

# Timing of the Pre-start Manoeuvre for an America's Cup Yacht



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Master thesis  
Stockholm August 2006

## Abstract

The importance of a perfect start in a match race as America's Cup is big. The majority of boats winning match races also won the start. The most important thing to make a perfect start is timing. With reliable information of how long time it takes to get to the starting line from a given point the timing gets much easier. This study is an attempt to create a computer supported routine for this timing exclusively for the Swedish America's Cup team Victory Challenge. The routine consists of a model that predicts how fast and which way the boat will sail to the starting line and out of that presents what is called time to burn, time difference between start time and predicted time of arrival at the starting line. Time to burn is used by the crew as an indication on when it is time to sail towards the starting line. The model is based on an equation of motion where the included components and constants are evolved with measured log data from previous races and continuously uses measurements from the onboard sensors as input data.

The final routine has not yet been tested onboard, only simulated tests with log data as input is done. These simulations show that an accuracy of 2 seconds for the models prediction is achieved at 70% of the computed cases. The main reason that the model did not get better is the fact that the log data used to trim the model has too much inconsequent variations.

## Nomenclature

$R_V$	Viscous resistance	[N]
$\rho$	Density	[kg/m <sup>3</sup> ]
$V$	Boat speed	[kn]
$S$	Wetted area	[m <sup>2</sup> ]
$C_V$	Viscous resistance coefficient	[-]
$C_F$	Frictional resistance coefficient	[-]
$k$	Geometric form factor	[-]
$Re$	Reynolds number	[-]
$L$	Characteristic length	[m]
$\nu$	Kinematical viscosity	[m <sup>2</sup> /s]
$k_V$	Viscous resistance constant	[kg/m]
$C_W$	Wave resistance coefficient	[-]
$F_N$	Froude's number	[-]
$R_W$	Wave resistance	[N]
$k_W$	Wave resistance constant	[kg·s <sup>4</sup> /m <sup>5</sup> ]
$\phi$	Heel angle	[rad]
$C_H$	Heel resistance coefficient	[-]
$T$	Draft	[m]
$T_C$	Draft of canoe body	[m]
$B_{WL}$	Beam of waterline	[m]
$R_H$	Heel resistance	[N]
$k_H$	Heel resistance constant	[kg·s <sup>2</sup> /m <sup>3</sup> ]
$A_L$	Lift producing area	[m <sup>2</sup> ]
$C_{Di}$	Induced drag coefficient	[-]
$C_L$	Lift coefficient	[-]
$e$	Efficiency factor	[-]
AR	Aspect ratio	[-]
$R_I$	Induced resistance	[N]
$k_I$	Induced resistance constant	[kg/m]
$R_{rudder}$	Resistance coupled to rudder angle	[N]
$A$	Area	[m <sup>2</sup> ]
$C_D$	Drag coefficient	[-]
$C_{L,2D}$	2D lift coefficient	[-]
$\alpha_{rudder}$	Rudder angle of attack	[rad]
$k_{rudder}$	Constant for the resistance coupled to rudder angle	[kg/m·rad <sup>2</sup> ]
$R$	Total resistance	[N]
$k_{V,I}$	Combined viscous and induced resistance constant	[kg/m]
$T$	Thrust	[N]
$\beta$	Apparent wind angle	[deg]
$V_A$	Apparent wind speed	[kn]
$L$	Lift	[N]
$D$	Drag	[N]
$k$	Constant for the equation of thrust	[kg/m]
$C_L/C_D$	Glide angle	[-]
$M$	Total mass of boat, crew and added water	[kg]
$a$	Acceleration	[m/s <sup>2</sup> ]
$f_{wind}$	Wind speed compensation function	[-]
$V_T$	True wind speed	[kn]

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$T_{to\ burn}$	Time to burn	[s]
$T_{start}$	Time for start	[-]
$T_{cross\ line}$	Time for crossing the line	[-]
$R_{turn}$	Turn radius	[m]
$\beta_{target}$	Target apparent wind angle	[deg]

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## Introduction

America's Cup is a sailing competition which is one of the oldest and most prestigious sport events in the world. The story about the America's Cup started in 1851 when the boat America won a boat race in England. The fact that it was a boat from America which won was a sensation because Great Britain had been a totally dominating country in the sailing world for a very long time. The prize in form of a cup was brought to America, donated to the New York Yacht Club and they stated that the cup would be the trophy for "a perpetual challenge cup for friendly competition between nations." Thus was the America's Cup born, named after the winning boat America.

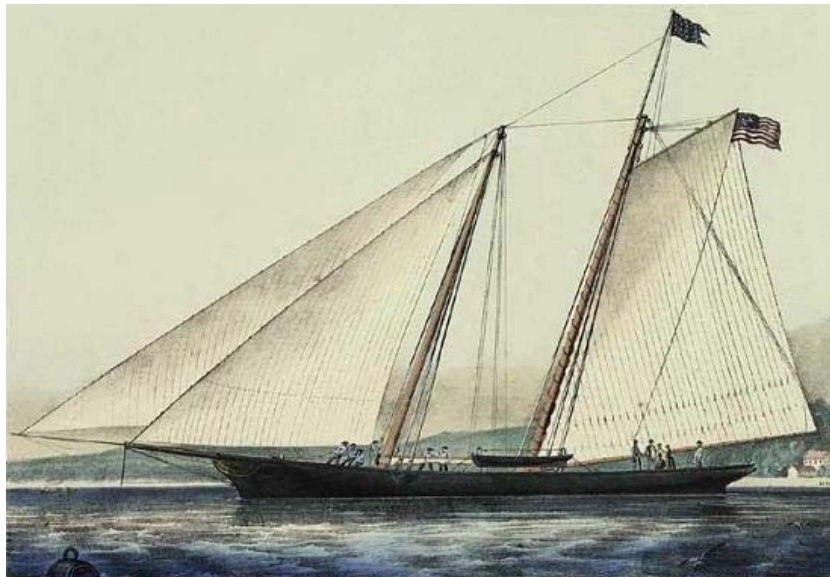


Figure 1. The yacht America which gave the name to America's Cup in 1851.

Today the America's Cup gathers the sailing world's best and most experienced sailors. It has also become a truly inspiring challenge for engineers. The effort of the engineers to design the fastest and most efficient boats consists of structural design, fluid mechanics, data analyzes and much more.

America's Cup is mainly a so called match race, which means that there are only two boats competing against each other on the course. Maybe one of the best explanations to this is the answer Queen Victoria got when she asked who was in second place as she watched the race in 1851. "Your Majesty, there is no second," came the reply which pretty much summarizes the power and brilliance of the Cup's simplicity. The actual Cup has during the years evolved to become a series of match races between the defender of the Cup (previous Cup winner) and a single challenger. The challenger is the winner of a qualification cup, called Luis Vuitton Cup. Luis Vuitton Cup is a trial between a numbers of teams where the winner will challenge the defender for the America's Cup.

In the upcoming 32<sup>nd</sup> America's Cup in 2007 the race course consists of up to three laps of a right handed windward-leeward course between a windward mark at the top of the course and a leeward gate near the bottom of the course. The start and finish line are the same at the bottom of the course.

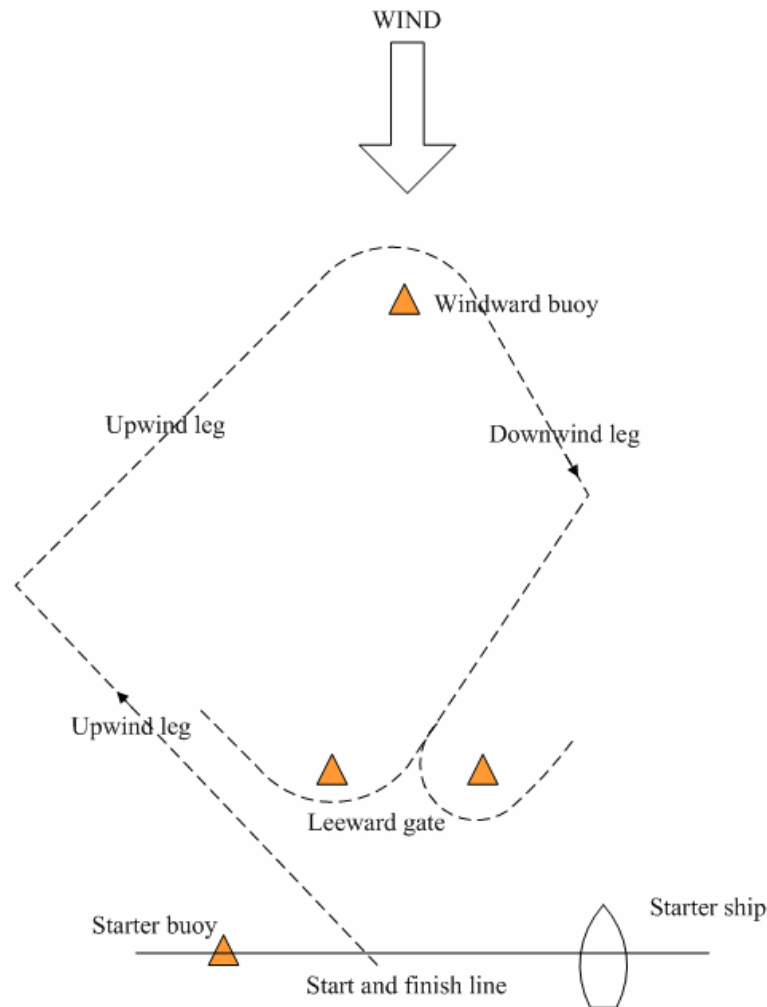


Figure 2. A schematic figure of the race course and a possible first lap. On the first upwind leg there are big opportunities to guard an advantage gained in the start procedure.

