Determination of Force Coefficients For Racing Yacht Sails Using Actual Force Measurements

By
Donald Blandford Peters

B.S. Civil Engineering
Pratt Institute (1988)

Submitted to the Department of Ocean Engineering in
partial fulfillment of the requirements for the degree of

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May 29, 1992

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ABSTRACT

The Massachusetts Institute of Technology's sail force measurement boat *Amphetrete* is used as the instrument platform to measure forces from a 42% scale International America's Cup Class (IACC) sailing rig. Computational fluid dynamics, using sail geometry from off-boat video analysis, is used to evaluate induced drag. Numerical sail force models for the Velocity Prediction Program (VPP) are prepared using the force measurements and analysis results.

Thesis Supervisor: Dr. Jerome H. Milgram
Title: Professor of Naval Architecture

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Chapter 1

Introduction

A racing yacht under sail is a complex system, the successful performance of which relies on the optimization of the parts. Subsystems such as hull, keel, sailing rig and sails must all be designed to work most efficiently together. The true test of design success is, ultimately, a successful racing boat. However, it is not economical to build a full scale boat in order to evaluate its design. Computer modeling of racing yachts is therefore a valuable tool in optimizing the design of both the subsystems and the whole system.

1.1 Background

Models of ships have been tested in towing tanks since the late nineteenth century, in order to predict full-scale ship resistance from the small-scale tests. Today essentially all "leading-edge" yachts and ships are tank tested. When a sailing yacht is tank tested, data is obtained which allows resistance, righting moment, and side force to be predicted for a large array of boat speeds, heeling angles and yaw angles. Given a reasonable prediction of the forces which its sailing rig will generate, it is possible to find the equilibrium point at which, for a given wind speed and direction, the rig forces and hull forces will balance. This balance occurs at some combination of boat speed, heel, and yaw, and results in a velocity prediction for the boat. A program which computes this balance point for various sailing angles has been developed at MIT and is referred to as the *Velocity Prediction Program*, or VPP.[1]

1.2 Numerical Modeling of Sails

The VPP can be used to compare the performance of different hulls using the same sail model, providing the sail model used is one which predicts sail forces close to those which the full-scale boats will be experiencing. Such sail force models have been, in the past, developed using numbers based on theory and some wind tunnel testing which give realistic full-scale performance prediction for existing yachts. Such sail models can help evaluate relative performance of different hulls. If more specific sail force information is available, the VPP can be used to compare the performance of various rigs and sail geometries for a given hull or in combination with different hulls. Obtaining reliable specific sail force models has been, until recently, a matter of trial and error with performance data from full-scale rigs and sails.

The purpose of this project is to develop good sail force models from the measured forces generated by sails on a medium-scale model rig fitted in an actual sailboat. The forces measured in this way reflect the performance differences of the various rig and sail geometries tested, along with the subtleties imposed on performance by actual sailing conditions which cannot be included as well by theoretical or wind

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[1] Justin E. Kerwin. *A Velocity Prediction Program for Ocean Racing Yachts.* Technical Report 75-17, M.I.T., December, 1975.

tunnel modeling. These include: the wind angle twist with height caused by the combination of the wind gradient and forward boat speed, and sea-induced motions.

Chapter 2

The Force Measurement Boat *Amphetrete*

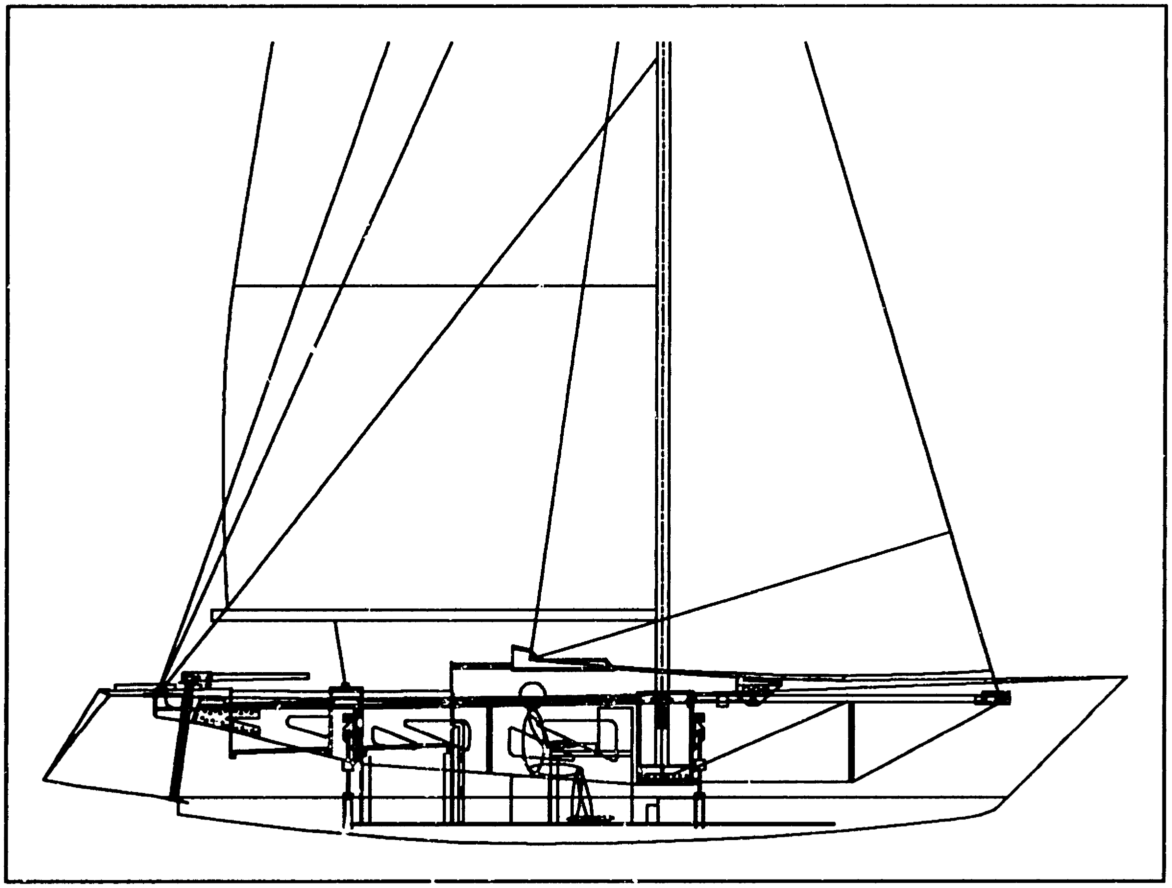

Figure 1. Inboard Profile of *Amphetrete* showing the rig, frame, and computer operator.

2.1 General Description and History

Amphetrete is a 35-foot, cold-molded wooden sailboat. Her lines are a modified scale version of *Matador*, an 83-foot maxi yacht. Additional topside height provides room inside the hull for a rigid space frame which supports the sailing rig. Everything connected to the sails, such as the mast, stays, sheets and winches, is connected only to this frame and does not touch the hull. The frame is connected to the hull through six stainless steel rods fitted with electrical force measuring units, or load cells. These rods, or *flexures*, so called because they are designed to be rigid under axial loads but compliant under off-axis loads, are located parallel to the vertical, fore-and-aft, and athwartships axes. The six flexures keep the frame from moving with respect to the hull, while their load cells allow for the recording of forces in the three principal directions and the computation of the three principal moments. In essence the frame acts as a six-component dynamometer, or six-dimensional scale, whose job is to measure the connected load: the sailing rig. For this reason, *Amphetrete* is also referred to as the *sailing dynamometer*.[2]

Amphetrete was built in 1987 and used in the *Matador*^{2} maxi design project. She was used to test both masthead and fractional rigs, and was instrumental in the decision to use a fractional rig for the final design of *Matador*^{2}. She was declared a total loss after falling off her jackstands to the ground in a boatyard in a winter storm in 1989. However, in August of 1990 it was decided to rebuild her and outfit her with a scale model of an International America's Cup Class (IACC) yacht sailing rig. She has since resumed sailing and has been used in the rig and sail development program of the America^3 Foundation for the 1992 America's Cup in San Diego.

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[2] James Stackpole Herman Jr. *A Sail Force Dynamometer: Design, Implementation, and Data Handling*. Masters Thesis, M.I.T., September, 1988.

2.2 Measuring Forces Generated By the Sails

On *Amphetrete* the sails exert force on the mast, headstay, and sheets, all of which are connected to the space frame and isolated from the hull. The forces which are measured are the six axial forces in the flexure rods at their various locations.

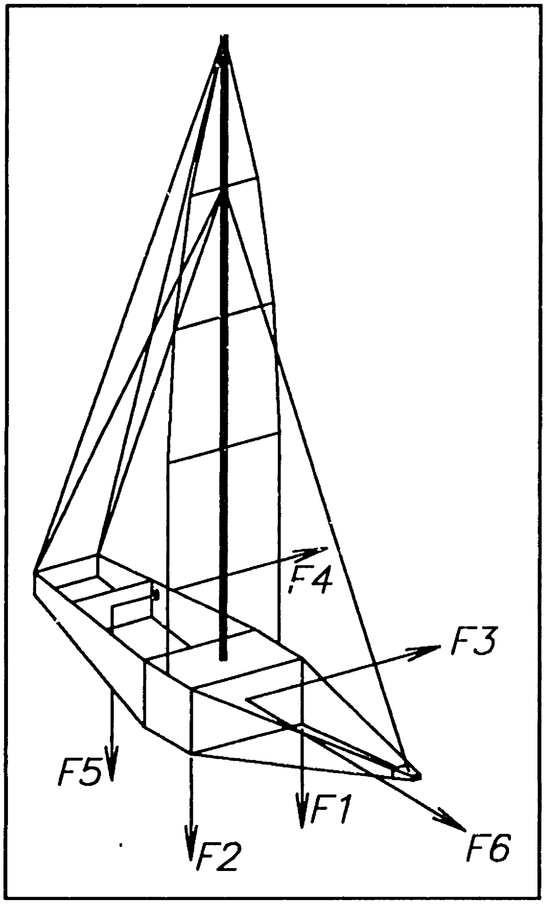

Figure 2. A representation of the frame and rig, showing the six measured forces.

The electrical signals from load cells mounted in the flexure rods are boosted by linear amplifiers, or signal conditioners, and read by a computer running on-board. The computer program uses preset factors to convert voltages from the signal conditioners to force in pounds. The six flexure forces are then used to compute three principal forces and three principal moments. The six loadcell readings, three forces and three moments are averaged and stored to a disk file at approximately 10-second intervals.

In addition to the force information, the computer is also continuously acquiring data on wind speed and direction, heel, pitch, and boat speed. From this data the program is able to compute lift force and drag force, and the nondimensional coefficients of lift *Cl* and drag *Cd*, given by,

$$Cl = \frac{Lift\ Force}{\frac{1}{2}\ \rho\ V^2\ A} \tag{1}$$

and

$$Cd = \frac{Drag\ Force}{\frac{1}{2}\ \rho\ V^2\ A} \tag{2}$$

where ρ is the density of air, the velocity V is the apparent wind velocity, and A is the sail area used to normalize the coefficients. This is normally the actual area of the mainsail and genoa.

2.3 Measuring the Wind

Measuring the wind has proven to be one of the most difficult tasks in this project, for several reasons. First, the sails affect the flow in their vicinity, so that the sensor used to measure the wind must be placed as far above the top of the sails as possible. This has been accomplished by mounting the sensor on a 10 foot section of carbon fiber wind surfer mast bolted to the masthead. Second, since the instrument is mounted to the mast, some error in angle measurement results due to the twisting of the mast under load. Third, the geometry required to relate wind measured in one place to wind occurring in another place is, while straightforward, capable of causing some confusion. Fourth, commercially available wind instruments provide accuracy which is only marginally acceptable for the sensitivity required. Extensive wind tunnel calibrations have been necessary in order to improve the accuracy of the sensors. And finally, leeway, or the deviation between course made good and heading, must be accounted for.

2.3.1 Wind Gradient

Sailboats operate within the boundary layer between zero wind velocity at the water surface and free stream velocity at a great height. The variation of wind speed with height is called the *wind gradient*. The wind gradient is dependent upon the roughness of the surface over which the wind is travelling. It is convenient and

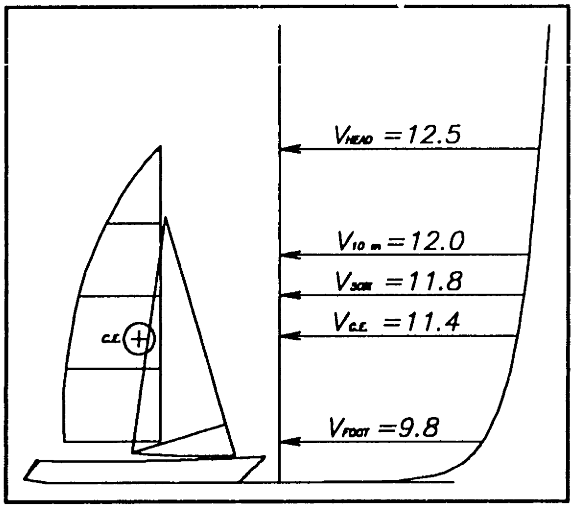

Figure 3. The logarithmic wind gradient for a V_{10} = 12.0 knots.

fairly accurate (as well as theoretically correct) to represent the wind gradient with a log function. At some large height the wind gradient becomes relatively constant, while at small heights the rate of change with height is relatively large. Sailboats sail relatively close to the surface and so wind gradient effect is of a good deal of importance. The convention used for wind gradient is a log function which relates wind at any height to the wind at a height of 10 meters. The function used by this program is,

$$V_z = V_{10m} \ln(304.8\ z) \tag{3}$$

where V_z is the wind velocity at height z, in feet, and V_{10} is the wind velocity at 10 meters.

