DATA COLLECTION AND ANALYSIS FOR THE 1987 *STARS & STRIPES* CAMPAIGN

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ABSTRACT

Data collection from full-scale 12-meter yachts was an important part of the project that led to the America's Cup challenger Stars & Stripes. A data system was developed around Ockam on-board instruments with a telemetry link to two DEC Microvax II computers, one aboard the tender and one on shore. Applications of the data obtained include validation and improvement of computer models and towing tank tests used in design; discrimination of performance differences associated with hull, keel and sail changes; and development of on-board computer systems to assist decision-making during races.

1. INTRODUCTION.

Sail America's 1987 challenge for the America's Cup was a team effort involving contributions from about 30 naval architects, engineers and scientists. The project encompassed development of new aerodynamic and hydrodynamic theory; collection and analysis of environmental data; analysis and computer modeling of many aspects of sailing yacht performance; towing tests of 32 one-third scale models; design and construction of four new 12-meter yachts and ten new keels; and instrumented sailing tests of these vessels.

The focus of this paper is on instrumented sailing tests. These played three basic roles in the overall program. First, they were used to validate, in both relative and absolute terms, the computer modeling and model testing that were at the core of the design process. Second, they were used for boat tuning and sail selection and trimming experiments, by measuring directly the differential performance of two boats. Third, they were the stage for developing on-board computer systems and data acquisition and analysis programs to be used during the actual defender eliminations and Cup races.

The Velocity Prediction Program (VPP) is the basic computer tool used to support most of the design decisions in either a new design or modification of an existing yacht. It is an attempt to represent the equilibrium of aerodynamic and hydrodynamic forces and moments which determines the speed of a yacht on a specified course. The computer can solve and optimize these equations with great numerical precision, but many of the force components are known today only in approximate or empirical terms. If the representation of one or more of the forces is erroneous, obviously the program can lead design in an erroneous direction. It is very important, then, to calibrate the tool by comparing its predictions with actual speed measurments. Areas in which it fails to provide realistic results can then be targeted for additional basic research; or at least empirical corrections can be developed which would extend the validity of the program.

In principle, a yacht equipped with a sensitive speedometer and compass, sailing in steady conditions, could optimize its tuning, trim and heading by reference to its instruments. Further, a change in the boat (e.g., a new keel) could in principle be evaluated by comparing optimized measured speeds before and after the change. In practice, the turbulent and ever-changing environment in which the yacht operates makes these comparisons very difficult. Two-boat testing is a practical alternative which can at present provide much sharper discrimination of differential performance changes. Proximity of the two boats cancels a considerable amount of the environmental variability. However, the two boats still experience somewhat different conditions, and they do interact to a degree. Recording continuous data during two-boat testing allows compensation for these effects during analysis of the test.

In a racing situation, data from instruments plays several important roles. Instrument readings and performance information derived from them can be directly applied to optimize sail selection, tuning, trim and heading. A comparison with past performance attained under similar conditions often can indicate room for improvement of tuning and trim. Instruments play a crucial role in navigation and in detection of wind shifts. In a protest hearing, data recorded from the boats is admitted as evidence, and is often crucial in reconstructing and analyzing the incidents in question. Accurate knowledge of differential speed against a competitor is important input to tactical considerations. A general calibration of speeds of various competitors provides useful strategic information for planning and preparing the boat for particular races. An onboard computer that processes information from the instruments and has in addition knowledge of the performance characteristics of the two boats, the aerodynamic and hydrodynamic interactions between them, weather patterns, the racing rules, and match racing strategy, has great potential for contributing to decision making throughout the race.

2. DATA SYSTEM.

In the Sail America program, data was gathered on each yacht from a variety of sensors, and managed by an Ockam Central Processing Unit (CPU) for both onboard display and data logging. The Ockam system is described in detail in Ref. [1]. All information on the Ockam bus was telemetered in real time to the tender BETSY ROSS, and received and managed there by a Digital Equipment Corporation Microvax 2 computer. This computer was dedicated primarily to logging the data on hard disk; its secondary function was to provide immediate summary reports which served to verify operation of the instruments, telemetry and logging system, and to indicate to the test manager whether the objectives of the test were achieved. Each day's data was transported by a backup tape to a second Microvax 2 onshore for analysis and archiving.

