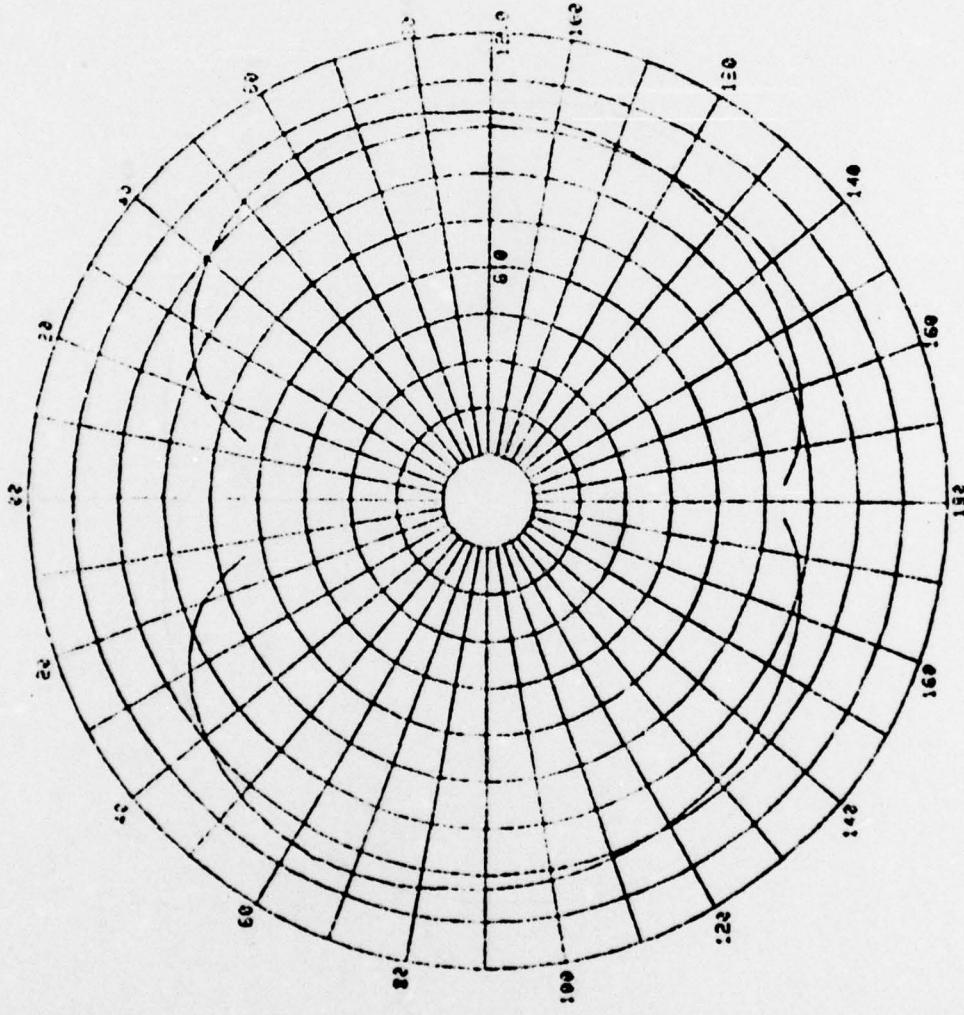
APPARENT WIND POLARS
TRUE WIND - 8 KNOTS

