World Leader in Rating Technology

OFFSHORE RACING CONGRESS

ORC VPP Documentation 2011

1 Background.

The following document describes the methods and formulations used by the Offshore Racing Congress (ORC) Velocity Prediction Program (VPP).
The ORC VPP is the program used to calculate racing yacht handicaps based on a mathematical model of the physical processes embodied in a sailing yacht. This approach to handicapping was first developed in 1978. The H. Irving Pratt Ocean Racing Handicapping project created a handicap system which used a mathematical model of hull and rig performance to predict sailing speeds and thereby produce a time on distance handicap system. This computational approach to yacht handicapping was of course only made possible by the advent of desktop computing capability.
The first 2 papers describing the project were presented to the Chesapeake Sailing Yacht Symposium (CSYS) in 1979.[1] This work resulted in the MHS system that was used in the United States. The aerodynamic model was subsequently revised by George Hazen[2] and the hydrodynamic model was refined over time as the Delft Systematic Yacht Hull Series was expanded[3].
Other research was documented in subsequent CSYS proceedings: sail formulations (2001[4] and 2003[5]), and hull shape effects (2003[6]). Papers describing research have also been published in the HISWA symposia on sail research (2008[7]).
In 1986 the current formulations of the IMS were documented by Charlie Poor[8], and this was updated in 1999[9]. The 1999 CSYS paper was used a basis for this document, with members of the ITC contributing the fruits of their labours over the last 10 years as the ORC carried forward the work of maintaining an up-to-date handicapping system that is based on the physics of a sailing yacht.

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[1] "A summary of the H. Irving Pratt Ocean race Handicapping Project". (Kerwin, J.E, & Newman, J.N.) "The Measurement Handicapping System of USYRU" (Stromhmeier, D.D)
[2] Hazen, G., "A Model of Sail Aerodynamics for Diverse Rig Types," New England Sailing Yacht Symposium. New London, CT, 1980.
[3] 1993, CSYS The Delft Systematic Yacht Hull (Series II) Experiments. Gerritsma, Prof. ir. J., Keuning, Ir. J., and Onnink, A. R.
[4] Aerodynamic Performance of Offwind Sails Attached to Sprits. Robert Ranzenbach and Jim Teeters
[5] Changes to Sail Aerodynamics in the IMS Rule Jim Teeters, Robert Ranzenbach and Martyn Prince
[6] Aerodynamic Performance of Offwind Sails Attached to Sprits. Robert Ranzenbach and Jim Teeters
[7] Fossati F., Claughton A., Battistin D., Muggiasca S.: "Changes and Development to Sail Aerodynamics in the ORC International Rule" – 20th HISWA Symposium, Amsterdam, 2008
[8] "The IMS, a description of the new international rating system" Washington DC 1986
[9] Claughton, A., "Developments in the IMS VPP Formulations," SNAME 14th CSYS, Annapolis, MD, 1999.

1.1 Contents.

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2 Introduction

2.1 Scope

The following document is a companion to the ORC Rating Rules and IMS (International Measurement System). The document provides a summary of the physics and computational processes that lie behind the calculation of sailing speeds and corresponding time allowances (seconds/mile).

The current ORC handicap system comprises 3 separate elements:

1) The IMS **measurement procedure** whereby the physical shape of the hull and appendages are defined, along with dimensions of mast, sails, etc.
2) A **performance prediction** procedure based on (1) a lines processing procedure which determines the parametric inputs used by the Velocity Prediction Program (VPP) to predict sailing speed on different points of sailing, in different wind speeds with different sails set.
3) A **race management system** whereby the results of (2) are applied to offer condition-specific race handicapping.

This document describes the methodology of the equations used to calculate the forces produced by the hull, appendages, and sails, and how these are combined in the VPP.

2.2 Overview

Predicting the speed of a sailing yacht from its physical dimensions alone is a complex task, particularly when constrained by the need to do it in the “general case” using software that is robust enough to be run routinely by rating offices throughout the world. Nevertheless this is what the ORC Rating system aims to do. The only absolute record of the VPP (and companion Lines Processing Program (LPP)) is the FORTRAN source code, so it is a difficult matter for a layman to determine either the intent or underlying methodology by inspection of this code. The purpose of this document is to describe the physical basis of the methods used to predict the forces on a sailing yacht rig and hull, and to define the formulations (equations) used by the VPP to encapsulate the physical model.

In order to do this the document has been set out to first layout the broadest view of the process, gradually breaking the problem down into its constituent parts, so that ultimately the underlying equations of the VPP can be presented.

2.3 Layout

The document is arranged in 6 sections:

- **Section 3** describes the methods by which the velocity prediction is carried out and the fundamental force balances inherent in solving the problem are laid out. Following this an overview of the “boat model” is presented, whereby the elements of the aerodynamic and hydrodynamic model are described.
- **Section 4** describes how the hull shape parameters are pre-processed to determine the parameters that are used in the hydrodynamic force model described in Section 8.
- **Section 5** describes how the yacht’s environment is characterized in terms of the incident wind field experienced by the sails.
- **Section 6** describes how the VPP results are presented as a rating certificate.
- **Section 7** describes the methods used to predict the aerodynamic forces produced by the mast, sails, and above-water part of the hull.
- **Section 8** describes how the hydrodynamic drag and lift of the hull and appendages are calculated.

3 VPP Methodology

The VPP has a two-part structure comprised of the **solution algorithm** and the **boat model.** The solution algorithm must find an equilibrium condition for each point of sailing where:

a) the driving force from the sails matches the hull and aerodynamic drag, and

b) the heeling moment from the rig is matched by the righting moment from the hull.

i.e. balance the seesaw in Figure 1[10],and optimize the sail controls (reef and flat) to produce the maximum speed at each true wind angle.

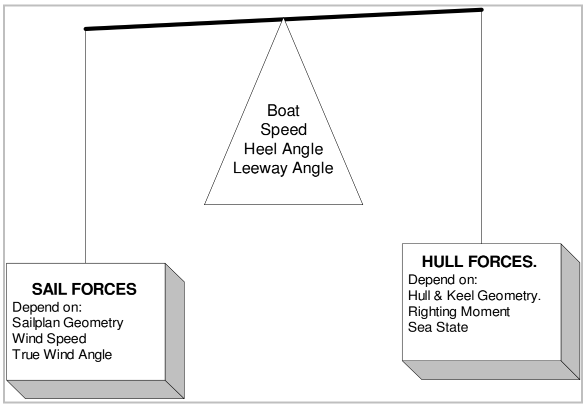

Figure 1. Force Balance See-saw

3.1 Solution Method

The VPP determines the steady state conditions by satisfying 2 equilibrium equations:
Firstly the net force along the yacht's track (its direction of motion) must be zero,
(i.e. Driving Force – Drag = 0)
Secondly the aerodynamic heeling moment produced by the mast & sails must be equal and opposite to the righting moment produced by the hull and crew.
(i.e. Heeling Moment – Righting Moment = 0)

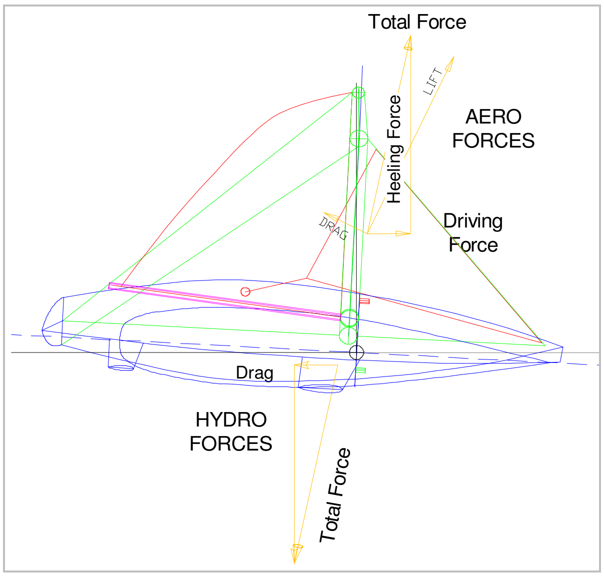

Figure 2. Force balance in the plane of the water surface

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[10] Milgram 1993

Figure 2 shows a yacht sailing on starboard tack. In order for the yacht to hold a steady course the magnitude and line of action of the aerodynamic and hydrodynamic forces must be the same. The VPP adopts an iterative procedure at each true wind speed and angle to find “equilibrium” sailing conditions, defined by unique values of boat speed (V_s), heel angle (ϕ), and the sail trim parameters (*reef, flat)* where;

1) Thrust (driving force) from the sails equals the hydrodynamic drag.
2) the heeling moment produced by the couple between the aerodynamic and hydrodynamic Heeling Force equals the hull righting moment, as shown in Figure 3.

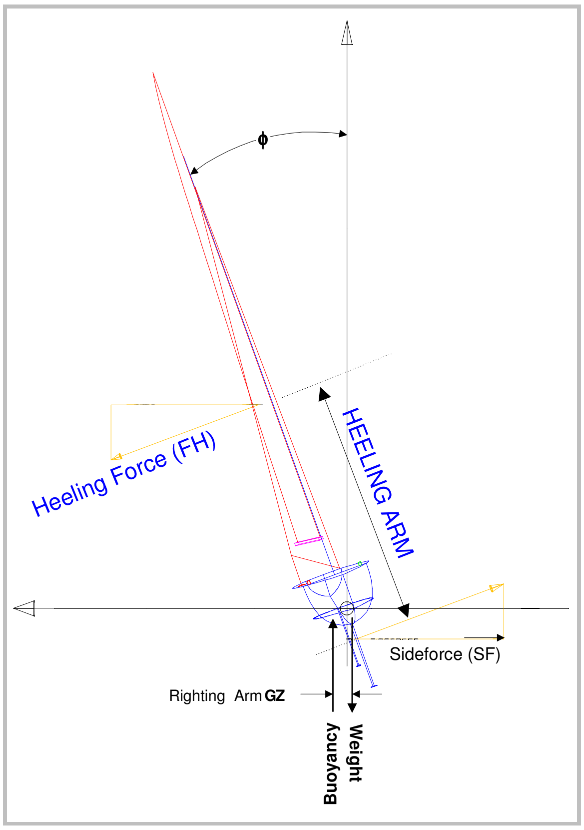

Figure 3. Roll Moment Equilibrium

It should be noted that the VPP solves only for a balance of force and moment about the track axis. The yaw moment balance is ignored so that sail trimming options, or speed and heel values that produce excessive yaw moments, are not reflected in terms of their influence on speed.

3.2 Boat Model

The boat model may be thought of as a black box into which boat speed, heel angle, and the sail trim parameters, reef and flat are input.

The output is simply four numbers:

- the aerodynamic driving force,
- the heeling moment from the above water part of the hull and rig,
- the drag of the hull keel and rudder and,
- the righting moment from the hull and crew.

The solution algorithm iterates to a solution by interrogating the boat model with each new guess of the input values until a set of conditions is found that produces a match of thrust and drag and heeling moment and righting moment. The solution algorithm also seeks to find the highest speed on each point of sailing by adjusting the sail trim parameters for optimum performance.

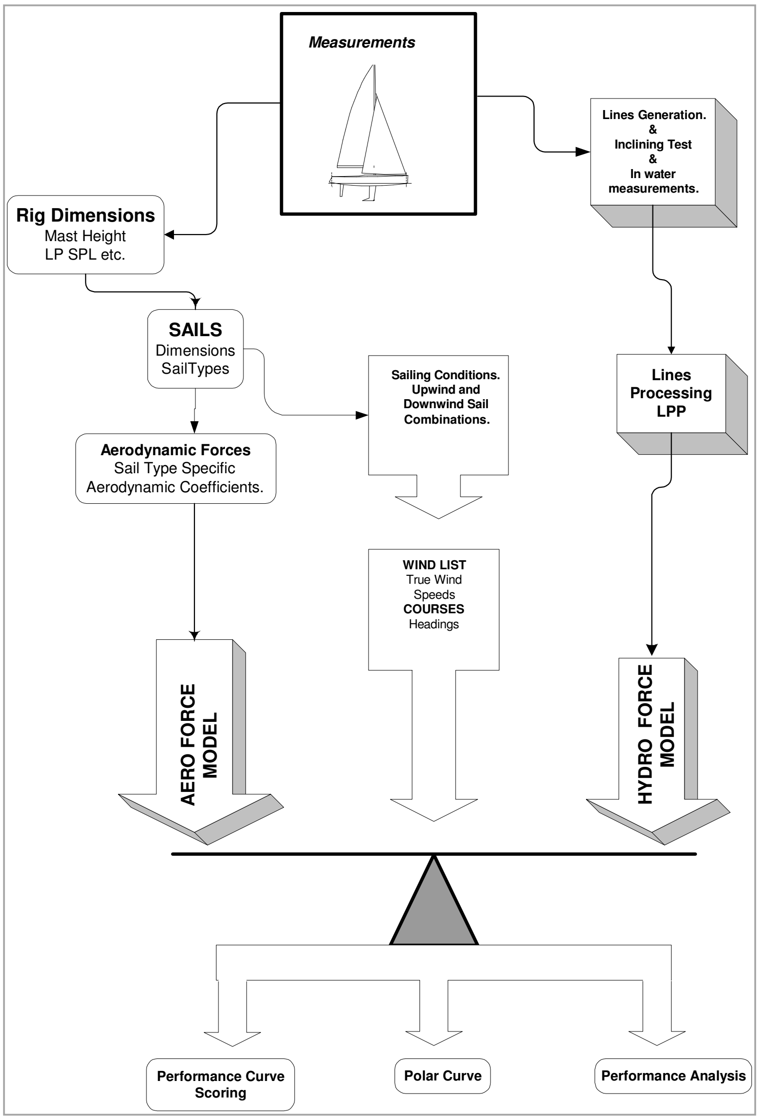

Figure 4. Schematic of ORC VPP

Figure 4 shows how the boat model is divided into two parts:

- **Aerodynamic Force Model**

For a given wind and boat model variable set (true wind speed (V_T), true wind angle (β_T), V_s, ϕ, *reef, flat*), determine the apparent wind angle and speed that the sails 'see' and predict the aerodynamic lift and drag they produce.
The aerodynamic forces are resolved into a thrust and heeling force.

- **Hydrodynamic Force Model**

Predicts the resistance (drag) and righting moment the hull produces for the assumed speed and heel angle, given that the hydrodynamic side force will equal the previously calculated aerodynamic heeling force.

3.2.1 Functional relationships:

Figure 5 shows the functional relationships that make up the elements of the VPP boat model.
In order to minimize amount of computational operations within the main iterative VPP loop the Rig Analysis and the Lines Processing parts are carried out before the computations of a steady state solution begin.

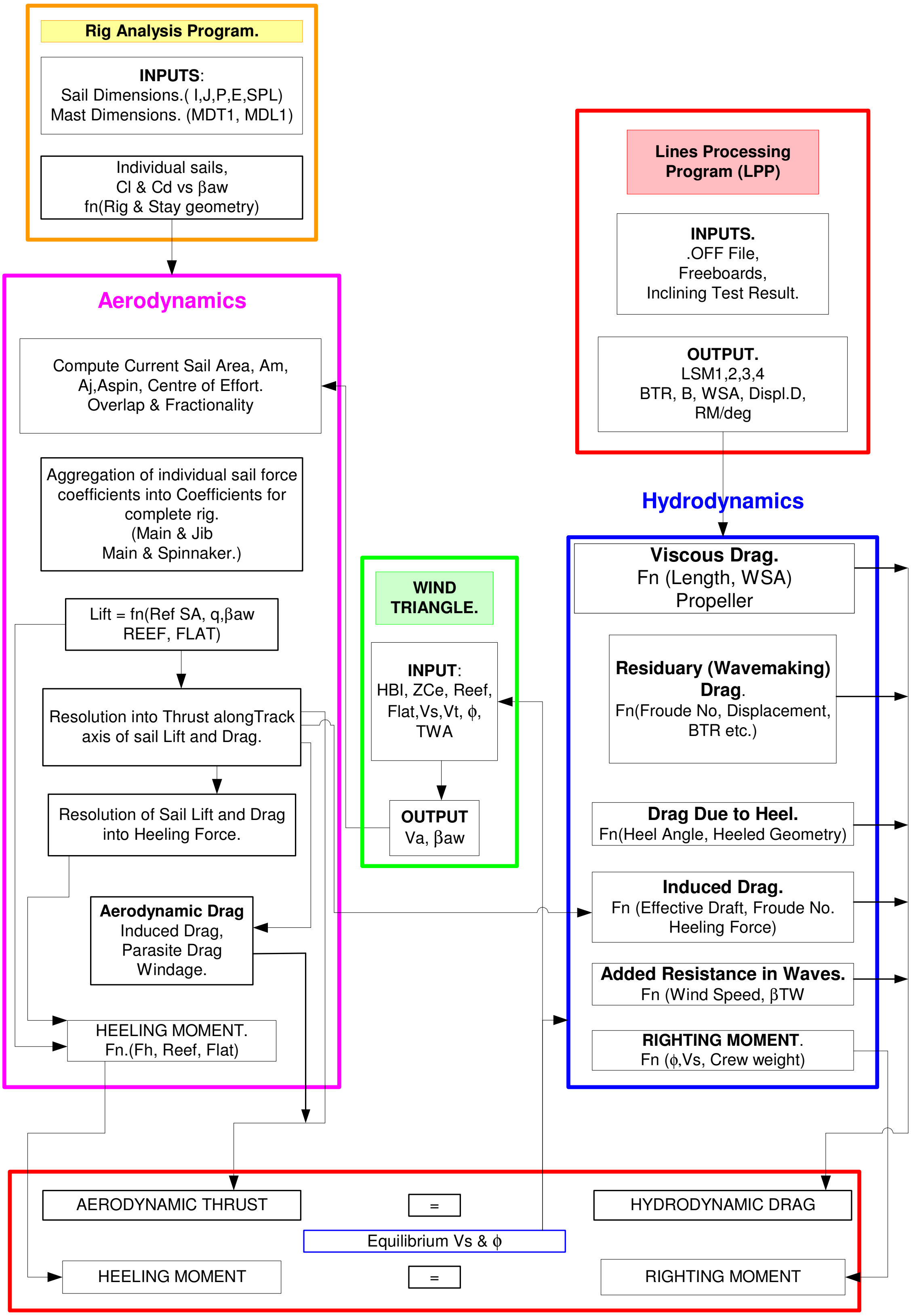

Figure 5. Functional Relationships in the VPP Boat Model

3.2.1.1 Rig Analysis Program

The Rig Analysis Program takes the measured sail and rig dimensions and calculates the areas and centres of effort for the mainsail, jib and spinnaker. Originally the Rig Analysis Program used the force coefficients for each individual sail to calculate a "collective" set of aerodynamic force coefficients for the rig in an upwind and downwind configuration. This collective table of lift and drag coefficients at each apparent wind angle is interrogated by the solution algorithm during each iteration as the program works towards an equilibrium sailing condition.
More recently[11] for the upwind sailing configurations the calculation of the "collective" sail force coefficients was moved inside the VPP optimization loop so that a more realistic model of sail heeling force reduction could be used.

3.2.1.2 Lines Processing Program (LPP)

The lines Processing program takes the measured hull shape, expressed as an offset file[12], and calculates the hull dimensions and coefficients that are used to calculate hull drag. The LPP also takes the inclining test results and uses this to determine the yachts stability in sailing trim.

Once these elements have been completed the iterative part of the VPP is started. At each wind speed and true wind angle the process starts with an initial guess at speed and heel angle, given this the wind triangle can calculate the apparent wind speed and angle for the aerodynamic model. With this information the total aerodynamic force can be calculated, based on the "collective" aerodynamic coefficients. The total aerodynamic force is resolved into the thrust and heeling force (See Figure 2).

Using the same initial guess for speed and heel angle, plus the calculated heeling force from the aerodynamic force model, the hydrodynamic model can calculate the total hull drag.

The available thrust and the drag can now be compared and a revised estimate of speed can be made, so the heeling moment and righting moment are compared to provide a revised value for heel angle. This process is repeated until speed and heel angle have converged to a steady value. The process is then repeated for a matrix of true wind angles and wind speeds.

The solution routine also includes an optimization element that ensures the sail trim parameters (reef and flat) are chosen to produce the highest speed on each point of sailing. The same routine is used to ensure that the VPP calculates an optimum up-wind and down-wind VMG for each true wind speed.

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[11] 2009
[12] .OFF File, a simple txt file of transverse (y) and vertical (z) coordinates of the hull surface at a fixed longitudinal (x) position.

3.3 Equations of Equilibrium

In order to produce a steady state sailing condition the VPP must solve the 2 equilibrium equations matching available driving force to drag, and the heeling moment to the hull righting moment. The accuracy of the VPP prediction is entirely reliant on the accuracy with which these 4 elements can be calculated from parametric data gathered during the measurement process

3.3.1 Driving Force – Drag

This is the basic equation for longitudinal force equilibrium, with the net force along the boat's track being zero:

$$FRA - FRW = 0 \quad [1]$$

where:

FRA = Total Aerodynamic Thrust.

FRW = Total Resistance.

The total resistance is treated as the sum of 5 separate components, shown in equation 2. In reality these divisions are not physically clear-cut, but the approach is adopted to make the problem tractable using a parametric description of the hull and its appendages.

$$FRW = D_{Viscous} + D_{Residuary} + D_{Heel} + D_{Induced} + D_{Raw} \quad [2]$$

where:

$D_{Viscous}$ = Drag due to the friction of the water flowing over the surface of the hull and appendages, and the propeller if one is fitted.

$D_{Residuary}$ = Residuary Drag, drag due to the creation of surface waves.

D_{Heel} = Drag due to the change in wetted surface and immersed hull shape as the yacht adopts an angle of heel.

$D_{Induced}$ = Induced Drag created when the hull keel and rudder produce sideforce

D_{Raw} = Drag due to the yachts motion in a seaway.

The aerodynamic driving force is the Aerodynamic driving force less the windage drag of the above-water boat components.

$$FRA = FRA_{b4windage} - FRA_{hull} - FRA_{mast} - FRA_{rigging} - FRA_{crew} \quad [3]$$

where:

$FRA_{b4windage}$ = Aerodynamic driving force

FRA_{hull} = Hull windage drag

FRA_{mast} = Mast windage drag

$FRA_{rigging}$ = Rigging wire drag

FRA_{crew} = crew windage drag

3.3.2 Heeling Moment – Rolling Moment

The aerodynamic heeling moment produced by the mast and sails must be equal and opposite to the righting moment produced by the hull and crew.

$$HM_{TOTAL} = RM_{TOTAL} \quad [4]$$

$$HM_{TOTAL} = HMA + RM4 \times FHA \quad [5]$$

$$HMA = HMA_{B4windage} + HMA_{hull} + HMA_{mast} + HMA_{rigging\_wire} + HMA_{crew} \quad [6]$$

Where:

HM_{TOTAL} = *Total heeling moment*
RM_{TOTAL} = *Total righting moment*
HMA = *Aerodynamic heeling moment about the waterplane*
$RM4$ = *Vertical CLR, below waterplane*
FHA = *Total aerodynamic heeling force*
(equal to hydrodynamic force normal to the yachts centre plane)
$HMA_{B4windage}$ = *aerodynamic heeling moment from sails*
HMA_{hull} = *Hull windage heeling moment*
HMA_{mast} = *Mast windage heeling moment*
$HMA_{rigging\ wire}$ = *Rigging wire heeling moment*
HMA_{crew} = *crew windage heeling moment*

FHA is the total aerodynamic heeling force.

$$FHA = FHA_{B4windage} + FHA_{hull} + FHA_{mast} + FHA_{rigging\_wire} + FHA_{crew} \quad [7]$$

where:

$FHA_{B4windage}$ = *aerodynamic heeling force from sails*
FHA_{hull} = *Hull windage heeling force*
FHA_{mast} = *Mast windage heeling force*
$FHA_{rigging\_wire}$ = *Rigging wire heeling force*
FHA_{crew} = *crew windage heeling force*

RM_{tot} is the total net righting moment available from the hull and crew sitting off centreline.

$$RMtot = RM\phi - RMV + RMaug \quad [8]$$

Where:

$RM\phi$ = *Hydrostatic Righting Moment*
RMV = *stability loss due to forward speed*
RM_{aug} = *Righting moment augmentation due to shifting crew*

3.4 Water Ballast and Canting Keel Yachts

The following section describes the VPP run sequences for yachts with moveable ballast and retractable dagger boards or bilgeboards.

3.4.1 Canting Keel

Two VPP runs are made and the best speed achieved on each point of sailing is used to calculate the handicap.

- First VPP run with canting keel on Centre Line (CL) without adding any Righting Moment increase (MHSD computed with the keel on CL)
- Second VPP run with canting keel fully canted adding Righting Moment increase (MHSD computed from the maximum of the two rudders and canted keel.)

3.4.2 Daggerboard (Centreline lifting appendage)

The daggerboard is input to the .DAT file with a special code to identify it as such.
Two VPP runs are made and the best speed achieved on each point of sailing is used to calculate the handicap.

- First VPP with the dagger board up. If the yacht has a canting keel this VPP run is done with the keel on centre line.
- Second VPP run with the dagger board down, viscous drag calculated as if it were a conventional fin keel. If the yacht has a canting keel this run is done with the keel at full cant angle. (MHSD is computed with maximum depth based on the keel canted, dagger board down and aft rudder)

3.4.3 Bilge boards (lifting boards off centreline)

Bilge boards are added to the .DAT file with special code for bilge board (angle and lateral position input also). Two VPP runs are made and the best speed achieved on each point of sailing is used to calculate the handicap.