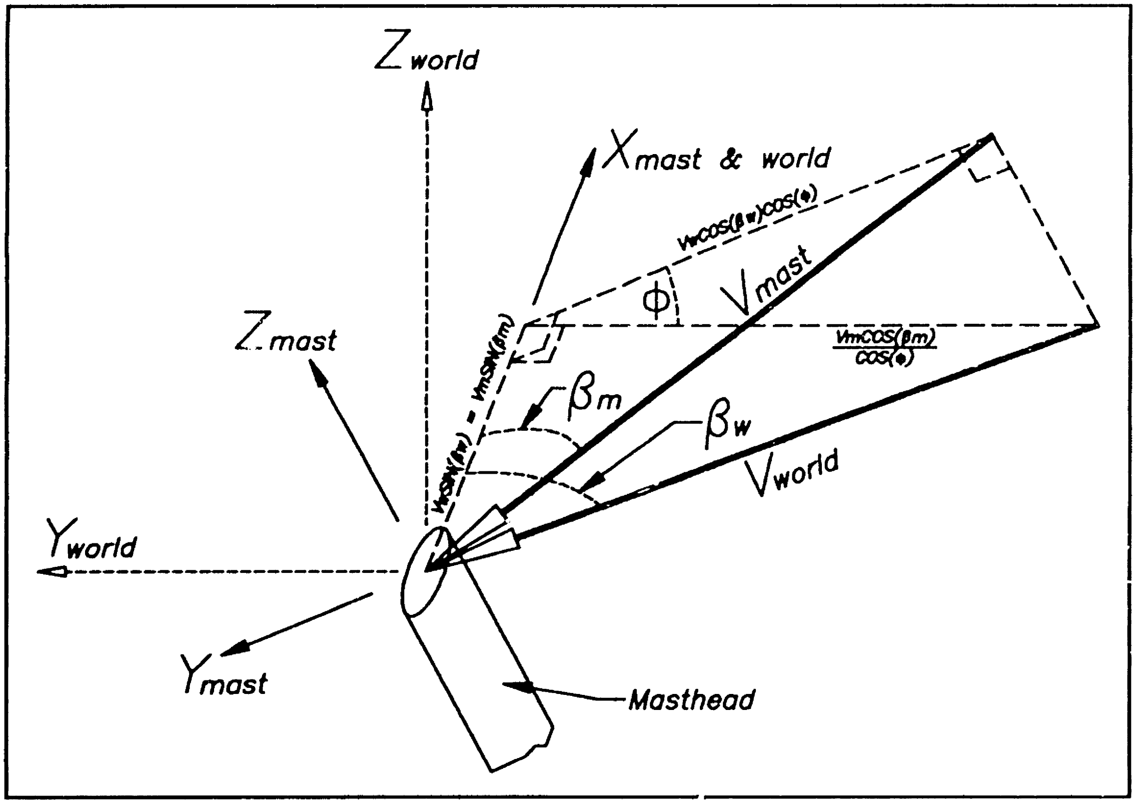

Figure 4. The geometry of transformation for apparent wind between the world coordinate system and the mast coordinate system.

2.3.2 Coordinate Systems

There are two principal coordinate systems used in this project. One is the most natural when thinking of a sailboat: origin somewhere near the base of the mast, x forward, y to port, and z up along the mast. This coordinate system moves with the boat and heels with the boat, so that z always points along the mast. This will be referred to as the *mast coordinate system.* The other system uses the same origin, but the z axis is always perpendicular to the plane formed by the water, and the x and y axes are always parallel to the water surface. This will be referred to as the *world coordinate system.*

The reason for needing these two systems is that when working with wind and wind gradient it is more convenient to use the horizontal world system, since wind moves horizontally; however when working with the forces on a sailboat it is usually the forward force and *heel force* (perpendicular to the mast, which is heeled) which are of interest.

In addition to these two basic coordinate systems, the sail force also must be resolved into lift and drag forces, where lift is perpendicular to the wind direction and drag is parallel to the wind direction. Lift and drag can be computed in either mast or world coordinates. In mast coordinates, forward and heel force are resolved into lift and drag, while in world coordinates only the horizontal component of heel force is considered.

2.3.3 Apparent Wind

As the boat moves through the water it generates some wind by virtue of its own motion. In a flat calm, an observer on deck would feel an amount of wind equal to the boat speed, coming from dead ahead. If there was some wind, the observer would feel a combination, or vector sum, of the wind from the boat's motion and the actual, or *true wind.* This is referred to as the *apparent wind,* and is in fact defined as the vector sum of the wind due to the boat speed and the true wind.

When there is naturally occurring wind moving over water, with a wind gradient, the true wind varies with height. This means that the vector sum of the boat speed and true wind, the apparent wind, also varies with height. The apparent wind varies in both magnitude and direction with height. Therefore, when measuring apparent wind from a sailboat, it is vital to know where the wind is being measured, as two different instruments at different heights will give two different answers.

2.3.4 Chase Boat Experiment

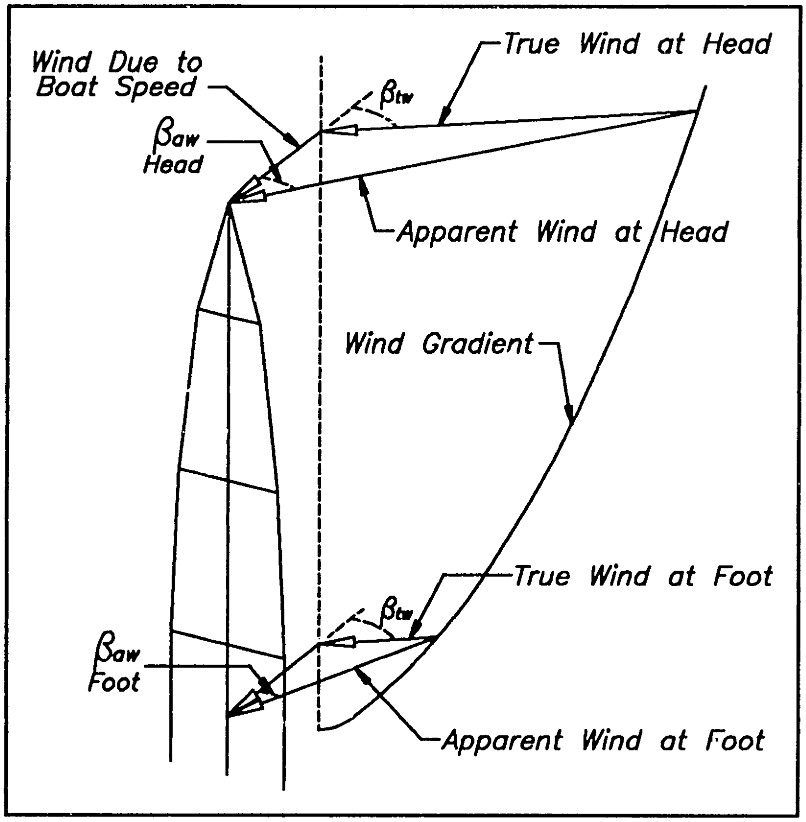

Figure 5. The change in apparent wind with height. The wind gradient is exaggerated and the mast is shown unheeled.

In order to further investigate the uncertainties involved in measuring wind from the masthead, a power boat was fitted with wind measuring instruments and was used to obtain comparative measurements at some distance from the sailboat. Measurements from the chase boat anemometer were recorded during several minutes while the chase boat maintained the same course and speed as *Amphetrete.* The experiment was performed both with no sails up and sailing, so that differences in wind measurement due to the effect of the sails could be deduced.

The tracking tests led to the conclusion that the wind measured by *Amphetrete* under sail was substantially correct. Effects of leeway and induced angle change essentially canceled for normal sailing conditions.

2.4 Measuring Sail Shapes

In order to check results and obtain some theoretical performance data with which to analyze the measured force data, an aerodynamic analysis of the sails was performed using the computational fluid dynamics (CFD) program SVL5, developed by Atlantic Applied Research Co. (AARC). This analysis requires the development of a reliable geometric model of the sails as they are set while the boat is under sail and measuring force.

2.4.1 Videotaping

Using the off-boat sail shape video program developed at MIT, the shapes of the sails were measured during some relatively brief (several minutes) and steady intervals of force measurement. The shape measurement involves videotaping the sails, which are marked with special stripes, from certain angles. The videotaping is performed from a chase boat, hence the term "off-boat" video. The procedure is detailed in a masters thesis by Drew S. Freides.[3]

2.4.2 Video Offtake and Editing

The videotape is viewed through a computer fitted with a graphics board capable of receiving video, and running a program developed by Noah Eckhouse of MIT. This system allows for measurement of sail dimensions from the video image displayed on the computer monitor. The video is paused on an appropriate frame and the program allows measurement with a mouse based on pixel distance calibrations. The measurements made

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[3] Drew S. Freides. *An Image Processing Based System for Three Dimensional Sail Shape Analysis*. Masters Thesis, M.I.T., June, 1991

possible by this system include sail chord lengths, twist, draft, and position of maximum draft.

The measurements obtained from the video are entered, in the form of a "geometry in" or *gin* file, into a graphical editing program called *Gred*, developed by Jack Kleene. This program allows the user to create a numerical model of the sails based on the measurements made coupled with fairing routines which ensure a smooth set of sails. The output is in the form of a "geometry" file, or *geo* file, which is used by SVL5 directly for sail geometry definition.

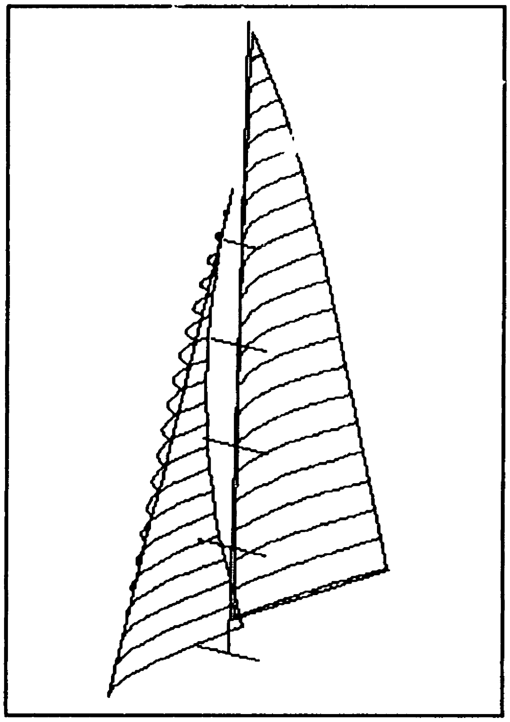

Figure 6. Graphical editor view of CFD input sail model made from offboat video system.

2.5 Summary of Measurements from *Amphetrete*

The data obtained from *Amphetrete* is stored in the form of a *log file*. The log file consists of a set of forces, instrument readings, and calculated values stored approximately every 10 seconds. The storage and averaging interval is controllable, so it is possible to choose an interval which allows enough averaging to remove large data scatter due to things such as pitching and small wind variations. An effort is made to record, or *log*, data when the boat is in a relatively steady state condition. For instance, if a power boat wake is encountered, logging is turned off until the boat has settled down and resumed smooth sailing.

Table 1. A 4-minute sample of data obtained by reading specific items from a log file. The last line consists of average values used for comparison with CFD results.

FM2B STANDARD PROFILE from 726a2.fvg (video log file fixed for pitch error and 8% wind error)

time	cd	cl	heel	fwd for	sid for	ver for	roll m	pitch m	yaw m	btspd	baw	corr vaw
09:20:14	0.23	1.26	12.73	34.12	-197.62	-25.51	3462.96	766.42	144.79	4.11	-21.00	9.53
09:20:22	0.21	1.28	13.26	39.15	-202.94	-22.81	3559.85	870.01	105.61	4.10	-21.50	9.63
09:20:29	0.18	1.17	13.23	37.15	-199.50	-23.41	3507.03	814.13	111.97	4.10	-20.10	9.98
09:20:37	0.18	1.13	12.34	32.99	-191.14	-24.98	3373.23	729.55	137.78	4.09	-19.70	9.93
09:20:44	0.22	1.15	12.15	32.76	-187.81	-23.04	3326.95	749.30	130.37	4.08	-22.00	9.72
09:20:52	0.26	1.28	13.21	39.93	-204.58	-19.97	3590.96	926.14	95.45	4.08	-23.90	9.62
09:20:59	0.26	1.27	14.04	42.07	-213.44	-19.42	3695.87	945.82	84.05	4.09	-23.70	9.91
09:21:07	0.24	1.26	14.14	40.41	-215.00	-21.34	3704.81	888.04	97.76	4.11	-22.50	9.96
09:21:14	0.26	1.24	13.94	36.65	-213.44	-22.37	3691.23	825.86	138.29	4.12	-22.70	9.96
09:21:22	0.26	1.24	13.75	35.76	-213.25	-22.85	3698.41	822.64	155.55	4.12	-22.50	9.96
09:21:29	0.24	1.26	13.83	36.16	-217.23	-22.02	3745.87	817.61	146.38	4.12	-21.40	10.01
09:21:37	0.20	1.17	13.15	33.76	-209.38	-22.81	3591.62	743.19	144.77	4.13	-19.70	10.20
09:21:44	0.19	1.14	12.67	31.81	-203.76	-22.90	3521.12	705.13	153.13	4.12	-19.40	10.16
09:21:52	0.20	1.09	11.92	28.48	-191.84	-24.05	3356.21	646.55	164.65	4.11	-19.70	10.08
09:21:59	0.22	1.12	12.14	29.71	-193.02	-23.73	3402.64	692.89	162.81	4.09	-20.70	9.97
09:22:07	0.22	1.13	12.27	30.67	-195.42	-23.30	3466.38	726.41	165.81	4.07	-20.80	10.02
09:22:14	0.22	1.20	13.28	33.89	-206.49	-22.46	3625.55	796.81	156.66	4.06	-20.60	9.99
09:22:22	0.23	1.26	13.27	36.29	-212.38	-21.13	3682.94	831.82	139.17	4.06	-21.00	9.89
09:22:29	0.24	1.28	12.93	36.47	-208.71	-21.43	3609.45	822.90	132.39	4.07	-21.50	9.72
09:22:37	0.22	1.32	13.09	39.09	-211.77	-19.71	3644.05	879.75	115.65	4.07	-21.10	9.67
09:22:44	0.21	1.29	12.98	37.48	-208.72	-20.07	3594.09	843.13	106.21	4.09	-20.30	9.71
09:22:52	0.21	1.27	13.82	39.09	-215.27	-20.40	3716.45	880.76	113.52	4.10	-20.50	9.96
09:22:59	0.21	1.20	13.49	35.09	-210.52	-21.32	3608.49	789.76	132.66	4.11	-20.30	10.11
09:23:07	0.21	1.17	13.58	33.81	-205.24	-21.98	3543.90	775.90	145.35	4.11	-20.50	10.10
09:23:14	0.19	1.12	12.83	29.82	-194.45	-22.80	3357.96	680.39	146.47	4.11	-19.40	10.01
09:23:22	0.21	1.16	12.84	30.73	-194.86	-22.52	3395.80	710.99	143.52	4.10	-20.20	9.86
09:23:29	0.24	1.20	13.13	31.98	-197.54	-22.34	3439.50	747.34	140.76	4.09	-21.50	9.75
09:23:37	0.26	1.28	13.44	34.43	-201.49	-21.90	3492.04	806.51	132.04	4.08	-22.30	9.53
09:23:44	0.25	1.34	13.92	38.02	-205.04	-21.35	3530.52	880.04	117.11	4.08	-22.20	9.41
09:23:52	0.27	1.39	13.78	38.00	-203.48	-20.61	3521.39	887.57	109.74	4.09	-22.60	9.22
09:23:59	0.29	1.37	13.34	36.30	-196.31	-20.45	3434.31	869.59	114.77	4.10	-23.70	9.07
09:24:07	0.29	1.26	13.01	32.98	-190.63	-20.94	3384.25	819.85	135.08	4.10	-24.10	9.30
09:24:14	0.27	1.25	13.16	33.13	-192.61	-21.19	3413.80	811.10	132.25	4.10	-23.00	9.41
09:24:22	0.25	1.16	12.34	29.35	-183.68	-22.16	3264.58	720.62	146.79	4.09	-22.10	9.53
09:24:29	0.25	1.26	12.81	35.12	-195.38	-19.67	3446.21	848.87	128.08	4.08	-22.60	9.46
09:24:37	0.28	1.37	14.04	42.75	-217.47	-17.10	3778.61	1006.02	113.14	4.10	-23.70	9.62
	0.23	1.23	13.16	35.15	-202.82	-21.83	3532.75	807.76	131.68	4.10	-21.51	9.78