STBD

PORT

BOAT SPEED
KNOTS

YACHT SYREN

APPARENT WIND POLARS
TRUE WIND = 10 KNOTS

STBD

BOAT SPEED
KNOTS

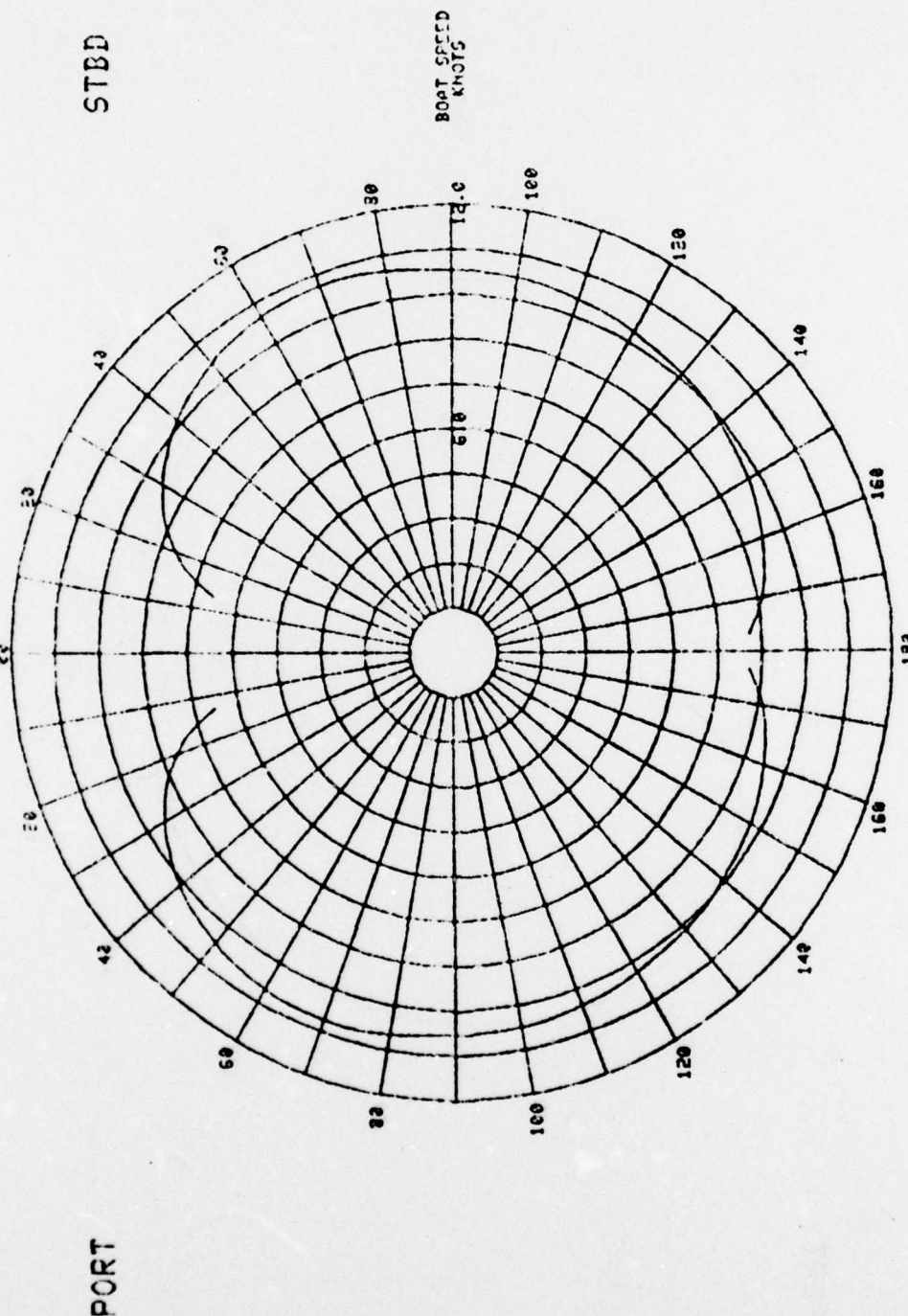PORT