Transducers; calibration

Ockam wind instruments. The standard Ockam anemometer and windvane masthead units were employed. The anemometers were individually calibrated in a wind tunnel.

Boatspeed. Two Signet paddlewheel transducers were employed, symmetrically positioned port and starboard, approximately 1.5 ft from center and 2 ft forward of the keel leading edge. These were calibrated by pushing the yacht over a 1/2-mile measured course in sheltered water with an inflatable tender. When heeled, readings were taken from the lee-side paddlewheel and the weather one was ignored.

Heel was measured by the standard Ockam transducer, a damped pendulum sensed by a potentiometer. Rudder and tab angles were also sensed by Ockam transducers, mechanically operated potentiometers. These were calibrated in static bench tests.

Compass heading was sensed by SailComp digital compasses.

Ship Motions. A special ship motions package supplied by Offshore Technology Corp. contained two gyroscopes to sense heel and pitch angles, and six accelerometers (3 in the central unit, 3 at remote locations in the hull) to sense accelerations in all six axes. This microprocessor-based instrument was custom programmed to achieve frequency response and sampling rates suitable for the range of frequencies of interest, and was calibrated in static bench tests.

Range and bearing. Radar and laser ranging methods were tried experimentally, but the most practical instrument for distance was an optical stadimeter incorporating a linear encoder. The mast height of the other yacht was used as a known target length, with a geometric correction for heel. Attaching a digital hand bearing compass to the stadimeter unit gave simultaneous bearings.

Wave buoy. A Waverider sea profile buoy was utilized during part of the project to record wave heights in the vicinity of the boats. This should have been an important part of the ship-motions segment of the research. However, operational difficulties of deploying, locating and recovering the buoy, combined with large discrepancies between its nominal sensitivity and readings taken during calibration tests, discouraged its use so that in fact it never yielded any useful data.

Telemetry

The data stream from each boat is a 4800 baud RS232 channel consisting of ASCII characters (approximately 480 chars. per second). The coding of the data is specified in Ref. [1]. Encryption of the data was considered, but was never undertaken. (We felt in fact that we had enough trouble making sense of the data, even knowing all we did about the constitution and calibration of the transducers; if any competitors wanted to try intercepting and analyzing it, this would probably be a fine way for them to spend their time, from our point of view.) In addition to the data, the stream carries clock signals and calibration settings.

3. DATA ORGANIZATION.

Data on the daily backup tape is organized into 5 types of files:

.DMP (dump) contains a continuous record of telemetry throughout the day, for backup purposes. This file is not retained if other files are satisfactory. The backup protection is mainly against errors or faults in the data processing aboard the tender.

.LIS (list) contains a text facsimile of the test report, specifying configurations, conditions, and statistics for some variables.

.SUM (summary) contains the same information as .LIS, but organized to fit into an RS1 data base maintained in the onshore computer.

.HDR (header) contains information (e.g. environmental) pertaining to the test, common to both boats.

.RAW (raw) contains instrument readings for a single boat, for the duration of the test.

The day's data is broken into test periods of usually 5 to 10 minutes, decided by the test manager. During a test, everyone aboard is concentrating on getting the best performance possible out of the boat under the conditions prevailing. The test may be terminated if the wind changes significantly, one boat is found to be out of trim, or the boats become too close together or too far apart. Between tests are periods of typically 5 to 10 minutes during which tacks, jibes or sail changes may be made, and the boats are positioned relative to one another for the start of a new test.

Roughly 10 to 20 tests per day is a typical yield. The raw data files for a day thus total approximately 6 megabytes. With this flow of data to handle almost every day on 70 Mb. of fixed disk, efficient analysis programs and well-organized data bases and tape archives became a priority.

4. TWO-BOAT TESTING.

In a windward straight-line test we are attempting to measure the best VMG (speed made good to windward) for each boat under the prevailing wind and sea conditions. If the wind were steady and the instruments perfectly accurate, all we would have to do is ask the sailors to trim the boat to best VMG and read off VS, gamma and VT. The two boats would have to be positioned so they are not helping or hurting one another. Relative range and bearing between the two boats could be taken, but this would just yield redundant information.

