AUSTRALIAN MARITIME COLLEGE

Master of Philosophy Thesis

Validation of a Sailing Simulator using Full Scale Experimental Data

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Professor Neil Bose

Thesis submitted in partial fulfilment of the requirements for the Degree of Master of Philosophy (Naval Architecture)

National Centre for Maritime Engineering and Hydrodynamics

AMC is an institute of the University of Tasmania

DECLARATION

I hereby declare that the whole of this submission is my own work and the result of my own investigation and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text of the project.

I further declare that the work embodied in this project has not been accepted for the award of any other degree or diploma in any institution, college or university, and is not being concurrently submitted for any other degree or diploma award.

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Nicholas Clark

November 2014

ACKNOWLEDGEMENTS

I acknowledge the patience of all parties with interest in this project. I thank the professional support given by my supervisor Dr Jonathan Binns and Co-Supervisor Professor Neil Bose. Personally, thank you to my family for the patience and encouragement you've given me.

This is dedicated to the memory of Thelma 'Grace' Rainbow. I promised I wouldn't give up this opportunity and see it through to the end. I did it Gracie!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

Symbol	Description	Units
AOA	Angle of Attack	°
AWS	Apparent Wind Speed	m/s
AWA	Apparent Wind Angle	m/s
F	Output Frequency of wind anemometer	Hz
g	Acceleration due to Gravity	m/s^2
hh	Hours	hr
kn	Knot	NM/hr
mm	Minutes	min
P	Atmospheric stability index	
ρ	Density of Air	t/m^3
ss	Seconds	s
T	Draft	m
TWS	True Wind Speed	m/s
TWA	True Wind Angle	m/s
U	Wind velocity	m/s
V_{DINGHY}	Forward dinghy velocity	m/s
Z	Reference Height above water	m

AXIS **SYSTEM**

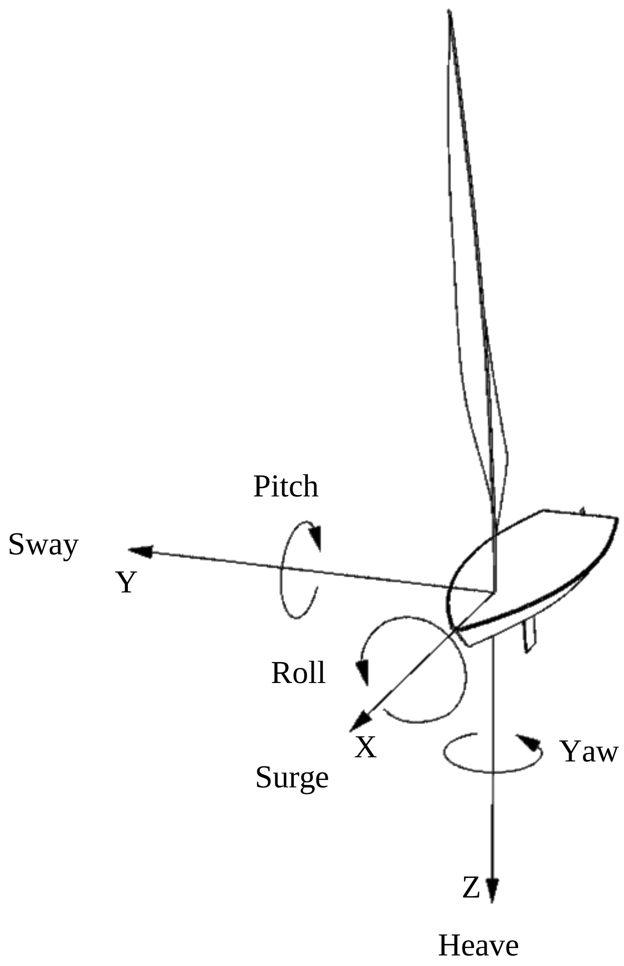

Figure 1-1: This figure illustrates the body fixed axis system used.

ABBREVIATIONS

AOA	Angle Of Attack
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
DAS	Data Acquisition System
GPS	Global Positioning System
HITL	Human In The Loop
TWA	True Wind Angle
TWS	True Wind Speed

TERMINOLOGY

Bow	Forward or Front region of dinghy
Stern	Aft or rear region of dinghy
Port	Left
Starboard	Right
Surge	Longitudinal motion in the x direction
Heave	Vertical motion in the z direction
Sway	Transverse motion in the y direction
Roll	Rotation about the longitudinal x axis
Yaw	Rotation about the vertical z axis
Pitch	Rotation about the transverse x axis
Tack	The manoeuvre of turning between starboard and port tack
Windward	To sail upwind
Leeward	To sail downwind

ABSTRACT

Virtual Sailing Pty Ltd is an Australian company that for over 10 years has invested significant time and resources into developing a ride on sailing simulator, which replicates several classes including the Laser and megabyte sailing dinghies. The simulator provides a means for training and performance assessment of sailors; including the feature of providing rehabilitation and training for disabled body sailors through the V-Sail Access Simulator.

Prior to this project, the sailing simulator had not been validated with experimental testing. It was proposed that an experimental Data Acquisition System be used in a series of manoeuvring trials, in order to obtain experimental validation data. Full scale experimental testing was performed at Albert Park Lake, Melbourne. The aim of testing was to acquire validation data including dinghy velocity over land; Apparent Wind Speed (AWS) and Apparent Wind Angle (AWA), Rudder angle and GPS position.

Subsequent testing on the simulator using experimental course data from Albert Park Lake was used to systematically repeat full scale course laps and manoeuvres in order to obtain simulated data for comparison with experimental data. Comparison between experimental and simulated data formed the validation component of the project.

The validation study found that the manoeuvring model employed in the simulator replicated the results from experimental testing, especially with regard to manoeuvring response of the simulator compared to experimental results. Average dinghy velocity through specific headings relative to true wind angle showed variation to the simulator (within an order of magnitude), which requires further investigation. Specifically, it is recommended that future work investigates the validation of the main resistance and powering components of the simulation, including but not limited to; hydrodynamic hull drag, righting moment provided/required by the sailor, and aerodynamic sail forces.

Finally, the Data Acquisition System and supporting equipment was found to be robust, and potentially applicable to other marine vessels.

1. INTRODUCTION

1.1. BACKGROUND

Over the past 10 years, Virtual Sailing Pty. Ltd. has continuously developed a human in the loop (HITL) simulator, dubbed the 'VSail Trainer'. Initially developed to assess the physiological performance of sailors (Walls, Gale, Saunders and Bertrand 1998), the simulator has evolved into a high fidelity training tool capable of training sailors of all levels from beginner through to Olympic, including disabled sailors (Mooney, Saunders, Habgood and Binns 2009). The simulator is a ride-on active dinghy sailing simulator consisting of a modified dinghy cockpit, mounted on a gimble which allows roll about the longitudinal axis. The sailor sits in the cockpit, with tiller and mainsheet controls at hand to control a virtual rudder and virtual sail position. The third user control input is positioning the hull in roll by 'hiking' off the side. This provides virtual righting moment to the dinghy. The three user control inputs of tiller, mainsheet and cockpit position also feature haptic (tactile) feedback, in that they provide force feedback to simulate forces that the sailor would experience in real sailing. Roll feedback is through a pneumatic ram, mainsheet through a progressive spring and rudder via electric solenoid actuator.

Cockpit roll, mainsheet and tiller inputs combined with other pre-programmed inputs to the simulated force balance consisting of virtual sail, rudder, centreboard and hull form coefficients produces forward thrust and velocity. Resultant movement is primarily visualised on a projector screen ahead of the sailor. A second visual display is available through 3D goggles which provide an immersed reality experience, allowing the sailor to look around the course in 360 degrees. On screen data gives feedback to the sailor in the forms of velocity, heading, wind direction, wind and water sound, position on a virtual course and various timing features including total race time and lap times.

The trainer is able to simulate a number of classes, including: Laser Standard; Laser Radial; Laser 4.7; Optimist; Byte; Mega Byte; Liberty, and 29'er (Binns, Bethwaite and Saunders 2002; Binns, Maher, Chin and Bose 2009). Applications of the VSail Trainer (Mooney, Saunders, Habgood and Binns 2009) are wide and varied, including:

- Training of beginners through to Olympic level sailors (Figure 1-1);
- The assessment of tactical and physical performance of elite level sailors, in a controlled environment, with data logging and simulation replay facilities;
- Training of disabled sailors, and

- Rehabilitation of spinal injury patients, utilising the rolling motion of the simulator.

In line with continual development of the VSail Trainer, Virtual Sailing aims to validate the current simulation to quantify the fidelity of the simulation in relation to real life.

Figure 1-1:AVSail Trainer suite, including dynamic rolling hull and on screen virtual course position. Source: www.virtualsailing.com.au.

1.2. PROBLEM DEFINITION

The project concentrated on the need to validate the Virtual Sailing Pty Ltd sailing simulator, with real world data. In order to validate the sailing simulation, a broad analysis approach comparing course lap times was undertaken. Subsequently the investigation shifted to more specific areas such as velocity polar plot comparisons and tacking analyses.

With key analysis areas known, validation data was required. The Data Acquisition System (DAS) made available by project collaborators at the University of Melbourne (Bennett, Manzie, Oetomo, Binns and Saunders 2010) allowed data acquisition to take place on an instrumented Laser class sailing dinghy.

The instrumented Laser dinghy was based in Melbourne which meant there was a choice between two local test sites: Port Phillip Bay or Albert Park Lake. Albert Park was chosen over the bay due the controlled environment offered. Tide and current drift effects on GPS position and velocity measurements were eliminated, and wave interference on accelerometer sensors greatly reduced (see Figure 1-2, Figure 1-3).

Figure 1-2 - Albert Park Lake, Melbourne is located alongside Port Philip Bay. The close proximity to the bay provides relatively steady wind speed and direction for testing. More ideal test sites such as a dessert lake or even Lake Wendouree in Ballarat may provide more stable wind conditions, however at the time of testing the Lake was dry and further travel abroad was not within the scope of the project budget.

Figure 1-3 - This close up satellite image of Albert Park Lake is of the test area located at the northern end of the lake. Wind direction is predominantly seen to come from the South West. The very North pocket of the lake.

The downside of testing on the lake was the influence of surrounding buildings and trees on wind direction and velocity. As winds experienced during testing were consistently South Westerly's, the Northern pocket of the lake experienced flukey winds due to the infrastructure and trees along the North Western side of the lake (East of the Lakeside Stadium) shown in Figure 1-3. To remedy the interference problem, the set course was to be to the south of the West of the Island where minimum interference was experienced..

To capture onboard rudder angle and wind velocity information during testing, a wireless Data Acquisition System (DAS) was constructed using remote monitoring stations communicating over a wireless network local to the dinghy. The system created by Bennett, Manzie, Oetomo, Binns and Saunders (2010) had several robust features which were an ideal match for the harsh marine environment.

The wireless communications of the system mean that no cable looming was required to set the system up on board (the system was transportable and generic to any sailing platform). Data was transferred over a wireless network from the I-mote senders to a mini-laptop secured to the deck in a waterproof bladder. One of the key features of using I-mote senders was that they were capable of storing a buffer of data, so that in the event of the signal being temporarily lost on board (for whatever reason), on resumption of transmission/reception all data is fully transmitted/received/recorded with no loss. The battery packs, accelerometers and I-mote data sender packs were all protected in waterproof boxes and anchored to the deck.

With full scale data acquisition available, the concept of experimental and simulated testing analysis was to start with high level analysis of laps sailed around a marked course; then concentrated on velocity polar analysis (dinghy velocity through 180 degrees of heading) and rudder angles during tacking manoeuvres.

To summarise the problem definition, the aim of this research was to quantify the accuracy of the current Virtual Sailing simulation when compared to real world manoeuvres.

The primary research questions were:

1. How accurate is the simulation?
2. How accurate does the simulation need to be?
3. How can the simulation be improved?

With key research questions identified, the aims of this study were to:

- Quantify the accuracy of the current Virtual Sailing simulation when compared to real world manoeuvres;
- Identify which sailing simulation parameters/coefficients should be investigated in validating the simulation;

- Investigate how the simulation model can be validated using the available data acquisition system;
- Obtain real world validation data from on water testing;
- Simulate on water conditions using the sailing simulator; and,
- Identify how the simulation can be improved.

1.3. Scope of Work

The aims of this study were achieved by conducting a series of manoeuvring tests in both the full scale and simulated domains, and a number of pre and post processing activities (Figure 1-4).

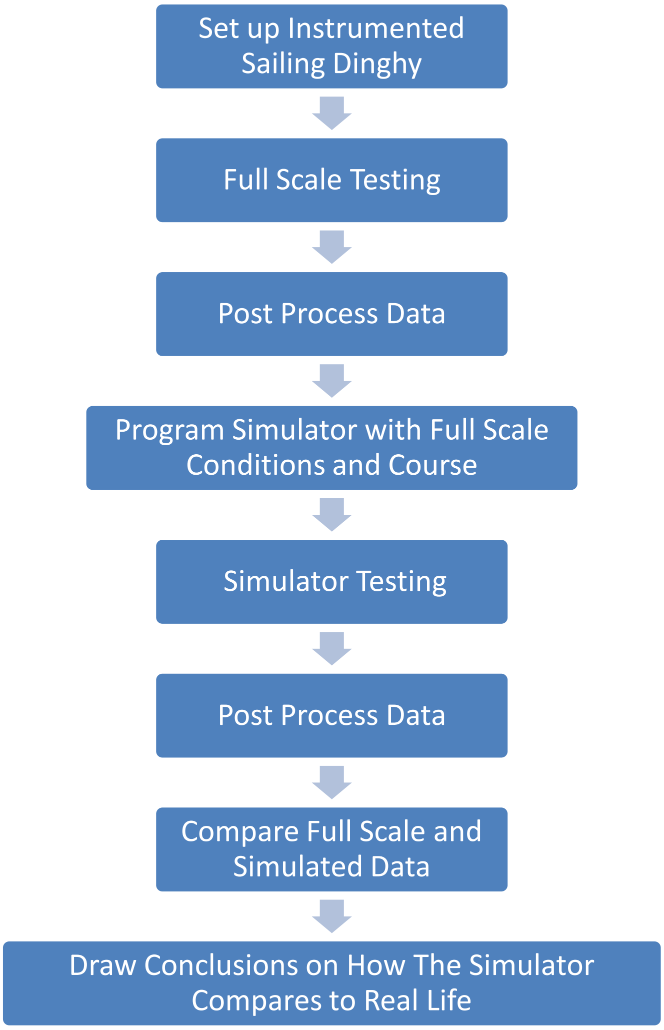

Figure 1-4: Simplified Work Scope Flow Chart.

Full scale Laser dinghy testing was carried out, in order to obtain; Time series GPS location, rudder angle and wind speed and direction data; Set course lap times for comparison in simulator; Dinghy pilot video and forward direction video.

GPS data combined with video vision of key rudder movements was used to time synchronise all data, and chronicle all manoeuvres carried out during testing.

GPS, wind anemometer direction and magnitude data channels were post processed to obtain Dinghy velocity over land (Vd), dinghy heading (relative to magnetic north), Apparent Wind Speed (AWS), Apparent Wind Angle (AWA), True Wind Speed (TWS); True Wind Angle (TWA) and, course orientation and lap times sailed during testing.

