Victorian Urban Wind Resource Assessment

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Contents

Executive Summary

This report presents the results of a wind resource assessment undertaken by the Alternative Technology Association (ATA) for Sustainability Victoria between September 2008 and March 2009.

Covering 10 sites within 25km of Melbourne's CBD, the aim of this project was to produce an empirical appraisal of the energetic characteristics of typical urban wind regimes, and provide commentary on the suitability of urban locations for installation of Micro Wind Turbines (MWTs).

This study focussed on wind data gathered from both rooftops and open areas in urban backyards; no significant differences in wind energy abundance were observed between these two kinds of anemometer sites. Analysis of three-dimensional wind velocity data from pitched and flat roofs included in the report suggests that vertical velocity components comprise only a small fraction of total wind energy.

Cup and Ultrasonic anemometers were installed on a variety of roof types and on masts in backyards for a minimum period of 100 days to provide a broad portrait of wind behaviour in the urban environment. Wind probability distribution curves (Weibull curves) have been fitted to data collected from these sites to estimate likely average wind power densities. Fluctuations in wind velocity over 1 and 10 minute time intervals were studied in an attempt to ascertain levels of turbulence at the measurement locations. The research presented here finds Weibull probability density functions to be a good approximation of the distribution of wind speed occurrence at urban locations. Data gathered during the study confirms that turbulence levels observed in built-up urban environments are significantly greater than in open semi-urban locations.

This research indicates that of 10 sites under consideration, only two are likely to be suitable for MWT installation. One of the sites is situated in a broad open area on the seashore in Williamstown and the other is on top of a large commercial building in Melbourne's CBD. Levels of turbulence were found to be much greater at the CBD location. Neither of these sites could be described as a typical domestic location. The gathered data suggests that common domestic sites are not likely to have sufficient available wind energy to make MWT use an attractive option.

The results of this study suggest that favourable wind energy characteristics are likely to be strongly associated with open terrain and/or substantial elevation above the aerodynamically rough layer of the urban landscape. MWTs installed in typical built-up urban terrain are likely to operate at low capacity factors, suffer protracted periods of non-operation and have long payback periods.

Bureau of Meteorology (BOM) data was used to compare wind speeds during this study to long term average wind speeds at BOM sites around Melbourne and suggested that the study's interval encompassed a period where wind speeds were higher than average. As a consequence, derived Weibull curves are likely to moderately overestimate wind power potential.

An analysis combining derived wind speed probability curves with a typical MWT power curve estimated the likely theoretical energy output from a commonly used MWT.[1]

It is recommended that further research in this area concentrate on establishing standards for measuring turbulence in urban environments, modelling the effects of turbulence parameters on MWT performance and verifying the accuracy of derived Weibull curves and manufacturer power curves in predicting MWT performance.

[1] Note; the turbine performance modelling presented in this document is not intended to be an estimate of end-user energy yield.

1. Measurement Methodology

1.1 Wind Power and Turbulence

Wind energy generators offer the potential to provide electricity that is renewable, virtually free of greenhouse gas emission and without reliance on centralised electricity distribution infrastructure. The commercial wind energy industry has enjoyed a period of tremendous growth in the last decade, with a growing level of interest in adapting wind generation technology to an ever increasing array of environments and specialist applications. While certainly not traditionally the domain of wind energy systems, built-up urban environments have been widely mooted as possible locations for the deployment of small wind turbines.

To gauge the feasibility of built up environments for the use of wind generation systems, turbine operation can be simulated by combining performance characteristics of specific turbine designs with a profile describing wind behaviour at a given location. A wind resource assessment is usually conducted to compile this site-specific profile of wind behaviour. The fundamental purpose of a wind resource assessment is to estimate the availability of wind energy at a specific site, through analysis of wind speed and direction data gathered over a significant time period. Resource estimation is essential to the economics of wind power investment, and must be rigorously undertaken to provide an accurate forecast of wind power density and return on capital investment.

The power [W] available in a uniform flow of moving air is equal to the density of air, ρ [kgm^{-3}], multiplied by the flow's cross sectional area A [m^2] and half the cube of flow speed, v [$m\ s^{-1}$]:

$$P_{wind}[W] \quad = \quad ½ \, . \, \rho \, . \, A. \, v^3$$

A fundamental feature of wind behaviour is the cubic proportionality between available power and speed in a flow (refer to section 2.2 of *The Viability of Domestic Wind Turbines for Urban Melbourne* for a basic derivation of this power relation). As a consequence, the average wind speed at a given site is very unlikely to yield the average available power if substituted into the power equation above (the average of a set of values cubed is not equal to the cube of the average value). In order to understand the availability of wind energy in an environment, consideration must be given to variations in wind speed and direction. Location-specific profiles of energy availability can be constructed by measuring the fluctuations in flow velocity at a given site, and by determining the probability with which different wind speeds are likely to occur.

Turbulent flows may be considered to be chaotically unpredictable moving systems of particles, where it is often computationally infeasible to determine the resultant state of a given system after a series of interactions. Turbulent wind flows are particularly likely to occur where topology is uneven, often resulting in swirling and eddying movement of air. Mechanical systems such as wind generators harness energy from flows by absorbing momentum from moving air, essentially by placing an obstruction (the turbine blade) in a plane perpendicular to the direction of movement of the flow and allowing the air to collide with the device. Turbulent flows make this much more difficult because the direction in which particles are moving is unpredictable and constantly variable.

High levels of turbulence hamper the performance of wind turbines due to reduced rates of energy transfer to the turbine and increased material stress placed on the moving parts of the system. A further effect of high material stress is heightened maintenance requirements and decreased infrastructure life spans.

Levels of turbulence are typically characterised by the non-dimensional parameter Turbulence Intensity (TI). TI is a measure of the variation of flow speed or velocity in a given interval (the Standard Deviation), and is non-dimensionalised by dividing by the average value in the interval. For a full definition of turbulence intensity please refer to the appendix to this document.

It is worth noting that the issue of how to measure and analyse turbulence affecting small wind turbines in built-up urban areas is, at the time of writing, largely a topic of research. Unlike large-scale commercial turbines, no international standards exist (such as the commercial turbine design code of IEC61400-1) that inform acceptable turbulence for MWTs. Turbulence is a significant factor influencing the efficacy of any wind generation system. Further work is required in the MWT field to establish design threshold levels for turbulence in three dimensions. Analysis of wind turbulence data taken from operating MWTs would also be useful in revealing the effects of turbulence on Vertical Axis Wind Turbines (VAWTs) and Horizontal Axis Wind Turbines (HAWTs) to assist turbine design selection.

1.2 Anemometers

This study used two different anemometer designs to measure the directional, energetic and turbulent properties of wind flow. Cup anemometers with wind vanes were stationed at each measurement site for the duration of the project, and two ultrasonic anemometers were also cycled from site to site every two weeks. A data logger was connected to each anemometer to record the data measured by the instrument.

In this resource assessment, cup and ultrasonic anemometers were used to gather data on the fundamental features of wind regimes: wind power density and turbulence.

Both the Gill and APRS anemometer systems were aligned to magnetic north on the ground with a magnetic compass at each site. Due to the difficulty in maintaining a precise directional orientation during the erection of a 10m meteorological mast, direction readings from both anemometers have an estimated uncertainty of ±10º. Directional offsets (of -11º) were applied to each logging system to produce data zeroed to true north.

In summary, data collection for each site in the study consisted of:

- Continuous measurement of 2-D wind speed (sampled at 1Hz), wind direction (sampled at 0.1Hz), with average wind speed, max 1Hz wind speed and instantaneous direction logged at 0.1Hz using cup anemometers.
- Two weeks of 3-D data collection using ultrasonic anemometers sampling at 10Hz and logging one and ten minute averaged data.

1.3 Cup Anemometers

Cup anemometers measure wind speed in a horizontal plane, and when combined with a wind vane can provide data on both the speed of a flow in two dimensions and the direction in which it is moving. APRS World cup anemometers and data loggers were used to gather two-dimensional wind speed and direction data. To maximise the value and utility of the data collected, the APRS data loggers were set to sample wind speed at 1Hz and record an averaged and maximum wind speed for each interval at a rate of

0.1Hz (once every ten seconds). The instantaneous wind direction was also logged at 0.1Hz. All raw data was processed after collection to produce ten minute average values of wind speed and direction. Refer to the appendix for the full specifications of this device and a method for calculating the average of circular variables such as wind direction.

Cup anemometers are mechanical systems that respond to changes in their environment with corresponding changes in the motion of their components. Because moving systems require time to accelerate or decelerate according to changes in the speed or direction of wind flow (response time), they are not well suited to recording rapid changes in turbulent flow.

Figure 1: APRS World cup anemometer and data logger.

1.4 Ultrasonic Anemometers

Ultrasonic anemometers measure wind velocity in three dimensions. They have no moving parts, making them ideal for taking frequent and accurate measurements of wind velocity in a rapidly fluctuating flow. In order to measure in three dimensions, ultrasonic anemometers require three pairs of transducers, each of which is capable of sending and receiving ultrasonic sound pulses (sound waves with frequencies beyond the range of the human ear). Ultrasonic anemometers function by sending high frequency sound pulses from an upper transducer to a lower transducer and vice versa, and by comparing the difference in the travel times of the two pulses. Sound waves propagate as a series of compressions and rarefactions in a physical medium (i.e. air). Movement of the medium itself will therefore delay or advance the arrival time of a signal. By comparing the travel times of signals from the three sets of transducers, the anemometer is able to output a three dimensional measurement of wind velocity.

The data logging systems used with the ultrasonic anemometers have a programmable interface allowing the recording of both measured values and derived quantities (such as turbulence intensity) based in the stream of data from the instruments. After consultation with experts from the Research Institute for Sustainable Energy (RISE) in Western Australia, the Gill Windmaster anemometers used in the study were set to sample wind conditions at 10Hz, and record time averaged data at one and ten minute intervals.

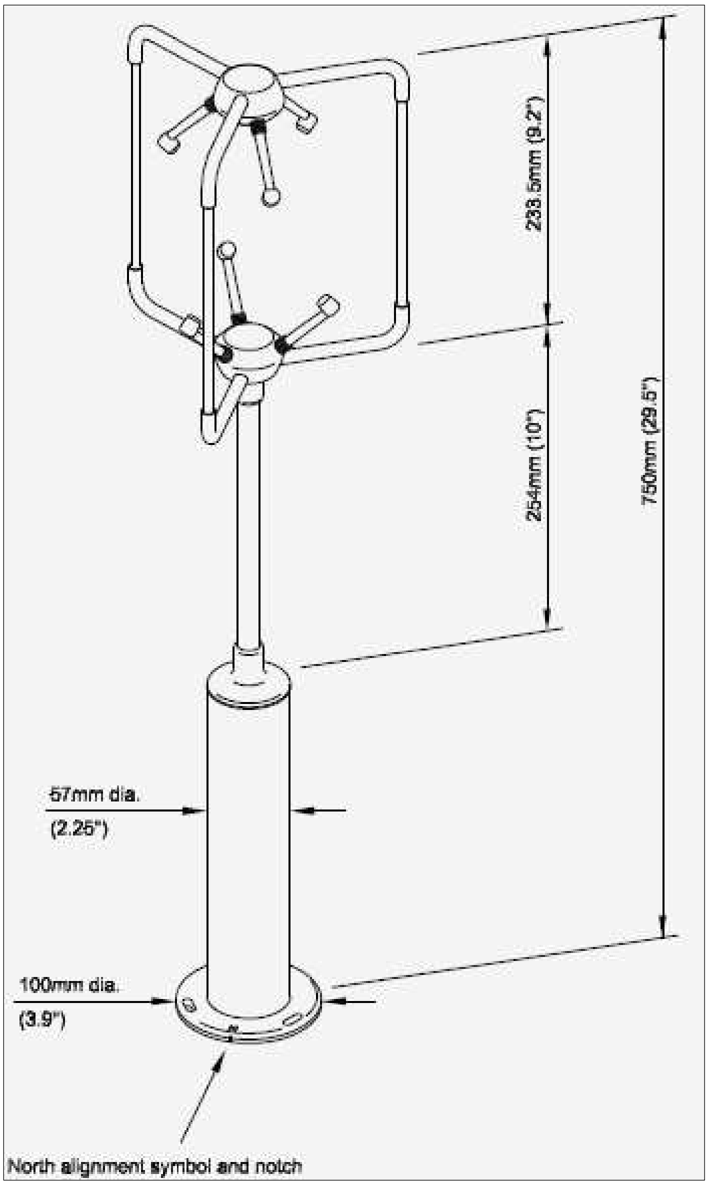


Figure 2: Gill Windmaster Ultrasonic Anemometer

Measurements taken at a high sampling rate (of the order of 10Hz) are required to capture the changes in flow velocity occurring on a turbulent time scale. Refer to the appendix for a full list of the measured and derived quantities logged and the operating specifications of the Gill anemometers.

During this study, two Gill Windmaster ultrasonic anemometers were deployed at 9 sites for a period of approximately two weeks. This two week interval was considered sufficient to gather a representative sample of wind turbulence data at each of the sites.

1.5 Speed and Velocity Averaging

The two types of anemometers used in this study recorded different parameters. The cup anemometers recorded horizontal wind *speed* whereas the ultrasonic units measured three-dimensional wind velocity, and recorded a range of derived values including the average and standard deviation.

The cup anemometers sampled horizontal wind *speed* every second and the data was logged every 10 seconds. Speed is a scalar quantity and is equal to velocity magnitude which will always be a positive value, regardless of direction.

The wind master ultrasonic anemometer sampled each of three perpendicular components of wind velocity 10 times per second (10 Hz) and logged an average value each minute. Logging all output from the anemometer at 10Hz proved prohibitively data intensive and instead summary data was generated by averaging the 600 samples each minute. In addition the derived parameters of mean and standard deviation of each velocity components were logged each minute.

This averaging led to some limitations in the comparability of datasets from the cup and ultrasonic anemometers.

The *velocity* averaging methodology employed with the ultrasonic anemometers has produced reduced values for wind velocity particularly in the low/speed velocity range. This is because velocity is a vector quantity and components vary in direction (by changing sign) within the 1 minute averaging period. This generally occurs in the component at right angles to velocity with a direction that primarily aligns with a cardinal direction. By example, a dominant Northerly wind may vary marginally to the West and East during the averaging period and the recorded average not show any evidence of this variation.

Subsequently, the 1 and 10 minute averages of velocity are likely to contain a mixture of positive and negative component measurements, which, if averaged, will give an average velocity magnitude that will always be less than a corresponding measure of average speed. The disparity between average speed and average velocity magnitude tends to become greater as the period of time over which the average is calculated increases. To illustrate this we can observe that the 1 minute average velocity magnitude, if averaged over ten 1 minute intervals, always provides an average magnitude greater than the logged 10 minute average for the same period.

The logging of velocity instead of speed also influences the calculation of turbulence intensity. Standard deviation of horizontal wind speed is customarily used by the commercial wind industry (as in IEC61400-1) to characterise turbulence. There are good arguments that other standards should be applied to MWTs in complex urban terrain due to the 3-D nature of the flow behaviour. The general trends in plots of turbulence intensity vs. wind speed/velocity are very similar (Appendix 1), however plots using velocity averages have significantly greater readings for very low wind speeds when velocity components are frequently changing sign in an interval. Despite this limitation the data from this study provides useful turbulence intensity measurements at the critical higher wind speeds. (Appendix 1)

Until clear standards are established for quantifying wind regimes and turbulence in urban environments, it is recommended that similar future studies using ultrasonic anemometers log both speed and velocity averages, to examine the relative merits of the two methodologies.

1.6 Bureau of Meteorology Data

Wind speed and direction data was requested from Bureau of Meteorology (BOM) stations around the city for the time period of the wind resource assessment. Data from the BOM has been used to verify the integrity of the project data and to moderate the wind energy estimates resulting from the analysis presented here to likely long term trends. It was also a secondary aim of this study to investigate how representative the BOM readings are of wind conditions experienced in typical urban environments. Further discussion and comparison of BOM and measured data sets can be found in section 2.8.

1.7 Data acquisition and logging difficulties

The project experienced a range of technical issues during the study period that impinged on the acquisition and collection of data. These issues related exclusively to the failure of storage media or the malfunctioning of anemometer units. Technical issues encountered during the project included:

- Operational failure of two Gill Windmaster ultrasonic anemometers. Both instruments suffered from an intermittent fault causing power supply to periodically drop out and initiate a restart self test. The frequency of the fault appeared to increase during field deployment. As the data logger was operated on an independent power supply and only logged at 1 and 10 minute averaged parameters, indicators of the fault were not necessarily apparent in the averaged data stream.

  One of the faulty instruments was installed at the CBD location, where reliable data was not collected until it was replaced with a functional instrument on 22/01/09.

  The other faulty ultrasonic anemometer was installed at East Brunswick, West Brunswick, Moonee Ponds and Manningham. As a result of operational downtime with these instruments, high frequency data was not collected at the Bentleigh, East Brunswick Roof and Moonee Ponds Mast sites.

- Recovery of 10Hz measurement data from DT80 loggers was hampered by unexpectedly long data upload times via the DT80’s USB interface. After it was observed that in excess of 9 hours would be required to upload 2 weeks of 10Hz ultrasonic data a decision was made to collect only 1 and 10 minute averaged data from the loggers. In this way the analysis presented in this report became committed to the velocity averaging techniques described in Section 1.5.

- Failure of 6 Verbatim SD cards manufactured in the same batch caused the loss of almost two months of data from both Moonee Ponds sites and the Blackburn site. On all occasions the SD cards, correctly formatted with a FAT file system as advised in the APRS data logger, were extracted from the logger in an unformatted state containing no readable data. Once replaced with SanDisk cards all loggers appeared to operate as expected.

- Malfunction of a wind vane unit installed at the West Brunswick Roof site. This faulty wind vane appears to have sent spurious data to the logger for most of the duration of the study. Wind speed measurements appear unaffected and correlate well with both the other instrument on this site and data from the BOM covering the same period. Error scripts periodically appear in the output from the device, which also failed to record data correctly for significant periods, usually directly after data was downloaded from the storage media.
  The logger was replaced at this site in January 2009, without any apparent positive effect on the output quality of stored data. Further measurement reliability issues at this site include the disruption of power systems used to run the data logger by renovations that were conducted over the period of the study.

One of the sealed boxes containing a data logger at the Seaholme Roof site filled with water during a very rainy period in mid December 2008, causing the logger to malfunction. Fortunately only 5 days of data was lost from this site before a replacement logger could be installed.

2. Measurement Sites and Results

2.1 Regional and Urban Terrain

Large-scale commercial wind farms have operated successfully in isolated regional areas since the 1980s. Commercial wind generation facilities are built at locations that have the highest possible wind power densities to maximise the return on infrastructure investment. Complex computer analysis of wind data is used to optimise the siting of individual turbines and increase overall energy yield. Modern HAWTs have been designed to perform optimally in wind regimes found in open terrain; environments that typically exhibit low turbulence levels and predominantly laminar flow with relatively small vertical velocity components. Commercial wind turbines are a mature and highly refined generation technology.

MWTs have been extensively used to generate electricity in small isolated and remote off-grid locations. Most MWTs of this type are very similar in design to commercial HAWTs, and with good reason. Turbines must be designed to optimally recover energy from a given wind regime profile (often represented by wind probability distributions). Due consideration must be given to the degree of directional variability, levels of turbulence, predominant wind direction and wind shear across the turbine’s structure. Turbine designs must be tailored to the wind behaviour at the installation site - optimised turbine design is wind profile specific.

The use of MWTs in urban environments presents a challenging re-adaptation of engineering principles deduced mostly in clear, unobstructed regional terrain. The value of wind generation systems in regional environments is beyond question; the value of MWTs installed in built-up areas is far from certain.

2.2 The site selection process

A series of online questionnaires of the ATA membership was used to select 10 sites within 25km of Melbourne’s CBD. The final participants were selected from a pool of more than 150 applicants. All site hosts participated on voluntary basis in what was a non-commercial agreement.

The guiding principle of site selection was to look for sites that were as qualitatively suited to MWT siting as possible, while still representing common and typical urban locations. Specifically, this meant looking for clear aspects in all directions with a minimum of localised geographic and architectural obstructions. Priority was also given to sites with relatively high roof peaks and sites situated on hills. Other practical features such as the presence of accessible power outlets close to anemometer installation points and the roof and backyard surface were also given consideration.

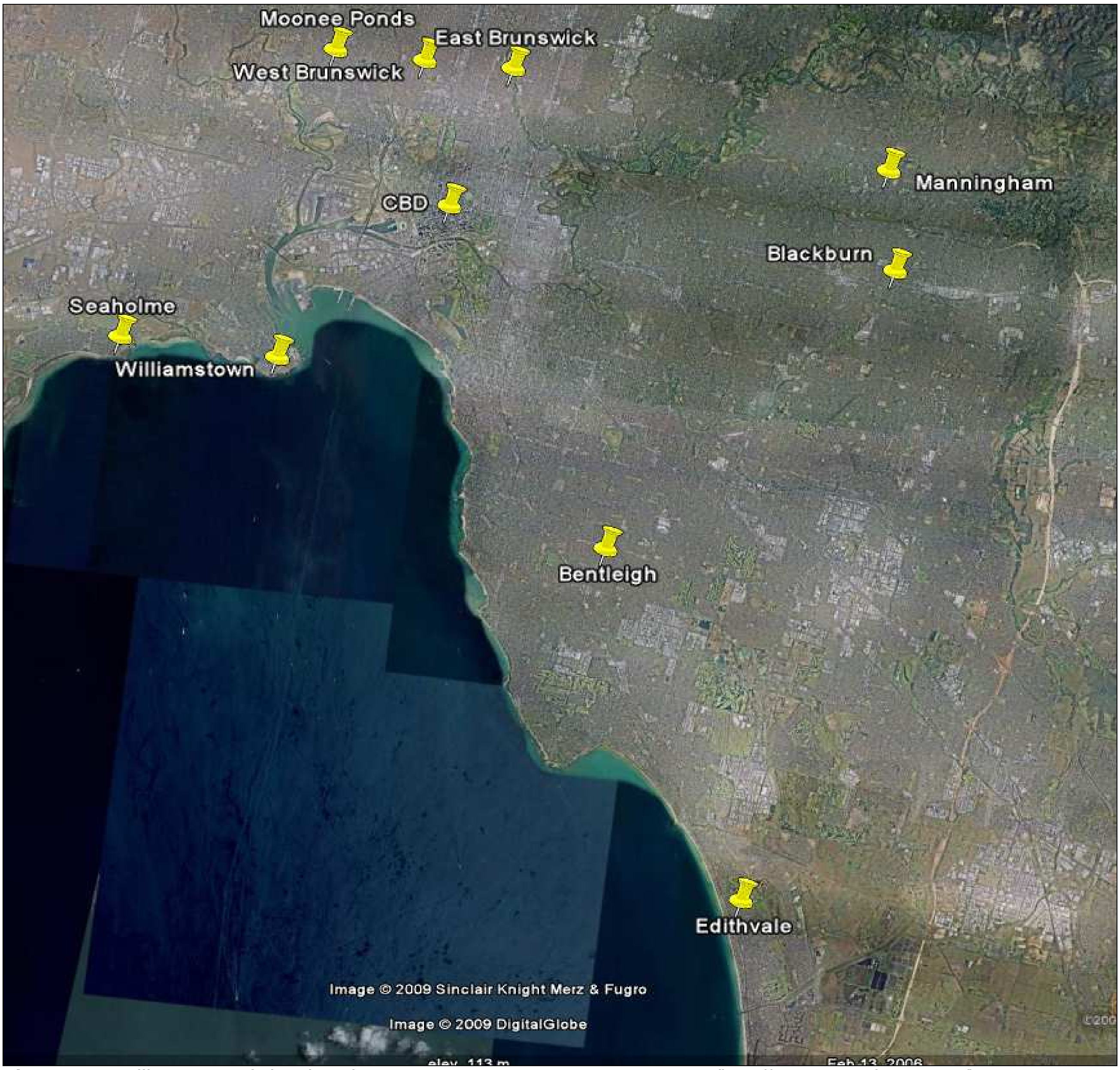


Figure 3: Satellite Image of sites locations (http://maps.google.com.au/)

The objective in selecting sites was to balance the generality of houses and backyards with optimality in terms of the expected available wind energy. The selection process aimed to find a range of sites with different expected wind energy availability. This research suggests that average domestic sites in the Melbourne area will lie within the bounds defined by the most and least optimal wind energy locations in this study. With only ten sites available for inclusion in this study, not all common urban/domestic terrain types were able to be investigated. The final selection of sites was chosen to be as broadly representative of urban environments as possible.