A lap consists of two legs<sup>1</sup>, one upwind and one downwind leg. The lengths of the legs are adjusted to the wind conditions to make a good compromise between the impact of boat speed and tactical performance. A short course would put too much importance in the tactics while a long course would benefit a fast boat. The leeward gate gives the boats an opportunity to choose which way to round up. The trailing boat gets a chance to break free from an otherwise predictable cover of the leading boat on the upwind leg. The starting line should be perpendicular to the wind direction, a buoy at the left hand side and a starter ship on the right forms the end points of the line.

The start in a match race is a very important part of the competition. Because of the fact that a boat only has to beat one other boat there is a chance or way that a boat can control an advantage and keep the other boat behind. The start is the first opportunity to gain such an advantage and can have huge importance for the outcome of the race. The advantage can be that the boat is in a favoured position since the starting line is not always exactly perpendicular to the wind or that for other reasons the conditions could be favourable on one side. The advantage can also consist of a true distance lead because of better timing than the other boat. The time before the start signal the boats try to get this kind of advantage. In the

<sup>1</sup> The sailed distance between two roundings is called a leg.

beginning of the start sequence the boats try to make the other boat to commit a mistake and break some rule of way which leads to a penalty. The penalty is in most cases a 360 degree turn which must be done after the start but before finishing. As the time passes the tactics change to be more about getting the best position compared to the starting line and the other boat. A good position to the line include the fact that both boats want to start as close to the start time as possible. This becomes the main target as time passes and the positions are more or less made up. With an estimation of the time it takes to reach the line compared with the time left to the start a quantitative measure of timing and positioning is retrieved. Even though it gets easier to make a good estimation of this when closing up on the starting line there becomes less opportunities how to speed up or slow down to adjust the timing of the start.

In most cases the boat is on purposely manoeuvred to be a bit too early for the start. In other words there is more time to the start signal than it takes to reach the line. This surplus time is called time to burn and gives information about when it is time to sail towards the starting line for a perfectly timed start. Close to the start the surplus time is burned by a more or less standardized manoeuvre, a kind of detour consisting of two turns, see Figure 3. When it is a fact that there really is time to burn, about 15-40 seconds before start the first turn away from the starting line is initiated. When the surplus time is burned next turn is initiated towards the starting line. Because a sailing boat can not sail straight towards the wind the course towards and crossing the starting line is angled due to the wind. The turn towards the starting line is ended when the boat reaches what normally is called target wind angle. The target wind angle is the most efficient wind angle to sail with when going upwind, target wind angle generates the greatest speed towards the wind. The maximum boat speed at target wind angle is naturally called target speed. A perfect start comprises that the boat cross the starting line with target wind angle and target speed at the exact time for the start. With good prediction of time to burn the chances to accelerate from the speed loss of the two turns up to target speed are improved.

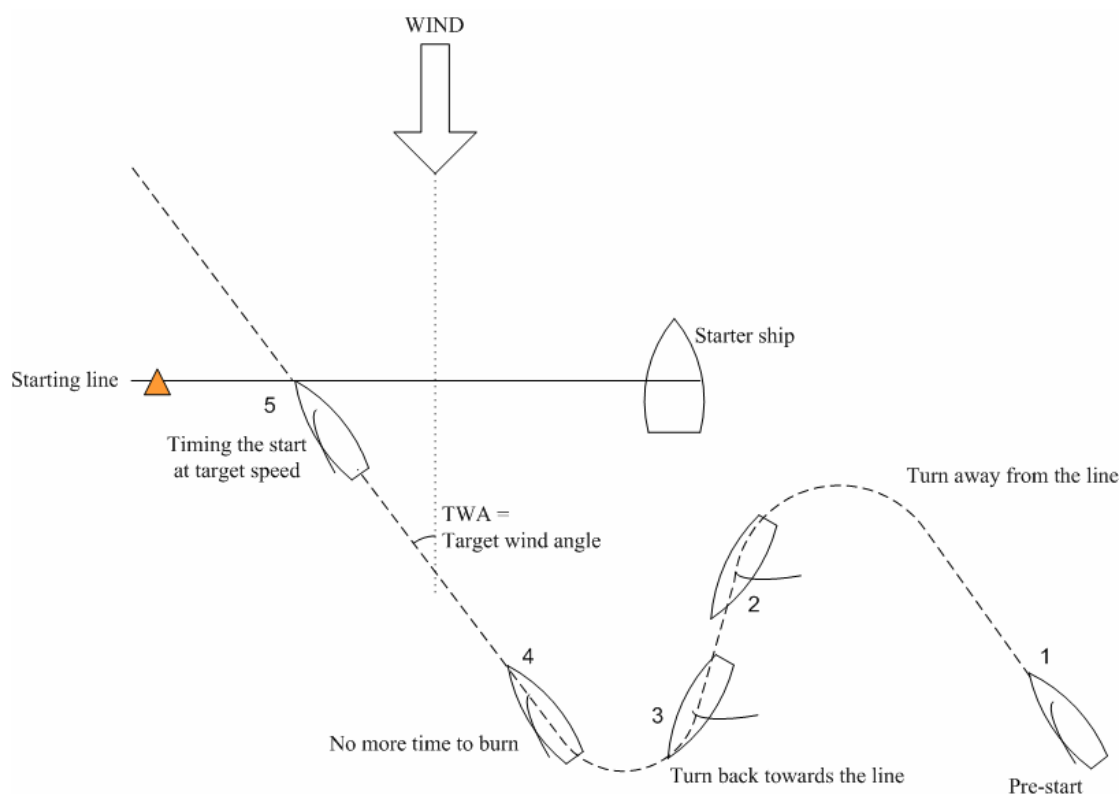


Figure 3. The pre start manoeuvre normally looks like this.



There are different ways to get information about the time to burn and when it is time to turn towards the line. The skipper continuously estimates this from his experience and feeling and a crewmember standing in the bow does the same and signals this to the skipper.



Figure 4. One way to help the skipper make a perfect start. The bowman signals the distance there is left to the starting line.

Another and maybe more consequent way is to use a numerical model. Today this is done by using an onboard computer with a program that continuously makes an estimation of how long it will take to reach the starting line and compares it with how long time remains to start, more or less the same procedure as the one that takes place in the mind of the skipper and bowman. The program estimates this with information from the onboard instruments and computes predicted time on basis of a mathematical model of the boats movement.

Today the Swedish team Victory Challenge uses a basic model of the boats movements in the computer program [1]. The model estimates time to burn by a combination of distance and speed prediction [1] and [2]. The distance is calculated by applying a turn with constant angular velocity until target wind angle is reached, this course remains until the starting line is crossed. The speed is calculated from the acceleration until target boat speed is reached. The magnitude of the acceleration is given by the difference between current boat speed and target boat speed. The main shortage of this model is the fact that the speed will be constant in the turn which is not the real case. Previously made starts indicate that the program miscalculate the time to get to the starting line with up to 5-6 seconds when following its instructions given by the computer [2]. The intention with this project is to reduce this miscalculation to one second on a prediction time period of about 25 seconds. The plan how to do that is mainly by creating a more accurate simulation model.

## The Boat

International America's Cup Class, IACC, is the boat type used in America's Cup. IACC is a construction class which means that the boats are not identically but are designed under some set rules concerning hull shape, materials sail areas, measurements and so on. Victory Challenge's current boat is named Örn. The main measurements and facts of the boat are:

Length:	24 m
Width:	3.9 m
Weight:	~24 tonnes
Bulb:	19 tonnes
Mast:	0.8 tonnes
Fin:	1.0 tonnes
Hull:	2.2 tonnes
Mast height:	34 m
Draught:	4.1 m
Main sail:	215-220 m <sup>2</sup>
Spinnaker:	500-530 m <sup>2</sup>
Genoa:	130-140 m <sup>2</sup>
Building material:	Carbon fibre composite
Design:	German Frers Jr.
Boat builder:	Chris Mellow/ Victory Challenge
Manufactured:	2001
Crew:	17 man



Figure 5. Örn, Victory Challenge's current boat. (Photo: Sally Collison/Victory Challenge)

The performance of Örn is best described by a polar diagram. The polar diagram present the boat speed in knots at different true wind angles for a set of specific wind speed. In Figure 6 there are polars counting from the centre for true wind speeds  $V_T$  of 7, 8, 9, 10, 12, 14, 16, 20 and 25 knots.