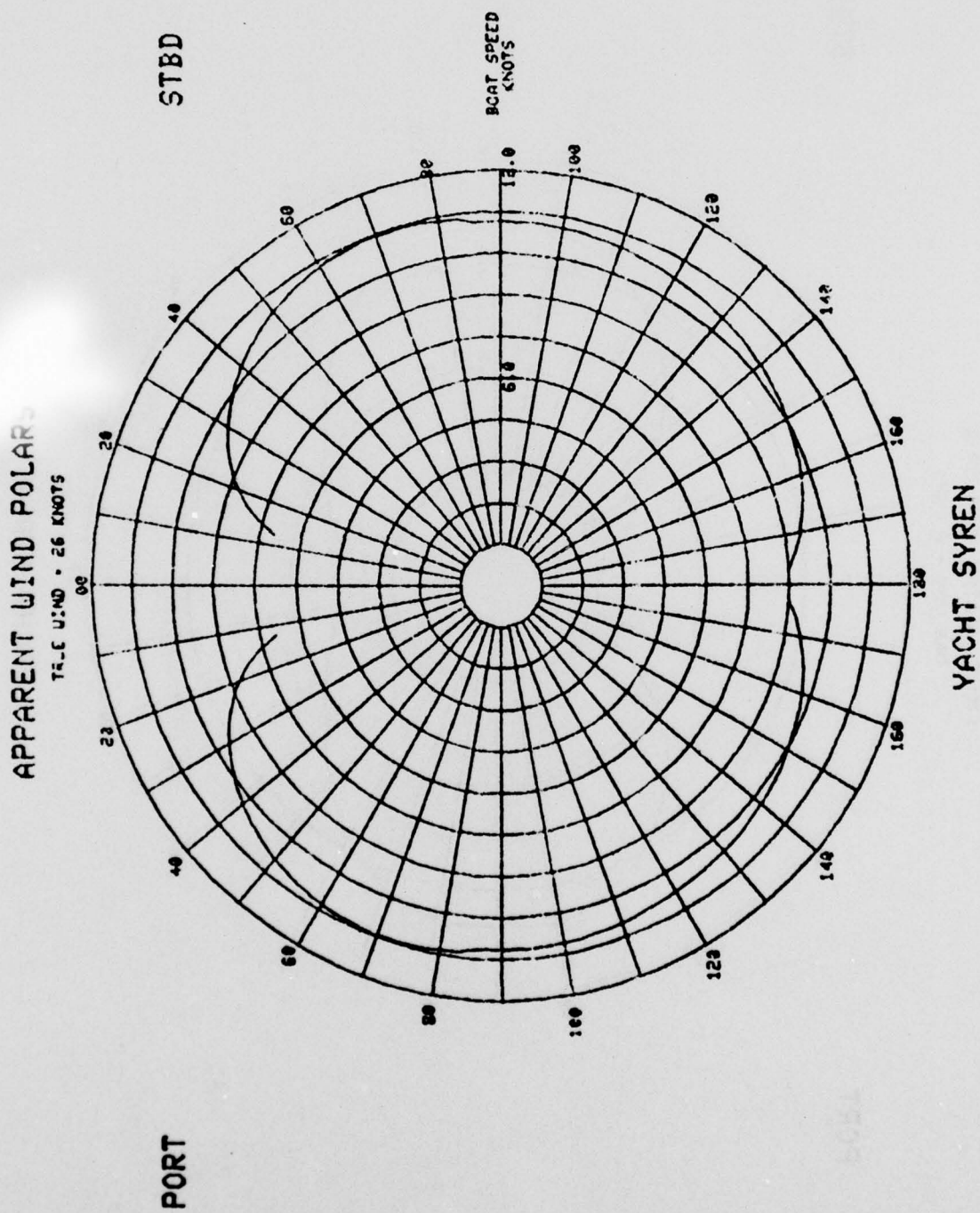YACHT SYREN

APPARENT WIND POLARS
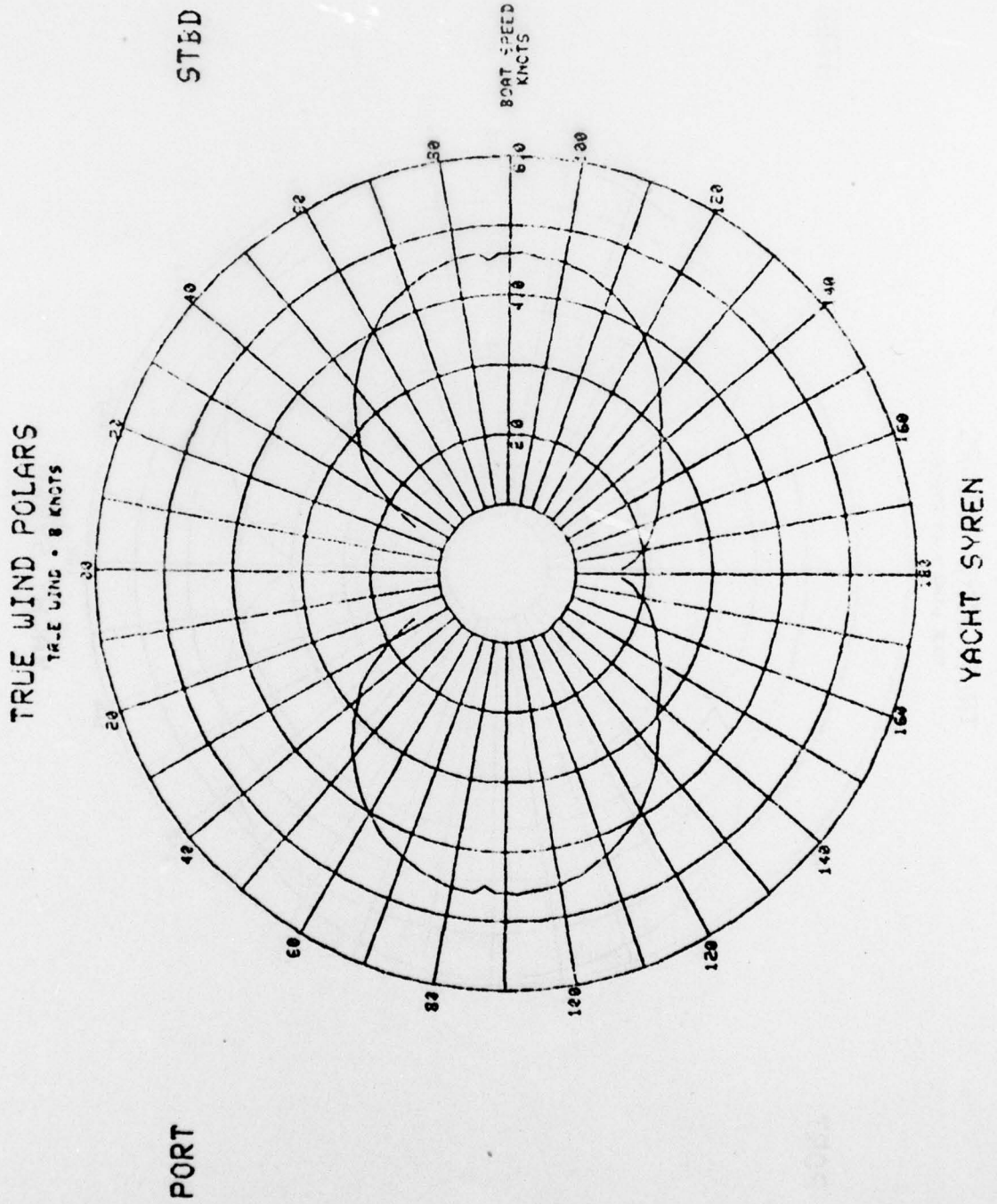