2.3 Anemometer Siting

MWTs can be mounted on existing building infrastructure or on free-standing towers. A profusion of factors can influence the siting of a MWT including, but not limited to: available wind energy, planning requirements, building structural limitations and noise and vibration.

The wind resource assessment was carried out at ten different locations containing 15 distinct measurement sites. All sites in this study were located within 25km of Melbourne's CBD and a range of private, commercial and municipal sites were included. Five of these sites had anemometers installed both on a roof and on free-standing masts in an open yard area of the site. The aim of the variation in anemometer siting was to investigate if there are any obvious differences in the available wind power density on roofs when compared to open areas caused by flow compression (the Venturi Effect).

Based on similar reasoning, anemometers were installed on pitched and flat roofs to investigate if there are any obvious trends in energy availability for different roof types.

Rooftop anemometers were positioned at heights considered to be likely for installation of a MWT without the use of additional mounting infrastructure, and ranged from one and a half to three meters above the roof surface.

For mast installs, anemometers were stationed at 10 meters above the ground, a height consistent with international meteorological measurement standards.

The distribution of site types in the wind resource assessment can be broken down as follows:

- 3 sites with cup anemometers installed on pitched roofs and on 10 meter masts in open backyard areas.
- 2 sites with cup anemometers installed on flat roofs and on 10 meter masts in open backyard areas.
- 2 sites with a single anemometer installed on flat roofs.
- 2 sites with a single anemometer installed on 10 meter masts.
- 1 site with a single ultrasonic anemometer installed on a communications tower at a height of 9m above the roof of a high rise building in the CBD.

In all, fourteen cup anemometers and three ultrasonic anemometers were used in this study. More detailed information on each site is contained in the appendix.

2.4 Summary of site data

The table shown overleaf summarises some of the key wind energy parameters of the locations studied in this resource assessment.

Most of the sites surveyed had a measured average horizontal wind speed between 3 ms^{-1} and 3.79 ms^{-1}. There were no obvious differences in wind power availability that could be clearly linked to the siting of anemometer on a pitched or flat roof or in an open backyard. The influence of anemometer position in determining wind energy characteristics seems to be rather small when compared to features like the sites height above the ground and the roughness of the surrounding terrain. The variety of results shown in the table emphasises the importance of gaining site specific data; there are substantial differences in average speed and projected turbine output between sites spread over small geographic areas.

The collected data suggests that the Williamstown and CBD sites are the only sites included in this study likely to be suited to MWT siting. Although there is a range of suitability in the sites reviewed here, all sites other than these two are likely to perform at a sub-standard level, operating with low capacity factors and with long energy and financial payback periods. As discussed at greater length in Section 2.7, further analysis and data collection is recommended to more accurately profile turbine operation at the CBD site. The feature that appears to make the Williamstown location unique (especially when compared to the similarly sited Seaholme and Edithvale sites) is the openness of the terrain around the measurement site. Such open sites are quite uncommon in domestic areas and may represent the best candidates for productive installation of MWTs close to urban centres.

The estimated annual turbine output figures (kWh) shown in the table overleaf acquire some useful context when compared to likely output from a similarly sized Solar PV array. According to Australian National University's PV panel performance simulator (http://solar.anu.edu.au/EduResources/applets/PVPanel/_PVpanel.php), a 1 kW PV system installed in Melbourne can expect to produce in excess of 1450 kWh of electricity annually. The losses in the electrical subsystem are included in this figure, which is greater than the simulated direct turbine output at all but the Williamstown site. It appears that PV systems are likely to offer greater energy outputs than similarly sized MWTs, without requiring the completion of a potentially time and cost intensive resource assessment.

Site	Install type	Terrain type	Average speed [ms^{-1}]	BOM moderated average wind speed [ms^{-1}]	Weibull scale constant k	Weibull shape constant c	Quality of Weibull Fit	Percentage of time at speed above 3 ms^{-1}	Forecast Output from Ampair 600 230 [kWh]	Number of days of data	Suitability for Turbine Installation
West Brunswick A	Mast	Urban	3.48	3.36	2.08	3.93	Good	57%	419	147	Marginal
West Brunswick B	Pitched Roof	Urban	3.40	3.17	1.95	3.83	Good	54%	416	101	Marginal
East Brunswick A	Mast	Urban	2.18	2.08	1.63	2.43	Fair	24%	112	171	Very Poor
East Brunswick B	Pitched Roof	Urban	3.12	3.03	1.89	3.51	Good	48%	323	171	Poor
Edithvale A	Mast	Coastal	3.76	3.62	2.04	4.24	Good	58%	550	119	Marginal
Edithvale B	Pitched Roof	Coastal	3.61	3.40	1.87	4.06	Good	57%	528	130	Marginal
Seaholme A	Mast	Coastal	3.79	3.59	1.75	4.26	Good	58%	654	124	Marginal
Seaholme B	Flat Roof	Coastal	3.66	3.51	1.81	4.11	Good	57%	569	122	Marginal
Moonee Ponds A	Mast	Urban	3.05	2.90	1.66	3.41	Good	45%	367	102	Poor
Moonee Ponds B	Flat Roof	Urban	2.70	2.61	1.47	2.96	Good	36%	281	102	Poor
Manningham	Flat Roof	Urban	3.16	3.09	1.98	3.56	Fair	49%	318	133	Poor
Blackburn	Flat Roof	Urban	1.61	1.55	1.54	1.79	Poor	11%	38	109	Very Poor
Williamstown	Light Tower	Open Coastal	5.82	5.46	2.12	6.59	Good	83%	1677	131	Excellent
Bentleigh	Mast	Urban	3.15	3.03	1.78	3.55	Fair	48%	366	125	Poor
CBD*	Comm Tower	Central Urban	3.94	NA	1.59	4.39	Good	NA	NA	75	NA

Table 1: Summary of site wind characteristics

*CBD site data summary based on 1 minute average 3D velocity

2. 5 Weibull Probability Distribution Functions

Data collected from the cup anemometers provides horizontal wind speed and direction data for the duration of the wind resource assessment project. Of great interest was the occurrence frequency of different wind speeds. This information can be used to produce a continuous curve used to estimate wind speed probability and hence predict the energy output of a wind turbine of known characteristics. Experience and repeated empirical application has shown that the probability density function of wind speed measurements in open environments can be very well approximated by a Weibull distribution (sometimes referred to as a Generalised Raleigh distribution). The fitted Weibull curves shown here do not always match the observed probability distribution of wind speed (especially for very low wind speed sites), but are an excellent model for wind behaviour at the medium and higher average wind speed sites.

Weibull distributions are commonly used in commercial wind energy analysis and when combined with a turbine's power curve, Weibull curves can produce very accurate forecasts of energy yield. Weibull distributions are functions of wind speed only and can be described completely by two parameters, a shape constant a, and scale constant k. The shape and scale parameters have been calculated individually for each of the sites in the resource assessment and are based on ten minute averages of wind speed produced from the cup anemometer data and are fitted to horizontal wind speed bins of width 1 ms^{-1}.

There is significant variation in how well the derived curves fit the data, and in the shape and scale parameters. Some of the sites with low average wind speeds (Blackburn in particular) display a probability distribution that does not conform to the Weibull curve generated to represent it. When interpreting the results of this data there are several factors that may affect the snugness of fit of derived Weibull curves:

- The resource assessment was conducted over a relatively short interval (between 92 and 172 days depending on the site). In order to capture seasonal variations in wind energy, longer periods of data collection (at least a year) would be necessary. Data collection took place over a period including seasonal change. Wind patterns in individual seasons can be seen to conform to a given set of Weibull parameters, yet there is the possibility of some 'Double Weibull' behaviour in the probability curves produced. The 'Double Weibull' phenomenon is caused by wind patterns associated with different seasons being represented in the same data set.

- No directional decomposition was performed on the collected data. This form of analysis would see a Weibull curve produced for each of a series of discrete directional intervals (from 0º to 45º true for instance) and can be used to isolate the influence of meteorological or geographic factors capable of influencing wind speed probability at a particular location.

- It is unclear how useful Weibull curves are in describing low energy wind regimes. The effect of energetic dissipation in wind flows moving over a terrain of high surface roughness may affect the applicability of the Weibull curve in low speed regimes with long periods of no wind. This may comprise a possible area for additional research, however the wind energy availability in such regimes is so low that resources may be better directed elsewhere.

Despite these caveats the fitted Weibull curves have been able to match wind speed occurrence probability extremely well in this study. To allow for comparison, the derived curves for all sites are shown on the same set of axes overleaf. The plotted curves and measured wind speed probability histograms may be found in the section on each site contained in the appendix to this document, along with a description of the mathematics used to generate the Weibull curves.

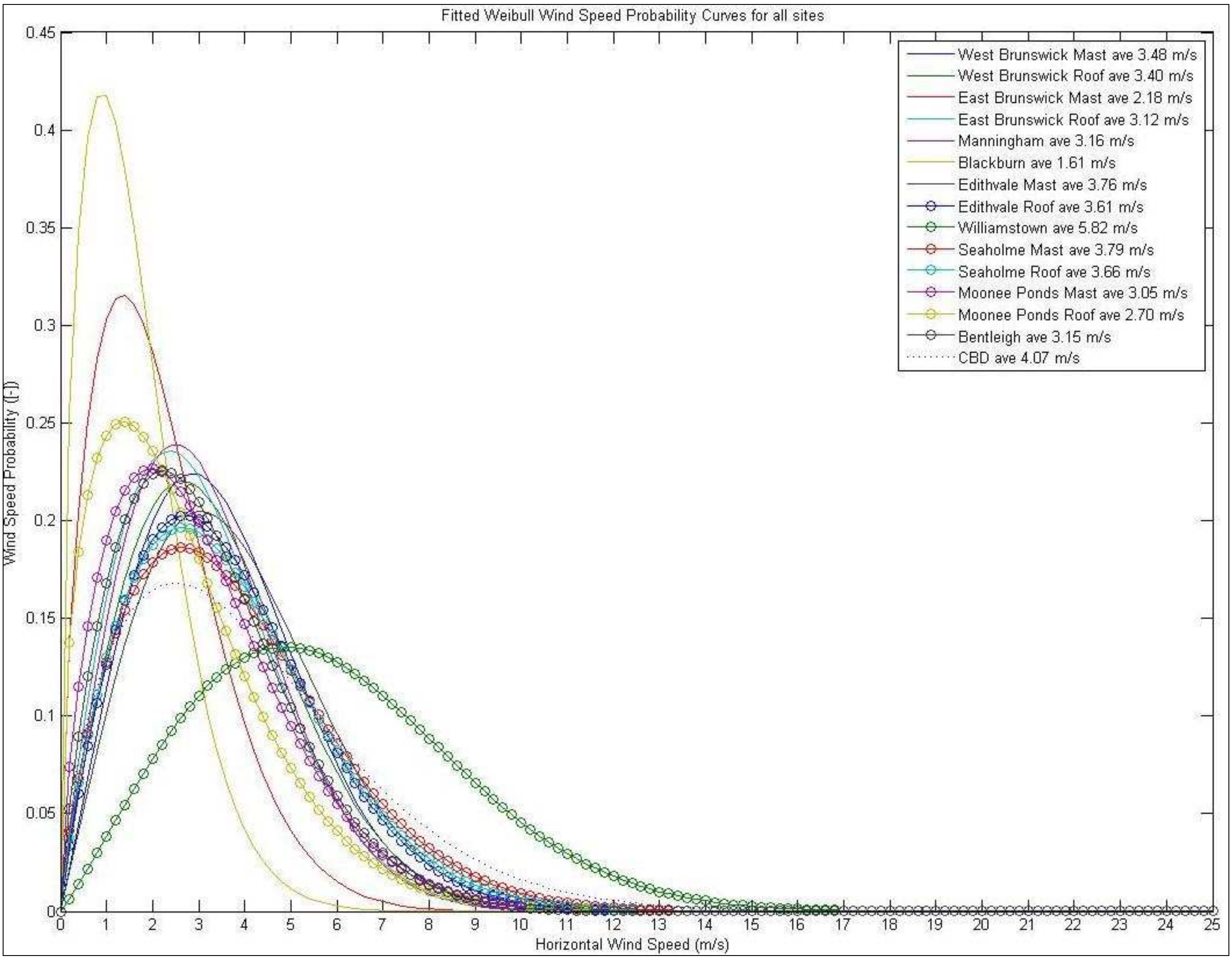


Figure 4: Weibull probability Distribution Functions for all sites.

2.6 Estimating turbine performance

This section on anticipated turbine performance has been included to illustrate the relative merits of the sites as possible locations for MWT deployment. Based on this modelling, the Williamstown site appears to be the only good candidate for MWT installation.

Anticipating the output of a wind turbine is a complex process requiring a synthesis of data produced from a resource assessment with turbine specific wind speed power data. Turbine power curves are curves fitted to empirical data that relate wind speeds (ms^{-1}) to turbine power output (kW). There is a profusion of factors that may affect the accuracy of an output estimate based on manufacturer's power curves, including turbulence levels and turbine subsystem and control system design (for a full discussion of turbine power curves please consult Section 2.2.2 of *The Viability of Domestic Wind Turbines for Urban Melbourne*).

It must also be noted that all factors capable of affecting the shape of the Weibull distribution derived for a wind energy site will similarly affect the energy output estimate. Analysis of BOM data collected during the period of this study suggests that the data collected represents a period slightly windier than normal for locations around metropolitan Melbourne.

For the purposes of articulating the likely range in available wind energy across the sites included in the wind resource assessment, the output from a vertical axis turbine, the Ampair 600-230 has been modelled here. The power curve and full specifications for the Ampair can be found in the appendix. The selection of this turbine for use in performance modelling is entirely arbitrary; modelling shown here is intended only to demonstrate the comparative merit of each of the sites in the broader context of this study.

The following features should be considered when interpreting the results of this performance simulation:

- The modelled energy output is from the turbine only; the turbine's control unit imposes parasitic energy requirements on the system, additional losses would be sustained in the inverter and electrical subsystem connected to the turbine.
- Estimated turbine performance is based on generated Weibull probability curves rather than long term data. It is expected that the figures shown here overestimate likely turbine output.
- Forecast turbine output is subject to the accuracy of the manufacturer's power curve.
- The effect of turbulence on energy output has not been included. A means for adjusting turbine output curves to average long term measures of turbulence is a likely topic for further research.

The Ampair 600-230 has a nominal rating of 698W and has a cut-in speed of $3ms^{-1}$, which can be considered as typical of MWTs of similar size and rated capacity.

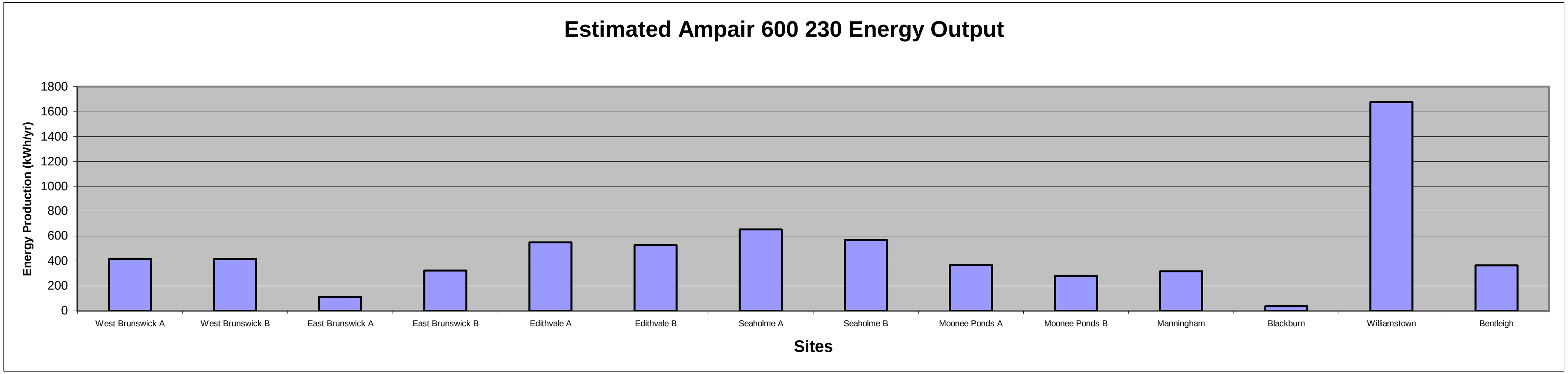


Figure 5: Forecast Turbine Direct Energy output

Site	Average speed (ms^{-1})	BOM moderated average wind speed (ms^{-1})	Percentage of time at speed above 3 ms^{-1}	Forecast Output from Ampair 600 230 (kWh)	Suitability for Turbine Installation
West Brunswick A	3.48	3.36	57%	419	Marginal
West Brunswick B	3.40	3.17	54%	416	Marginal
East Brunswick A	2.18	2.08	24%	112	Very Poor
East Brunswick B	3.12	3.03	48%	323	Poor
Edithvale A	3.76	3.62	58%	550	Marginal
Edithvale B	3.61	3.40	57%	528	Marginal
Seaholme A	3.79	3.45	58%	654	Marginal
Seaholme B	3.66	3.37	57%	569	Marginal
Moonee Ponds A	3.05	2.90	45%	357	Poor
Moonee Ponds B	2.70	2.61	36%	281	Poor
Manningham	3.16	3.09	49%	318	Poor
Blackburn	1.61	1.55	11%	38	Very Poor
Williamstown	5.83	5.25	83%	1677	Excellent
Bentleigh	3.15	3.03	48%	366	Poor

Table 2: Wind energy characteristics and modelled MWT output for all sites

Some interesting insights into the wind energy behaviour are evident on close analysis of Table 2. For example, the Manningham site had a higher average speed than East Brunswick B in the measurement interval, but the modelled output of the Ampair 600-230 is less than what is predicted at the site with lower average wind speed. The East Brunswick site's Weibull curve is slightly flatter than that of Manningham, meaning that mid range speeds are relatively less likely and (higher energy) higher range speeds are slightly more likely. When combined with the turbine's power curve the East Brunswick Weibull curve results in a higher net energy production.

Similar trends are evident in a comparison between the Edithvale Mast and Seaholme Roof sites, where once again the Edithvale Mast site has higher average speed, but less modelled energy production. The higher speed range overlap of the respective site Weibull curves is shown below:

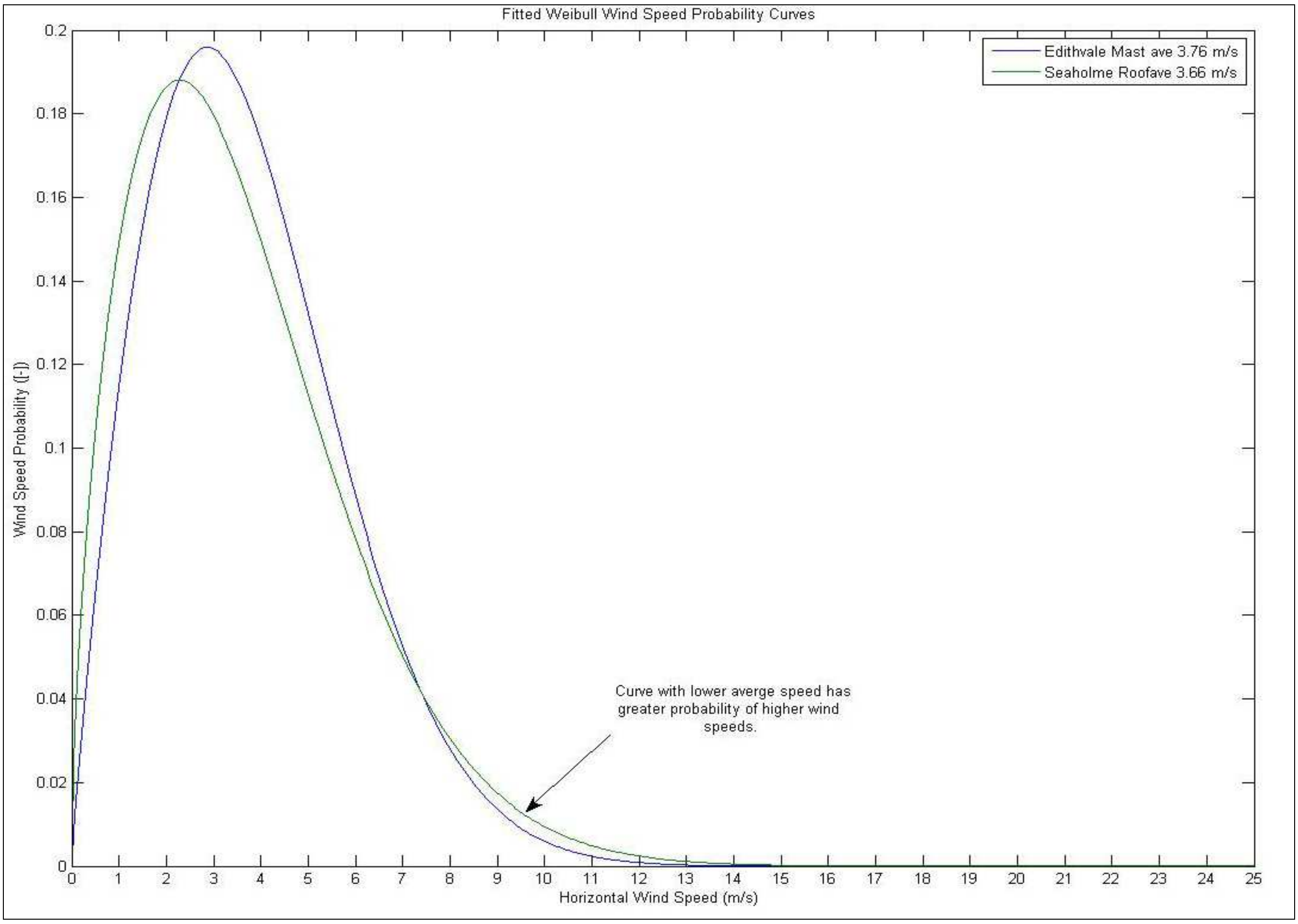


Figure 6: Derived Weibull Probability Density Functions for Edithvale Mast and Seaholme Roof

This disparity between the average wind speeds and power output at different sites is a clear example of why average wind speed alone is not a completely sufficient criterion for judging wind energy availability. However, differences in the power density functions at different sites will usually only serve to separate sites with very similar average wind speeds; sites with very low average wind speeds are not going to outperform sites with high average wind speeds. As a generality, the use of average wind speed still has applicability as a crude measure of wind energy abundance at a given site.

The possibility of differences in the shape of the Weibull curves shown in Figure 6 could be linked to levels of turbulence at different sites. Curves with thick tail sections (such as Seaholme Roof) may be more likely to have higher levels of turbulence, as the flatness of the curve suggests higher variability in speed, which may correlate with higher turbulence intensity. Further examination of the time series data from each location would be required to substantiate this hypothesis, and if indeed turbulence is the explanation for the curve's flatter profile, it is likely that the estimate of higher energy production at the Seaholme site would not reflect actual turbine performance at this site.

2.7 Review of CBD site data

One of the Windmaster ultrasonic anemometers was installed on a disused communications tower, 9m above the roof of one of the tallest commercial buildings in Melbourne's CBD. As discussed at the beginning of this section, data analysis indicates that these sites, along with the Williamstown site, are the only two locations under scrutiny here likely to be well suited to MWT installation.

The ultrasonic anemometers used in this wind resource assessment were programmed to record 1 and 10 minute averages of the three vector components of wind velocity. The wind velocity probability distributions of both the 1 and 10 minute average data sets are found to closely match Weibull distributions. Refer to the appendix to view the measured and fitted probability distributions.

There are limitations to the wind profile that may be drawn from this vector averaged data. The effect of calculating velocity vector averages is to underestimate wind speed, as velocity readings are likely to change sign in a measurement interval. In general, the extent of the underestimation will increase as the interval over which the averages are calculated increases. By example, the average of 1 minute average velocity at the CBD site was recorded as 3.93 ms^{-1}, in contrast to an average of 10 minute averaged velocity of 3.61ms^{-1}.