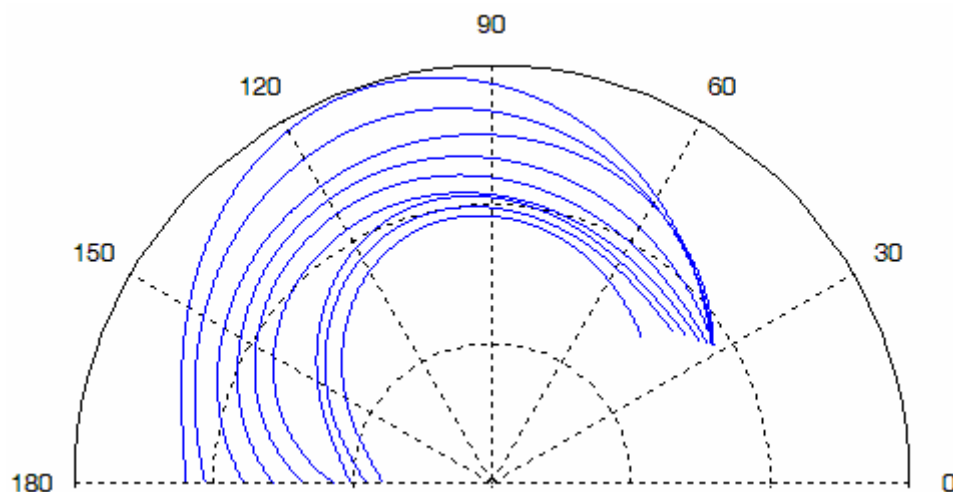


Figure 6. Performance diagram in the form of polars at different wind speeds for the IACC yacht Örn. Axis as; boat speed in knots at the radial axis versus true wind angle. Counting from the centre there are polars for wind speeds of 7, 8, 9, 10, 12, 14, 16, 20 and 25 knots.

## The Model

The main target with the model is to predict how long time it will take to get to the starting line and compare it with how long time there is left to start. This is i.e. a prediction of the previously mentioned time to burn. The keystones to do this prediction are to generate one model of the path for the more or less standardized manoeuvre from Figure 3 and couple this with a model of how the forces acting on the boat generates movement. Inspired by [3] and [4] the new model will be evolved on a physical approach where the acting forces is approximated. Newton states that the sum of the forces acting on a body will be equivalent to the acceleration times the mass of that body i.e. the equation of motion

$$\sum F = Ma \quad (1)$$

where  $F$  is the acting forces,  $M$  is the mass of the body and  $a$  is the acceleration. The approximation of the forces is based on how different parts of the resistance and driving force can be expressed as mathematical functions of parameters as for example wind speed and wind angle. By using measured data as a reference the model is trimmed. Because of the complex behaviour of a boat there may be forces or parts of forces that will not be included in the simplified mathematical expressions of the forces. To include these forces results from reference comparisons must be analyzed to determine how the mismatch of the measured data and the model could be expressed. This reference comparison will make the model a combination of physical and empirical parts. The empirical parameters may be physically explained as a better understanding of the forces will be developed during the work.

The time before the start can be divided into different parts. Referred to the numbers in Figure 3 this division is; Point 1, it becomes a fact that there is time to burn and this extra time has to be burned by turning away from the starting line. Point 2, the time to burn decreases as the direction differs from the target direction. Point 3, the time to burn is zero and by turning towards the starting line and target wind angle reached at point 4, time to burn will stay zero. Between 4 and start at 5 the boat accelerates and if there is enough time between those points of time target speed will be reached. The model will be a simulation of the manoeuvre from point 3 to 5. The most important part of the simulation besides the force model is the model of the path for the turn made at point 3, i.e. the beginning of the simulation. The model for this will be generated from looking at how the turn has been done at previously made starts.

The onboard computer continuously logs measurements from the onboard instruments with samples every second and saves it to a text file. From every time the boat has been sailing (racing, training or testing) there is a log file with this data. This means that there is a big amount of data available to be used as reference. The data has to be sorted to get the sequences that are of interest. The most obvious parts that are useful are sequences in the starts where it is possible to find the previously described manoeuvre. Another part that can be applied is the turn that is performed when rounding the leeward mark to start the upwind leg again. These kinds of sequences are searched in all log files and are cut out and saved in separate files to get a library of sequences which can be used in the work of evolving and trimming the model for the movement of the boat.

## Accuracy of the model

The accuracy of the model can be quantified by looking at the already mentioned parameter, the time difference between prediction and reality when reaching the starting line. The desired accuracy of the model in this meaning was stated to be about 1-2 seconds [2]. To get a picture and quantify how accurate the speed has to be predicted a simplified calculation example is done. The boat sails with an average speed of 12 knots during the 25 seconds left to the start (a normal case for most of the start situations), this means a traveled distance of ca

$$12 \frac{1852}{3600} \text{ m/s} \cdot 25 \text{ s} \approx 150 \text{ m.}$$

If the model makes a prediction of the speed with an average of one knot too high speed for this distance it means a predicted time to get to the start of

$$\frac{150 \text{ m}}{13 \frac{1852}{3600} \text{ m/s}} \approx 23 \text{ seconds.}$$

I.e. a wrongly made prediction of 2 seconds when the boat reaches the starting line. A prediction for the same example where the speed is underestimated with an average of one knot would mean a predicted time to get to the starting line of ca 27.3 seconds, 2.3 seconds too slow. Below in Figure 7 the example is illustrated for some different average errors in the predicted speed.

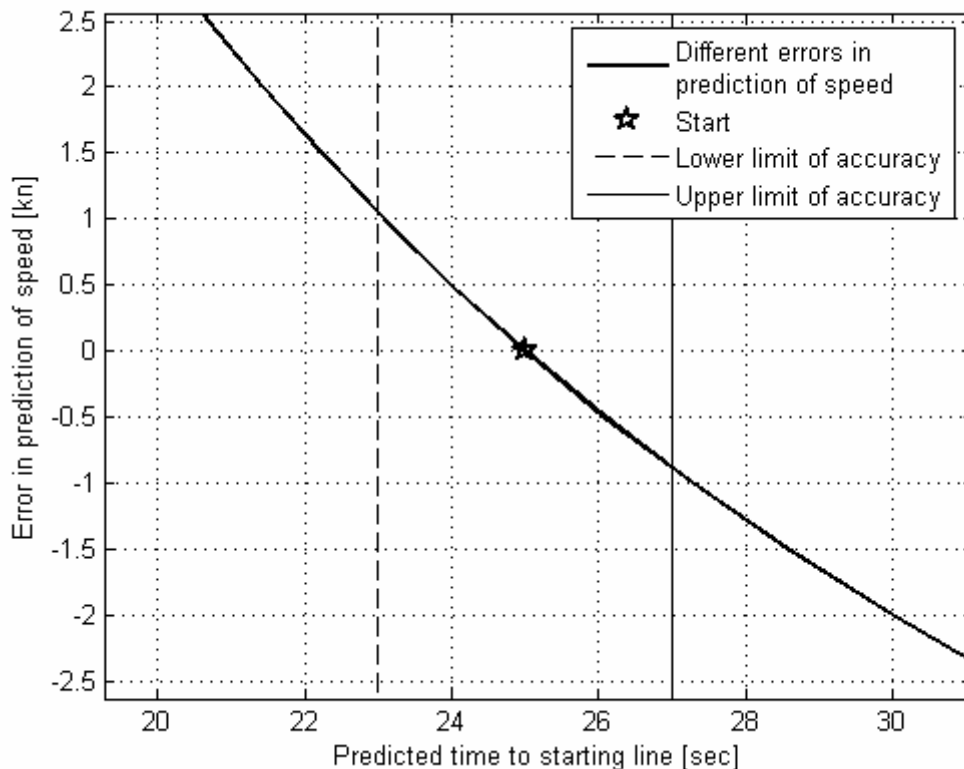


Figure 7. Visualization of what accuracy in the speed prediction that is necessary to maintain the accuracy in the time prediction.

## 1. Data analysis

There are several files in the \*.txt format that contains logged data from the onboard measuring system. The system is based on a Hercules system from Brooks & Gatehouse, B&G.

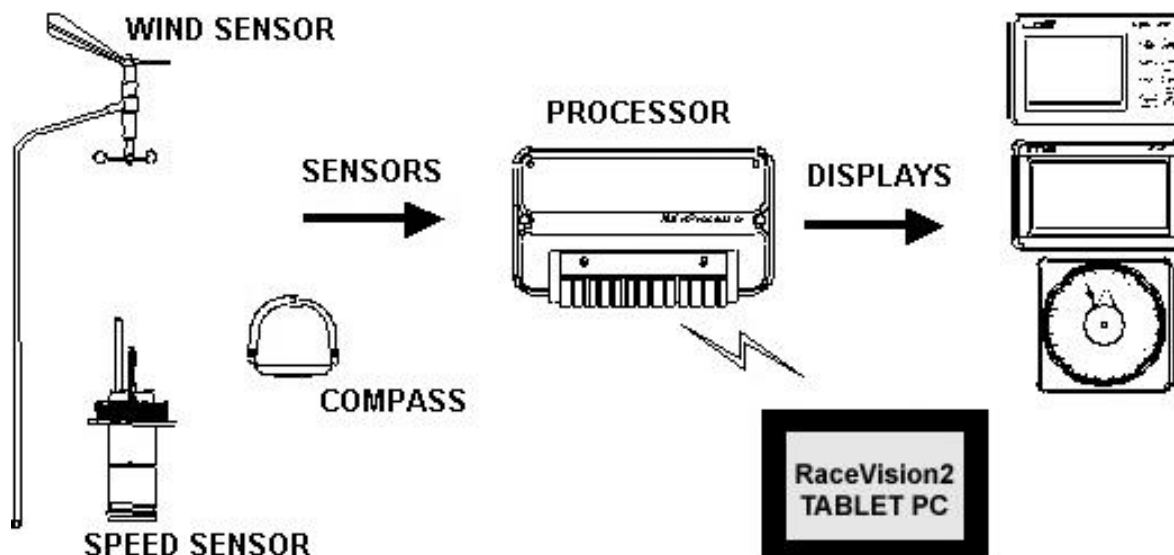


Figure 8. The measuring system.