- First VPP run with the bilge board up.
  If the yacht has a canting keel this VPP run is done with the keel on centre line.
- Second VPP run with the leeward bilge board down, viscous drag calculated as if it were a conventional fin keel. If the yacht has a canting keel this run is done with the keel at full cant angle. (MHSD computed with maximum depth between keel canted, fwd leeward bilge board down and aft rudder)

3.4.4 Water ballast

Two VPP runs are executed, with and without water ballast, the fastest speed is used for handicapping.
When water ballast volume is input directly, the following values are assumed:

$$\text{water ballast VCG} = 0.50 \times \text{freeboard\_aft}$$
$$\text{Water ballast LCG} = 0.70 \times \text{LOA}$$
$$\text{Water ballast Moment arm} = 0.90 \times \text{crew\_arm}$$

3.4.5 Measurement

Dimensions and locations of dagger boards, bilge boards, forward rudders, etc. can now be added to the .DAT files rather than by direct measurement of their offsets with the wand or laser scanner.
For water ballast yachts the volume and location of the water ballast may be edited into the .DAT file instead of by direct measurement.

3.5 Dynamic Allowance (DA)

Dynamic Allowance is an adjustment which may be applied to velocity predictions (i.e., time allowances) to account for relative performance degradation in unsteady states (e.g., while tacking) not otherwise accounted for in the VPP performance prediction model. DA is a percentage credit calculated on the basis of six design variables deemed to be relevant in assessing the performance degradation and is applied (or not applied) as explained below.
Even where applied, the result of the calculated credit may be zero. The design variables considered are described in section 3.5.1 below. Where applied, the calculated amount of credit will vary with point of sail and wind velocity.
These credits are therefore applied individually to each respective time allowance cell in the large table on the Rating Certificate (see Table 16) entitled, "Time Allowances." The credit is also automatically carried forward into the “Selected Courses” time allowances table, because these course time allowances are comprised of the appropriate proportions of various time allowances from the larger table. Likewise, any credit is carried forward into the General Purpose Handicap (GPH) and the "Simplified Scoring Options." The single value for DA which is actually displayed on the Certificate is that which was applied to GPH and is shown only to give a comparative reference to the average DA applied for the yacht.
For yachts of Cruiser/Racer Division which comply with IMS Appendix 1, the DA percentage credits are always fully applied to the time allowances. For other yachts, no DA is applied for the first three

years of age (as defined in 2 below). Thereafter, DA is applied incrementally with only 20% of the full calculated DA being applied in the forth year and a further 20% in each of the following years until full DA is applied in the eighth year. The various credits are derived from a statistical study of a fleet of Cruiser/Racers and Racers, based on IMS L to take into account a scaling factor. For each parametric ratio, an area in the Cartesian plane (Ratio/L) is fixed, limited by two boundary lines which represent a statistical approximation of the Cruiser/Racers and the Racers respectively. For a given "L", a difference is calculated as the distance between the boundary limits. The individual contribution of each parameter for the given yacht will be the ratio of the distance between the individual yacht's parameters relative to the Racer boundary line and the previously computed distance between the boundaries, with a cap value for each of the parameters.

3.5.1 Credits

The credits are then calculated as follows:

$$\mathrm{Credit} = \mathrm{MaxCredit} \times (\mathrm{Racer\_Slope} \times \mathrm{L} + \mathrm{Racer\_intcpt} - \mathrm{RATIO}) / \{(\mathrm{Racer\_Slope} - \mathrm{Cruiser\_Slope}) \times \mathrm{L} + (\mathrm{Racer\_intcpt} - \mathrm{Cruiser\_Intcpt})\}$$

Where:

RATIO	racer_slope	racer_intcpt	cruiser_slope	Cruiser_intcpt	MAXIMUM CREDIT
btgsa/vol	0.5411	15.4028	0.3289	11.1019	1.15%
runsa/vol	1.1019	32.9297	0.727	25.093	0.30%
btgsa/ws	0.0636	2.4976	0.0294	2.38	1.50%
runsa/ws	0.1024	4.1816	0.059	3.924	0.30%
L/vol	0.0654	4.616	0.055	3.985	0.35%
d/l	-0.0028	0.21	-0.0045	0.198	1.50%

3.5.1.1 *Beating credit*

Applied full strength to VMG Upwind, then linearly decreased to zero at 70° True Wind Angle (TWA), varied with True Wind Speed (TWS) as follows:

$$Beating\_Credit = (btgsa / Wetted\ Area\ Credit) \times (20 - TWS) / (20\ \ 6) + (BSA / Volume\ Credit) \times (TWS / 20)$$

btgsa/Wetted Area Credit is caclulated with complete Sail Area (mansail + genoa), BSA/ Volume Credit is calculated with Sail Area = Mainsail + foretriangle

3.5.1.2 *Running credit*

Applied full strength VMG Downwind, then linearly decreased to zero at 90° TWA, varied with TWS as follows:

$$\mathrm{Running\_Credit} = (runsa / \mathrm{Wetted\ Area\ Credit}) \times (20 - \mathrm{TWS}) / (20\ \ 6) + (\mathrm{DSA / Volume\ Credit}) \times (\mathrm{TWS} / 20).$$

3.5.1.3 *Length/Volume ratio*

Applied full strength to all TWA and TWS

3.5.1.4 *Draft / Length ratio*

Applied full strength VMG Upwind, then linearly decreased to zero at 70° TWA.

3.5.2 Calculation Procedure

1) Compute the table of polar speeds and GPH without any credit (like all racing boats)

2) Compute DA credits for each true wind speed and wind angle to obtain a matrix with the same row and columns as the table of speeds.
3) Divide any polar speed of the table by corresponding computed credit and re-calculate the new GPH. To compute the DA value (that is printed on certificate only as reference) the ratio between new and the original GPH is used.

The typical distribution of DA over True wind speed and angle is shown in Figure 6.

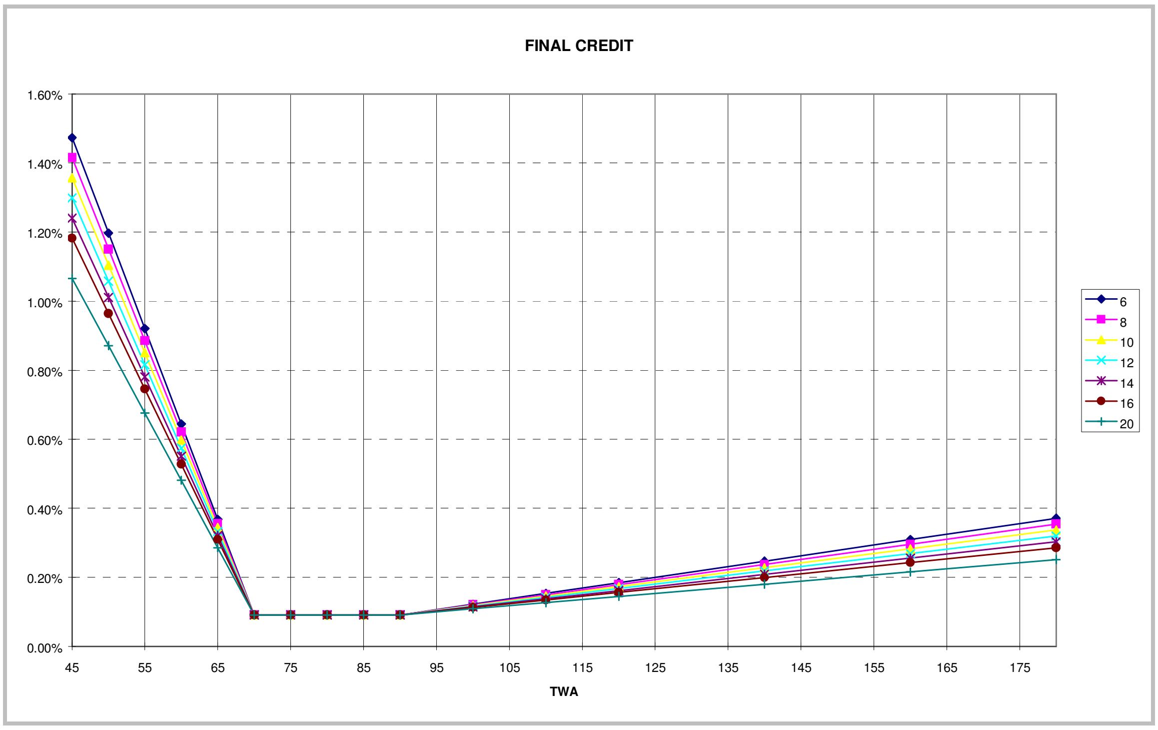

Figure 6. DA Credit vs. True wind angle

4 Lines Processing Program

The LPP is a companion program to the VPP which processes the measurements taken from the hull and appendages into an Offset (.OFF) file and uses this point by point geometric definition to calculate integrated physical quantities that the boat model can use to perform its calculations. The LPP uses the hull shape defined by the offset file and the results of the inclining test to determine the righting moment at each heel angle.

The LPP uses a definition of hull and appendage shape derived from physical measurement of the hull. The measurement of the hull (wanding) is carried out at pre-determined transverse stations according to the measurement instructions. A typical offset file is shown in figure 7. The format of the .OFF file is described in Appendix A.

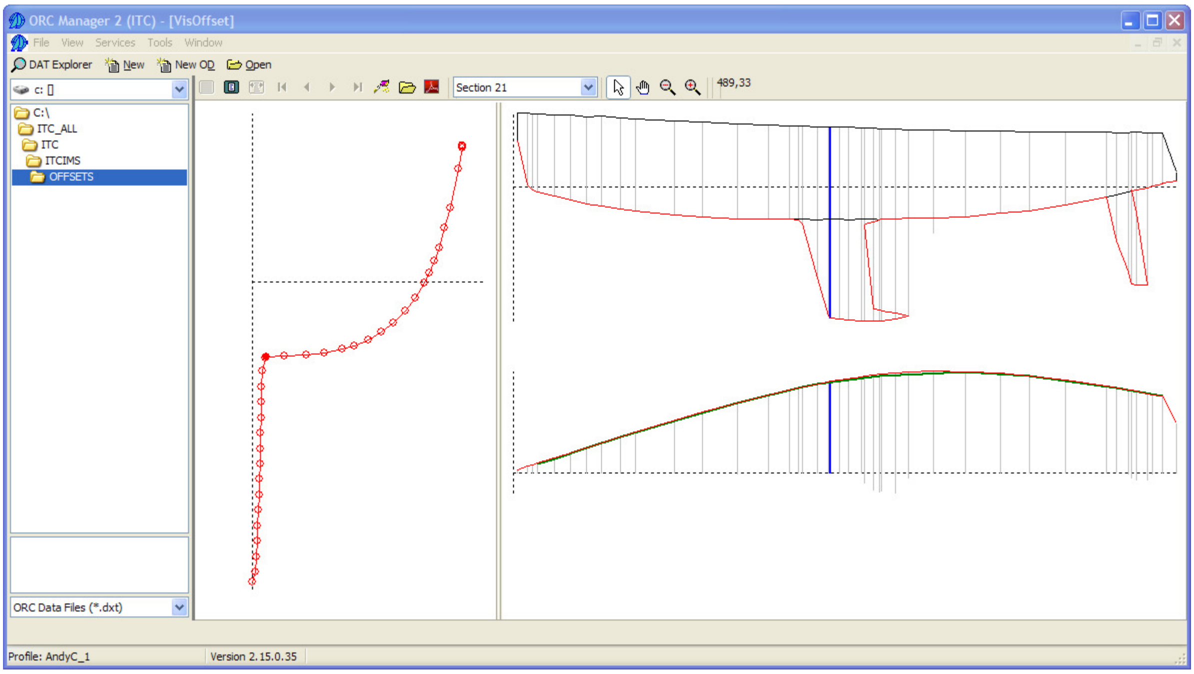

Figure 7. Offset file station distribution and typical section

4.1 Hydrostatics

As part of the afloat measurements an inclining test is carried out and the freeboards in "measurement trim" are determined. The first task of the LPP is calculate a righting moment vs. heel angle curve for the yacht in its sailing condition. The following steps are carried out:

- Determine measurement trim displacement from the immersed volume of hull and appendages below the flotation waterline, using the offset file as a definition of the immersed hull and appendages
- Use the inclining test results to determine the vertical centre of gravity position (VCG) in measurement trim
- Calculate the displacement and VCG in sailing trim by the addition of weights for crew and gear
- Calculate a righting moment at specified heel angles
- Calculate the Limit of Positive Stability (LPS), the heel angle above which the yacht will capsize

4.2 LPP Output parameter definitions

In addition to the traditional "hydrostatic" calculations the LPP also calculates a number of parameters that are used by the hydrodynamic force model.

4.2.1 Appendage stripping

Once the offset file has been acquired and checked, the LPP "strips" off the appendages to leave a "fair" canoe body. Various hydrostatic characteristics and physical parameters are calculated using the flotation waterline determined at the in-water measurement. The characteristics of the appendages are handled separately to determine the parameters that affect their resistance.

4.2.2 The Sailing Length (L)

The Sailing Length (L) is an effective sailing length which takes into account the hull form at the ends of the yacht. L is a weighted average of lengths for three conditions of flotation: two with the yacht upright and one with the yacht heeled. The upright condition (LSM1) is for the yacht floating in Sailing Trim. The heeled condition (LSM2) is for the yacht at an angle of heel (2 degrees) at Sailing

Trim displacement. The "sunk" condition (LSM4) approximates trim at speed with the hull in the trough between bow and stern waves (Figure 8).

$$L = .3194 \times (LSM1 + LSM2 + LSM4) \quad [9]$$

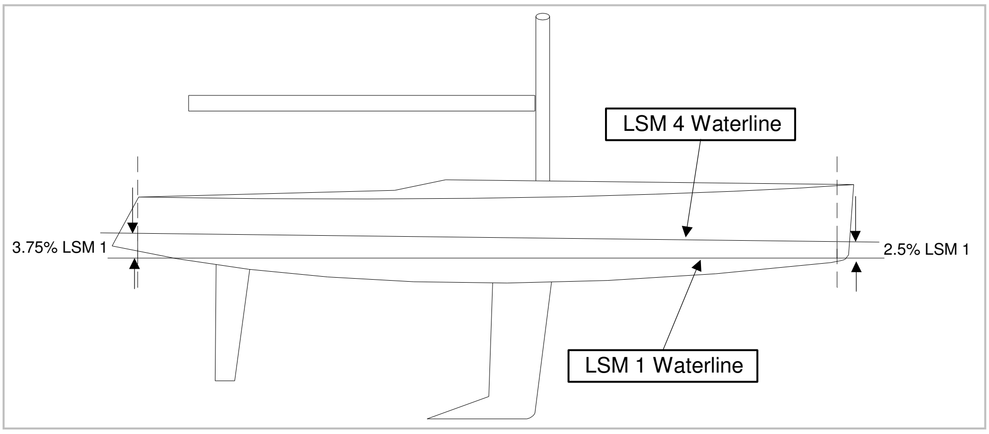

Figure 8. Flotation Waterline positions

The second moment lengths are:

LSM0 is for the yacht in Measurement Trim floating upright
LSM1 is for the yacht in Sailing Trim floating upright
LSM2 is for the yacht in Sailing Trim floating with 2 degrees heel
LSM4 is for the yacht in a deep condition such that compared to Sailing Trim

4.2.2.1 Sailing Trim

To achieve sailing trim the default crew weight and gear weight are combined and added to the yacht 0.1 LSM0 aft of the Longitudinal Centre of buoyancy and (0.5*LSM0 +0.36) m.. above the measurement trim flotation plane.
The LSM4 waterline is sunk 0.025xLSM1 forward and 0.0375xLSM1 aft, floating upright. This is to assess the contribution of the yacht's overhangs to the sailing length.

4.2.2.2 Crew Weight

The default value for the Crew Weight (kg.) is calculated as follows:

$$CW = 74.95276 \cdot \left(\frac{DSPM}{LSM0^3} \right)^{0.375} \cdot \left(\frac{RM}{DSPM \cdot MB} \right)^{0.4} \cdot LSM0^{1.55} \quad [10]$$

The owner may accept the default calculated weight, but can declare any crew weight which shall be recorded in the certificate.
The declared crew weight is used to compute increased righting moment while default crew weight will be used to compute sailing trim displacement.
The longitudinal position of the combined crew longitudinal centre of gravity is calculated from the formula:

$$\text{X\_loc\_of\_crew\_cg} = 0.1 \text{ LSM0 aft LCB} \quad [11]$$

4.2.2.3 Gear Weight

Gear weight is calculated from equation below:

$$\text{Gear Weight} = 0.16 \times \text{Crew Weight} \qquad [12]$$

4.2.2.4 Second Moment Length (LSM)

$$LSM = 3.932\sqrt{\left(\frac{\int x^2 \sqrt[4]{s}dx}{\int \sqrt[4]{s}dx}\right) - \left(\frac{\int x\sqrt[4]{s}dx}{\int \sqrt[4]{s}dx}\right)^2} \qquad [13]$$

Where:

s = *an element of sectional area attenuated for depth*

x = *length in the fore and aft direction*

This method of deriving the Effective sailing length from a weighted sectional area curve is a legacy of the original MHS system. Originally the length calculation took note of the longitudinal volume distribution of the hull, rather than include directly in the residuary resistance calculation terms that were calculated from the sectional area curve.

The depth attenuation of sectional areas is performed by multiplying each Z (vertical offset) by $e^{(-10*Z / LSM0)}$.

4.2.3 Beam Depth Ratio (BTR)

The LPP also computes the effective beam and draft of the yachts canoe body, along with the maximum effective draft of the keel.

The Beam Depth Ratio (BTR) is the effective beam (B) divided by the effective hull depth (T).

$$BTR = B/T \qquad [14]$$

4.2.3.1 The Effective Beam (B).

The effective beam is calculated based on the transverse second moment of the immersed volume attenuated with depth for the yacht in Sailing Trim floating upright. This approach "weights" more heavily elements of hull volume close to the water surface [15].

Formula for Effective Beam (B), ():

$$\text{Effective Beam} = 3.45\sqrt{\frac{2/3\iint\left(b^3 e^{-10z/LSM0}\right)dzdx}{\iint\left(be^{-10z/LSM0}\right)dzdx}} \qquad [15]$$

where: b is an element of beam;
e is the Naperian base, 2.7183
z is depth in the vertical direction
x is length in the fore and aft direction

4.2.3.2 Effective Hull Depth (T)

The Effective Hull Depth is a depth-related quantity for the largest immersed section of the hull. It is derived from the area of the largest immersed section attenuated with depth for the yacht in Sailing Trim floating upright (AMS2) divided by B:

$$T = 2.07 \times \left(AMS2/B\right) \qquad [16]$$

4.2.3.3 Maximum Section Areas

Maximum section areas used for the derivation of Effective Hull Depth (T).

AMS1 is the area of the largest immersed section for the yacht in Sailing Trim floating upright.

AMS2 is the area of the largest immersed section attenuated with depth for the yacht in Sailing Trim floating upright.

Formulae for Maximum Section Areas, (where b is an element of beam; e is the Naperian base, 2.7183; and z is depth in the vertical direction):

AMS1 = maximum of $\int b\, dz$ over length

AMS2 = maximum of $\int b * e^{(-10*z/LSM0)}\, dz$ over length

4.2.4 Maximum Effective Draft (MHSD)

To inform the calculation of hydrodynamic induced drag (drag due to lift[13]) during the VPP force balance calculations the "effective draft" of the hull and keel combination must be calculated. The value of the effective draft (MHSD) is determined by the LPP using the original expression for a "reduced draft" (T_R) which is calculated based on the local section maximum draft and hull cross sectional area. This expression which treats the hull and keel as one half of a slender axi-symmetric body, calculates the effect of streamline contraction around the canoe body. In this way the influence of a deep hull on effective draft is accounted for.
The maximum effective draft of the keel is found by calculating the following parameters at each immersed station along the length of the hull.

TRMAX = xxy1 =Maximum reduced draft.
TRD = xxy = Centreline immersed depth
TRSA = sectional area.
TRX = longitudinal location of station.

$$xxb = \sqrt{\frac{4 \times S(i)}{\pi \times BTR}}$$

S(i) is the sectional area at station i [17]

$$\mathrm{xxr1} = 0.5\left[\mathrm{xxy}/\mathrm{xxb} + \sqrt{(\mathrm{xxy}/\mathrm{xxb})^2 + 0.25BTR^2 - 1}\right]$$

$$xxr2 = \sqrt{xxr1^2 - 0.5(1 + 0.5 \times BTR)} \qquad [18]$$

$$xxy1 = xxb \times \left(xxr2 - 0.25\left[0.25BTR^2 - 1\right] / xxr2 \right)$$

$xxy =$ centreline immersed depth of station (i)

These computed quantities are only important as intermediate results. The information is stored for the station yielding the greatest value of xxy1, "MHSD" (MHS draft), and is determined from [19]:

$$MHSD = 0.92 \times \max(xxy1) \qquad [19]$$

[13]Described in section 8.4.3

4.2.4.1 Centreboards

Centreboards, drop keels, dagger boards etc. are treated in a similar manner.
In the calculation of xxb S(i) is taken as the cross sectional area for the section at the same longitudinal position as the point of maximum draft for the appendage.
Also xxy is now taken as the corrected draft for the hull with the fixed keel plus the corrected centerboard extension (ECE).

$$xxb = \sqrt{\frac{4 \times S(\max depth)}{\pi \times BTR}}$$

$$DEF = DHK\_Effective + ECE$$

$$\text{xxr1}=0.5\left[{DEF}/{\text{xxb}} + \sqrt{\left(DEF/\text{xxb}\right)^2 + 0.25BTR^2 - 1} \right]$$

$$xxr2 = \sqrt{xxr1^2 - 0.5\left(1 + 0.5 \times BTR\right)}$$

$$xxy1 = xxb \times \left(xxr2 - {0.25\left[0.25BTR^2 - 1\right]}/{xxr2} \right)$$

MHSD is again calculated from the formula $MHSD = \max((0.92 \times xxy1), MHSD_{Nocentreboard)})$.

4.2.4.2 Twin (Double)Keels[14]

The twin keel is defined by the following inputs:

- keel distance from bow
- vertical span
- mean chord lengths and thicknesses
- y-offset (distance from CL of fin)
- angle of fin to vertical

The viscous drag is calculated using the method described in Section 6.1.2, with the exception that the keels are not divided into horizontal stripes for the purpose of calculating the local section characteristics. The induced drag is calculated using the standard method described in section 4.2.4

4.2.5 Bulb/Wing Effects

The geometry of the keel tip is influential on the induced drag of the keel fin. These effects may be both positive and negative,

- A ballast **bulb** with circular (or elliptical) cross section reduces the effect span of the keel fin.
- A well designed **wing** keel extends the effective span of the keel.

The VPP contains an algorithm which detects the type and degree of “bulb” keel or “wing” keel and modifies the effective span, derived according to section 4.3.4.

4.2.5.1 Definitions

DHK0	geometric overall draft of keel
MAXW	max width of keel
TMAXW	draft at max width of keel
	MAXW and TMAXW are corrected by « 10° line test »
FLAGBULB	= 1 if bulb is detected
FLAGWING	= 1 if winglets are detected
UPBULBF	upper shape factor for bulb
DeltaD	effective draft correction due to bulb and/or winglet.

[14] 2011

4.2.5.2 Winglet detection

Winglets exist if a line from the maximum width location to a point located in a vertical plane of symmetry, in the same transverse section, vertically distant from the maximum width location less than MAXW/4 which does not lie somewhere in keel (Figure 9-1). Then WWING: width is added by the wing.

4.2.5.3 Bulb detection

If winglets are not detected, a bulb exists if a line from the maximum width location to a point located in vertical plane of symmetry, in the same transverse section, vertically distant from max width location less than MAXW which does not lie somewhere in keel (Figure 9-2). Then WBULB is width added by bulb.