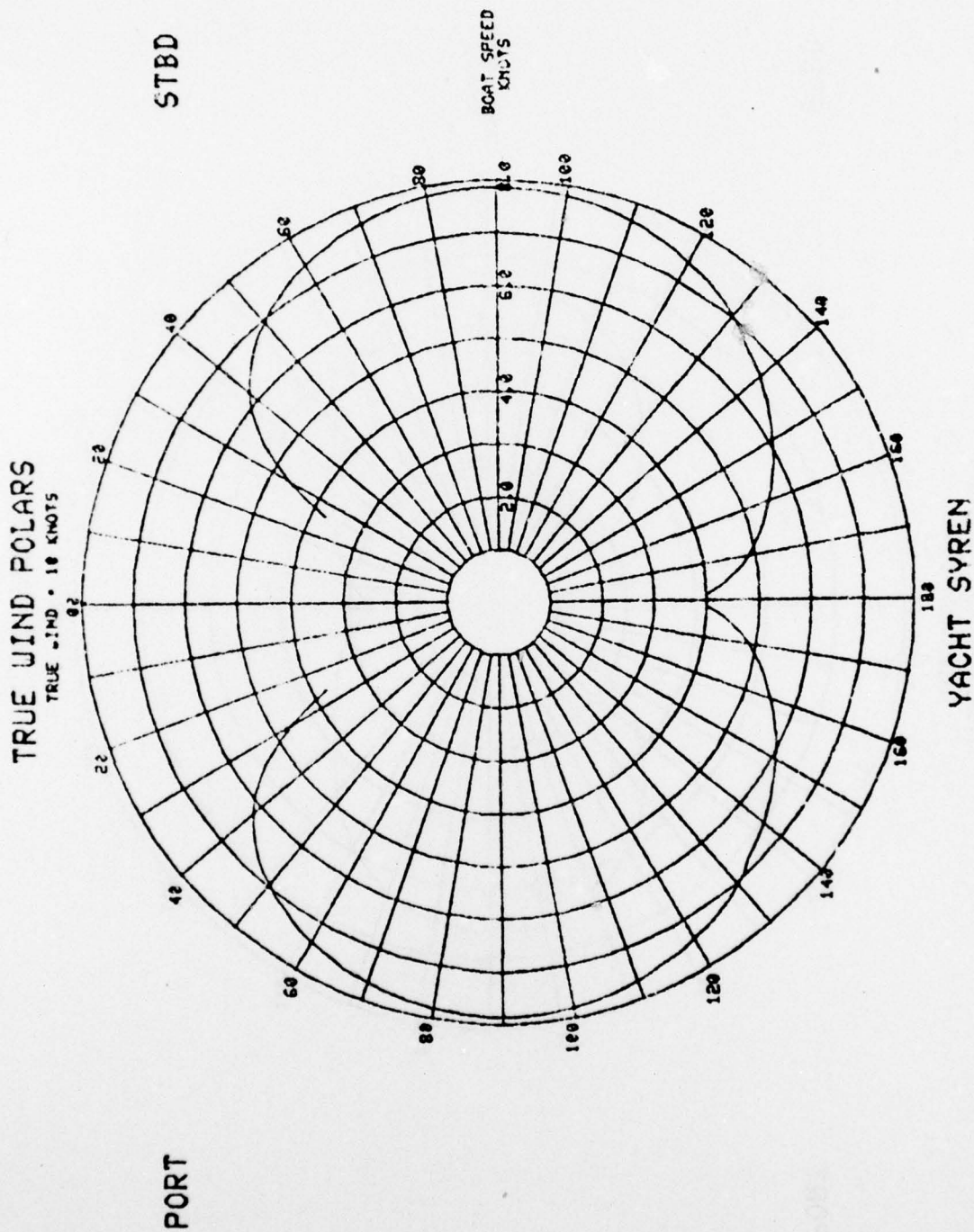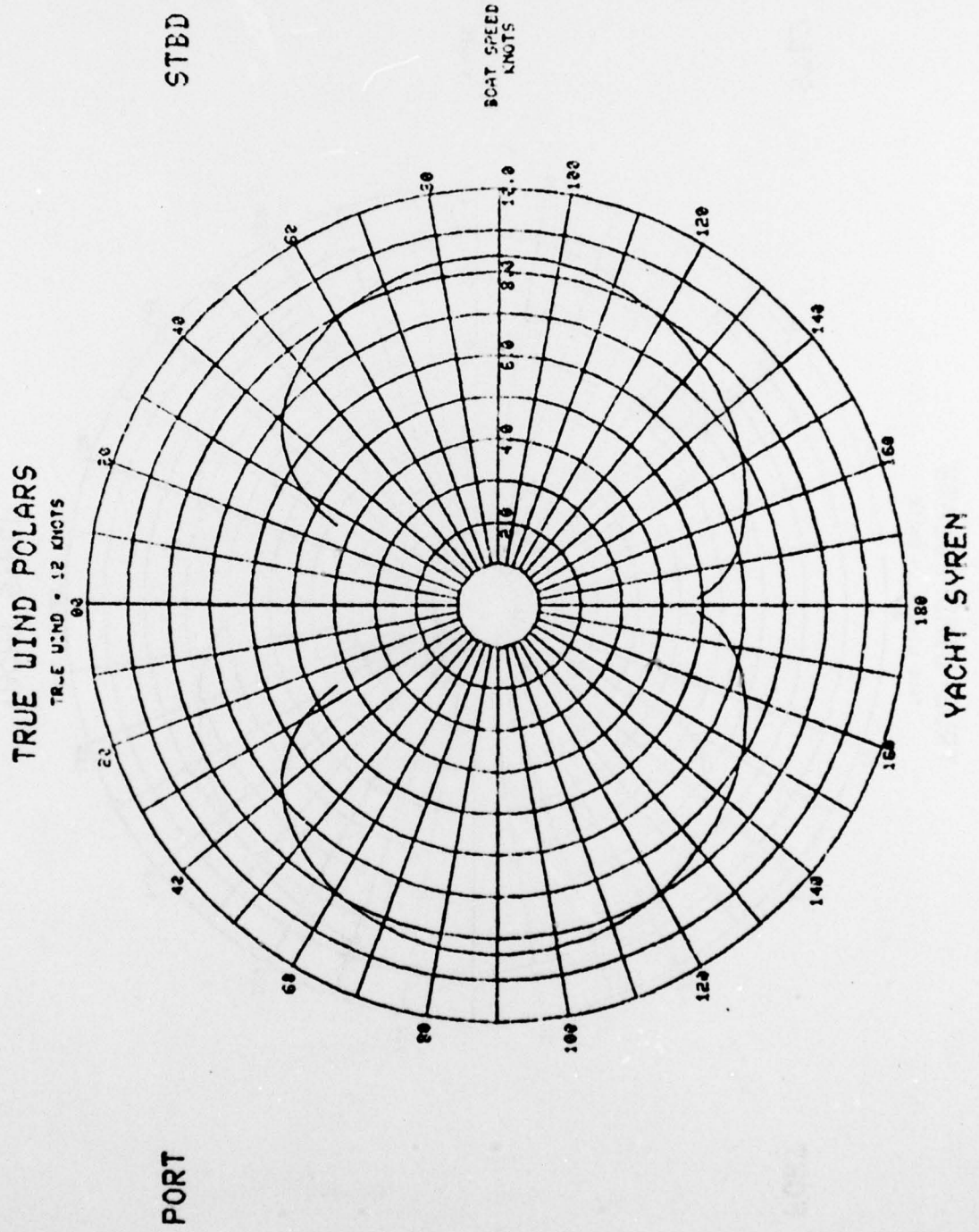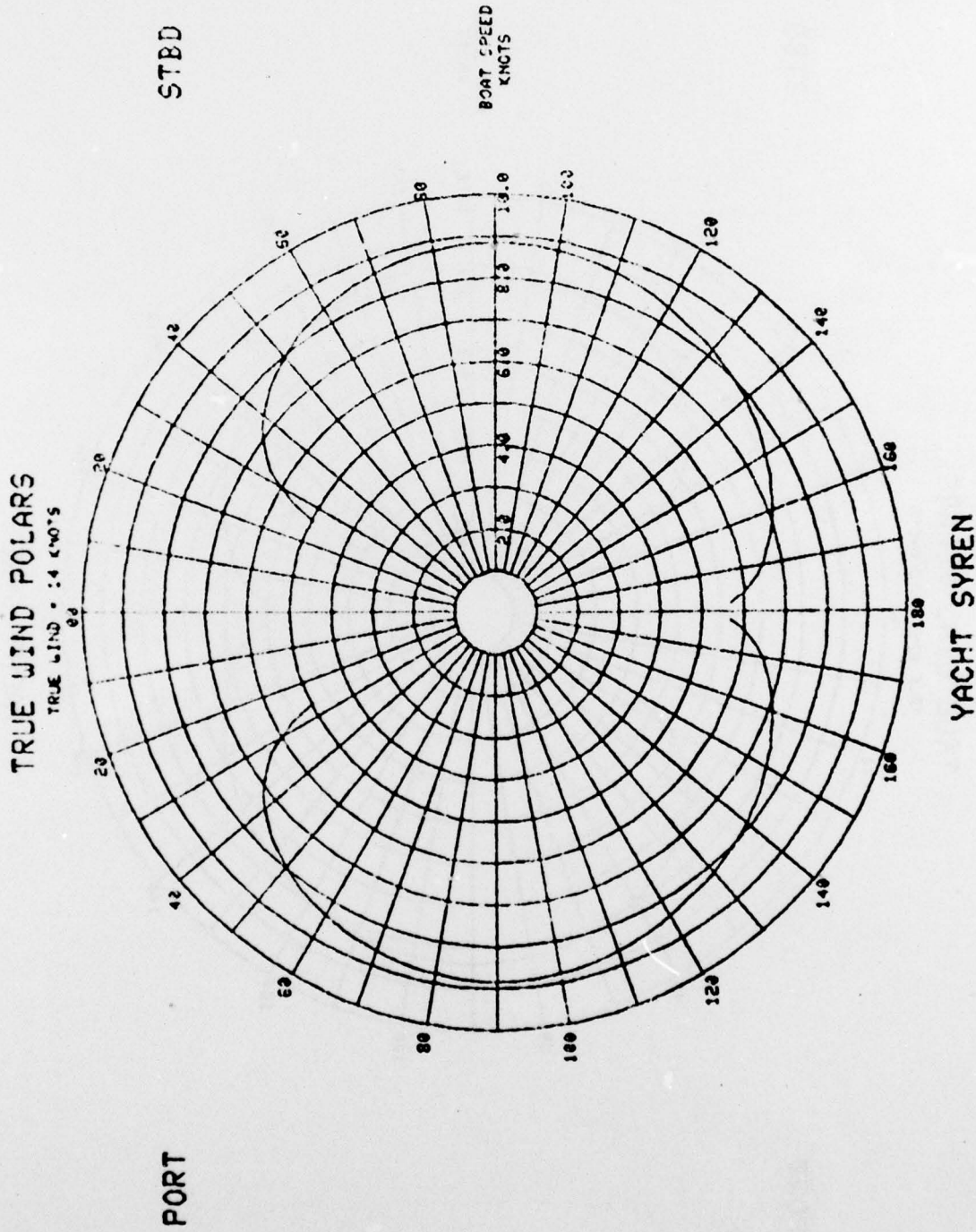TRUE WIND - 12 KNOTS