The data items stored in the log file are the six flexure forces, the three principal forces and three principal moments, apparent wind at the masthead, apparent wind at the center of effort, heel, pitch, boat speed, Cl, and Cd.

In addition to the data stored in the log file, the sails may have been videotaped during sailing. In this case, information is available on the shapes which the sails were trimmed to during some period of logging. This shape information can then be used for force confirmation and estimation of induced drag.

Chapter 3

The VPP Sail Model

The force data from *Amphetrete* for a range of sailing angles must be put in a form suitable for VPP input. Data for spinnaker sailing is handled in a different manner from upwind sailing data. The range of usable upwind sailing data is for apparent angles of approximately 15 to 60 degrees. However, for apparent wind angles greater than 50 degrees, IACC yachts use spinnakers.

The input to the VPP consists of a set of coefficients with which the program will compute sail forces. The forces generated by the sails are computed in terms of lift and drag. These lift and drag forces are a function of not only wind angle but also predicted sail settings. For this reason the sail model consists of something akin to, but more detailed than, a simple pair of lift and drag coefficient for each sailing angle.

3.1 Components of Sail Force

Sail force, while distributed over the sails, can be thought of as forward, side, and vertical force vectors, each acting at its *center of effort* (CE). The vectors can be resolved into any three principal directions depending upon the choice of axes. In the case of *Amphetrete*, the force is originally measured in the form of the three principal coordinates of the mast coordinate system. The coordinates of interest for the VPP are the standard ones for airfoil theory: parallel and perpendicular to the undisturbed flow approaching the sail, and perpendicular to the mast. The force perpendicular to the flow is the lift, and the force parallel to the flow is the drag.

The lift force is a force which can be accounted for by potential flow theory. Drag, however, is composed of several components and cannot be theoretically predicted in its entirety. One component of drag, the *induced drag*, is predicted by potential theory and can be computed. Components of drag caused by viscosity must be measured or estimated, as they cannot be computed analytically.

The VPP sail model computes drag based upon a given amount of each component in a manner consistent with theory and such that the total drag for any sail angle or setting equals the total amount of measured drag.

3.2 CFD Analysis and Estimation of Induced Drag

The CFD analysis is run for two reasons. First, to provide theoretical confirmation of the forces measured: given the good sail shape information provided by the off-boat video system, and providing wind measurements are correct, SVL5 should predict the same amount of lift force as was measured when the video was taken. Second, to provide an estimate of the amount of induced drag produced by the sails: since all the drag predicted by SVL5 is induced drag, it is possible to study the ratio of Cd/Cl^2 for a variety of sailing conditions. This ratio is, theoretically, a function of sail shape and should be characteristic of a given set of sails and relatively insensitive to small angle of attack variations for upwind sailing conditions.

After videotape is processed and a geo file has been produced, a sample of sailing data with relatively steady heel angle, apparent wind angle, boat speed, and forces is selected from data logged during the videotaping. The videotaping commonly takes about 5 minutes, and a steady data sample is usually selected for about one to four minutes of sailing. This data is averaged as in Table 1, and the information on apparent wind, boat speed, and heel are entered into a spreadsheet called Ftrans (for Force Translator). The apparent wind measured at the masthead, in mast coordinates, is translated into true wind at the masthead, in world coordinates, for input to SVL5. SVL5 is run and the predicted forces, in world coordinates, are translated into lift and drag in mast coordinates for comparison with actual forces measured.

Table 2. Summary of measured and computed forces. The value of C_e is computed from the inviscid results.

```
FTRANS SUMMARY PRINTOUT

SVL5 RUN = 80124.slf

     MEASURED WIND         SVL5 WIND

    baw =     24.10      baw =     26.81
    vaw =     13.19      vaw =     13.49


                 MEASURED

   Lift =   398.008      Cl =      1.148
   Drag =    63.114      Cd =      0.182


                 COMPUTED

   Lift =   401.600      Cl =      1.158
   Drag =    39.655      Cd =      0.114

              Ce =  Cd/Cl^2 =     0.085
```

In addition, the ratio of Cd/Cl^2 is computed, in the Ftrans spreadsheet, for force coefficients normalized to mast coordinate apparent wind at the center of effort, as utilized by the VPP, and for coefficients normalized to world coordinate apparent wind at the masthead, as output by SVL5. The latter provides a check that the numbers entered into Ftrans were correct. The former is used directly in the formulation of the VPP model (Table 2). The entire output for a sample SVL5 run can be found in Appendix A.

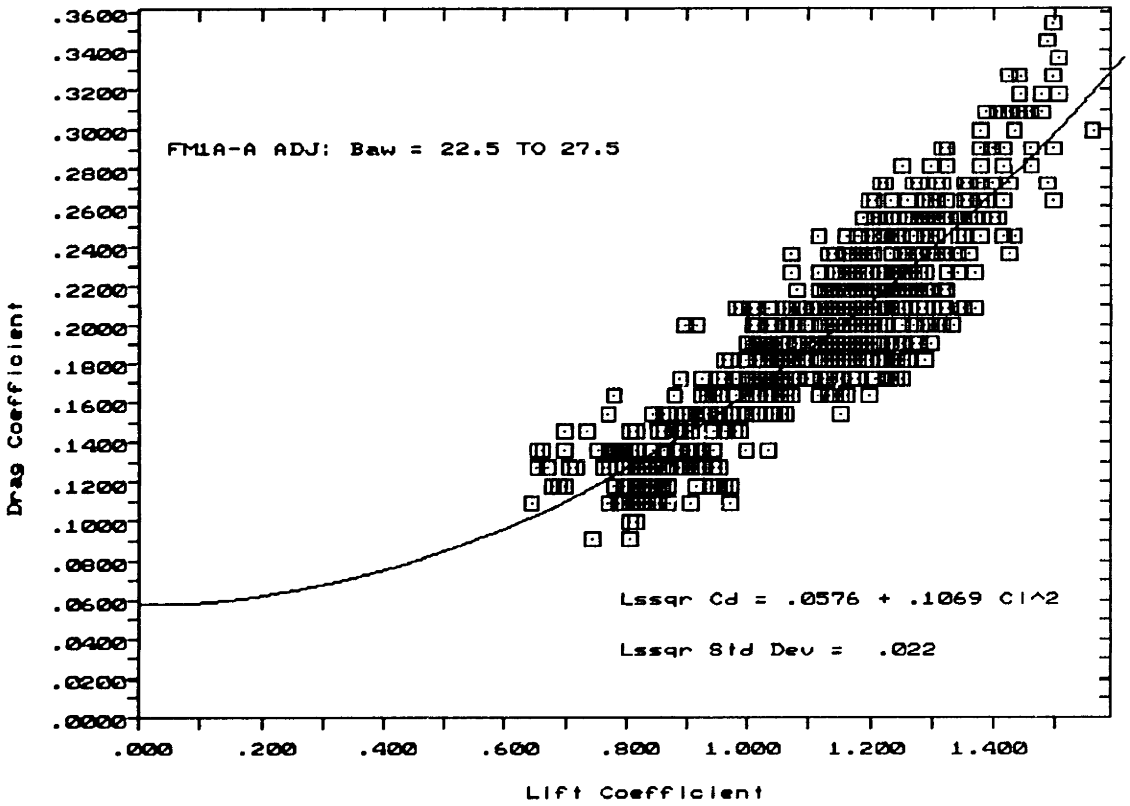

Figure 7. Typical 5-degree bin plot of Cd vs. Cl from sailing data. The best fit quadratic curve can be seen.

3.3 The Upwind Sail Model

Sail force coefficients of lift and drag are sorted according to apparent wind angle, and are separated into "bins" of from 2 to 5 degree apparent angle increments. For each bin a graph is made of lift coefficient vs. drag coefficient. A representative graph is shown in the Figure 7. A full set of such graphs for upwind sailing are included in Appendix B.

The VPP model requires an input of maximum attainable lift coefficient for a given apparent wind angle, and a corresponding maximum drag coefficient. The program may reduce lift and hence drag if it so chooses, to achieve optimum performance. The sail force data plotted includes data from high lift & drag, or "full" sailing, as well as low lift & drag, or "flat" sailing. The sail force model is designed so that for a given sailing angle and maximum lift coefficient, a good drag prediction can be computed for reduced lift coefficients at the same angle. In essence this means that the predicted lift & drag pair will always fall within the measured data.

The model assumes that the drag as a function of apparent wind angle is a quadratic function of the lift, plus some constant component. The drag components which are functions of the lift squared are the induced drag and part of the separation drag. The constant components of drag are the friction drag and parasitic drag of the rig. The VPP uses a combination of the rig and aerodynamic hull drag. The drag can therefore be written as the following function of lift coefficient and apparent wind angle,

$$Cd = \frac{C_{Dp0}}{r^2} + (f\,Cl)^2\,[Ce(\beta) + C_{D2}(\beta)] + C_{D_p}(\beta) \qquad (4)$$

Where C_e is induced drag coefficient, and is in fact the ratio Cd/Cl^2 computed during CFD analysis, C_{Dp0}/r^2 is the parasitic drag coefficient of the rig and hull adjusted for reefing, r; f is a factor used to reduce Cl by "flattening" the sails to the working Cl; C_{D2} is two-dimensional separation drag dependent upon lift coefficient and previously determined in water tunnel measurements[4]; and C_{D_p} is mainly friction drag.

---

[4] Jerome H. Milgram. *Section Data for Thin, Highly Cambered Airfoils in Incompressible Flow.* M.I.T., 1971

3.4 Making the Upwind Sail Model

Figure 7 shows a sample of sailing data in the form of a plot of pairs of lift and drag coefficients, along with a least-squares quadratic curve fit through the data.

The VPP requires a maximum lift coefficient value for each apparent angle, which is referred to as *Max Cl*. This is obtained from the data plots by choosing the value given by the average *Cl* for the bin plus 1.5 standard deviations of *Cl*. The *Max Cl* values for each bin are plotted against apparent angle and a smooth curve fit through them.

The corresponding drag coefficient for each maximum lift coefficient is picked from the best-fit curve on the data plot. The equation of the best-fit curve is of the form,

$$Cd = A + B\,Cl^2 \tag{5}$$

The coefficients A and B can be used directly in the VPP model, such that,

$$A = C_{Dp} + C_{Drig} \tag{6}$$

and

$$B = C_e + C_{D2} \tag{7}$$

The coefficient of drag of the rig, C_{Drig}, is obtained by measuring the force on the rig alone, with no sails up. From this it is possible to obtain C_{Dp}, since

$$C_{Dp} = A - C_{Drig} \tag{8}$$

Similarly, since values for C_{D2} have been previously obtained in the water tunnel, we can determine C_e from

$$C_e = B - C_{D2} \tag{9}$$

The values for these coefficients can be plotted against apparent wind angle and smoothed in such a way that the total drag predicted by the model equals the total measured drag.