4.2.5.4 Bulb+ Winglet detection

In any case: MAXW= WBULB+WWING (Figure 9-3)

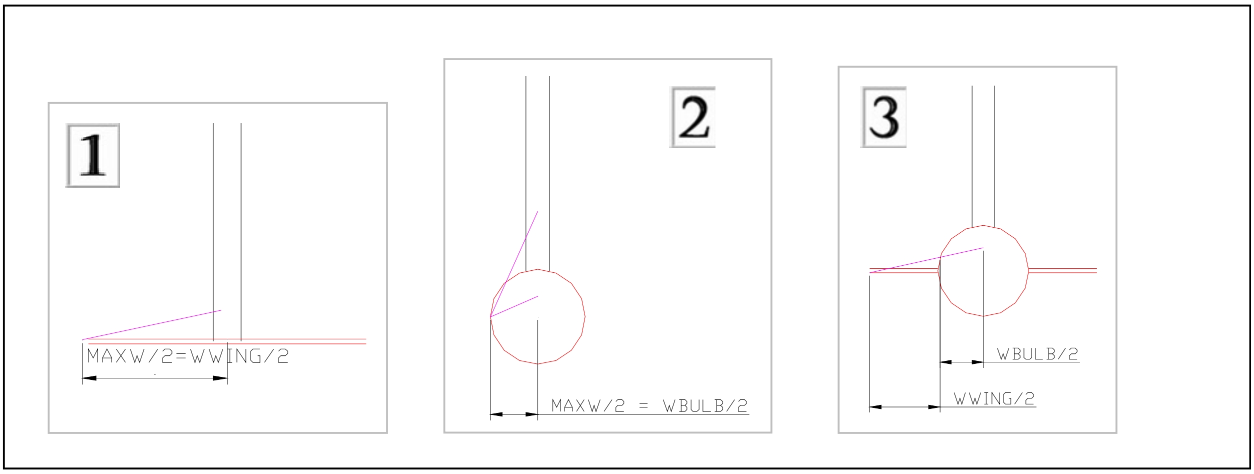

Figure 9. Bulb and Winglet detection scheme

4.2.5.5 DeltaD formulas

DeltaD is calculated with the following formulae and then corrected by the “limitations” defined below. The formulations are based on CFD calculations for eight bulb or winglet configurations. The multiplier of 0.5 applied to f2 is an arbitrary reduction of the bulb credit.

$$DeltaD / MHSD = f1\left((DHK0 - TMAXW)/(0.5 \times MAXW)\right) \times \left\{ \begin{array}{l} Flagbulb \times UPBULBF \times 0.5 \times f2\left((WBULB / DHK0)\right) \times WBULB / (Flagwing \times WWING + WBULB)) \\ + Flagwing \times f3(MAXW / DHK0) \end{array} \right\} \quad [20]$$

Note that:

- f2 addresses the bulb effect if there is no winglet
- f3 addresses winglet effect if there is no bulb
- in the case where bulb and winglet exist the interactions are taken into account by multiplying f2 value by the *WBULB/(Flagwing*WWING+WBULB)* term

Where :

f1(X)	=	*if X<1*	*1+ k1*X*
		if X>1	*1+k1*
f2(X)=	=	*if X>wbu_T0*	*k2_0 + k2_1*(X-wbu_T0)*
		if X<=wbu_T0	*k2_0 * X / wbu_T0*
f3(X)=	=	*if X < wwi_T0*	*k3_0* X / wwi_T0*

if X>= wwi_T0 *k3_0 + k3_1 * (X-wwi_T0)*

k1	0.6
k2_0	-0.06
k2_1	0.19
k3_0	0.05
k3_1	0.02
wbu_T0	0.15
wwi_T0	0.5

4.2.5.6 Upper shape factor for bulb

UPBULBF is introduced to take into account that end effect of the bulb depends of the shape of the top of the bulb. A straight shape (e.g., a Scheel Keel) has a positive effect, although a round shape has negative effect on effective draft.
Moreover UPBULBF helps to smooth the jump of DeltaD when a bulb becomes winglet.

UPBULBF is defined as follows:

a. consider the rectangle defined by opposite corners at the maximum width bulb point and a point on the top surface of the bulb located at 0.05 * DHK0 off the centerline. Calculate the area Ar
b. Consider the enclosed part of the bulb in the rectangle. Calculate the area Abu
c. Define the upper bulb shape factor UPBULBF = f4(Abu/Ar): f4 (1)= 1 for x=0.825, f4(0.3)= 0.3, f4 linear function.
d. In the bulb wing formula, multiply f2 by UPBULB .

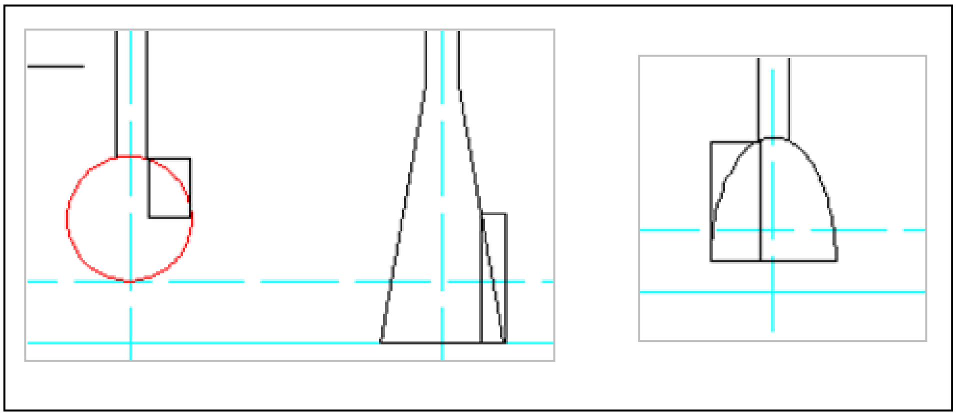

Figure 10. Upper Bulb Shape factor examples

4.2.5.7 Limitations

DeltaD > - 0.025 * DHK0 (credit bulb limitation)
If the widest point of the bulb or winglet is not enough deep with respect to DHK0 and MAXW, the bulb or winglet are considered to have no effect:

DeltaD = 0 if TMAXW + 3 * MAXW/2 < DHK0
DeltaD is not affected if TMAXW + MAXW/2 > DHK0
DeltaD varies linearly between those two situations.

4.2.5.8 Smoothing technique

Because the detection scheme must work on old offset files, which may sparse data points in the area of the keel tip, it is important to avoid catching spurious "widest points." When, going down along the bulb/winglet section, you find the point of max width, at that point the "10 deg line test" is applied.
The test is to trace an almost vertical line downward, inclined 10 degrees inboard. The lowest offset point that lies "external" to that line is taken as the widest point of the section, in way of the actual widest point. At this point the test is applied for winglet and bulb (see Figure 11).

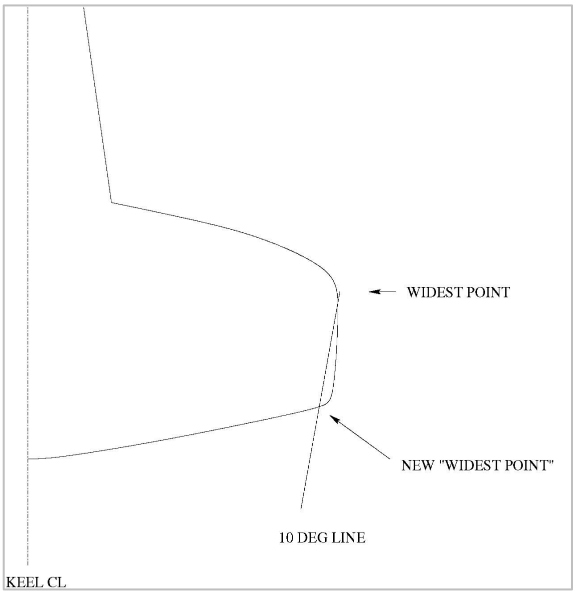

Figure 11. Widest Point detection

4.3 *Appendage wetted areas and lengths.*

The original VPP formulations were concerned only with "conventional" fin keel and rudder configurations. Subsequently the ability to handle off centre appendages, and canting keels has been added.

4.3.1 Conventional Fin keel and rudder

The keel and rudder are divided into 5 horizontal strips and a wetted surface area together with a mean length and thickness to chord ratio is calculated for each strip. These values are used to calculate the viscous resistance of the appendages.
In this case the volume of the fin keel and any associated bulb is calculated so that the contribution to wave making resistance may be calculated

4.3.2 Other appendages

The LPP can deal with twin rudders, centreboards, forward rudders, fixed or retractable dagger boards. These appendages can be added into the .DAT file based on their measured dimensions, rather than including them in the wanded .OFF file data.
Only the viscous drag of these appendages is calculated, based on methods described in detail in section 8.1.2.
The LPP also calculates any reduction of wetted surface area that occurs if any dagger board, twin rudder etc. comes above the flotation waterline.

4.4 Righting Moment

4.4.1 Righting Arm Curve

The LPP calculates a righting arm against heel angle curve (Figure 12).

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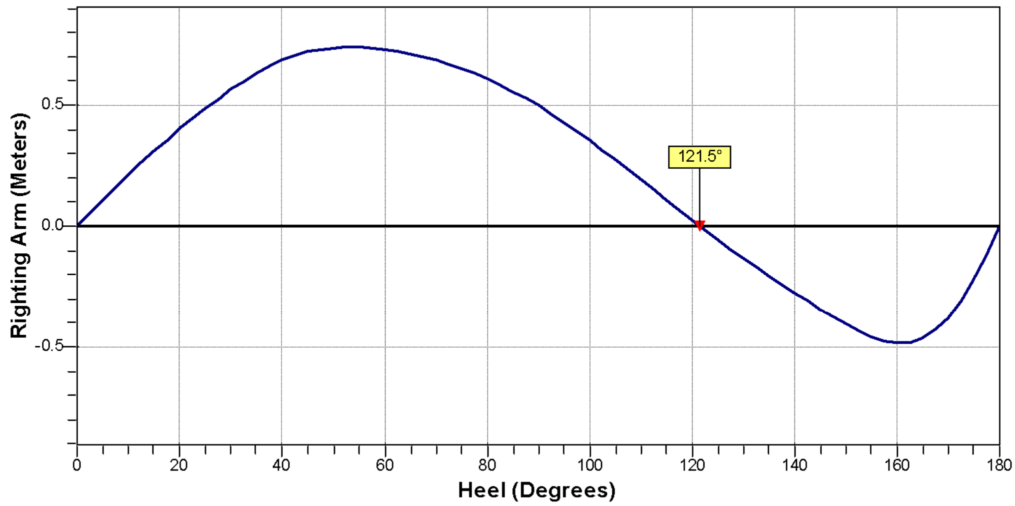


STABILITY CURVE

Righting Moment at 1°	137.1	Stability Curve Positive Area	25.768	Stability Curve Ratio	3.2899	Stability Index	122.0
Limit of positive stability	121.5°	Stability Curve Negative Area	7.833	Water Ballast Volume	0 l	BLR Index	0.0000

Righting Arm (meters)

		0°	2°	10°	20°	25°	30°	40°	60°	90°	120°	150°	165°	180°
Default Crew Weight	689 kg	0.000	0.043	0.211	0.401	0.485	0.561	0.684	0.725	0.496	0.025	-0.402	-0.461	0.000
Declared Crew Weight	815 kg	0.000	0.042	0.208	0.397	0.480	0.555	0.676	0.714	0.482	0.013	-0.408	-0.464	0.000

BOAT

Name	PARAGON OF VIRTUE
Sail Number	US-12345
Class	TRIPP 40
Designer	TRIPP
Builder	
Age Date	05/1991
Measured	22/05/1991
Measurer	STIMSON
Issued On	05/06/2009 - VPP beta16

HULL CHARACTERISTICS (MEASUREMENT TRIM)

Length Overall	12.410 m		
Maximum Beam	3.630 m	Maximum Beam Station	7.327 m
Draft	2.305 m	Maximum Draft Station	6.891 m
Moment Unit Trim	9.3 kg•m/mm		
Displacement Unit Immersion	19.58 kg/mm		
Block Coefficient	0.3833	Prismatic Coefficent	0.5270

FLOTATION (MEASUREMENT TRIM)

Forward Freeboard at 0.614 m	1.228 m
Freeboard at mast at 4.250 m	1.122 m
Aft Freeboard at 11.190 m	1.009 m
Overhang Forward	0.793 m
Overhang Aft	1.710 m
Length Waterline	9.908 m

HYDROSTATIC DATA

Trim	Measurement	Sailing
Displacement	5,747 kg	6,677 kg
Wetted Area	26.41 m²	28.03 m²
Water Plane Area	18.76 m²	19.95 m²
Water Plane Beam	2.818 m	2.898 m
Longitudinal Centre of Flotation	6.384 m	6.499 m
Longitudinal Centre of Buoyancy	6.237 m	6.342 m
Vertical Centre of Gravity	-0.091 m	0.049 m
Max. Section Area	1.23 m²	1.35 m²
Max. Section Area Station	5.857 m	5.857 m
Sail Area Upwind	83.49 m²	
Sail Plan Centre of Effort Height	7.921 m	

CONFORMITY WITH LIMITS

ORC International Certificate LPS > 103°:	Yes
Offshore Special Regulations Category:	0

Figure 12. Typical Righting arm curve and hydrostatic data output

4.4.2 Hydrodynamic Centre of Pressure

The hydrodynamic vertical center of pressure RM4 is given by:

$$RM4 = 0.43\ T_{max} \qquad [21]$$

4.4.3 Crew righting moment

The crew righting moment is based on the declared crew weight or a default crew weight calculated from equation [10]. The assumed individual crew weight is 89 kg and the number of crew is calculated by dividing the crew weight by this value.
Two less than the total number of crew are distributed along the deck edge of the boat centered about the assumed centre of gravity position, a single crew member is assumed to occupy a width of 0.53m.
The lever arm of the crew on the rail is the average hull beam over the length of side deck occupied by the crew.
The remaining 2 crew members, the helmsman and main trimmer are assumed to have transverse centre's of gravity at 70% of the yachts maximum half beam. [22]

4.4.3.1 LSM greater than 4.9m (16 feet)

For yachts with LSM greater than 4.9 m the crew weight on the rail is 2 less than the total crew, the remaining 2 are assumed to sit slightly inboard:

$$Crew \cdot rightingarm = \left(CARM \times CREWRW + 0.7 \times 2 \frac{B\max}{2} \times \mathrm{bodywt} \right) \cos(\mathrm{heel}) \qquad [22]$$

Where:

CARM	=	Crew righting arm
CREWRW	=	Crew weight on the rail
B_{max}	=	Hull maximum
bodywt	=	Average crew body weight.
heel	=	Heel angle

4.4.3.2 LSM less than 4.9m

For yachts with LSM greater than 16m the crew weight is all sat on the rail.

$$Crew \cdot rightingarm = \left(CARM \times CREWRW \right) \cos(\mathrm{heel}) \qquad [23]$$

4.4.3.3 Crew weight transverse position

Sailing with the upwind sails the crew righting moment is only applied in full once the heel angle exceeds 6 degrees.
When using the downwind sails (i.e. not a jib), the crew position is set with everyone to leeward up to a heel=10 deg., then it sinusoidally changes from leeward to neutral from 10 to 14 degrees of heel, and then sinusoidally moves all the crew to windward from 14 to 18 degrees of heel[15].

4.4.4 Dynamic Righting Moment. RMV

RMV [24] is a term intended to account for the difference between the hydrostatic righting moment calculated by the LPP, and the actual righting moment produced by the hull when moving through the water. This term was in the VPP from its first implementation[17].

$$RMV = \frac{5.955 \times 10^{-5}}{3} \times DISPL \times LSM \times (1 - 6.25 \left(\frac{B_{cb}}{\sqrt{AMS1_{cb}}} - 2.1 \right) \times SLR \times \phi \qquad [24]$$

Where

[15] 2011
[17] The divisor of 3 in the first term was introduced in 2000 to correct an over-prediction of RMV for contemporary hull forms.

Displ=Displacement

B_{cb} = Canoe body beam

$AMS1_{cb}$ = Maximum section area of canoe body

SLR = speed length ratio

4.4.4.1 Dynamic Stability System (DSS)

The DSS is the deployment of an approximately horizontal hydrofoil on the leeward side of the yacht that generates a vertical force component to augment the yachts righting moment. For 2010 the VPP will be able to calculate the drag and increased righting moment available from a DSS.
The data input file take in the geometrical data of the foil's size and position and use a simple algorithm to calculate the increased righting moment of the foil. The lift force is proportional to the square of the yachts speed, and the maximum extra righting moment capped at a percentage of the yachts typical sailing righting moment.
Like all features of the IMS VPP this force prediction algorithm is intended to provide an equitable handicap for yachts fitted with the DSS. It is not a "design and optimization" tool.

4.4.5 Rated Righting Moment

The rated righting moment used in the VPP calculations is the average between the measured and default RM as follows:

$$RM_{rated} = \frac{RM_{measured} + RM_{default}}{2}$$

Default righting moment is calculated as follows:

$$RM_{default} = \left(a0 + a1 \cdot BTR + a2 \cdot \frac{\sqrt[3]{VOL}}{IMSL} + a3 \cdot \frac{SA * HA}{B^3} + a4 \cdot \frac{B}{\sqrt[3]{VOL}} \right) \cdot DSPM \cdot IMSL \qquad [25]$$

where all the variables are calculated by the VPP using the following coefficient values.

a0 = -0.00410481
a1 = -0.00003999
a2 = -0.00017008
a3 = 0.000019183
a4 = 0.003602739
VOL = canoe body volume
SA = sail area upwind
HA = heeling arm, defined as
(CEH main*AREA main + CEH jib*AREA jib) / SA + HBI + DHKA*0.45
CEH = height of centre of effort
DHKA = Draft of keel and hull adjusted

Default righting moment shall not be taken greater than $1.3 * RM_{measured}$ nor smaller than $0.7 * RM_{measured}$.

For movable ballast boats the default righting moment intends to predict the righting moment of the boat without the effect of movable ballast (water tanks empty, or keel on the center plane), is then decreased by a factor (1- RM@25_movable/RM@25_tot), where RM@25_movable is the righting moment due to the contribution of movable ballast at 25 degrees of heel, and RM@25_tot is the total righting moment at 25 degrees, with keel canted or windward tanks full. For these boats, the max and min bounds are set to 1.0 x $RM_{measured}$ and 0.9 x $RM_{measured}$ respectively.

5 Aerodynamic Forces

The VPP assumes that each individual sail, mainsail, jib, spinnaker, gennaker or code zero can be characterized by a maximum achievable lift coefficient and a corresponding viscous drag coefficient that are continuous functions of apparent wind angle. The values of these coefficients are adjusted depending on the exact sail type and the mast and rigging configuration. The individual coefficients are then combined into a set of complete sail plan (main and jib, or main and spinnaker) coefficients. In order to simulate the reduction of heeling force by the crew trimming and changing sails "Flat" and "Reef" parameters are used.

The flat parameter is used to simulate the reduction of the lift coefficient. It reduces from a value of 1.0, associated with maximum lift, to a minimum value of 0.6 for normally rigged yachts [18], i.e. the lift coefficient reduced by 40%.

The reef parameter simulates the reduction of sail area. When reefing is required to achieve optimum performance the genoa sail area is first reduced until the genoa reaches it minimum foot length, if further heeling force reduction is required the mainsail is reefed.

The VPP optimizer is at liberty to de-power the sails by reducing the maximum lift coefficient (Flat) and reduce sail size (Reef) to achieve best performance at each prescribed True wind angle.

5.1 Methodology

The aerodynamic forces acting on the yacht are resolved into two orthogonal components, lift and drag. The lift force acts perpendicular to the apparent wind direction and the drag force acts parallel to it. The force model incorporates 3 sources of drag:

1. The base drag associated with the windage of the hull, spars, rigging and crew;
2. The parasitic drag associated with the skin friction drag of the sails, and the pressure drag associated with flow separation. The parasitic drag is assumed not to depend on the sail lift force, it does however vary with the point of sailing;
3. The induced drag, which arises from the three-dimensional nature of the flow around the sails, and the loss of circulation from the head and foot of the sails. The induced drag is assumed to vary as the square of the lift coefficient. A two-dimensional lift dependant drag term is also added to the basic induced drag.

Analysis of the rig begins by ascribing the appropriate coefficient set to the main, jib and offwind sails. The frontal and side areas associated with the mast, hull and rigging are also calculated. Each area has an associated vertical centre of force which represents the height at which all the aerodynamic loads could be concentrated to produce the same overall rolling moment. Because the presence of a wind gradient implies that the wind velocity is a function of height, the vertical heights of the centres of force are used when evaluating the dynamic pressure acting on any aerodynamic surface.

5.1.1 Individual Sail Areas and 2-Dimensional Aerodynamic Force Coefficients

The fundamental components of the aerodynamic model are the individual sails, characterised by the following parameters, which are shown diagrammatically in Figure 13:

- Sail area
- Centre of effort height above the sail's datum
- Cl_X and Cd_P versus β_{AW} envelope. (Maximum lift coefficient and parasitic (viscous) drag coefficient versus apparent wind angle).

[18] This minimum flat value of 0.6 is based on the lift force reduction that has been observed in wind tunnel tests.

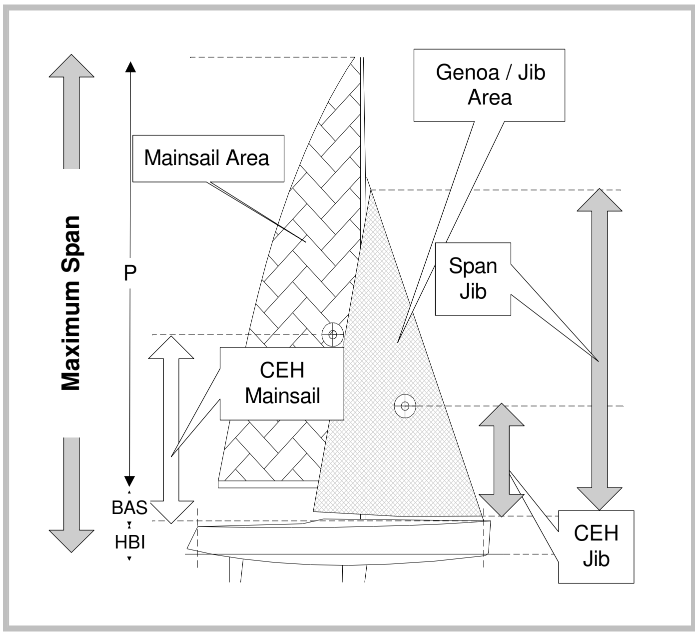


Figure 13. Sail Parameters

SAILS (Maximum Areas)										
Mainsail	HB	MGT	MGU	MGM	MGL	MSW		Area	Area (r)	Formula
	0.210	1.25	2.20	3.60	4.70	22.00		52.10	52.42	P/8 · (E + 2·MGL+ 2·MGM + 1.5·MGU + MGT + 0.5·HB)
Jib/Genoa	JH	JGT	JGU	JGM	JGL	JL	LPG			
	0.00	0.00	0.00	0.00	0.00	0.00	6.33	48.20		0.1125·JL·(1.445·LPG+2·JGL+2·JGM+1.5·JGU+JGT+0.5·JH)
Symmetric	SL	SMG	SF						Area (r)	
	14.39		7.60					103.21	103.69	SL · (SF + 4·SMG) / 6

Figure 14 shows the individual two-dimensional coefficients for the 3 sail types originally supported by the VPP. The characteristics of the mainsail and jib and spinnaker were derived empirically when the sail force model was introduced. The coefficient values, which are based on cloth area, show typical effects:

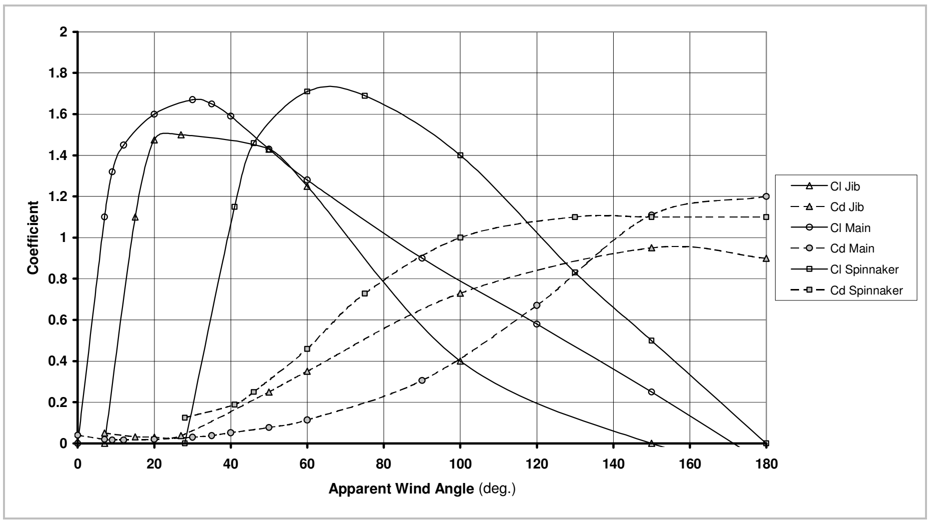


Figure 14. Basic Sail Force Coefficients

- As apparent wind angle increases a rapid rise in lift to a peak value prior to the onset of separation and stall.
- The sails 'fill' at different apparent wind angles, reflecting the different sheeting arrangements and shapes of the sails.
- At an apparent wind angle of 180 degrees, approximating to an angle of attack of 90 degrees, the lift has declined to zero and the drag coefficient increased to 1.0.

5.1.2 "Simplified" Rigging Coefficients

This reflects the ability of yachts with more complex fore and aft staying arrangements to adjust their sails for best performance. The Mainsail and Jib may have varying lift and drag force coefficients depending on the ability to change the camber of the sails by adjustable stays.
For both sail types a low and a high set of lift and drag coefficients exist. In the application of the coefficients adjustable forestays, backstays, and running backstays are considered. The details of the scheme are described in sections 7.2.1 for the mainsail and 7.2.2 for the jib.

5.1.3 De-powering

The de-powering scheme is based on new VPP variables ftj, and rfm working with a new[19] optimisation parameter RED that replaces the traditional Reef parameter.

ftj = jib foot parameter ftj=1 full size jib, ftj=0 minimum jib
rfm = is the main reduction factor, Rfm=1 full main, rfm=0 no main.
Works like the old Reef function but on the mainsail only.

RED is a combination of these 2 factors into a single optimisation parameter.
RED = 2 then ftj=rfm=1, i.e. full sail
RED=1 then ftj=0, rfm=1, i.e. jib at minimum size
RED <1 then ftj=0 and rfm<1.

The progressive de-powering scheme is shown graphically in Figure 15. At each stage in the process the current sail area, fractionality and overlap are calculated and the values used to calculate the Effective rig height and vertical centre of pressure position.