The speed sensor consists of a standard paddlewheel speed sensor which is a pulse sensor. The wind sensor is a so called Vertical Mast Head Unit with a non standard but longer arm to reach more undisturbed wind. The wind sensor is also a pulse sensor. There are several compasses on the boat, in total three different constructions. One of them is a standard Halcyon 2000 Fluxgate Compass. For further information and technical data of the wind sensor and compass see appendix A. The communication of the sensor network is done in B&G:s own protocol called Fastnet. The processor in Victory Challenge's measuring system is exchanged to a so called Wave Technology Processor (WTP) which actually is a real computer with a Pentium processor and Windows CE installed. Starting from the measured wind speed and angle at the masthead, the WTP incorporates data from gyro sensors for measuring the pitching and rolling of the boat. It is from this corrected wind information that the true wind direction and speed are calculated. Besides of the mentioned sensors there is also a GPS system onboard. The GPS consists of an antenna from Leica that provides information according to NMEA 0183-protocol. Finally a navigator computer installed on deck communicates with the WTP and presents information through the software Deckman. Examples of useful available data for this thesis consist of:

- Boat speed
- Course
- Position
- Apparent wind speed
- True wind speed
- Wind direction
- Apparent wind angle
- True wind angle

## 1.1 Selection of data

Due to the huge amount of log files and to get relevant data there has to be a selection. For a better understanding of what precision could be expected for a model, partially based on logged data it is relevant to examine the quality or more correctly the variation of the data. In order to be able to use the data efficiently, sequences of interest is extracted/copied from the data log files and put together into a library of sequences. In the selected sequences the boat has to be sailed race adjusted, trimmed and handled as a race situation would demand. Therefore, the first selection of data is actual races and practice races or sequences where relevant practice is made. This can be verified by reading the notes written for each log file. Then the choice of sequences within this selection is made from the fact that there is a certain manoeuvre that is supposed to be simulated. As previously mentioned this manoeuvre basically consists of a turn from a course where surplus time is burned towards the course giving target wind angle. Naturally this manoeuvre is found in the starts. A similar and adaptable manoeuvre could also be found in the rounding up from going downwind to upwind. In total 34 individual start and 49 roundup sequences was extracted from all log data files.

## 1.2 Quality of data

The frequency of the measurements is only 1 Hz. This is a problem as the pre start turn that will be modelled only takes about 10 seconds, but at the same time there are quite a big collection of turns that will make a statistically replacement for this lack of data points. To make a relevant judgement of how consistent the data is, it is crucial to find places where it is possible to compare measurements, places where the boat perform the same regardless of which race or practise that is examined. For instance, the boat should sail approximately at the same speed for a given wind speed regardless of time when going upwind on a beat, except for some tactical differences maybe. When this theory was investigated by looking at data from upwind sailing this was confirmed. As seen in Figure 9 the points representing the boat speed for certain wind speed at upwind sailing, forms what seems to be a logarithmic function and is well gathered.

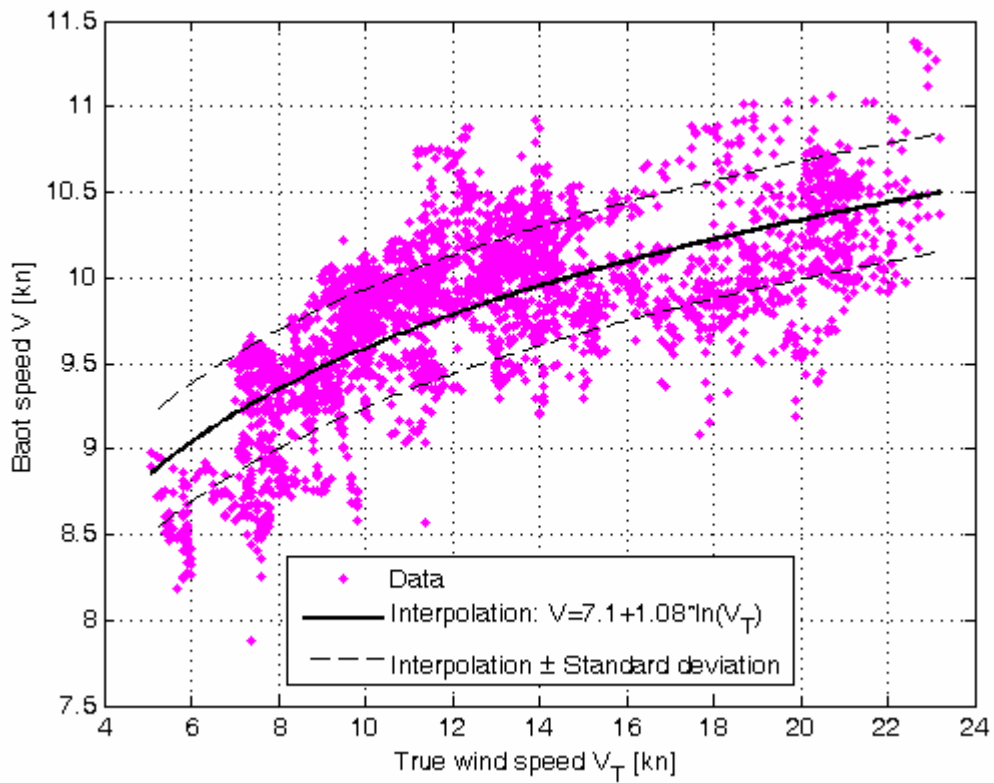


Figure 9. Data for upwind boat speed as function of true wind with an interpolated function.

The standard deviation from the interpolated logarithmic function became 0.35 knots and is presented in Figure 9 as the dashed lines.

## 2. Modelling of the external forces

An estimation of the relevant external forces acting on the sailing boat forms the left hand side of the equation of motion (1). By integrating (1) in time speed is given. The speed can then be compared with the data to make the model more accurate. This comparison is extended to simulated tests by running the model with input from a data file. This is a continuous process during the whole model development phase. Functions that describe differences between simulation and logged data are adapted to the physical model. These functions can hopefully be explained with physical phenomena, for instance there can possibly be a factor which describes the delay of the trimming of the sails when the boat changes direction and it takes a few seconds to sheet the sails. But it will also make the model partly empirical.

### 2.1 Estimation of forces

The physical approach is more or less an estimation of the forces acting on a sailing boat. These forces can be separated into forces acting in different directions. A convenient way is to sum all forces in the direction of movement and the transverse direction. In this stage of the model development, when the main target is to simulate the speed it is sufficient to look at the forces in the direction of movement.

#### 2.1.1 Resistance

The dragging force or shortly the resistance consists of several parts. The resistance is mainly a hydrodynamic effect of speed and can further be divided into six main components according to van Oossanen [5].

Viscous resistance

Wave resistance

Resistance due to heel

Induced resistance

Added resistance in waves

Resistance due to hull attitude

The viscous resistance consists of two parts, frictional resistance and viscous pressure resistance. The frictional resistance is more or less the force that is required to overcome the tangential stresses between water and hull. The viscous pressure resistance is a consequence of the pressure differences between the bow and stern of the hull. This pressure difference is due to the growth of the viscous boundary layer which causes a lower pressure in the stern compared to the pressure in the bow [5]. The viscous resistance  $R_V$  is expressed as

$$R_V = 1/2 \rho V^2 C_V S, \quad (2)$$

where  $\rho$  is the density of the water,  $V$  is the speed of the boat,  $S$  is the wetted area and  $C_V$  is the viscous resistance coefficient given by

$$C_V = C_F (1 + k), \quad (3)$$

here  $C_F$  is the frictional resistance coefficient and  $k$  is a geometric form factor. The form factor describes in a sense how voluminous the hull is, i.e. how big the pressure difference between bow and stern is.  $C_F$  is semi empirical expressed [6] as a function of Reynolds number



$$C_F = \frac{0.075}{(\log R_E - 2)^2} \quad (4)$$

and Reynolds number  $R_E$  is given by the characteristic length  $L$  as

$$R_E = \frac{VL}{\nu}, \quad (5)$$

where  $\nu$  is the kinematic viscosity which is considered constant for this application. The variance of  $C_F$  in the Reynolds number range of interest is small and  $C_F$  can here be considered constant.