In the real world, two things upset this simple picture. First, the wind and boatspeed instruments are not nearly accurate enough on an absolute basis to measure the small differences in speed and angle that we need to detect. For example, we are often trying to discern performance differences of, say, 3 seconds per mile, which, over the 11 windward miles of the America's Cup course, would produce a very significant advantage of about 33 seconds. However, in a 10-minute test the distance sailed to windward is about 1 mile; 3 seconds can be gained by 0.5% change in speed, or 0.4 degrees change in angle with respect to the true wind direction. These differences can hardly be measured with a speedometer calibrated to approximately plus or minus 0.1 kt (1.2%) or wind instruments that are rounded to the nearest degree. On the other hand, a difference of 30 feet in distance to windward is readily discernable, and measurable to plus or minus 10 feet with the stadimeter and bearing compass. Thus, range and bearing emerges as the primary discriminant.

Second, true wind speed and direction vary in space and time, so it is not trivial to relate changes of range and bearing to performance differences. One boat may have more wind velocity during part of the test, or wind shifts during the test may give it an advantage.

At the beginning of our experimental program the standard procedure for upwind tests was to establish a specific nominal true wind direction, and judge the performance of the boats on the basis of the component of distance traveled in this direction. Nominal true wind direction was chosen as the average wind direction during an initial portion of the test (e.g. the first 30 seconds). At the start and end of the test, the relative position vector between boats A and B would be projected on the nominal true wind direction, and the boat that had gained in this sense would be the winner. We learned that this procedure has several flaws:

(1) Maximizing this performance measure requires the boat to sail off its best VMG point (i.e., pinch or foot) whenever the wind varies from its nominal direction. Therefore we were not testing VMG.

(2) The strategy for maximizing this measure is not obvious to the sailors and probably not equally understood by them. It is different from normal windward sailing. Varying strategies introduce undesired variability in measured performance.

(3) If a nominal true wind direction is to be used this way, the initial wind is a poor choice; the average wind direction is the best choice in the sense of requiring the least squared deviation from the best VMG point. If true wind direction is sampled only at the beginning and end of the test, these two values should be averaged for the nominal true wind direction.

The following arguments are intended

to demonstrate the above points.

Without loss of generality, assume the nominal true wind is north. The boat's objective is to make as much northing as possible during the test, but tacking is prohibited. Figs. 4.1A and B show the port-tack polar with the wind veered and backed, respectively, from nominal and demonstrate that a strategy of pinching while headed and footing while lifted will maximize northing.

The required degree of pinching and footing depends on the detailed shape (curvature) of the polar, but in any case the deviation from the best-VMG heading will be directly proportional to the deviation of true wind angle from nominal, over a moderate range of true wind angles. Therefore, to minimize the integral squared deviation in heading, the nominal direction should be the mean true wind direction over the duration of the test.

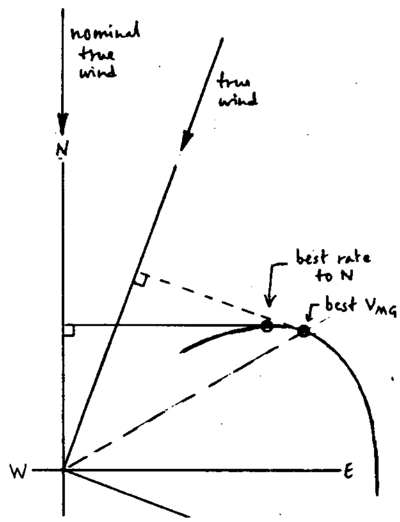
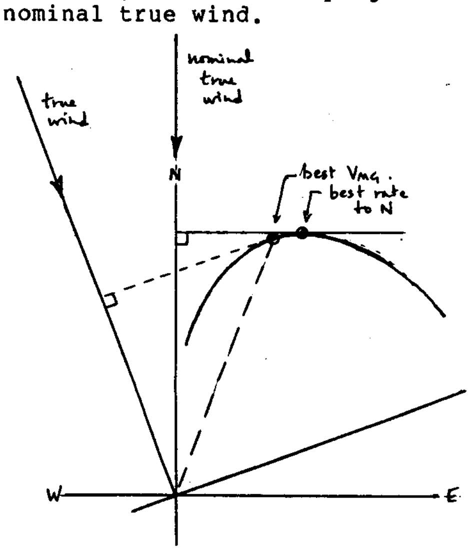


Figure 4.1A. In a header, the boat needs to pinch, to maximize progress against the nominal true wind.