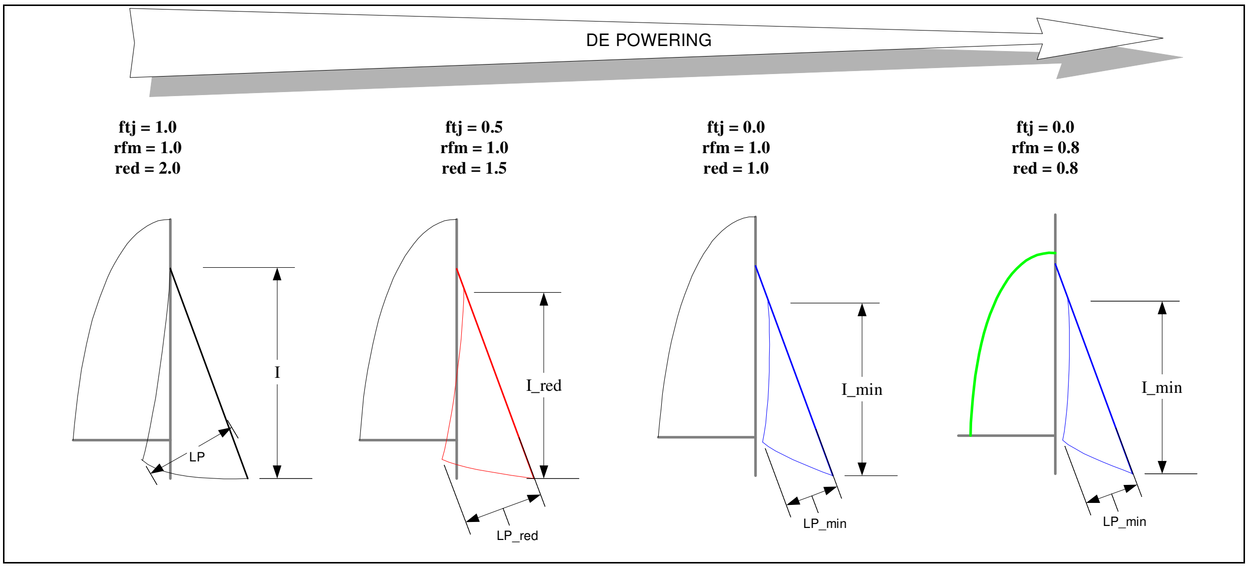


Figure 15. De-powering scheme

The total sail forces are now calculated during each VPP iteration[20]. The process is described in Figure 16.

[19] 2009
[20] *rather than adopting the "RIGANAL" approach of the old code where as much of the aero model as possible was pre-calculated before the VPP itself was run. The current approach would not have been possible even 10 years ago due to the extra burden of calculation making the VPP too slow to run routinely.*

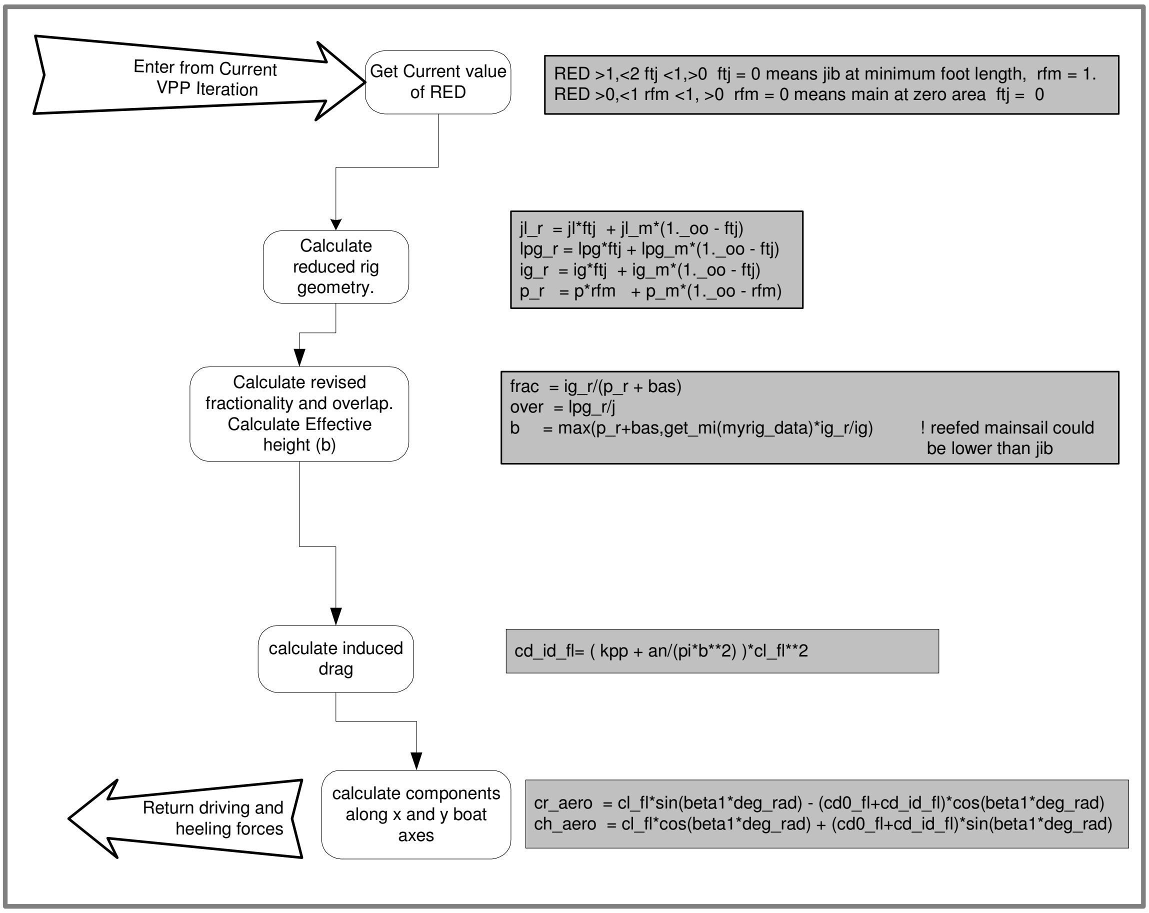


Figure 16. Routine for de-powering

5.1.3.1 Revised Optimisation Scheme[21].

Traditionally (pre 2010) the VPP aerodynamic model has been free to adjust the sail power (Flat) and area (Reef) independently to achieve the highest sailing speed at each True Wind Angle. This is time consuming for the optimisation computer code, and does not reflect the way in which yachts are sailed, in that reefing is usually delayed until the sails are fully flattened.
The new sail trimming scheme adopts the following methodology to reduce sail heeling moment as wind speed increases.

1. Reduce Flat progressively to $Flat_{MIN}$.
   $Flat_{MIN} = 0.6 \times Flat\ at\ 8\ knots\ True\ wind.$
2. Once $Flat_{MIN}$ is reached reduce jib area progressively to the minimum jib area.
   (Still using $Flat=Flat_{MIN}$)
3. Once the Minimum jib area is reached reduce mainsail area.
   (Still using $Flat=Flat_{MIN}$)

5.2 Sail Areas & Coefficients

5.2.1 Mainsail

5.2.1.1 Mainsail Area

Mainsail area is the physical cloth area of the largest mainsail in the yacht’s sail inventory calculated as follows:

[21] 2010

$$Area\_Main = \frac{P}{8}\left(E + 2 \cdot MGL + 2 \cdot MGM + 1.5 \cdot MGU + MGT + 0.5 \cdot HB\right) \quad [26]$$

The boom depth (BD) limit is 0.06 * E.
If BD exceeds its limit, mainsail area shall be increased by 2*E*(BD - 0.06*E).
In 2010 a revised scheme for determining the height of the girth sections was adopted.
The heights are calculated using the following formula which must be calculated in the order presented.

mgmh = p/2 + (mgm-e/2)/p*e
mglh = mgmh/2+ (mgl-(e+mgm)/2)/mgmh*(e-mgm)
mguh = (mgmh+p)/2 + (mgu-mgm/2)/(p-mgmh)*mgm
mgth = (mguh+p)/2 + (mgt-mgu/2)/(p-mguh)*mgu

A parameter "roach" is calculated to define the planform shape of the mainsail.
A roach value of zero is a triangular main. A value greater than this indicates a degree of "big headedness"

$$roach = \frac{Area\_main}{P \times E / 2} - 1.0 \quad [27]$$

5.2.1.2 *Mainsail Coefficients*

The mainsail may have either of two coefficient sets as shown in Table 1, the standard mainsail and one based on having no adjustable check stays. The "simple" main without checkstays is characterised by a reduced maximum available Lift Coefficient resulting from the inability to increase sail camber in light airs through the use of check stays, as shown in Figure 17.

beta	*bmnc*	0	7	9	12	28	60	90	120	150	180
CL_low	*clmnc*	0.000	0.862	1.052	1.164	1.347	1.239	1.125	0.838	0.296	-0.112
CL_hi		0.000	0.948	1.138	1.250	1.427	1.269	1.125	0.838	0.296	-0.112
CD_low	*cdmnc*	0.043	0.026	0.023	0.023	0.033	0.113	0.383	0.969	1.316	1.345
CD_hi		0.034	0.017	0.015	0.015	0.026	0.113	0.383	0.969	1.316	1.345

Table 1. Mainsail force coefficients

Nomenclature

beta Apparent wind angle (deg)
CD Drag Coefficient
CL Lift Coefficient

The low set of lift and drag coefficients (CL_{low}) is used when there is neither a backstay nor a pair of running backstays or in case of one pair of running backstays only. With two or more backstays (regardless of type) the high set of coefficients (CL_{high}) is applied.

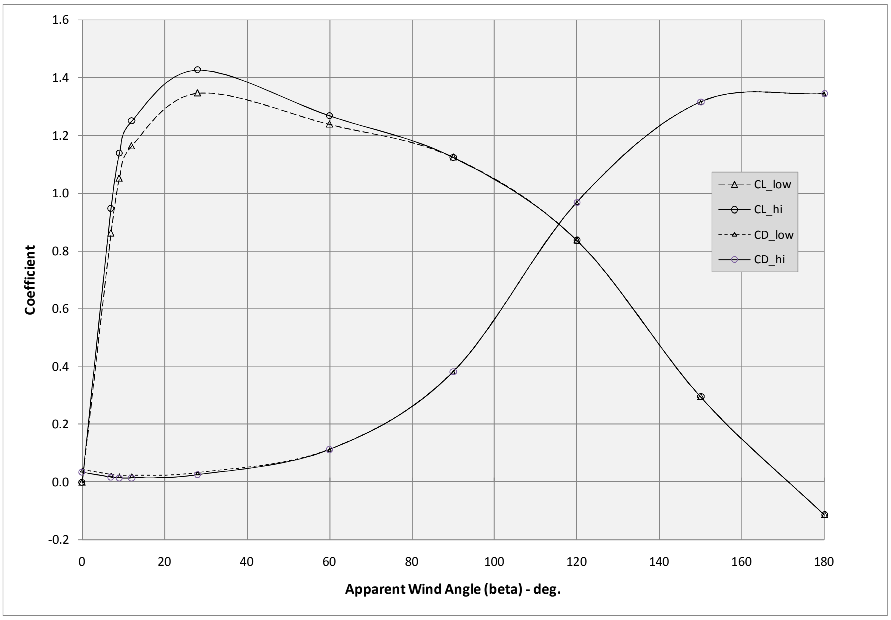


Figure 17. Alternative Mainsail Force Coefficients[22]

Table 2 shows the matrix of rated rigging arrangements and corresponding main sail force coefficient sets.

L = Low Lift associated with low mainsail adjustability.
H = High Lift associated with increased mast bend control.
M = intermediate coefficient set depending on rig fractionality.

Mainsail Coefficients				
BACKSTAY	FORESTAY			
	fixed	adj fwd	adj aft	adj aft&fwd
None	L	L	error (M)	error (M)
Backstay only Running Backstay only	L warning (L)	L warning (L)	M L	M L
2 or more Backstays and/or adjustable inner forestay	H	H	H	H
L = C_low M = C_moderate = C_low*(1-Coef/2) + C_high_new*Coef/2 H = C_high_new = (C_low + C_high_old) / 2				

Table 2. Application of Alternative Coefficient sets for Mainsails

In the case of a backstay being fitted but without running backstays, a fractionality coefficient f_{Coef} is derived which controls the effect of the backstay on the mainsail shape. This is shown diagrammatically in Figure 18.

$$f_{Coef} = \sqrt{sin(\frac{\pi}{0.6})*min(0.3; max(0; \frac{1}{Fractionality} - 1))} \qquad [28]$$

22 C:\Documents and Settings\Andy\My Documents\Projects\ORC Documentation\XLS\New_Coefs_Main_Jib_mod.xls

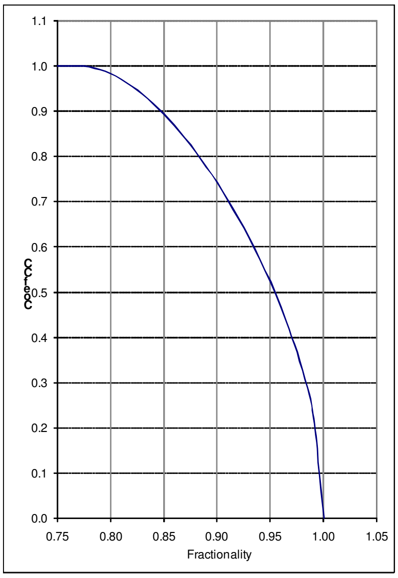


Figure 18. Fractionality Coefficient

For the configuration with one pair of backstays only, a medium level set of coefficients is calculated [29]

$$C_{medium} = C_{low} \cdot \left(1 - \frac{f_{Coef}}{2}\right) + C_{high} \cdot \frac{f_{Coef}}{2} \qquad [29]$$

5.2.1.3 Centre of Effort (CE) calculation

The mainsail centre of effort is calculated as the centre of area of the projected mainsail area, plus a constant to unify the calculation with earlier equations. The constant added to CE/P is 0.024 which makes the center of effort height for a mainsail with default girths = 0.39xP.

5.2.2 Jib or Genoa

The jib also has 2 possible coefficient sets depending on whether the forestay can be adjusted whilst racing. If it can be adjusted the jib has a higher maximum Lift Coefficient to reflect the fact that sail camber can be increased in light airs by easing the head stay.

5.2.2.1 Genoa Area

Jib rated area is be the biggest area of any jib/genoa in the sail inventory calculated as follows:

$$\text{JIB AREA} = 0.1125 * \text{JL} * (1.445 * \text{LPG} + 2 * \text{JGL} + 2 * \text{JGM} + 1.5 * \text{JGU} + \text{JGT} + \text{JH} / 2) \qquad [30]$$

Using the girths measured as per the ERS.
A default Jib Area is calculated from the following formula:

$$Jib_{DEFAULT} = 0.9 \times \sqrt{(IM^2 + J^2)} \times 0.9 \times J/2 \qquad [31]$$

If Jib Area > $Jib_{DEFAULT}$ then rated area = actual area.
If Jib Area < $Jib_{DEFAULT}$ then rated area = default area.

5.2.2.2 Genoa Aerodynamic Coefficients

A similar approach to the mainsail is applied for the set of lift and drag coefficients of the jib, as shown in table 3. The low set of coefficients is applied only when there is neither a backstay nor an adjustable forestay. If the forestay is adjustable or in the case of one or more pairs of running backstays the high set of coefficients is used. The coefficients are plotted in Figure 19.

beta	bjyb	7.000	15.000	20.000	27.000	50.000	60.000	100.000	150.000	180.000
CL_low	cljnb	0.000	1.000	1.375	1.450	1.430	1.250	0.400	0.000	-0.100
CL_hi	cljyb	0.000	1.100	1.475	1.500	1.430	1.250	0.400	0.000	-0.100
CD_low	cdjnb	0.050	0.032	0.031	0.037	0.250	0.350	0.730	0.950	0.900
CD_hi	cdjyb	0.050	0.032	0.031	0.037	0.250	0.350	0.730	0.950	0.900
dCL	dclj	0.000	0.100	0.100	0.050	0.000	0.000	0.000	0.000	0.000

Table 3. Genoa Force Coefficients

Headsail Coefficients				
BACKSTAY	FORESTAY			
	fixed	adj fwd	adj aft	adj aft&fwd
None	L	H	error (M)	error (H)
Backstay only	L	H	M	H
Running Backstay only	warning (H)	H	H	H
2 or more Backstays	H	H	H	H

L = C_low
M = C_moderate = C_low*Coeff + C_high*(1-Coef)
H = C_high

Table 4. Application of Alternative Coefficient sets for jibs

Table 4 shows the matrix of rated rigging arrangements and corresponding jib/genoa sail force coefficient sets.

L = Low Lift associated with a non adjustable forestay which does not allow genoa camber to be controlled.

H = High Lift associated with increased forestay control.

In case of a backstay being fitted but no running backstays, a medium level set of coefficients is calculated similar to the procedure applied for the mainsail. The intermediate coefficients are derived with the same fractionality coefficient f_{Coef} given above by using the following formula:

$$C_{medium} = C_{low} \cdot f_{Coef} + C_{high} \cdot \left(1 - f_{Coef}\right) \quad [32]$$

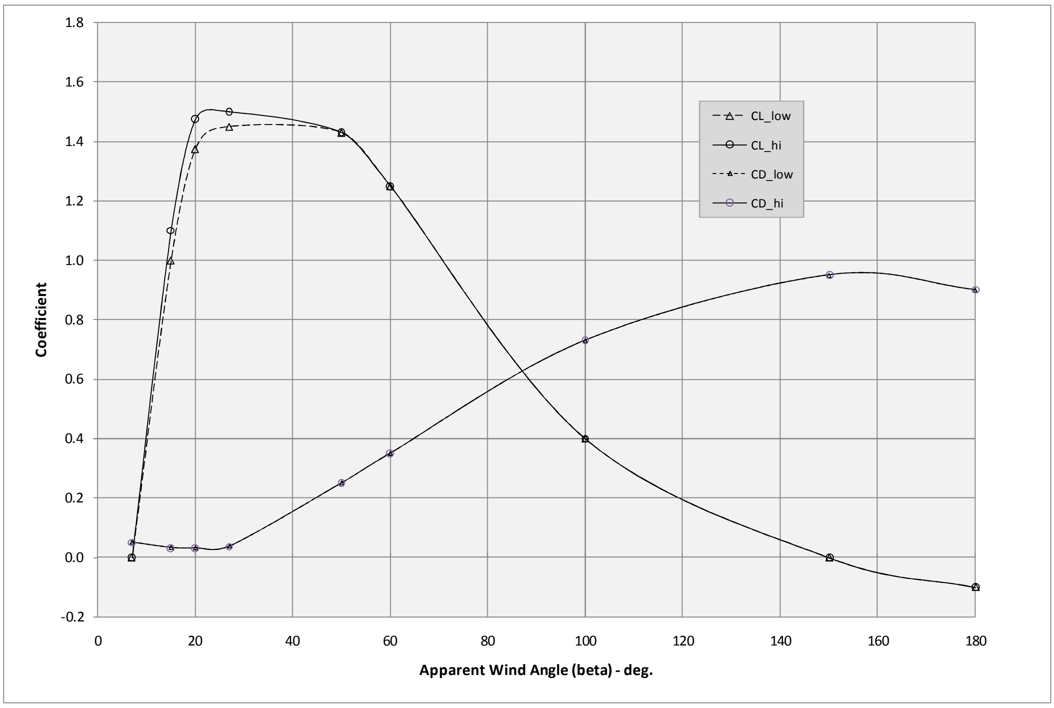


Figure 19. Alternative Jib Force Coefficients

5.2.2.3 *Roller Furling Genoa*

For a roller furling genoa the lift coefficient is reduced by the following amount at each apparent wind angle. *The modified coefficients are applied only if the genoa has an LP > 110% of J, <u>and</u> there is only one headsail carried onboard.*

AWA	7.0	15.0	20.0	27.0	50.0	60.0	100.0	150.0	180. 0
Delta Cl	0.0	0.10	0.10	0.05	0.00	0.00	0.0	0.0	0.0

5.2.2.4 *Poled out jib*

In 2011 the poled out jib coefficients were removed. For non-spinnaker handicaps on downwind courses the sail coefficients are taken as those for an asymmetric spinnaker set on a pole with a spinnaker sail area equal to 1.035 × the area of the largest rated headsail carried onboard.

5.2.2.5 *No Spinnaker Configuration.*

For the "No Spinnaker" configuration the yacht is run through the VPP with the normal jib force coefficients. Also a sail set called "jib downwind" between True Wind Angles of 60° and 180° using the asymmetric on centerline coefficients and a sail area equal to the jib area.
For handicapping the best speed from each of the polar curves is selected.

5.2.2.6 *Jib Centre of Effort (CE) calculation*

The jib centre of effort is the centre of area of the jib planform, calculated using a trapezoidal integration of the measured girths.

5.2.3 <u>Spinnakers</u>

The following configurations can be handicapped:

1. No spinnaker
2. symmetric spinnaker on pole only (with and without CODE 0)
3. asymmetric spinnaker on tacked on CL (with and without CODE 0)
4. asymmetric spinnaker on pole , asymmetric on CL and symmetric on pole (with and without CODE 0)

5.2.3.1 *Spinnaker Area*

The VPP and the sail areas published on the certificate are now actual sailcloth areas[23]. The concept of a "rated sail area" that reflects different types of sail plan has been replaced by more sophisticated force coefficient sets.

$$\text{SPINNAKER AREA} = SL * (SF + 4 * SMG) / 6 \qquad [33]$$

For asymmetric spinnakers and code zero's , SL = (SLU+SLE)/2.

A default spinnaker area is calculated, From 2011 onwards if the measured area is less than the default area the default spinnaker area is used in the VPP calculation.

Default (minimum) values for symmetric spinnakers:

SL default = $0.95*\sqrt{(ISP^2+J^2)}$
SF default = 1.8 * maximum of SPL or J
SMG default = 0.75 SF default

If SPL is not recorded it will be set SPL=J

---

[23] 2008 Change

For the asymmetric spinnaker:
ASL default = $0.95*\sqrt{ISP^2+J^2}$
ASF default = maximum of (1.8 * SPL or 1.8*J or 1.6*TPS)
AMG default = 0.75 ASF default
In the case that the configuration is only asymmetric on CL and TPS is not recorded it will be set TPS = J + SFJ

If there is no spinnaker aboard; boat will be rated with an asymmetric spinnaker tacked on centerline with the same area as the largest jib/genoa.

5.2.3.2 Force Coefficients [24]

beta	28	41	50	60	67	75	100	115	130	150	180
Cd	0.213	0.321	0.425	0.587	0.598	0.619	0.850	0.911	0.935	0.935	0.935
Cl	0.000	0.978	1.241	1.454	1.456	1.437	1.190	0.951	0.706	0.425	0.000

Table 5. Symmetric Spinnaker Force Coefficients

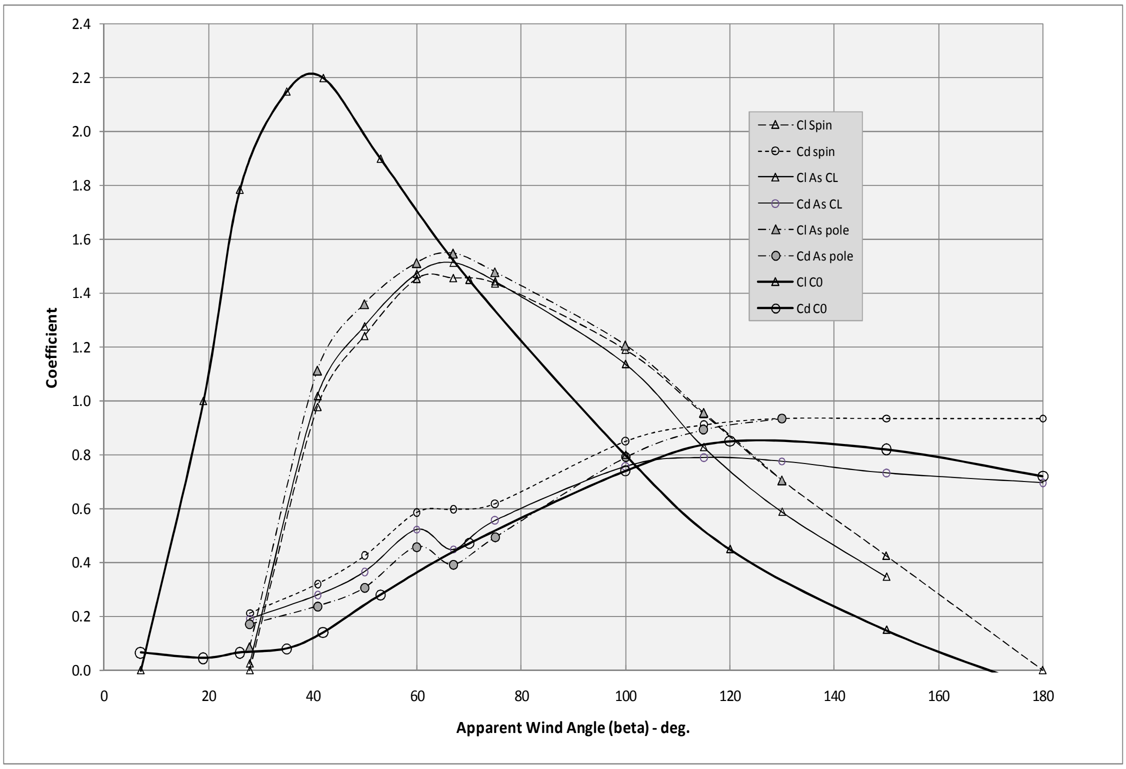
beta	28	41	50	60	67	75	100	115	130	150	180
Cd	0.191	0.280	0.366	0.523	0.448	0.556	0.757	0.790	0.776	0.733	0.696
Cl	0.026	1.018	1.277	1.471	1.513	1.444	1.137	0.829	0.589	0.348	0.000

Table 6. Asymmetric Spinnaker tacked on centreline Force Coefficients

beta	28	41	50	60	67	75	100	115	130	150	180
Cd	0.170	0.238	0.306	0.459	0.392	0.493	0.791	0.894	0.936	0.936	0.936
Cl	0.085	1.114	1.360	1.513	1.548	1.479	1.207	0.956	0.706	0.425	0.000

Table 7. Asymmetric Spinnaker tacked on a pole Force Coefficients

The Spinnaker Coefficients are plotted in Figure 20.