The constants are gathered to one single constant  $k_V$  and the viscous resistance expression is simplified and expressed as

$$R_V = k_V V^2. \quad (6)$$

The wave resistance is a result of the waves the boat generates. When the hull is moving, the water surrounding it must move as well and because it is almost incompressible the water moves in the form of waves [7]. The magnitude of this contribution to the total resistance is related to the energy it takes to generate these waves and could be expressed as

$$R_W = 1/2 \rho V^2 C_W S, \quad (7)$$

where  $C_W$  is the wave resistance coefficient which is a function of the Froude's number,  $F_N$  as

$$C_W = c F_N^n. \quad (8)$$

Here  $c$  and  $n$  are constants and Froude's number,  $F_N$  is given by

$$F_N = \frac{V}{\sqrt{gL}}. \quad (9)$$

In the Froude's number range of interest for this application the constant  $n$  can be approximated [5] to be  $n=4$ . With all constants in equations (7)-(9) put together to one,  $k_W$  the equation for the wave resistance  $R_W$  could be compressed to

$$R_W = k_W V^6. \quad (10)$$

The resistance due to heel represents the change in viscous and wave resistance between an upright hull and an angled (heeled). This is i.e. a non physical force it is just a convenient way to compensate for the change of resistance that the previously mentioned equations does not take into account. Larsson [8] present an empirical expression for this change of resistance

$$R_H = 1/2 \rho V^2 C_H S F_N^2 \phi, \quad (11)$$

where  $\phi$  is the heel angle in radians and heel resistance coefficient  $C_H$  is given by [8] a number of geometrical parameters as

$$C_H = \left[ 6.747 \frac{T_C}{T} + 2.517 \frac{B_{WL}}{T_C} + 3.710 \frac{B_{WL}}{T_C} \frac{T_C}{T} \right] \cdot 10^{-3}, \quad (12)$$

where  $T$  is the total draft,  $T_C$  is the draft of the canoe body (i.e. the hull in this case) and  $B_{WL}$  is the beam of the water line. All the geometrical parameters are practically constant and therefore formed to just one constant here. In comparison with the rest of the resistance components the resistance due to heel is small and in this stage negligible. Another reason to skip the resistance due to heel term is the fact that it would claim one more degree of freedom in the equation of motion (1) to be simulated [9]. The forces that contribute to the heeling moment is not in the same directions as the other resistance components and driving force, so to simulate the heeling angle an equation for this rotational acceleration would be necessary. This is too complicated and would need to much work to try to implement. Besides, the heeling of an America's Cup yacht is quite constant. This together with equations (9), (11)-(12) gives an equation for the resistance due to heel  $R_H$  as

$$R_H = k_H V^4, \quad (13)$$

with the total constant  $k_H$ .

Induced resistance: To counteract the side force the sail is producing the keel and rudder must create lift. As an effect of this lift there will be an induced resistance [5]. This force can be expressed as

$$R_I = 1/2 \rho V^2 A_L C_{Di}^2, \quad (14)$$

where  $A_L$  is the lift producing area and  $C_{Di}$  is the induced drag coefficient that is further given by

$$C_{Di} = \frac{C_L^2}{\pi e AR}, \quad (15)$$

where  $C_L$  is the lift coefficient,  $e$  is an efficiency factor and AR is the aspect ratio, describing the geometry of the lift producing body. One can consider all these to be constant and hereby get the simplified expression for the induced resistance

$$R_I = k_I V^2 C_L^2, \quad (16)$$

with a total constant  $k_I$ .

The added resistance in waves is a result of the wave generated motion of the boat which in turn creates a hull generated wave system. The energy that takes to create these waves lead to an increase in the total resistance. However this increase is not further investigated in a physical perspective but can become a subject of investigation if differences in simulation and measured speeds appear as the statistically based optimization part of the model development begins.

The resistance due to hull attitude is approximated by using the information of what angle of attack the rudder has which indirectly tell the attitude of the hull. Using this fact one can express this as

$$R_{rudder} = 1/2 \rho V^2 A C_D, \quad (17)$$

where  $A$  is some area that is angled against the water flow and  $C_D$  is the drag coefficient [10] given by

$$C_D = \frac{C_L^2}{\pi AR} \quad (18)$$

and the lift coefficient  $C_L$  can be further expressed as

$$C_L = \frac{C_{L,2D}}{1 + 2/AR} \cdot \alpha_{rudder}. \quad (19)$$

Here is the aspect ratio and the  $2D$  lift coefficient  $C_{L,2D}$  constant.  $\alpha_{rudder}$  is naturally the rudders angle of attack and the resistance due to hull attitude approximated with this angle with the total constant  $k_{rudder}$  is given by

$$R_{rudder} = k_{rudder} V^2 \alpha_{rudder}^2. \quad (20)$$

All these contributions from equations (6), (10), (16) and (20) summarized gives an expression for the total hydrodynamic resistance  $R$  which becomes

$$R = V^2 (k_V + k_I + k_w V^4 + k_{rudder} \alpha_{rudder}^2) = V^2 (k_{V,I} + k_w V^4 + k_{rudder} \alpha_{rudder}^2). \quad (21)$$

The viscous and induced resistance constants are here gathered to one constant  $k_{V,I}$ .

### 2.1.2 Driving force

The sails of a sailing boat is the engine of the boat. It is the sails that produce the driving force, here called thrust  $T$ . From aerodynamics it is known that the total aerodynamic force can be divided into two parts, the so called lift acting perpendicular to the airflow and the drag acting in the same direction as the airflow. As a result of the fact that the boat is moving the airflow the sails experience (which the forces directions is referred to) will be different from the true wind speed and true wind angle that are measured with a stationary observer. This is what normally is referred to as the apparent wind speed and apparent wind angle. The thrust acting in the same direction as the boats movement can now be expressed as the sum of the projection of the lift and drag in that direction

$$T = L \sin \beta - D \cos \beta, \quad (22)$$

where  $\beta$  is the apparent wind angle which the foil in form of a sail experience [11]. The forces  $L$  and  $D$  corresponding to the lift and drag could be expressed using the coefficients for lift and drag together with the dynamic pressure

$$\begin{aligned} L &= 1/2 \rho V_A^2 AC_L \\ D &= 1/2 \rho V_A^2 AC_D \end{aligned} \quad (23), (24)$$

where  $V_A$  is the speed of the airflow acting on the sail, in other words the apparent wind speed.  $A$  is the area of the sails and  $\rho$  is the density of the air. Now the thrust is given by

$$T = kV_A^2 \left( \sin \beta - \frac{1}{C_L/C_D} \cos \beta \right), \quad (25)$$

where constants as the density and sail area is gathered to one constant  $k$  and the ratio of  $C_L$  over  $C_D$  could be referred to as glide ratio.

### 2.1.3 Equation of motion

The model of the boats movement is based on the equation of motion, EOM. According to Newton the sum of all forces that is acting on a body is equal to the acceleration of that body times the mass of it. Here motion in only one dimension is analyzed. This corresponds to analyzing the boat speed without really take into account the direction of the movement. By using the previous derived expression for the driving force  $T$  and the resistance  $R$  the equation of motion becomes

$$T - R = Ma, \quad (26)$$

where  $M$  is the total mass accelerated with the acceleration  $a$ . Applying this to a part of a log file gives an indication of how well the model fits to data. Using the first measurement of the speed as a start point one can calculate the acceleration in that point with input from the log file and then integrate over time to compute the speed, acceleration and travelled distance in the next time position. The integration scheme used is

$$\begin{aligned} \dot{s}_i &= \text{measured} \\ \text{for } i & \\ T &= f(\dot{s}_i), R = f(\dot{s}_i) \\ \ddot{s}_i &= \frac{T - R}{M} \quad , \\ \dot{s}_{i+1} &= \ddot{s}_{i-1} \cdot dt + \dot{s}_{i-1} \\ s_{i+1} &= \frac{1}{2} \ddot{s}_{i-1} \cdot dt^2 + \dot{s}_{i-1} \cdot dt \\ \text{end} \end{aligned} \quad (27)$$

where  $s$  denotes a length coordinate in the direction of motion and a dot is the same as the time derivative  $\frac{d}{dt}$  meaning that  $\dot{s}$  is the boat speed  $V$  and  $\ddot{s}$  is the acceleration  $a$ . The integration is repeated for every point of time in the log file and a simulated curve for the speed is retrieved. In Figure 10 this is done for a start sequence.

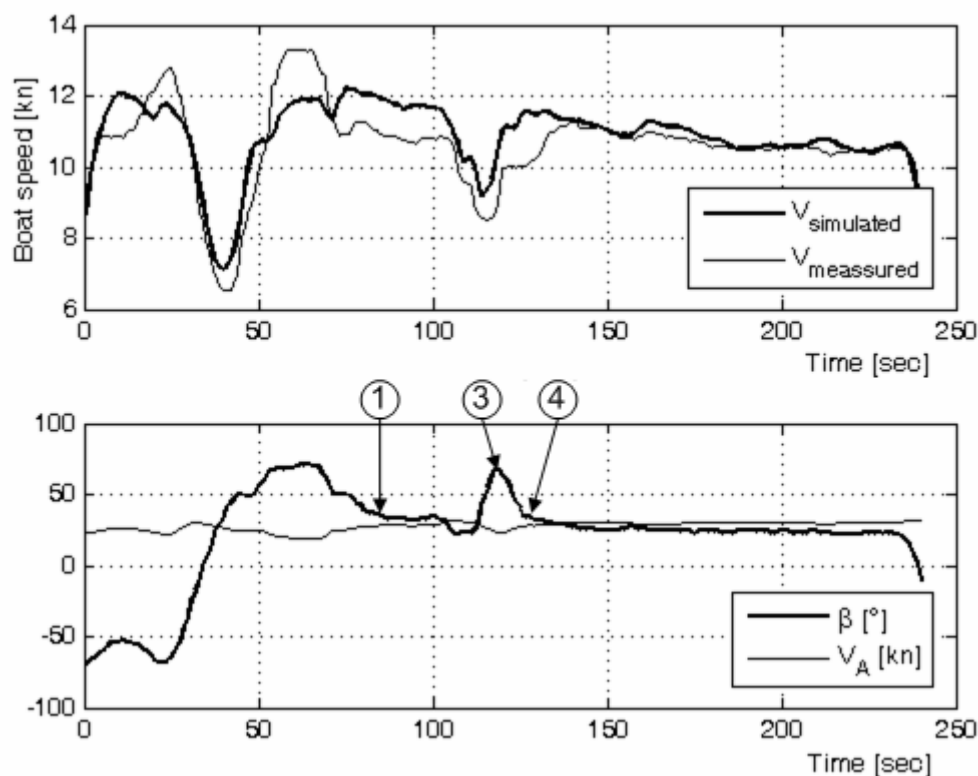


Figure 10. A prediction of the speed for a start sequence, simulated and measured boat speed follows even when there is big changes in the apparent wind angle. The boat tacks at time  $\approx 30$  sec.