STBD

PORT

YACHT SYREN

BOAT SPEED
KNOTS

APPARENT WIND POLARS
TRUE WIND = 14 KNOTS

STBD

PORT

BOAT SPEED
KNOTS

YACHT SYREN

APPARENT WIND POLARS
TRUE WIND - 16 KNOTS

STED

PORT

YACHT SYREN

BOAT SPEED
KNOTS

APPARENT WIND POLARS
TRUE WIND - 18 KNOTS

STBD

BOAT SPEED
KNOTS

YACHT SYREN

PORT
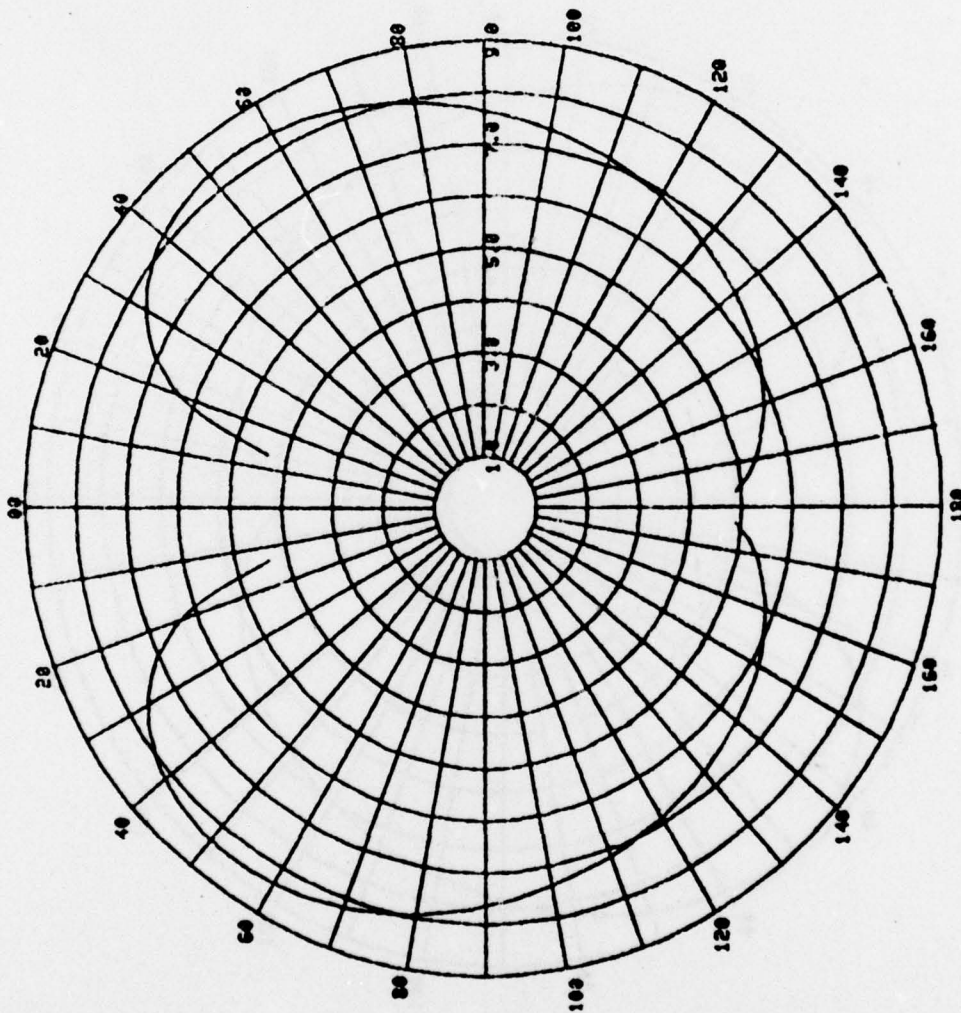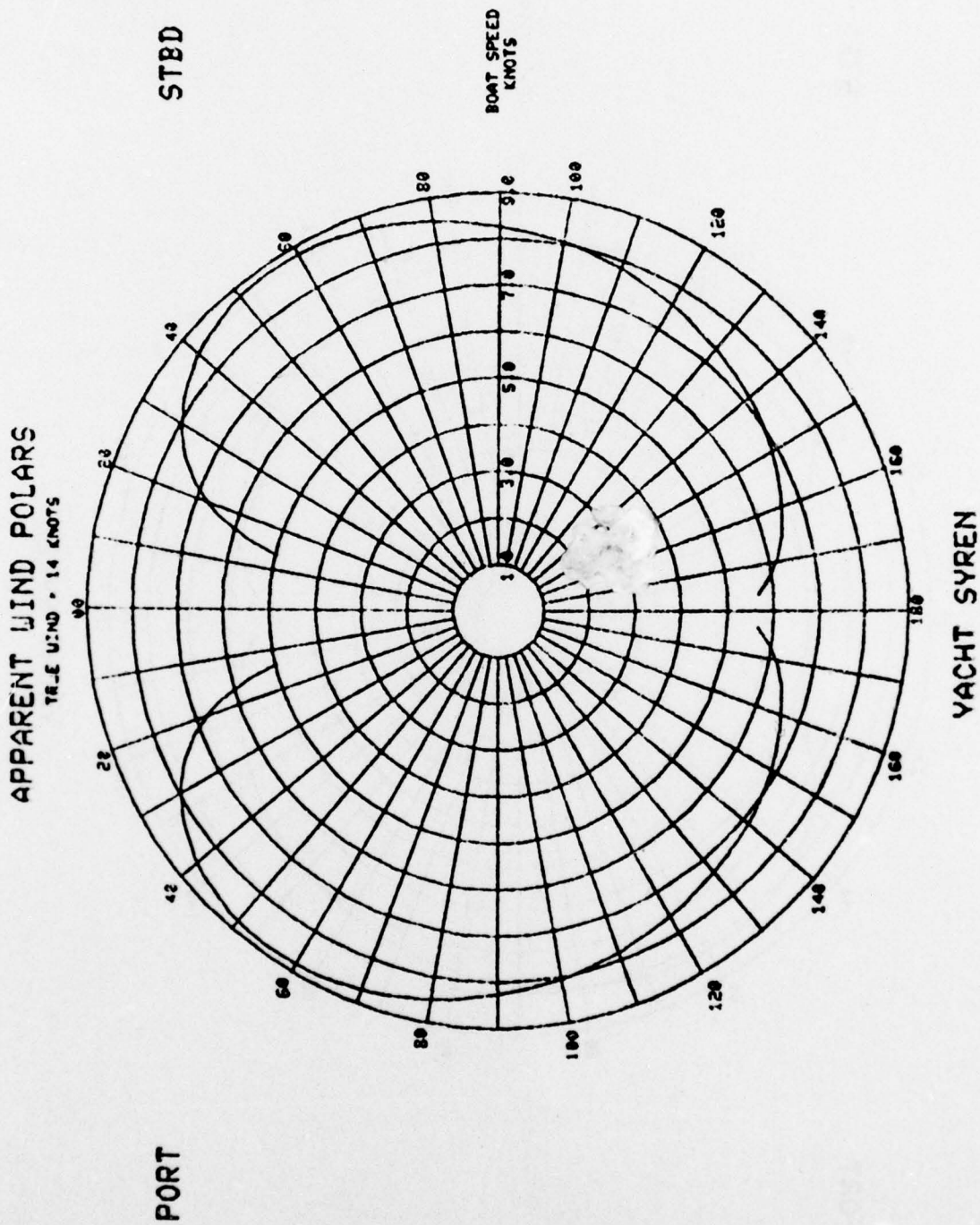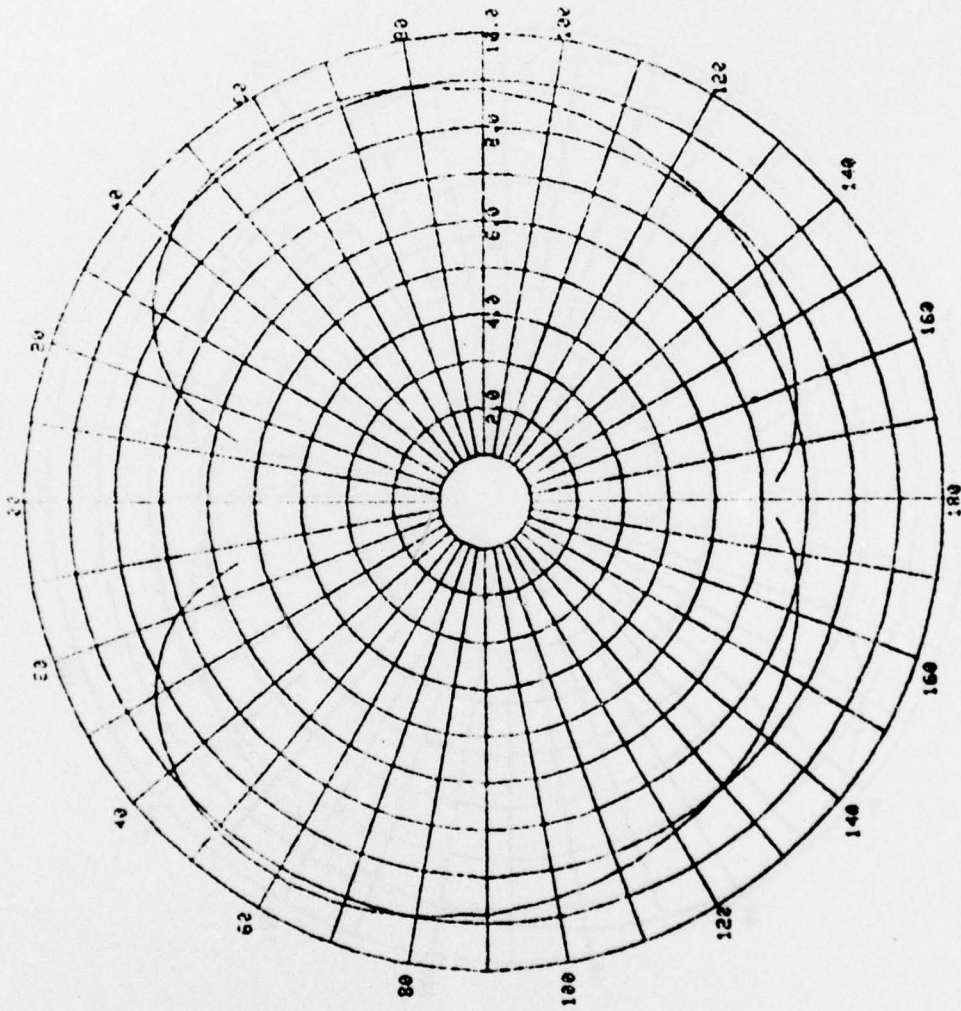
APPARENT WIND POLARS
TRUE WIND • 20 KNOTS