[24] 2011

Figure 20. Spinnaker and Code zero Coefficients

5.2.3.3 Reduction in Drive Force from large spinnakers in light airs.[25]

It is an observed effect that large spinnakers set on short spinnaker poles do not fly to their full projected area as well as the smaller sails. To address this "type forming" towards smaller spinnakers a power loss factor for larger sails was developed.
The shape function will reduce the effective area of a spinnaker that is bigger than the "reference area", where the reference area is calculated from the following:

$$SL_{Ref} = ASL_{ref} = 0.95 \times \sqrt{ISP^2 + J^2}$$
$$SMG_{ref} = SF_{ref} = 1.8 \times J$$
$$AMG_{ref} = ASF_{ref} = 1.8 \times J$$

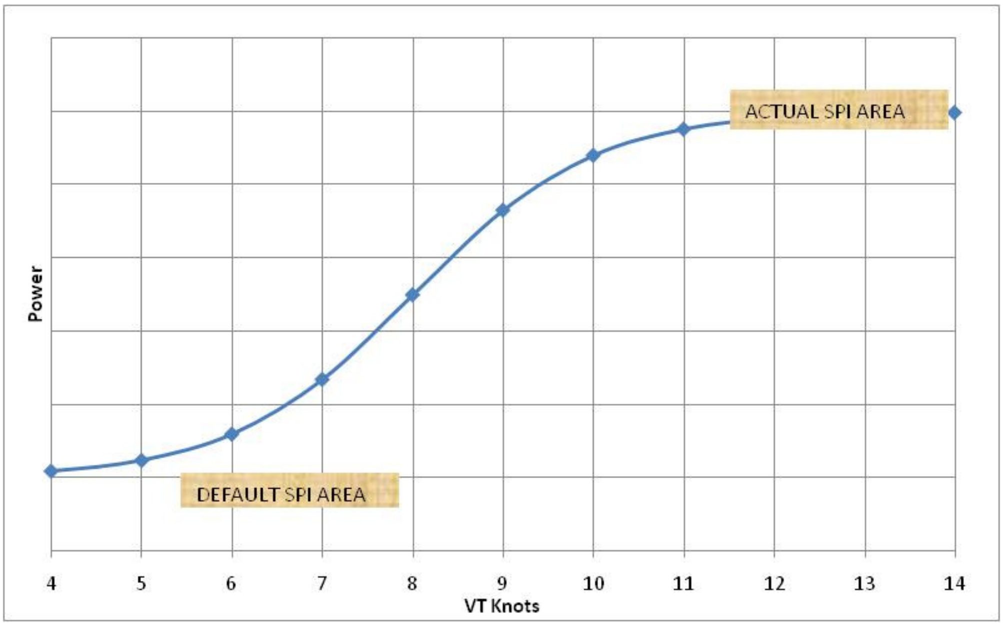


Figure 21. Large Spinnaker Force Correction in light winds

with the transition represented in Figure 21. For spinnaker area below default area, no further reductions will be made, while the maximum reduction will be limited to 75% of measured area.

5.2.3.4 Spinnaker Centre of effort height

The centre of effort height is 0.565×ISP above the base of I

5.2.3.5 Spinnaker Jib Crossover[27]

The 2011 modifications to the spinnaker coefficients were largely driven by the desire to "force" the VPP to adopt crossover points from spinnaker to jib at apparent wind angles that more closely reflect the angles observed whilst sailing.
Additionally the maximum heel angle allowed under spinnaker was fixed at 28 degrees, and the minimum REEF factor allowed was fixed at:
0.85 x Spin. Area/Default Spin. area

5.2.4 Code Zero

[25] 2011
[27] 2011

5.2.4.1 *Code Zero area*

For the CODE0:

ASL default = 0.95*√(ISP^2+J^2)

ASF default = 1.6*TPS

AMG default = 0.55 ASF default

If TPS is not recorded it will be set TPS = J + SFJ

The minimum mid girth for a Code 0 is 55% of the foot length.

The boats performance with the code zero sail set as a “code zero” and as an asymmetric spinnaker is calculated and the best performance at each true wind angle is used for handicapping purposes.[28]

Figure 22.

5.2.4.2 *Code Zero Centre of Effort Height*

The Code Zero centre of effort (CEJ) is 0.39*I above the base of I

5.2.4.3 *Code zero Coefficients*

beta	7	19	26	35	42	53	70	100	120	150	180
Cd	0.065	0.045	0.065	0.08	0.14	0.28	0.47	0.74	0.85	0.82	0.72
Cl	0	1	1.785	2.15	2.2	1.9	1.45	0.8	0.45	0.15	-0.07

Table 8. Code Zero force coefficients

The Code zero force coefficients are plotted in Figure 20.

5.2.5 Blanketing and the Effect of Spinnaker pole and bow sprit length (2010).

5.2.5.1 *Blanketing.*

The VPP aerodynamic model contains a Blanketing term that modifies the spinnaker/gennaker force coefficients if the spinnaker pole length (SPL), or gennaker tack point (TPS) is short relative to the mid girth.

This is accomplished by two inter-related functions, blanketing and power.

The blanketing function (Bkt) is a reduction in spinnaker/gennaker force coefficients at apparent wind angles (beta) greater than 135°. At apparent wind angles less than 135° Bkt = 1.0

$$fsb = \min\left[\frac{am}{as}, 1 - 1.48822 \times \frac{\mathbf{ISP} \times \mathbf{SPL}}{\mathbf{Area_{Spin}}} \frac{spl}{smg}\right]$$

Usually the (am/as) ratio is the higher term, and only modifies the Bkt function if the mainsail is very small.

$$x = \frac{\mathbf{beta - 135}}{\mathbf{45}}$$

$$Bkt = 1 - fsb \times x^2$$

5.2.5.2 *Spinnaker tack position “Power” Function*

In order to more equitably handicap the influence of increasing the length of the spinnaker pole or bowsprit relative to the spinnaker, gennaker and Code zero mid-girth a “power” function was introduced to the mainsail blanketing algorithm as shown in the equation below.

The power calculation is triggered by the value of the termfsp

[28] 2011

$$\mathbf{fsp} = \left(1 - 1.488 \times \frac{spl}{smg\left(Spi\frac{Area}{ISP}\right)}\right) - 0.17$$

If this is less than 0.0 then the spinnaker pole is considered longer than the norm and the power function increases above 1.0

$$Power = 1 + 1.0 \times (ABS(fsp))^{1.5}(ABS(fsp)^2 \times 2.5)$$

The “Power” function does not credit poles or bowsprits shorter than the norm, and the maximum power increment is 20% above the base level.
In order to calculate the force from the spinnaker/gennaker the sail area is multiplied by the blanketing (Bkt) and the Power functions.

5.3 Windage Forces

The windage drag is incorporated into the force balance by adding to the aerodynamic drag a windage drag determined from equation [34].
Each of the (n) windage elements is ascribed its own dynamic head (q_n) based on an apparent wind velocity appropriate to its centre of effort height (Z_{CE}), reference area (A) and drag coefficient (Cd).

$$D_{WINDAGE} = \sum_{1}^{n} q_n \cdot A_{REF} \cdot Cd_n \qquad [34]$$

The windage drag for each element is calculated at apparent wind angles of 0 and 90 degrees and a shape factor is used to calculate the drag coefficient at intermediate angles. The calculation of Centre of Effort Height (ZCE), Drag Coefficient (Cd0) and reference area (A_{REF}) at apparent wind angles of 0 and 90 degrees is shown in the table below, the values for 180 degrees are the same as those for the headwind case.

	Apparent. Wind Angle 0°		
WINDAGE ELEMENT	Z_{CE}	C_D	A_{REF}
HULL	0.66(FBAV+Bsinϕ)	0.68	FBAV*B
MAST-Sail	HBI+EHM*reef/2	0.4[a]	Front Area
MAST-Bare	HBI+EHM*(1-reef)/2	0.8[a]	Front Area
RIGGING	HBI+I/2	1.0[b]	I**f*(Default. Rigging wt.)
Non round rigging[29]	HBI+I/2	0.25[b]	I**f*(Default. Rigging wt.)
CREW	HBI+0.5+B/2sinϕ	0.9	0.25
	Apparent. Wind Angle 90°		
WINDAGE ELEMENT	Z_{CE}	C_D	A_{REF}
HULL	0.66(FBAV+Bsinϕ)	0.68	*f*(HSA*L,ϕ)
MAST-Sail	HBI+EHM*reef/2	0.6[a]	Side Area
MAST-Bare	HBI+EHM*(1-reef)/2	0.8[a]	Side Area
RIGGING	HBI+I/2	1.0[b]	I**f*(Default. Rigging wt.)
CREW	HBI+0.5+B/2sinϕ	0.9	0.5*Mvblcrew
a modified by EDM factor for non standard mast section aspect ratio. *b plus spreader factor = 0.2*			

Table 9. Windage force model

Hull side area (HSA) $HSA = \int_0^n Freeboard \quad dl$

Where n = number of measurement stations.

5.3.1 Rigging

The drag of the rigging wire is calculated based on the default rigging weight. The square root converts wire cross-sectional area to wire diameter, and the factor of 2 means four stays.

$$\begin{aligned} &\text{Diameter\_of\_Rigging\_Wire} = 2 \times \sqrt{(4.d0 \times \text{WT\_Deflt\_Rigng/MI/Steel\_density}/\pi)} \\ &\text{Area\_Rigging\_Wire\_Windage} = I \times \text{Diameter\_of\_Rigging\_Wire} \\ &\text{Cd0\_Rigging\_Wire} = \text{CD\_Rigging\_Wire} \times (1 + \text{spreader\_FACTOR\_windage}) \end{aligned} \quad [35]$$

5.3.1.1 Spreaders

If the rig has bona-fide spreaders their drag is added in as a multiplier as shown in equation [35], where spreader_FACTOR_windage is set to 0.2.

5.4 Total Aerodynamic Lift and Drag

The next phase is to combine the individual sail's characteristics to produce a set of lift and drag coefficients that describe the aerodynamic behavior of the entire rig.
This is accomplished by a weighted superposition of the individual sail force coefficients at each apparent wind angle. This process is described in more detail in section 7.4.1.
The weight given to each sail's coefficients during this process is proportional to the product of its area and the "blanketing" factor, which modifies the individual sails coefficients depending on the

[29] 2011

apparent wind angle. After summing the weighted coefficients the total is normalized with respect to the reference sail area (A_{REF}).

When calculating the collective vertical centre of force the weight given to each sail's contribution is proportional to the product of the area, the blanketing factor, and the total force coefficient.

The induced drag coefficient is calculated from knowledge of the effective rig height. (H_E)

$$Cd_I = \frac{Cl^2 \cdot A_{REF}}{\pi H_E^2} \quad [36]$$

The effective rig height is calculated from the sail plan geometry at each iteration of the VPP through the aerodynamic force calculation loop.

The effective rig height is a function of:

- the mainsail roach,
- the relative positions of the mainsail head and the jib head expressed as "fractionality" and
- the overlap of the headsail

5.4.1 Lift and Drag of complete sail set

The aggregate maximum lift and linear parasite drag coefficients are the sum of each sail component's contribution normalized by reference area, and modified by a blanketing function B_i:

$$\begin{aligned} Cl\max &= \sum Cl\max_i \times B_i \times A_i / A_{ref} \\ Cdp &= \sum Cdp_i \times B_i \times A_i / A_{ref} \end{aligned} \quad [37]$$

A typical form of the collective sail force coefficients is shown in Figure 22. The "Drag" Curve is the parasitic drag contribution, and the Total Drag curve includes the induced drag contribution.

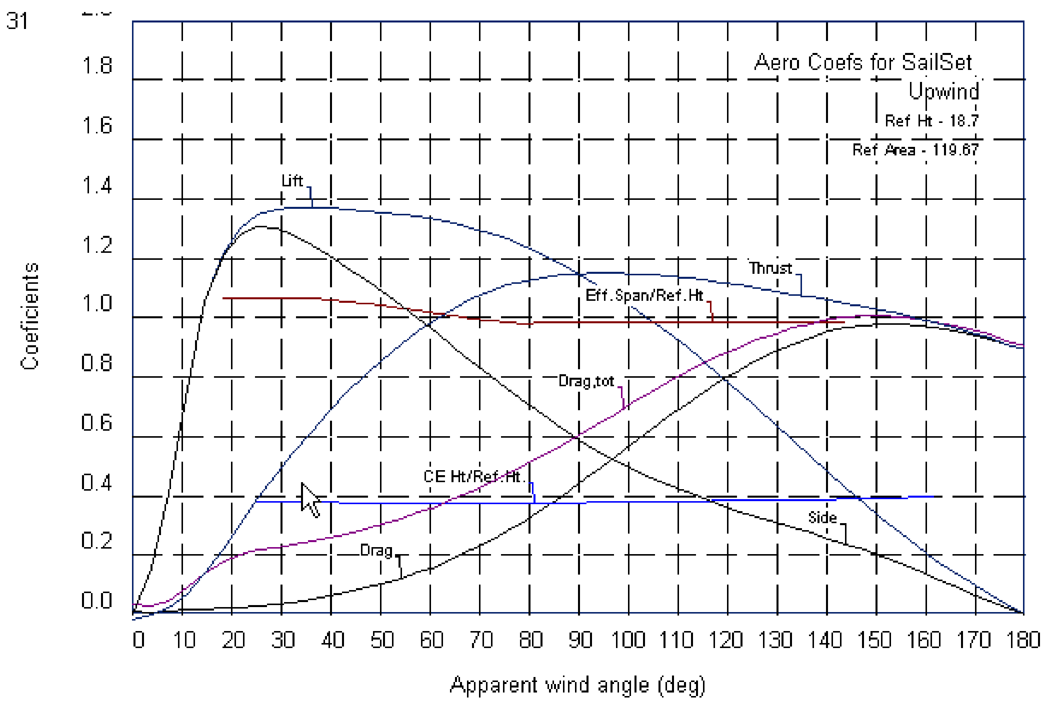


Figure 23. Typical Form of "Collective" Upwind Sail Force Coefficients

5.4.2 Center of Effort Height

Center of effort height Z_e is evaluated by weighting each sail's individual center of effort height by its area and partial force coefficient (comprised of lift and linear component of parasitic drag):

$$Zce = \sum Zce_i \sqrt{(Cl\max_i^{\,2} + Cdp_i^{\,2})} \times B_i \times A_i \,/\, A_{REF} \,/\, \sqrt{(Cl\max^2 + Cdp^2)} \qquad [38]$$

5.4.3 Induced Drag

In order to calculate the induced drag component an efficiency coefficient is derived. The efficiency coefficient is such that when multiplied by the collective lift coefficient squared it yields the collective induced drag of the sails.

The efficiency coefficient is comprised of 2 parts;

- The 2 dimensional part describing the increase of viscous drag that occurs as the sail produces more lift,
- and the "induced drag" which depends on the effective rig height.

5.4.3.1 Quadratic Parasite Drag

The viscous drag of the sails varies according to the square of the lift coefficient

This quadratic parasite drag coefficient *KPP* is the sums of the individual sails contributions:

$$KPP = \sum KPP_i \times Cl\max_i^2 \times B_i \times A_i \Big/ A_{ref} \,/\, Cl\max^2 \qquad [39]$$

5.4.3.2 Effective rig height

Three parameters - "fractionality", "overlap" and "roach"- are determined in order to calculate the Effective rig height which determines the induced drag of the sails.

Fractionality = $I_{current}/(P_{current}+BAS)$

Overlap = $LPG_{current}/J$

Roach = Mainsail Area /(P x E / 2) -1

The influence of sail plan geometry is first calculated from [40] to derive a corrected effective span coefficient.

$$eff\_span\_corr \;=\; 1.1 \;+\; 0.08(\text{Roach}-0.2)+0.5(0.68+0.31\times fractionality+0.075\times overlap - 1.10) \qquad [40]$$

The effective span coefficient is approximately 1.10 with a masthead rig (fractionality = 1.0) and 150% overlap genoa.

The effective span coefficient is then further modified to reflect the fact that as the sails are eased at wider apparent wind angles the effective span is reduced as the sealing of the jib and the hull is lost and the sail interactions become less favourable.

$$\begin{aligned} cheff_{Upwind} &= eff\_span\_corr \times (0.8 + 0.2 \times be) \\ cheff_{Downwind} &= cheff\_\max\_spi \times (1.0 + 0.1 \times be) \end{aligned} \qquad [41]$$

The term *be* varies from 1 to zero as apparent wind angle widens from 30 to 90 degrees (Figure 23).

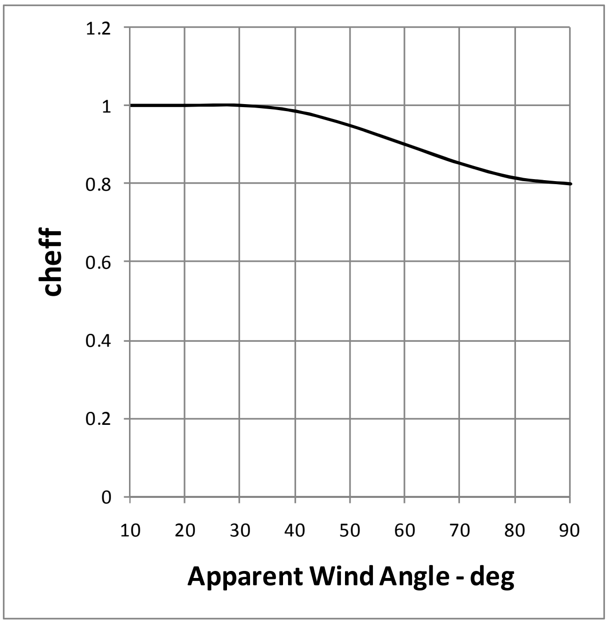


Figure 24. Variation of Effective span factor with Apparent wind angle

Finally the effective height "heff" is calculated from the product of "cheff" and the the highest point of the sail plan "b" above the water surface. This is either the mainsail head (P+BAS) or jib head (IG). If the jib head is higher than the mainsail head then the average is taken.

$$heff = cheff\,(b + HBI) \qquad [42]$$

The efficiency coefficient "CE" is comprised of the induced drag coefficient and the parasitic drag coefficient that is proportional to lift squared.

$$CE = KPP + {SailArea}/{\pi \times heff} \qquad [43]$$

Finally at each apparent wind angle the total lift and drag coefficient for the sails can be calculated from the lift, and drag coefficients and the "efficiency coefficient" (CE).

$$\begin{aligned} Cd_{Sails} &= Cd_{Parasite} + CE \times Cl^2 \times FLAT^2 \\ C_L &= FLAT \times Cl_{MAX} \end{aligned} \qquad [44]$$

The FLAT parameter characterizes a reduction in sail camber such that the lift is proportionally reduced from the maximum lift available. Thus flat = 0.9 means 90% of the maximum lift is being used.

What this means in practice is shown in Figure 24, in "full power" conditions (FLAT=1) the available aerodynamic force is determined by the maximum Cl and associated Cd. The total Cd at max Cl is affected by $Cd_{parasite}$ and by the effective rig height that determines the induced drag component. When the sails are flattened to reduce the total force, and therefore the heeling moment, it does so along the Cd vs. Cl^2 line shown in figure 24.

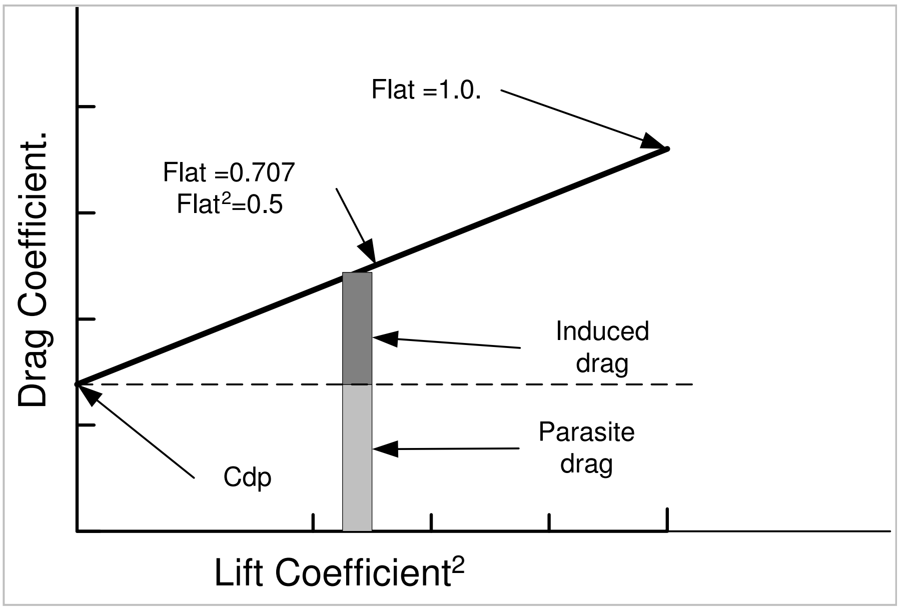


Figure 25. Variation of Drag Coefficient with Flat parameter

5.5 Resolution of Forces

In order to determine the total thrust and heeling moment the aerodynamic forces are resolved into two orthogonal components; along the yachts track (C_R) and perpendicular to the mast plane (C_H). The windage forces are then added to these components.

Throughout the evolution of the VPP there has been a constant trend that the VPP appears to overstate the value of high righting moment. This has been particularly noticeable in light airs on windward/leeward courses, i.e. Mediterranean conditions.
Two strategies have been adopted in the aerodynamic force model to overcome this, the PHI_UP, and TWIST parameters.

5.5.1 PHI_UP

In the VPP as the yacht heels the apparent wind angle seen by the sails reduces, but on the water the crew have traveler and jib lead controls that permit adjustment of angle of attack.
To reflect this the PHI_UP function modifies the heel angle that is used in the calculation of the apparent wind angle at which the collective curves of lift and drag coefficient are evaluated.

$$phi\_up = 10 \times (\phi / 30)^2 \quad [45]$$

phi	phi_up
0	0.0
10	1.1
20	4.4

Table 10. Calculated PHI_UP values

5.5.2 Twist Function

In order to reflect the fact that as sails are de-powered the centre of effort height moves lower a “twist function” was introduced. The extent of the centre of effort lowering was determined from wind tunnel test results, which showed that this effect was proportional to the fractionality (I:(P+BAS)) ratio.

$$Zce = Zce \times [1-0.203\times(1-flat)-0.451\times(1-flat)\times(1-frac)] \quad [46]$$

To reflect the ability of fractionally rigged boats to de-power more readily than mast head rigged boats the twist function links the vertical centre of effort position to the flat parameter. Fractional rigged boats more lowering of the centre of effort position as the FLAT parameter reduces, as shown in Figure 25.