Sailing simulation course markers and wind speed were reprogrammed to match the triangular course and conditions experienced during testing.

A virtual representation of the course sailed on Albert Park Lake (See Section 1.2)'Virtual Albert Park' was sailed on the simulator by the same pilot that carried out real testing, to obtain simulated dinghy velocity and rudder information.

Dinghy velocity polar plots were generated and comparisons made between simulated and full scale data. Rudder angles were analysed in comparing tacking manoeuvres between simulated and full scale testing.

1.4. LITERATURE REVIEW

Throughout the maritime world, training of personnel using simulators and simulation is becoming more and more common. In order to ensure simulators realistically replicate reality, research has been carried out to develop, validate and improve simulations covering ship simulation (Duffy 2005; Duffy, Renilson and Thomas 2009), large sailing craft (Binns, Hochkirch, Bord and Burns 2008; Mansbridge 2013); (Capdeville 2010; Lidtke 2013) and smaller sailing craft; with the exception of validation of the smaller craft themselves.

While small sailing simulators have been and are being developed around velocity prediction programs and regression data (Mulder 2013), there was no direct experimental data available for validating the V-Sail trainer. This project focussed on that knowledge gap and sought to obtain experimental data in order to validate the Vsail trainer simulation and simulator.

The sailing simulator was originally developed to assess the physiological performance of sailors (Walls, Gale, Saunders and Bertrand 1998), other examples of which included work by Cunningham (2007). After a review of the simulator's strengths and weaknesses, work carried out by Binns, Bethwaite and Saunders (2002) was the first major overhaul of the simulator.

After the programming upgrade, the sailing simulation was now similar to FRIENDSHIP Systems Velocity Prediction Program (VPP) (Richardt, Harries and Hochkirch 2005), with sail lift and drag coefficients derived from Marchaj (1988) and modified to suit the simulated sail parameters due to an absence of experimental data (Binns, Bethwaite and Saunders 2002). This lead to the use of data which was not always ideal. In the case of work by Walls, Gale, Saunders and Bertrand (1998), wind data was used which was measured on land, which may not necessarily reflect conditions on the water. In experimental testing, this can be addressed by an onboard anemometer. Ultimately, the development approach taken has led to a sailing simulator with performance that ‘feels’ very similar to reality and is indeed a physically demanding training tool, but the question remained as to how closely did it match reality in terms of performance?

Simulation Verification, Validation and Calibration (VVC) is common practice (Rakha, Hellinga, Aerde and Perez 1996; McFarlane 2002) during the development/upgrade life-cycle phase of a simulation program. Specifically, the International Towing Tank Conference (ITTC) outlines procedures and guidelines (ITTC 2002) that are to be followed when validating a maritime vehicle/simulation. However, the guidelines have been developed to suit marine vehicles with engine propulsion, not sails, leading to the need for a more suitable series of manoeuvre tests. Binns, Hochkirch, Bord and Burns (2008) outline a modified series of manoeuvres that are designed specifically to obtain manoeuvring coefficients for sailing yachts.

Project collaborator Graham Bennett, and a team from the University of Melbourne (Bennett, Manzie, Oetomo, Binns and Saunders 2010) developed a low cost wireless Data Acquisition System (DAS) to carry out yacht system identification, or characteristic dynamic movement identification (not limited to manoeuvring coefficients). To suite the resources offered by the DAS, select manoeuvres outlined by Binns, Hochkirch, Bord and Burns (2008) such as luffing into the wind, and monitoring rudder angle during tacking angles, while logging position/velocity/heading with GPS were used. Additional resistance validation data for a full scale Laser dinghy has been published by Carrico (2005), and it is recommended that a comparison be made with the simulation drag curve in future.

Once raw test data had been obtained, post-processing of all data was required. In order to obtain dinghy heading, True Wind Angle (TWA) and True Wind Speed (TWS) relative to the course, Longitude and Latitude information needed to be converted to 360 degree heading by using a modified version (Rick 2001) of ‘Great Circle Navigation Formulae’ (Williams 2011).

With time series of velocity and heading obtained, assessment of yacht performance was represented by a polar plot of velocity over land through 360° heading with assumed constant wind direction (Binns, Bethwaite and Saunders 2002).

1.5. LASER CLASS SAILING DINGHY

The class of yacht used for experimental and simulated analysis was the Laser Class Sailing dinghy, with Olympic sized rig (the size of the sail). The Laser class sailing dinghy is a concept first developed in 1969 by Bruce Kirby (Tillman 2005). It is considered to be the most popular one design sailing class in the world, with competitive events held from club racing to world championships. To ensure that no competitor gains unfair advantage, all dimensions of the Laser class dinghy are clearly stipulated by Laser class rules (ILCA 2014). The particulars of the standard Laser class dinghy are shown in Table 1-1, and dimensions of components used in testing are presented in Figure 1-5, Figure 1-6, Figure 1-7 and Figure 1-8.

For simplicity of presentation in this report, the 'Laser class sailing dinghy' will be referred to as 'dinghy' from herein.

Table 1-1:Standard Laser class dinghy principal particulars

Parameter	Value	unit
L_{OA}	4.23	m
L_{WL}	3.81	m
A_{SAIL}	7.06	m^2
T	0.30	m
Δ_{HULL}	59	kg

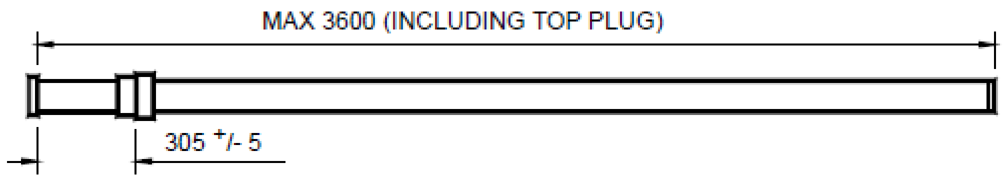

Figure 1-5: Upper mast section sizing common to all Laser classes, used for all full scale tests. All dimensions are in millimetres, drawing is not to scale. Source: Laser Class Rules (February, 2008).

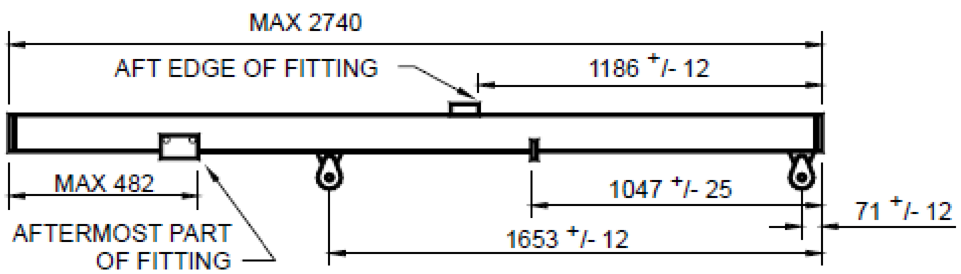

Figure 1-6: Boom section sizing common to all Laser classes, used for all full scale tests. All dimensions are in millimetres, drawing is not to scale. Source: Laser Class Rules (February, 2008).

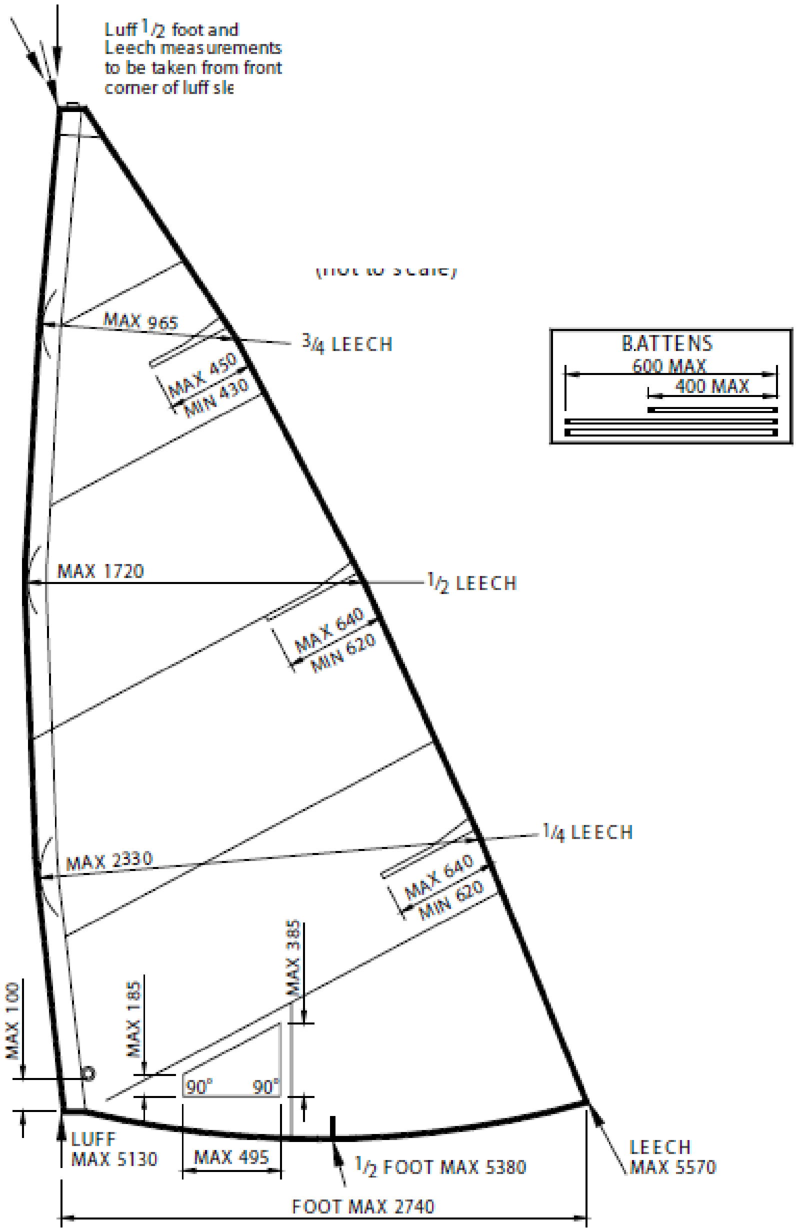

Figure 1-7 Governing sail dimensions for the full size Olympic class sail. This sail size has been used for all full scale testing. All dimensions are in millimetres, drawing is not to scale. Source: Laser Class Rules (February, 2008).

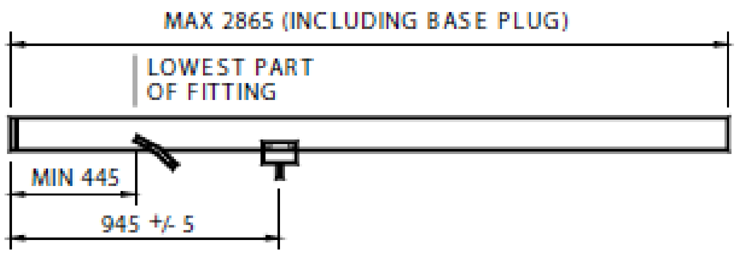

Figure 1-8: Lower mast section sizing of the full size Olympic class mast used for all full scale tests. Mast is split into two sections for ease of transport. All dimensions are in millimetres, drawing is not to scale. Source: Laser Class Rules (February, 2008).

2. FULL SCALE TESTING AND DATA ACQUISITION

The following chapter discusses experimental procedure, processing of data, results, discussion, conclusions and recommendations for the third full scale testing session conducted on Albert Park Lake, Melbourne, during early June 2011. Testing was conducted in conjunction with project collaborator and wireless Data Acquisition System (DAS) developer, Graham Bennett.

2.1. INTRODUCTION

The overall goal of full scale testing was to provide a set of time series dinghy performance data, given measured wind speed and direction on a set course. The course and wind data were subsequently input into the simulator and simulated testing carried out (See Section 3: *Sailing Simulator Testing and Data Acquisition*). Specifically, the aims of the test session were to:

- Create and define with GPS measurements, a marker buoy defined course for measurement and replication in the sailing simulation;
- Obtain a series of lap times for the marked course;
- Obtain time series measurements of Apparent Wind Speed (AWS) and direction for the duration of testing, to subsequently be combined with dinghy velocity and heading to produce True Wind Speed (TWS) and direction that would be replicated in the simulator;
- Obtain time series measurements of rudder angle; and,
- Carry out consecutive upwind tacks.

The wireless Data Acquisition System developed by Graham Bennett (Bennett, Manzie, Oetomo, Binns and Saunders 2010) was used to acquire the required information during full scale testing. 4 days of testing were carried out over an 8 day period, with the first 3 days used to shakedown and become familiar with the DAS and test apparatus. Bugs were ironed out of the DAS and calibration procedures set based on lessons learnt from the first 3 days. The final test day of 4 was the most successful day from the points of view of equipment calibration through to data acquired and weather conditions experienced. The analysis of this project is based on the information obtained from the final day of testing.

2.2. EXPERIMENTAL SETUP PROCEDURE

The following is an introduction to key experimental setup procedures. For a complete guide to experimental setup, please see Appendix A – Experimental Procedures.

GoPro HD cameras were placed on the forward deck (Figure 2-1), facing forward and aft, to give video footage of course direction, pilot position and rudder position. Video footage of the dinghy leaving and arriving at the start/finish pontoon combined with video timestamps, formed a part of time synchronising the GPS and onboard data channels.

Rudder calibration took place using markings placed on the aft deck with a protractor (Figure 2-4**),** so that rudder angle could be obtained from the raw encoder information**.** At the start of each test session, the rudder was held centred then stepped through:

- 20 degree steps every ~5 seconds to starboard, centre, port and centre, and
- 10 degrees every 5 seconds to starboard, centre, port and centre.

The 20 degree step check was to provide a quick rough check to compare data for each test session, and the 10 degree check was for finer calibration should any parameters change from test to test.

2.2.1. BOOM ANGLE ATTACHMENT AND CALIBRATION

The mast encoder designed to measure boom rotation angle was tied to the mast with a piece of elastic cord. Recording boom angle through mast rotation was possible since boom angle relative to the mast was fixed at boom/mast joint.

Using a similar calibration procedure to rudder angle calibration, the boom was held in line with the centreline at 0° rotation, then stepped through 45°, 90° and 180° rotation angles through both the port and starboard sides.

2.2.2. DATA STORAGE

The onboard DAS used a sealed notebook in a waterproof bag to collect recorded data. The bag was anchored to the deck with D shackles (Figure 2-6).

A Velocitek SC-1 GPS unit (Figure 2-7) was located inside the cockpit of the dinghy. It was housed in a waterproof case specifically designed for use in the marine environment.

2.2.3. RUDDER ANGLE ATTACHMENT AND CALIBRATION

A rudder encoder was attached to the rudderstock using an elastic cord (Figure 2-2, Figure 2-2).

Figure 2-1: Dark (Micro-computer) and Light grey (Transmitter) boxes attached to the deck. The Port/Aft facing camera is attached, with a plate ready for starboard camera mounting. The mast encoder can be seen to the central left, whilst the base of the anemometer is to the extreme right at the bow. All this equipment was structurally robust and watertight, ideal for the harsh conditions.

Figure 2-2: Rudder belt attachment.

Figure 2-3: Encoder belt attachment.