Data produced from the ultrasonic anemometer at the CBD is not comparable to the cup anemometer data collected at the other sites. The use of vector averaging leads to significant uncertainties in the estimation of the available wind energy at the site, and thus the location's suitability for turbine use. The average of 1 minute average wind velocity readings is greater than any of the long term 2-D average speeds recorded at the other sites included in this study, and certainly appears to be an under-estimation of 3-D wind speed. How much these readings underrate wind speed is unclear and is dependent on the wind direction and set of wind fluctuations in the sample period in which the average is calculated.

The height of the site (at around 185m) and relative lack of built up obstruction at roof level allow for exposure to much higher speed flow than what is experienced on the ground. The data suggests that tall commercial buildings of the kind included in this report are likely to be promising locations for MWT use and it is recommend that further work be undertaken to more precisely describe wind behaviour in high-rise environments. The data collection protocol for the ultrasonic anemometers has not allowed for the generation of cohesive data sets representing available wind energy. Further research is also recommended on the effect of the high levels of turbulence measured at this site on MWT performance.

2.8 Moderation of Measurement Data with Bureau of Meteorology (BOM) data

In order to comment on long term wind trends it is best to analyse wind data gathered over a long period of time. This wind resource assessment would certainly be considered a short term study by the standards of the wind energy industry. The data gathered in the relatively short interval of this study is susceptible to the bias of short term weather patterns prevalent in the Melbourne metropolitan area. Linear correlation of the study data with BOM data suggests that data gathered in this resource assessment is likely to over-estimate the long term average wind conditions.

Data gathered from six BOM stations around the city (Melbourne Regional, Melbourne Airport, Moorabbin, Viewbank, Laverton RAAF and St Kilda Bay) during the period of the study has been compared to long term data in an attempt to address the following objectives:

- To assess the value of BOM data in predicting wind energy abundance at average metropolitan sites
- To verify the wind patterns in data collected in this study;
- To estimate the likely effect of short term weather effects on the collected data

Correlation of site data with BOM measurements taken in the same period can be employed as a useful (but approximate) mechanism to scale site measurements based on long term data.

The wind and weather patterns experienced at a given location are caused by a combination of large-scale meteorological effects and macro-scale geometric effects. Due to the geographic separation of measurement sites and BOM reference sites, there will be a lag (and a likely change in effect intensity) between the times when the effect of a given meteorological cycle is felt at disparate sites. The influence of this phenomenon on a time series correlation is reduced by averaging wind speed measurements over each day.

The international meteorological standard for measuring wind speed and direction (as implemented by the Australian BOM) is to collect data at a height of ten meters by averaging wind speed measurements in the last ten minutes of each half hour.

Overleaf is a plot of daily average wind speed at St Kilda Bay BOM and daily averages formulated from data gathered from the Williamstown instrument between October and December 2008. The similarity between wind behaviour at the BOM and the project sites is clearly apparent.

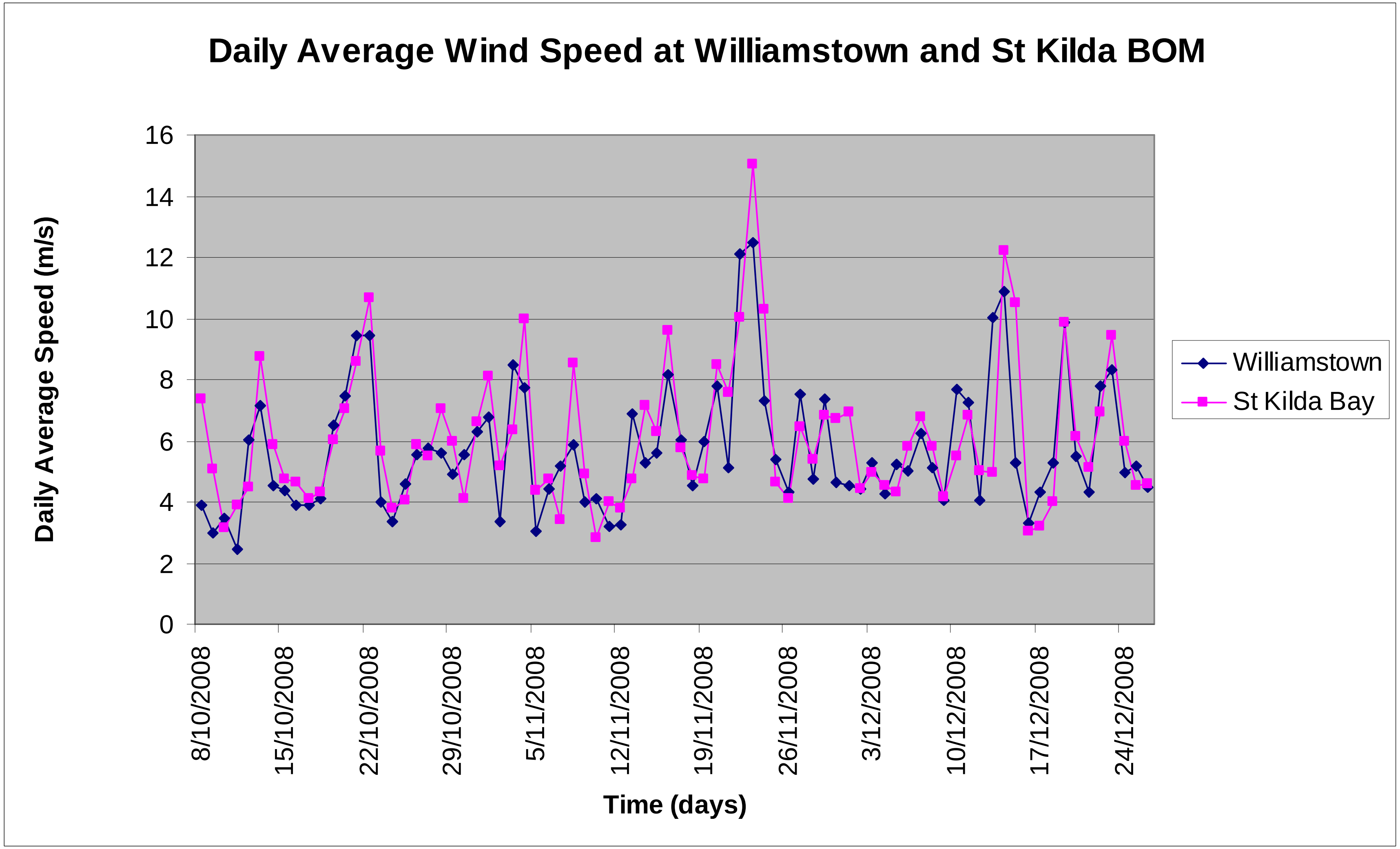


Figure 7: Comparison of daily average wind speed at Williamstown and St Kilda Bay BOM

A linear correlation between the BOM and the project data can be estimated using a line of best fit placed through a plot of daily average wind speed at both sites on the same day:

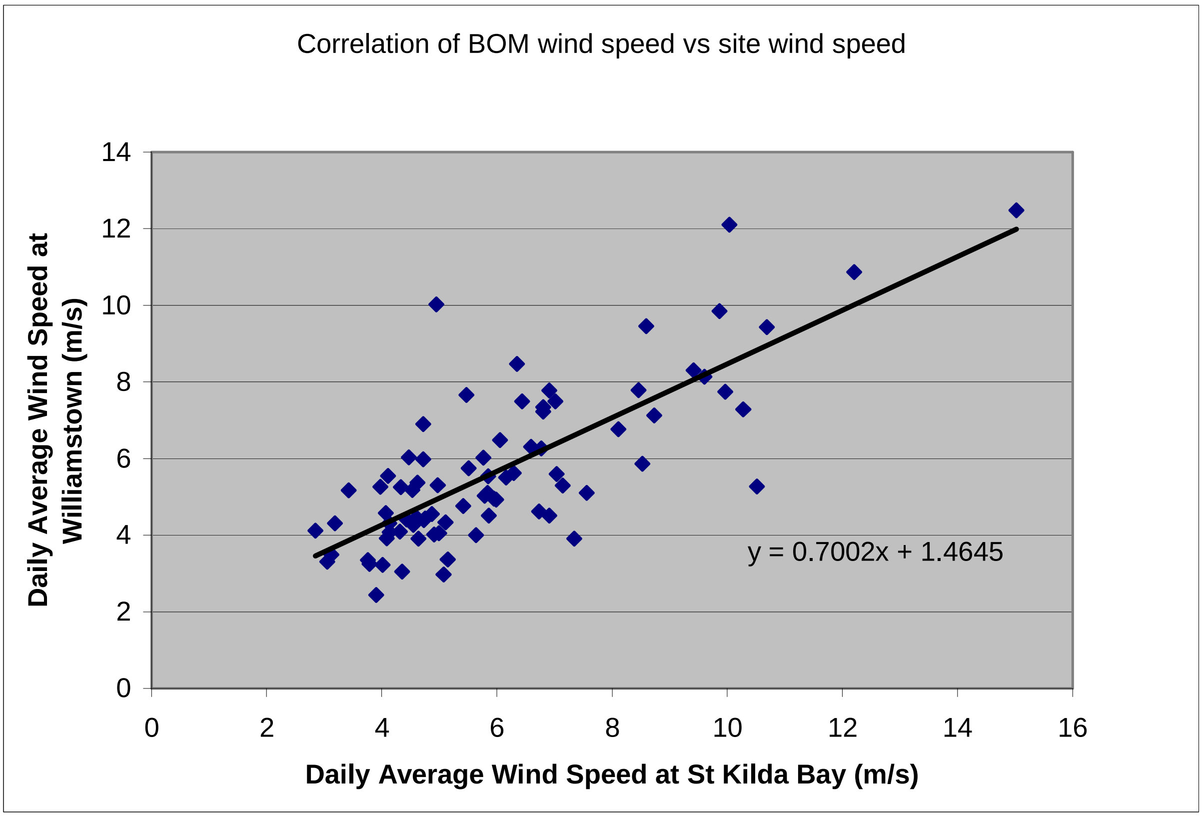


Figure 8: Correlation of daily average wind speed at Williamstown and St Kilda Bay BOM

The linear relation resulting from the line of best fit provides a relation connecting wind speed at the Williamstown site with wind speed at the BOM site. If the long term average wind speed at the BOM site is known, this relation can be used to estimate long term average wind speed at the study site. Correlations of this kind work best if based on at least 10 years of data.

The long term average wind speeds at each of the six BOM sites around the city are lower than those recorded during the interval of the study:

Site	BOM long term observation period (yrs)	Long Term Annual Average Wind Speed(m/s)	Average Speed in measurement Period (m/s)
Laverton	10	4.79	5.19
Melbourne Airport	10	5.27	5.68
Melbourne Regional	10	1.83	1.89
St Kilda Bay	2	5.41	5.99
Moorabbin	10	4.56	4.89
Viewbank	8	3.51	3.71

Table 3: BOM long term and average wind speeds

The choice of BOM reference sites to moderate the project data was based on proximity to the measurement site and the period of time for which records exist at the BOM sites. Complete details of the moderated average wind speeds for study sites are shown in Table 4**:**

Site	BOM Reference Site	Measured Average Speed (m/s)	BOM Moderated Average Speed (m/s)
West Brunswick A	Viewbank	3.48	3.36
West Brunswick B	Viewbank	3.40	3.17
East Brunswick A	Viewbank	2.18	2.08
East Brunswick B	Viewbank	3.12	3.03
Edithvale A	Moorabbin	3.76	3.62
Edithvale B	Moorabbin	3.61	3.40
Seaholme A	Laverton	3.79	3.59
Seaholme B	Laverton	3.66	3.51
Moonee Ponds A	Viewbank	3.05	2.90
Moonee Ponds B	Viewbank	2.70	2.61
Manningham	Viewbank	3.16	3.09
Blackburn	Viewbank	1.61	1.55
Williamstown	Laverton	5.83	5.46
Bentleigh	Moorabbin	3.15	3.03

Table 4: Moderated average wind speeds at measurement sites

Linear correlation of data in this manner is far from precise in its predictive capabilities. It will, however, be able to successfully scale results towards likely long term trends. The clear inference resulting from the long term correlation is that measured wind regime characteristics in a period that was significantly windier than usual. This conclusion has a bearing on many of the data constructs presented in the context of this report and carries the following likely implications:

- It is expected that the long term average wind speed at each site to be less than what has been measured in the project observation period.
- Long-term site Weibull probability curves are likely to be more pointed, have thinner tail sections and be situated closer to the vertical axis when compared to curves derived from the project data.
- The example MWT energy production estimate based on the project data in this report will almost certainly overestimate the long term annual energy yield from similar devices.
- Assessments of wind power density based on data from this resource assessment alone will overrate wind energy potential in urban areas.

Further to these conclusions, it is clear that the use of BOM data to model MWT energy output for average sites is wholly inappropriate at almost all locations. BOM sites in urban locations, positioned in open terrain and with clear aspects are likely to produce estimates of wind energy representing the very upper end of the spectrum of site suitability. It would seem that only a very small percentage of urban sites will exhibit similar wind profiles to this kind of reference site (the Williamstown site is likely to be one such location). This conclusion comes as no surprise; the geographic qualities of these reference type sites approach those found in the open regional areas where commercial wind farms continue to operate very successfully. In a continuum of wind energy availability we find commercial wind sites at the end of relative abundance, while sheltered sites in highly built up areas on the side of relative sparsity, and urban reference sites somewhere between the two.

Due to the structural complexity of the urban environment and the unique geometry of each urban location there appears to be no obvious way to systematically scale wind measurements from BOM reference sites to reflect wind behaviour at nearby domestic sites. There are no satisfactory alternatives to a site-specific resource assessment in gauging the suitability of a particular location for installation of a MWT.

2.9 Overview of Turbulence Data and Analysis

During this project, two Gill Windmaster ultrasonic anemometers were moved from site to site while a third remained deployed at the CBD site. Ultrasonic anemometers are especially suited to measurement of high speed fluctuations in wind velocity and direction. The objective of this research was to use the small window of time available at each location (from 2 to 3 weeks except at the CBD site) to look for patterns in turbulent behaviour. As discussed in previous sections of this report, turbulence is a critical factor likely to impair MWT performance in built-up areas.

The short period of time over which the ultrasonic anemometers were installed at each site, and the limitations of the vector averaging technique used to calculate turbulence parameters (as discussed in Section 1.5 of this report) restrict the strength of any conclusions that may be drawn from this data. Analysis of wind turbulence in urban areas is a highly specialised area of study, and the commentary presented here will focus on apparent trends in the data instead of more general remarks.

Turbulence intensity is the traditional characteristic used to measure the magnitude of turbulence in a flow. Turbulence intensity is a non-dimensionalised parameter obtained by dividing the standard deviation of wind speed or velocity by the mean speed or velocity, and is not a unique or absolute measure of the amount of turbulent energy in a flow. For example, low and high speed flows may exhibit the same value of turbulence intensity provided the relative fluctuations in wind speed are just so. Turbulence intensity instead is a relative measure of how much a flow is varying. For this reason plots of turbulence intensity vs. 3D velocity are included in the appendix of this report. For an absolute measure of turbulence, indicative of the amount of turbulent energy present in an environment, the standard deviation of wind velocity is a more suitable metric.

Table 5 shows summary data produced from the ultrasonic anemometers.

The Windmasters were deployed at each site for different time periods, and were thus subject to the influence of different weather patterns. Bearing this and the other limitations in mind, the following observations may be made on analysis of the tabulated data:

- The average W (upwards) component magnitude is likely to make up a very small amount of total average velocity magnitude. This may effect design selection between HAWTs and VAWTs. Cup 2D anemometers are also likely to provide output that is closely representative of available wind energy. The average W vector component is very likely to be positive (directed away from the ground) on pitched roofs.

Site	Install type	Average 3D Velocity [ms^{-1}]	Average 2-D Wind Speed in same period [ms^{-1}]	Average 3D Turbulence Intensity [-]	Average 3D Turbulence Intensity [-] for Velocity > 1 ms^{-1}	Standard Deviation 3D velocity [ms^{-1}]	Standard Deviation of wind Direction [º true]	Average W vector [ms-1]	Average W magnitude [ms^{-1}]
West Brunswick A	Mast	3.41	3.94	0.28	0.27	0.88	17.78	0.02	0.12
East Brunswick A	Mast	1.61	2.24	0.58	0.45	0.74	37.45	0.07	0.20
East Brunswick B	Pitched Roof	2.78	3.4	0.26	0.26	0.70	17.44	0.25	0.27
Edithvale A	Mast	3.24	3.69	0.23	0.23	0.71	14.27	-0.02	0.10
Edithvale B	Pitched Roof	3.26	3.66	0.22	0.22	0.71	13.71	0.19	0.20
Seaholme A	Mast	3.33	3.47	0.23	0.22	0.72	15.03	0.03	0.10
Seaholme B	Flat Roof	3.33	3.58	0.23	0.23	0.72	15.71	0.02	0.08
Moonee Ponds B	Flat Roof	2.59	NA	0.29	0.28	0.69	18.52	0.13	0.18
Manningham	Flat Roof	2.70	3.15	0.29	0.28	0.73	19.12	-0.01	0.12
Blackburn	Flat Roof	1.45	1.22	0.42	0.40	0.58	28.88	-0.05	0.11
Williamstown	Light Tower	7.03	6.78	0.14	0.13	0.76	8.91	0.23	0.27
CBD*	Mast	3.94	NA	0.33	0.27	0.95	22.83	0.18	0.27

Table 5: Summary table of Ultrasonic anemometer data
* CBD site is based dataset covering a period of 75 days. All other datasets span between 13 and 21 days.

- There is no clear pattern connecting the readings for average 2D wind speed to the average of 1 minute averaged 3D wind velocity. It is therefore difficult to finely assess the suitability of the CBD site for turbine installation unless further data is gathered from this site.
- High standard deviation of wind direction correlates very well with high average 3D turbulence intensity. This means that sites with relatively large periodic fluctuations in wind velocity are also very likely to have large periodic fluctuations in wind direction. This factor may also assist with design selection.
- High turbulence intensity correlates very well with qualitative assessments of terrain roughness.

As would be expected, higher absolute levels of turbulence (high values of standard deviation of 3D velocity) are found mostly (though not always) at sites with high average wind speeds.

Of particular interest in Table 5 is the comparison of average speed (as measured by the cup anemometers) and average velocity (measured by the ultrasonic anemometers). As discussed in detail in Section 1.5, we would expect the vector nature of velocity averaging to produce smaller values than scalar averaging. This is clearly not the case with the Williamstown and Blackburn sites.

Likely reasons why the ultrasonic anemometer may record a higher value for average velocity than the cup anemometer‘s average speed include:

- The mechanical response characteristics of the cup anemometer cause it not to record zero speed below a critical threshold. The ultrasonic anemometer is, however, much more sensitive. This effect is particularly evident at low wind speed sites (Blackburn).
- The inclusion of the W (upwards) component of wind speed in the calculation of 3D velocity.
- Uncertainty in the measurements produced by both instruments (especially the cup anemometers).

Figure 9, shown overleaf, is a plot of average turbulence intensity calculated over 0.5ms^{-1} bins of average 3D velocity for all the sites included in the resource assessment. This plot provides an interesting counterpoint to Figure 4 on page 19. The less energy abundant sites (Blackburn and East Brunswick) exhibit narrow, sharp wind probability density functions, and also appear to have the highest average relative levels of turbulence intensity.

Another interesting analogue to Figure 4 is the clustering of turbulence trends from the majority of sites into the thin band of turbulence intensity between 0.2 and 0.3. Without further data collection it is difficult to speculate, yet this grouping and clustering observed in Figure 4 appear to indicate regions of typical wind regime behaviour for sites with clear aspects in rough urban.

Of particular note when considering figure 9 is that the higher speed right hand end of each curve is based on significantly less samples than the lower speed left hand end (due to the nature of wind probability). Because of this feature, we observe zig-zagging on the right hand extreme of some of the plots that is unlikely to be representative of long term average turbulence conditions at the site. For a clearer picture of turbulence behaviour, refer to the site specific plots of turbulence intensity found in the appendix of this report.

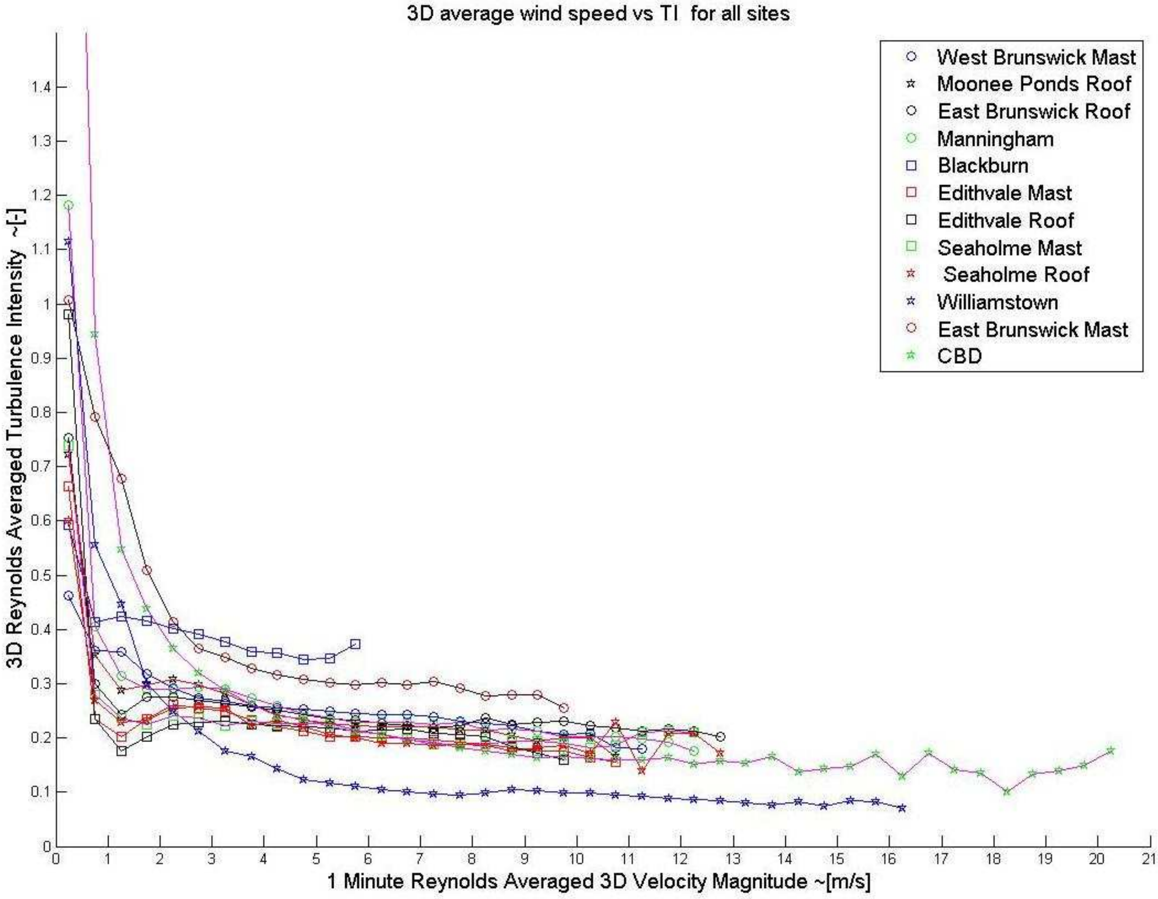


Figure 9: Binned average turbulence intensity vs. 3D wind velocity for all sites

The analysis of turbulent wind behaviour in urban areas has become a burgeoning area of research, as ever more specific niches for boutique MWT designs are identified. From the point of view of this wind resource assessment, the details of turbulent fluctuations are most pertinent when they relate to sites suited to MWT installation.

2.10 Turbulence at Williamstown and the CBD

The geography and surrounds of the CBD and Williamstown sites are in marked contrast. The Williamstown site is located next to a sports oval and lies within 30 meters of Williamstown Beach. The CBD site too is surrounded largely by open air, with the closest building of similar height more than two building heights further north.

As discussed in detail in Section 1.7 of this report, more wind data is needed to create a Weibull probability distribution that is indicative of available wind power. However, clear trends in the turbulence behaviour at this site may be deduced from the data. The 1 minute averaged absolute levels of turbulence at the CBD site are greater than at any other site in the study (0.98 ms^{-1}). This is especially striking in the context that the Williamstown site probably has higher average wind speeds and has significantly lower absolute turbulence values (0.76 ms^{-1}). Overleaf is a plot of turbulence intensity (averaged over 0.5 ms^{-1} bins) vs. 1 minute average 3D wind velocity. In order to clarify the effect of the observation period on the turbulence trend (much more data is available for CBD), data from the CBD site covering the Williamstown observation period is also plotted on the same axes.