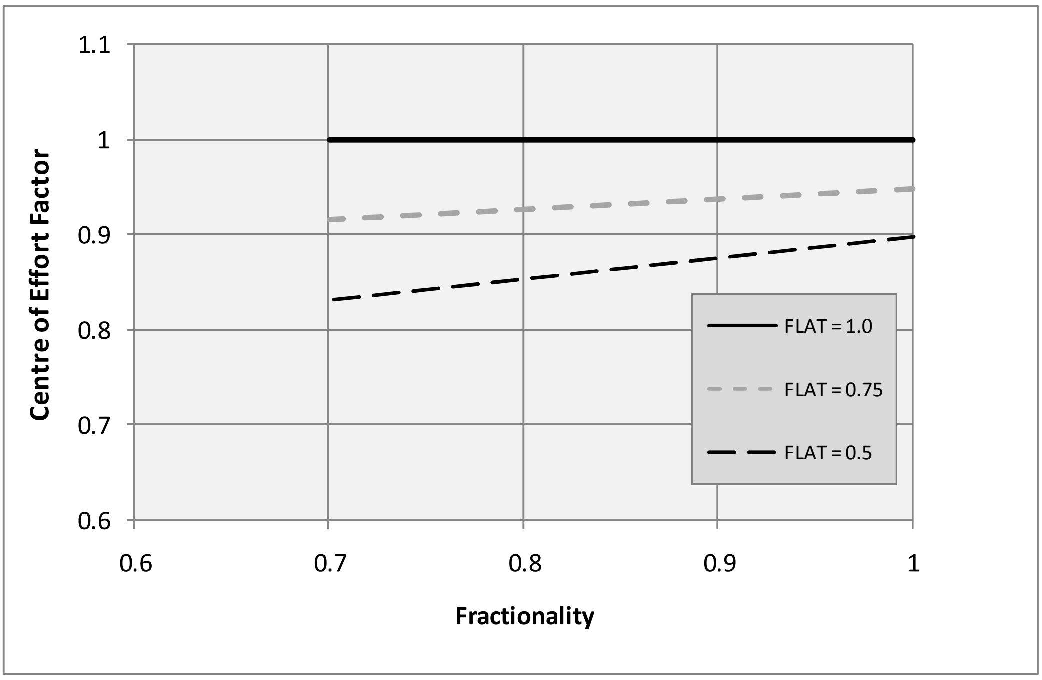


Figure 26. Twist Function

5.5.3 Thrust and Heeling Force

The collective lift and drag forces from aerodynamic model are resolved as follows:

$$C_R = C_L \sin\beta - C_D \cos\beta$$
$$C_H = C_L \cos\beta + C_D \sin\beta \quad [47]$$

The coefficients are translated into forces:

$$\text{FRA\_B4\_Windage} = \text{CR} \times \tfrac{1}{2} \rho V_a^{\,2} \times A$$
$$\text{FHA\_B4\_Windage} = \text{CH} \times \tfrac{1}{2} \rho V_a^{\,2} \times A \qquad [48]$$

Where:

– = air density

V_a = apparent wind speed

A = Reference sailarea

The total aerodynamic force (FRA) is then calculated by adding the windage components:

$$\text{FRA} = \text{FRA\_B4\_Windage} + \text{FRA\_hull} + \text{FRA\_mast} + \text{FRA\_Rigging\_Wire} + \text{FRA\_crew}$$
$$\text{FHA} = \text{FHA\_B4\_Windage} + \text{FHA\_hull} + \text{FHA\_mast}Ź\ \text{FHA\_Rigging\_Wire} + \text{FHA\_crew} \qquad [49]$$

5.5.4 Aerodynamic heeling Moment

The aerodynamic heeling moment is the sum of the sail heeling moment (HMA_B4_Windage) and the heeling moment from the windage elements.

$$\text{HMA} = Ź\text{HMA\_B4\_Windage} + \text{HMA\_hull} + \text{HMA\_mast} + \text{HMA\_Rigging\_Wire} + \text{HMA\_crew} \qquad [50]$$

The sail heeling moment is the product of the heeling force (CH) and the moment arm above the waterline.

$$\text{HMA\_B4\_Windage} = \tfrac{1}{2} \rho V_a^{\,2} \times A_{REF} \times \text{CH} \times (\text{HBI} + \text{ZCEB} \times \text{REEF})$$

6 Hydrodynamic Forces

The VPP hydrodynamic force model divides the drag into two sources; viscous or skin friction drag arising from the flow of the water over the immersed surface, and residuary or wave making drag arising from the creation of surface waves.
The calculation of viscous drag is based on standard naval architectural practice.
The calculation of residuary drag is based on the results of towing tank tests carried out on over 50 models by the staff at the Delft University of Technology[30], and IMD[31], plus results from tests at the Wolfson Unit[32] on five IOR maxi models.
The VPP can make performance predictions not only for conventional fin keel yachts, but also water ballasted and canting keel yachts that have asymmetric rudder and keel configurations. Whilst the estimate of performance for these yachts is based on plausible physics, there has been a deliberate policy not to reach a situation where these types of yachts are favored.

6.1 Viscous Resistance

In its original form the viscous resistance of the canoe body and appendages were calculated from the ITTC 1957 model-ship correlation line based on the total wetted area of the hull and appendages, using 0.7LWL as the characteristic length. The current ORC VPP still uses this method to calculate the viscous resistance of the canoe body, but applies a more sophisticated scheme to the keel and rudder.

6.1.1 Canoebody

The canoe body viscous drag R_{VC} is calculated using the following expression:

$$\mathrm{R}_{\mathrm{VC}} = q \times Cf_C \times WSA_C(\phi) \qquad [51]$$

In which:

Cf_C = *0.075/(log(Rn)-2)²* , friction coefficient from the ITTC formulation and Reynolds number *Rn* is evaluated using 0.7 LSM 1.

$WSAc(\phi)$ = canoe body wetted surface at heel ϕ in still water

q = “dynamic head” = $\frac{1}{2}\rho V^2$

6.1.2 Appendages

The currently implemented scheme divides each appendage into 5 segments as shown in Figure 26, and determines the viscous coefficient of resistance of each strip based on the local (strip specific) Reynolds Number and thickness/chord (t/c) ratio.

[30] Delft URL
[31] IMD
[32] WUMTIA

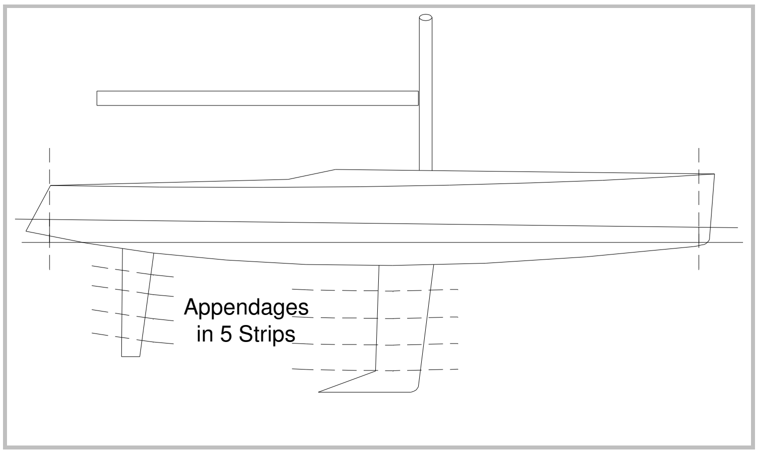


Figure 27. Strip wise segmentation of appendages

The viscous resistance of each strip is then calculated from the product of the dynamic head, the local wetted surface area and an appropriate skin friction resistance coefficient. (Cf). The determination of the appropriate Cf is based on data presented in Fluid Dynamic Drag (Hoerner 1965). The calculation[33] is based on 4 Reynolds Number regimes, calculated for a flat plate and t/c ratios of 10 and 20%, as shown in table 11

Reynolds No.	1000*Cf Flat plate	1000*Cf t/c = 0.1	1000*Cf t/c = 0.2	Bulb
3.162E+03	24.85	42.07	44.12	59.29
1.00E+04	13.86	28.93	30.51	44.00
3.162E+04	7.73	20.20	21.42	32.66
1.00E+05	4.95	10.74	11.50	16.54
3.162E+05	3.46	4.99	5.40	6.51
1.00E+06	3.00	3.62	3.94	4.49
2.512E+06	3.00	3.62	3.94	4.49
6.310E+06	3.00	3.62	3.94	4.49
1.585E+07	2.81	3.39	3.69	4.21
5.012E+07	2.39	2.88	3.14	3.57
1.995E+08	1.96	2.36	2.59	2.93

Table 11. Appendage Cf. values used in the VPP

This approach works well for plain fin keels and rudders, but for keel bulbs which occupy the lowest appendage strip some further calculation must be done to ensure that appropriate characteristics are derived. The following approach is currently used:

(a) Use a chord length equal to the average of the top of the bottom strip and the longest fore and aft length occurring in the bottom strip.

(b) Use a maximum thickness equal to: $volume / (area \times 0.66)$.

(c) Use a reference area equal to the maximum of the strip projected area, and the wetted surface area.

The total viscous drag of the appendages is determined as shown in equation [52].

[33] Scheme devised by Karl Kirkman, Dave Greeley and Jim Teeters

$$R_{VA} = \frac{1}{2}\rho V^2 \left[\sum_{N=1}^{N=5} \left[A_{StripN} Cf(rudder)_{stripN} + A_{StripN} Cf(keel)_{stripN} \right] \right] + A_{centreboard} Cf_{centreboard} + A_{canard} Cf_{canard} \quad [52]$$

The total frictional resistance is the sum of the appendage and canoe body contribution.

$$D_{FRICTION} = R_{VC} + R_{VA} \quad [53]$$

6.1.2.1 Double rudders (2010)

The Offset file has now been configured to accept double rudder configurations as detailed in Appendix A. The viscous drag is calculated according to Table 11, with no velocity deficit for the keel wake. The immersed wetted area is calculated at each heel angle assuming an undisturbed static waterplane.

6.1.2.2 Centreboards

Because centerboards are often not as well refined as keel fins a different drag formulation[34] is adopted [54]:

$$\text{Centreboard drag} = 0.006 \times \tfrac{1}{2} \rho V^2 A_{cb}$$
$$\text{Wetted area Centreboard } (A_{cb}) = 2 \times \text{ecm} \times \frac{(\text{cbtc} + 2 \times \text{cbmc} + \text{cbrc})}{4} \quad [54]$$

Where:

ecm	*Centre board extension*
ρ (rho)	*Water density*
cbtc	*Centerboard tip chord*
cbmc	*Centerboard mid chord*
cbrc	*Centerboard root chord*

If there is no data for centerboard chord then the following formula is applied.

$$\text{Wetted area Centreboard } (A_{cb}) = 2 \times 0.6 \times \text{ecm}^2$$

6.1.2.3 Dagger Boards, Bilge Boards

Bilge boards and dagger boards are treated as per Table 11 based on their area and mean chord length.

6.1.2.4 Trim Tabs

The use of a trim tab to reduce the viscous drag of the keel fin by shifting the viscous "drag bucket" to higher lift coefficient is reflected in a formula that reduces the viscous drag coefficient for a keel with a trim tab[35].

$$\text{Lift\_Coefficient } Cl = 0.75 \times \frac{Sideforce}{qA} \quad \text{where } q = \tfrac{1}{2}\rho V^2 \quad [55]$$

$$\text{Drag Coeffcient } Cd = 0.00977 \times Cl^2 + 0.00029 \times Cl + 0.0034$$
$$Cd\_diff = 0.33(Cd - 0.0034) \quad [56]$$

Where A is the keel area and q is the dynamic head.

34 1987 ERFXNEW.FOR, MODLDIM2.FOR

35 The form of the code reflects that the drag reduction has been reduced over time because the original formulation was regarded as too punitive in terms of handicap.

Cd_diff is subtracted from the keel strip friction drag coefficient.

6.2 Propeller

The drag of the propeller is calculated as follows:

$$DPROP = \frac{1}{2}\rho V_s^2 \times 0.81 \times PIPA \qquad [57]$$

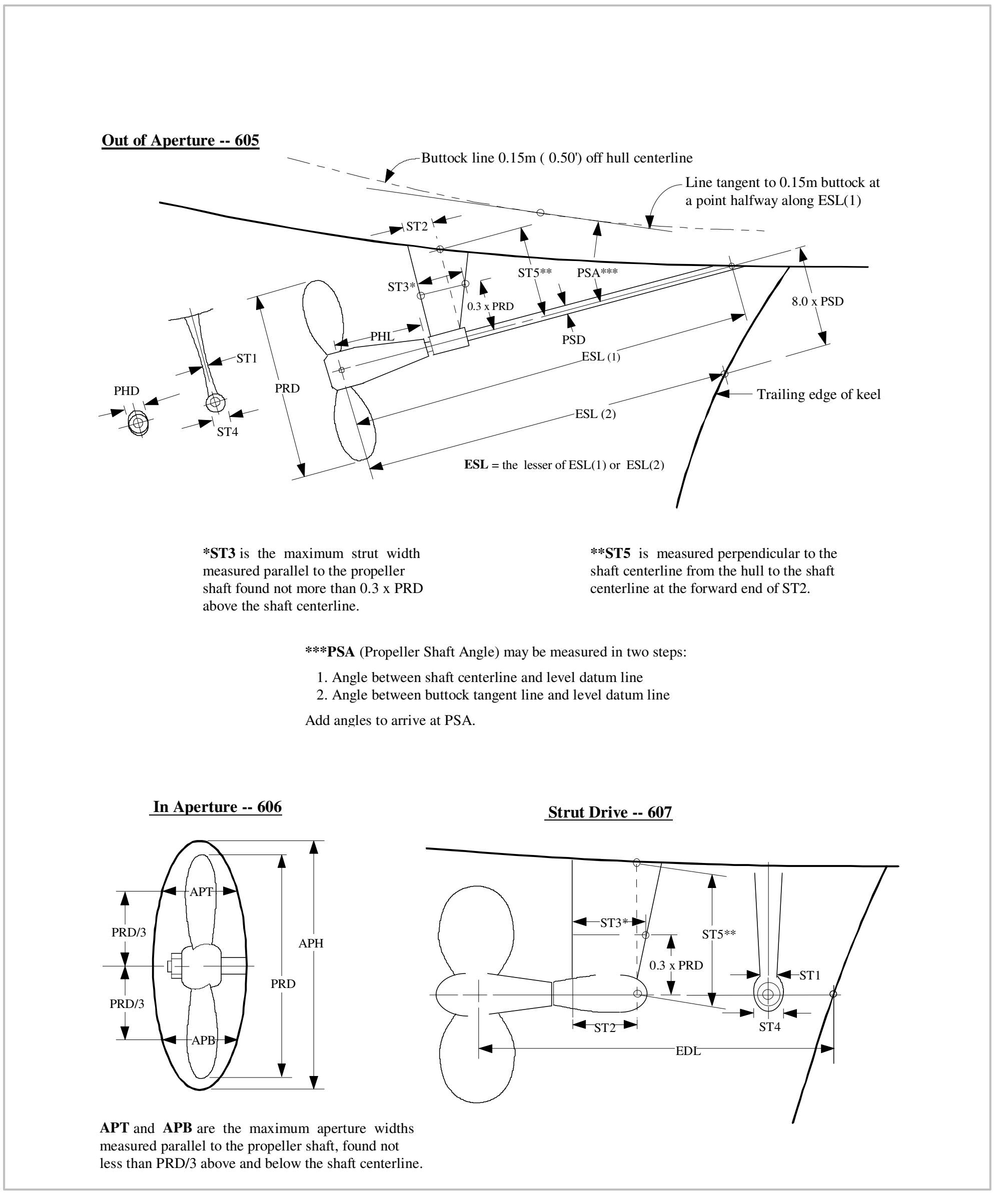


Figure 28. Propeller Installation Dimensions

PIPA is calculated according to the following formulae which depend on the type of installation.

6.2.1 Shaft installation

For all propellers with shaft installation, IPA is calculated according to equation [58]:

$$IPA=(0.04+\sin(PSA))^3\times(PSD(ESL-ST2-PHL)+ST4(ST2+PHL))+0.03\times ST1(ST5-ST4/2) \qquad [58]$$

6.2.1.1 Folding

$$PIPA=IPA+0.65\times(0.9\,PHD)^2 \qquad [59]$$

For a folding propeller PHD shall not be taken greater than 3.5xPSD in the above formula.

6.2.1.2 Feathering

$$PIPA = IPA + 0.70 \times (0.9 PHD)^2 \qquad [60]$$

For a feathering propeller PHD shall not be taken greater than 4.0*PSD in the above formula.

6.2.1.3 Solid 2 blade

$$PIPA = IPA + 0.10 * (PRD)^2 \qquad [61]$$

6.2.1.4 Solid 3 and more blades

$$PIPA = IPA + 0.12 (PRD)^2 \qquad [62]$$

If ESL is less than PRD, PIPA shall be multiplied by 0.5.

6.2.2 strut drive

PIPA shall be determined as follows:

6.2.2.1 Folding or 2 Blade Feather

$$PIPA = 0.06 \times ST1 \times (ST5 - 0.5 \times ST4) + 0.4 \times (0.8 \times ST4)^2 \qquad [63]$$

6.2.2.2 Feathering 3 Blade

$$PIPA = 0.06 \times ST1 \times (ST5 - 0.5 \times ST4) + 0.42 \times (0.8 \times ST4)^2 \qquad [64]$$

6.2.2.3 Solid 2 Blade

$$PIPA = 0.06 \times ST1 \times (ST5 - 0.5 \times ST4) + 0.10 \times PRD^2 \qquad [65]$$

6.2.2.4 Solid 3+ Blades

$$PIPA = 0.06 \times ST1 \times (ST5 - 0.5 \times ST4) + 0.12 \times PRD^2 \qquad [66]$$

Notes:

1. For any strut drive, if EDL is less than 1.5 * PRD, PIPA shall be multiplied by 0.5.
2. The shape of the strut may be modified, but the full functionality of the standard model must be retained and ST1-ST4 values may not be reduced below the unmodified standard dimensions. For handicapping purposes ST1-ST4 shall not be taken bigger than the unmodified standard dimensions.
3. ST4 shall be measured at the aft end of the hub instead of at the point of maximum projected area, better representing the flow separation drag.
4. An upper ST4 limit will be used for the PIPA. This limit depends on the L of the yacht. The maximum is defined by a curve of values just above those typical of most common production units, faired over an ample length range.
   The upper limit for ST4 is thus defined as the lesser of:

$$(4 * 10^{-5} * L^3 - 0.0011 * L^2 + 0.0125 * L + 0.05) \textit{ or } 0.2 \text{ (but never less than 0.1)} \qquad [67]$$

6.2.3 In an aperture

For propellers of any type installed in an aperture PIPA shall be taken as the least of the values determined by the formulae:

$$PIPA = 0.07 \times (PRD)^2$$
$$PIPA = 0.07 \times (APT/4)^2$$
$$PIPA = 0.07 \times (APH/1.125)^2 \quad [68]$$
$$PIPA = 0.07 \times (APB/4)^2$$

6.2.4 Tractor propellers

For tractor propellers of any type installed out of aperture PIPA shall be zero.

6.2.5 Twin screws

IMS has an input to signify twin propeller installations. If this is indicated, PIPA is doubled for any type of installation or propeller.

6.3 Residuary Resistance

The calculation of the wave-making or residuary resistance is based on the calculation of a residuary resistance coefficient at preset values of Froude Number (Fn)[69]. The Fn is a non-dimensional speed based on the yachts IMS L [9]

$$Fn = V / \sqrt{g \times L} \quad [69]$$

The hull is the main element of the residuary resistance, with a small contribution from the appendages.

6.3.1 Canoe Body

The residuary resistance against speed curve is determined over a Fn. Range of 0.125-0.9 in steps of 0.025, using the equation shown below. At each Fn. the coefficients a0-a7 are determined by a least squares regression fit to the tank test data base.
The regression is based on the following:

- A Database of 46 models, the basis DSYHS set plus Delft Sysser 60-63 and “Boxy” boats 1 & 2 with double weighting
- Dense spacing .OFF files
- Resistance measured with sail trimming moment applied
- Data for Froude Number above 0.6 is available for 19 models, 27 estimated by extrapolation
- The coefficients are only valid within the limits shown in Table 12 below.

$$1000Rr/\Delta = a_0 + a_1 Cp + a_2 \frac{B}{T_C} + a_3 L_{VR} + a_4 \frac{A_{WP}}{\nabla^{2/3}} + a_5 \frac{L_{CB}}{L_{VR}} + a_6 \frac{L_{CB}^{\ 2}}{L_{VR}} + a_7 L_{VR}^{\ 2} + SBF \quad [70]$$

$$Where \ \ L_{VR} = L / \nabla^{1/3}$$

		Maxima	Minima
Cp	a_1	.58660	.53060
B/T	a_2	9.46154	2.41549
$L/VOL^{1/3}$	a_3	8.68108	4.32531
$WA/VOL^{2/3}$	a_4	10.46890	3.79808
$LCB/(L/VOL^{1/3})$	a_5	.85842	-.08296
$LCB^2/(L/VOL^{1/3})$	a_6	4.24884	.00163
$(L/VOL^{1/3})^2$	a_7	75.36117	18.70831

Table 12. Residuary Resistance Coefficient Limits

The actual value of residuary resistance (Rr) at the equilibrium speed is calculated from a cubic spline fit through the 26 pre-calculated data points.
The Coefficients are shown in Appendix B

The DSYHS were tested with a standard transom overhang length that had the transom tip a fixed percentage of the waterline length astern of the aft waterline ending. Also the algorithm for calculating the residuary resistance until 2010 contained a “tail effect” which extended the effective waterline length of boats with immersed transom area. Subsequent investigations have demonstrated this assumption to be incorrect and in 2010 a completely revised treatment of stern geometry was implemented. This comprised 3 main effects:

- Removal of LSM4, the sunk length from the determination of L and the associated “tail effect”
- Introduction of a scheme to predict the wave profile along the hull and it’s interaction with the stern overhang. The wave profile is used to calculate an effective overhang which calculates a Froude Number adjustment to reflect the influence of longer and shorter stern overhang on residuary resistance.
- Making a calculation of the extra resistance associated with any area of immersed transom that arises from the calculated wave profile.

6.3.1.1 Transom Overhang

The following section describes the modification of the residuary resistance for boats with overhang lengths different from the standard Delft SYSSER overhang length.
A number of studies on stepwise truncated overhangs performed in Towing Tanks of St.John’s, Southampton, and Delft provided the data to devise a method to adjust the residuary resistance for boats which have different overhangs than the Delft models of which the tank test results are the base for the resistance estimate.

In order to calculate the residuary resistance for a boat, the residuary resistance curve obtained by means of the table of coefficient is modified by changing the Fn for smaller or greater overhang ratios than 0.135, which is the standard of the Delft models. The overhang ratios are taken as LSM5c/LSM1c. LSM5c is the integrated L of the boat sunk to the lowest point of the transom. It reflects the sailing length when the transom begins to be immersed. Both integrated parameters are calculated using the non appended hull.

The change of the Fn is calculated as

$$dFn = Fn \times \frac{\left(\frac{LSM5c}{LSM1c}\right)}{\left(\sqrt[4]{\left(\frac{LSM5c}{LSM1c}\right)_{AverageDelft}}\right) - 1} \times \frac{\left(1 + \sin\left(\frac{0.85 - Fn}{\pi/2}\right)\right)^3}{1.5}$$

$$Fn_{corr} = Fn + dFn$$

This correction is valid over the full Fn-range from .125 to .9.

6.3.1.2 Immersed transom

The following section describes a generic wave height calculation procedure for assessing the immersed transom areas as a function of Froude Number and the calculation of the drag due to the immersed transom
The height of the wave at the end of the static WL was found from the wave elevation observations of 13 non appended models of the Delft Systematic Series to be approximately

$$WH_{WLend} = a1 \times {VLR_{mult}}/{10} \times LSM1c \times c_{vlr}{}^{5}$$

c_{vlr} = Min(mult. 15 , 1.0)

where

$$VLR_{mult} = 2.51 \times \sqrt[3]{VOLc}/{LSM1c^{1.5}LSM1c}^{1.5} - 0.037$$

$$a1 = 1.233 \times \log(Fn) + 1.985$$

Two different stern flow conditions are considered.

a) In the case of the flow separation from the profile of the overhang the wave height at the transom with an standard overhang length of 0.135 × LSM1c is calculated by linear interpolation from the wave height at the end of the static waterline WH_{Wlend} and the point of separation which is defined as the non-dimensional length a2

$$WH_{stdOverhLength} = WH_{WLend} \times \left(1 - {1}/{a2}\right)$$

where

$$a2 = Min\left(506 \times (Fn(L) - 0.19920)^{1.75} \times Overh_{separPt(Fn=.3)}, 1.0\right) 50 \times (Fn(L) - 0.199)^{1.7}$$

and

$$Overh_{separPt(Fn=.3)} = 0.30 + \left(\frac{0.115}{VLRmult}\right)^{4}$$

being the overhang separation point at Fn=0.3

b) In the case of transom flow separation, which occurs when a2 is becoming 1 or greater, the wave height at the transom with an standard overhang length of .135*LSM1c is calculated as

$$WH_{stdOverhLength} = WH_{WLend} \times a3 \times a4(i + x),$$

x = 0 ... 3

with

$$a3 = \frac{(1.1 - Fn)}{\square} 0.975$$

and with a4 being a degradation factor with increasing Fn's and (i) denoting the Fn-index at which a2 becomes 1

a4(i) = 0.25

a4(I + 1) = 0.5

a4(I + 2) = 0.75

a4(I + 3) = 1

The wave height at the real transom is again calculated by linear interpolation (Fig.1) as

$$[WH]_{stern} = dWH \times (0.135 \times LSM1c - ((0.15 \times LSM1c - Overhang)/(0.15 * LSM1c)\ (Overhang$$

with

$$dWH = WH_{Wlend} - WH_{stdOverhLength}$$

and with

$$Overhang = LSM5c - LSM1c,$$

LSM5c being the LSM of the boat sunk to the lowest point of the transom, if above WL.
2011 The wave height at the transom is reduced by the trim effect of shifting the crew 10% LSM 1 forward[36].
The immersed transom area is the area below a horizontal plane of the height $WH_{aboveWL}$

$$WH_{aboveWL} = WH_{stern} + H_{TrProf}$$

with
H_{TrProf} being the intersection of the transom and the regression line from the profile points of the afterbody of the hull.

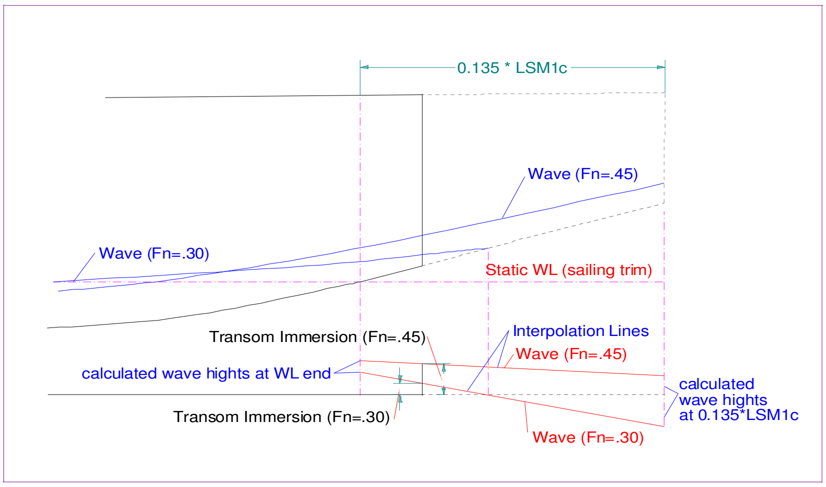


Figure 29. Principle of estimating transom immersion

The viscous drag component due to an immersed transom is calculated by means of Hoerner's formula for the base drag of a fuselage with a truncated tail end.