Figure 2-4: Rudder angle markings drawn on the aft deck. Deck markings were used before each test to obtain rudder angle calibration data. The rudder was rotated through incremental steps of 10 ° and 20° from side to side to a maximum of 60°, starting at the centre.

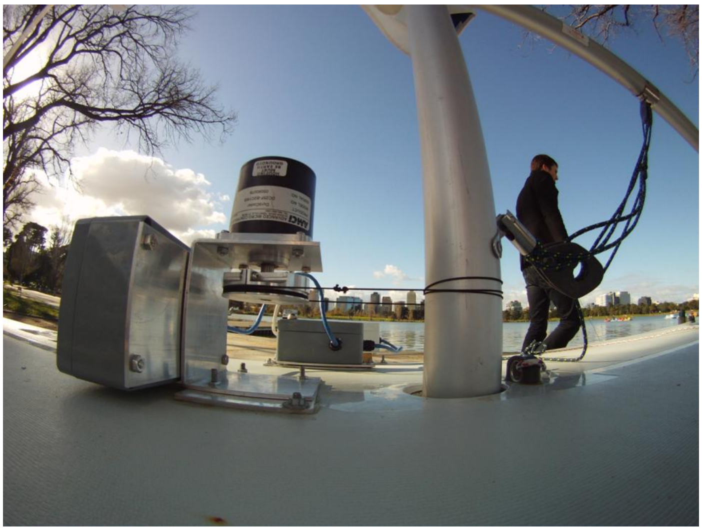

Figure 2-5: Mast Encoder Attached with three loops of fine elastic cord around both mast and encoder.

Figure 2-6: DAQ Laptop, and GPS unit (bottom right of bag) in waterproof bag. The bag was shackled to the deck.

Figure 2-7: Velocitek SC1 GPS unit in waterproof buoyant casing.

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2.3. On-water Test Manoeuvres

The two following manoeuvres were conducted on Albert Park Lake, Melbourne, with the aim of obtaining full scale validation data required to complete this study.

2.3.1. Test 1 – Laps of A Set Course

Marker buoys with anchor weights were dropped in the lake to form a triangular course (Figure 2-10). When dropping the buoys into position, station was held next to each one whilst GPS was recording in order to accurately measure the course. The purpose of marker measurement was to later reproduce the course in the sailing simulator.

Marker drift was minimal as there were no tidal effects present, and the mooring catenary was relatively short (3 to 4 metres), due to the shallow nature of the lake.

Multiple laps were completed by rounding the course to the port side; starboard side and upwind/downwind 'hotdog' laps. All position data was recorded by GPS.

2.3.2. Test 2 – tacking manoeuvre

Tacking (changing direction when sailing upwind) performance of sailor, yacht and simulator is an area that when improved can reduce course times. Multiple tacks were carried out per lap in negotiating the course. In addition to tacks completed during course runs, multiple consecutive upwind tacks were completed without following the course to obtain a comprehensive data set. Tacks were executed whilst sailing in the best apparent Velocity Made Good (VMG, upwind course velocity). Tacking analysis is a good real world indicator of simulator performance.

2.4. DATA PROCESSING AND ANALYSIS

Raw anemometer data, rudder angle and boom angle encoder data was logged by the onboard system and stored in .txt files. Raw data obtained was post processed and converted into a MATLAB compatible format use the *'Data Condition'* MATLAB tool written by University of Melbourne collaborator Graham Bennett.

In order to be able to post process data obtained from testing, calibration and measurement procedures were carried out prior to each test session (see section 2.2 and Appendix B). Calibration information was used in conjunction with rudder angle encoder and wind anemometer Original Equipment Manufacturer (OEM) conversion formulas to convert raw data signals into meaningful values. For example, rudder angle encoder voltage to degrees (Figure 2-8) and wind anemometer voltage pulses per second into wind velocity.

In addition to converting raw data into meaningful data, DAS GPS and Video time all synchronized required synchronizing to provide one continuous time series of data.

2.4.1. SYNCHRONISING DATA

Data Acquisition System (DAS), GPS and video data required synchronising, as all started recording at different times, and with different time stamp information. Video footage of rudder movement and boat location at the start of each run, combined with DAS rudder measurement and GPS track/time analysis provided sufficient information to sync all data.

The procedure to sync all 3 data streams firstly involved synchronising rudder DAS data to video time. Characteristic rudder movements and durations were noted from onboard video footage, which took place at the start of each days test session; this gave a link between data 'bit' time and video time. Secondly, GPS time was required to be linked to video time. Video footage was reviewed and times were noted when the dinghy started sailing at the start of each on water test. GPS Action Replay Pro was then used to find the corresponding start of each run using visualization of the course sailed and the point at which velocity data increased from zero. A link between GPS time and Video time was now obtained.

Table 2-1 shows DAS Bit data that has been related to video time, and GPS time related to video time (all highlighted in blue). The delta of 2:10 between the two video times has been deduced from GPS time, to give one synchronised point in time across all data sets. The accuracy of synchronising between video time is within ±0.5 seconds, and between Video to GPS time of ±1 seconds (due to the 0.5Hz GPS sample rate). This level of accuracy is deemed acceptable to carry out the analysis required.

Table 2-1 - Synchronised GPS data with DAS data using Video timestamp references

Bit value	Video Time	GPS Time
(N/A)	(hh:mm:ss)	(hh:mm:ss)
50490	**0:03:28**	13:05:05
	0:05:38	**13:07:15**

2.4.2. RUDDER ANGLE DATA

Rudder calibration took place using markings placed on the aft deck with a degrees wheel (Figure 2-4**).** At the start of each test session, the rudder was held centred then stepped through:

- 20 degree steps every ~5 seconds to starboard, centre, port and centre, and
- 10 degrees every 5 seconds to starboard, centre, port and centre.

The raw data that resulted from this process is shown in Figure 2-8.

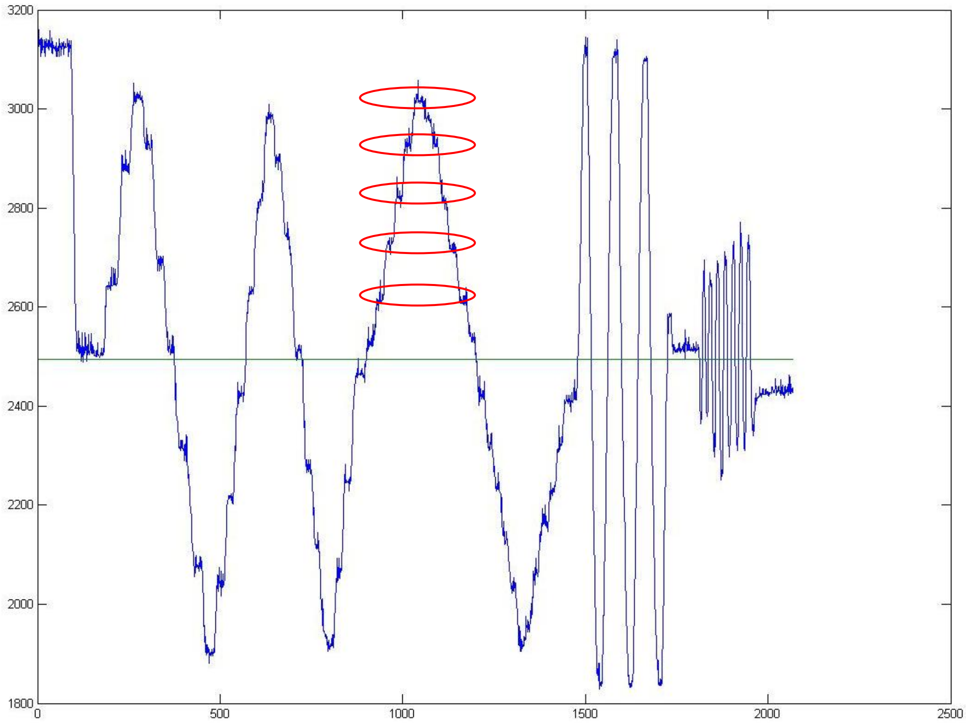

Figure 2-8: Raw time-series rudder encoder data obtained from a rudder angle calibration check. The x-axis is discrete data recorded at 20Hz (20 data points represents 1 second), and the y-axis is 12bit unsigned data (upper values are when rudder is to starboard). One example of incremental rudder angle steps recorded during calibration are highlighted in red. The central transverse mean line indicates zero rudder angle.

With changes in encoder recordings correlated to changes in rudder angle, a relationship between rudder angle and encoder value was obtained.

2.4.3. WIND ANEMOMETER CALIBRATION

Calibration of the wind anemometer was divided into two measurement areas: direction and speed. Directional calibration took place at the start of the test, where the wind vane was held in line with the dinghy, and facing forward. Once zeroed, directly forward of the dinghy represented 0/360 degrees (Figure 2-9) and angle magnitude increased to starboard (direction rotating clockwise).

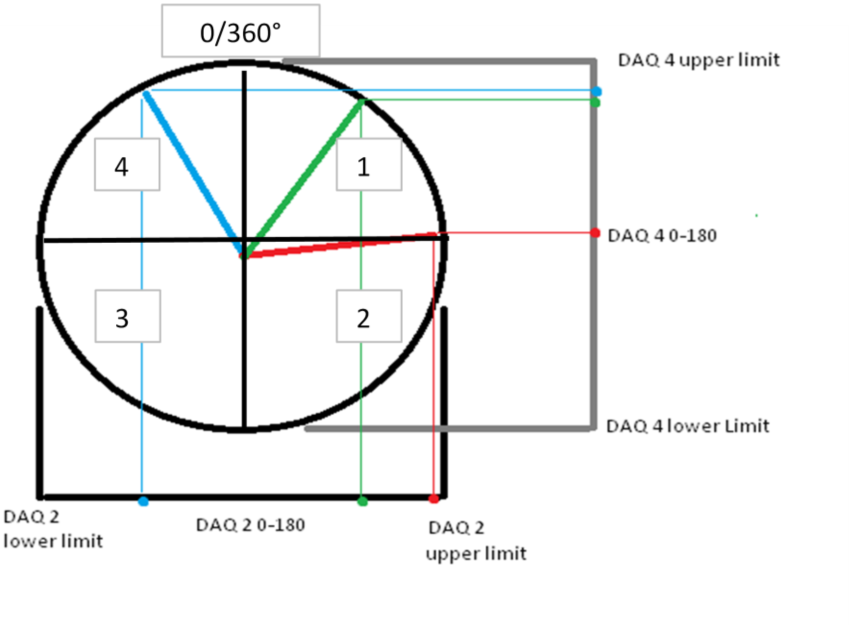

Figure 2-9: Anemometer measurement orientation

Wind speed calibration factors were provided by the manufacturer (Vaisala 2009). The characteristic transfer function gave velocity as:

$$U = 0.24 + 0.699 * F \tag{2.1}$$

Where U=wind speed (m/s) and F=output frequency (Hz).

Processing of the raw wind speed data showed that wind speed data had been altered when processed into an electrical signal, and required the transfer function to be modified. A modified transfer function was provided by Graham Bennett where:

$$U = \frac{0.699}{130} * [DAQ3] - \frac{6}{130} \tag{2.2}$$

Where U=wind speed (m/s) and DAQ3 is the data channel containing transformed wind speed information (Hz).

2.4.4. GPS DATA - DINGHY POSITION, HEADING AND VELOCITY

GPS data was logged on a VELOCITEK SC1 sailing GPS device, at a sample rate of 0.5Hz. GPS data included:

- Date and time (used for synchronising with DAS recorded data, as data is independent of one another);
- Latitude and Longitude (used in heading calculations); and,
- Velocity and distance.

GPS data was recorded separately to the DAS system by the standalone GPS Velocitek GPS unit. Files were recorded in the .VCC format, which were then post-processed using *GPS Action Replay Pro*. Replay pro was used to visualize (Figure 2-10) and identify key start/finish times of specific pieces of information such as lap start/finish positions, course marker positions, characteristics of laps and manoeuvres carried out, and synchronizing of DAS/Video/GPS data.

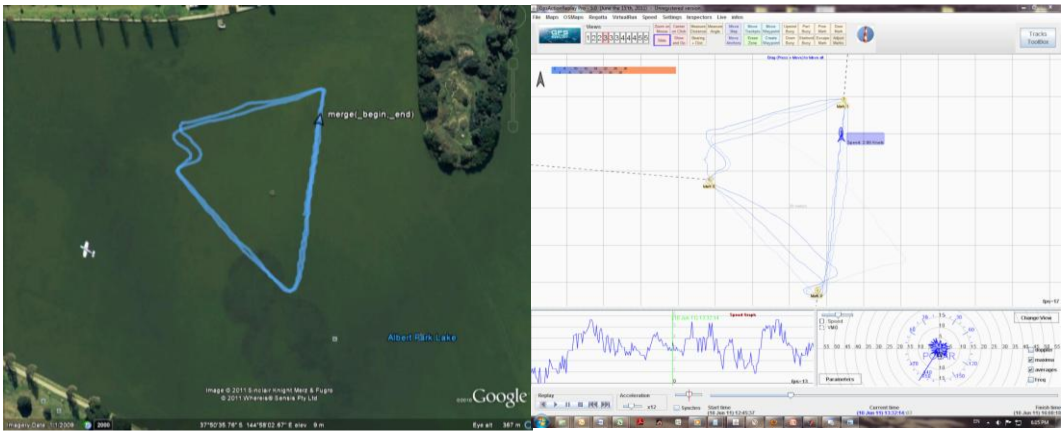

Figure 2-10: Comparison of recorded track overlay (Left) and a track being analysed in the post processing tool GPS Action Replay Pro.(right).

GPS data was also used to obtain time series dinghy heading, using the theory and methodology of ‘Great Circle Navigation Formulae’ (Williams 2011), which takes into account the curvature of the earth. Time series based latitude and longitude information were converted to 360 degree heading information (provided the dinghy was moving) relative to true north. Dinghy heading and velocity was required to calculate true wind angle (TWA) and velocity, given apparent wind angle and velocity recorded from the onboard anemometer. Figure 2-11 demonstrates the influence that dinghy velocity has on True Wind Speed and Angle to give Apparent Speed and Angle.

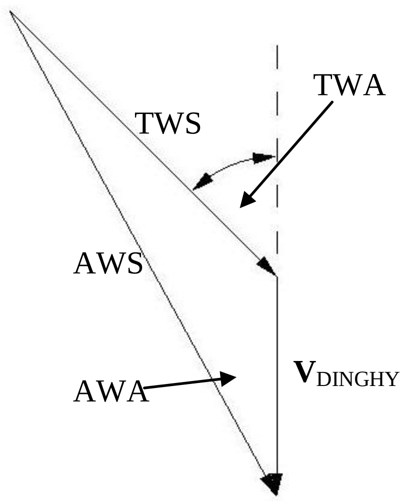

Figure 2-11 - Visual representation of the influence Dinghy velocity has on True Wind Speed and Angle to result in Apparent Wind Speed and Angle at the dinghy and onboard anemometer.

Leeway angle, or slip, has not been included in the analysis as the magnetic heading component of the recording system, required to determine leeway, was not functional at the time of testing.