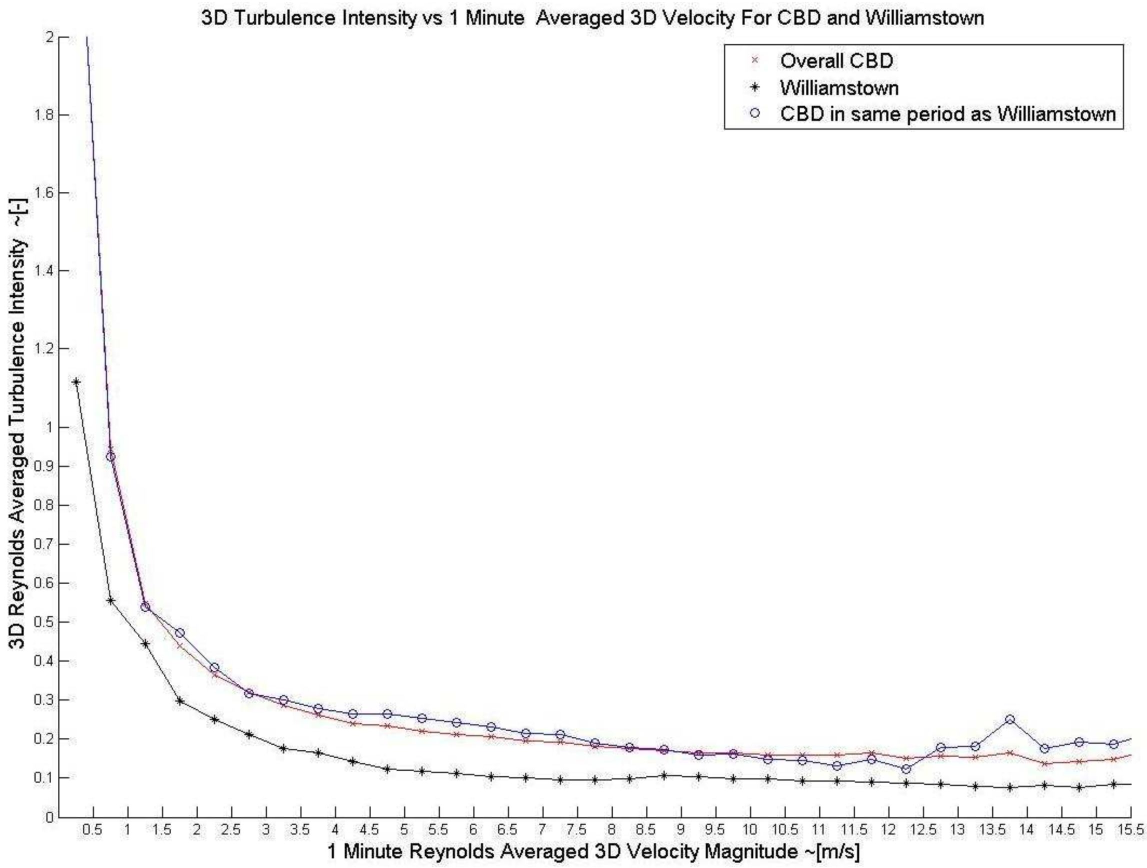


Figure 10: Binned average turbulence intensity vs. 3D wind velocity for CBD and Williamstown

Clearly the CBD location is significantly more turbulent than the Williamstown site across a broad range of speed conditions. It is also notable how closely the two week and 75 day trends match for the CBD site (with the exception of the right hand side of the plot where occurrence counts are very low). The level of similarity between these two curves suggests that a two week period of high speed wind measurement may be sufficient to gain a reasonable basis for typical turbulence behaviour. This correlation may also act to strengthen the credibility of the other deduced trends presented in this section.

The plot in Figure 10 shows us what we would expect: in a high rise urban environment wind flow will tend to impact against the body of the high rise structure and stagnate, before slipping around or over the top of the building. Turbulent vortices are likely to form as the flow is deviated around the obstruction, as anyone who has stood on the edge of a tall building will attest. The dynamic nature of these vortices will produce the varying magnitude and directional flow conditions described by the ultrasonic anemometer data.

Williamstown however, represents a terrain type much closer to that found in the realm of commercial wind energy. Flow appears to be mostly laminar, exhibiting relatively low 1 minute averaged variation in wind velocity and direction. That the Williamstown site has the lowest 1 minute averaged turbulence intensity of any of the sites in the resource assessment is especially significant given that it is also the most energetic of the sites.

There is very little else that can be concluded about the effects of turbulence on MWT performance until further work has been undertaken on how to incorporate turbulence measurements into MWT performance simulation. Without standardisation, the primary value of this data is to corroborate qualitative expectations on turbulence levels by substantiating the claim that open coastal areas are less turbulent than high-rise urban environments.

3. Areas of Interest for Further Research

Micro wind turbines are not yet a mature technology, and the small turbine marketplace abounds with products of contrasting style and design. It is not yet clear what the broader environmental value of MWT is to domestic communities, and much work still remains in discovering the niches where this technology is likely to function productively.

Of the two sites singled out in this report as having wind power potential, the Williamstown and CBD sites, only the latter has a truly urban character. The Williamstown site has a wind profile similar to those found in open regional areas, where years of engineering practice have produced optimised turbine designs and clear siting guidelines. It is at urban locations like the CBD site, with high speeds and high relative levels of turbulence, that a technological niche for new turbine designs may be available.

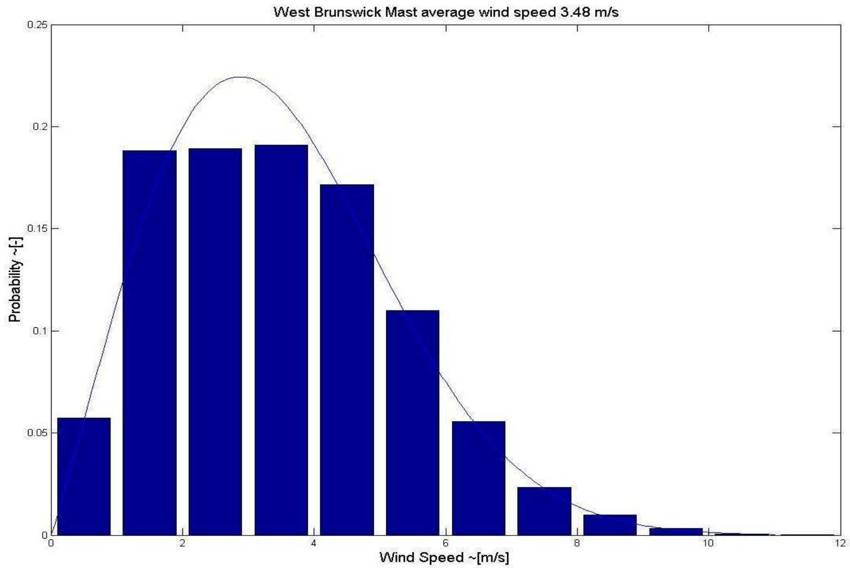
Many ideas for possible future research emerged from this study of wind regimes in suburban Melbourne. It is recommended that further effort in this area should focus on:

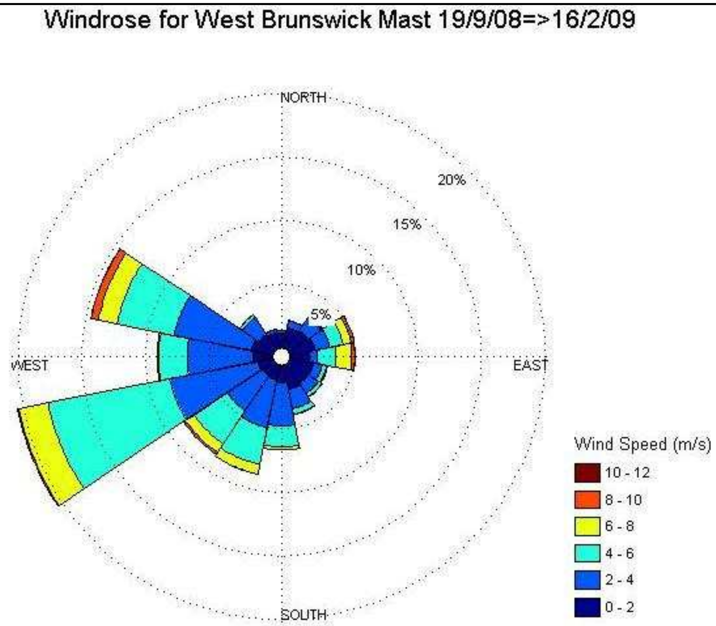
- The accuracy of derived Weibull curves and turbine power curves in predicting actual electrical output from operating turbines through field trialling of MWTs at suitable sites. Suitable urban sites are likely to be found at significant heights above the built up urban terrain and in cleared and coastal areas of the domestic landscape.
- A methodology of scaling MWT output modelling to include the influence of turbulence characterisation parameters. This area of research could include taking turbulence measurements from sites involved in field trials.
- Further data collection to investigate the extent of wind power potential at high rise urban locations.
- The suitability of HAWT and VAWT designs for use at locations similar to those identified as promising wind energy sites in this report.
- Establishing a standard for measuring turbulence in urban environments, including design-guiding specifications for acceptable turbulence limits. Further work on incorporating turbulence into turbine simulation would greatly benefit from implementation of standardised methodologies for measuring flow variation.

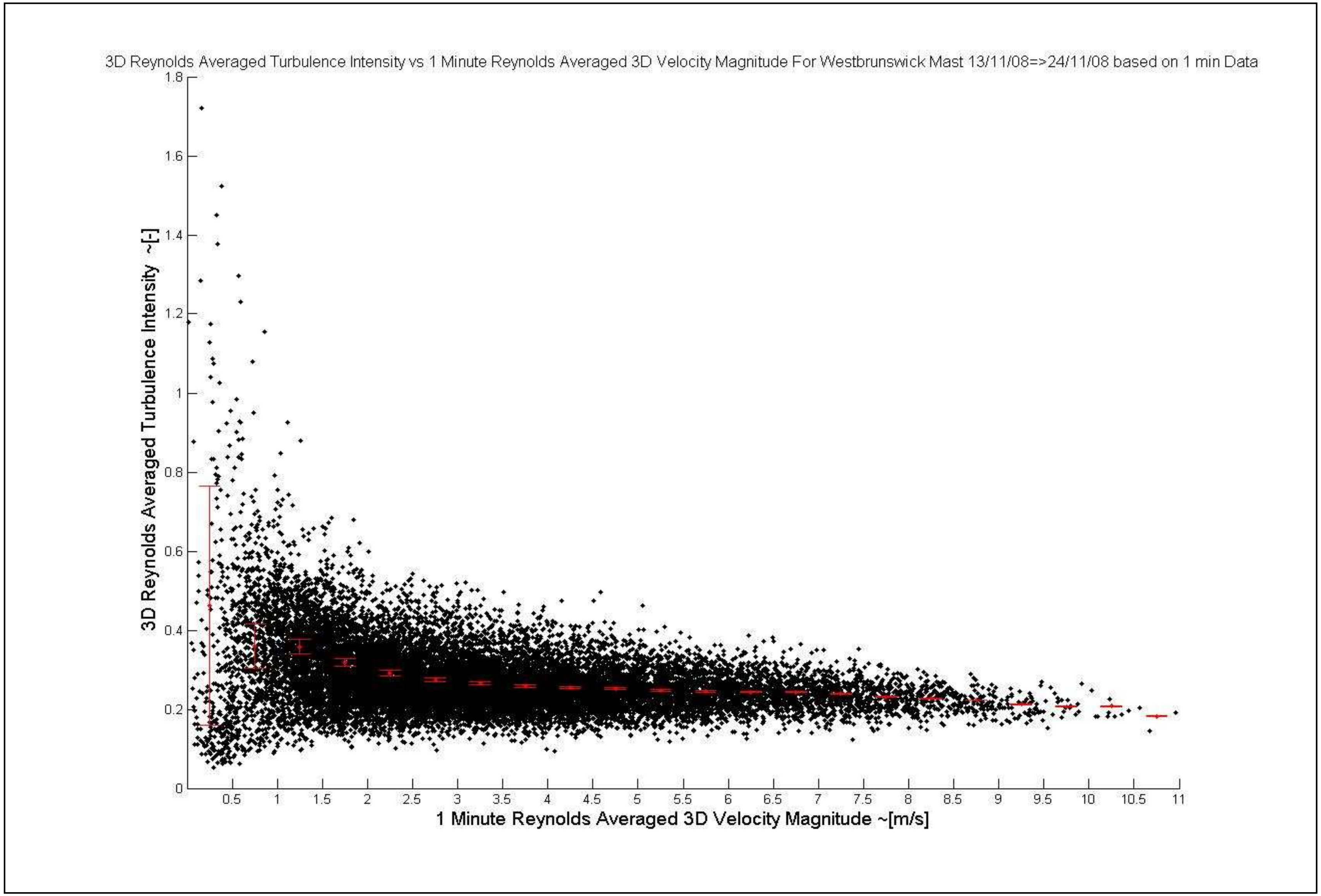
i. West Brunswick Mast

This anemometer was installed on a 10 m mast in an open area on the western side of the large pitched roof dwelling. This site lies about 750m east of the Western Link section of Citylink's Tullamarine Freeway and is on the eastern lip of Moonee Ponds Creek.

Dwellings to the south of the mast have pitched roofs at a height about 1 meter below the top of this mast. Apart from this there are no significant local obstructions to wind flow at this site.






3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Westbrunswick Mast 13/11/08=>24/11/08 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
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1.2
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7.5
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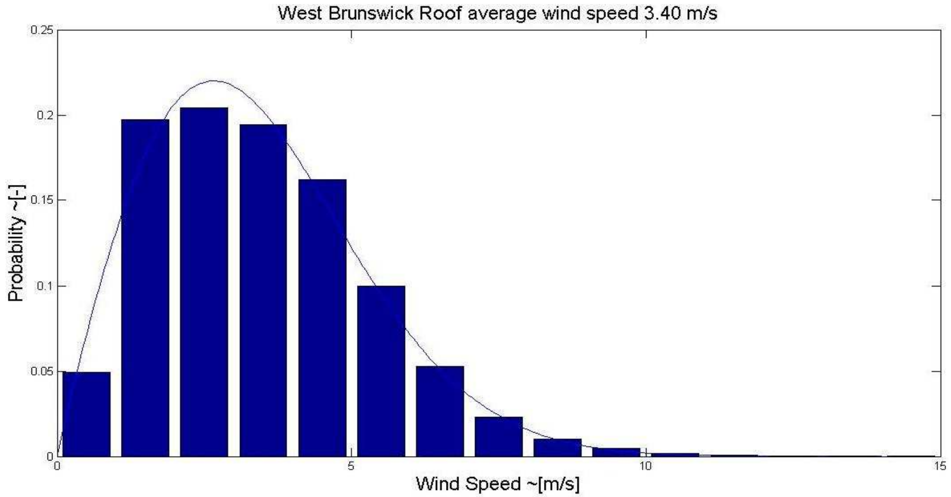
8.5
9
9.5
10
10.5
11

ii. West Brunswick Roof

This anemometer was installed at a height of about 10m, 1m above a chimney on the south end of the building's central pitched roof section.

Two apartments within 20m of the pitched roof section on which the anemometer is installed have roofs around 1m below this height.

There are no other significant nearby obstructions to wind flow in the area at anemometer height.

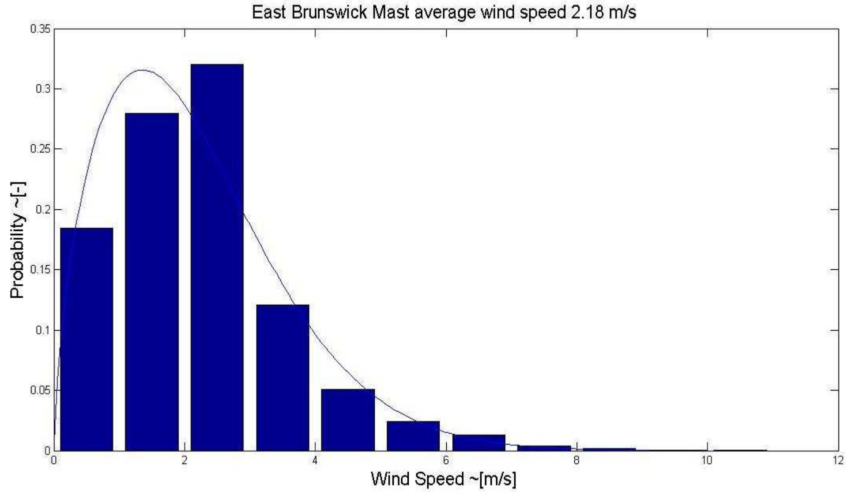


iii. East Brunswick Mast

This property is situated in a bend on the western side of Merri Creek. The yard area of the house slopes down towards the creek bed.

Due to the slope the 10m mast installed in the yard area was about 2.5m below the roof of the house and the neighbouring house to the west. This sheltering of this instrument by the nearby dwellings is likely to be responsible for the high levels of turbulence recorded at this site.

The air around this mast installation was clear of obstructions to the north and east.



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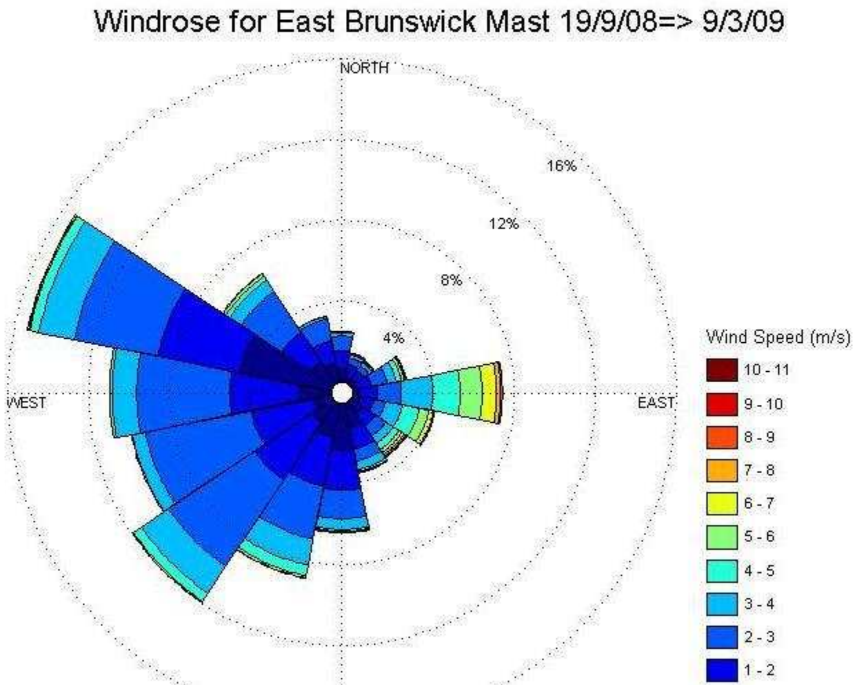

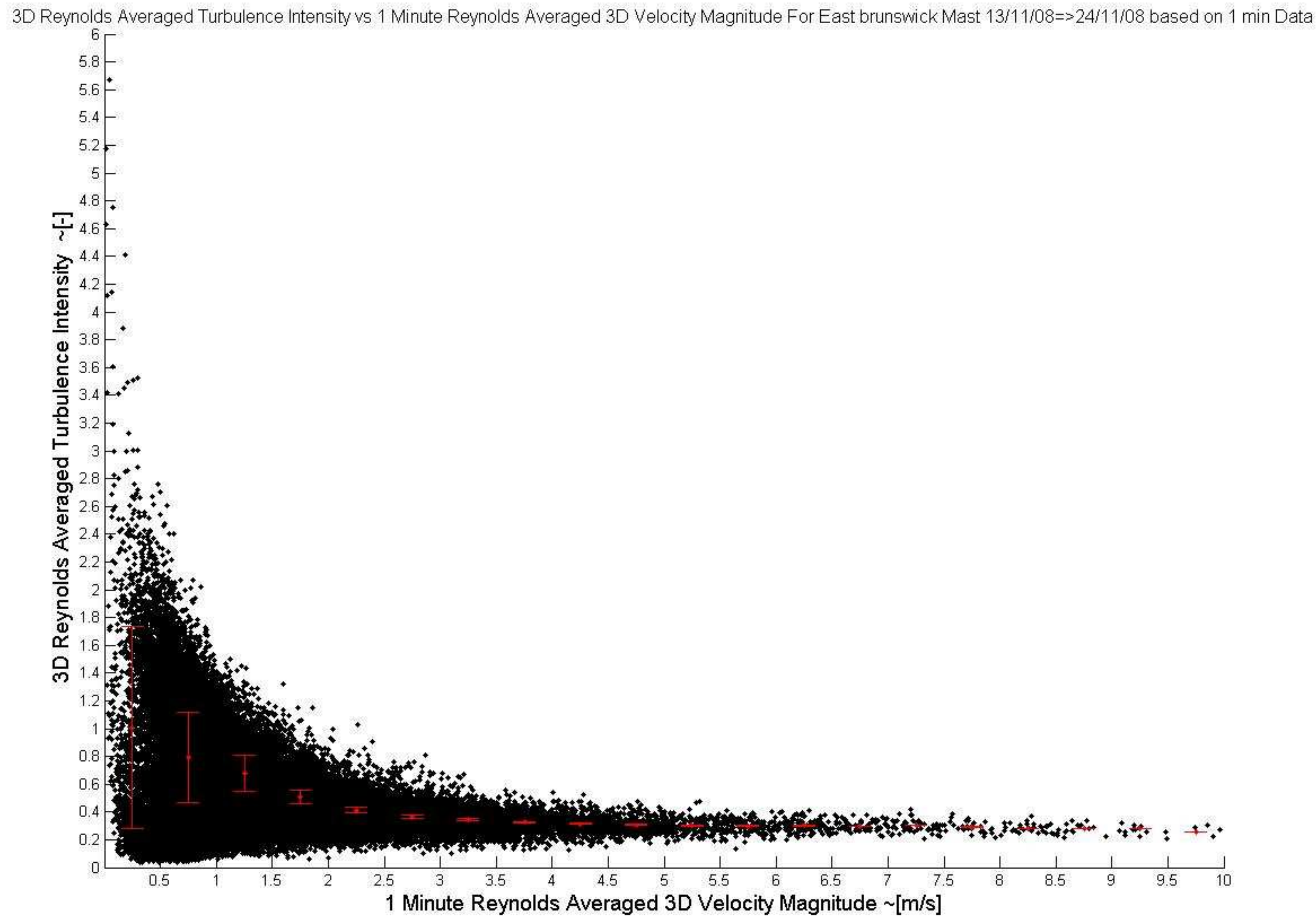
3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For East brunswick Mast 13/11/08=>24/11/08 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
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1.6
1.8
2
2.2
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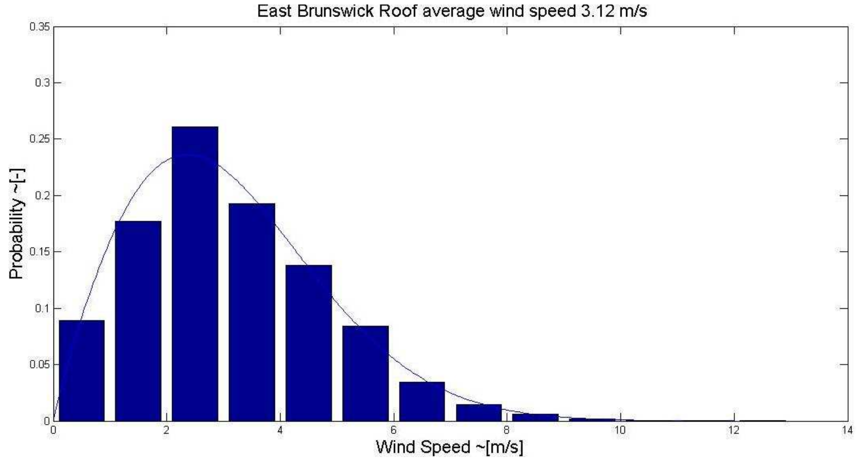
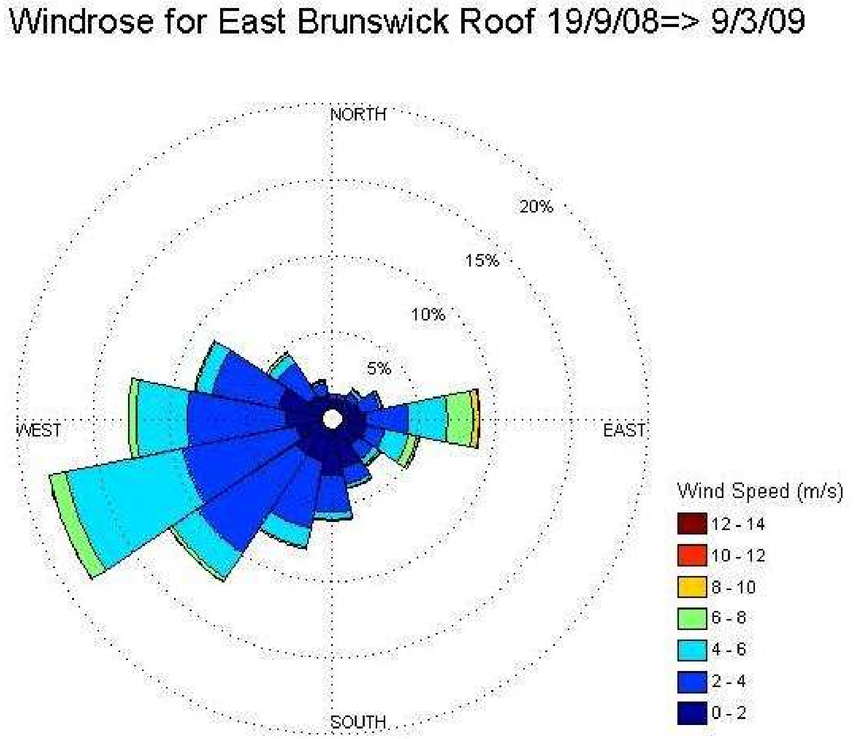
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10