[36] This was done to discourage the adoption of extreme stern down trim.

$$Cdtransom = .029 \times \frac{(ATR \cdot AMS1c)^{\frac{3}{2}}}{Cdhull}$$

ATR = the immersed transom area as calculated by the above outlined procedure
AMS1c = the midship section area in sailing trim
$Cd_{hull} = Rf_{hull} / (rho/2 * v^2 * AMS1c)$
Rf_{hull} = the frictional resistance of the canoe body

6.3.1.3 SBF

Historically the VPP has been perceived to penalize light boats i.e. high Length/Volume (LVR) boats relative the mainstream fleet. To provide more equitable speed predictions the SBF[37] [71]modifies the residuary resistance coefficients in the Froude number range 0.225-0.375, the term is zero outside this range.

$$SBF = 2.5 \times SBF\_Const \times (1-(5.5/LVR)) \quad [71]$$

Fn	0.2	0.225	0.250	0.275	0.300	0.325	0.350	0.375	0.4
SBF_Const	0.0	0.100	0.300	0.650	1.000	1.350	1.500	1.100	0.0

6.3.2 Appendages

The original Delft Series models had all been tested with a standard keel and rudder and consequently the original MHS approach was to include the appendages as part of the total displacement for the purposes of calculating residuary resistance. On yachts with hull forms where the appendage/canoe body interface was less than well defined this worked satisfactorily. Over time however a more sophisticated treatment was sought, and now all of the DSYHS models have been tested as bare canoe bodies. An algorithm for appendage residuary resistance that is sensitive to both keel volume and depth was derived[38]. The residuary resistance of an element of keel or bulb is based on 2 baseline curves shown in Figure 29. These show the resistance per unit volume 59ormalized against Fn^2 for an element of keel fin or bulb at the standard depth, 0.1L and 0.2L respectively.

[37] 2008
[38] Jim Teeters US Sailing

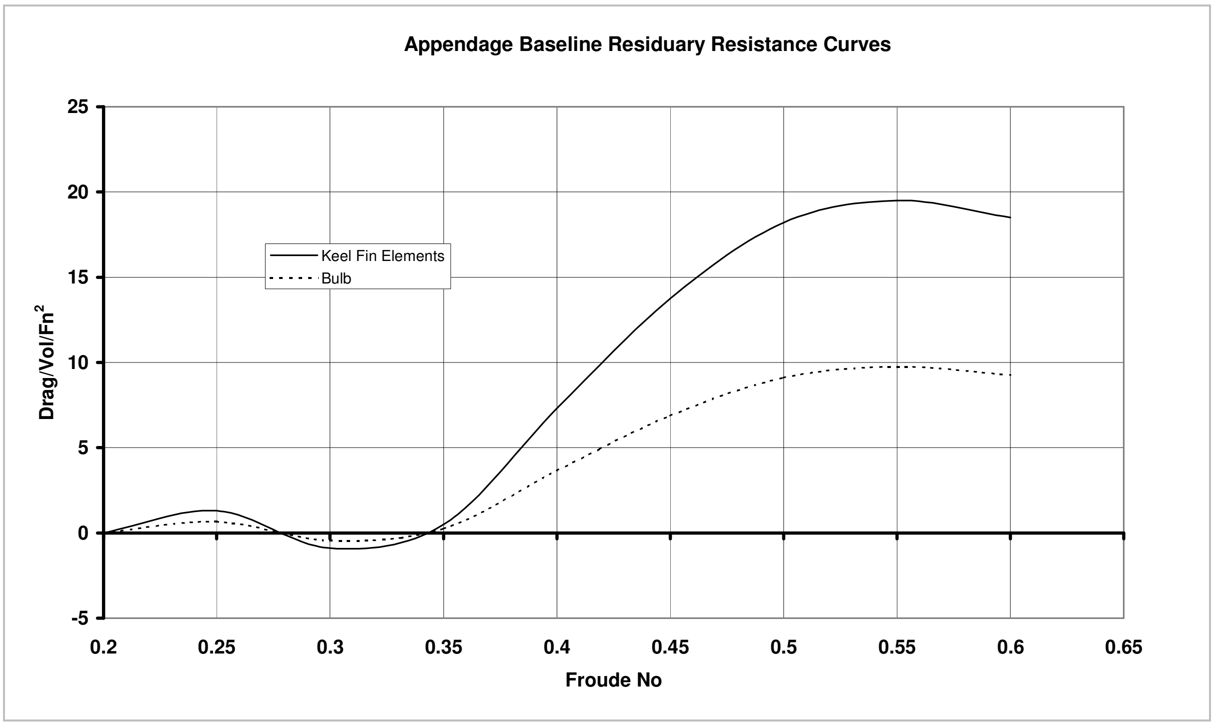


Figure 30. Appendage residuary resistance per unit volume at standard depth

As described in section 8.1.2, the VPP divides the keel into 5 fore and aft strips, stacked on top of each other. The volume and average depth of each strip is calculated. The major factors that influence the wave-making drag of an appendage "strip" are:

1) Appendage strip volume
2) Appendage strip depth below the free surface
3) Boat speed
4) Whether or not that piece of volume is a bulb or part of the vertical foil

Bulbs are more three-dimensional in nature, apparently cause less disturbance to the water flow, and have less drag per unit volume. The drag of bulbs per unit volume is approximately half that of keel strips. The attenuation of drag with depth is approximately linear for both keel strips and bulbs. Currently, the VPP looks for bulbs only in the deepest strip of a keel. The test criterion is the ratio of the chord length of that deepest strip to the chord length of the strip above it. If that chord ratio is ≥ 1.5, then the deepest strip is considered to be a bulb. If the ratio ≤ 1.0, the strip is a keel strip. If the ratio is between 1.0 and 1.5, the drag is found by linear interpolation over chord ratio of the two drags found by treating the strip as a bulb and as a keel.

Where the upper keel strip is determined to be greater than 1.5 x the average of strips 2,3, & 4 then the residuary resistance of the strip is calculated using the "Bulb" residuary resistance line[39].

For traditional style hulls where the keel chord exceeds 50% of LSM1 then the keel volume is added to the canoe body volume for the purposes of calculating the residuary resistance.

$$D_{RESIDUARY} = Rr_{Canoe} + Rr_{Appendage} \quad [72]$$

6.4 Drag due to heel

Drag due to heel arises from three sources:

[39] 2011 To address the use of high volume keel strakes.

1) A modification of the viscous resistance of the heeled hull, this arises from changes to the wetted surface area with heel angle, and also a modification the pressure form drag due to the change in hull surface curvature experienced by the water flowing past
2) A modification to the residuary resistance due to a change in immersed length of the hull
3) A change to the residuary resistance of the hull due to the asymmetry of the heeled shape.

Once again the VPP divides the drag into components that are treated as viscous, or residuary in nature.

6.4.1 Viscous Resistance

The change in viscous resistance due to heel is assumed to reflect the change in wetted surface area of the canoe body as heel angle changes.

6.4.2 Residuary Resistance

The residuary resistance change due to heel is determined as a function of the hull parameters (Length, Beam/Draft ratio etc.) at each heel angle compared to their upright equivalents. It is apparent that the changes in the yacht's drag with heel angle are not just due to a simple change in wetted area and residuary resistance, there are almost certainly a viscous form factor effect which is hard to quantify.
In the interests of simplicity the drag due to heel is held within the residuary drag formulation, but the corrector is conditioned by a "Froude Number Curve"[74] which amplifies the residuary correction at low Froude numbers.

6.4.2.1 Heeled Residuary Resistance Multiplier

Definitions & Limits

ϕ = *sailing heel angle*
Fn = *non-dimensional speed*
$WPA00$ = *waterplane area upright.*
$WPA\phi$ = *waterplane area at the sailing heel angle*

$Lxx\_L00 = Lsm1\varphi / xCanoeLsm1$ Limit $0.9 \le \text{Lxx\_L00} \le 1.1$

$LBR = xCanoeLsm1 / xCanoeB$ Limit $2.0 \le LBR \le 6.0$

$BTR = xCanoeBTR$ Limit $3.0 \le BTR \le 7.0$

$LVR = \dfrac{CanoeIMSL}{\sqrt[3]{xCanoeVol}}$ Limit $4.0 \le LVR \le 8.0$

$$HeelExp = -1.2806 - 0.1092BTR + 0.4385LVR \quad [73]$$

$$FnCurve = 1.01506 + 0.29348 \times \left(ARCTAN((Fn - 0.25495) / -0.01369) + \frac{\pi}{2} \right) / \pi \quad [74]$$

$$RRMULT = 1.0 + (FnCurve - 1.0) \times 0.02307 \times \varphi^{HeelExp} + \frac{(0.9613 - 0.1123 \times Fn - 1.0)}{0.03} \times (Lxx\_L00 - 1) \quad [75]$$

$$LWPACorr = (LSM1\phi / LSM1) \times \sqrt{\frac{WPA00}{WPA\varphi}} \quad [76]$$

$$RRMULT = \frac{RRMULT}{LWPACorr} \quad [77]$$

6.4.3 Induced Drag

The induced drag arises from the production of lift, and is predominantly associated with the energy losses in the tip vortex created by the keel and rudder. The induced drag is proportional to the keel lift coefficient and the yacht's effective draft (MHSD section 4.3.4). It is calculated from the formula:

$$Drag_{INDUCED} = {F_H}^2 \big/ \pi\rho V^2 MHSD \qquad [78]$$

where F_H = Heeling Force.

6.4.3.1 Froude Number Effects

If the yacht sailed in a homogeneous fluid then the above equation would be a satisfactory description of the induced drag. However in practice both speed and heel angle affect the value of effective draft. As the yacht sails faster the mid-ship wave trough deepens, and as the yacht heels the root of the keel and rudder move closer to the free surface. Both of these effects allow the pressures on the keel and rudder to produce surface waves, or in the worst case ventilation, particularly at the rudder root. These effects mean that the water surface acts less and less as a reflection plane as speed and heel angle increase. In order to account for these effects a speed and heel angle correction to the upright, zero speed effective draft was adopted[40]. The form of the correction for two hulls with BTR = 4 and 2 are shown in Figure 30. The figure shows how the deleterious effects of speed and heel angle on induced drag are reduced as beam to draft ratio is reduced. Once again, like the heel drag factor it is a plausible and appropriately sensitive representation of a complex physical phenomenon.

[40] 1994

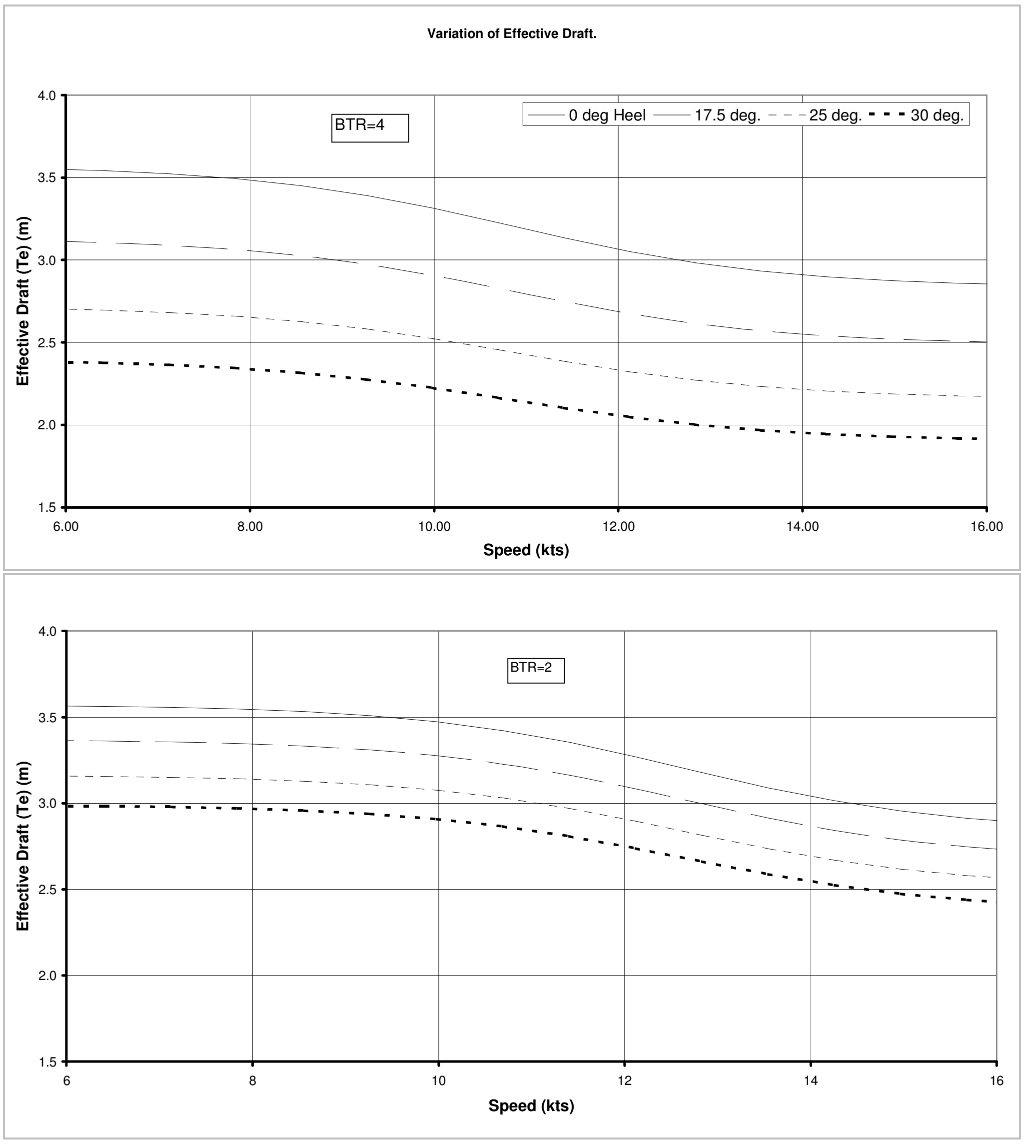


Figure 31. Variation of effective draft with speed and heel angle (Upper BTR = 4; Lower BTR =2)

6.4.3.2 *Unsteady Effects*

A final modification to the effective draft formula was subsequently adopted to address a trend towards deeper and deeper keels on racing yachts. This trend arose because of the nature of fleet racing in yachts of similar performance: it was found that extra draft, even though the VPP predicted higher speeds, was beneficial in being able to achieve and maintain a place in the front rank of the race to the windward mark. Also on windward/leeward races which, by definition, involve a lot of tacking the deep draft keel proved to be more competitive in the “down speed” condition coming out of tacks. Equation [78] shows that if heel angle, and therefore heeling force, are constant the induced drag is inversely proportional to speed^2. Thus the effect of keel draft is handicapped only for the induced drag at “full speed”, whilst in a race with a lot of tacking some note should be taken of the additional induced drag occurring when sailing at lower speed.

This effect is taken into account by the use of an “unsteady factor” (FUNSTEADY). The “unsteady factor” is based on a mean IMSD/length ratio of 0.19, at shallower draft than this FUNSTEADY is reduced, at deeper draft FUNSTEADY is increased. This is purely a type-forming modification to the VPP. The final equation for induced drag is shown in Equation [79]. The function in speed and heel angle $fn(\phi V_S)$ is that shown in Figure 31.

$$D_I = \frac{{F_H}^2 / MHSD^2 \pi \rho V^2}{FUNSTEADY^2 \times \left[fn(\phi V_S) \right]^2} \qquad [79]$$

Where: $FUNSTEADY = 0.95 + (T_R / L - 0.19)$

6.4.4 Rail-under drag

Rail-under drag is not intended to calculate the drag of immersing the lee rail, it is an artifice intended to prevent the VPP finding equilibrium sailing conditions at high heel angles. Rail-under drag is zero up to a heel angle of 30 degrees. Above this value the upright residuary resistance is multiplied by a factor and added to the total drag.

$$DRU = 0.0004 \times D_{RESIDUARY} \times (\phi - 30)^2 \qquad [80]$$

6.5 Added Resistance in Waves, R_{AW}

The addition of an added resistance in waves (R_{AW}) module to the VPP[41] was brought about by the fact that cruising yachts, with outfitted interiors, were disadvantaged relative to their “stripped out” racing rivals. This is not surprising, since reducing the yacht’s moment of inertia by concentrating weight close to the centre of gravity will yield a performance gain when sailing in waves. The US Sailing funded project to introduce this feature into the VPP had three aims which tackled the fundamentals of predicting R_{AW} :

1) Define a sea spectrum (wave energy density function) appropriate to the sailing venue
2) Devise a plausible and appropriately sensitive physical model of how parametric changes to the yacht affect R_{AW} when sailing in the sea state defined in 1
3) Devise a method by which a yacht’s pitch inertia could be determined directly by a physical test, in the same way that stability is measured by an inclining test.

6.5.1 Wave Climate

As part of the research prior to introducing the R_{AW} module, US Sailing funded the deployment of a wave height measuring buoy at several popular sailing venues. The buoy was deployed during typical races and the water surface elevations were recorded together with the wind speed. On the basis of these measurements a single definition of wave climate was derived in the form of a wave energy spectrum normalised for a true wind speed of one knot. This approach has the merit that it is relatively easy to apply, because, whilst the significant height becomes a function of wind speed the modal period remains fixed at 5 seconds.

[41] 1990

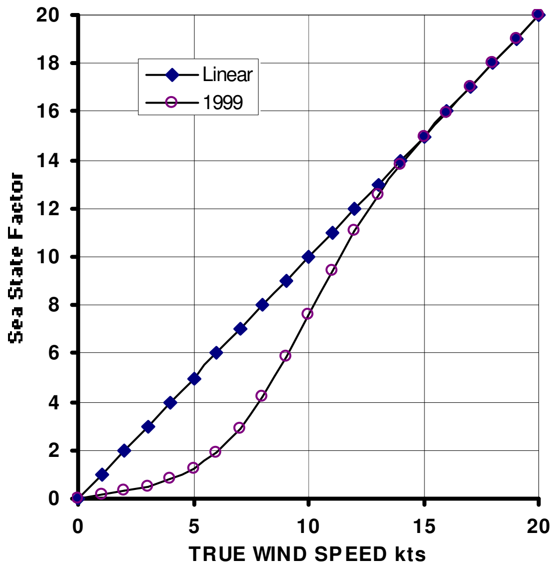


Figure 32. Wave energy as a function of True Wind Velocity

When this experimentally-derived linear variation of wave energy with wind speed was implemented it was found that the magnitudes of R_{AW} were too high. Added resistance effects were seen to be dominating handicaps in 6 to 8 knots of wind when the sailors could see that no waves were present on the race course. In order to correct this a "bubble" (or more correctly a dimple) was put in the curve that defined the wave energy as a function of wind speed.
Figure 31 shows the original linear sea-state factor together with the further reduction in the light wind wave energy agreed at the 1998 annual meeting. The formulation is shown in equation [81].

$$f(V_T) = V_T \left\{ -0.8375 \left[1.175^{\left(-0.00248 \cdot V_T^{3.5}\right)} \right] \right] \qquad [81]$$

The $f(V_T)$ function is shown in Figure 31.

6.5.2 Determination of added resistance response

Equation [82] shows how the added resistance is calculated from the product of the wave energy spectrum and the R_{AW} RAO. The wave spectrum in each wind speed is defined by a constant times $f(V_T)$. The task facing the handicappers was to produce RAO values for parametric variations of sailing yacht hull forms.

$$\overline{R_{AW}} = 2 \cdot \int_0^\infty R_{AW} \Big/ \zeta_a^2 \cdot S_\zeta(\omega) d\omega \qquad [82]$$

Equation [83] shows the formulation[42] and the baseline parametric values are shown in Table 13.

$$R_{AW} = 2\rho g L f_S f(Vt) \cdot 0.55 \cdot f(\beta_T) \times f(L_{40}) \times \left\{ 0.00146 + f(Fn) + f(K_{YY}) + f\left(\frac{L}{B}\right) + f\left(\frac{B}{T}\right) + f(LCB - F) \right\} \qquad [83]$$

Where:

[42] 1999

$$f_S = 0.64\,(Fn - .325)$$

$$f(Fn) = 0.00191\,(Fn - .325)$$

$$f(k_{YY}) = 0.01575\,(GYR - 0.25)$$

$$f(L/B) = [(5.23^{-L/B}) - (5.23^{-3.327})] / 8.494$$

$$f(B/T) = (0.000166 * (B/T_C - 4.443))$$

$$f(LCB - F) = 0.01150 * [(LCB - LCF) - (-0.03)] + 0.05780 * [(\text{LCB-LCF})^2 - (-0.03)^2]$$

$$f(L_{40}) = 0.5059 \times \log(L/40) + 1$$

$$f(\beta_T) = \cos(\beta_T) / \cos(40)$$

PARAMETER	SERIES RANGE	BASE VALUE
GYR	0.2-0.32	0.25
L/B	2.77-4.16	3.327
L^3/∇	103-156	125
LCB	0.50-0.56	0.53
LCF	0.54-0.60	0.57
B/T_C	--	4.443
LCB-LCF	--	-0.03
Fn	--	0.325

Table 13. Added Resistance in Waves; parametric limits and base values

In equation [83] the f_S factor provides a means to adjust the added resistance values and perhaps can be thought of as a sea energy or strength coefficient. A value of 0.64 is used.

The 0.55 factor represents the wave direction function, necessary because the R_{AW} calculations for the series were done in head seas, but yachts sail at approximately 45 degrees to the prevailing wind and sea direction.

The $f(\beta_T)$ function makes the added resistance a cosine function of heading with 40 degrees true wind (wave) heading as the basis.

The remaining functions in equation [83] take the difference between the boat and the base boat and then evaluate the increase or decrease in R_{AW}. The calculation of R_{AW} is done using the physical parameters (L, B, T_C) appropriate to the sailing heel angle.

6.5.2.1 Determination of Pitch Radius of Gyration (Kyy)

The third element of the added resistance calculation is the determination of the pitch inertia of the yachts hull and rigging.

A yachts base radius of gyration is calculated from the equation [84], and then other declared features of the yachts construction and rig accrue adjustments (Gyradius_inc) to this base gyradius. For example carbon fibre hull construction attracts a gyradius_inc of -0.010.

$$K_{YY} = 0.222 \times (LOA + LSMH)/2 \qquad [84]$$

Where:

$$LSMH = 0.3194 \times (2 \cdot LSM1 + LSM4)$$

$$GYR = K_{YY} / LSMH - 0.03 + Gyradius\_inc$$

Adjustments are made to the base gyradius according to the following recorded characteristics of the yacht:

1. If Mast Weight (MWT) and Mast Center of Gravity (MCG) have been recorded, the gyradius contribution of the mast is assessed as compared to that of a hypothetical base aluminum mast (Default mast weight – DMW) and a corresponding mathematical gyradius adjustment is made;

   Default Mast Weight:
   DMW = (((.00083*IG*(IG+HBI))+(.000382*IG*TML)))*(YP)^0.5 (lbs)
   Default Mast VCG:
   DMVCG = 0.415*(IG+P+BAS)/2 –BAS (ft) above BAS
   Default Rigging Weight:
   DRW = LRW+JRW (lbs)
   Default Rigging VCG:
   DRVCG = (0.372*IG*LRW+0.5*(P+BAS+0.85*IG)*JRW)/DRW – BAS (ft) above BAS.
   Default Mast+Rigging Weight:
   DMW+DRW (lbs)
   Default Mast+Rigging VCG above BAS:
   (DMW*DMVCG+DRW*DRVCG)/(DMW+DRW) (ft).
   Where:
   LRW (Lower Rigging Weight) = 0.000155*IG*YP (lbs)
   JRW (Jumpers Rigging Weight) = 0.000027*(P+BAS-0.85*IG)*YP (lbs) (0 for masthead)
   YP = (((RM25 * 25) + CARM * CW * cos(25°)) / (CP/2))
   TML (Top Mast Length) = 0 on masthead and P + BAS – IG on fractional
   RM25 = Righting Moment per degree at 25° heel
   CARM = Crew Righting Arm
   CW = Crew Weight
   CP = Calculated Chainplate Width : Max(0.46 * J, 0.135 * IG)
   "Masthead" is defined as an IG >= 0.95*(P + BAS).

2. For a yacht with a carbon mast, where MWT and MCG are not recorded, the base gyradius shall be adjusted taking as mast weight:

   MWT = DMW *SQRT (70000/130000)

   The mast weight for carbon mast is decreased of the square root of the ratio of the Young Modulus of aluminium (70000 Mpa) and that of a very high modulus carbon mast (130000 Mpa) If the boat is fitted with fiber rigging (PBO, carbon or similar) the rigging weight will be taken as: Rigging Weight = 0.2 * DRW, being 20% of a conventional normal rod rig the weight of a aggressive fiber weight.

3. Where MWT and MCG are not recorded, the number of spreader sets (including jumpers – one or zero), adjustable inner forestays and running backstays (see 810.2I) are totaled. Gyradius is increased by 0.002*CANOEL multiplied times the number by which the above total is less than 6.
   This total is not taken less than zero;

4. If a yacht has a mizzen mast, Gyradius is increased by 0.002*CANOEL.

5. An adjustment is made for the classification of hull construction as follows:
   SOLID: 0.016*CANOEL is added to Gyradius
   CORED: 0.008*CANOEL is added
   LIGHT: No adjustment
   CARBON: 0.005*CANOEL is subtracted
   CARBON FOR C/R 0.010*CANOEL is subtracted
   HONEYCOMB: 0.006*CANOEL is subtracted where applicable in addition to adjustments listed above;

6. For each year the yacht's Age Date is less than 1989, 0.002*CANOEL is added to Gyradius, with a maximum addition of credit for 8 years (an Age Date prior to 1981 is taken as 1981).