2.4.5. ERRORS IN TEST MEASUREMENTS

Binns, Hochkirch, Bord and Burns (2008) show that the positional data for the full scale tests was obtained by differential GPS measurements for which error estimates are generally around ±3 m but can be as low as ±1 m (Farrell and Barth 1998). The GPS data was sampled at 0.5 Hz. An estimate of the steady state error of ±0.5 knots on boat speed over land has been used although dynamic measurement errors may be greater. It should be noted that while dynamic motions may be greater, they are not considered to be significant due to the calm nature of the lake test area, and the relative stiffness of the test rig compared to the magnitude of wind measurements that were recorded.

The rudder and tab angle measurements were performed with a rotary potentiometer as such the errors on the actual measured angle were largely confined to the calibration process and the play in the coupling between the rudder and potentiometer. The calibration errors have been estimated at ±1.0° and the coupling errors at ±1.0° combining to make a total error of ±2.0°.

Boat heading was recorded with differential GPS measurements and the wind speed and direction measured using onboard wind instruments, with error margins given by the manufacturer (Vaisala 2009) of ±0.3m/s for speed and less than ±3° for direction. The true wind angle measurement therefore had errors due to boat speed, boat heading, wind speed and wind direction measurements.

Error analysis was conducted based on the adaptation of the method demonstrated by Binns, Hochkirch, Bord and Burns (2008), where error estimates can be obtained using the first term in a Taylor series expansion of the uncertainty in the true wind angle. For implementation of the adapted equations (see Appendix C), as per manufacturer specifications apparent wind angle (AWA) can be measured to an accuracy of ±3°, apparent wind speed (AWS) ±0.3m/s and it is assumed that this measurement can be related to the heading of the yacht to ±1°. The propagation of these errors into true wind speed and true wind angle errors are plotted in Figure 2-12 and Figure 2-13 for sailing to windward during the duration of full scale experimental testing. From these figures it can be seen that the error in the true wind speed ranges from ±0.58 to 0.62 m/s and the error in the true wind angle ranges from ±1.75 to 3°.

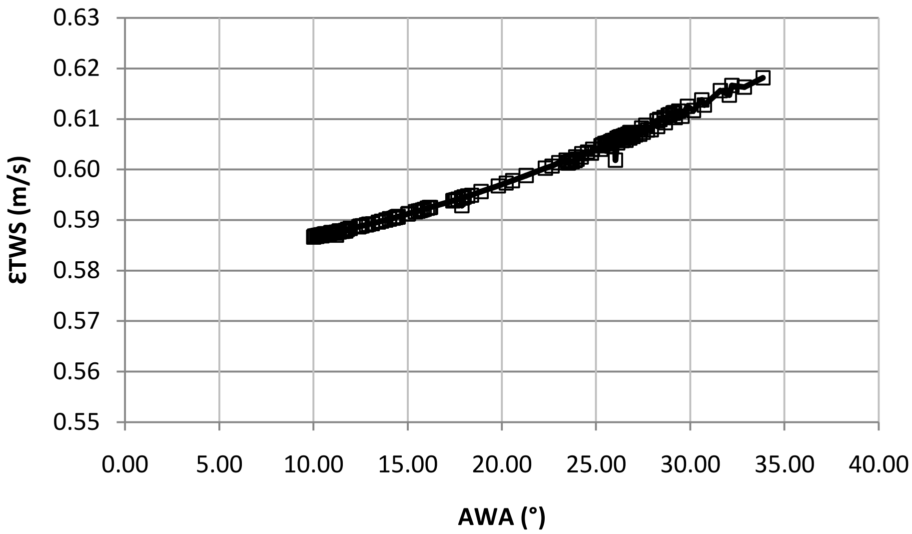

Figure 2-12 - Error in true wind velocity with respect to apparent wind angle, for an upwind continuous leg.

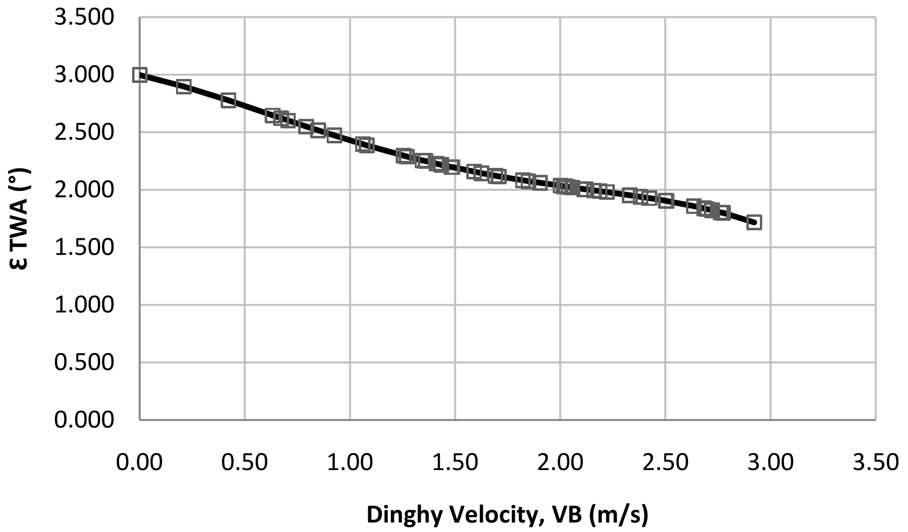

Figure 2-13 - Error in true wind angle for average wind speed of 12.5 knots with respect to boat speed. Data was from the windward data set, from 10° to 35° AWA.

2.5. RESULTS AND DISCUSSION

2.5.1. TEST 1 – LAPS OF A SET COURSE

The results of course analysis are shown below in Table 2-2. Each Lap distance was measured, along with time duration to obtain average velocity over land. True Wind Speed (TWS) was averaged for each lap, using Apparent Wind Speed (AWS) and dinghy velocity. The results obtained from this data would be later used to set the conditions in the simulator.

Table 2-2 - Albert Park Course Lap Results

Lap	Distance	Time		Dinghy Velocity		Average TWS	
No.	(m)	(min)	(s)	Knots	(m/s)	Knots	(m/s)
1	457.96	0:04:23	263	3.40	1.75	13.65	7.02
2	445.60	0:04:18	258	3.36	1.73	13.17	6.78
3	464.00	0:04:11	251	3.64	1.87	13.86	7.13
4	459.80	0:04:21	261	3.43	1.76	13.34	6.86
5	473.30	0:05:37	337	2.78	1.43	10.97	5.64
6	483.68	0:05:08	308	3.11	1.60	12.18	6.26
7	513.02	0:05:51	351	2.89	1.49	10.68	5.50
8	514.20	0:05:04	304	3.33	1.71	13.06	6.72
9	711.76	0:07:10	430	3.23	1.66	12.58	6.47
10	518.59	0:05:54	354	2.89	1.49	10.79	5.55
11	545.10	0:05:31	331	3.25	1.67	13.52	6.95
		Mean	313	3.21	1.65	12.53	6.44
		1 Std Dev	54.67	0.27	0.14	1.20	0.62

Course marker positions were identified by holding station (position) at the markers for 10-15 seconds per each with GPS logging on. The results are shown in Table 2-3, and were programmed into the simulator as shown in chapter 3.

Table 2-3 - Course Marker Locations

	Longitudinal (m)	Transverse (m)	Depth (m)
Marker 1	-77.5	0	0
Marker 2	0	97.4	0
Marker 3	77.5	0	0

2.5.2. DINGHY VELOCITY POLAR PLOT

Velocity polar plots are a good visual indication of a sailboats maximum speed performance through all heading angles for a given wind speed. For experimental testing, True Wind Angle (TWA) relative to dinghy heading were used to plot polar performance, as shown in Figure 2-14. The axis extending radially outwards represents the dinghy velocity in Knots (Nautical Miles per Hour, Knts), and extending clockwise around the graph is dinghy heading relative to the True Wind Angle (TWA).

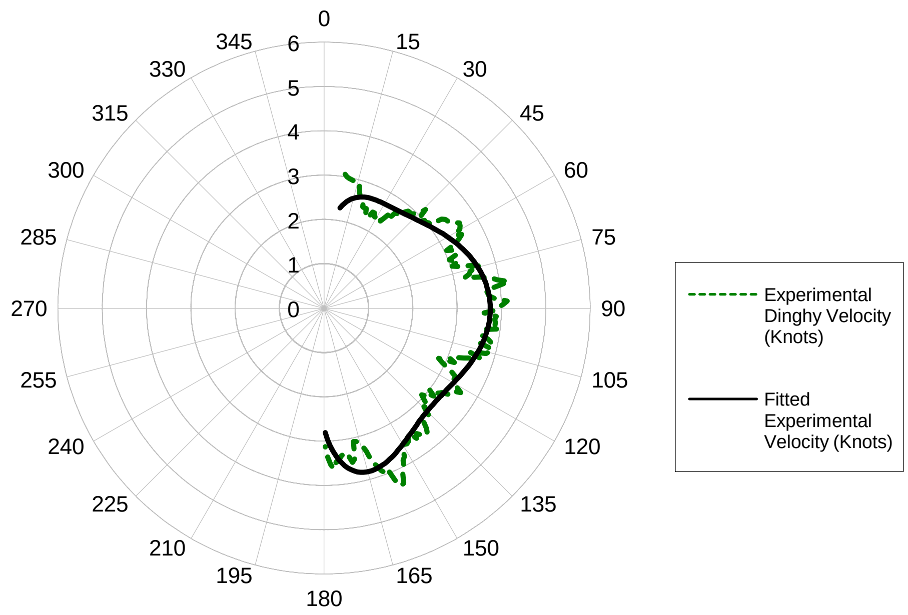

Figure 2-14 - Polar plot of dinghy velocity (knots) through 360degrees of heading relative to True Wind Angle (TWA) recorded during experimental testing. A 10 point moving average smoothed the data, and best fit curve was applied. Note that there are flat spots in the data, especially between 105 to 130 degrees and 150 to 165 degrees. This may be due to a lack of downwind reach runs conducted, as sailing down the course was primarily at 180 degrees to the wind.

The difference in trend in the upper 15 degrees of heading between fitted and measured in Figure 2-14 data is due to the regression analysis tracing back to a velocity of zero m/s at zero m/s heading. Headings above 15 degrees with power in the sails resulting in forward velocity are highly unlikely, due to already passing the stall heading. Measured data above 15 degrees appears to contradict the previous statement, however this is due to the measurement of velocity whilst tacking/changing course upwind.

The dinghy velocity polar plot was obtained using several calculation steps. Firstly, the method previously discussed in section 2.4.4 and illustrated in Figure 2-11 was used to obtain True Wind Angle (TWA) and dinghy velocity for any point in the time series data. To obtain this information, Apparent Wind Speed (AWS) and Apparent Wind Angle (AWA) combined with dinghy velocity obtained from GPS data were used.

The time series data of dinghy velocity and AWA were then mirrored from 360° to 180° which combined Port and Starboard tacks into one heading, then placed in data 'bins' for every 1° of heading. Maximum dinghy velocity for each 1° of heading was then obtained, and the resultant maximums smoothed using a 10 point moving average. The 'roughness' of the data in Figure 2-14 is due to the 1° increments of the data.

2.5.3. TEST 2 – TACKING MANOEUVRE

The GPS tracks of the lapped course were analysed for tack manoeuvres, with corresponding rudder angle data and duration obtained. The focus was on maximum angle and overshoot correction at the end of each tack. Resultant data is shown below in Table 2-4.

The logic behind each column in Table 2-4 is as follows: column 1 shows tack number; column 2 shows maximum rudder angle during the tack; column 3 shows time taken for the rudder to go from centred at the start of tack, up to maximum and return to zero; column 4 shows overshoot correction time where rudder input is required to pull the dinghy back to the correct heading after overshooting the intended path (Figure 2-17); column 5 shows the total manoeuvre duration from tack initiation to achieving a steady desired heading.

Examining the tack durations, tacks 9 and 10 may be considered outlier data. Excluding these tacks, the mean duration is 6 seconds. Uncertainty for manoeuvre time is increased once course overshoot correction is taken into account. Overshoot correction is required where heading is overshot, leading to a rudder correction back into course.

Table 2-4 - Maximum rudder angles from a series of laps and consecutive upwind tacks.

Full Scale, Albert Park					
Tack	**Max Rudder Angle**	**Centre to Centre**	**Overshoot Correction**	**Total**	**Tack Direction**
(No.)	(Deg.)	(seconds)	(seconds)	(seconds)	
1	48.04	5	0	5	Port to Starboard
2	50.63	5	0	5	Starboard to Port
3	44.45	6	0	6	Starboard to Port
4	52.09	5	0	4	Port to Starboard
5	47.03	5	0	5	Port to Starboard
6	37.49	7	2	9	Starboard to Port
7	53.01	7	0	7	Port to Starboard
8	38.84	6	0	6	Port to Starboard
9	54.27	2	0	2	Port to Starboard
10	61.52	4	0	4	Starboard to Port
11	42.52	8	2	10	Port to Starboard
12	59.72	6	0	6	Starboard to Port
Mean	49.13	6.00*	2.00	5.75	
1 Std Dev.	7.57	1.20*	0.00	2.18	

Typical rudder angle profiles found during the duration of each tack are shown in Figure 2-15 and Figure 2-16. The durations of each tack are 5 and 6 seconds respectively, with no overshoot correction required at the ends.

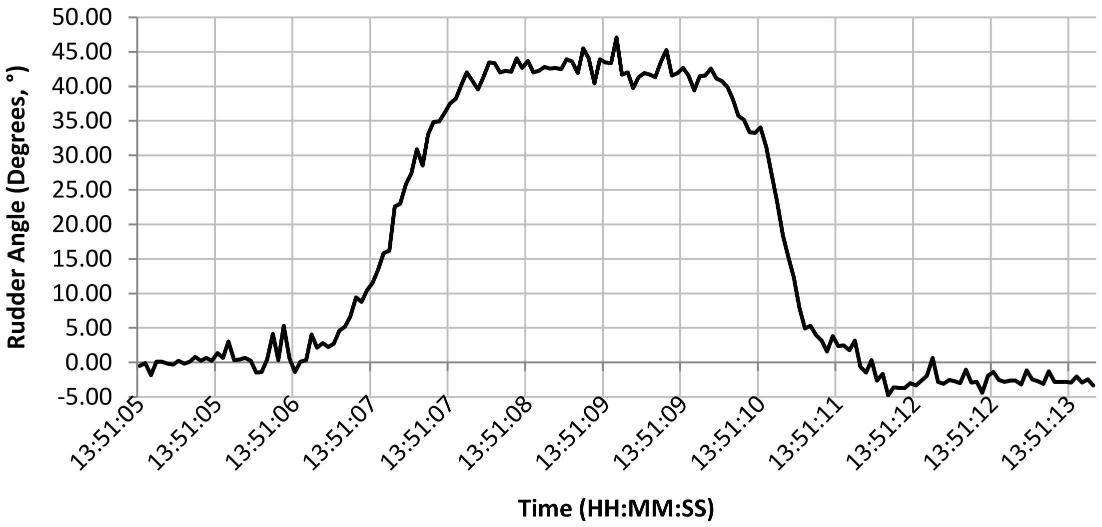

Figure 2-15 - Rudder angle during tack number 5 (see Table 2-4) is shown over time. Note that in this example there is virtually no overshoot correction at the end of the manoeuvre. Of the tacks analysed, overshoot correction or course correction was identified twice in tacks 6 and 11 (see Table 2-4).