Figure 4.1B. When freed, the boat needs to foot off, to maximize progress against the nominal true wind.



Alternative Measure: "Integrated VMG"

We propose that the objective of the upwind test should be

$$J = \int_0^T \vec{V} \cdot \hat{t} \, dt = \int_0^T V_S \cos\theta \, dt$$

where $\vec{V}$ is the boat velocity vector, $\hat{t}$ is the unit vector in the true wind direction, and θ is measured from the true wind direction at time t. Aside from some minor dynamic effects discussed below, we are asking that the sailors keep the boat operating at all times at the heading for maximum VMG in the current wind. This is a clearly defined task which they know how to do, or at least spend a lot of time trying to learn. We believe it is identical with correct strategy for upwind sailing, as long as you have decided to hold one tack.

We still don't have perfect instruments, so we have to relate this new performance measure to relative range and bearing. First, let's assume that range and bearing (vector $\vec{x}_{AB} = \vec{x}_A - \vec{x}_B$) are measured a number of times during the test, while true wind direction $\hat{t}$ is logged continuously. This should be a single consensus true wind, the average direction obtained at the two boats. Then the performance difference between A and B is

$$J_A - J_B = \int_0^T \vec{V}_A \cdot \hat{t} \, dt - \int_0^T \vec{V}_B \cdot \hat{t} \, dt =$$

$$= \int_0^T (\vec{V}_A - \vec{V}_B) \cdot \hat{t} \, dt = \int_0^T \frac{d}{dt} (\vec{x}_{AB}) \cdot \hat{t} \, dt$$

Now $\vec{x}_{AB}$ is a slowly changing quantity (because of the inertia of the boats). It should be perfectly safe to interpolate it linearly between observations. This makes the derivative in the last formula a step-function in time, so the last integral is very easy to evaluate.

Without automatic data logging, J is more trouble to obtain, but all that it requires is that true wind direction be manually logged as regularly as practicable during the test. In the worst case, where range and bearing are observed only at the beginning and end of the test, the most plausible assumption is that they varied linearly with time; the differential performance then reduces to

$$J_A - J_B = \Delta\vec{x}_{AB} \cdot \; (1/T) \int_0^T \hat{t} \, dt$$

that is, the change in relative position projected on the average true wind direction -- exactly what was identified as the "best" nominal-true-wind criterion in the previous section.

Dynamic Optimization

The above quasi-steady analysis overlooks some dynamic effects in the response of the boat in unsteady winds, and control of the boat's heading to maximize J. Using a boat model appropriate to light winds, and a wind varying in speed but not direction, Copps [2] finds an optimal feedback law for control of heading. This is very interesting work which we believe has considerable application in tacking and accelerating from any slowed condition, but we don't think it is very significant in upwind testing. The basic reason for this view is that boat speed is nearly constant in upwind testing, except in very light wind, so the dynamic effects (mass x acceleration) are small compared with the steady-state forces.

Downwind Testing

The same arguments apply to tacking downwind, and suggest J (integrated VMG) is again the appropriate measure. One bothersome difference downwind is that the optimum headings for two boats may well be widely different, so they would move apart relatively quickly and not share the same true wind.

Boat Positions, Interference

A lifting wing and its vortex wake induce flow velocities in the surrounding fluid, extending to infinity but dying away with distance except near the downstream wake. Another wing operating in this disturbed flowfield may have its drag increased or decreased, depending on its position. Prandtl provided a biplane theory for the mutual effects between two wings [3], which can yield a useful model for interference between two yachts. Prandtl gives numerical results only for the unstaggered case (a line joining the wing centers is perpendicular to the free stream) with elliptic load distributions, but he also derives the formula for staggered biplanes with general load distribution as a double integral. Table 1 and Figure 4.2 give results calculated for load distributions consisting of Glauert modes 1 and 3, with coefficients in the ratio 1:-1/3, over the whole double span of yacht and image. One simple result is clear: if the two wings have equal span and loading, their drags are equal only when they are unstaggered; with stagger, the wing that is forward has less drag.