STBD

PORT

YACHT SYREN

BOAT SPEED
KNOTS

APPARENT WIND POLARS
TRUE WIND = 22 KNOTS

STBD

PORT

YACHT SYREN

BOAT SPEED
KNOTS
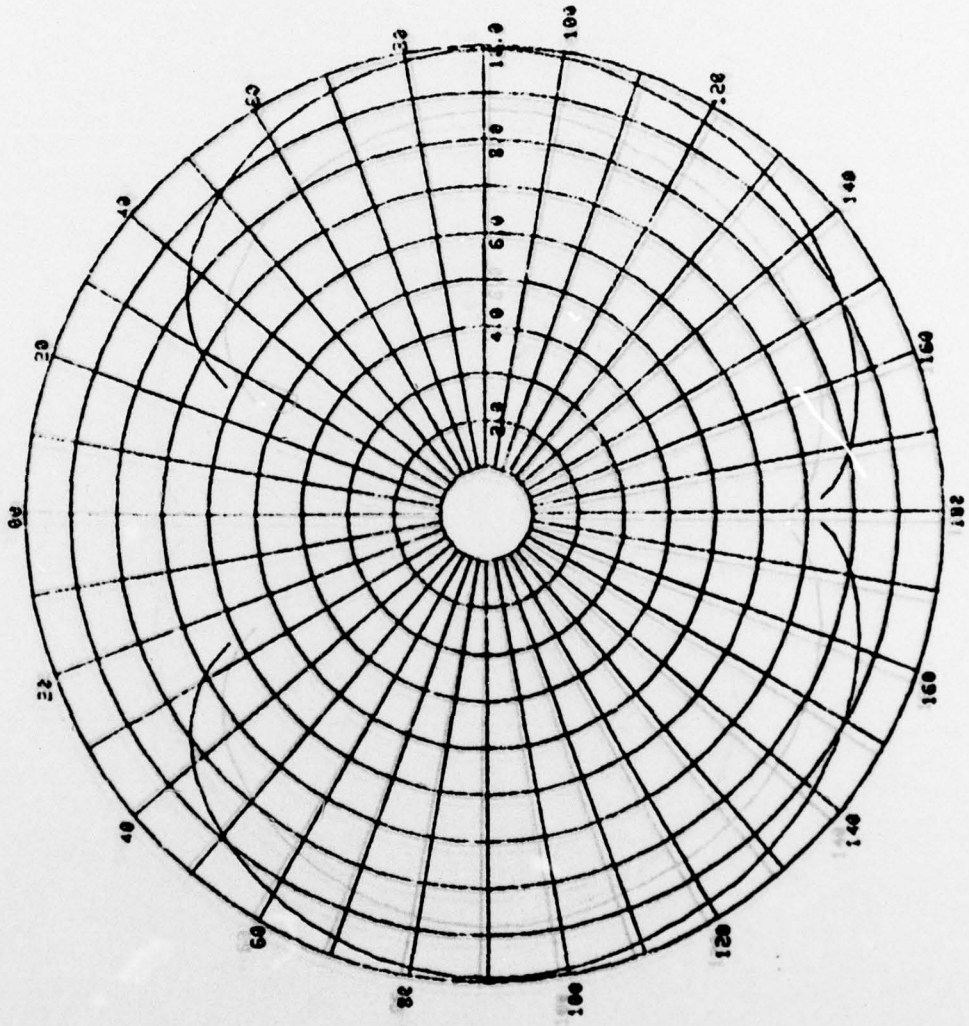
APPARENT WIND POLARS
TRUE WIND - 24 KNOTS