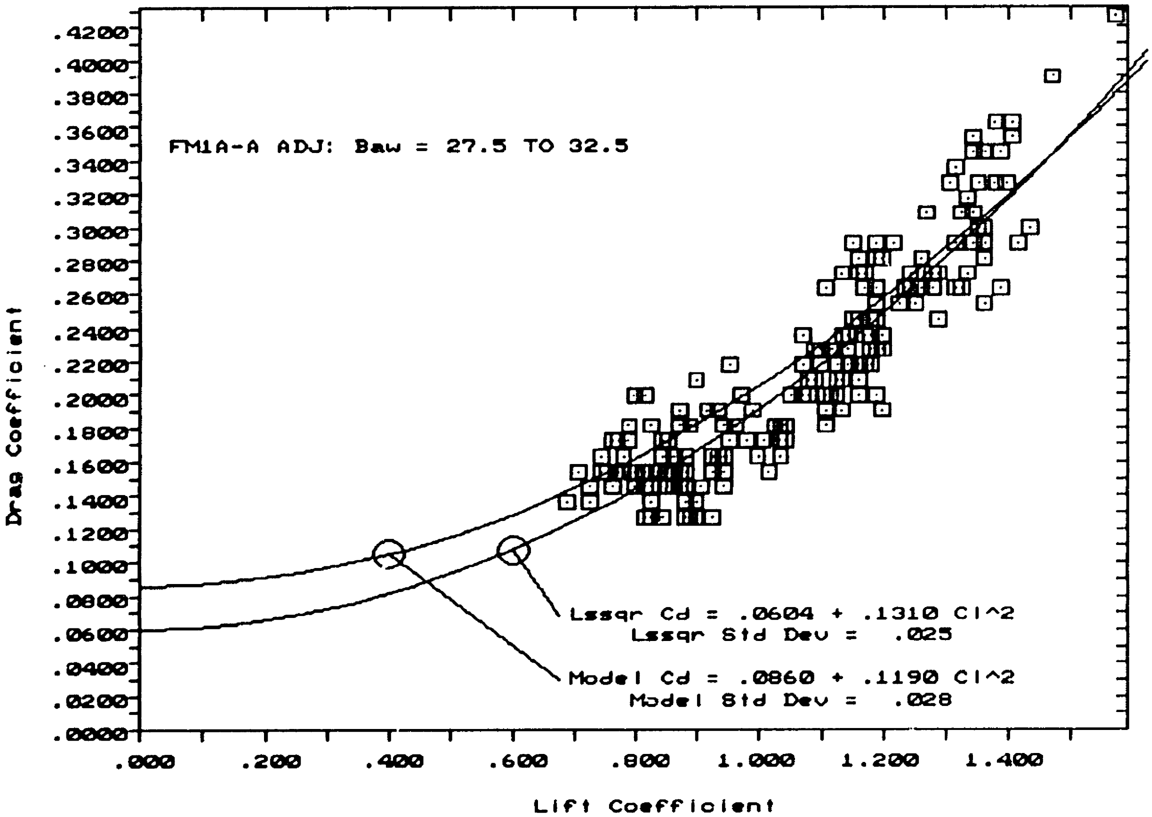

Figure 8. A data bin plot showing both the best fit curve (Lssqr Cd) and the curve plotted from a good sail model (Model Cd).

The procedure outlined above assumes that the statistical fit equation is the best place to start in estimating the various components of drag. Figure 8 illustrates how this is not necessarily true.

In Figure 8, a data bin is shown with two quadratic curves plotted through the data points. The curve identified as 'Lssqr (Least Squares) Cd' is the best-fit curve where

$$Lssqr\ Cd = 0.0604 + 0.131\ Cl^2 \tag{10}$$

with the coefficients $A_L = 0.0604$ and $B_L = 0.131$. The curve identified as 'Model Cd' is

$$Model\ Cd = 0.0860 + 0.119\ Cl^2 \tag{11}$$

with the coefficients $A_M = 0.0860$ and $B_M = 0.119$. If we use (9) to compute C_e we have

$$C_e = 0.131 - 0.025 = 0.106 \tag{12}$$

using the previously determined value $C_{D2} = 0.025$. And if we use (8) to compute C_{Dp} we get

$$C_{Dp} = 0.0604 - 0.040 = 0.0204 \tag{13}$$

using the rig drag coefficient of $C_{Drig} = 0.040$.

There are two problems with these results. First, CFD analysis gives us a value of $C_e = 0.094$ at 30 degrees, which indicates that the best-fit value $B_L = 0.131$ is too large. Second, a $C_{Dp} = 0.0204$ is unreasonably small for this sailing angle, indicating that the best-fit value $A_L = 0.0604$ is too small. In some cases, the best-fit value of A is actually smaller than the measured rig drag. For instance, for the 35 degree bin from this data set, which can be found in Appendix B, the best fit value of A is 0.0193, which is less than the rig drag of 0.042. This clearly cannot be.

The 'Model Cd' curve was developed using the C_e values obtained from the CFD analysis. This curve has a smaller quadratic coefficient and larger constant coefficient. In addition to incorporating more accurate information about C_e, this curve also gives a more reasonable value for C_{Dp}, of 0.046.

The standard deviation of the measured *Cd* about both the 'Lssqr Cd' and 'Model Cd' curves is indicated in the data bin plots. For the 30 degree bin shown in Figure 8, the standard deviation of measured *Cd* about the 'Lssqr Cd' curve is 0.025, and about the 'Model Cd' curve it is 0.028. The 'Model Cd' curve, therefore, agrees well with the measured data.

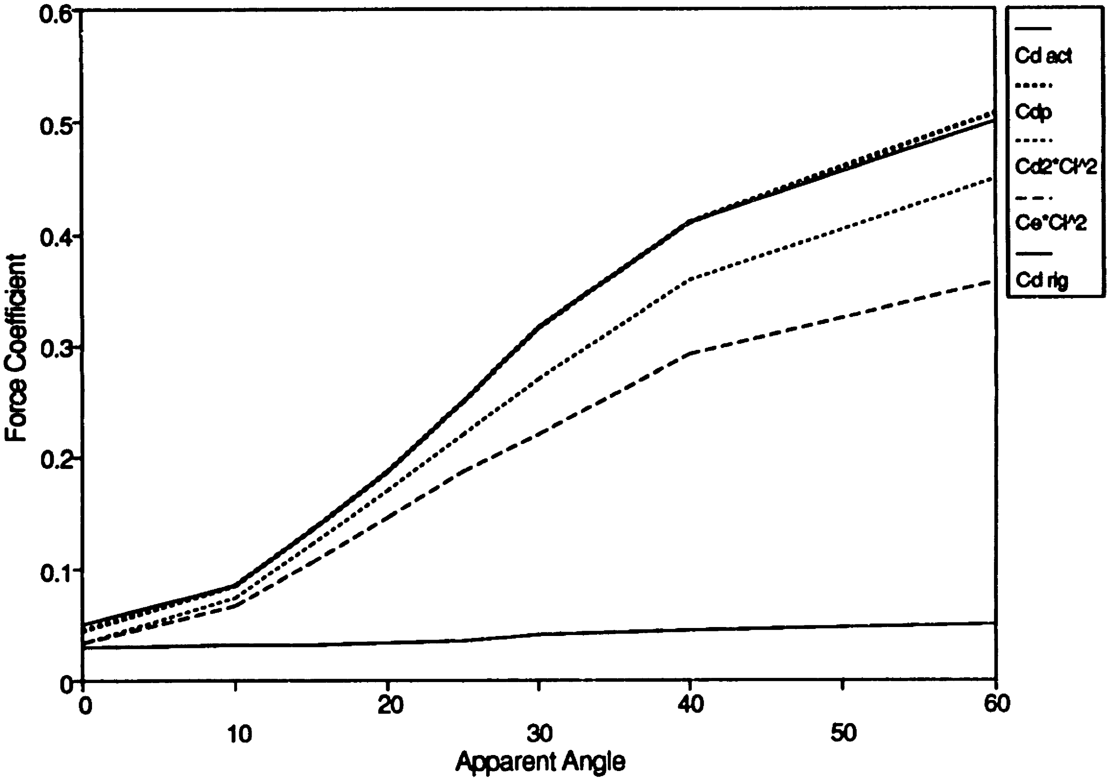

Figure 9. Graph of the various components of drag coefficient plotted against apparent wind angle.

Figure 9 shows the various components of drag as used in a VPP model developed during this project. The lines represent the summation of given drag components as computed by the VPP, using (4) and the values of *Max Cl* determined previously. The coefficients are assembled into a file and can be seen in Table 3.

3.5 The Downwind Sail Model

Downwind, spinnaker forces have been measured on *Amphetrete*, and a record similar to the upwind data has been obtained. The data is plotted in the form of lift coefficient vs. apparent angle and drag coefficient vs. apparent angle. A curve is fit through the data in each of these plots and a lookup table is developed for spinnaker lift and drag coefficients (*sCl* and *sCd*) vs. apparent wind angle (Figure 10).

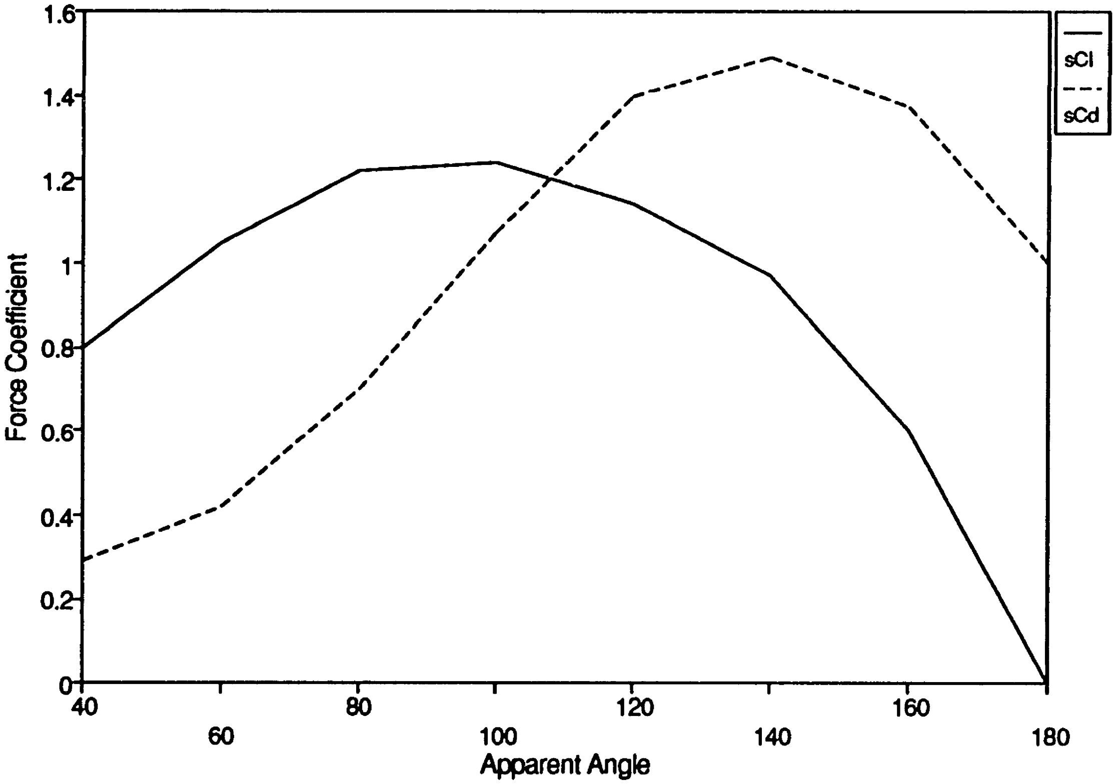

Figure 10. Graph of Spinnaker Lift and Drag Coefficients Used by the VPP.

For apparent angles greater than 45 degrees, the VPP will set a spinnaker. In this case the sail force computed by the program uses total lift and drag coefficients obtained from the force data, without breaking the drag into various components. The sail force becomes,

$$Sail\ Force = \frac{1}{2}\,\rho\ Vaw^2\ A\ (sCl\ \sin(Baw)\ -\ sCd\ \cos(Baw)) \tag{14}$$

where for 90 degrees apparent wind all of the forward sail force is from lift, and for 180 degrees (dead downwind), all of the forward force is from drag.

3.6 Input to the VPP

The final product of the reduction of the force data is a file which consists of a list of the various coefficients for wind angles from 0 to 180 degrees (Table 3). The underlined values are dummy values which are neither determined from measurements nor used by the VPP: i.e. spinnakers are not set at 20 degrees apparent wind and the upwind sail model is not used downwind, when the spinnaker model is used. These values are included for reasons of VPP program structure only.

Table 3. The format of the VPP *.in file of coefficients determined from sailing data.

Baw	0	10	15	20	25	30	40	60	80	100	120	140	160	180	
CLmax	0.010	0.690	1.000	1.230	1.330	1.390	1.480	1.650	1.960	1.610	1.060	0.560	0.200	0.010	CLmax
Ce	0.074	0.074	0.074	0.074	0.085	0.094	0.113	0.117	0.251	0.318	0.390	0.446	0.495	0.530	Ce
Cd2	0.015	0.015	0.016	0.017	0.019	0.025	0.030	0.035	0.040	0.043	0.046	0.049	0.050	0.050	Cd2
Cdp	0.011	0.012	0.013	0.015	0.030	0.046	0.052	0.058	0.650	0.940	1.120	1.180	1.190	1.200	Cdp
sCl	0.000	0.160	0.220	0.300	0.500	0.660	0.800	1.050	1.220	1.240	1.140	0.970	0.600	0.001	sCl
sCd	0.220	0.220	0.230	0.230	0.240	0.250	0.290	0.420	0.700	1.070	1.400	1.490	1.370	1.000	sCd

The coefficients in this file are interpolated by a splining program whose output is a file containing the coefficients in one degree apparent angle increments. The VPP uses this interpolated set of coefficients to compute sail forces.