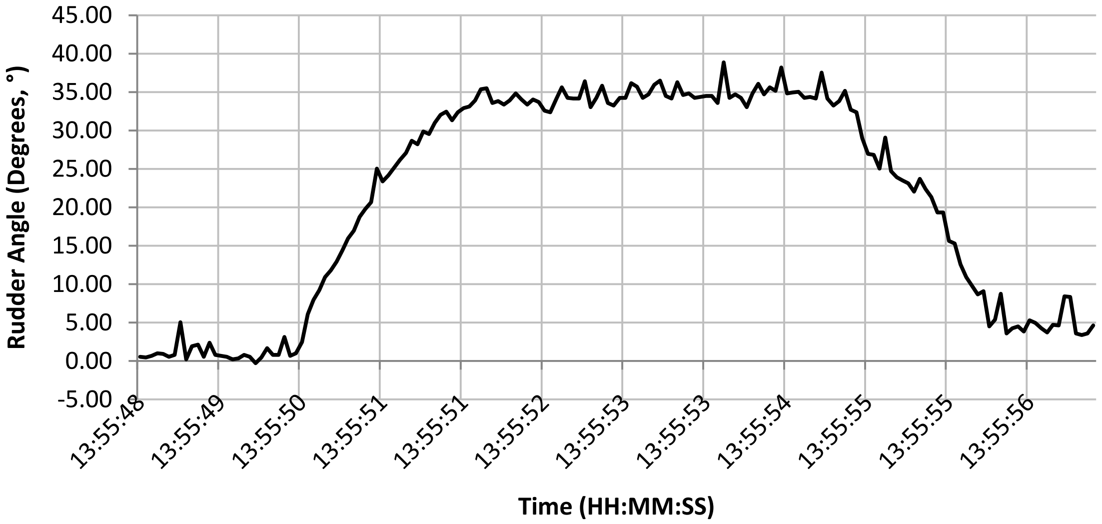

Figure 2-16 - Rudder angle during tack number 8 (see Table 2-4) is shown over time.

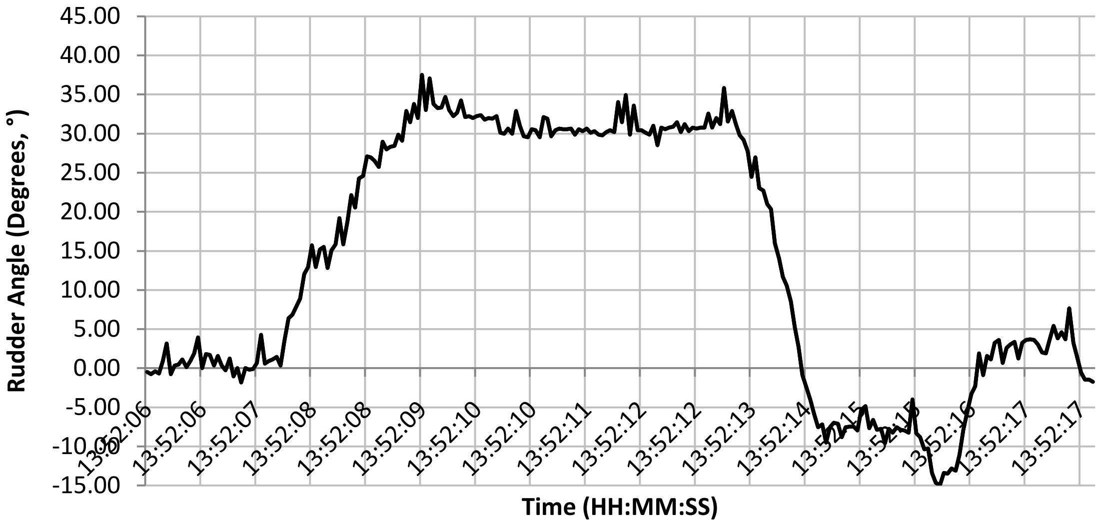

Figure 2-17 - Rudder angle during tack number 6 (see Table 2-4) is shown over time. Note the course correction required due to overshoot at 13:52:14 to 13:52:16, after 7 seconds of rudder input to execute the tack.

Figure 2-17 was one of two examples found in full scale testing where heading exiting the turn was overshot, requiring course correction. Any course correction is a waste of propulsion energy and should be avoided.

2.5.4. Manoeuvre Testing Discussion

All tests listed in section 2.3 investigating full lap times and manoeuvring characteristics were carried out. These included laps of a marked course and consecutive upwind tacks. After a significant amount of post processing the raw data, meaningful data was obtained.

It has been previously stated in Binns, Bethwaite and Saunders (2002) that the added mass and damping terms may be refined in future, but would require considerable research and would result in only a relatively small improvement in simulator performance.

The results obtained from full scale testing were used in simulator testing, and the same analysis involving velocity polars, tacking duration and rudder angle magnitudes were carried out in section 3.

2.6. Conclusions and Recommendations

Full scale experimental testing was carried out, with a range of time series data obtained including dinghy velocity and heading, Apparent and true wind speed and direction, and rudder angle. Specific manoeuvres were carried out and times recorded through GPS track analysis. Manoeuvre times were used to isolate relevant data. Statistical data for course wind speed and direction were obtained, along with course marker locations that were programmed into the sailing simulator for comparison in chapter 3.

It was found that typical maximum rudder angles required to tack to windward were 49 degrees, tacking durations took on average 5.9 seconds to complete. Maximum VMG to windward was 2.6 knots and 3.75 knots to leeward.

It is recommended that if possible in future, a larger test site, possibly a lake, that experiences less aerodynamic influence from surrounding trees and buildings be used. This may enable the broadening of the scope of testing, and add certainty to wind direction data over the whole course.

The Data Acquisition System and supporting equipment was found to be robust, and potentially applicable to other marine vessels.

It is recommended that hydrodynamic and aerodynamic resistance be the focus of future work, with the option of using data obtained during experimental testing.

3. SAILING SIMULATOR TESTING AND DATA ACQUISITION

The following chapter discusses the procedure, analyses conducted, results and conclusions obtained in carrying out simulator testing using course orientation, wind orientation and wind velocity parameters obtained from experimental testing outlined in chapter 2.

3.1. INTRODUCTION

The aim of simulator testing was to set the conditions of the simulator to accurately reflect conditions experienced in full scale experimental testing, and then conduct the simulation to obtain a data set that can be directly compared with real life data. Testing on the sailing simulator commenced once sufficient course condition data was obtained from post-processing the experimental data.

3.2. EXPERIMENTAL SETUP

Experimental data that was input into the simulator were wind speed, course orientation, and course size. A Laser standard size with Olympic rig (Section 1.5) was selected from the pre-programmed option list, as the same type was used in experimental testing.

A standard programmed wind speed of 12 knots (with no gusts) was selected based on an average of 12.53 knots (see Table 2-2 in section 2.5.1) which lies well within the 95% confidence interval of ±2.4 knots. Markers were added to the simulation in the same configuration used during experimental testing on the Albert Park Lake Course, as shown in Table 2-3 section 2.5.1. Their location also took into account the True Wind Direction at Albert Park, which ran directly down the course.

The simulator was set to its dynamic mode that required the pilot’s bodyweight to provide a righting moment. A new Haptic (force) feedback device at the rudder was activated for a majority of the runs.

Figure 3-1: Sailing the virtual Albert Park lake course on the sailing simulator. Course position, wind speed and wind direction data obtained from experimental testing were all input into the simulation to replicate experimental conditions.

3.3. Testing Procedure

With sailing conditions and markers set, the course was sailed with a number of consecutive laps completed, as well as upwind tacking runs to obtain sufficient rudder angle data. The laps and upwind tacking runs were completed to replicate the runs carried out during experimental testing at Albert Park lake.

3.4. Data Processing and Analysis

Post Processing the data obtained from simulator testing was a lot simpler when compared to the significant effort required to obtain meaningful data from the experimental test. During the course of a sailing run the *Analysis V7.0* tool was switched on to record time series: X and Y position on the course, Fwd Velocity, Side (slip) Velocity, wind velocity, Hiking effort, Boom angle, Rudder Angle and actual wind speed.

3.4.1. Course Analysis

Much like the analysis of the experimental data, time series position data was plotted to allow inspection of the approximate start/finish positions per lap. From the inspections, data was then isolated to show maximum X values (lowest position on the course) where the start of each lap occurred. Lap runs were now isolated.

With individual laps identified, the sum of resolved X,Y position differentials was used to obtain distance sailed per lap, and consequently time per lap and average speed.

3.4.2. RUDDER ANGLE ANALYSIS

Consecutive upwind tacks were carried out (each tack was initiated after velocity and heading stabilised after the previous tack), in order to obtain velocity and rudder angle information to validate against experimental data. Tacks from full course laps were also analysed.

Visualization of sailing simulator data (time series heading and x,y course position) was used to identify tacking manoeuvres, after which a detailed inspection isolated the tacking manoeuvre: from steady rudder angle/velocity prior to entering the turn, to steady velocity/rudder angle at the exit.

3.5. RESULTS AND DISCUSSION

3.5.1. TEST 1 – LAPS OF A SET COURSE

Several different test configurations were run including various combinations of wind strength, simulator roll active feedback and rudder active feedback. Ultimately, the correct setup that would match the conditions experienced in experimental testing yielded three complete laps to windward.

Table 3-1 - Sailing Simulator "Virtual Albert Park" Lap Results

Lap	Distance	Time		Dinghy Velocity		Average TWS	
No.	(m)	(min)	(s)	knots	(m/s)	knots	(m/s)
1	461.54	00:03:08	188	4.76	2.45	12.00	6.17
2	534.30	00:03:44	224	4.64	2.39	12.00	6.17
3	562.51	00:03:44	224	4.88	2.51	12.00	6.17
		mean	212	4.76	2.45	12.00	6.17
		1 std dev	0.00	0.12	0.06	0.00	0.00

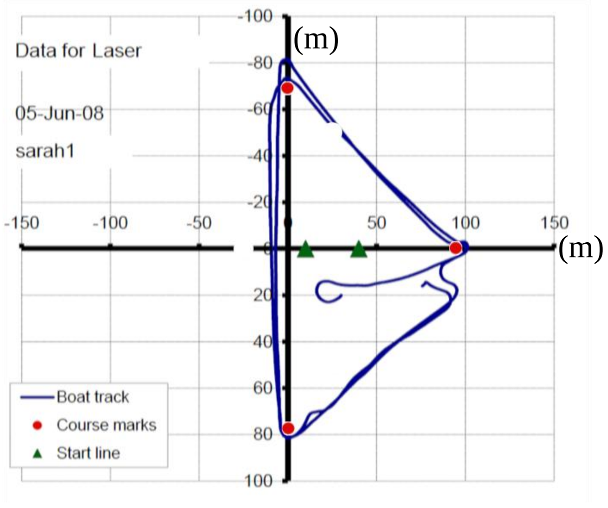

Figure 3-2 - Sample lap of the set course to windward.

3.5.2. DINGHY VELOCITY POLAR PLOT

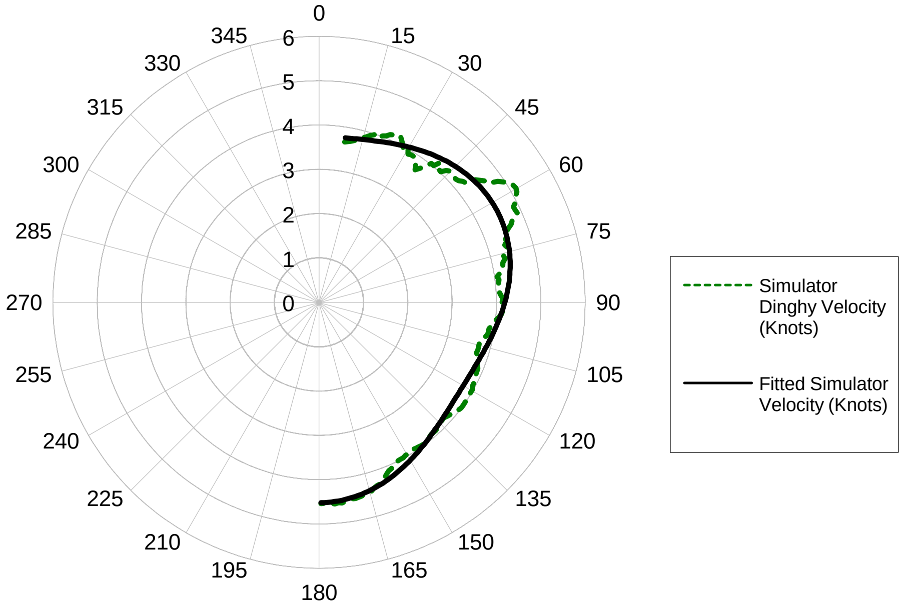

Figure 3-3 - Dinghy velocity polar plot through 180 degree of heading. The data was originally through 360 worth of heading, and mirrored about 180 degrees. A ten point moving average was used to smooth the data and regression analysis applied to provide a curve of best fit. The peak velocity at around 60 degrees heading of 5 knots was found to occur at steady maximum heel angle on the simulator. This is thought to be due to reaching maximum heel limits of the simulator, thus adding to the heeling moment physically available from the sailor. This outlier data was removed when conducting the average velocity curve fit.

Figure 3-3 shows dinghy velocity through 180 degrees of heading relative to True Wind Angle (TWA). In the case of testing on the simulator, the direction of true wind ran directly down the course from the top mark to bottom mark. Data above 30 degrees should ordinarily be ignored, as it is above the heading that was able to be sustained under sail power and was recorded during a change in heading during upwind tacks. In other terms, data less than 30 degrees heading is unsteady, whereas the plot is intended to present steady state data.

The polar plot is noticeably smoother than the results that were obtained from full scale experimental testing (Figure 2-14). The smoothness (stability) discrepancy is likely due to difference in control of variables between full scale and experimental, where wind strength, direction and even minor waves on the experimental course may combine to affect dinghy speed.

3.5.3. TEST 2 – TACKING MANOEUVRE

Table 3-2 shows that maximum angles were very consistent. Whilst it would be nice to think that these results are due to pilot skill, it is more likely that it's due to the rudder reaching the physical maximum angle available. Total tack times were typically 8 seconds (7.2 to 9 seconds with 95% confidence), which included 6 seconds from initiating the tack to returning the rudder back to zero degrees, and a further 2 seconds to overshoot the rudder angle to the opposite direction of the turn (see Figure 3-4, Figure 3-5). Overshooting was required to reduce and stop the dinghies yawing velocity when exiting a tack.

Table 3-2 - Maximum rudder angles from a series of laps and consecutive upwind tacks.