STBD

BOAT SPEED
KNOTS

PORT

YACHT SYREN

APPARENT WIND POLAR

TRUE WIND = 26 KNOTS
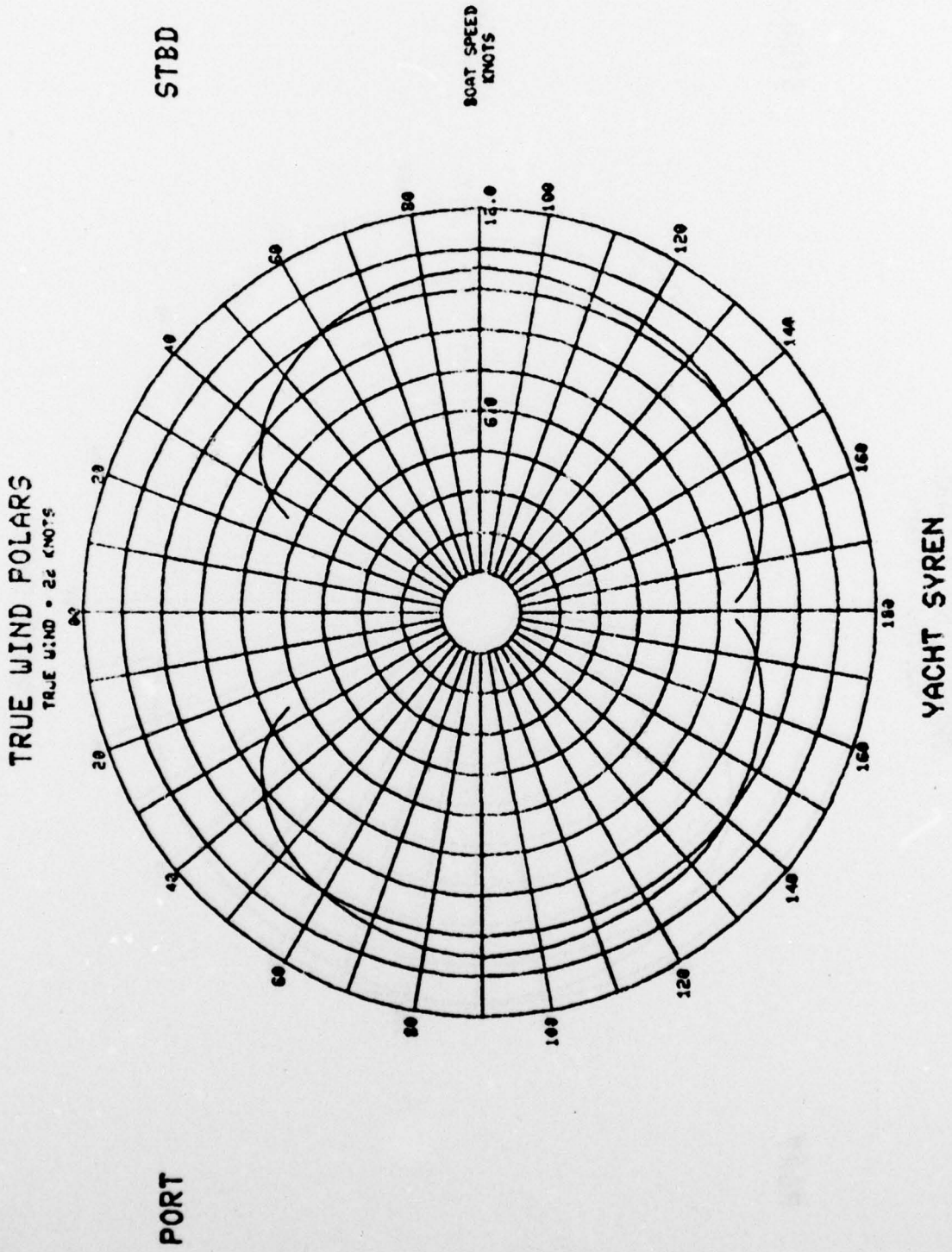
STBD

PORT

BOAT SPEED KNOTS

YACHT SYREN

TRUE WIND POLARS
TRUE WIND - 6 KNOTS

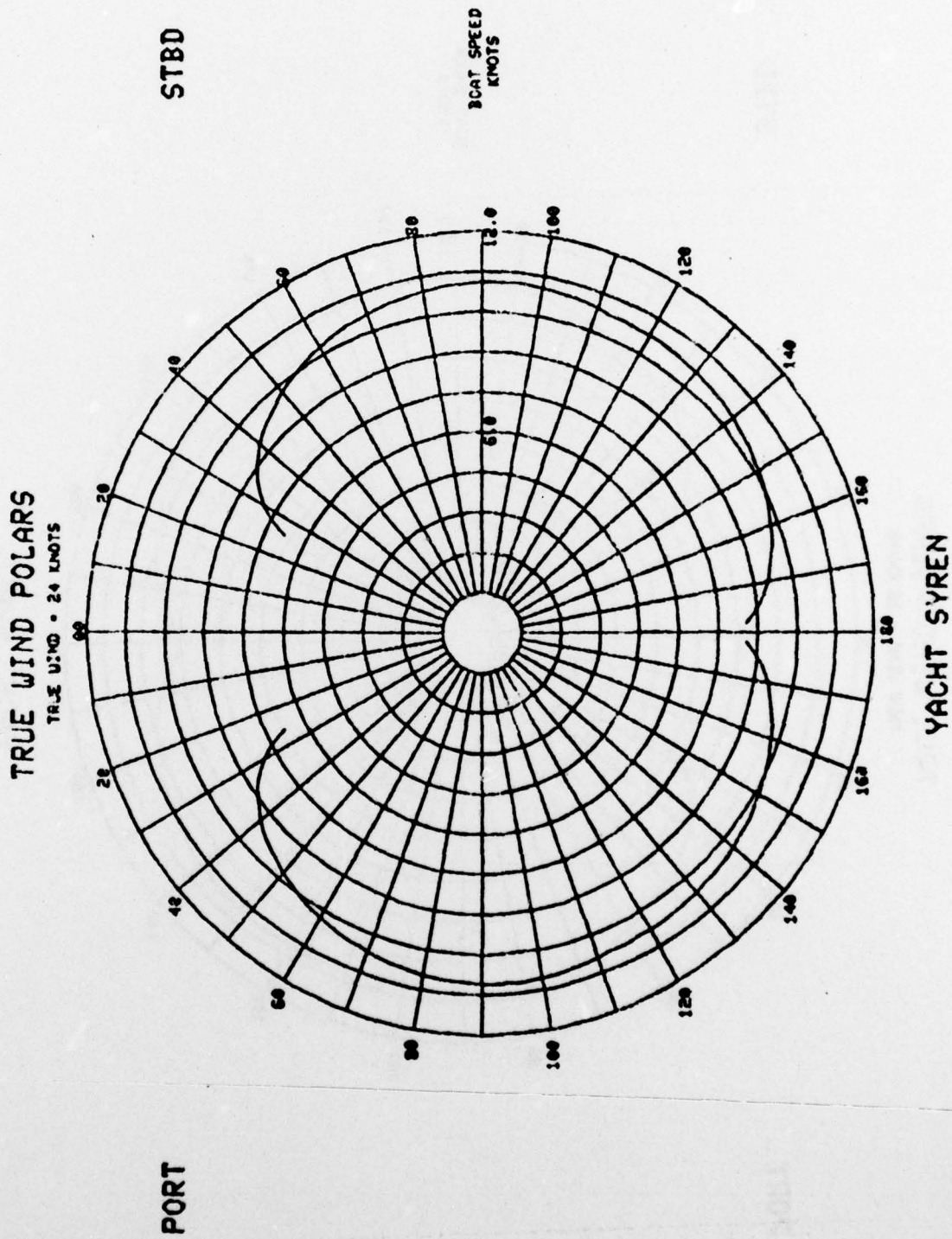STBD

PORT

YACHT SYREN

BOAT SPEED
KNOTS

TRUE WIND POLARS
TRUE WIND - 8 KNOTS

STBD

PORT

BOAT SPEED
KNOTS

YACHT SYREN

TRUE WIND POLARS
TRUE WIND • 10 KNOTS

STBD

PORT

YACHT SYREN

BOAT SPEED
KNOTS

TRUE WIND POLARS
TRUE WIND - 12 KNOTS

STBD

PORT

YACHT SYREN

BOAT SPEED
KNOTS

TRUE WIND POLARS
TRUE WIND : 14 KNOTS

STBD

BOAT SPEED
KNOTS

PORT

YACHT SYREN

STBD

BOAT SPEED
KNOTS

TRUE WIND POLARS
TRUE WIND - 16 KNOTS

YACHT SYREN

PORT

STBD

BOAT SPEED
KNOTS

TRUE WIND POLARS
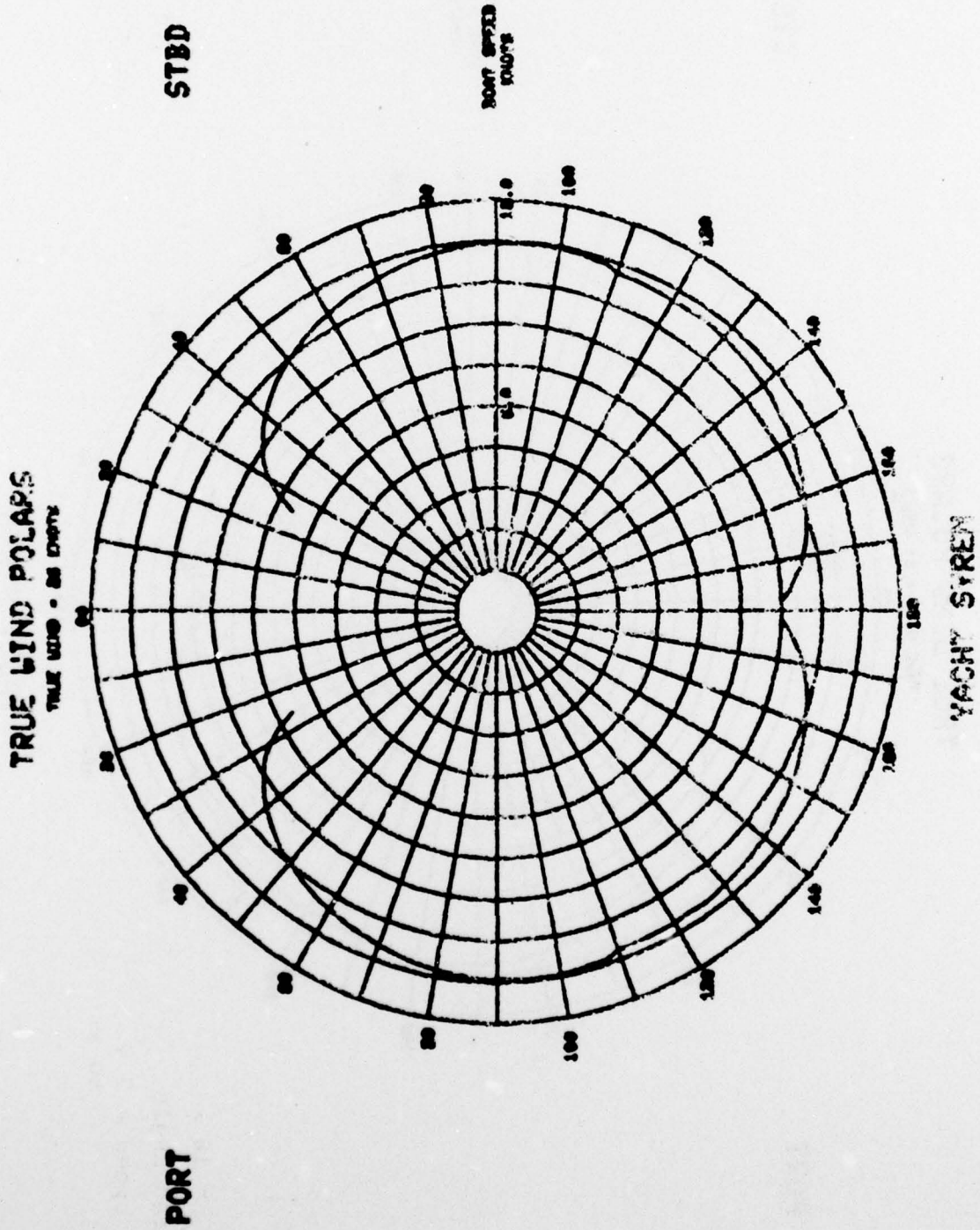TRUE WIND - 18 KNOTS

YACHT SYREN

PORT
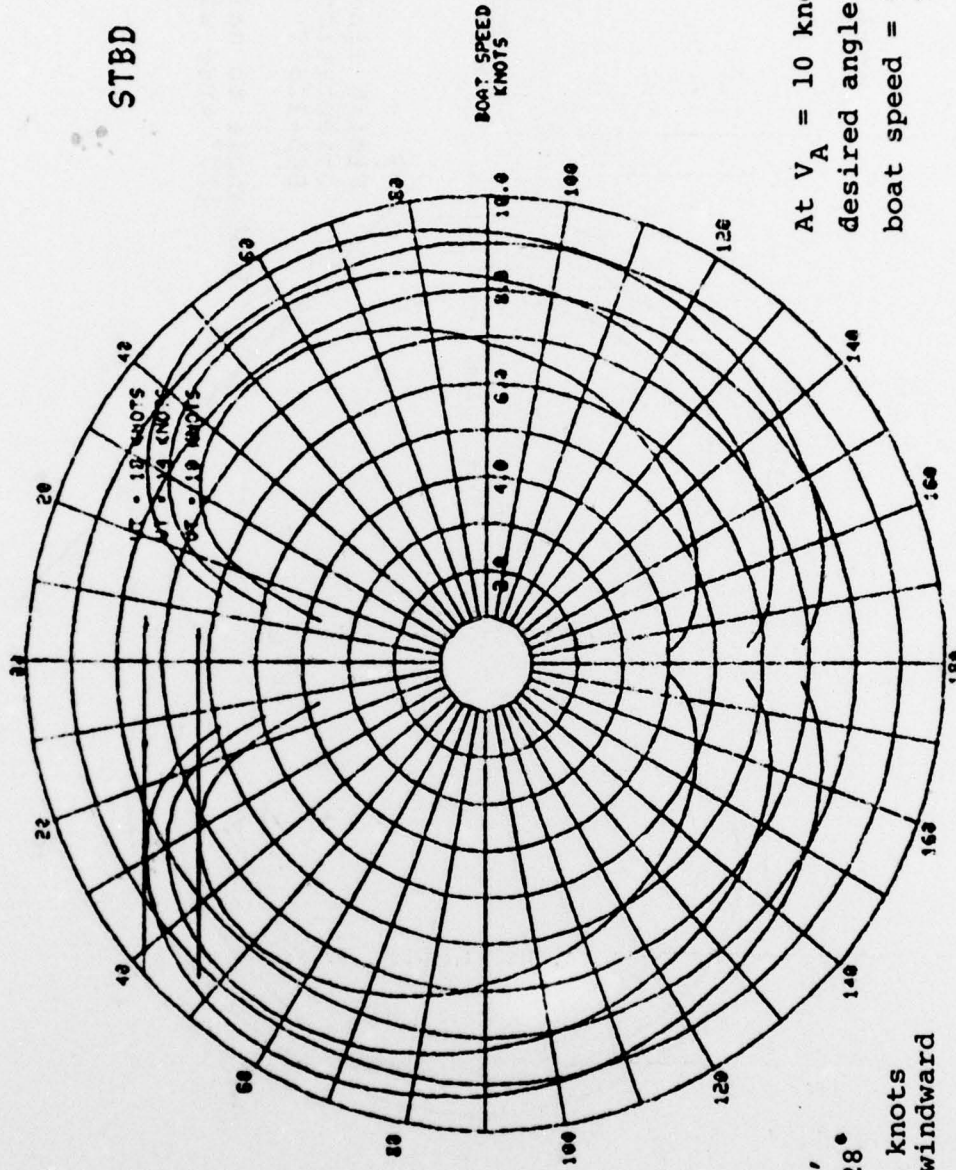
TRUE WIND POLARS
TRUE WIND - 22 KNOTS

STBD

BOAT SPEED
KNOTS

YACHT SYREN

PORT

TRUE WIND POLARS
TRUE WIND = 22 KNOTS

STBD

PORT

BOAT SPEED
KNOTS

YACHT SYREN

STBD

BOAT SPEED
KNOTS

TRUE WIND POLARS
TRUE WIND - 24 KNOTS

YACHT SYREN

PORT

TRUE WIND POLARS
TRUE WIND · 25 KNOTS

STBD

PORT

YACHT SIREN

APPARENT WIND POLARS

PORT

STBD

YACHT SYREN

BOAT SPEED
KNOTS

At V_A = 10 knots
desired angle = 32°
boat speed = 6.3 knots
to windward

At V_A = 18 knots,