Chapter 4

Results and Conclusions

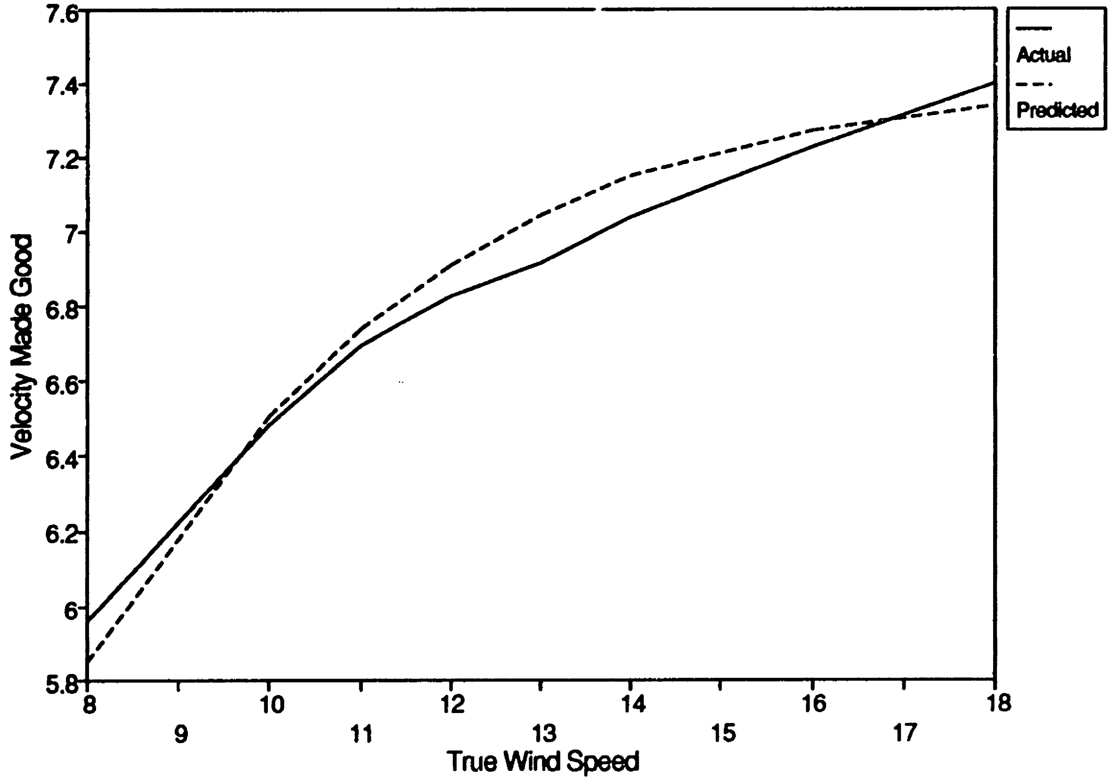

Figure 11. Plot of VMG for USA-18 under actual sailing conditions and as predicted by the VPP.

4.1 VPP Results Compared With Actual IACC Performance

The VPP predictions for upwind sailing of USA-18 have been compared with the actual performance of the boat. The VPP uses towing tank data for USA-18 and the sail model developed in this project. Added resistance due to waves, based on the sea spectrum in San Diego, is computed using a method developed by Paul Sclavounos at M.I.T. The output of the VPP run is included in Appendix C. Based on speed measurements and tacking angle information for various wind speeds, it is possible to compute optimum VMG (velocity made good, or speed in the direction of the wind) for the actual boat. This is compared with the optimum VMG computed by the VPP for a range of wind speeds in Figure 11. The predicted VMG is, in general, within 0.1 knot of the actual VMG. This is within the range of uncertainty of measurement of actual VMG, which is subject to speedometer error and the difficulty in measuring true wind angle.

Appendix A

SVL5 Output

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.......................................................................... .

        +++ SAIL VLM PROGRAM INPUT PARAMETERS +++

    ID: M  FM1A+fg2b 12/6/91 dp revision of jk; trial 11/13, 11:41 to 11:50
    COMP. DATE:   06-Dec-91     13:47:35

    SAIL ID:                  MAIN             JIB

    BODY PRESENT:                1               1
    SPANWISE PANELS:            20              20
    CHORDWISE PANELS:            8               8
    CONTROL POINTS:            160             160
    TOTAL PANELS USED IN COMPUTATION:  320

    BOAT SPEED (KTS):       4.710      RHO (SL/FT**3):       0.00234
    IMAGE STRENGTH:         1.000      HEEL (DEG):           24.62
    APPARENT WIND                      TRUE WIND
    AT MASTHEAD:                       AT MASTHEAD:
         DIRECTION (DEG):  20.69            DIRECTION (DEG):  29.06
         SPEED (KTS):      15.71            SPEED (KTS):      11.43
    WIND GRADIENT TYPE      VPP
    Y VALUE OF
    IMAGE PLANE            -3.800

                          **   MAIN          **

    SPAN (FT):  41.599


SECTION    X AT    Z AT                        MAX.     LOCATION OF    ANGLE    ANGLE
HEIGHT      LE      LE     CHORD     TWIST    CAMBER    MAX. CAMBER    AT LE    AT TE
 (FT)      (FT)    (FT)    (FT)      (DEG)    (F/CHD)     (X/CHD)      (DEG)    (DEG)
 5.968    0.512   0.000   13.750     2.500    0.0331      0.4783       6.539    4.618
16.348    0.641   0.000   12.719     8.630    0.0734      0.4643      14.328   10.240
26.747    0.910   0.000   11.481    14.500    0.0893      0.4732      19.187   14.470
37.147    1.347   0.000    9.006    19.500    0.0991      0.4854      19.537   14.676
43.387    1.704   0.000    5.005    21.700    0.1060      0.4955      22.459   15.816
47.547    1.964   0.000    0.206    23.000    0.1102      0.4822      26.241   17.672

                          **   JIB           **

    SPAN (FT):  33.158


SECTION    X AT    Z AT                        MAX.     LOCATION OF    ANGLE    ANGLE
HEIGHT      LE      LE     CHORD     TWIST    CAMBER    MAX. CAMBER    AT LE    AT TE
 (FT)      (FT)    (FT)    (FT)      (DEG)    (F/CHD)     (X/CHD)      (DEG)    (DEG)
 3.527  -10.827   0.000   15.028     8.990    0.0600      0.4064      18.093   10.110
11.816   -7.862  -0.335   10.839    13.750    0.1165      0.4451      31.097   16.646
20.106   -5.049  -0.429    7.026    19.280    0.1603      0.4561      35.993   24.624
28.395   -2.362  -0.320    3.528    25.450    0.1905      0.4752      37.024   29.093
36.685    0.192  -0.000    0.240    32.000    0.2000      0.4939      36.536   29.768
```

```
                         TABULATED WAKE PARAMETERS

                    WAKE SEGMENT LENGTH        XMULT
                    MAIN             :  2.00   1000.00
                    JIB              :  2.00   1000.00

                                               INDUCED V/VAW
                SPAN:     0.0       0.2       0.4       0.6       0.8       1.0

        MAIN          :
                   UX1:  0.023     0.031     0.028     0.022     0.004     0.011
                   UZ1:  0.222     0.222     0.155     0.103     0.112     0.042

                   UX2:  0.013     0.028     0.020     0.008     0.014    -0.026
                   UZ2:  0.126     0.134     0.055     0.015     0.066    -0.091

        JIB           :
                   UX1:  0.055     0.093     0.065     0.028    -0.034    -0.065
                   UZ1:  0.009     0.183     0.172     0.123     0.026    -0.168

                   UX2:  0.021     0.045     0.038     0.036     0.034     0.016
                   UZ2: -0.104     0.186     0.146     0.096     0.068     0.038
-----------------------------------------------------------------------------


                         BVP RESULTS

        ID: M  FM1A+fg2b 12/6/91 dp revision of jk; trial 11/13, 11:41 to 11:50

        WIND CONFIGURATION NO.: 1
        REFERENCE WIND VELOCITY (VAWREF) IS VAW AT TOP OF HEELED MAST.
        VAWREF(KNOTS) =   15.7100       VAWREF(FT/SEC) =   26.5342

        BOUND VORTEX SHEET DENSITY = 10*GAMMA/(2*PI*VAWREF)  (NON-DIML)
        BOUND CIRCULATION = CIRCULATION/(2*PI*VAWREF) (FEET)

        NOTE:  CL VALUES LISTED BELOW ARE APPROXIMATE!!!


                         *** MAIN          SOLUTION ***

                                        VORTEX DENSITY

                    X/C      0.010    0.084    0.222    0.402    0.598    0.778    0.916    0.990
R/SPAN    CL2D      CIRC.
 0.025    0.324    0.296    -0.082   -0.001    0.196    0.355    0.370    0.230    0.097    0.004
 0.075    0.389    0.358    -0.481   -0.066    0.253    0.464    0.487    0.309    0.144    0.022
 0.125    0.402    0.370    -0.844   -0.143    0.276    0.523    0.551    0.345    0.165    0.033
 0.175    0.403    0.371    -1.162   -0.215    0.288    0.567    0.597    0.367    0.179    0.044
 0.225    0.404    0.371    -1.436   -0.276    0.297    0.603    0.638    0.388    0.194    0.057
 0.275    0.410    0.373    -1.668   -0.325    0.309    0.637    0.675    0.408    0.210    0.072
 0.325    0.420    0.379    -1.859   -0.360    0.324    0.669    0.711    0.429    0.226    0.087
 0.375    0.436    0.389    -2.009   -0.379    0.345    0.699    0.746    0.452    0.243    0.101
 0.425    0.458    0.403    -2.115   -0.380    0.377    0.730    0.777    0.475    0.258    0.112
 0.475    0.487    0.422    -2.179   -0.360    0.424    0.770    0.801    0.492    0.269    0.119
 0.525    0.523    0.445    -2.202   -0.322    0.475    0.821    0.831    0.504    0.271    0.119
 0.575    0.566    0.470    -2.164   -0.260    0.509    0.861    0.884    0.526    0.270    0.113
 0.625    0.614    0.495    -2.001   -0.138    0.533    0.856    0.937    0.564    0.272    0.105
 0.675    0.667    0.514    -1.663    0.078    0.645    0.768    0.942    0.591    0.274    0.096
 0.725    0.726    0.523    -1.244    0.290    0.844    0.771    0.835    0.573    0.264    0.086
```

```
 0.775    0.786  0.515     -0.648    0.417    0.884    0.928    0.769    0.520    0.242    0.075
 0.825    0.823  0.468     -1.047    0.305    0.835    0.988    0.975    0.595    0.271    0.083
 0.875    0.820  0.373     -1.341    0.231    0.822    1.001    1.019    0.634    0.301    0.095
 0.925    0.820  0.252     -1.496    0.206    0.838    1.019    1.040    0.639    0.306    0.099
 0.975    0.942  0.114     -0.895    0.443    1.005    1.118    1.071    0.628    0.296    0.098


 CIRCULATION COEFFICIENTS:

  A1 =   0.5013
 A2/A1 =  -0.0115   A3/A1 =   0.1155   A4/A1 =   0.1632   A5/A1 =  -0.0055

APPROX. CHORDWISE LOADING DECOMPOSITION:

 R/SPAN:   0.025 0.075 0.125 0.175 0.225 0.275 0.325 0.375 0.425 0.475 0.525 0.575 0.625 0.675 0.725 0.775 0.825 0.875 0.925
 CLF:      0.408 0.589 0.696 0.776 0.843 0.903 0.958 1.010 1.058 1.104 1.148 1.187 1.205 1.188 1.154 1.077 1.214 1.275 1.301
 CLA:     -0.098-0.219-0.316-0.396-0.463-0.520-0.566-0.603-0.629-0.646-0.654-0.649-0.615-0.536-0.437-0.304-0.410-0.478-0.509-
 CLT:      0.310 0.371 0.381 0.380 0.380 0.383 0.392 0.407 0.428 0.457 0.494 0.538 0.591 0.652 0.717 0.774 0.804 0.797 0.791
FLBA:     -0.315-0.591-0.829-1.041-1.220-1.356-1.444-1.482-1.469-1.413-1.324-1.206-1.041-0.821-0.609-0.393-0.510-0.600-0.644-


                    *** JIB            SOLUTION ***

                                      VORTEX DENSITY

                   X/C      0.010     0.084    0.222    0.402    0.598    0.778    0.916    0.990
R/SPAN    CL2D    CIRC.
 0.025    0.459  0.421     -0.160    0.261    0.416    0.400    0.363    0.245    0.101    0.007
 0.075    0.672  0.601     -0.212    0.378    0.633    0.599    0.543    0.375    0.171    0.034
 0.125    0.830  0.714     -0.277    0.461    0.802    0.750    0.684    0.485    0.236    0.054
 0.175    0.964  0.791     -0.357    0.524    0.945    0.881    0.811    0.588    0.304    0.079
 0.225    1.082  0.841     -0.450    0.571    1.071    1.001    0.930    0.686    0.370    0.106
 0.275    1.189  0.870     -0.552    0.606    1.183    1.114    1.045    0.776    0.432    0.134
 0.325    1.286  0.880     -0.658    0.629    1.283    1.222    1.155    0.862    0.490    0.162
 0.375    1.374  0.874     -0.766    0.644    1.371    1.324    1.262    0.943    0.544    0.189
 0.425    1.454  0.854     -0.873    0.651    1.448    1.421    1.365    1.019    0.594    0.216
 0.475    1.527  0.822     -0.977    0.652    1.513    1.513    1.465    1.091    0.640    0.240
 0.525    1.592  0.778     -1.074    0.648    1.568    1.599    1.559    1.157    0.681    0.260
 0.575    1.648  0.723     -1.164    0.640    1.612    1.678    1.647    1.218    0.716    0.274
 0.625    1.695  0.660     -1.246    0.628    1.645    1.749    1.728    1.271    0.745    0.284
 0.675    1.732  0.589     -1.319    0.613    1.666    1.812    1.802    1.318    0.767    0.287
 0.725    1.760  0.511     -1.382    0.594    1.676    1.865    1.867    1.355    0.781    0.285
 0.775    1.776  0.428     -1.434    0.572    1.673    1.909    1.921    1.382    0.786    0.276
 0.825    1.780  0.341     -1.471    0.546    1.658    1.941    1.964    1.399    0.783    0.262
 0.875    1.774  0.252     -1.484    0.520    1.632    1.961    1.995    1.406    0.773    0.243
 0.925    1.765  0.164     -1.430    0.508    1.600    1.972    2.015    1.405    0.756    0.221
 0.975    1.800  0.078     -1.097    0.589    1.609    1.996    2.039    1.414    0.755    0.209


 CIRCULATION COEFFICIENTS:

  A1 =   0.7752
 A2/A1 =   0.3094   A3/A1 =  -0.0195   A4/A1 =   0.0281   A5/A1 =   0.0276

APPROX. CHORDWISE LOADING DECOMPOSITION:

 R/SPAN:   0.025 0.075 0.125 0.175 0.225 0.275 0.325 0.375 0.425 0.475 0.525 0.575 0.625 0.675 0.725 0.775 0.825 0.875 0.925
 CLF:      0.581 0.845 1.048 1.227 1.391 1.542 1.682 1.812 1.933 2.043 2.143 2.230 2.306 2.368 2.415 2.447 2.462 2.458 2.436
 CLA:     -0.131-0.186-0.233-0.280-0.327-0.375-0.421-0.466-0.509-0.550-0.588-0.622-0.652-0.678-0.699-0.716-0.726-0.728-0.714-
 CLT:      0.450 0.659 0.815 0.947 1.063 1.167 1.261 1.346 1.424 1.493 1.555 1.609 1.654 1.690 1.716 1.732 1.735 1.730 1.722
```

```
FLBA:      -0.292-0.281-0.286-0.296-0.308-0.321-0.334-0.346-0.358-0.368-0.378-0.386-0.394-0.401-0.407-0.413-0.418-0.421-0.415-

                          *** WAKE VELOCITIES ***

     WAKE SEGMENT LENGTH:
                    MAIN          :  2.00
                    JIB           :  2.00


                                                INDUCED V/VAW
                N          SPAN:  0.0     0.2     0.4     0.6     0.8     1.0
     MAIN             :

                1          VX:   0.023   0.030   0.027   0.020   0.006   0.006
                           VZ:   0.227   0.222   0.151   0.104   0.106   0.024

                7          VX:   0.016   0.032   0.023   0.012   0.008  -0.024
                           VZ:   0.145   0.156   0.071   0.029   0.055  -0.088

               13          VX:   0.013   0.028   0.019   0.009   0.012  -0.027
                           VZ:   0.128   0.133   0.052   0.019   0.055  -0.097
     JIB              :

                1          VX:   0.056   0.092   0.066   0.035  -0.021  -0.073
                           VZ:   0.021   0.186   0.169   0.107  -0.004  -0.177

                7          VX:   0.071   0.061   0.062   0.064   0.062   0.036
                           VZ:   0.012   0.221   0.195   0.149   0.109   0.067

               13          VX:   0.022   0.046   0.038   0.035   0.033   0.014
                           VZ:  -0.096   0.191   0.146   0.094   0.069   0.034
------------------------------------------------------------------------------

                              FORCE RESULTS


     ID: N  FN1A+fg2b 12/6/91 dp revision of jk; trial 11/13, 11:41 to 11:50
     JJ =  1


FORCE AND MOMENT COEFFICIENTS:
FORCES AND MOMENTS ARE DIVIDED BY INFLOW VELOCITY HEAD
AARC COORDINATES ARE USED.
     MAIN              LEADING EDGE SUCTION FACTOR = 1.00
     JIB               LEADING EDGE SUCTION FACTOR = 1.00
     TIP SUCTION FACTOR = -.09


                *** POTENTIAL FLOW FORCES AND MOMENTS ***

          FX/Q         FY/Q         FZ/Q        MX/Q        MY/Q        MZ/Q
MAIN  -3.832E+01   8.253E+01  -1.666E+02   5.012E+03   1.804E+03  -5.086E+02
JIB   -6.181E+01   7.351E+01  -2.033E+02   3.620E+03   1.613E+02  -1.206E+03
TOTAL -1.001E+02   1.560E+02  -3.699E+02   8.632E+03   1.965E+03  -1.715E+03

                    *** TOTAL FORCES AND MOMENTS ***

       TOTAL FX/Q:     -100.1364          TOTAL MX/Q:      8631.6660
       TOTAL FY/Q:      156.0334          TOTAL MY/Q:      1965.2161
```

```
          TOTAL FZ/Q:     -369.9366        TOTAL MZ/Q:     -1714.7115

                              CEX            CEY             CEZ
AARC COORD.S:
MAIN                         7.656         -24.754         -11.344
JIB                         -1.598         -15.456          -7.083
OVERALL                      2.686         -19.659          -9.009
MAST COORD.S:
MAIN                         7.656         -27.230           0.000
JIB                         -1.598         -17.001           0.000
OVERALL                      2.686         -21.625           0.000

                        *** DIMENSIONAL RESULTS ***

                        POTENTIAL       FRICTIONAL       TOTAL
          FX (LBS):      -82.4780         0.0000        -82.4780
          FY (LBS):      128.5180         0.0000        128.5180
          FZ (LBS):     -304.7007         0.0000       -304.7007



                          *** LIFT AND DRAG ***

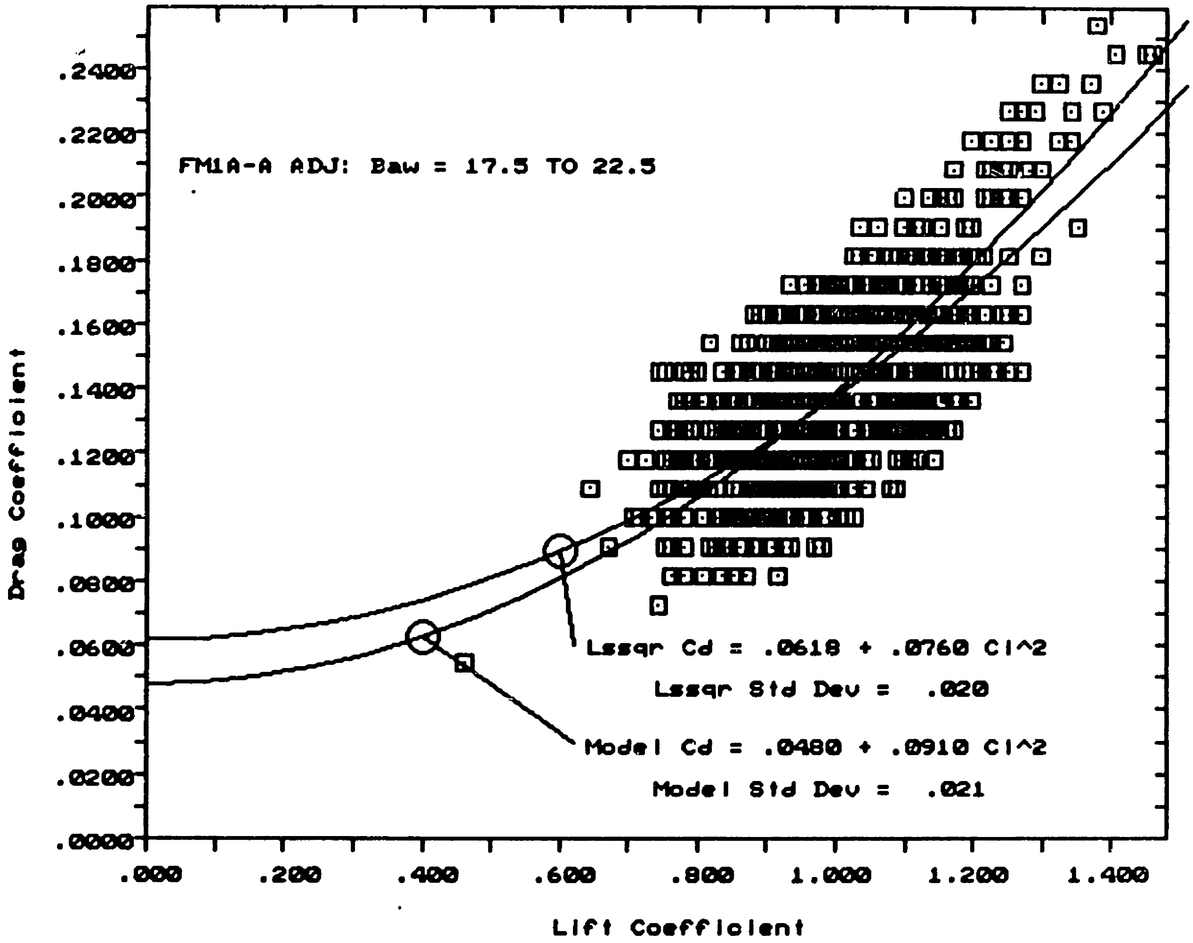
AARC COORD.S:
                 LIFT/Q     DRAG/Q  LIFT (LBS)  DRAG (LBS)      L/D       CL       CD   CD/CL**2     AREA
 MAIN          169.4022    23.0125    139.5292     18.9544   7.3613   0.3934   0.0534   0.3453   430.6231
 JIB           212.0550    14.0122    174.6605     11.5412  15.1336   0.8779   0.0580   0.0753   241.5493
 TOTAL         381.4572    37.0247    314.1897     30.4957  10.3028   0.5675   0.0551   0.1710   672.1724

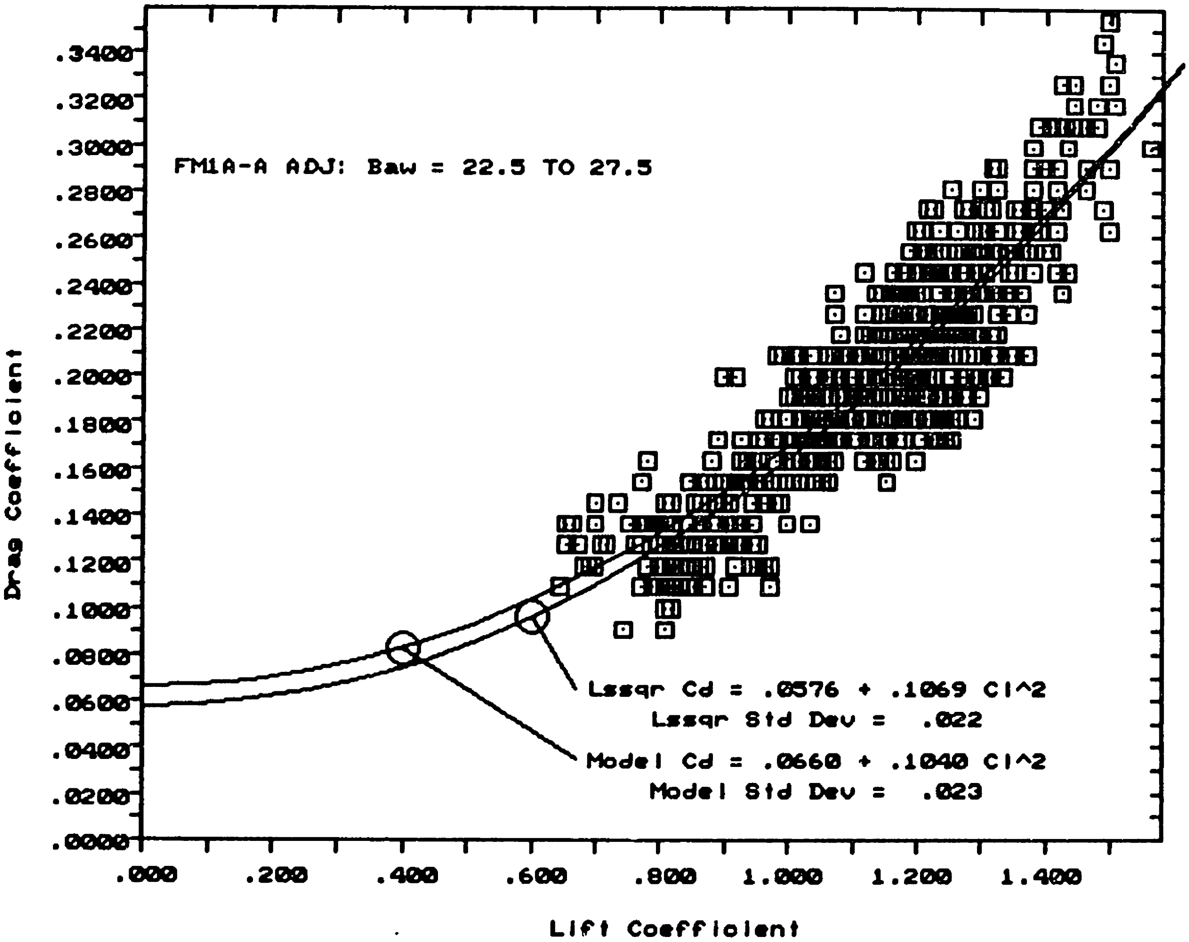
MAST COORD.S:
 MAIN          188.2156    24.1018    151.6665     19.4216   7.8092   0.4371   0.0560   0.2930   430.6231
 JIB           223.8627    11.5052    180.3913      9.2711  19.4574   0.9268   0.0476   0.0555   241.5493
 TOTAL         412.0783    35.6071    332.0578     28.6926  11.5729   0.6131   0.0530   0.1409   672.1724