12 knots winds, active feedback					
Tack	Max Rudder Angle	Centre to Centre	Overshoot Correction	Total	Tack Direction
(No.)	(Deg.)	(seconds)	(seconds)	(seconds)	
1	45.70	6	2	8	Port to Starboard
2	45.70	5	2	7	Port to Starboard
3	45.70	6	2	8	Starboard to Port
4	46.41	-	-	-	Port to Starboard
5	45.00	6	1	7	Port to Starboard
Consecutive Tacks					
1	45.00	6	2	8	Port to Starboard
2	45.00	8	2	10	Port to Starboard
3	45.35	6	2	8	Port to Starboard
4	45.00	7	2	9	Starboard to Port
5	45.00	6	2	8	Port to Starboard
Mean	45.39	6.22	1.89	8.11	
1 Std Dev.	0.48	0.83	0.33	0.93	

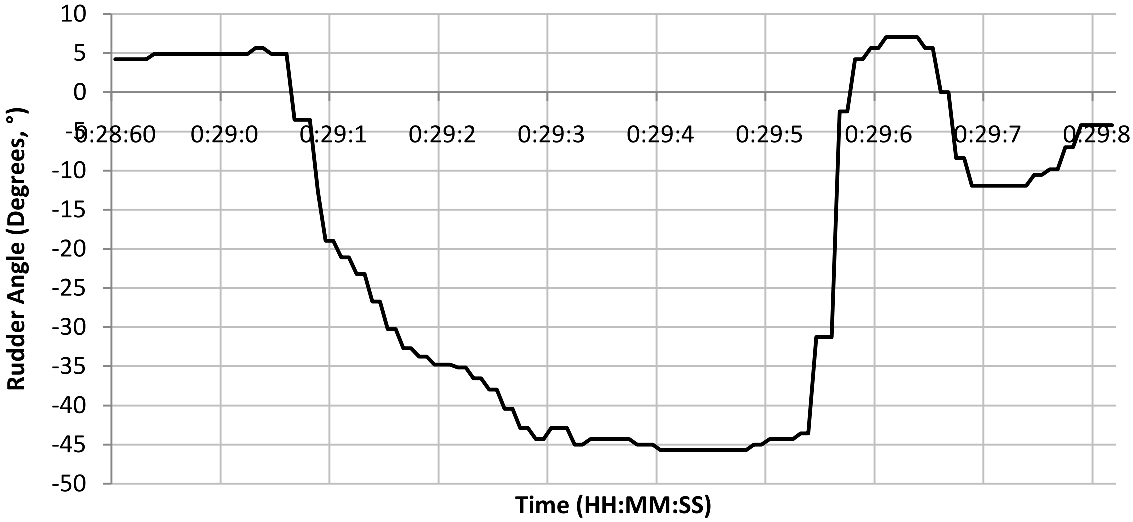

Figure 3-4 - Rudder angle over time is shown during an upwind Port to Starboard tacking manoeuvre. Note the overshoot angle at the end of the manoeuvre, which was observed at the end of all tacks. Correction was to decelerate the yacht in yaw whilst exiting the tack. Consistently correcting the turning manoeuvre may be a sign of a less experienced sailor, as an experienced pilot would be expected to not waste as much energy and time and turn smoothly out of the turn.

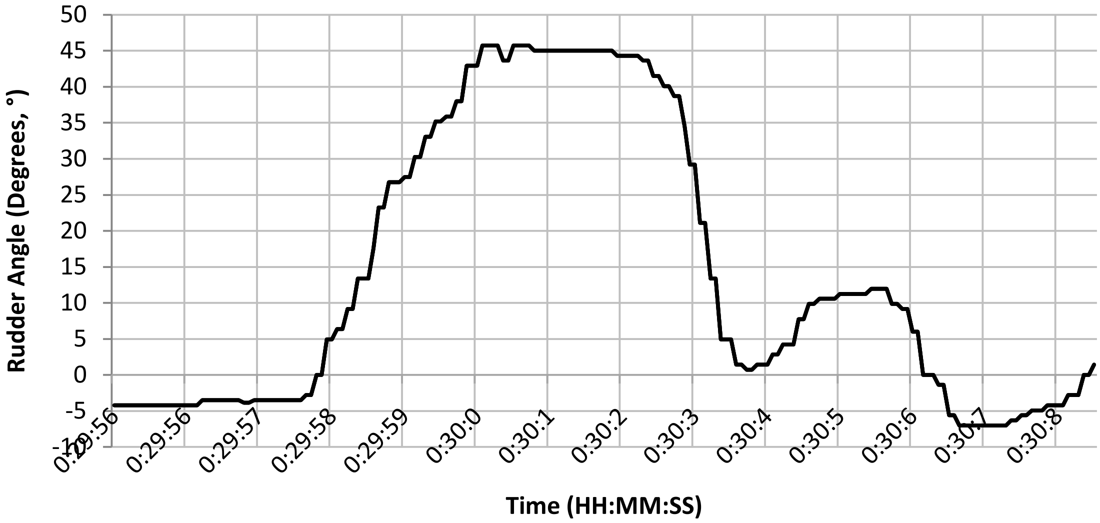

Figure 3-5 - Rudder angle over time is shown during an upwind Starboard to Port tacking manoeuvre. In this example the overshoot correction occurs (~0:30:6 to 0:30:8) after a second ruder input (0:30:4 to 0:30:6) is used to fully turn the dinghy to the desired heading. Both corrections at the end of the turn are examples of opportunities to refine the sailors technique, to minimize energy used during tacking.

3.6. CONCLUSIONS AND RECOMMENDATIONS

Testing and data acquisition onboard the sailing simulator was carried out successfully, with scale data from experimental testing used to set the course orientation, wind speed and direction. Consecutive course laps and upwind tacking runs were carried out to replicate testing at Albert Park Lake.

Maximum rudder angles were observed to be very consistent at ~45 degrees (compared with 49 degrees from experimental testing), which may be due to physical limitations of the simulator apparatus. Tack durations were typically 6.2 (5.9s experimental) seconds, with 1.90 seconds of overshoot time at the end of each tack to correct for course under/over shoot. Maximum VMG to windward was 3.7 knots (2.6 knots experimental) and 4.56 knots to leeward (3.75 knots experimental).

To ensure completeness of the simulator dataset, further testing should be carried out on the sailing simulator with the Albert Park course in use, 12 knots of wind speed and active roll and tiller feedback in use. Testing should concentrate on predominantly downwind runs, in order to obtain more extensive data for dinghy velocity polar plots. This is due to the concentration of simulator testing being on upwind steady state sailing. Simulator human in the loop rather than just the Velocity Prediction Program (VPP) is recommended due to the human interaction required to mimic full scale experimental testing.

Whilst not critical to improving the simulator, increasing maximum rudder angle if practical would be beneficial to take a further step towards replicating a real dinghy.

4. SIMULATION VALIDATION: COMPARISON OF FULL SCALE AND SIMULATION DATA

4.1. INTRODUCTION

This was the first time that the sailing simulator and simulation had been validated using full scale experimental data. The aim was to validate resistance/powering and manoeuvring aspects of the simulation, and provide recommendations on areas for improvement.

4.2. PROCEDURE

Data obtained from both full scale testing and simulated testing were post-processed and scrutinized using analysis software from virtual sailing for the simulated data, and GPS action Replay Pro combined with Go Pro video to isolate lap time and manoeuvre timing information for the experimental data.

With start times for course laps and manoeuvres for both experimental and simulated testing obtained, the analysis approach taken in validating the simulator results with the experimental data obtained started with a high level analysis of course lap times, average velocities per lap, then focussed on velocity polars through 180° heading and onto tacking manoeuvres focussed on rudder angle analysis.

4.3. FULL COURSE ANALYSIS AND RESULTS

As previously described in section 2, testing on Albert Park lake took place on a triangular course marked with three marker buoys. Each buoy was placed down, and station held next to each buoy and GPS position recorded. The onboard anemometer recorded relative wind speed and direction, which when combined with dinghy velocity was translated to true wind speed and direction. Course marks, wind speed and direction were input into the sailing simulator and the virtual course sailed.

Full lap analysis was carried out in order to validate the resistance and powering components of the simulation. Course lap times and average velocity over upwind tacking, reaching and running legs of the course were the first high level simulation areas to be validated. Results in Table 4-1 show that leeward maximum and average velocities experienced in the simulator lie relatively close to the experimental data. Larger discrepancies occur when examining the windward data, where maximum velocity was increased by 22% on experimental, and average velocity is up 37%, indicating significantly more time is spent at higher velocities when sailing to windward on the simulator. The key difference between the two appears to be for angles between 45° to 65°(Figure 4-1).

As the simulator was tested in dynamic mode during this testing, it was thought that when sailing to windward the dinghy may have been sailed on the roll stoppers (maximum roll angle) when in dynamic roll feedback mode. Sailing on the stoppers in this mode would mean the velocity prediction program would see unrealistic heeling force input from the sailor, leading to unrealistically high velocities to windward. Further analysis of the simulator data showed time spent at maximum lean angles accounted for 3 seconds of the test session, proving that 'sailing on the stoppers' did not occur.

Comparison analysis of simulated and experimental roll angles was not carried out, as at the time of experimental testing, recording and post processing of gyroscopic roll information wasn't mature enough to be of use.

The actual velocity difference when sailing to windward is in the order of 1 knot (Figure 4-1). A check of time spent sailing to windward during full scale testing shows that as a percentage of total lap time, 61% (+-3% to 95% confidence) is spent sailing upwind (for the course configuration used).

Overall, the source of the discrepancy in speed is difficult to pinpoint. Any combination of: the simulator VPP under predicting resistance or over predicting total sail force; or the rigging on the experimental set up was not being optimally set compared to what was assumed in the simulator; may result in dinghy velocity variations.

Comparing average velocities *per lap* (Table 2-2, Table 3-1) as a function of distance travelled and time, shows average velocity over a lap is up by almost double what the velocity polars indicate. This result is potentially due to the simulator running in a more efficient state, where not all factors contributing to drag during a lap are captured in the simulation, that might ordinarily be experienced in full scale conditions. This may include added drag in turns, waves and other factors that are outside the scope of this project, which future work may focus on

Table 4-2 - Average dinghy velocities per lap, averaged over all laps recorded during testing.

	Average Lap Velocity (Knots)	Average Polar Dinghy Velocity (Knots)
Experimental	3.21	3.29
Simulated	4.76	4.14
Difference	48.29%	25.84%

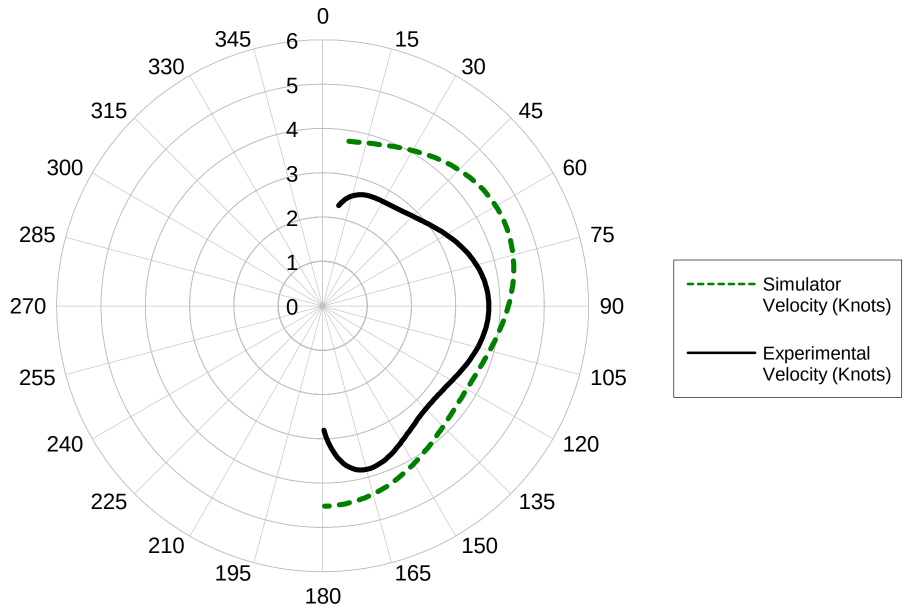

Figure 4-1 - Dinghy Velocity Polar plot comparing best fit experimental and simulator results through 180 degrees heading relative to True Wind Angle (TWA), or the direction of the wind. Experimental velocity is noticeably slower when going to windward (0°-90°) where as velocities are much closer when sailing downwind (90°-180°). Between 0°-30° it was not considered realistic that the Laser dinghy produces lift and velocity through this heading range. The resultant velocities were most likely recorded during tacking manoeuvres when changing heading with speed from a previous tack remaining.

Table 4-1 - Upwind and Downwind (Windward and Leeward) difference between maximum and average dinghy velocities between Experimental and Simulated, for laps conducted during testing. This data includes time whilst moving only, time when stationary is not a part of the data set.

	Maximum		Average		Overall Average
	Windward Dinghy Velocity (Knots)	Leeward Dinghy Velocity (Knots)	Windward Dinghy Velocity (Knots)	Leeward Dinghy Velocity (Knots)	Average dinghy velocity (knots)
Experimental	4.2	4.56	3.08	3.51	3.29
Simulated	5.13	4.36	4.23	4.06	4.14
Difference	22.14%	-4.39%	37.34%	15.67%	25.84%

Table 4-2 - Average dinghy velocities per lap, averaged over all laps recorded during testing.

	Average Lap Velocity (Knots)	Average Polar Dinghy Velocity (Knots)
Experimental	3.21	3.29
Simulated	4.76	4.14
Difference	48.29%	25.84%

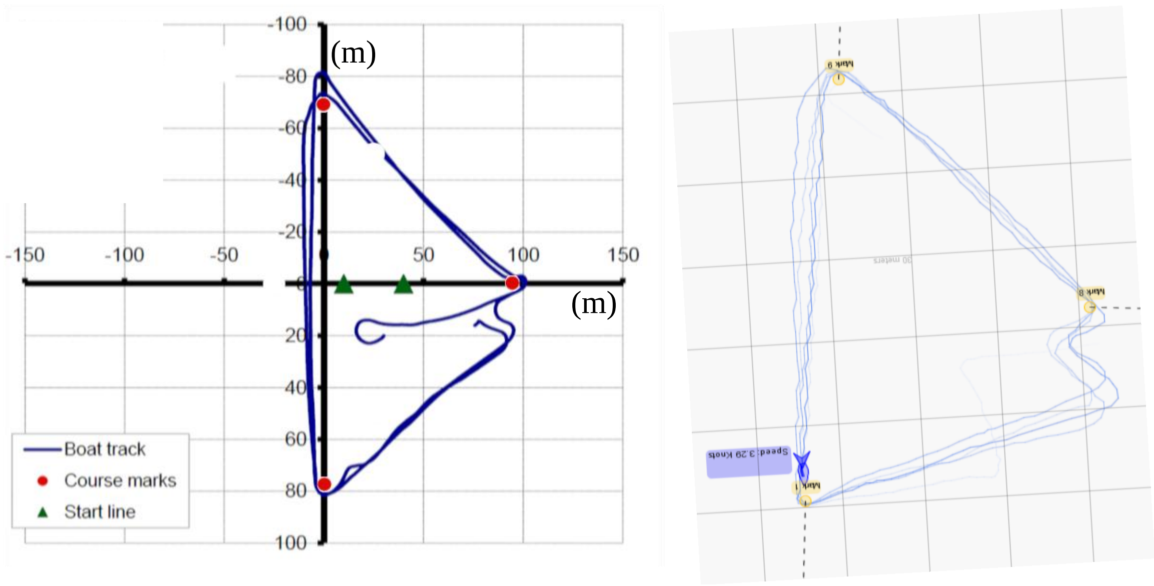

Figure 4-2: Comparison between simulated (left) and real (right) course track plots. The right hand plot is inverted, as the wind is coming from the South when the post processing plotter only faces North.