desired angle = 28°
boat speed = 7.4 knots
to windward
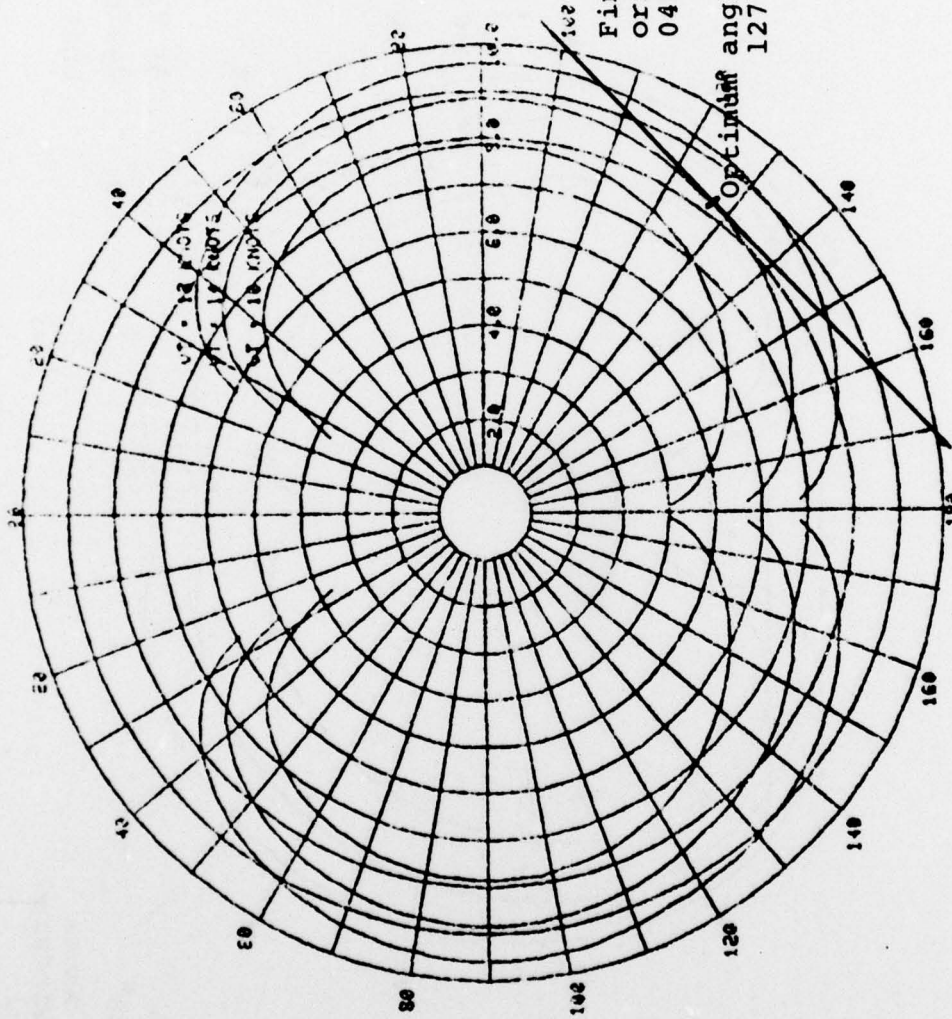
TRUE WIND POLARS

STBD

BOAT SPEED
KNOTS

Finish line
orientation
045-225°T

Optimum angle to sail at:
127° true wind

YACHT SYREN

PORT

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Presented to the Chairman of the Trident Scholars of the U.S. Naval Academy.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Sailing
Yachts and yachting.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The specific problem investigated during this project, involved the determination of the near-optimal trajectory, with respect to speed through the water, of a sailcraft subjected to steady-state and random wind and wave forces.

The results of the project surpassed existing empirical techniques in that a method was developed for preparing, beforehand, using a set of digital computer programs, an accurate near-optimal performance package for

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any yacht possessing a valid International Offshore Racing (IOR) certificate.

Initial verification of the performance package for the U.S. Naval Academy's fifty-eight foot Sparkman & Stevens sloop SYREN indicated extremely close agreement between predicted and actual performance.

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