Applying this to the upwind test, the two wings are the two yachts. As 12-meters they certainly have equal spans, and we assume they are trimmed to carry equal lift. Heel could be included but isn't so far. The wings are unstaggered when a line joining them is perpendicular

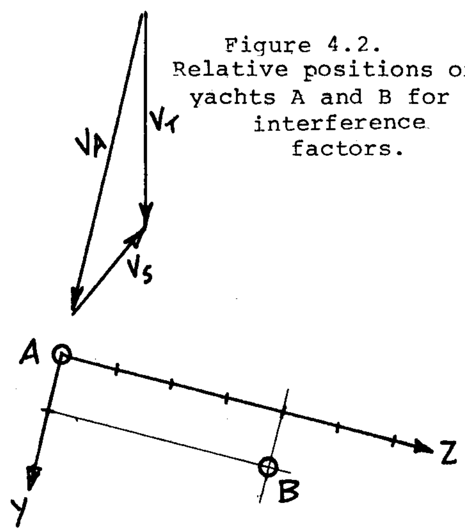


Figure 4.2.
Relative positions of yachts A and B for interference factors.

Table 1. Interference factors between two yachts.

Y = distance astern (lengths)

Z = distance to the side (lengths)

Y	Z = 1		Z = 2		Z = 3		Z = 4		Z = 5	
0	0.324	0.324	0.143	0.143	0.076	0.076	0.047	0.047	0.031	0.031
1	-0.068	0.717	0.024	0.261	0.030	0.123	0.025	0.069	0.019	0.043
2	-0.059	0.707	-0.015	0.300	0.003	0.149	0.009	0.084	0.010	0.053
3	-0.035	0.684	-0.019	0.304	-0.006	0.159	0.000	0.093	0.003	0.059
4	-0.022	0.671	-0.015	0.300	-0.008	0.161	-0.003	0.096	-0.000	0.062
5	-0.015	0.664	-0.012	0.297	-0.008	0.160	-0.005	0.098	-0.002	0.064

First column is relative change in A's induced drag.
Second column is relative change in B's induced drag.
(in each case, as the fraction of the induced drag for an isolated boat)

Example: As diagrammed, B is four lengths to the side (Z = 4) and one length astern (Y = 1). According to the table, A's aerodynamic induced drag will be 2.5% higher than an isolated boat, while B's will be 6.9% higher. (Induced drag is about 75% of total aerodynamic drag.)

to the apparent wind; this would be an even start according to the biplane theory. In an abreast starting position, the leeward boat is to the rear and so is being hurt. Once the test is underway, as either boat pulls ahead it gets more help and the boat behind gets hurt more. To some extent this situation acts as an amplifier of performance differences, which could provide a more sensitive discriminatory capability. The biplane theory can also be applied to correct this effect out of the test results.

5. TACKING TIME HISTORIES.

The comparison of measured speeds and sailing angles with computer predictions was not limited to steady-state VPP speeds, wind angles and heel angles. On the project's theoretical side, an important extension of the VPP concept was analysis of the dynamics of the tacking maneuver. Allowance for maneuvering penalties in race simulation would often lead to an entirely different ranking of candidate yachts than would result from straight-line performance alone. Full-scale measurements were used to guide the development of the tacking model, and to test and improve its representation of physical reality.

Figure 5.1 shows typical measured results. This test was in moderate winds of about 15 knots. The turn occupies approximately 30 seconds and shows maximum yaw rates of about 5 deg. per second. The speed holds up well during the first 10 degrees of the turn, then drops by slightly more than 1 knot in about 15 seconds. Reacceleration is gradual, and 33 seconds after the speed minimum, when the record ends, boatspeed is still about 0.2 kts. low. Sometimes the boat would bear away a few degrees beyond the steady-state course during the acceleration phase, but this record showing an almost monotonic approach to steady-state course is more typical.

Figure 5.2 shows time histories for a complete 10-minute upwind test including one tack, in lighter winds of about 9 kts.

6. DEAD RECKONING.

Forward integration of boat speed and heading produces a dead reckoning track for the boat. Leeway, of course, enters the calculation significantly. It is calculated using lift curve slope as measured in tank tests; the side force used in the calculation includes a sail force inferred from the heel angle, plus a centrifugal force term (mass times velocity times yaw rate). Leeway is then calculated using tank-test results for lift curve slope. Applications aside from navigation include visualizing test conditions during later analysis, and evidence for protest hearings.