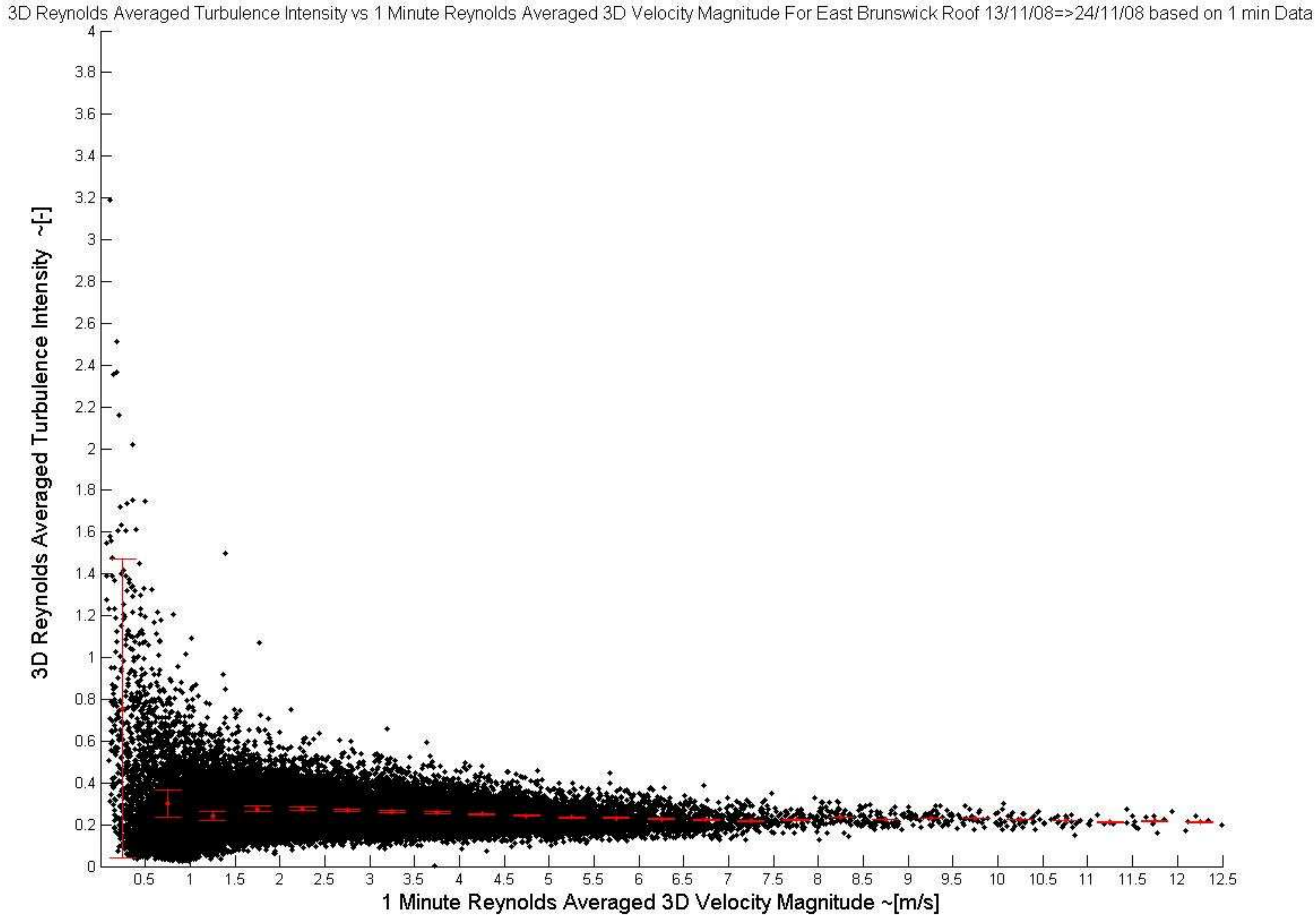
iv. East Brunswick Roof

This instrument was installed at a height of about 11.5m, around 1m above the pitched roof of the dwelling. The environment around the house was relatively clear at this height, with no significant obstructions to interrupt or perturb air flow.

This site is located on a cul de sac at the end of its street where it is among the tallest houses.





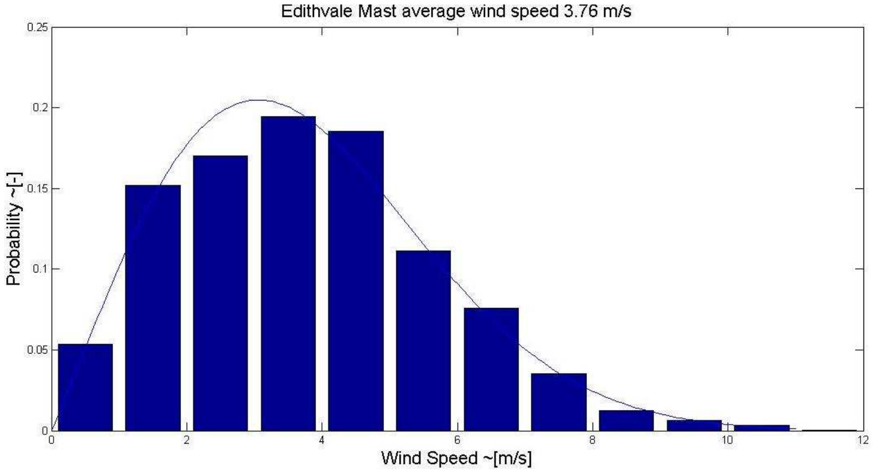

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For East Brunswick Roof 13/11/08=>24/11/08 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5

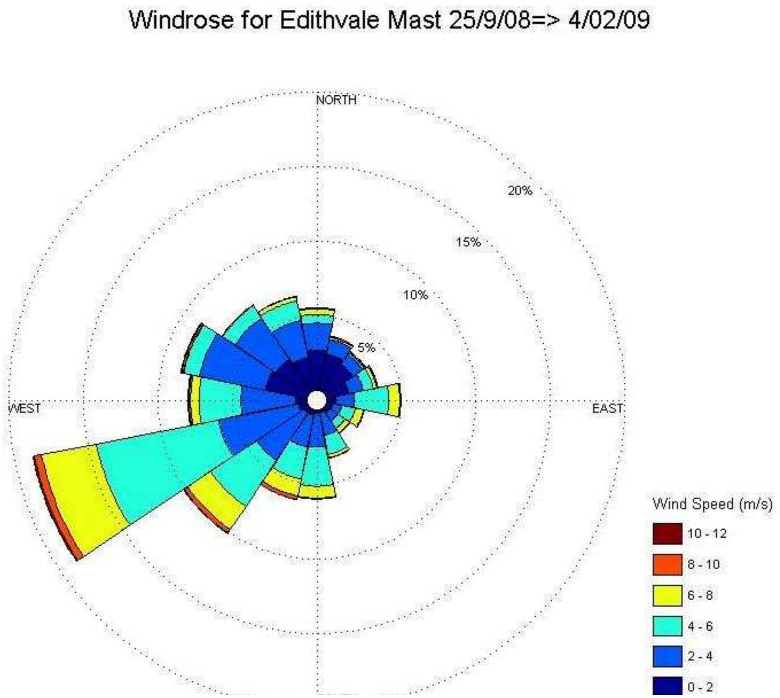
v. Edithvale Mast

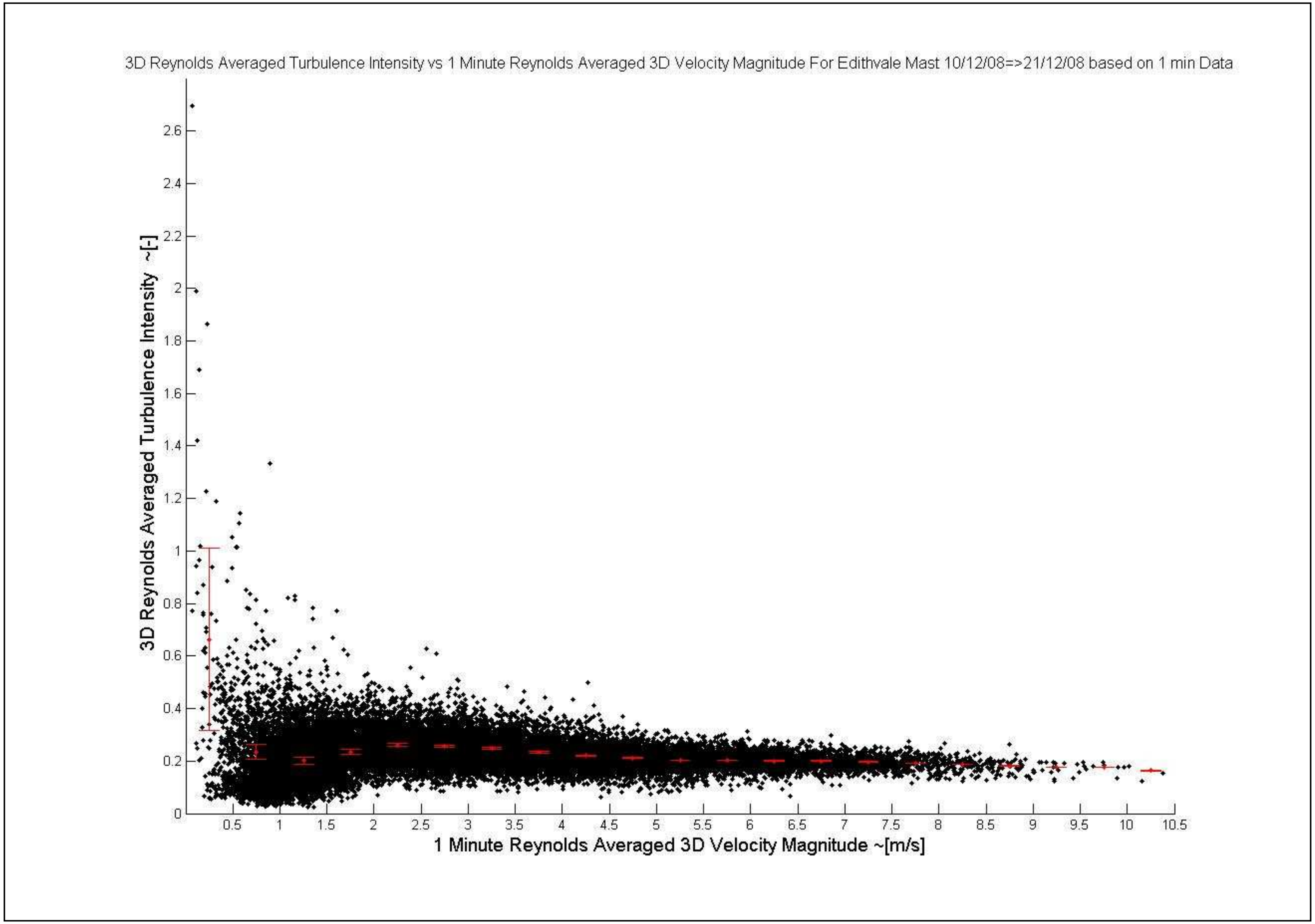
The mast at this site is installed in the backyard of a property located around 400m from Edithvale Beach.

The instrument on the top of the mast was positioned at a level about 2m above the dwelling on the property.

There were no substantial obstructions in the vicinity to shade this instrument from wind flow.





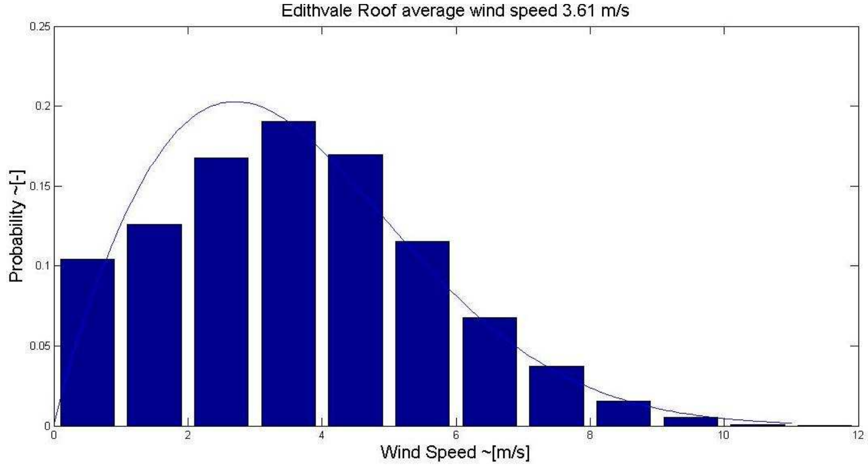


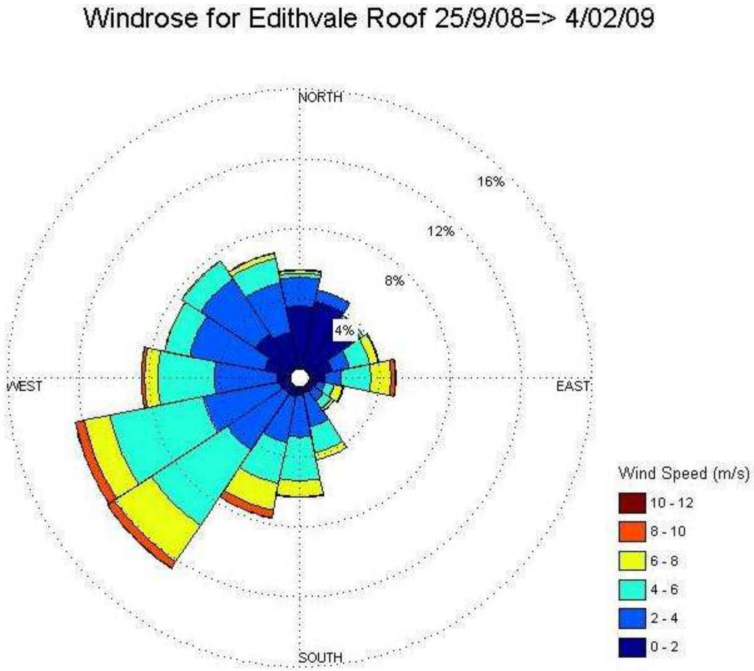
3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Edithvale Mast 10/12/08=>21/12/08 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]

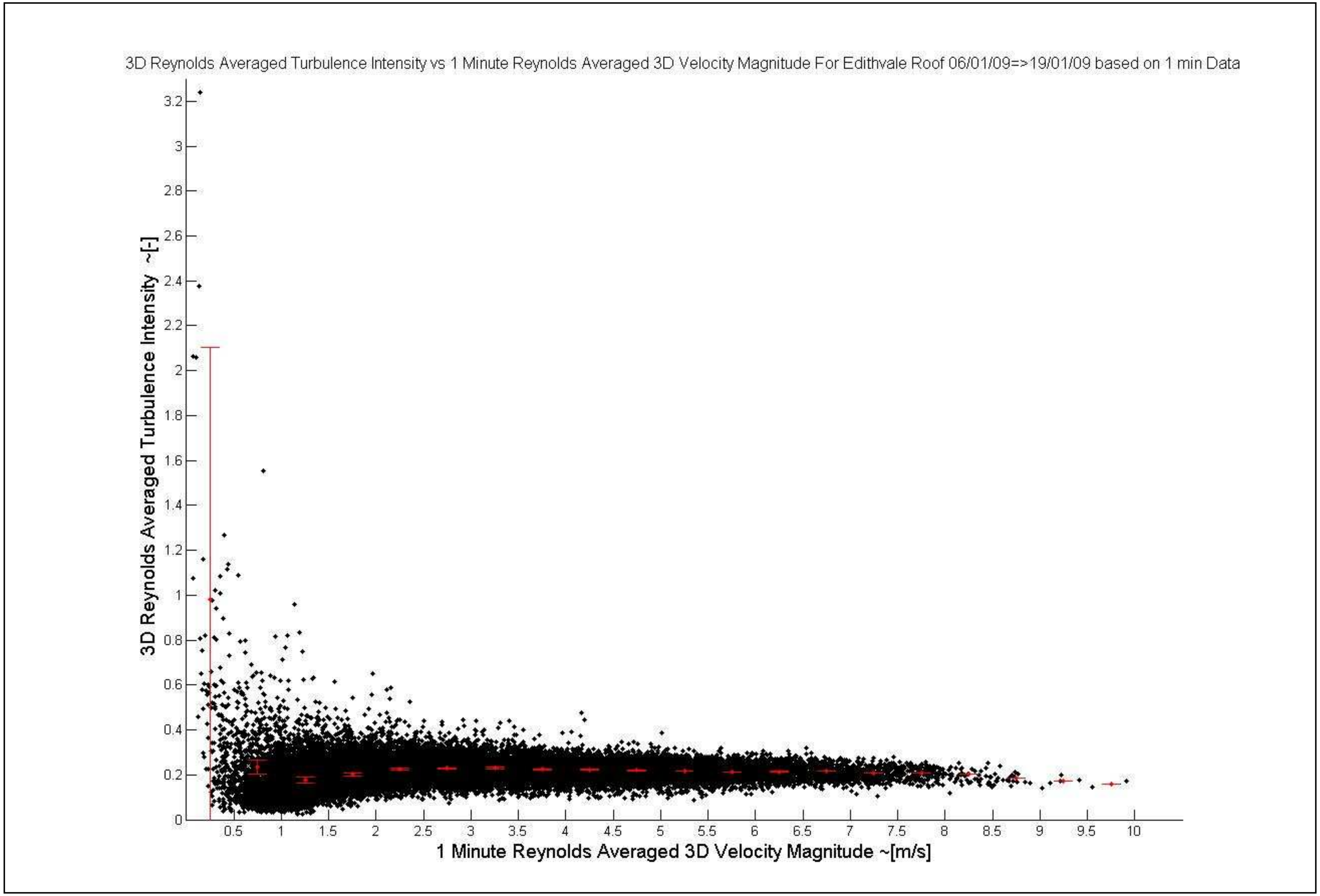
vi. Edithvale Roof

The pitched roof of this site lies about 8m above ground level, with the anemometer installed at a height of about 10m above the ground on the western roof of the building.

The air space around the house is clear of obstacles at this height. In the street in front of the house a pair of trees of around 8m in height although the roof instrument did not appear to experience more turbulence than the anemometer on top of the mast in the yard.

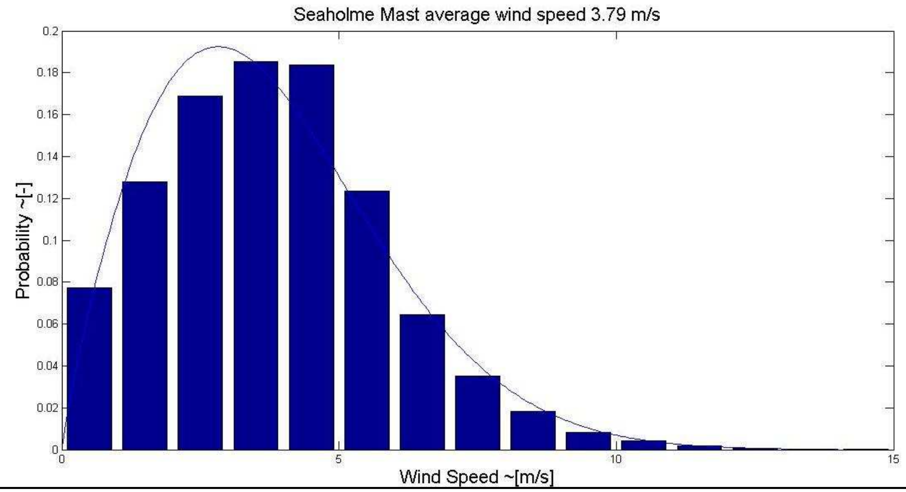


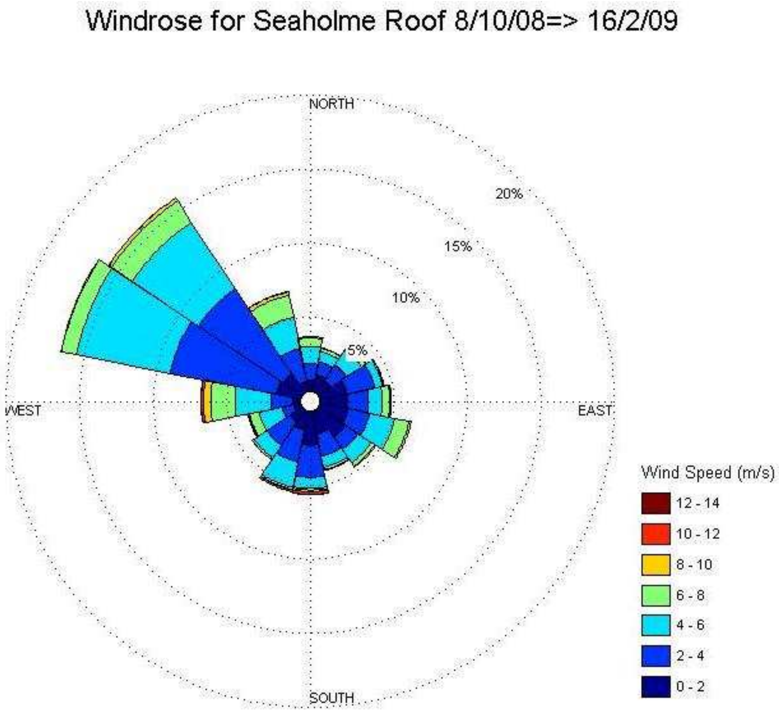


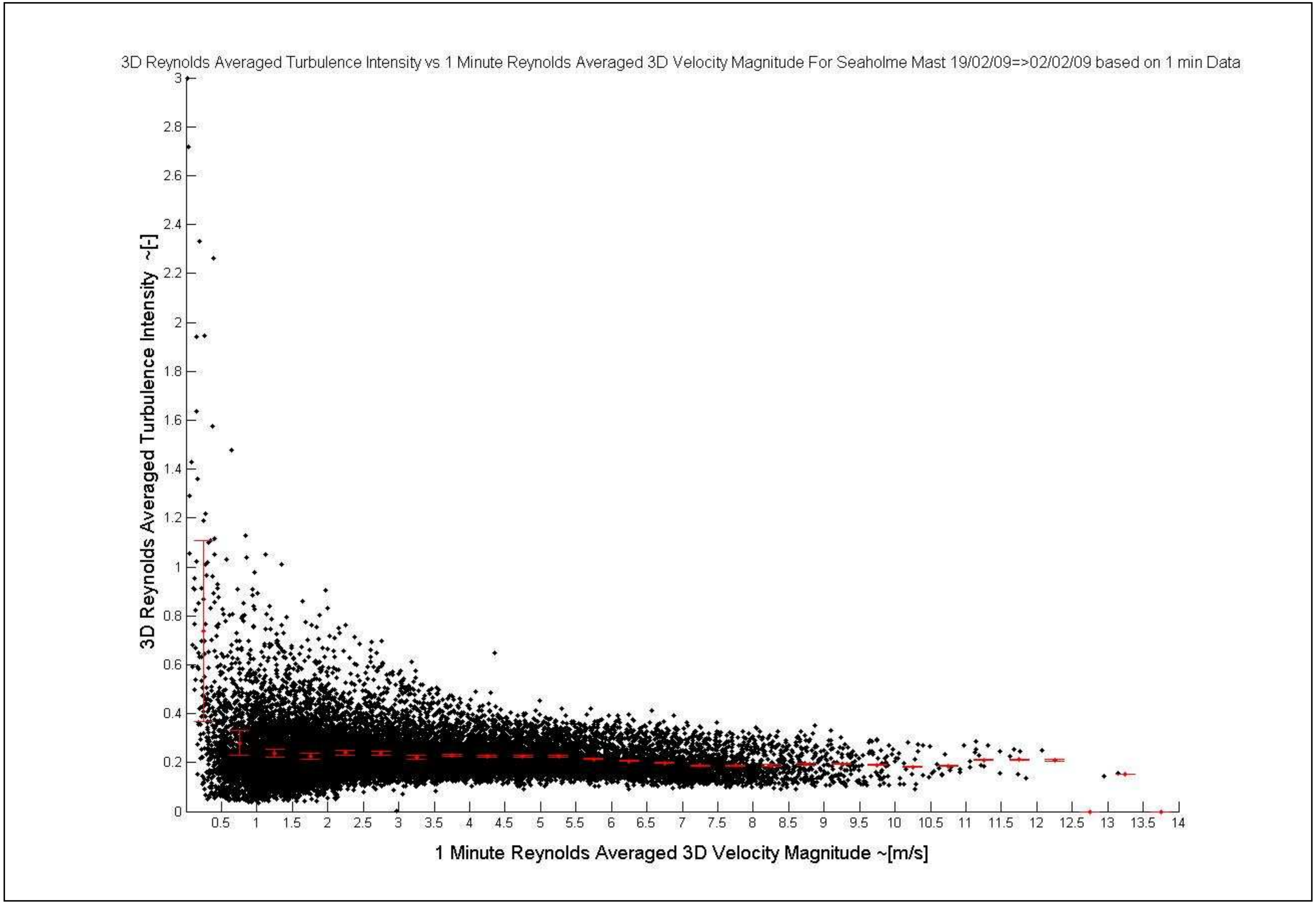

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Edithvale Roof 06/01/09=>19/01/09 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]

vii. Seaholme Mast

This site is located on the beachfront esplanade at Seaholme. The mast was installed at a height of 8m above a 2m shed in the backyard are of the house, bringing the anemometer height 10m above the ground. There are no large features hindering air flow in any direction at this site.