7. If the yacht has Forward Accommodation, FWD ADJ = 0.004 (see 11 below);

8. If the yacht's rudder construction is carbon fiber, 0.003*CANOEL is subtracted from Gyradius;

9. If the yacht is in the cruiser/racer division and complies with IMS Appendix 1, C/R ADJ = 0.006 (see 10 below);

10. Any FWD ADJ (7 above) and any C/R ADJ (10 above) shall be added together and the sum reduced according to an indicator of performance potential, i.e., sail area /volume ratio. The resulting Accommodation Gyradius Increment is calculated as follows:
    ACC GYR INCR = (C/R ADJ + FWD ADJ) * ((0.6763 * L + 19.6926 – SA/VOL)/(0.2263* L + 2.6926)).
    The term multiplying (C/R ADJ + FWD ADJ) shall be neither negative nor greater than 1.0.
    SA/VOL = (AREA MAIN + AREA GENOA) / $(DSPS/1025)^{2/3}$.
    ACC GYR INCR * CANOEL is added to Gyradius.

6.5.2.2 Cruiser/Racer pitch gyradius allowance scheme

This credit scheme is intended to allow for the greater pitching inertia of boats that race with anchor and chain in the bow (anchor and chain should be located in the forward 30% of the boat and should be lodged in forepeak fully reachable from deck.

The total gyradius increment due to the anchor and chain shall not be taken as more than 0.013*CANOEL. The gyradius increment will be added to the gyradius derived in [84].

7 Environment

7.1 Wind Triangle

The wind triangle relationships as implemented in the VPP include the effects of heel and the assumed wind gradient. The VPP resolves the total aerodynamic force relative to the fore and aft center plane of the mast, a lift force normal to it and a drag force in the plane of the mast. Therefore in order to introduce the effect of heel the True wind vector is modified as follows: First, the True wind vector is resolved into components perpendicular and parallel to the yacht's velocity vector. Only the perpendicular component is multiplied by the cosine of the heel angle. To account for the variation in True Wind Velocity with height, both components are multiplied by a factor representing this change. Once this is done, the now modified True wind vector can be used in the normal vector analysis to yield the apparent wind vector at the centre of effort of the sails.

$$V_{Tz} = V_{Tzref} . (z / zref)^{0.109} \quad [85]$$

Where:

Z = *height above water plane*

$zref$ = *reference height for V_T measurements*

The apparent wind angle (β_A) is calculated from the following formula.

$$\beta_A = \tan^{-1}\left\{\frac{V_T \sin\beta_T \cos(\phi)}{V_T \cos\beta_T + V_S}\right\} \quad [86]$$

The corresponding apparent wind speed (V_A) is calculated as follows.

$$V_A = \sqrt{(V_T \sin\beta_T \cos\phi)^2 + (V_T \cos\beta_T + V_S)^2} \quad [87]$$

7.2 Sailing Angles

The VPP calculates the sailing speed at the following True Wind Angles and wind speeds:

Velocity Prediction in Knots for True Wind Speeds							
Wind Velocity	6 kt	8 kt	10 kt	12 kt	14 kt	16 kt	20 kt
Beat Angles	44.5°	42.1°	39.2°	37.7°	36.7°	36.1°	35.7°
Beat VMG	3.85	4.63	5.07	5.34	5.51	5.62	5.71
52°	5.98	6.91	7.33	7.55	7.70	7.79	7.88
60°	6.37	7.19	7.59	7.80	7.95	8.05	8.15
75°	6.66	7.41	7.87	8.15	8.32	8.44	8.60
90°	6.63	7.45	7.99	8.27	8.57	8.77	8.99
110°	6.40	7.29	7.85	8.33	8.76	9.06	9.46
120°	6.03	7.03	7.64	8.13	8.60	9.07	9.85
135°	5.10	6.37	7.16	7.70	8.16	8.61	9.61
150°	4.21	5.39	6.40	7.12	7.65	8.09	8.95
Run VMG	3.65	4.67	5.55	6.29	6.94	7.46	8.31
Gybe Angles	140.8°	144.4°	151.7°	162.2°	169.9°	174.1°	175.3°

Table 14. VPP True wind angle and wind speed matrix

The calculations are done for the upwind sails (mainsail and jib) and downwind for the mainsail with each declared off wind sail.

The results are polar curves for each True wind speed, and the program then chooses the sail combination to produce best speed and uses this in the table of handicaps.

7.2.1 Velocity Made along the Course. (VMC)[43]

The VMC concept is similar to the VMG for upwind or downwind sailing. The goal is to reach the mark, which is at an hypothetical prescribed heading, in the minimum time. This is accomplished sometimes by a course different from the straight, shortest one. Sometimes a course made of two

[43] 2011

legs, one closer to the wind and the other farther from it, is faster than the direct one. The implementation of this concept is made by calculating the best VMC for the (TWS,TWA) printed in the certificate, but using a splined continuous polar of the best performance of the boat evaluated at two degree intervals.

8 Handicapping

8.1 VPP results as used for scoring

8.1.1 Velocity prediction

All the calculations performed by LPP and VPP after taking in account Dynamic and Age allowances are eventually used in calculations of speed predictions for 7 different true wind speeds (6-8-10-12-14-16-20 knots) and 8 true wind angles (52°-60°-75°-90°-110°-120°-135°-150°), plus the 2 “optimum” VMG (Velocity Made Good) angles: beating (TWA=0°) and running (TWA=180°), which are calculated obtaining an optimum angle at which the VMG is maximized. The calculations are done for the upwind sails (mainsail and jib) and downwind for the mainsail with each declared off wind sail, where the program then chooses the sail combination to produce best speed.

Velocity Prediction in Knots for True Wind Speeds							
Wind Velocity	6 kt	8 kt	10 kt	12 kt	14 kt	16 kt	20 kt
Beat Angles	44.6°	42.4°	39.6°	38.1°	37.3°	36.7°	36.3°
Beat VMG	3.88	4.66	5.09	5.35	5.53	5.63	5.72
52°	6.04	6.98	7.39	7.62	7.76	7.86	7.94
60°	6.44	7.27	7.66	7.88	8.02	8.12	8.23
75°	6.92	7.66	8.04	8.27	8.42	8.54	8.72
90°	7.04	7.74	8.21	8.57	8.79	8.96	9.23
110°	6.62	7.43	7.98	8.47	8.93	9.31	9.88
120°	6.18	7.15	7.76	8.26	8.74	9.21	10.14
135°	5.22	6.50	7.28	7.82	8.29	8.75	9.79
150°	4.31	5.50	6.51	7.24	7.76	8.21	9.09
Run VMG	3.73	4.76	5.65	6.39	7.05	7.58	8.44
Gybe Angles	140.7°	144.2°	151.8°	162.2°	170.4°	174.7°	175.7°

Table 15. Velocity prediction printed on the 1st page of the ORC International certificate

8.1.2 Time allowances

The unique feature of ORC Rating system, making it fundamentally different from any other handicap system and much more precise, is its capacity to give and rate different handicaps for different race conditions because yachts do not have the same performance in different conditions. For example, heavy under-canvassed boats are slow in light airs but fast in strong winds. Boats with deep keels go well to windward and light boats with small keels go fast downwind.
This means that yachts will have a variable time allowance in any race depending on the weather conditions and the course configuration for that particular race as managed by the Organizer.
For the purpose of the Performance Curve Scoring as defined in the ORC Rating Rule 402, velocity predictions are also expressed as time allowances in s/NM where TA = 3600/v.

TIME ALLOWANCES							
Wind Velocity	6 kt	8 kt	10 kt	12 kt	14 kt	16 kt	20 kt
Beat VMG	927.6	771.9	706.8	672.3	651.5	639.0	629.8
52°	596.0	516.0	486.9	472.6	463.8	458.3	453.2
60°	559.0	495.3	469.7	457.0	448.8	443.4	437.7
75°	520.1	469.7	447.8	435.3	427.3	421.5	412.9
90°	511.1	465.1	438.4	419.9	409.5	401.9	389.9
110°	544.2	484.5	451.2	425.2	403.3	386.6	364.4
120°	582.1	503.2	464.1	435.8	411.9	390.7	355.0
135°	690.3	554.2	494.4	460.3	434.1	411.5	367.8
150°	835.9	654.7	552.7	497.3	463.8	438.3	396.0
Run VMG	965.2	756.0	637.5	563.1	510.7	475.2	426.7
Selected Courses							
Windward / Leeward	975.5	787.0	689.5	632.1	594.5	569.5	539.1
Circular Random	790.4	643.4	565.5	520.4	492.2	473.0	447.3
Ocean for PCS	899.6	708.8	601.4	534.7	490.1	458.2	413.9
Non Spinnaker	849.0	683.5	594.3	542.0	509.4	487.9	460.5

Table 16. Time Allowances and Selected Courses on the 1st page of the ORC International certificate

From the time allowances calculated for 9 wind angles and 7 wind speeds, 4 types of pre-selected courses are also available:

a) **Windward/Leeward** (up and down) is a conventional course around windward and leeward marks where the race course consists of 50% upwind and 50% downwind legs;
b) **Circular Random** is a hypothetical course type in which the boat circumnavigates a circular island with the true wind velocity held constant;
c) **Ocean for PCS** is a composite course, the content of which varies progressively with true wind velocity from 30% Windward/Leeward, 70% Circular Random at 6 knots to 100% Circular Random at 12 knots and 20% Circular Random, 80% reach at 20 knots;
d) **Non-Spinnaker** is a circular random course type (see above), but calculated without the use of a spinnaker.

8.1.2.1 Wind averaging

The selected courses are calculated applying a “wind averaging” operator that smooths the individual performance curves for each yacht, taking into account not only each considered wind speed as calculated by the VPP, but a normal distribution across the range that accounts for the 23.58% of the accounted wind speed, 19.8% for 2 kts above and below, 11.73 for +-4 kts, 4.89 for +-6 kts, and 1.79 for +- 8 kts.
The wind averaging operator algorithm for the Windward/Leeward (W/L) selected course is different from the one used for the other selected courses. It is not used for the constructed course method.

8.2 Simple scoring options

ORC International and ORC Club certificates are also providing simple scoring options using the ratings determined as single, double or triple number. For any of the simple scoring options, ratings are given for the offshore (coastal/long distance) and for the inshore (windward/leeward) courses.

SCORING OPTIONS	OFFSHORE COASTAL / LONG DISTANCE			INSHORE WINDWARD / LEEWARD		
Time On Distance	581.9			646.5		
Time On Time	1.0311			1.0441		
Performance Line	PLT 0.838		PLD 84.1	PLT 1.207		PLD 377.4
Triple Number	Low 1.0309	Medium 1.2987	High 1.4539	Low 0.7807	Medium 1.0450	High 1.2089

Table 17. Simple scoring options on ORC International & ORC Club certificate

8.2.1 Time on Distance

Corrected time = Elapsed time – (ToD x Distance)

Offshore Time on Distance coefficient is GPH, a General Purpose Handicap also used as an average representation of all time allowances for simple comparisons between boats and possible class divisions. It is calculated as an average of the time allowances of 8 and 12 knots true wind speed for the Circular Random pre-selected course.

Inshore Time on Distance coefficient is calculated as the average of windward/leeward time allowances in three conditions below multiplied by their respective weights:

25% WW/LW 8
40% WW/LW 12
35% WW/LW 16

8.2.2 Time on Time (ToT)

Corrected time = ToT x Elapsed time

Offshore Time on Time coefficient is calculated as 600/Offshore ToD.
Inshore Time on Time coefficient is calculated as 675/Inshore ToD.

8.2.3 Performance line

*Corrected time = (PLT * Elapsed time) – (PLD * Distance)*

Performance Line Scoring is a simplified variation of Performance Curve Scoring, where curve of time allowances as a function of wind speed is simplified by the straight line intercepting the performance points of 8 and 16 knots of wind for a given course (Figure 32).

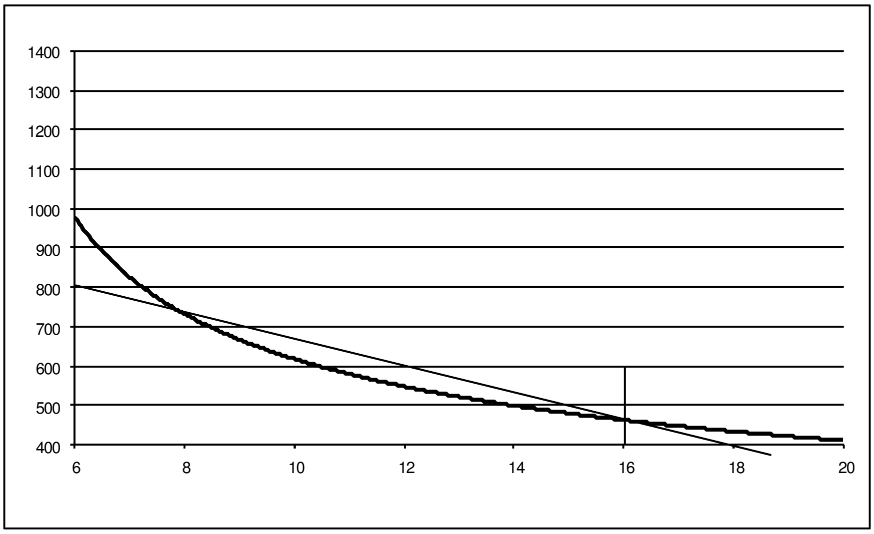


Figure 33. Performance line scoring

Offshore Performance line coefficients are calculated using time allowances for the Ocean type of pre-selected course.
Inshore Performance line coefficients are calculated using time allowances for the Windward/leeward type of pre-selected course.

8.2.4 Triple Number

Corrected time = ToT (Low, Medium or High) x Elapsed time

Triple number scoring coefficients are given are given for three wind ranges:

1) Low range (less than 9 knots)
2) Medium range (equal or more than 9 but less than 14 knots)
3) High range (14 or more knots)

The ToTs displayed on the certificate are derived as follows. The three wind velocity ranges (Hi, Medium, Low) are each comprised of weighted averages of several Time Allowances (s/NM) selected from the familiar seven ORC wind speeds. The “cookbook” recipe for proportions in each of the three wind ranges is given in table 18. The result is a form of wind-averaging for each of the three Triple Number wind ranges:

Wind Speed:	6 kt	8 kt	10 kt	12 kt	14 kt	16 kt	20 kt
Low Range	1 part	1 part					
Med Range		1 part	4 parts	4 parts	3 parts		
Hi Range					2 parts	3 parts	3 parts

Table 18. Time allowance weighting table

Once a single weighted average sec/mi Time Allowance has been calculated for each of the three wind ranges, these are converted to a ToT by the formula ToT = 675/TA.
Offshore Triple Numbers coefficients are calculated using time allowances for the Circular Random type of pre-selected course.
Inshore Triple Numbers coefficients are calculated using time allowances for the Windward/leeward type of pre-selected course.

9 Appendix A: Offset File (.OFF) Format

Offset file describes the shape of the hull together with appendages as a sequence of point measurements arranged in transverse stations. Points along the selected stations are taken from the bottom up with an ORC approved hull measurement device capable to produce a list of the points in the co-ordinate system as follows:

a) X axis – longitudinal with 0 at stem and positive towards the stern
b) Y axis – transverse with 0 at the centerline and positive towards the beam
c) Z axis – vertical with 0 at the waterline and positive upwards

Stations are taken at 5% intervals, doubled to 2.5% in the front 15% of the hull. The measurements taken on port and starboard sides are collapsed in the OFF file as if they were on a single side, but they are identified by a station code, which is 1 for starboard and 2 for port. Freeboard stations are measured from both sides. Appendages such as keel and rudder are measured along transverse stations as any other, and extra stations need to be placed at any vertex of appendage in its profile.
Moveable appendages as centerboards, daggerboards and bilgeboards if fitted, don't need to be measured. There is a maximum limit in the LPP of 180 points per station and 180 stations. The LPP may add points and stations internally.

Units may be in decimal feet *100, or integer millimeters.

OFF file is an ASCII file format with the fields separated by commas and in the required character positions as follows:

First 4 lines are header with general hull data as follows:

```
HH:MM:SS, DD/MM/YY,MEAS#,MACH,   FILE,CLASS                        ,1MMYY
   0.000,   0.000,   0.000,   0.000
   0.000,   0.000,   0.000,   0.000
     NST,    LOA ,     SFJ,  SFBI
```

Line 1

Label	Columns	Explanation
HH:MM:SS	1-9	Time of measurement
DD/MM/YY	11-20	Date of measurement
MEAS#	22-26	Measurers code
MACH	28-31	Machine code. (If ≤ 0 measurements are in ft*100)
FILE	33-39	File name
CLASS	41-64	Class
1MMYY	66-70	Age date with month and year. "1" in front is added for 2000 and following years

Line 2&3 (Metric System)

```
   SFFPs,   FFPVs,   SAFPs,   FAPVs
   SFFPp,   FFPVp,   SFFPs,   FAPVp
```

Label	Columns	Explanation
SFFPs, SFFPp	1-8	Distance from stem to the forward freeboard station (port & starboard)
FFPVs, FFPVp	10-16	Vertical distance from the forward freeboard station uppermost point to the sheerline where sheer point can not be taken (port & starboard)
SAFPs, SAFPp	18-24	Distance from stem to the aft freeboard station (port & starboard)
FAPVs, FAPVp	26-32	Vertical distance from the forward freeboard station uppermost point to the sheerline where sheer point can not be taken (port & starboard)

Line 2&3 explanation (US option)

```
-99,FFLAP,FALAP,FGOLAP
LBGLAP,KLEPFG,dummy,dummy
```

In this alternative format that is associated with a number of HMI US machines in line 2 field 1 is a negative number, which means also that measurements are in ft*100. This is followed by IOR existing freeboard measurements and locations, and the “wing keel” indicator, that usually is defined by a code “4” applied in the wing/bulb widest point. This is obsolete after 2005 due to a different treatment of the wing/bulb keel aerodynamics.
The last 2 fields of line 3 are just spare in this optional formatting.

Line 4

Label	Columns	Explanation
NST	6-8	Number of stations
LOA	10-16	Length overall
SFJ	18-24	Distance from the stem to the forward end of J
SFBI	26-32	Stem to mast distance, SFJ + J. This is used to locate the mast to get HBI (Height of sheer at the Base of I).

Note: SFJ and SFBI are set to zero in most files and are not relevant.

Stations definitions

The stations are arranged from bow to stern (increasing X) regardless of being port or starboard. The first station should be placed so the stem of the yacht is at X=0.0. X should never be a negative number. Stations should be taken so that a plot in elevation view of the bottom points of the stations defines all discontinuities in the underwater profile. Stations are needed at all knuckles, where the keel and rudder meet the canoe body, the bottom corners of the keel, bulb and rudder. The maximum thickness of the appendages should also be defined, and a double station in way of the keel is recommended. A station should be taken close to the stem and the extreme aft end of the boat.

Line 5 and the following lines contain information about each section in the following sequence:

```
    X,NPT,SID,SCD,sta#
 Z(1),       Y(1),PTC
 Z(2),       Y(2),PTC
 Z(3),       Y(3),PTC
 Z(4),       Y(4),PTC
…
…
Z(NPT),      Y(NPT),1
```

First line of each station

Label	Columns	Explanation
X	1-10	Distance from the stem for each station in millimeters for metric units, in hundredths of feet for imperial units
NPT	12-14	Number of points in a section. Important to be correct.
SID	16-18	Side code: 1-Port; 2-Starboard; 3-Both
SCD	20-22	Station label: 1-Forward freeboard; 2-Aft freeboard; 3-Station contains prop shaft exit point; 4-Station contains propeller hub point
sta#	24-27	Station count, not necessary, but included for convenience

Station points definition

Label	Columns	Explanation
Z(n)	1-10	Vertical co-ordinate for points on a half section, positive up, negative down in millimeters for metric units, in hundredths of feet for imperial units
Y(n)	11-21	Horizontal distance from the centerline for points on a half section. Negative only in the gap in section for example, between the canoe body and the trailing edge where point code PTC is set to 2.
PTC	23-25	Point code as explained below

Point codes:

0 - Normal hull point.
1 - Sheer point. If no point on a station has a point code of 1, the top point on the station becomes the sheer point.
2 - Poke-through (empty space in a gap bounded by the point immediately above and below. More commonly represented by a Y (transverse offset) of less than -0.3 feet.
3 - Propeller or shaft exit point (the appropriate station code having already been entered).
4 - Maximum width points of a wing keel.
5 - US measurement machine centerline points (has no rating effect).
6 - Propeller aperture bottom point (may exist in some old US offset files).
7 - Propeller aperture top point (may exist in some old US offset files).
8 - Poke-through on the leading edge of an appendage. Most of the time, the program can decide automatically if one or more stations with poke-throughs are leading or trailing edge. If an appendage with leading edge poke-throughs plots incorrectly, this may help.
9 - Poke through on the trailing edge of an appendage. If an appendage with trailing edge poke-throughs plots incorrectly, this may help.
10 - Poke-through in a closed hole through an appendage. There is no automatic recognition of holes.

11 - Poke-through in a contiguous set of stations that all have poke-throughs which completely sever the appendage from the hull. This code will limit the appendage profile to only those points below the poke-throughs.
12 - Do NOT clip at this specific point. Use on points which are the inside corner of a left turn while scanning down the section. This is typically used to prevent clips at hard chines with lips or lapstrake type construction.
13 - Prevent clipping of entire stations narrower that 3 percent of BMAX by setting this code on any point in the station. This would be typically used on the very tip of a transom that comes to a point. This code will not prevent a clip at a left turn or poke through in the station.
14 - If this code is set on any point in the station, you force clipping of the entire station even though it may be wider than 3% of BMAX, and regardless of any poke-throughs and left turns.
15 - Do not clip this station in any way, either entirely or at any point if this code is set on any point in the station.
16 - Force a clip at this point.

Double Rudder.

Data on the double rudder are entered as an extra input line in the .OFF file.

r_yoff	r_xoff	r_span	r_chordroot	r_chordtip	r_thicknessroot
Y offset	X offset	Rudder Spa	Root Chord	Tip Chord	Root thickness
r_thicknesstip	Angle y_off	r_xoff	angle		
Tip Thickness	the stagger form CL of the root. if =0 means single rudder.	longitudinal position of centroid.	lateral inclination angle compared to vertical		

.

10 Appendix B: RR Coefficients

Fn	0.125	0.150	0.175	0.200	0.225	0.250	0.275	0.300	0.325	0.350	0.375	0.400	0.425	0.450
Constant	1.9601	1.9673	1.4537	1.0724	1.1950	0.7886	-1.5413	-4.6139	-6.6772	-7.2105	0.8640	24.493	60.517	107.036
Cp	-3.7100	-3.0335	-1.3922	0.0186	1.0381	3.8750	10.5299	18.2764	24.4120	30.3437	25.1851	-0.2272	-31.100	-54.4307
B/T	-0.1622	-0.1044	-0.0752	-0.0809	-0.1866	-0.2648	-0.1291	-0.4683	-1.3867	-0.8502	0.7523	2.5649	4.6065	6.8301
L/VOL^1/3	-0.0961	-0.1690	-0.2622	-0.3965	-0.6929	-1.0170	-1.1446	-1.5104	-2.4288	-2.3700	-0.8100	1.1400	2.0500	0.0700
WA/VOL^2/3	0.2600	0.1869	0.1636	0.2106	0.4504	0.6243	0.4693	1.0462	2.6343	2.2111	-0.3019	-3.2406	-6.5443	-10.0000
LCB/(L/VOL^1/3)	0.2331	0.1654	0.0576	0.0133	-0.1167	-0.5327	-1.1869	-1.8767	-1.9370	-3.3500	-6.7100	-10.747	-14.750	-18.1525
LCB^2/(L/VOL^1/3)	-0.0431	-0.0310	-0.0025	0.0135	0.0413	0.1425	0.3206	0.5535	0.7049	0.9561	1.3000	1.8300	2.4400	2.9500
(L/VOL^1/3)^2	-0.0057	0.0033	0.0118	0.0209	0.0317	0.0472	0.0595	0.0575	0.0514	0.0400	-0.0082	-0.1170	-0.2053	-0.1530

Fn	0.475	0.500	0.525	0.550	0.575	0.600	0.650	0.700	0.750	0.800	0.850	0.900
Constant	185.358	278.777	376.177	455.785	504.000	534.000	578.925	617.300	649.000	677.700	705.0000	734.0000
Cp	-69.851	-80.000	-85.200	-86.900	-87.290	-87.400	-87.400	-87.400	-87.400	-87.400	-87.4000	-87.4000
B/T	7.950	8.260	8.240	8.030	7.717	7.450	7.243	7.420	8.000	8.870	9.8800	11.0000
L/VOL^1/3	-13.140	-33.175	-56.600	-76.300	-88.300	-95.700	-107.10	-117.08	-125.5	-133.320	-140.00	-145.90
WA/VOL^2/3	-11.500	-11.530	-10.619	-9.290	-8.240	-7.400	-6.000	-4.900	-4.000	-3.300	-2.8100	-2.4800
LCB/(L/VOL^1/3)	-21.300	-24.100	-26.850	-29.400	-31.700	-33.800	-37.500	-40.500	-42.800	-44.500	-45.7500	-46.7000
LCB^2/(L/VOL^1/3)	3.460	3.900	4.330	4.740	5.120	5.490	6.170	6.800	7.330	7.773	8.1000	8.3500
(L/VOL^1/3)^2	0.588	1.784	3.208	4.370	5.090	5.530	6.210	6.780	7.250	7.679	1.784	4.370