7. ANALYSIS OF SAIL FORCES IN UNSTEADY TESTS.

The separated flow that prevails in downwind sail settings precludes analytical prediction of sail forces, and their dependence on such design variables as mainsail aspect ratio, spinnaker girth and pole length. Therefore we are dependent on empirical sail coefficients in constructing this portion of the VPP and evaluating sail alternatives. One past approach to obtaining such coefficients, e.g. [4], was to log boatspeed, heel angle, and apparent wind speed and angle at times when these variables seemed to be satisfactorily steady. Alternatively, the observed quantities can be averaged over some time period to reduce the variability, e.g. [5]. Then the known hydrodynamic and hydrostatic characteristics of the hull can be used to deduce the sail forces. Because of the fundamentally unsteady character of the natural wind, sufficiently steady conditions comprise only a small percentage of the time available for testing, and reliable results for sail coefficients have proven very difficult to obtain.

Having a continuous record of the pertinent variables allows inertial forces to be taken into account, so we are freed from the need to select rare periods when wind speed, boat speed, etc. are steady. Each test provides hundreds of redundant measurements of VPP boat constants such as sail thrust coefficients. Statistical methods are available for estimating these constants, with error bars.

The basic theory will be developed for the simplest case, straight downwind sailing. We assume that the sail force is proportional to the square of the apparent wind speed $V_A = V_T - V_S$, and that the resistance R is a function of boatspeed only, ignoring memory effects due to free surface waves. Then the equation of motion is

$$m' \, dV_S/dt = \tfrac{1}{2} \rho_a P_S \, (V_T - V_S)^2 - R(V_S) \tag{7.1}$$

where m' = apparent mass of hull for longitudinal motion

ρ_a = air density

P_S = parasite drag area of sails

m' can be obtained from potential flow calculations. For 12-meters of minimum displacement, m' is about 8% greater than the hull displacement. $R(V_S)$ can be inferred by scaling upright tank test data for the hull model.