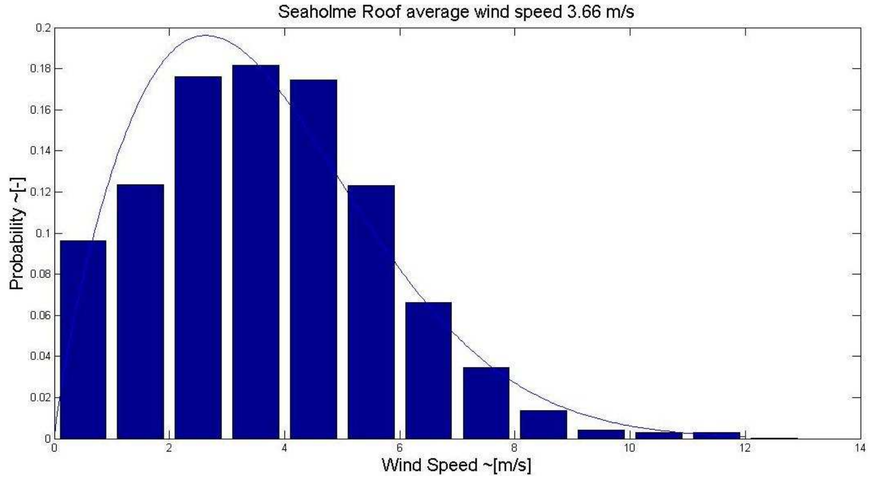


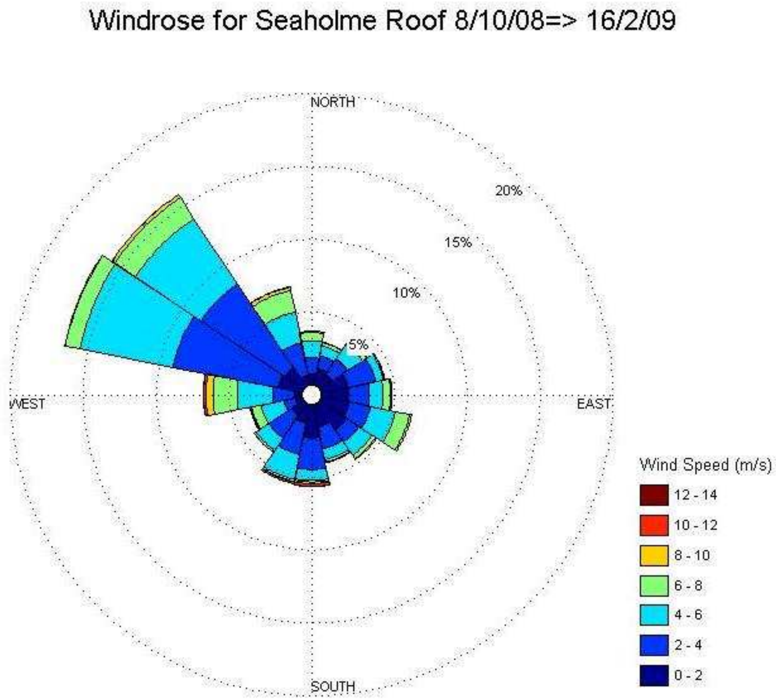

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Seaholme Mast 19/02/09=>02/02/09 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13
13.5
14

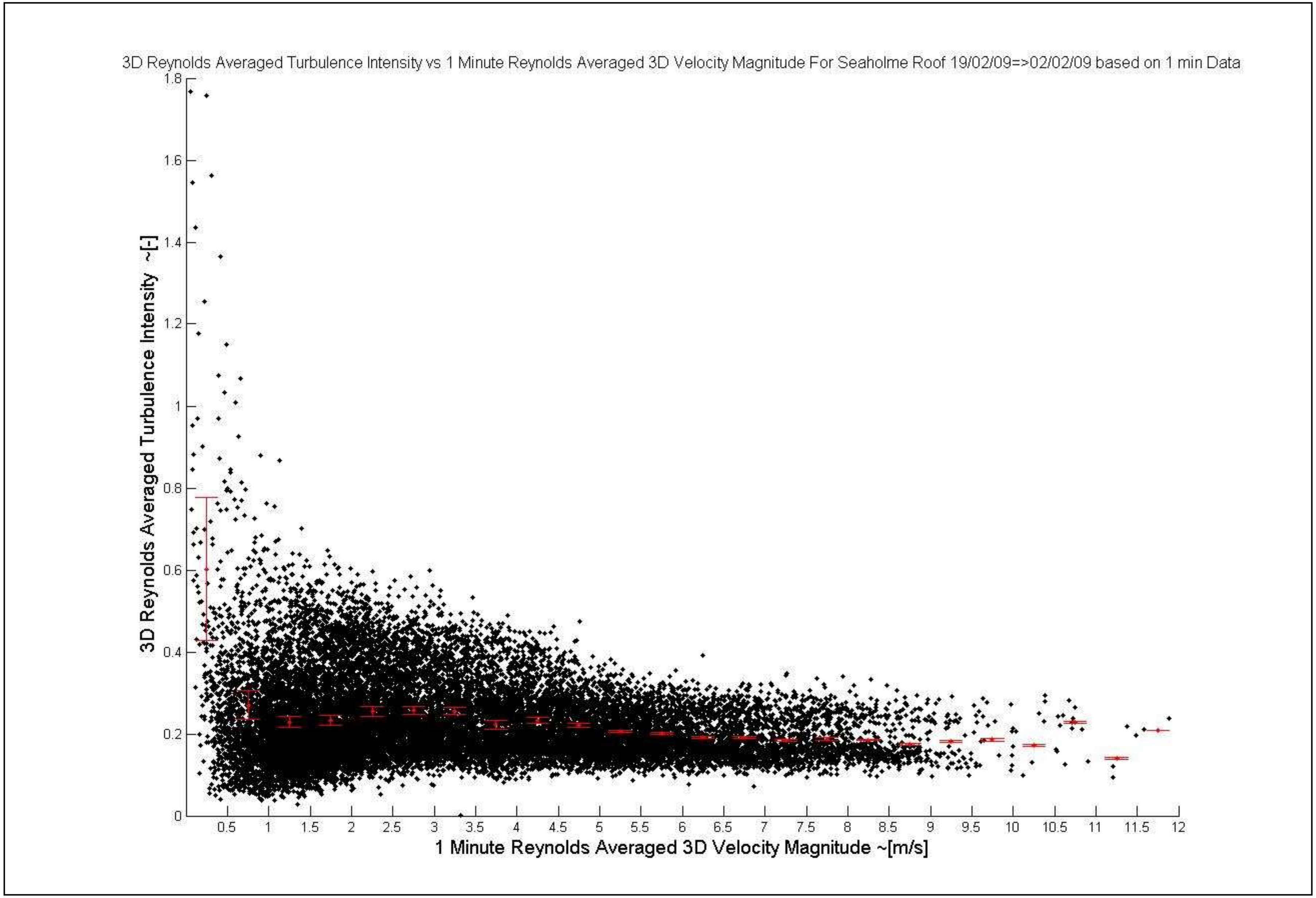
viii. Seaholme Roof

This anemometer was installed at a height of 2m above the 8m high flat roof of the double storey Seaholme dwelling.

This site was one of the most wind exposed locations in this study, facing out towards the open expanse of Port Philip Bay and clear aspects in all directions



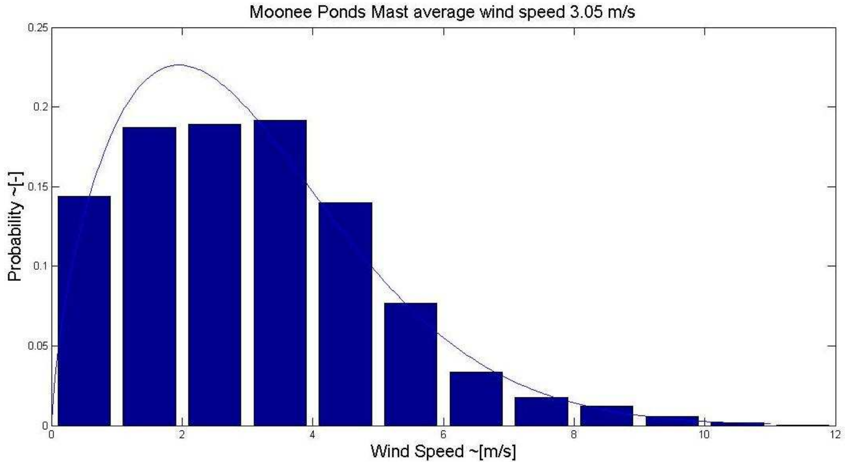


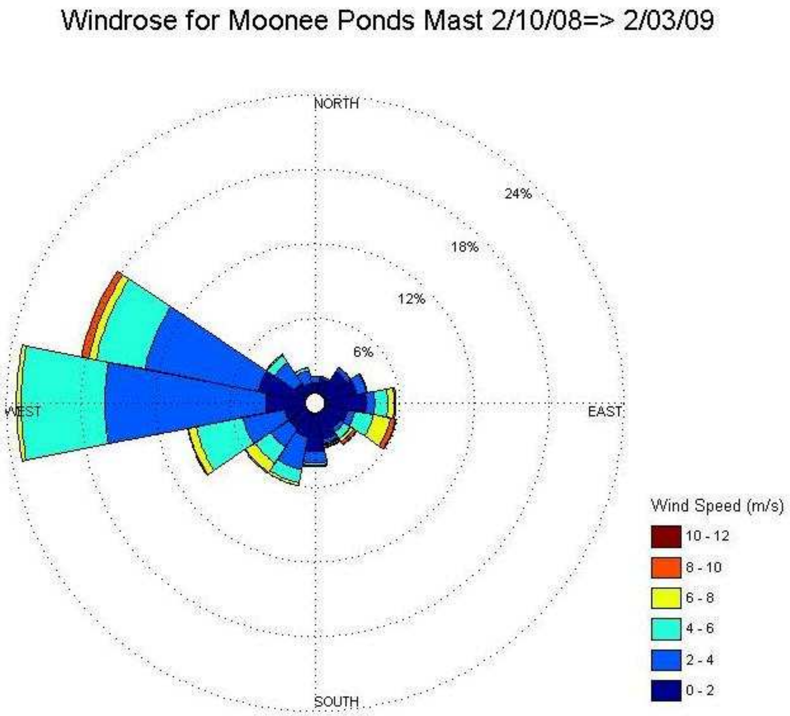

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Seaholme Roof 19/02/09=>02/02/09 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12

ix. Moonee Ponds Mast

This Moonee Ponds property lies on the west side of a ridge with Moonee Ponds Creek to the east and the Maribyrnong River to the west.

The property is on a slope with the yard area at the back of the dwelling at a lower elevation than the house itself. The mast was installed at a hight of 10m, at 8m above the roof of a 2m high flat roofed shed/storage room.

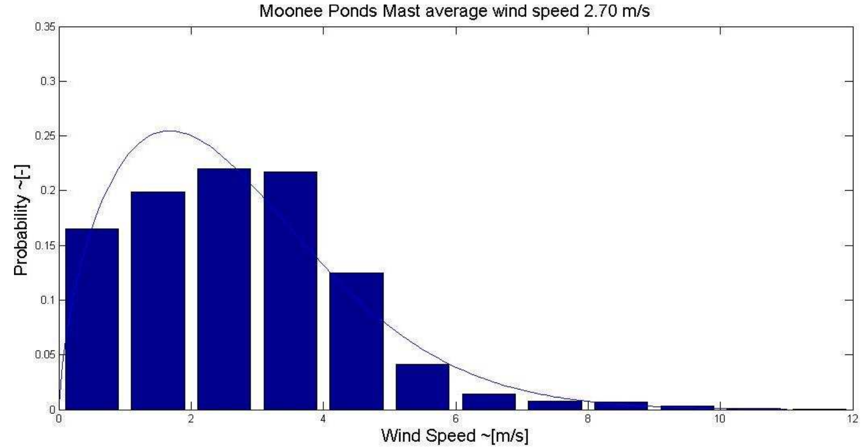


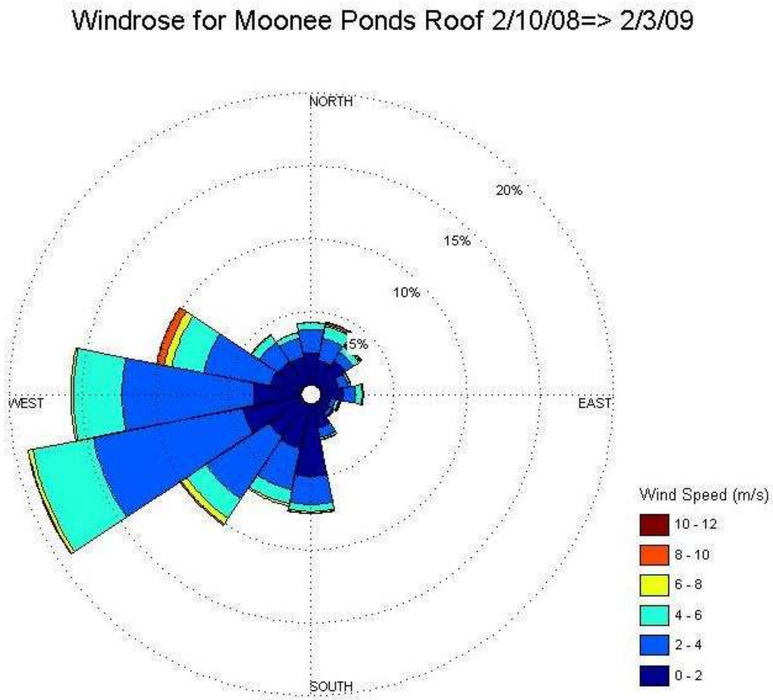


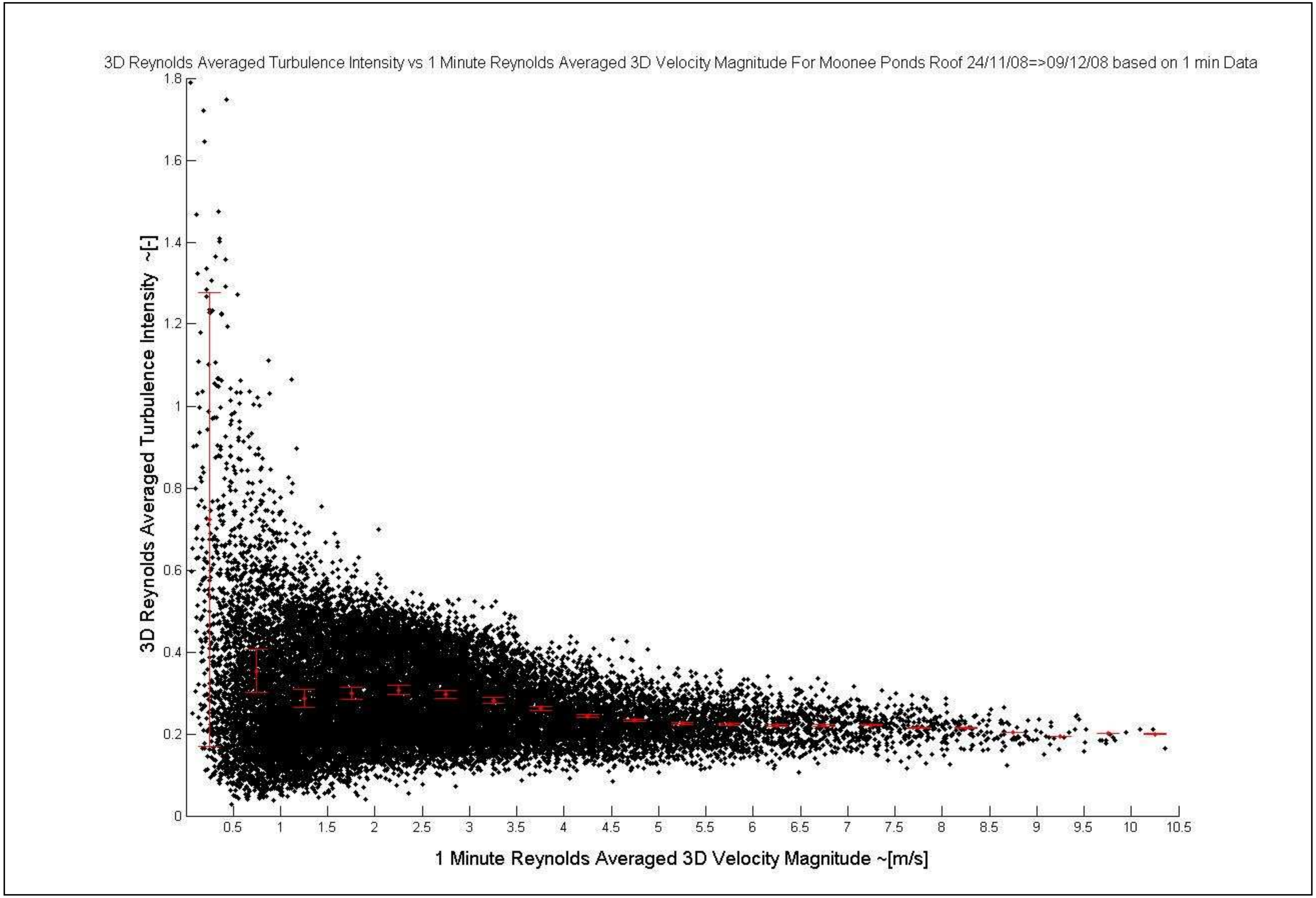
x. Moonee Ponds Roof

This anemometer was installed at a height of about 7.5m at 1m above the flat roof of the house. This location has clear sightlines at this height, with the exception of a pair of 7.5m tall trees encroaching on the south west corner of the lot.

The roof on which the anemometer was installed had not yet been built when the satellite photograph below was taken.



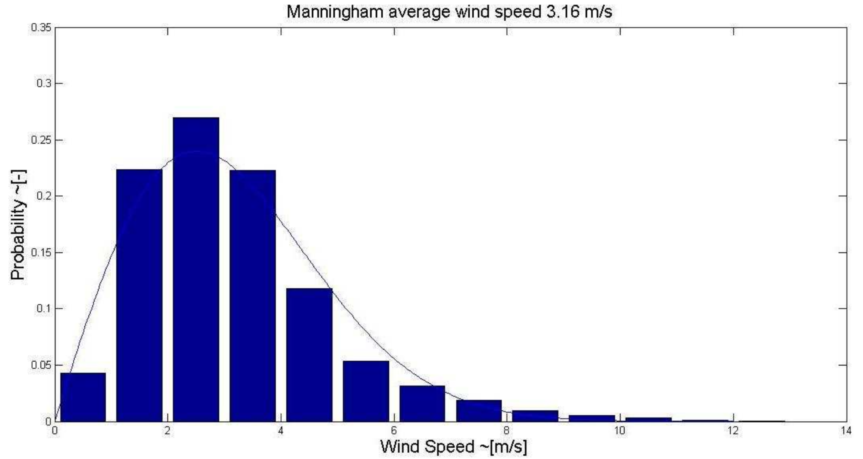


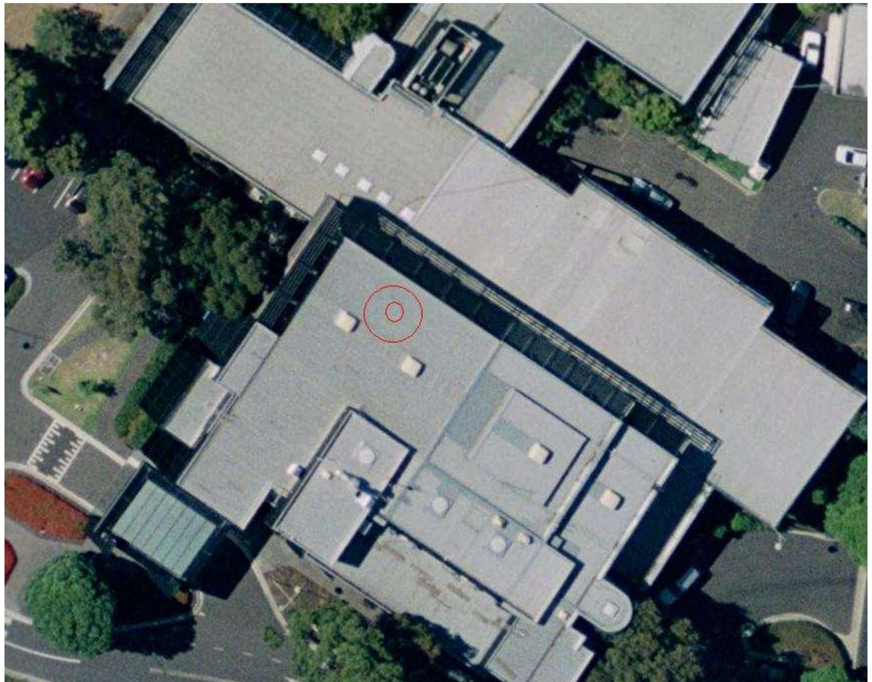

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Moonee Ponds Roof 24/11/08=>09/12/08 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5

xi. Manningham

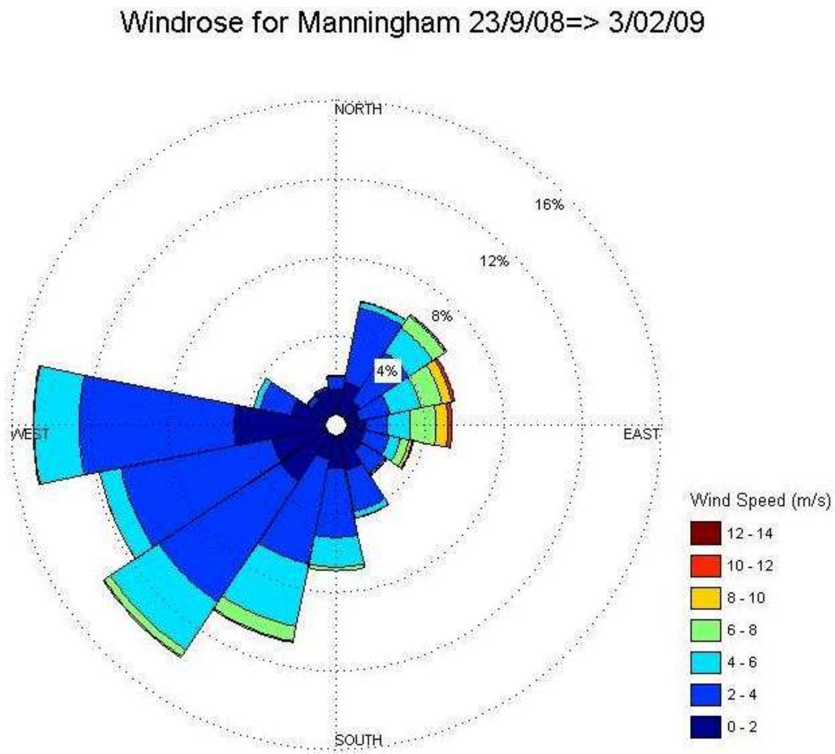
The Manningham site lies on top of an office complex on the south bank of Koonung Creek. The anemometer was installed on the flat roof of the building at a height of about 16m above ground level on a 3m mast.