Referred to Figure 3 the start sequence in Figure 10 can be connected to the manoeuvres different parts. At point 1 the boat sails upwind towards the line somewhere it becomes a fact that there is time to burn and it turns away and the apparent wind angle increases. At point 3 the time to burn is burned and it starts to turn towards the line, the apparent wind angle decreases. At point 4 the boat has reached target wind angle and heads towards the starting line. In the time interval between 50 and 130 seconds the speed prediction differs from reality with approximately 1 knot. As discussed in the introduction and shown in Figure 7 this can be tolerated for a prediction time of about 25 seconds at normal boat speed. But regarding to the results in Figure 9 where the scattered data points indicate variation in boat speed this “big” error is not unexpected.

## 2.2 Empirical parameter identification

The results from the trimmed physical model are compared with empirical data, i.e. a prediction made with the model of the speed in every next position with data from the present position is done. By comparing for a number of different log files the predicted speed with the measured speed the model is evaluated. Differences are identified, physically explained and tried to be compensated for with parameters.

### 2.2.1 Wind speed compensation

After a first comparison between model and measured data it was concluded that the speed prediction accuracy differs much with wind speed. This could be a result of the choice previously made in the physical modelling where the added resistance due to heel and the added resistance in waves were disregarded. These two terms would most likely have been functions of present wind conditions if they would have been accounted for.

To compensate for this difference a function that describes it is evaluated. By manually for each selected log file change an empirical correction function  $f_{wind} = f(V_T)$  multiplied with the resistance model from equation (21)

$$R = f_{wind} V^2 (k_{V,I} + k_w V^4 + k_{rudder} \alpha_{rudder}^2) \quad (28)$$

until predicted and measured speed match. This will produce data points for different wind conditions. The change of the constant is the same as the function that will describe the wind speed difference. In Figure 11 this work is presented graphically and a function interpolated.

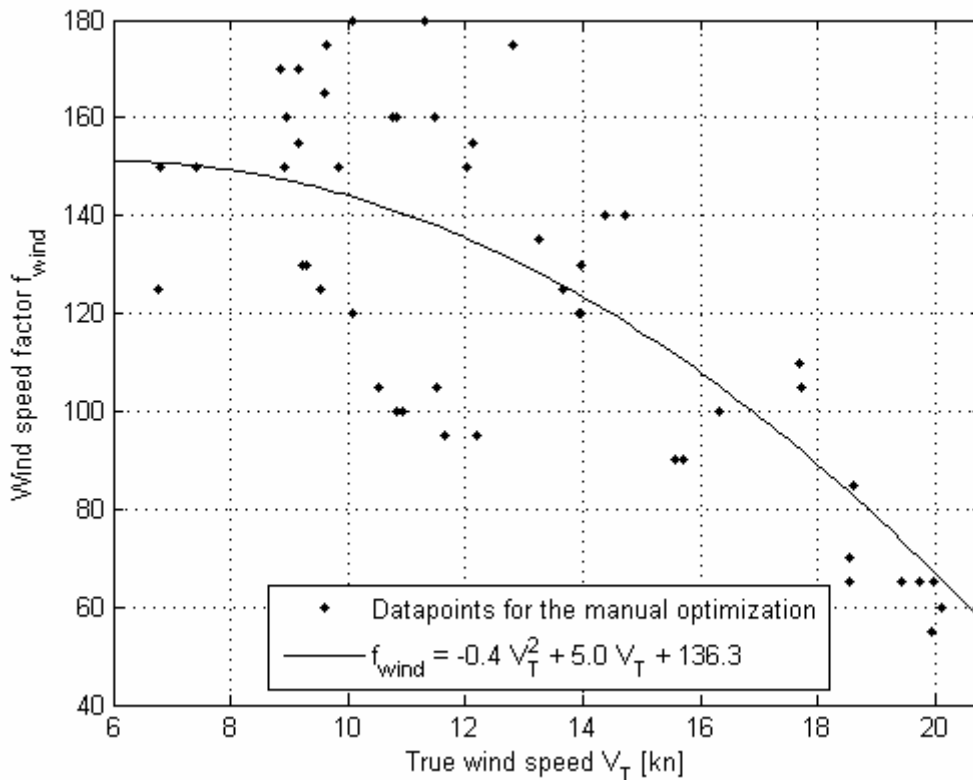


Figure 11. The manually trimmed wind speed factor is plotted against the true wind speed and an interpolation for the data is done.

The interpolated function to this manual optimization is given by

$$f_{wind} = -0.43 \cdot V_T^2 + 5.0 \cdot V_T + 136. \quad (29)$$

Especially in low wind speeds the data points are widely spread and the accuracy of the interpolation decrease.

### 3. Real time system

When sufficiently good accuracy of the speed predicting model is maintained it is time to expand the model to emphasize geometry and time in order to make it a real time system. To enable a real time use of the model with the onboard computer a program has to be written. This program handles the model along with information on position of the starting line and boat position. The build up of the program is schematically shown in the flowchart Figure 12. This real time system is also tested against data files.

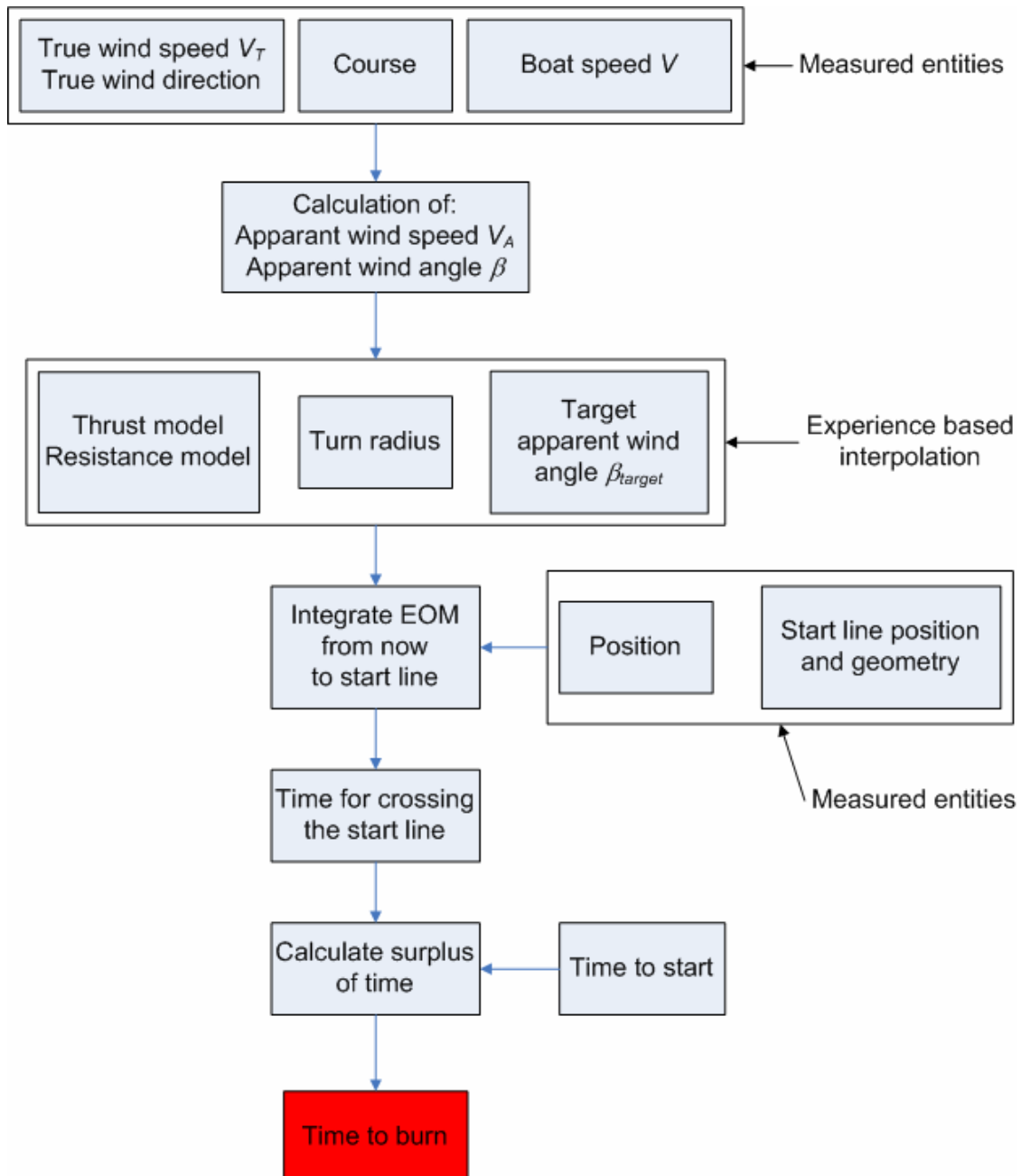


Figure 12. Flowchart for the build up of the real time system. Input data together with the model results in a prediction of time to burn in every calculation. The process that is described in the flowchart is recalculated all the time with new inputs.