Given a record of V_A and V_S vs. time, dV_S/dt can be approximated by numerical

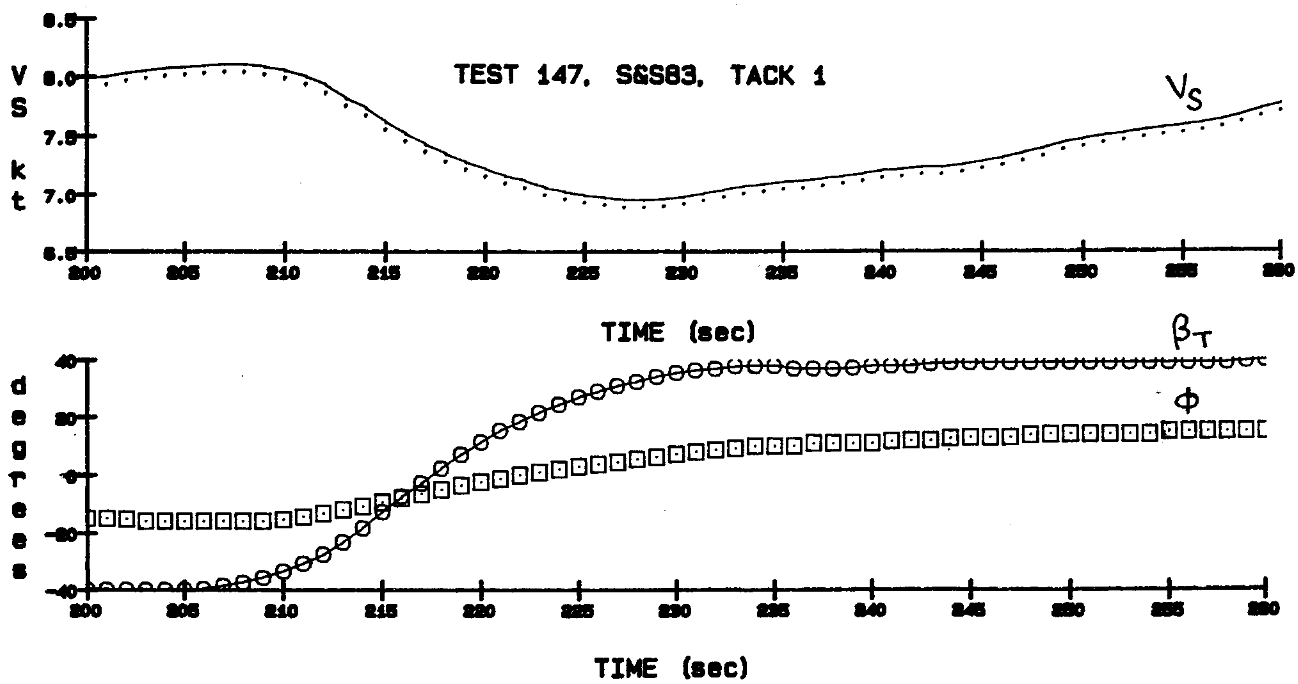
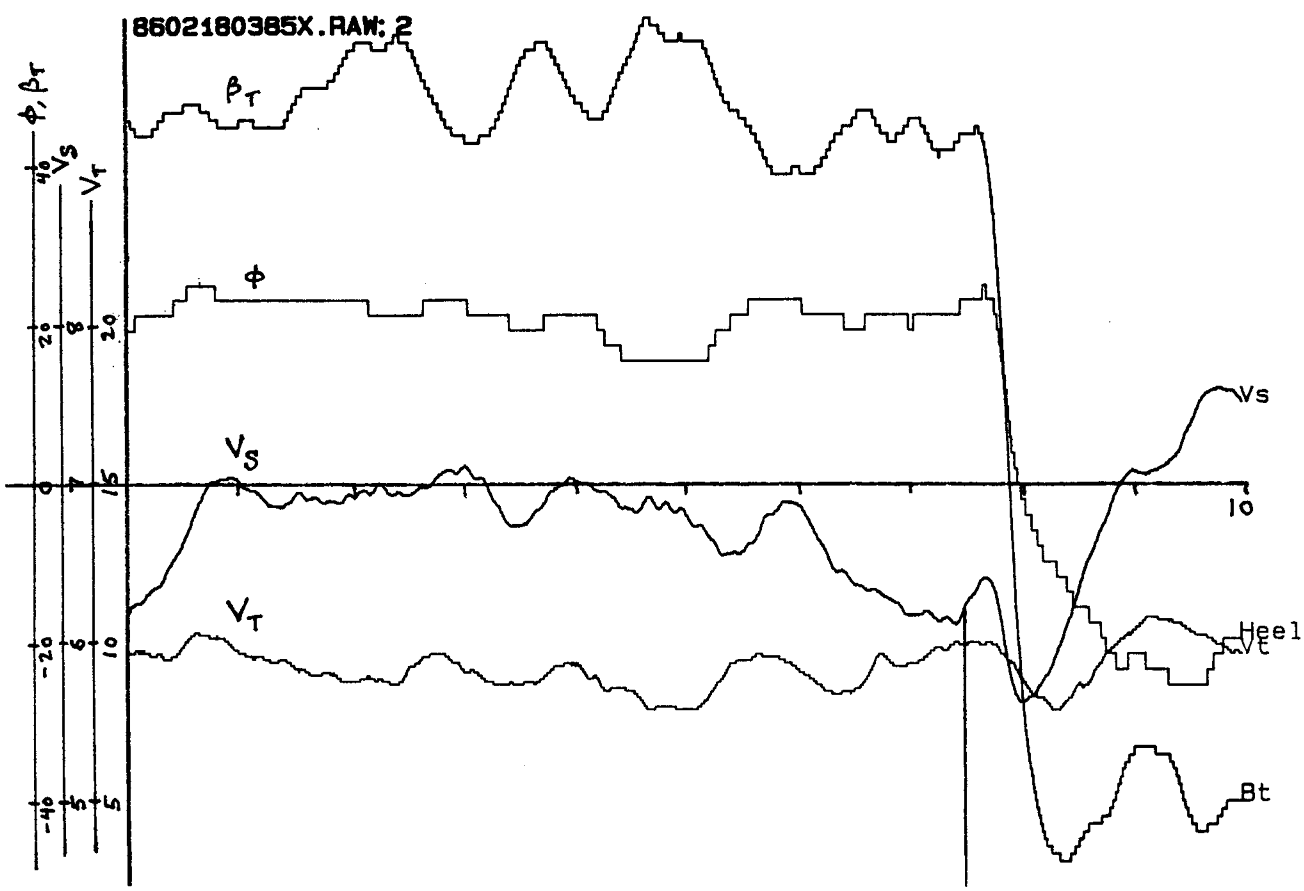


Figure 5.1 (above). Time histories for one tack in S&S-83.
(True wind approx. 15 knots.)