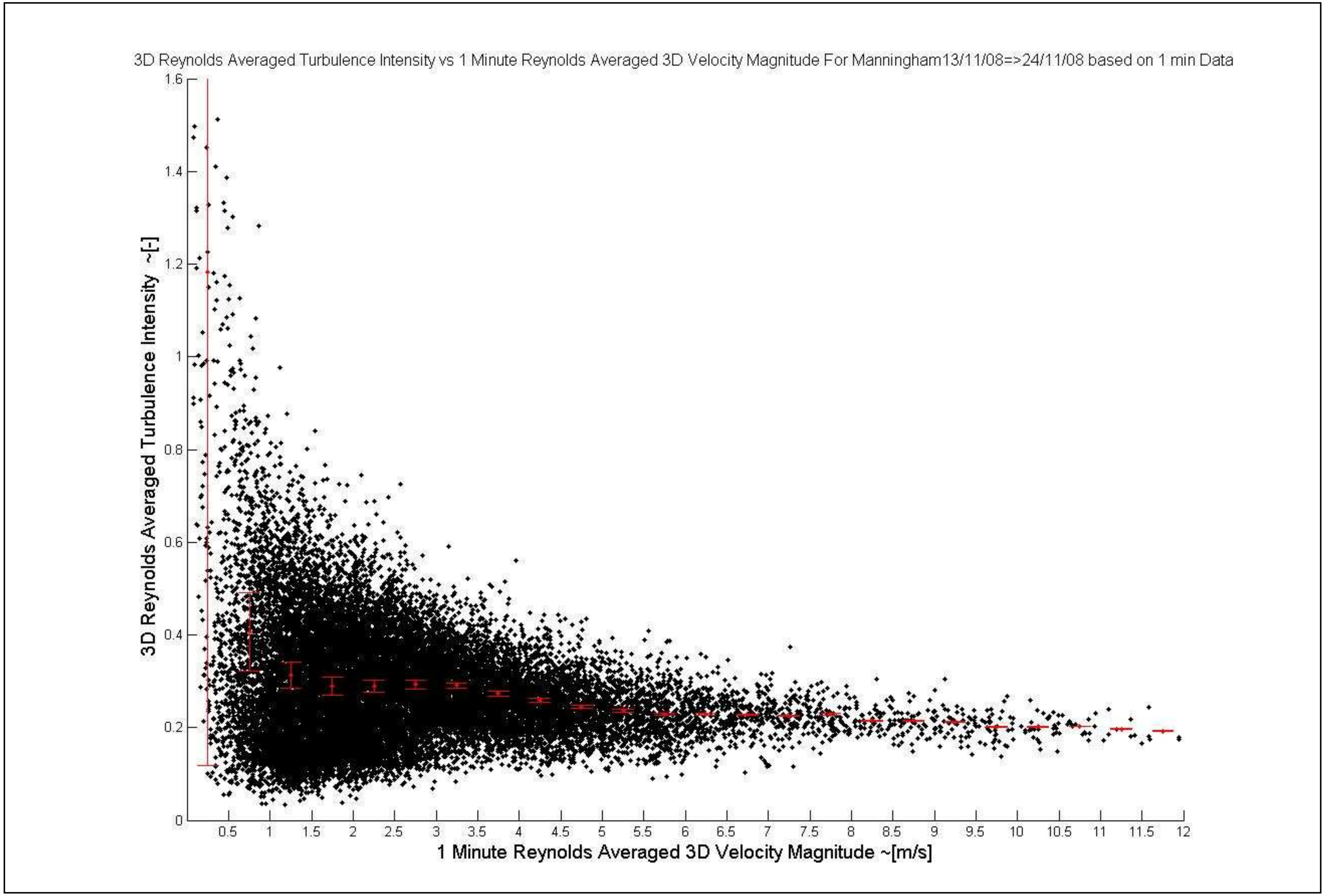
The northern aspect of the site is very clear for many kilometres, although there are individual trees within 40m at the anemometer height to the north west, south and south east. There is a mobile phone tower about 50m away to the north east of the anemometer extending beyond the height of the building.





©2009 Google-Imagery ©2009 Sinclair Knight Merz & Furgo

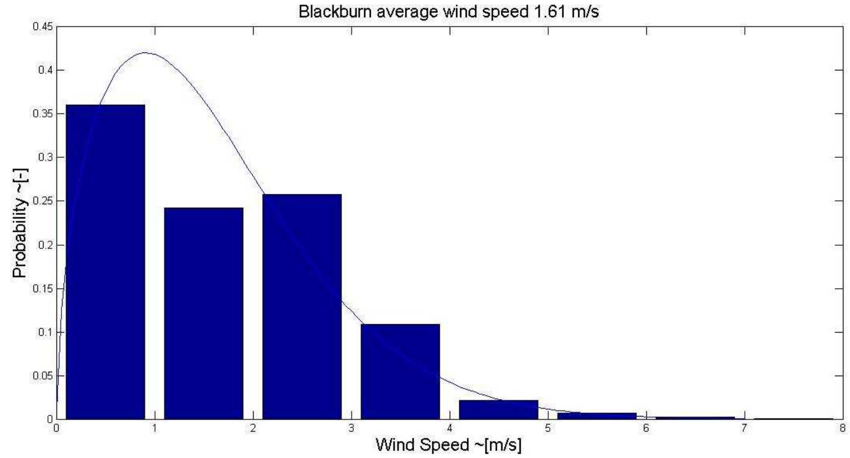


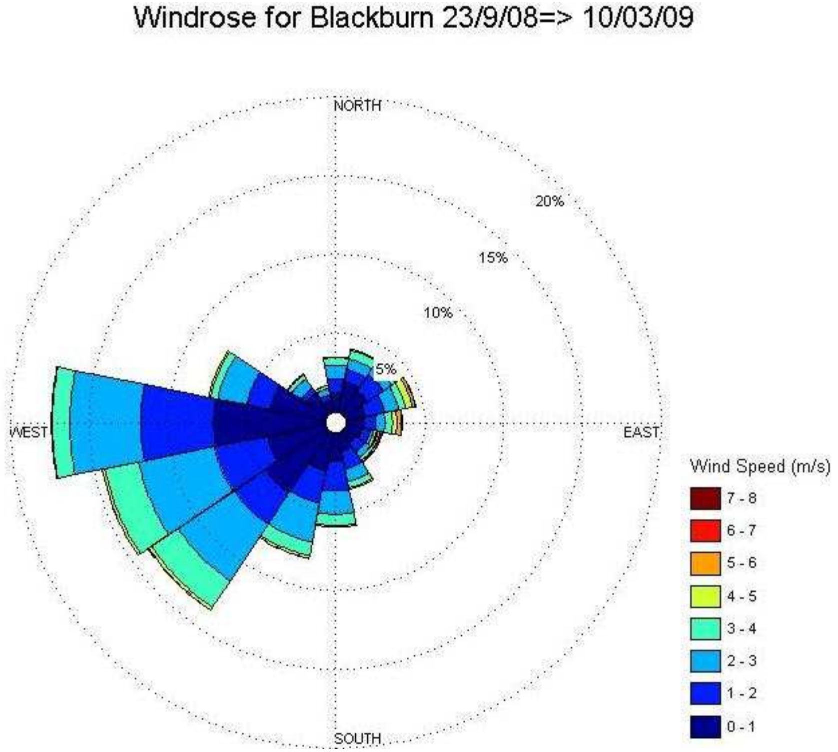

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Manningham13/11/08=>24/11/08 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12

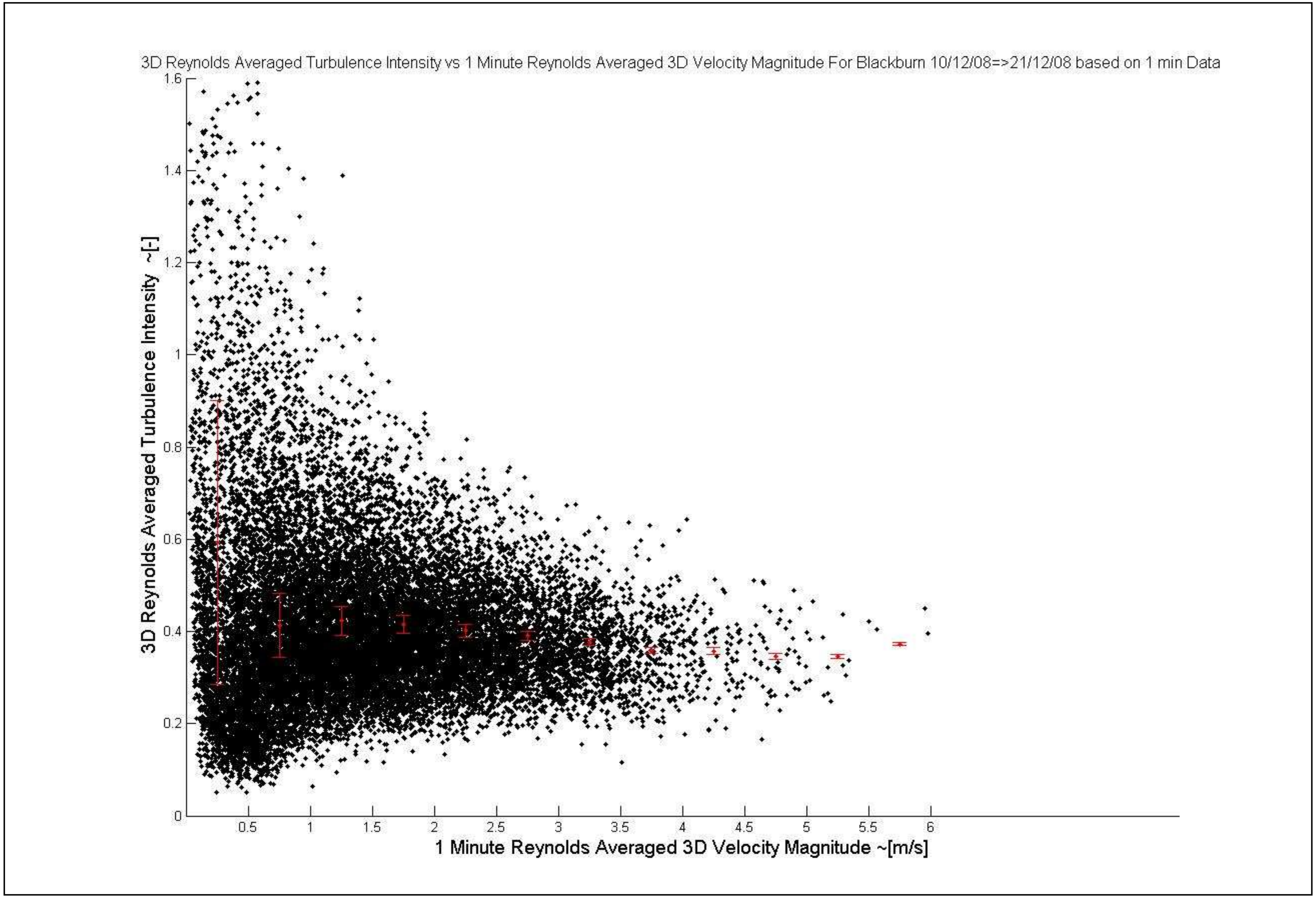
xii. Blackburn

This flat roofed site is located about 2km north west of Blackburn lake and is within suburban region of low relative elevation. The site has a backyard that slopes away from the house. This anemometer was installed at a height of about 9m above ground level and 2m above the single storey house's flat roof.

Sightlines around the house are clear except 50m away to the north east of the anemometer where trees reach beyond the building's height.



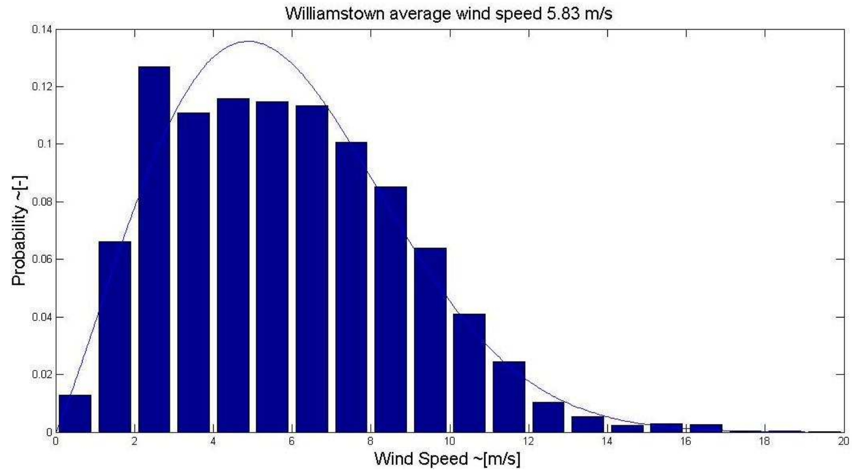


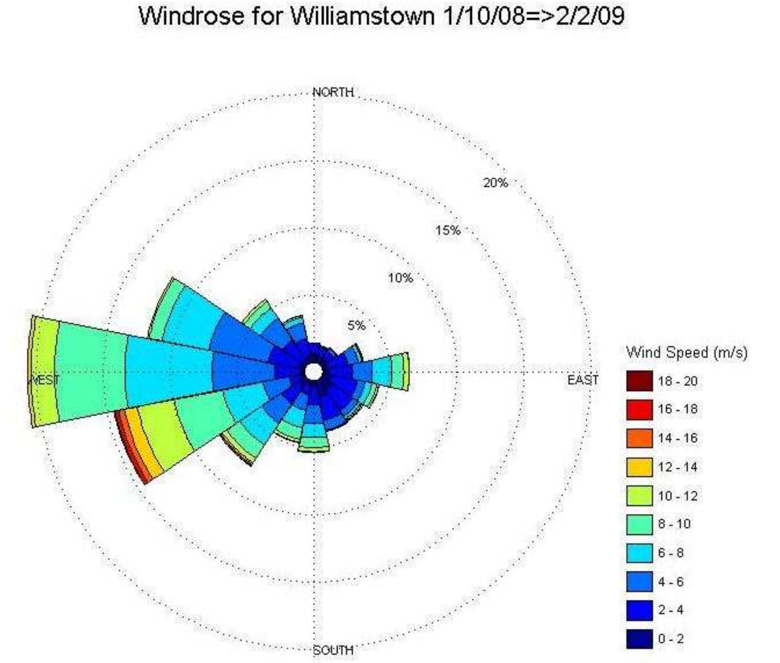

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Blackburn 10/12/08=>21/12/08 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6

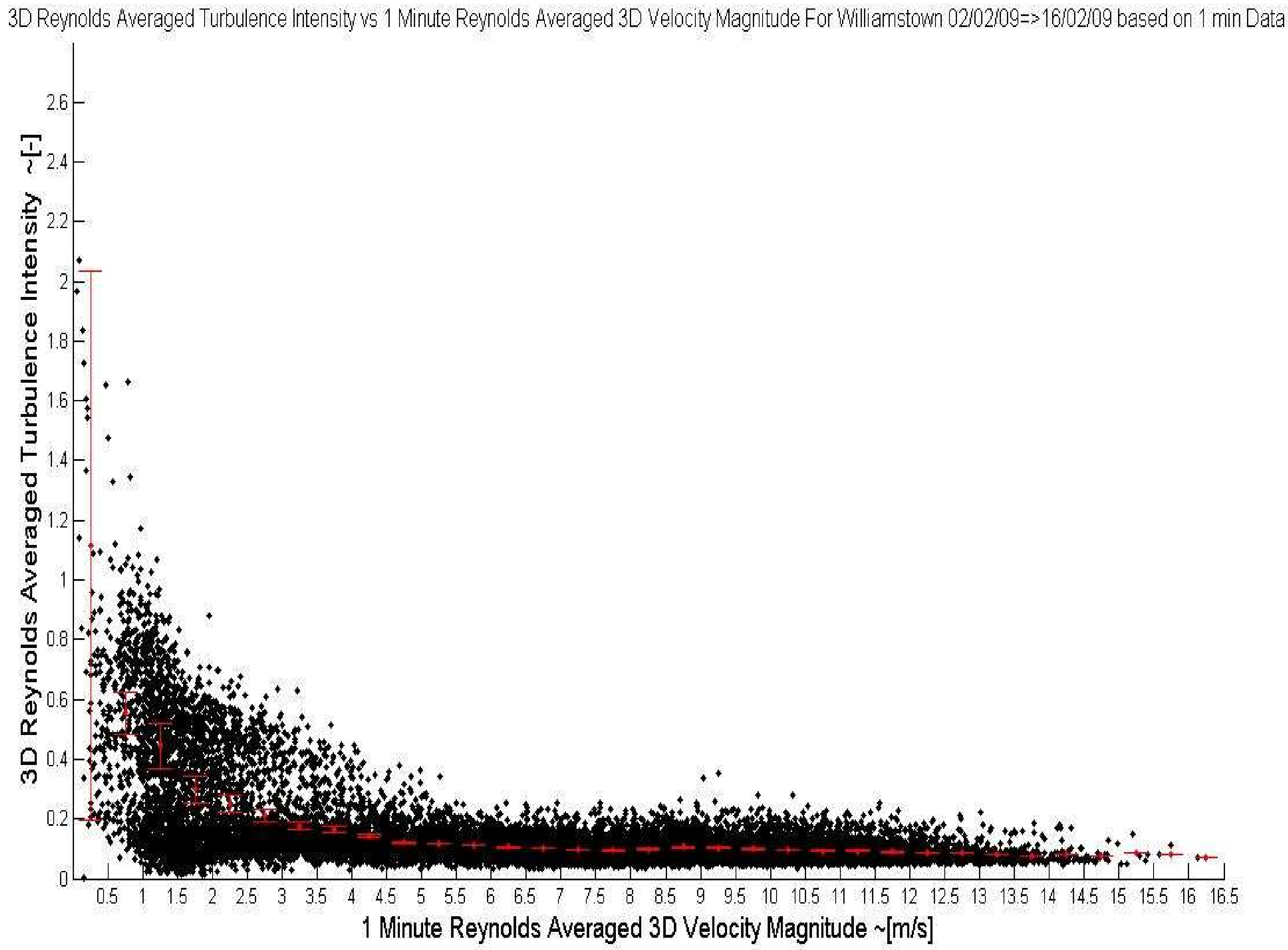
xiii. Williamstown

The Williamstown site is unique in this study and is surrounded by mostly clear space. Anemometers were installed at a height of 10m above ground level on a pre-existing light tower.

The site is located between a sporting oval and Port Philip Bay, and enjoys clear air in all directions but 40m to the west, where a sporting pavilion of height 30m is situated.



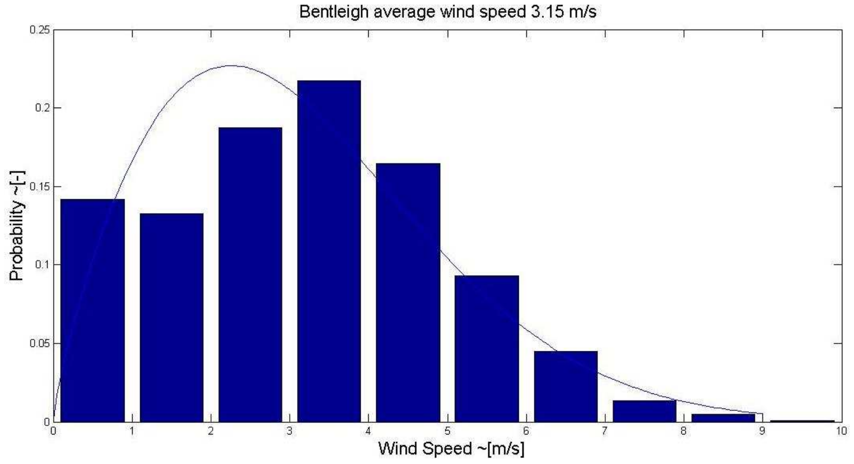


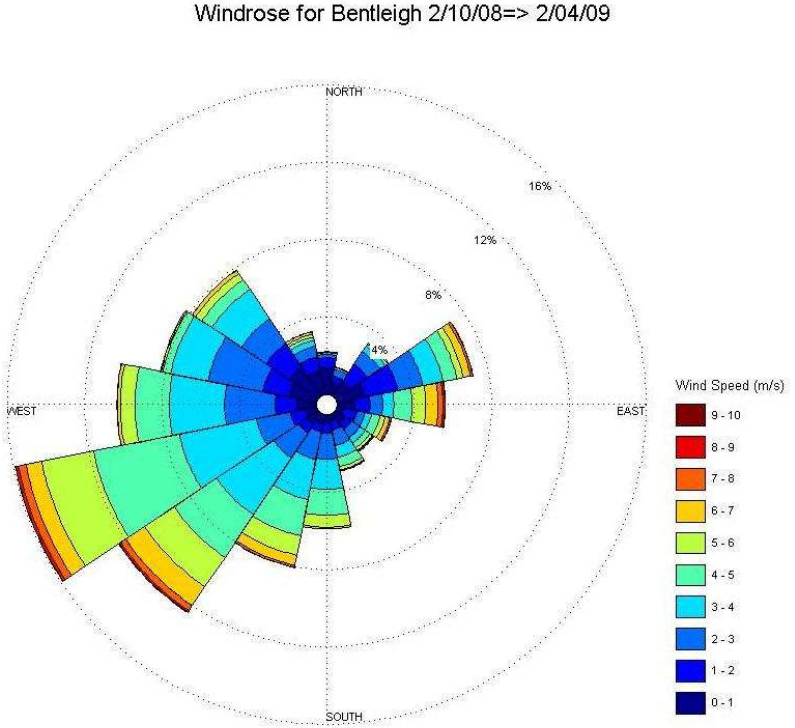

3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For Williamstown 02/02/09=>16/02/09 based on 1 min Data
3D Reynolds Averaged Turbulence Intensity ~[-]
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11 11.5 12 12.5 13 13.5 14 14.5 15 15.5 16 16.5

xiv. Bentleigh

This 10m mast was situated in the backyard area of the single storey Bentleigh house. Surrounding this site is a typical flat suburban landscape, filled with single storey houses and without much vegetation growing beyond roof height.

The immediate surrounds of the Bentleigh site were completely clear of flow obstruction at mast height.