The calculation procedure visualized in the flowchart is based on the idea that a turn towards the starting line is initialized in every calculation point of time. From that a prediction that tells the skipper if he will come too early or too late to the line is done. This prediction is based on measured entities as input to the derived models for forces, turn radius and target wind angle.

### 3.1 Time aspect

The most obvious thing that needs to be done when the system is expanded to a real time system is the introduction of time aspects. The time of interest is the surplus time when the boat reaches the line compared to the start time. This surplus time is the same as the amount of time until it is time to start to turn or the amount of time to burn for a perfect start. Here surplus time is called time to burn and it is defined by the difference between the point of time of the start and the point of time of arrival at the starting line

$$T_{to\ burn} = T_{start} - T_{cross\ line} . \quad (30)$$

Obviously time to burn can come to be both positive and negative which means prediction of coming too early or too late to the starting line. The point of time of the start is given while the point of time of arrival at the starting line is predicted by calculation with information on what time it is at the moment and how long it will take to get to the line.

### 3.2 Geometry of the turn

In order to calculate the time when the boat reaches the starting line, the travelled path has to be calculated. The model has so far only predicted speed in one direction which means the only thing known of the new position is the travelled distance from the starting point. To be able to predict the position and travelled path a model of the geometry of the turn is developed. Turns are extracted from all log sequences (start and round sequences) by denoting start and end of the turn. The geometry of the turn is approximated with an arc with constant radius,  $R_{turn}$ . A function describing a circle is minimized to fit the curve of the measured positions in the extracted turns with respect to radius and position of the circle.



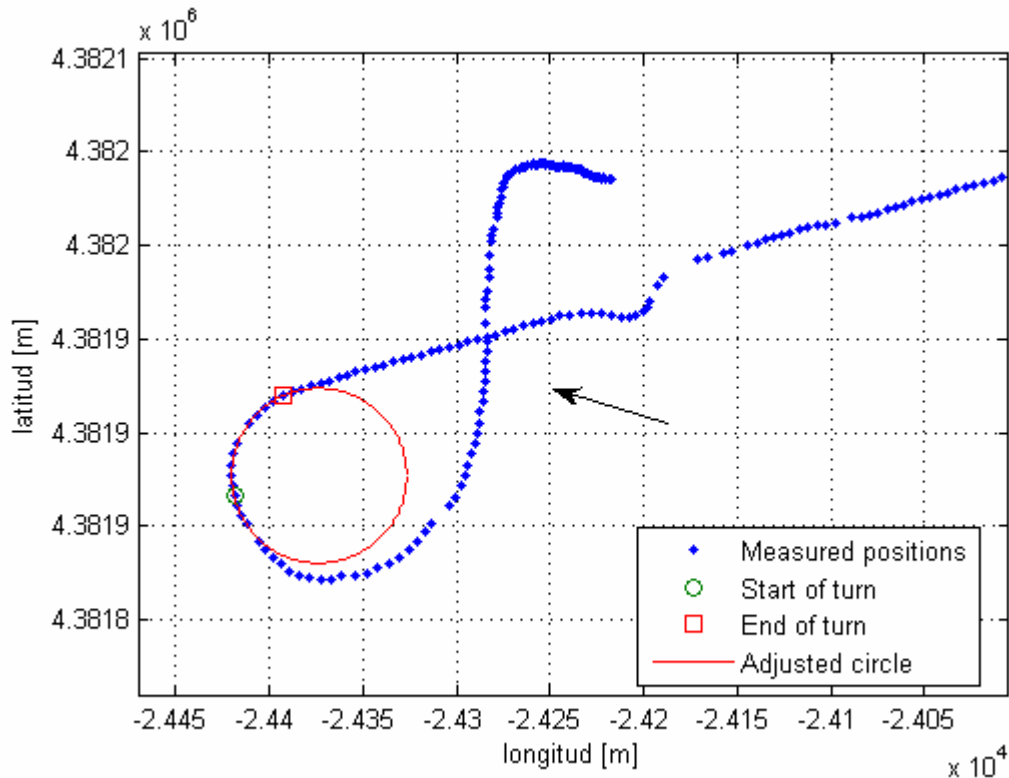


Figure 13. An example of a minimized function of a circle to a turn given by measured positions. The start and end (circle and square) of the turn has manually been chosen and defines the data the circle has been adapted to.

When a circle, or more correctly a turn with constant radius has been fitted to all the extracted turns, a function that describes the change of turn radius is looked for. With the starting point that there is a “normal” turn the skipper turns with for a given condition one can consider different parameters that would describe this function. Obviously these parameters would include wind speed and wind direction for example, but after an examination it was found that the boat speed at the initiation of the turn describes the turn radius most accurate. This is maybe natural because the boat speed is in some sense a function of those parameters. Below in Figure 14, the turn radius is plotted against initial boat speed.

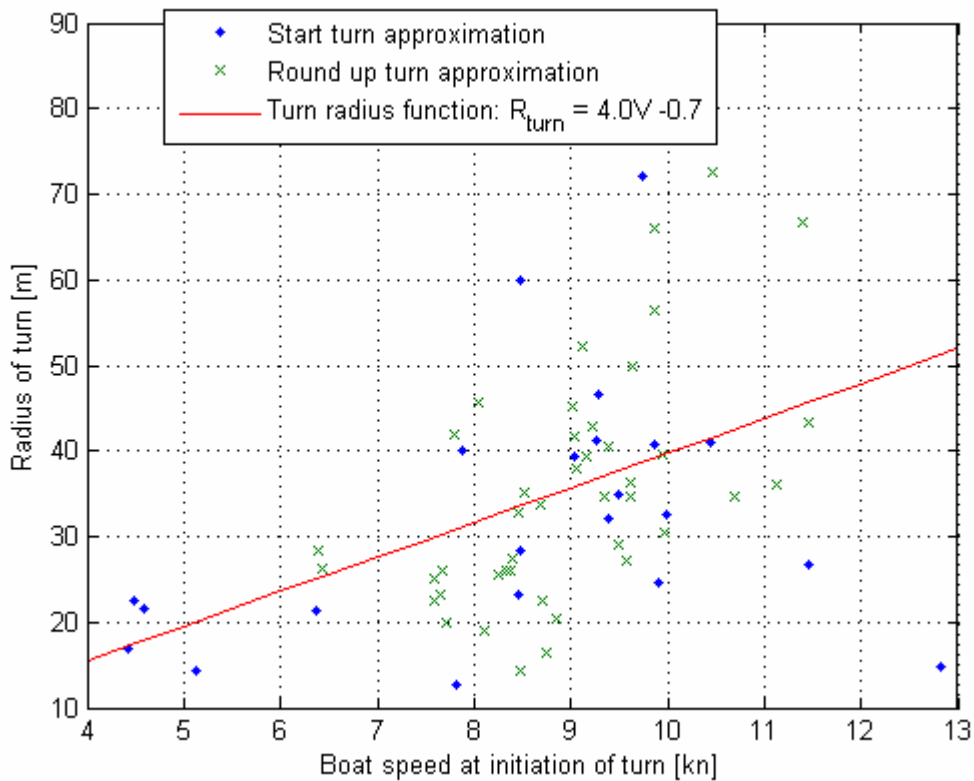


Figure 14. The data for all approximations of turn radius in the extracted sequences plotted against initial boat speed. A linear interpolation to the data gives the function that describes the change of turn radius for different initial boat speed that is used to choose the geometry of the turn.

A linear function that will be used to choose turn radius was interpolated to the data shown in Figure 14 and approximately became

$$R_{turn} \approx 4 \cdot V . \quad (31)$$

### 3.3 Target

As the boat turns the apparent wind angle will decrease. When the boat reaches a certain apparent wind angle the turn will be interrupted and the boat starts to sail towards the line. This certain apparent wind angle is given of what normally is called the target apparent wind angle,  $\beta_{target}$  and is the most efficient angle to sail towards the wind given the present wind speed. The target wind angle is given by evaluating the selected turn sequences.

The apparent wind angle the boat sails after a turn until a beat is approximately the target wind angle. The variation of this angle as a function of the wind speed is shown in Figure 15 below.