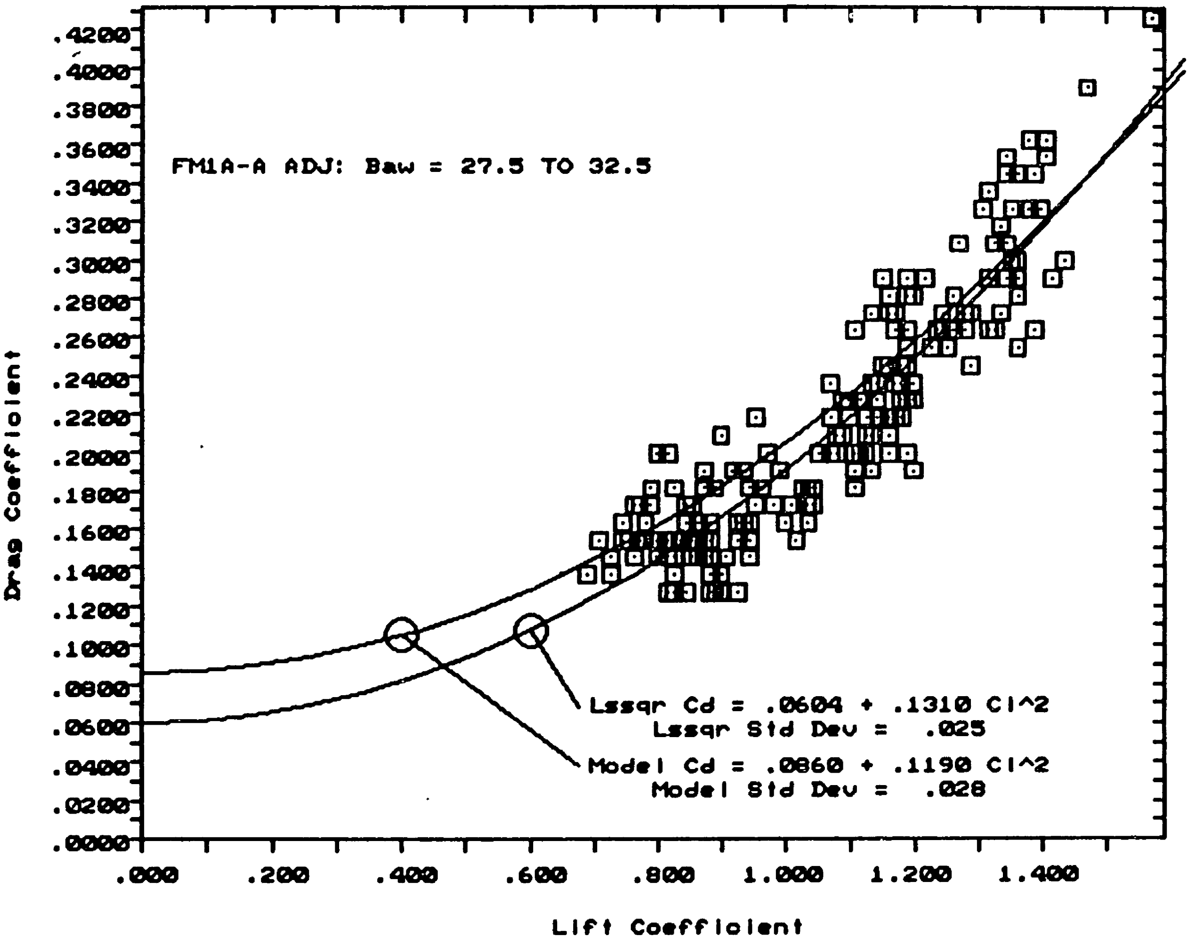
APPARENT WIND, DYNAMIC PRESSURE ( ** NOTE:  VREF = VAW,top ** )
                    VAW (KTS)     BAW (DEG)     VX (KTS)     VZ (KTS)     Q
     AARC COORD.S     15.71          20.69       14.70        -5.55     0.8237
     MAST COORD.S     15.54          18.95       14.70        -5.05     0.8058
```

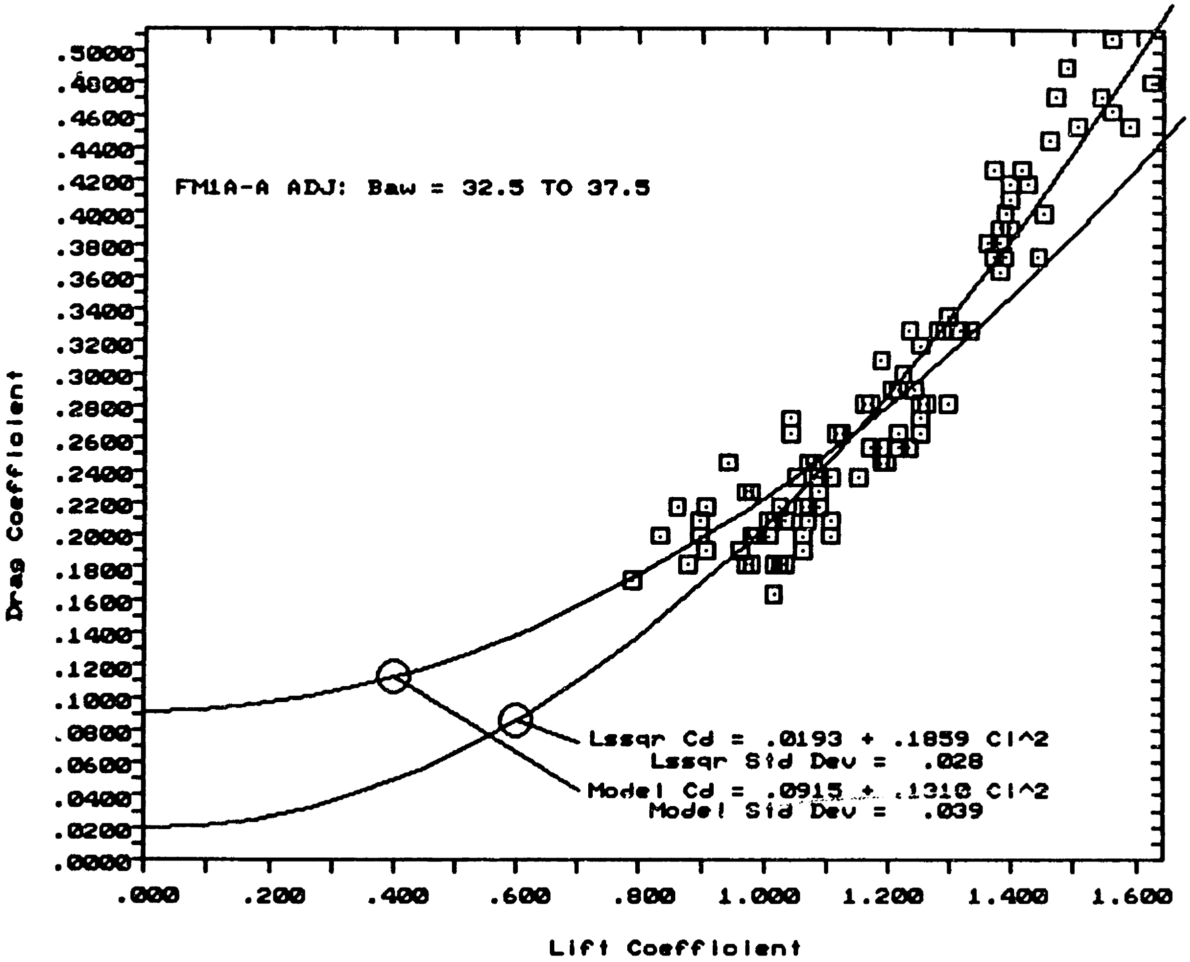
Appendix B

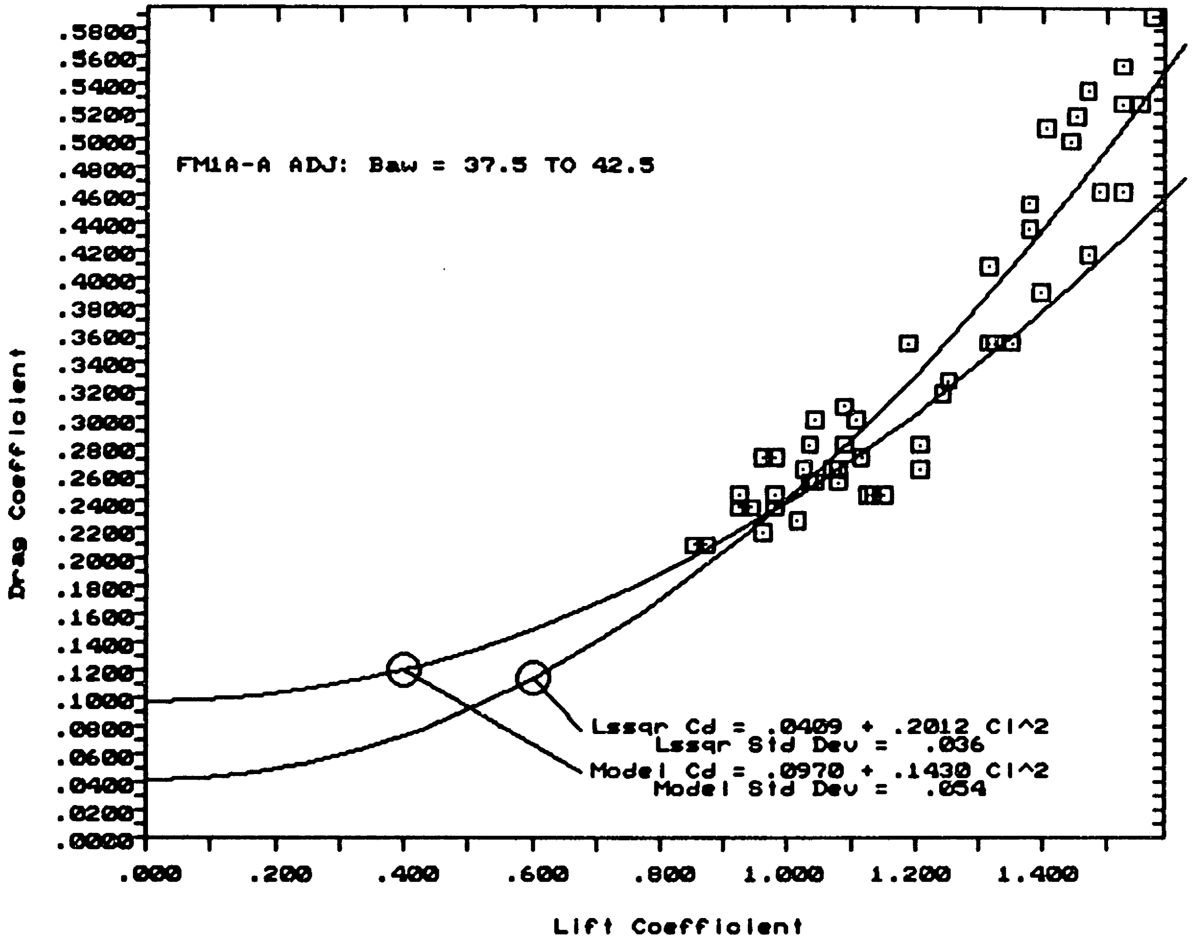
Plots of Cl vs. Cd from Sailing Data


FM1A-A ADJ: Baw = 17.5 TO 22.5
Lssqr Cd = .0618 + .0760 Cl^2
Lssqr Std Dev = .020
Model Cd = .0480 + .0910 Cl^2
Model Std Dev = .021
Drag Coefficient
Lift Coefficient
.0000
.0200
.0400
.0600
.0800
.1000
.1200
.1400
.1600
.1800
.2000
.2200
.2400
.000
.200
.400
.600
.800
1.000
1.200
1.400


FM1A-A ADJ: Baw = 22.5 TO 27.5
.3400
.3200
.3000
.2800
.2600
.2400
.2200
.2000
.1800
.1600
.1400
.1200
.1000
.0800
.0600
.0400
.0200
.0000
Drag Coefficient
.000
.200
.400
.600
.800
1.000
1.200
1.400
Lift Coefficient
Lssqr Cd = .0576 + .1069 Cl^2
Lssqr Std Dev = .022
Model Cd = .0660 + .1040 Cl^2
Model Std Dev = .023


FM1A-A ADJ: Baw = 27.5 TO 32.5
Lssqr Cd = .0604 + .1310 Cl^2
Lssqr Std Dev = .025
Model Cd = .0860 + .1190 Cl^2
Model Std Dev = .028
Drag Coefficient
.4200
.4000
.3800
.3600
.3400
.3200
.3000
.2800
.2600
.2400
.2200
.2000
.1800
.1600
.1400
.1200
.1000
.0800
.0600
.0400
.0200
.0000
.000
.200
.400
.600
.800
1.000
1.200
1.400
Lift Coefficient


FM1A-A ADJ: Baw = 32.5 TO 37.5
Drag Coefficient
.5000
.4800
.4600
.4400
.4200
.4000
.3800
.3600
.3400
.3200
.3000
.2800
.2600
.2400
.2200
.2000
.1800
.1600
.1400
.1200
.1000
.0800
.0600
.0400
.0200
.0000
.000
.200
.400
.600
.800
1.000
1.200
1.400
1.600
Lift Coefficient
Lssqr Cd = .0193 + .1859 Cl^2
Lssqr Std Dev = .028
Model Cd = .0915 + .1318 Cl^2
Model Std Dev = .039



FM1A-A ADJ: Baw = 37.5 TO 42.5
Drag Coefficient
Lift Coefficient
.5800
.5600
.5400
.5200
.5000
.4800
.4600
.4400
.4200
.4000
.3800
.3600
.3400
.3200
.3000
.2800
.2600
.2400
.2200
.2000
.1800
.1600
.1400
.1200
.1000
.0800
.0600
.0400
.0200
.0000
.000
.200
.400
.600
.800
1.000
1.200
1.400
Lssqr Cd = .0409 + .2012 Cl^2
Lssqr Std Dev = .036
Model Cd = .0970 + .1430 Cl^2
Model Std Dev = .054

Appendix C

VPP Output for USA-18