Figure 5.2 (below). Time histories for a full 10-minute upwind test
with one tack in Stars & Stripes '85. (True wind approx. 9 knots.)



differentiation; then every term in Eq. (7.1) is known, except P_S . Each observation thus provides a measurement of P_S ; the average of these provides the best estimate of P_S , and their standard deviation indicates error levels.

In reaching and downwind tacking, the situation is more complicated because of the presence of heeling force, side force and induced resistance. Nevertheless, the equations of motion can be written as two simultaneous equations with two (or more) unknown sail coefficients appearing in linear form. Each of the many observations provides one instance of the two equations; the whole set can then be "solved" in the least-squares sense as an overdetermined system.

8. TARGET POLARS.

The Ockam system has the capability to store polar families in EPROMs, representing boatspeed vs. true wind speed and true wind angle. The source of data for these chips can be either VPP projections, or empirical past observations of boat performance.

Initially, VPP polars would be supplied for a new boat. This would give the crew particular numbers to aim for, and a quick comparison between real speeds attained and the projected performance of the boat. When enough performance data had been logged and analyzed, empirical polars could be programmed, which would represent an improvement in accuracy over the VPP polars. These were useful for making a quick onboard comparison between past and current performance, revealing at some times a lapse in setting up and tuning the boat, and at other times malfunctions of the instruments. They also were of great value in orienting and training new helmsmen.

Programming ROMs with empirical performance data required curve fitting and smoothing. The function

$$V = [A\ V_T^{-4} + B\ V_T^{-2} + C]^{-1/4}$$

was found to represent well both VS and VMG's for both upwind and downwind cases. Note that for small VT, V is asymptotically proportional to VT; for large VT it is asymptotic to a constant. It has the advantage of being a simple quadratic curve when rewritten as

$$V^{-4} = A\ V_T^{-4} + B\ V_T^{-2} + C$$

An example of fitting performance data for S&S-83 is given in Fig. 8.1.

ACKNOWLEDGMENTS. The entire Sail America team was behind the data collection effort. Special appreciation is due Test Manager Robert Hopkins, who daily balanced the requirements of quantitative testing with those of boat preparation and crew training; Dave Hammond and Rex Dewell, who installed and maintained the instruments, telemetry and on-board computer systems; and Lee Davis and Hanne Kooy of Galson Technical Services, who helped design the data logging and archiving system. We are particularly grateful to Digital Equipment Corp. for the donation of two Microvax computers. The support of Science Applications International Corporation, Ship Hydrodynamics Division, is acknowledged with thanks.

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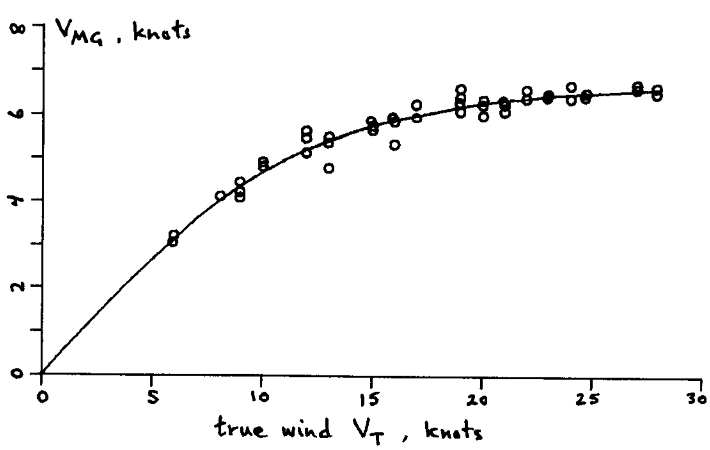

Figure 8.1. Curve fitting to some upwind VMG's.