4.4. TACKING MANOEUVRE ANALYSIS AND RESULTS

Tacking manoeuvre analysis was carried out to broadly validate the manoeuvring characteristics of the simulation. The areas examined were rudder angle required to execute a 'tack' or upwind turn across the wind, the characteristics of the rudder yaw (whether overshoot or undershoot of the angle occurs in the simulator prior to executing a steady turn) and duration of rudder input to execute a tack.

4.4.1. RUDDER ANGLE ANALYSIS

Figure 4-3 shows average maximum rudder angles found during tacking, with 95% confidence intervals. The intervals for both overlap, giving a strong indication that rudder angle inputs required to tack the simulated dinghy, replicate real life.

Tacking durations (excluding overshoot correction, see Figure 4-4) show that average tacking manoeuvre times for experimental and simulator testing correlate very well, with mean times being 6.0s and 6.22s for experimental and simulator tests respectively. This is a good indication that manoeuvring dynamics of the simulator reflect reality.

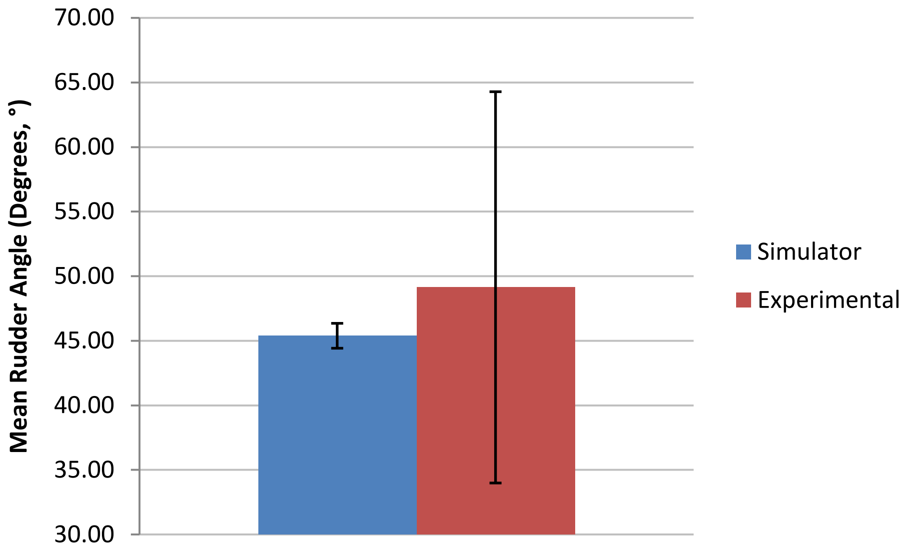

Figure 4-3 - Average maximum rudder angles experienced during tacking is shown, with error bars showing 95% confidence intervals. Due to the consistency of maximum angles during simulator testing (most likely due to physical rudder limits), the confidence interval is quite small, whereas in real world conditions the interval is larger as the rudder has a much larger range of movement. Overlap between the two intervals gives confidence that rudder angles in the simulator reflect real life.

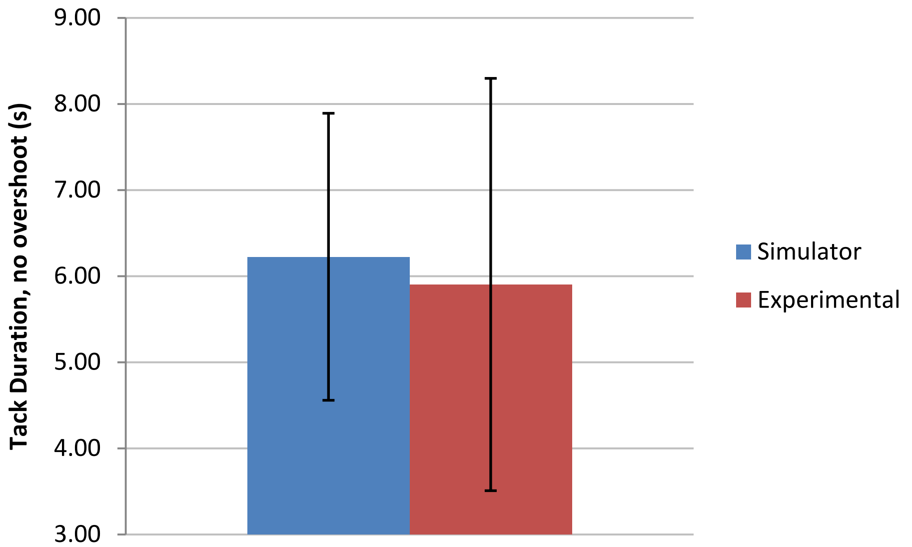

Figure 4-4 - Experimental compared with simulated average tack times (excluding overshot correction at the end of each tack if present), with 95% confidence intervals. Mean values were 5.90s for the simulator and 6.22s for the simulator. This represents a 5% difference in tacking durations.

A comparison of full scale and simulated rudder angles during a typical tacking manoeuvre is shown in Figure 4-5. Duration and magnitude for each is very similar, with slight divergence at the end. Course correction after each tack was required in almost all simulator tacks, whereas full scale testing experienced the opposite with minimal corrections. This may be subjectively attributed to less pilot 'feel' in the simulator as the only yaw velocity feedback is visual on the screen which may make it difficult to know when to pull the dinghy out of the tack.

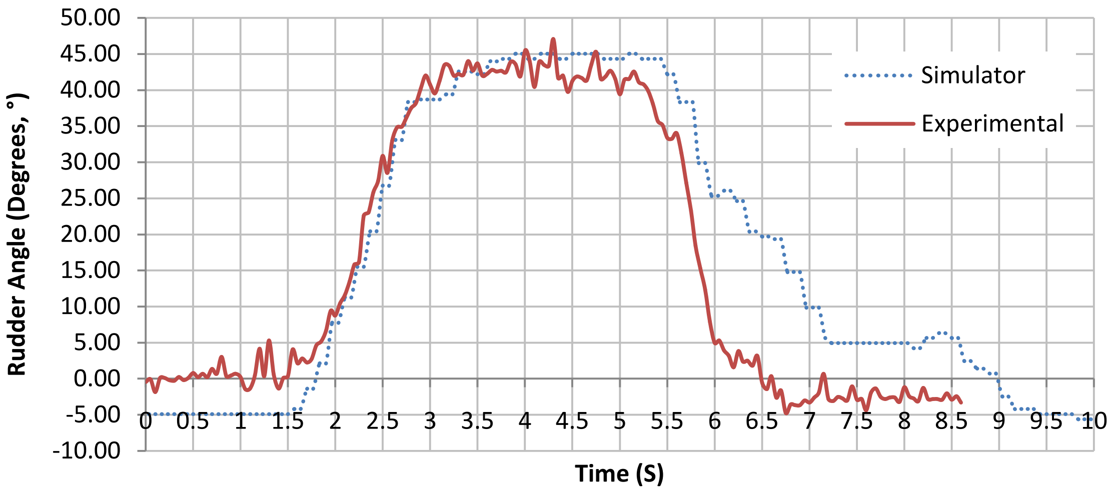

Figure 4-5: Comparison of full scale 'on water' rudder angle during a tack manoeuvre, compared to simulated tacks with active rudder feedback using the same pilot. For this example, results show close correlation both in terms of maximum angle and durations between simulated and experimental data.

Given that maximum rudder angle on the simulator appeared to be physically limited to approximately 45 degrees, when compared to full scale experimental angles, 45 degrees is realistic.

What is more difficult to validate with the equipment available at the time of testing is the impact that rudder angle had on yaw acceleration and velocity. GPS recording did not have sufficient accuracy to measure turn radius (see Figure 4-6). There was intent to use the onboard accelerometers to measure yaw accelerations to obtain velocities, however the understanding of how to use the on-board accelerometers and interpret the output data had not reached a practicable level.

Figure 4-6 -Two upwind tacks show GPS resolution is lacking to obtain accurate turning information.

4.5. CONCLUSIONS AND RECOMMENDATIONS

When Experimental and Simulated results were compared, velocity polars showed that there was close correlation between leeward experimental and simulated data, with simulator velocity 4.4% lower than experimental data, and increased by 15.6% overall on average. Windward results showed larger margin, with the simulator showing velocities increased by 22% and 37% for maximum and average velocities respectively. This would indicate that a potential reduction of simulator efficiency to windward of up to 30% would bring the simulator in line to match the experimental data.

Average velocity over a simulated lap when compared to an experimental lap is increased by 48% using average time per lap and 25% using average polar velocity for the test session. This may be due to added resistance components that are not included in the simulation. Further investigation is required.

Rudder angle durations and maximums were found with 95% confidence to lie within range of each other, which shows correlation between simulated and real life rudder use. This shows based on the data at hand that the simulator's manoeuvring model accurately reflects full scale experimental data and real life. Average maximum rudder angles on the simulator were -8% from experimental data. This may be explained by the full scale dinghy having more rudder angle available than the simulator.

Tacking durations on the simulator were found to be within 5% of experimental data. It was also found that simulator rudder angles during tacks and straight line course correction are within ±5.0 degrees or 8%, of full scale recorded angles.

It was recommended that further investigation is required of the velocity variance between experimental and simulated results.

5. CONCLUSION

5.1. Summary

A method was successfully developed for the validation of a Human in The Loop (HiTL) sailing simulator. Full scale experimental testing was carried out, and data obtained by a custom onboard Data Acquisition System (DAS) and GPS/video logging. Experimental data was post-processed to obtain course size and conditions for programming into the simulator. Simulator testing was carried out, data obtained and post processed, and results compared with experimental data.

Simulator leeward (downwind) velocity showed correlation with experimental data, down 4.4% and 15.6% for maximum and average velocities. Windward (upwind) velocity showed larger margin, with increases of 22% and 37% for maximum and average velocities. This would indicate a need to reduce efficiency to windward in the order of up to 30%.

Average velocity over a simulated lap when compared to an experimental lap was increased by 48% using average time per lap and 25% using average polar velocity for the test session. This may be due to added resistance components that are not included in the simulation. Further investigation is required.

Tacking durations were found to be +5% from experimental data, and average maximum rudder angle -8% from experimental data.

It was found that Simulator rudder angles during tacks and straight line course correction are within ±5.0 degrees of full scale recorded angles.

5.2. Conclusions

A method for capturing and post-processing full scale experimental raw data into useful data was developed and implemented. The Data Acquisition System and supporting equipment was found to be reliable and robust once the set up and operational requirements were fully understood. Given the wealth of information gained from the system, it is potentially applicable to other marine vessels that require full scale experimental analysis in a dynamic and unforgiving marine environment.

The sailing simulator was successfully set up and utilised to replicate experimental course and environment conditions. Based on comparisons of tacking and rudder angle data, the manoeuvring model shows correlation with real life and well within an order of magnitude.

The velocity prediction component requires further investigation, to understand the discrepancies found with full scale experimental data.

The data set obtained from the sailing simulator was extensive, which many future projects can make use of. For example, the addition of heel moment sensors, combined with load cells in the toe strap can give insight into the efficiency of the sailor in the 'Human in The Loop' simulation.

Outside of the scope of this study, active feedback from the tiller (as opposed to no feedback) provided excellent sensation of how the dinghy was behaving throughout a turn. From the sailors point of view, tiller feedback is the main source of information of how the dinghy is handling at any point in time. Combined with the existing capability of active feedback in roll, the simulator proved to be an excellent training tool.

5.3. RECOMMENDATIONS FOR FUTURE WORK

In future if possible, the instrumented Laser dinghy should be moved to a new test site that experiences less aerodynamic interference from the surrounding environment (buildings, trees etc). The environment shall also ideally be a lake or have no tidal flow to limit GPS velocity measurement errors due to tidal drift. These recommendations are made such that a larger test area featuring more certain wind direction and speed be used for future testing.

In the interest of proving the experimental testing apparatus and approach, it would be interesting to use the data acquisition system again and test a different class of dinghy (e.g. megabyte, 420 etc.) that the simulator replicates. It is recommended that the same testing procedures be followed, with modification to suite where necessary.

Given results showing average lap speed in the simulator being higher than what the velocity polars indicated, that hydrodynamic and aerodynamic resistance validation be a focus of future work, with the option of using data obtained during experimental testing.

In future when conducting further simulator testing, especially to windward, that care is taken not to sail on the roll stoppers (maximum roll angle) when in dynamic roll feedback mode. Sailing on the stoppers in this mode means the velocity prediction program will see unrealistic heeling force input from the sailor, leading to unrealistically high velocities to windward.

To ensure completeness of the simulator dataset, further testing should be carried out on the sailing simulator with the Albert Park course in use, 12 knots of wind speed and active roll and tiller feedback in use. Testing should concentrate on predominantly downwind runs, in order to obtain more extensive data for dinghy velocity polar plots. This is due to the concentration of simulator testing being on upwind steady state sailing.

Whilst not critical to improving the simulator, increasing maximum rudder angle if practical would be beneficial to take a further step towards replicating a real dinghy.

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APPENDIX A – EXPERIMENTAL PROCEDURES

1. Attach all hardware. This involves bolting down all devices onto plates already rigidly mounted to the deck and hull.
2. Install FULLY CHARGED batteries in dark grey boxes first, then light grey boxes second (Figure 0-1:).

Figure 0-1: Dark (Micro-computer) and Light grey (Transmitter) boxes attached to the deck. Go-Pro cameras are optional.

3. Attach rudder encoder belt (Figure 0-2Figure 0-2). This requires the two elastic cord ends to be tied.

Figure 0-2: Rudder belt attachment.

Figure 0-3: Encoder belt attachment.

4. Turn on GPS (small black box, Figure 0-4) sender before turning on Laptop.
5. Turn on Laptop.

6. Plug in GPS to laptop.
7. Hit reset on the GPS. The light on the GPS will flash green → red → flickering green (Flickering green means it is working).
8. On laptop, go to my Bluetooth places on the desktop.
9. Start console application.
10. After starting *console* application, check that it is connected to my Bluetooth places. If the DOS display reads:

    "v101 = press return to exit"

    Then the system is recording.
11. Seal the laptop and black GPS sender in waterproof bag. Anchor the bag to the deck with d shackles (Figure 0-4)

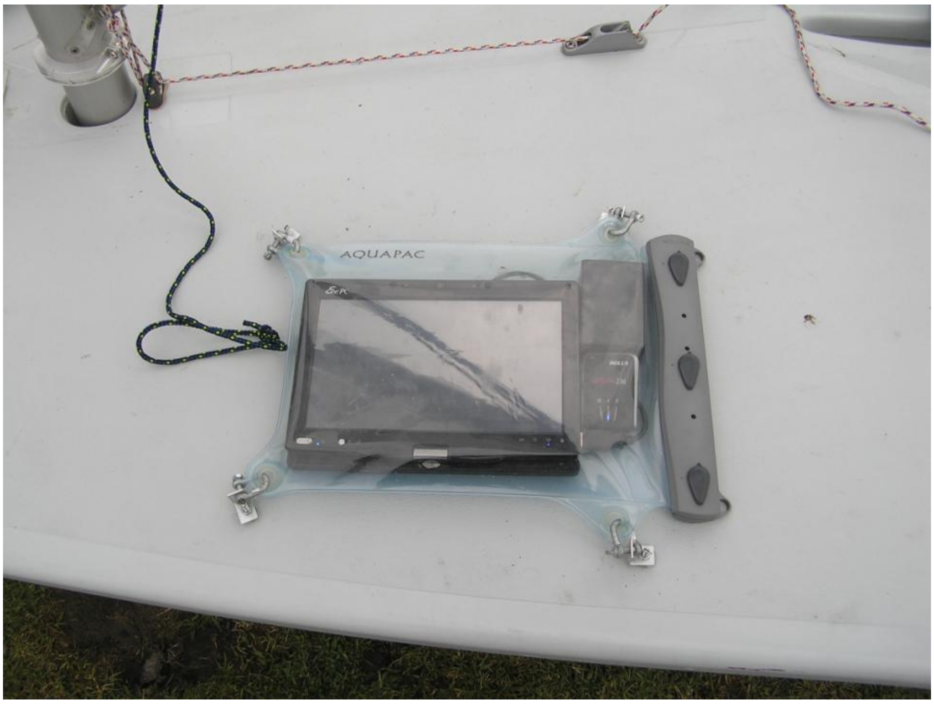

Figure 0-4: DAQ Laptop, and GPS unit (bottom right of bag) in waterproof bag. Bag is shackled to the deck using plates attached to the deck and d-shackles.