```
AMERICA'S CUP CLASS VPP                SAN DIEGO WAVES              IDF=1.000        AWAVE= .00
TIAVE: January Configuration
----------------------------------------------------------------------------------------------------------------
   LSM(1)---------- 61.96            BEAM------------- 12.03          AREA(MAX SECTION)--  25.36
   LSM(2)---------- 61.96            KEEL DRAFT------- 13.26          PROP AREA(PROJ)----   .000
   LSM(3)---------- 60.68            CENTERBOARD EXT--   .00          DISPLACEMENT-------  59636
   LSM(4)---------- 71.58            BEAM/DEPTH-------  3.34          RM/DEG AT  2 DEG--- 9372.0
   AVERAGE LENGTH-- 62.51            WETTED SURFACE--  815.2          RM/DEG AT 25 DEG--- 9487.0
----------------------------------------------------------------------------------------------------------------
   MAIN MAST DIAM--  1.18            SAIL AREA------- 3909.5          AVG FREEBOARD------   4.41
   HEIGHT OF MAIN--111.04            MIZZEN DIAM------   .00          CREW WT ON RAIL----   1700
   AREA(KEEL TE)--- 20.44            HEIGHT OF MIZZEN-   .00          REDUCED DRAFT------  11.23
----------------------------------------------------------------------------------------------------------------
      TOTAL RESISTANCE COEFFICIENTS AT CORRESPONDING SPEED-LENGTH RATIOS
   VRL:     .68        .75        .81        .88        .95       1.02       1.08       1.15
    CT:   .00316     .00318     .00322     .00326     .00335     .00347     .00358     .00378
----------------------------------------------------------------------------------------------------------------
VTW  VT-CE  BTW    VAW    BAW      V     VMG    PHI  REEF  FLAT   FR RI+RN RAD    FN     CL    CI    CD   ALF
----------------------------------------------------------------------------------------------------------------
7.0  7.15 150.0   3.61  82.49  6.668 -5.775    .7  1.00  1.00  334    1    0  319.2 2.165 .000 1.586   .3
7.0  7.15 135.0   5.52  66.27  7.279 -5.147   2.9  1.00  1.00  412    7    0  776.0 1.713 .000 1.353   .7
7.0  7.15 120.0   8.50  46.52  9.422 -4.711   5.4  1.00  1.00  850   21    0 1304.7 1.587 .121  .379   .7
7.0  7.14 100.0  11.05  38.73  9.863 -1.713  10.3  1.00  1.00 1059   57    0 2340.5 1.541 .125  .395  1.2
7.0  7.13  90.0  12.09  35.17  9.880   .000  12.5  1.00  1.00 1088   78    0 2805.1 1.512 .122  .376  1.4
7.0  7.12  43.7  13.50  20.69  7.485  5.408  14.4  1.00  1.00  586   99   54 3217.2 1.336 .097  .244  2.7
7.0  7.15 148.0   3.87  78.74  6.823 -5.786   1.0  1.00  1.00  351    1    0  377.2 2.117 .000 1.526   .4
----------------------------------------------------------------------------------------------------------------
8.0  8.18 150.0   4.11  83.68  7.534 -6.525   1.1  1.00  1.00  443    2    0  410.3 2.173 .000 1.606   .3
8.0  8.17 135.0   6.26  67.12  8.214 -5.808   4.0  1.00  1.00  560   12    0 1002.7 1.750 .000 1.364   .7
8.0  8.17 120.0   9.21  49.76 10.037 -5.018   6.2  1.00  1.00 1108   27    0 1479.6 1.606 .119  .369   .7
8.0  8.15 100.0  11.93  41.14 10.403 -1.807  12.0  1.00  1.00 1364   76    0 2700.0 1.557 .125  .398  1.2
8.0  8.14  90.0  13.03  37.19 10.378   .000  14.6  1.00  1.00 1378  106    0 3259.4 1.529 .124  .389  1.5
8.0  8.12  43.1  14.91  20.76  8.014  5.851  17.7  1.00  1.00  720  142   62 3928.3 1.337 .097  .245  3.0
8.0  8.18 149.0   4.25  81.72  7.622 -6.533   1.3  1.00  1.00  457    3    0  446.8 2.158 .000 1.574   .4
----------------------------------------------------------------------------------------------------------------
9.0  9.20 150.0   4.61  85.30  8.344 -7.226   1.6  1.00  1.00  573    4    0  508.1 2.180 .000 1.634   .4
9.0  9.19 135.0   6.98  68.16  9.096 -6.432   5.1  1.00  1.00  742   19    0 1251.0 1.794 .000 1.377   .7
9.0  9.19 120.0   9.87  53.19 10.506 -5.253   7.0  1.00  1.00 1389   33    0 1640.8 1.629 .119  .374   .7
9.0  9.16 100.0  12.76  43.42 10.857 -1.885  13.6  1.00  1.00 1709   96    0 3033.6 1.571 .124  .392  1.3
9.0  9.14  90.0  13.89  39.07 10.785   .000  16.7  1.00  1.00 1697  139    0 3693.5 1.544 .125  .396  1.6
9.0  9.12  42.3  16.21  20.89  8.403  6.214  19.6  1.00   .93  822  172   70 4331.8 1.249 .097  .224  3.1
9.0  9.20 148.0   4.93  81.40  8.538 -7.240   2.0  1.00  1.00  608    5    0  600.8 2.155 .000 1.568   .4
----------------------------------------------------------------------------------------------------------------
10.0 10.22 150.0  5.11  87.31  9.091 -7.873   2.1  1.00  1.00  727    6    0  611.5 2.185 .000 1.670   .4
10.0 10.21 135.0  7.62  70.35  9.784 -6.918   6.3  1.00  1.00  996   27    0 1501.3 1.880 .000 1.405   .8
10.0 10.21 120.0 10.50  56.49 10.901 -5.450   7.9  1.00  1.00 1687   40    0 1830.2 1.658 .124  .408   .7
10.0 10.17 100.0 13.57  45.42 11.290 -1.960  15.2  1.00  1.00 2085  121    0 3366.7 1.582 .122  .384  1.3
10.0 10.16  90.0 14.73  40.69 11.170   .000  18.7  1.00  1.00 2041  178    0 4124.1 1.554 .125  .398  1.7
10.0 10.12  41.3 17.42  20.97  8.669  6.508  21.2  1.00   .87  908  203   78 4668.2 1.168 .097  .205  3.3
10.0 10.22 150.0  5.11  87.31  9.091 -7.873   2.1  1.00  1.00  727    6    0  611.5 2.185 .000 1.670   .4
----------------------------------------------------------------------------------------------------------------
11.0 11.24 150.0  5.62  90.88  9.649 -8.356   2.6  1.00  1.00  923    8    0  710.1 2.188 .000 1.738   .4
11.0 11.23 135.0  8.24  72.83 10.372 -7.334   7.5  1.00  1.00 1305   36    0 1754.4 1.967 .000 1.439   .8
11.0 11.22 120.0 11.14  59.48 11.268 -5.634   9.1  1.00  1.00 1996   50    0 2082.4 1.693 .133  .476   .8
11.0 11.17 100.0 14.37  47.16 11.710 -2.033  16.8  1.00  1.00 2483  149    0 3704.9 1.591 .121  .377  1.3
11.0 11.14  90.0 15.54  42.07 11.538   .000  20.7  1.00  1.00 2404  224    0 4551.5 1.563 .125  .396  1.8
11.0 11.12  40.1 18.54  20.96  8.813  6.736  22.3  1.00   .81  971  229   87 4910.4 1.086 .097  .187  3.4
11.0 11.24 159.0  4.26 109.10  9.101 -8.497    .6  1.00  1.00  725    2    0  306.1 2.437 .000 2.192   .2
----------------------------------------------------------------------------------------------------------------
```

```
 VTW  VT-CE   BTW    VAW     BAW      V     VWB   PHI  REEF   FLAT   FR  RI+RN  RAD    FN     CL     CI     CD   ALF
----------------------------------------------------------------------------------------------------------------------
12.0  12.26  150.0   6.14   94.25  10.165  -8.803   3.1  1.00  1.00 1157    10    0   816.9  2.194  .000  1.808   .4
12.0  12.24  135.0   8.84   75.55  10.864  -7.682   8.7  1.00  1.00 1665    46    0  2004.7  2.046  .000  1.478   .8
12.0  12.23  120.0  11.77   62.16  11.615  -5.808  10.7  1.00  1.00 2314    65    0  2414.0  1.732  .146   .575   .8
12.0  12.17  100.0  15.15   48.64  12.126  -2.106  18.4  1.00  1.00 2897   184    0  4052.4  1.599  .120   .372  1.4
12.0  12.13   90.0  16.33   43.23  11.894    .000  22.7  1.00  1.00 2778   277    0  4975.3  1.578  .124   .393  1.8
12.0  12.12   39.2  19.61   20.98   8.921   6.912  23.5  1.00   .76 1034   260   96  5168.0  1.023  .097   .174  3.5
12.0  12.27  159.0   4.74  111.93   9.681  -9.038    .9  1.00  1.00  930     2    0   351.9  2.464  .000  2.271   .2
----------------------------------------------------------------------------------------------------------------------
13.0  13.28  150.0   6.69   97.63  10.616  -9.194   3.6  1.00  1.00 1446    13    0   930.0  2.217  .000  1.885   .4
13.0  13.26  135.0   9.44   78.06  11.328  -8.010   9.9  1.00  1.00 2055    58    0  2258.7  2.104  .000  1.516   .8
13.0  13.24  120.0  12.40   64.53  11.952  -5.976  12.6  1.00  1.00 2642    88    0  2818.0  1.771  .162   .693   .9
13.0  13.17  100.0  15.92   49.90  12.542  -2.178  20.1  1.00  1.00 3320   226    0  4410.6  1.607  .119   .369  1.4
13.0  13.11   90.0  17.08   44.21  12.240    .000  26.7  1.00  1.00 3156   338    0  5395.7  1.575  .123   .389  1.9
13.0  13.12   38.4  20.65   21.08   8.986   7.046  24.1  1.00   .70 1075   277  105  5294.4   .945  .097   .160  3.6
13.0  13.29  159.0   5.25  114.88  10.197  -9.520   1.1  1.00  1.00 1167     3    0   401.4  2.445  .000  2.350   .2
----------------------------------------------------------------------------------------------------------------------
14.0  14.30  150.0   7.25  100.52  11.064  -9.581   4.2  1.00  1.00 1792    15    0  1051.1  2.257  .000  1.956   .4
14.0  14.27  135.0  10.04   80.32  11.778  -8.329  11.2  1.00  1.00 2466    71    0  2517.6  2.142  .000  1.551   .9
14.0  14.24  120.0  13.00   66.59  12.284  -6.142  14.7  1.00  1.00 2978   119    0  3272.9  1.807  .177   .815  1.0
14.0  14.16  100.0  16.67   50.94  12.961  -2.251  21.9  1.00  1.00 3746   275    0  4780.1  1.613  .119   .368  1.4
14.0  14.09   90.0  17.79   45.02  12.576    .000  26.7  1.00  1.00 3532   406    0  5811.2  1.579  .123   .386  2.0
14.0  14.11   37.8  21.66   21.20   9.045   7.146  25.1  1.00   .66 1129   306  114  5505.6   .894  .097   .151  3.8
14.0  14.31  158.0   5.94  115.59  10.701  -9.922   1.6  1.00  1.00 1500     4    0   506.3  2.431  .000  2.368   .2
----------------------------------------------------------------------------------------------------------------------
16.0  16.34  150.0   8.41  104.80  12.004 -10.396   5.5  1.00  1.00 2620    19    0  1311.9  2.350  .000  2.072   .4
16.0  16.29  135.0  11.25   84.00  12.691  -8.974  13.7  1.00  1.00 3334   103    0  3059.2  2.175  .000  1.611   .9
16.0  16.22  120.0  14.10   69.98  12.934  -6.467  19.4  1.00  1.00 3661   213    0  4256.9  1.864  .206  1.046  1.2
16.0  16.12  100.0  18.08   52.41  13.830  -2.401  25.5  1.00  1.00 4580   400    0  5547.8  1.623  .119   .371  1.4
16.0  16.06   90.0  19.35   46.89  13.224    .000  28.4  1.00   .92 4181   483    0  6173.5  1.469  .121   .333  1.9
16.0  16.10   37.0  23.61   21.57   9.106   7.269  26.4  1.00   .59 1207   352  131  5798.1   .796  .098   .138  4.0
16.0  16.35  155.0   7.54  113.84  11.769 -10.667   3.2  1.00  1.00 2396     9    0   850.1  2.458  .000  2.323   .3
----------------------------------------------------------------------------------------------------------------------
18.0  18.38  150.0   9.57  107.50  13.040 -11.293   6.8  1.00  1.00 3559    20    0  1600.8  2.409  .000  2.147   .4
18.0  18.29  135.0  12.42   86.44  13.702  -9.689  16.5  1.00  1.00 4233   149    0  3641.6  2.183  .000  1.654   .8
18.0  18.16  120.0  15.05   72.63  13.574  -6.787  24.0  1.00  1.00 4331   348    0  5241.5  1.904  .229  1.239  1.4
18.0  18.06  100.0  19.40   53.49  14.681  -2.549  28.8  1.00   .99 5346   547    0  6228.9  1.609  .119   .367  1.5
18.0  17.98   90.0  20.97   48.69  13.840    .000  28.8   .96   .90 4721   529    0  6437.3  1.444  .120   .318  1.8
18.0  17.96   37.1  25.45   22.41   9.201   7.337  26.5   .94   .60 1280   379  147  6097.9   .816  .099   .152  4.1
18.0  18.39  154.0   8.86  114.95  12.790 -11.496   4.6  1.00  1.00 3329     9    0  1142.8  2.444  .000  2.352   .3
```

```
T1AVE: January Configuration

AMERICA'S CUP COURSE RACE TIMES (MINUTES)

   SAN DIEGO WAVES

WIND SPEED  WINDWARD    LEEWARD   135 REACH  100 REACH    TOTAL

     7.00    107.63      69.48      29.67      15.21     221.99

     8.00     99.48      61.53      26.30      14.42     201.73

     9.00     93.65      55.52      23.75      13.82     186.74

    10.00     89.42      51.06      22.08      13.29     175.85

    11.00     86.40      47.31      20.83      12.81     167.34

    12.00     84.20      44.48      19.88      12.37     160.93

    13.00     82.60      42.23      19.07      11.96     155.86

    14.00     81.44      40.52      18.34      11.57     151.87

    16.00     80.07      37.69      17.02      10.85     145.62

    18.00     79.32      34.97      15.76      10.22     140.27


Sail Data File is:  C:\AC\FM2B5.DAT
Spinnaker Data File is:  C:\AC\ACTBSFIX.DAT
d(DK/Q)=  .000000   DK/DKbase= 1.0000   d(QDF)=   .000000   QDF/QDFbase= 1.0000
```

```
Sail Data File is:  C:\AC\FK285.DAT
Spinnaker Data File is:  C:\AC\ACT8SFIX.DAT
d(DK/Q)=  .000000   DK/DKbase= 1.0000    d(QDF)=    .000000   QDF/QDFbase= 1.0000


TIAVE: January Configuration
 61.961    61.961    60.675    71.576    12.026    13.259      .000
  4.413   815.221    25.362      .000 59636.000 9372.000  9487.000
  1.180   106.625  3909.500      .000      .000     3.335    20.444
7603.700    8.868    28.000    11.942    61.155      .558      .524
   .543    15.056    .03188    1.0000

c11 =     .0007390        c22 =     .0004900
```