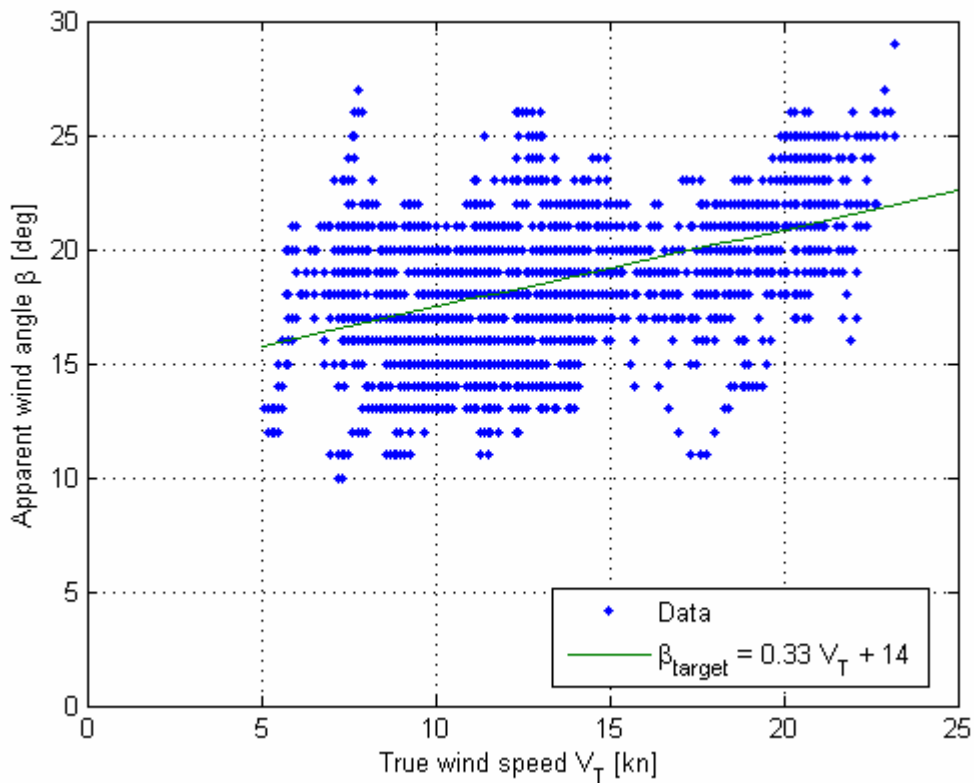


Figure 15. Data for which apparent upwind wind angle that is sailed for different true wind speeds and the interpolated function for the target apparent wind angle as a function of the true wind speed. This function decides when the turn should be interrupted.

The data is not very consequent but a linear fitting was made and became

$$\beta_{target} = 0.33 \cdot V_T + 14. \quad (32)$$

### 3.4 Connect equation of motion and geometry

The model consists of more or less two main parts, one that predicts a travelled distance out of an equation of motion and input data of the present conditions and one part that predicts the travelled path (geometry of turn and target wind angle) also with respect to the present conditions. The connection between these parts makes the model complete.

The connection is not very advanced, the input variables that is necessary for both the EOM and the geometry model is continuously updated during the iterative calculation. The calculation starts with input from the instruments, from that starting point the travelled distance for a small time interval and the speed in the new position is integrated out of the acceleration given by the EOM and the inputs. Also from inputs of the instruments a path is chosen/predicted for the calculated travelled distance. Together this gives enough information to calculate new inputs to the EOM and the geometry model and a new integration can be done. This procedure continues until the calculated position crosses the starting line.

## **3.5 Special conditions**

There are some situations and conditions that have to be accounted for to make the program work. Exceptions need to be taken care of to make the program robust.

### **3.5.1 Above the starting line**

To start with, the basic concept of the choice of path starts with a turn until target wind angle is obtained. This makes the program a bit limited, in some cases for example when the boat is above the starting line it can happen that the predicted path would not cross the starting line. This is taken care of by simply not do the calculation when the present position is on the wind side of the starting line.

### **3.5.2 Outside the starting line**

There is also the case when the predicted crossing of the starting line is outside the start buoys i.e. on the extension of the starting line. This case is not taken care of more than a warning flag is returned from the calculation.

## 4. Evaluation

Evaluation of the generated routine for predicting time to burn is an important part. It is a way to confirm the developed functions and a last chance to correct mistakes. The evaluation is done in two different ways, one done by using data log files as input and comparison and one live test on board of the Swedish America's Cup boat Örn.

### 4.1 Evaluation of the model

To evaluate the precision of the model a comparison with measured data is done. This evaluation is done by denoting a virtual starting line perpendicular to the wind a given time period ahead in a log file and compare how long time the model predicts that it would take to get to the line. Because it is approximately 20 seconds left to start when the need of information on how much time there is to burn becomes essential this is a reasonable evaluation time period. The evaluation is done for a number of different starting points and extracts of log files and the result is shown in Figure 16 below.

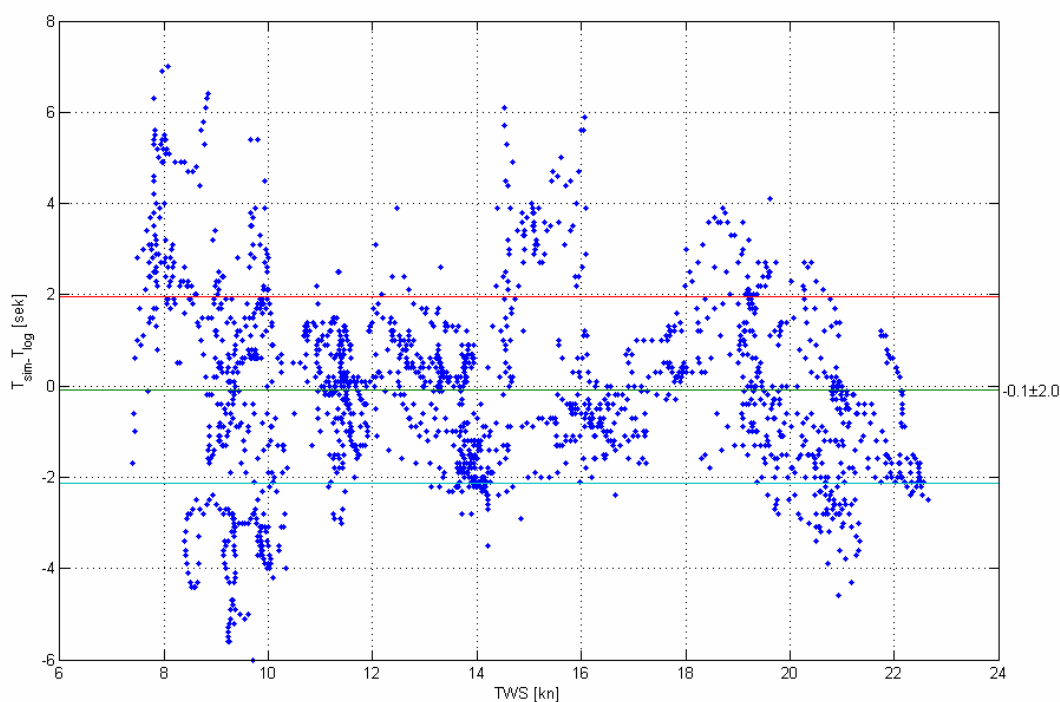


Figure 16. The evaluation of the model using log files and a virtual starting line. For this 20 second long prediction time the standard deviation became 2 seconds.

The choice of log sequences for this evaluation is somewhat complicated, in real time which the log files represent; the skipper will always make adjustments in form of turns from and against the wind as new information about time to burn is presented. In theory these adjustments would be or almost be unnecessary with a very accurate prediction of time to burn. Therefore most of the sequences evaluated here are parts of upwind sailing and small extractions of start sequences where few corrections have been done.

The result of the evaluation shown in Figure 16 gives a hint of how accurate the prediction of the program is. A quantitative measure of it is the standard deviation which became 2 seconds.

This means that statistically 68% of all predictions (with 20 seconds evaluation time) will fall in between  $\pm 2$  seconds miscalculation. Another conclusion from the evaluation is that in the lower wind speed region the accuracy is unsatisfying. Further the error seems to be equally spread around zero; there are both over- and underestimations. This further indicates that the model is quite poor in the lower wind regions which one possibly can relate to the results from Figure 11.

## 4.2 Conclusions

The goal with the model was to make it so accurate and consistent that it would make every prediction with an accuracy of 1-2 seconds. The simulated tests of the model show that the majority of the calculations are as good as or better than the target accuracy. But approximately one third of the calculations will not be good enough. There are some possible reasons to this inaccuracy. All of the reasons are related to the big unexplained and non consequent variation of the data. In Figure 9 where boat speed at upwind was extracted and compared a first indication of scattered data was given. For the same wind conditions the boat speed should not vary that much. Figure 14 with interpolated turn radius contradicts the theory of a “standard turn”. The interpolated turn radius can vary as much as 50 m for the same boat speed at the initiation of the turn and therefore is the curve (which is the base to the turn radius function) fitted to those interpolations poor. The third example of the data variation is the extracted sailed target apparent wind angles shown in Figure 15 which vary about  $15^\circ$  for the same wind speed. These unexpected variations in different used parameters make it very hard to get a model with good accuracy for all predictions.

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## **Appendix A, Sensor specifications**

### **Wind Sensor specifications**

#### **213 Mast head unit specifications**

Construction: sealed electronic housing in injection moulded conductive plastic for electrostatic discharge protection incorporating heavy weather skirt. Bracket mounted with a high quality connector via a black painted aluminium spar. Sealing to IP66

Spar Length: 530mm (20.9")MHU

Weight: 0.4kg (0.88lb)

Cable: Light weight 6 core PVC sheathed cable with CEFOR strength member. Custom extra lightweight cables available to order as an optional extra

### **Compass Sensor Specifications**

#### **Halcyon 2000 Compass Sensor Specifications**

Construction: Robust plastic casing with multi-way connector at base

Compass Type: Auto-calibrating electronic flux-gate