12. Raise the mast with sail wrapped around mast and tied off to prevent flogging in the wind (Figure 0-6). Locate the boom on mast.
13. Attach mast encoder (Figure 0-5).

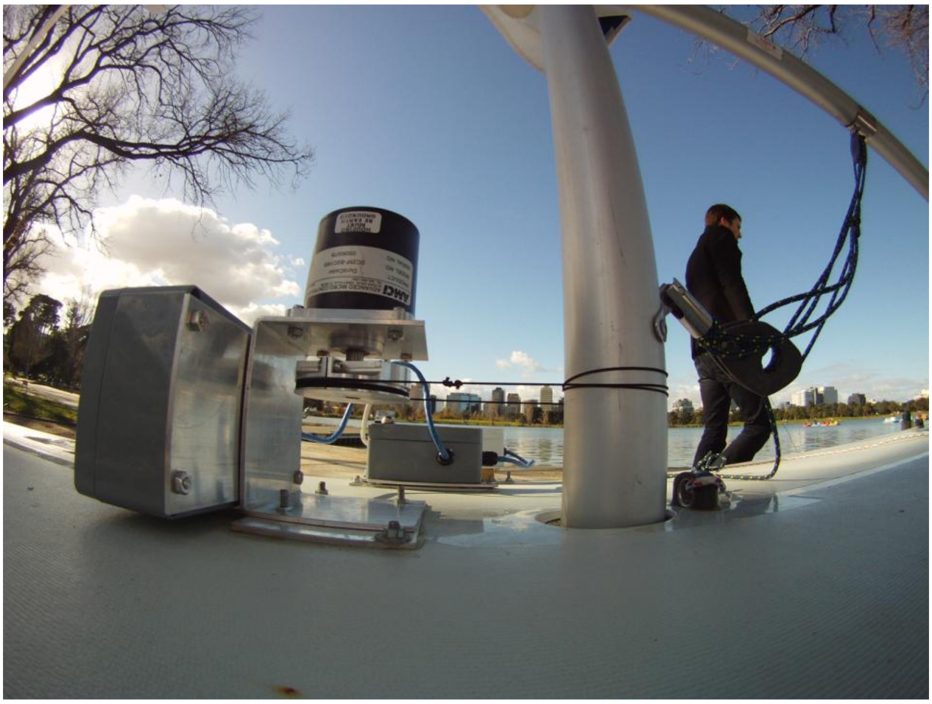

Figure 0-5: Mast Encoder Attached with three loops of fine elastic cord around both mast and encoder.

14. Zero the mast encoder (zero boom rotation). This procedure involves rotating the mast (Figure 0-6 to Figure 0-18) and holding for 5-10 seconds through a series of positions: 0°, 90°, 0°, -90°, 0°, 45°, 0°, -45°, 0°, 180°, 0°, -180°, 0° (Starboard is positive, Port is negative). These rotational movements of the mast (holding the boom) allow for a zero rotation point to be located when post-processing the data at a later stage.

    NOTE: In order to simplify finding the mast zero rotation point in post-processing, it is recommended that future testers synchronise the encoder zero point with zero mast/boom rotation.

Figure 0-6: 0 Degrees.

Figure 0-7: +90 Degrees.

Figure 0-8: 0 Degrees.

Figure 0-9: -90 Degrees.

Figure 0-10: 0 Degrees.

Figure 0-11: +45 Degrees.

Figure 0-12: 0 Degrees.

Figure 0-13: -45 Degrees.

Figure 0-14: 0 Degrees.

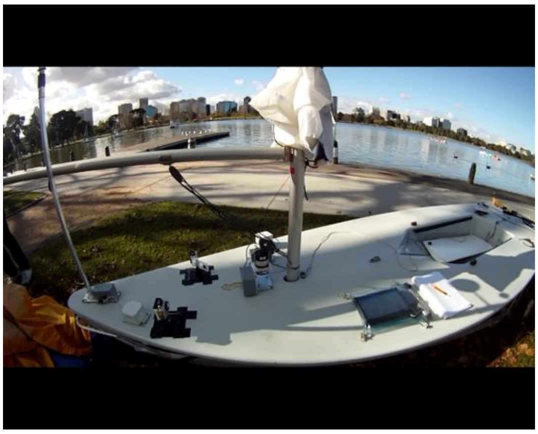

Figure 0-15: +180 Degrees.

Figure 0-16: 0 Degrees.

Figure 0-17: -180 Degrees.

Figure 0-18: 0 Degrees

15. Zero the rudder encoder. Mark the zero point on the deck and hold in this location for 10 seconds (so as to identify data when post processing). Stepping through 20° increments to port and starboard in order to calibrate the encoder may also be conducted.

Previous and current procedure also dictates that the rudder be rotated to extreme Port/Starboard angles, with the mid-point being zero rudder angle. As the maximum angles are not equal, care must be taken when calculating zero rudder angle.

16. Zero the accelerometers. Roll and pitch the Laser on the trailer. Complete two sets of picking up the Port, Forward, Starboard and Aft sides of the Laser (video)

Figure 0-19: Picking up the Port Side.

Figure 0-20: Picking up the Bow.

Figure 0-21: Picking up the Starboard Side.

Figure 0-22: Picking up the Stern.

SHUTDOWN PROCEDURE

1. On dry land (away from water sources) open the laptop bag and press *enter* to stop data sampling.
2. Cut the encoder belts (at knot location, belts can be re-used) and remove rigging.
3. Open all components containing batteries; Switch them off and remove batteries. Order of component shutdown is not important. It's important to keep track of charged and discharged batteries, as 12-18 hours charge time is required between tests to fully charge all batteries. Fully charged batteries must always be used to maximize test time, and to ensure components do not fail. Typical continuous system run time is 3-3.5 hours.

DATA ANALYSIS PROCEDURE

1. Raw data obtained by the system is stored in .txt files, *TestFile1* and *TestFile3*. *TestFile1* contains accelerometer information; *TestFile3* contains raw GPS data, anemometer, rudder angle and boom angle encoder data.
2. In order to post process the data in matlab, it must first be converted from raw format to a MATLAB compatible format. To do this, copy the *DataCondition* program files into the folder containing the two test files. Run *DataCondition.exe* (source code available), which produces *TestFile4* (conditioned GPS data)and*TestFile5* (conditioned accelerometer and encoder data).
3. Open Matlab and set the folder *ScriptsofValue* as your working directory.
4. In the command window, type: nodedata=read() [takes a few seconds to load), select *TestFile4* or *TestFile5*. NOTE: *Nodedata* is the variable and *read* is the command.
5. *TestFile4* (NOTE: Not working at time of pub. Exceeding matrix problem). When data is imported using step 4, it is accessed via the *Variable Editor* (Figure 2) window. Both files contain Longitude and Latitude data w.r.t time.

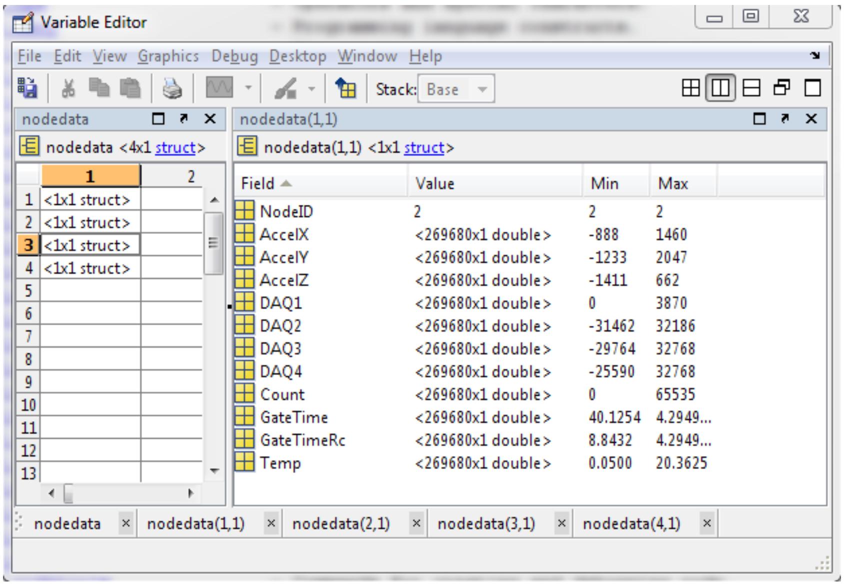

Figure 0-1 - Variable Editor Window

6. TestFile5 contains information as shown in tables 1,2,3,4. File 1,1, File 2,1 etc corresponds to row 1, column 1 in the nodedata window as shown previously in Figure 0-1. All data is 12 bit unsigned, with the exception of Gyro data, which is 12 bit signed. For clarification: *unsigned* (capable of representing only non-negative integers) and *signed* (capable of representing negative integers as well).

Table 0-1 - File 1,1 data

File = 1,1	Node = 2
DAQ 1	Rudder Angle
DAQ 2	Gyroscope
DAQ 3	Gyroscope
DAQ 4	Gyroscope

Table 0-2 - File 2,1 data

File = 2,1	Node = 3
DAQ 1	Magnetometer (in front of mast)
DAQ 2	Magnetometer (in front of mast)
DAQ 3	Mast angle (must unwrap data)
DAQ 4	Magnetometer (in front of mast)

Table 0-3 - File 3,1 data

File = 3,1	Node = 4 (wind direction and speed information)
DAQ 1	Blue (wind direction)
DAQ 2	Dark Green
DAQ 3	Red (wind direction)
DAQ 4	Aqua Green
	When plotting data, red and blue indicate wind direction. Green indicates wind speed. See Vaisala WM30 fact sheet

	for calibration information.

Table 0-4 - File 4,1 data

File = 4,1	Node = 5 (rudder angle and gyro readings)
DAQ 1	-
DAQ 2	Redundant Gyroscope
DAQ 3	Redundant Gyroscope
DAQ 4	Redundant Gyroscope

APPENDIX B – EQUIPMENT ERROR

Wind anemometer equipment calibration information is as per below.

Wind speed

Measurement range	0.5 ... 60 m/s
Starting threshold	< 0.4 m/s
Distance constant	2 m
Transducer output	1 Hz ~ 0.7 m/s
Accuracy (within range 0.4 ... 60 m/s)	
wind speed < 10 m/s	± 0.3 m/s
wind speed > 10 m/s	± 2%
Characteristic transfer function	U = -0.24 + 0.699 × F
(where U = wind speed [m/s], F = output frequency [Hz])	

Wind direction

Measurement range	
WMS301 with 1-wiper potentiometer	0 ... 355°
WMS302 with 2-wiper potentiometer	0 ... 360°
Starting threshold	< 1.0 m/s
Damping ratio	0.3
Overshoot ratio	0.4
Delay distance	0.6 m
Accuracy	better than ±3°

General

Supply voltage	3 ... 15 VDC
Electrical connections	5-pin male with 12 mm threads
Recommended connector at cable end	BINDER 99 1436 814 05
Operating temperature	-40 ... +55 °C (-40 ... +131 °F)
Storage temperature	-60 ... +65 °C (-76 ... +149 °F)
Material	
housing	AlMgSi, gray anodized
cups	PA, reinforced with carbon fibre, black
vane	PA, reinforced with fiberglass, white
Dimensions	265 (h) × 360 (Ø) mm
Weight	360 g

Accessories

Mounting adapter	WMS30KIT
Sensor connector	19370
Sensor connector and cable, 10 m	19904

Test compliance

Wind tunnel tests	ASTM standard method D5366-93
	ASTM standard method D5096-90

Complies with EMC standard EN61326-1:1997 + Am1:1998 + Am2:2001; Generic Environment

APPENDIX C – ERROR ANALYSIS OF TRUE WIND DIRECTIONS AND VELOCITIES

If the coordinate system is rotated such that the origin is along the boat track then the true wind angle will be defined by

$$TWA = \operatorname{atan}\left(\frac{AWS.\sin AWA}{AWS.\cos AWA + V_B}\right) \qquad (1)$$

where AWS is the measured apparent wind speed, AWA is the measured apparent wind angle minus the measured heading angle and V_B is the measured boat speed. Using the first term in a Taylor series expansion of the uncertainty in the true wind angle, the error estimate will be (Beckwith and Marangoni 1990)

$$\varepsilon_{TWA} = \sqrt{\left(\frac{\partial TWA}{\partial AWS}\right)^2 {\varepsilon_{AWS}}^2 + \left(\frac{\partial TWA}{\partial AWA}\right)^2 {\varepsilon_{AWA}}^2 + \left(\frac{\partial TWA}{\partial V_B}\right)^2 {\varepsilon_{VB}}^2} \qquad (2)$$

Where ε_{AWS} is the anemometer wind velocity measurement error, ε_{AWA} is the anemometer angle measurement error and ε_{VB} is the boat velocity error.

Symbolically evaluating these differentials and substituting for $D = AWS^2 + 2.AWS.V_B\cos(AWA) + {V_B}^2$ the following equation is found for the error in the true wind angle, ε_{TWA}:

$$\varepsilon_{TWA} = \sqrt{\left(\frac{V_B \sin AWA}{D}\right)^2 {\varepsilon_{AWS}}^2 + \left(\frac{AWS^2 + AWS.V_B \cos AWA}{D}\right)^2 {\varepsilon_{AWA}}^2 + \left(\frac{-AWS.\sin AWA}{D}\right)^2 {\varepsilon_{VB}}^2} \qquad (3)$$

A similar expression can be developed for the uncertainty in the true wind velocity (TWS), resulting in:

$$\varepsilon_{TWS} = \sqrt{\left(\frac{AWS + V_B \cos AWA}{\sqrt{D}}\right)^2 {\varepsilon_{AWS}}^2 + \left(\frac{-AWS.V_B \sin AWA}{\sqrt{D}}\right)^2 {\varepsilon_{AWA}}^2 + \left(\frac{V_B + AWS.\cos AWA}{\sqrt{D}}\right)^2 {\varepsilon_{VB}}^2} \qquad (4)$$