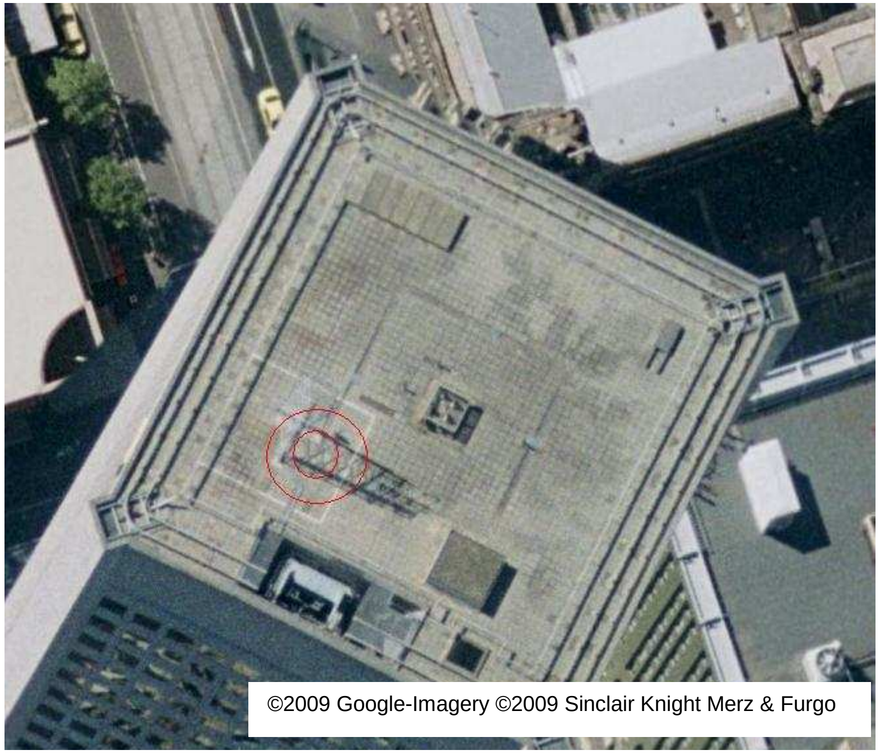


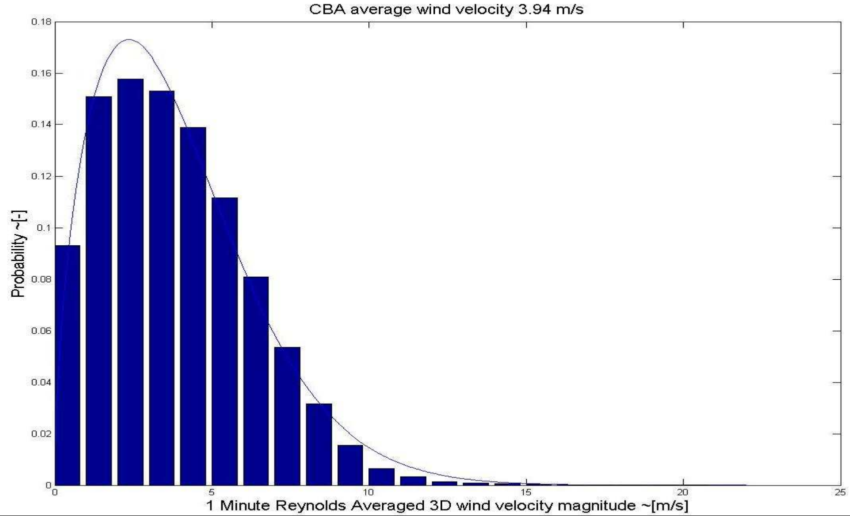


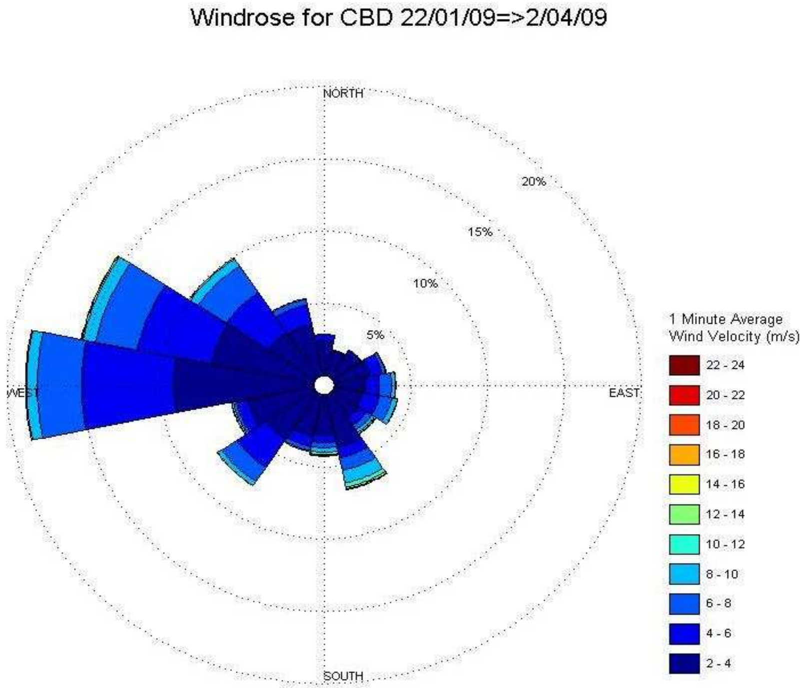
xv. CBD

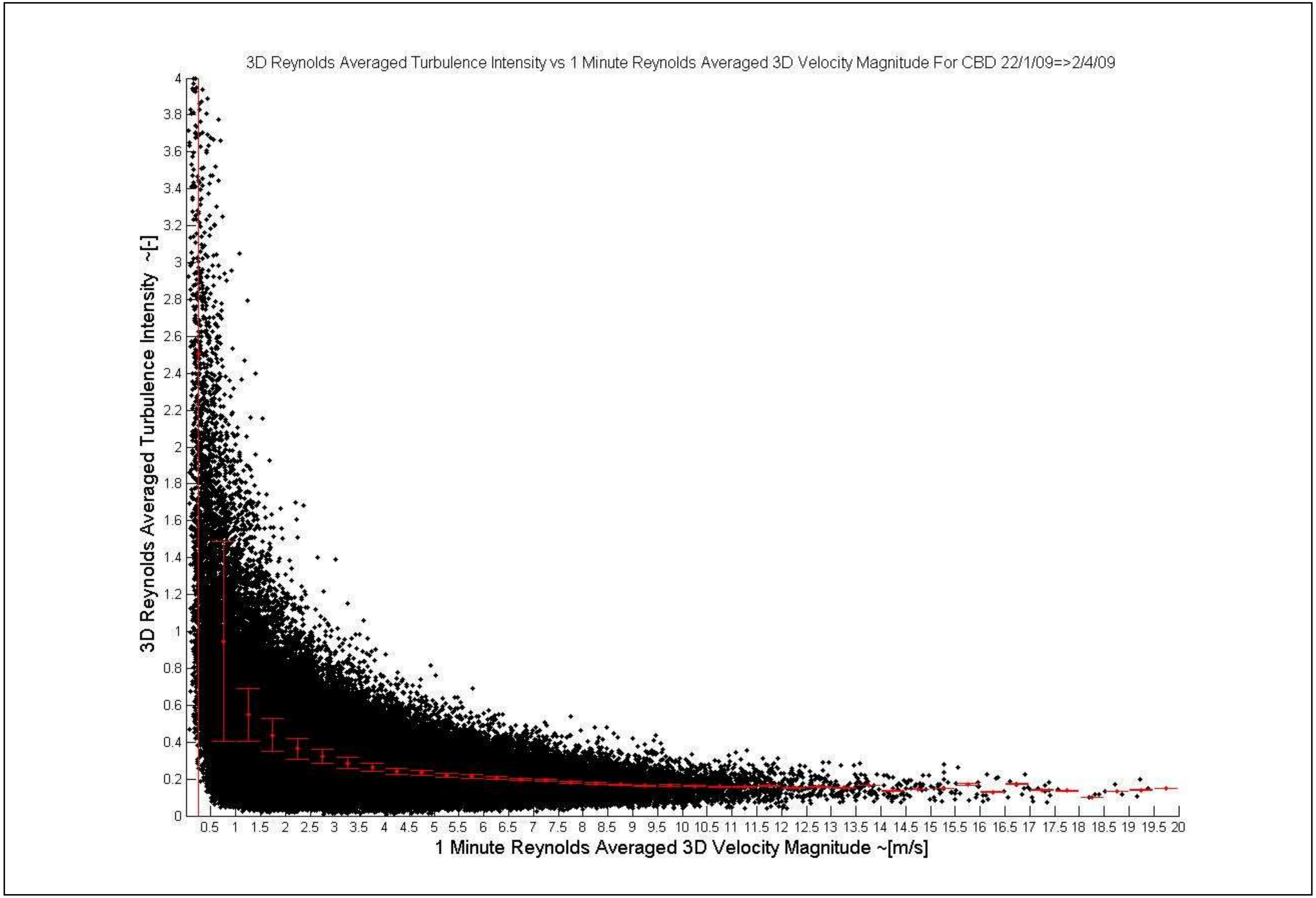
A Windmaster ultrasonic anemometer was located on the roof of one of the tallest commercial buildings in Melbourne's CBD. The building has a square cross-section with side of length approximately 40m. The vertices of the building's cross-section are aligned approximately to the cardinal compass directions.

The anemometer was installed on a 9m tall triangular sectioned tower positioned about 14m from the western corner of the building, along the line connected the eastern and western corners.








3D Reynolds Averaged Turbulence Intensity vs 1 Minute Reynolds Averaged 3D Velocity Magnitude For CBD 22/1/09=>2/4/09
3D Reynolds Averaged Turbulence Intensity ~[-]
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6 3.8 4
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11 11.5 12 12.5 13 13.5 14 14.5 15 15.5 16 16.5 17 17.5 18 18.5 19 19.5 20
1 Minute Reynolds Averaged 3D Velocity Magnitude ~[m/s]

Appendix 2

i. Anemometer Specifications

APRS World Cup Anemometer Specifications

ANEMOMETER

- Three digital anemometer inputs
- Supports dry contact switch, hall effect switch, or TTL level signal
- RC low pass filter on each input (f_c=159 Hz)
- Inputs pulled to 5 volts with internal 4.7k resistor
- Capable of displaying and logging in miles per hour (MPH), meters per second (m/s), kilometers per hour (KPH)

WIND VANE

- Two analog inputs support either one dual wiper potentiometer or one single wiper potentiometer type wind vane
- Accessible through RJ-45 connector marked "ANEMOMETER"
- Displays 0° to 359°

LOGGING AND STORAGE

- Logs at 10 to 16,000 second intervals
- Secure Digital™ or Multi Media Card™
- Supports 128 megabyte or smaller cards
- Data files in Comma Separated Vertical (CSV). Can be used with spreadsheet software, databases, or custom software
- One data file per calendar day
- Approximately 100 bytes of data per record. Over one year of storage possible on 128 megabyte memory card.

POWER

- 7 to 40 volts DC
- 2.1 x 5.5 mm power jack

- 0.35 watts peak power while writing to SD card
- 0.20 watts with backlight on
- 0.16 watts with backlight off
- All sensors inputs have Transient Voltage Suppression (TVS) protection

REAL-TIME CLOCK

- +-10 minutes per year accuracy
- Battery: CR1225 / BR1225, 3 volt lithium, 48mAh
- Battery life: 9 years minimum, 17 years typical
- Leap year compensation
- Accurate calendar until year 2099

Tables courtesy of APRS World, LLC: http://www.aprsworld.com

Gill Windmaster Specifications

OUTPUTS	
Internal sample rate	32 or 40Hz
Output rate	1, 2, 4, 8, 10, 16, 20 & 32(option)
Units of measure	m/s, mph, KPH, knots, ft/min
Format	UVW, Polar
Averaging	Flexible 0 - 3600 s
WIND SPEED	
Range	0 - 45 m/s
Resolution	0.01 m/s
Accuracy (12 m/s) Generic	1.5% RMS *
Accuracy (12 m/s) Custom	1% RMS *
DIRECTION	
Range	0-359°
Resolution	0.1° or 1°
Accuracy (12 m/s) Generic	2°
Accuracy (12 m/s) Custom	0.5°
SPEED OF SOUND	
Range	300 - 370 m/s
Resolution	0.01 m/s
Accuracy	< ± 0.5% @ 20°C
POWER REQUIREMENT	
	9 - 30 Vdc, 55 mA @ 12 Vdc
DIGITAL OUTPUT	
	RS232, 422, 485 network upto 8 anemometers
Baud rates	2400-57600
Format	ASCII

SONIC TEMPERATURE	
Range	-40°C to +70 °C
Resolution	0.01°C
ANALOGUE OUTPUTS (OPTIONAL)	
Resolution 12 bits or 14 bits	4 channels available
Selectable Range	User selectable full scale wind speed
Output Type	0-20mA, 4-20mA, 0-5V, ±2.5V, ±5V
ANALOGUE INPUTS (OPTIONAL)	
Resolution 12 bits or 14 bit	Up to 4 single ended or 2 diffferential
Input Type	±5V
GENERAL	
Weight	1.0 kg
Size	750mm x 240mm
Environmental	IP65
Operating Temp	-40°C to + 70°C
Humidity	<5% to 100%
Precipitation	Operation to 300mm/hour
EMC	Emissions BS EN 61000 - 6- 3
	Immunity BS EN 61000 - 6 -2

* Accuracy spec applies for wind speed, and for wind incidence up to ± 30° from the horizontal

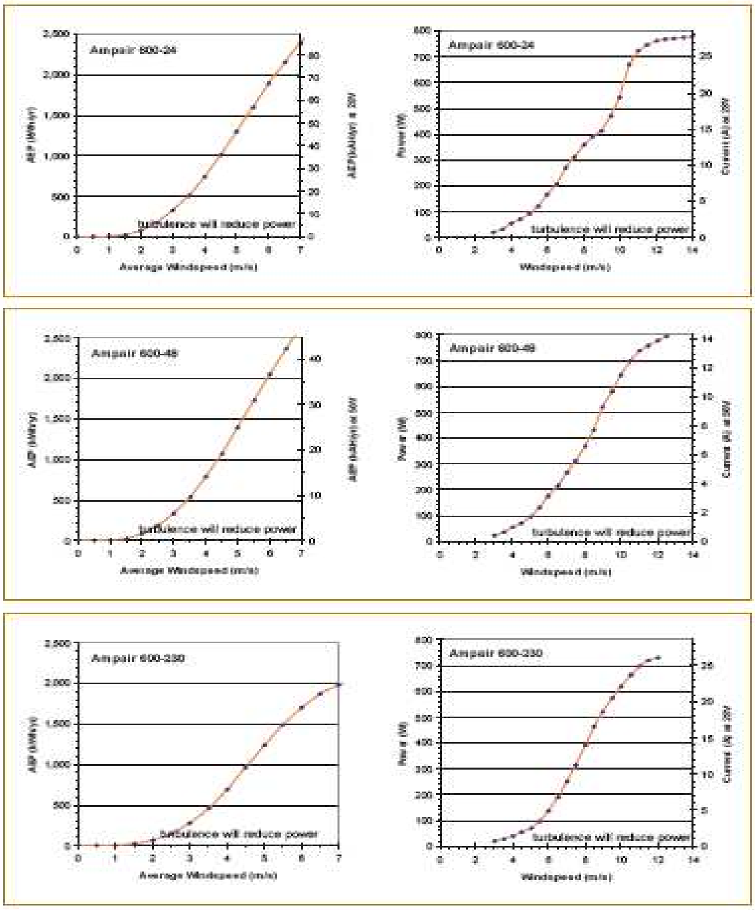
Table courtesy of Gill Anemometers: www.gill.co.uk

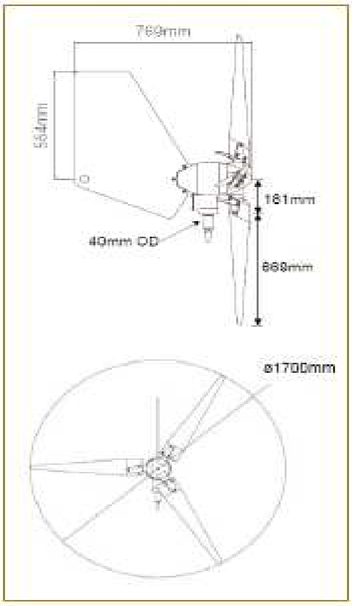
ii. Power curve and Specs for Ampair 600 230

Ampair® 600 wind turbine.

24 or 48 V battery charging
230 V grid connection

	24 V DC battery charge	48 V DC battery charge	230 V AC grid connected
Reference power at 11.0m/s (24.6mph)	723 W (into battery)	741 W (into battery)	698 W (into grid)
Reference annual energy at 5.0 m/s	1300 kWh/yr; 48 kAh/yr	1394 kWh/yr;25 kAh/yr	1232 kWh/yr (to grid)
Cut-in windspeed	3.0 m/s	3.0 m/s	3.0 m/s
Cut-out windspeed	n/a	n/a	n/a
Maximum power	1050 W	1140 W	730 W
Maximum voltage	24 V nominal	48 V nominal	230 V nominal
Maximum current	30 A	17 A	3.2 A
Power form	24 V DC	48 V DC	230 V AC single phase 50Hz
Power input	<0.5 W	<0.5 W	0.1 W sleep, <4 W standby
Rotor swept area	$2.27m^2$		
Generator output	3-phase AC (to external rectifier)		
Turbine diameter	1.70 m		
Overspeed control	Blade pitch control and dump load		
Weight	16.0 kg (turbine h ead including blades & tail fin)		
Construction	powder coated die cast aluminium body; 3 blades of GRP construction		
Generator	direct drive NeFeBr permanent magnet generator producing three phase		
Noise	Max 1-3 dBA above background		
Longevity	Expected 15 ye ar operational life		





Tables courtesy of Ampair: http://www.ampair.com

iii. Equations used

Available Wind Power

The power [W] available in a uniform flow of moving air is equal to the density of air, ρ [kgm^{-3}], multiplied by the flow's cross sectional area A [m^2] and half the cube of flow speed, v [m s^{-1}] :

$$P_{wind}[W] = \tfrac{1}{2} \cdot \rho \cdot A \cdot v^3$$

Standard Deviation and Turbulence Intensity

The sample standard deviation of a random variable set is a measure of the spread or variability of data in the set. Low values of standard deviation indicate a set that is tightly grouped about the mean, whereas larger values of standard deviation indicate more widely dispersed readings. Standard deviation is a particularly useful measure of statistical variation because it has the same units as the units of the sample measurement. The standard deviation, σ, of a random sample of readings taken from the population may be calculated using the mean value of the set, $\bar{v}$, containing n members as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(\bar{v}-v_i)^2}{n-1}}$$

Turbulence is measured by Turbulence Intensity (TI) in the wind energy industry. Turbulence Intensity is a dimensionless quantity which is defined as the random variable standard deviation of velocity readings, v_i, in an interval of n measurements, divided by the mean velocity in the interval $\bar{v}$:

$$TI[-] = \frac{\sqrt{\frac{\sum_{i=1}^{n}(\bar{v}^2 - v_i^2)}{n-1}}}{\bar{v}}$$

$$= \frac{\sigma}{\bar{v}}$$

Averaging wind direction readings

Angular measures are circular variables and contain a discontinuity around 0 or 2π in case or arc degree and radian measures. This discontinuity means that circular variables cannot be averaged in the same way as continuous variables. Trigonometric relationships may instead by used to determine the average, $\theta_{AVE,}$ of a set of *n* angular measurements, θ_i (in radians or degrees), in the following way:

$$S_{AVE} = \sum_{i=1}^{n} \sin\theta_i$$

$$C_{AVE} = \sum_{i=1}^{n} \cos\theta_i$$

$$\theta_{\mathrm{AVE}} = \arctan\left(\frac{S_{AVE}}{C_{AVE}}\right)$$

Because arctan(θ_{AVE}) is only defined on the range $\frac{-\Pi}{2} < \theta_{\mathrm{AVE}} < \frac{\Pi}{2}$, an offset must be applied based on the sign of S_{AVE} and C_{AVE} to determine the quadrant in which θ_{AVE} lies. All direction averaged data included in this report has been calculated in this way.

Yamartino Method for Standard Deviation of Wind Direction

Similarly to above, circular variables standard continuous variable methods cannot be used to calculate the standard deviation of variable methods. The Yamartino Method (Yarartino, R.J. 1984) has been used in the research presented here to calculate standard deviation. The Yamartino method is an empirical supported algorithmic method for determining standard deviation of a circular variable, $\sigma_{\theta,}$ in a single pass (ie, without having to access all variables in a set more than once), making it ideal for use in a programmable data logger. It is calculated as shown:

$$\varepsilon = \sqrt{1-(S_{AVE}{}^2 + C_{AVE}{}^2)}$$

with

$$\sigma_\theta = \arcsin(\varepsilon).\left[1+\left(2/\sqrt{3}-1\right).\varepsilon^3\right]$$

iv. Generating Weibull Probability Density Functions

Weibull Probability Density Functions (WBDF) are versatile statistical distributions used in many empirical fields to model system behaviour. Weibull curves are functions of a single real valued variable, u, and are also characterised by a pair of constants k (the scale factor k>0) and c (the shape factor c>0). The general form of a WPDF is:

$$W(u) = \left(\frac{k}{c}\right).\left(\frac{u}{c}\right)^{k-1}.\exp\left(-\left(u/c\right)^{k}\right)$$

The Cumulative WPDF ($CW(u)$) may be used to determine the proportion of samples that are less that a given value of u, U_e for instance, and may be expressed as shown:

$$CW(U_e) = \int_0^{U_E} W(u)du = 1 - \exp\left(-\left(\frac{U_e}{c}\right)^{k}\right)$$

When fitting a WBDF to an empirical dataset, values of the shape and scale constants must be found to match the fitted curve as closely as possible to the distribution of values observed in the data. First we set that the average value in the empirical set, u_{MEAN}, as equal to the average value of the fitted curve:

$$u_{MEAN} = \frac{\int_0^{\infty} u.W(u)du}{\int_0^{\infty} W(u)du}$$

Because W(u) is a probability distribution we have $\int_0^{\infty} W(u)du = 1$, so the above expression reduces to:

$$u_{MEAN} = \int_0^{\infty} u.W(u)du = \int_0^{\infty} k.\left(\frac{u}{c}\right)^{k}.\exp\left(-\left(u/c\right)^{k}\right)du$$

By applying a change of variables: $T = \left(u/c\right)^{k}$ we can simplify to produce:

$$u_{MEAN} = c\int_0^{\infty} T^{\frac{1}{k}}.\exp\left(-T\right)dT$$

Using the Table of Standard Integrals we have:

$$\int_0^{\infty} T^{n-1}.\exp\left(-T\right)dT = \Gamma(n)$$

Where $\Gamma(n)$ is the Gamma function and for positive values of n, $\Gamma(n) = (n-1)!$

Together these produce an expression for u_{MEAN}:

$$u_{MEAN} = c.\Gamma(1+\frac{1}{k}) \qquad (*)$$

If we consider the expression above for the Cumulative WPDF from above:

$$CW(U_e) = 1 - \exp\left(-\left(\frac{U_e}{c}\right)^k\right)$$

Taking the natural logarithm of both sides we can linearise this expression:

$$\ln(1-CW(U_e)) = -\left(\frac{U_e}{c}\right)^k \Rightarrow \ln\left[-\ln\left(1-CW(U_e)\right)\right] = k.\ln\left(\frac{U_e}{c}\right)$$

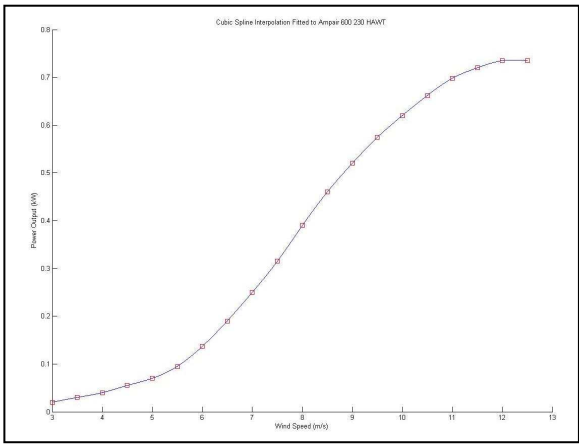
$$\Rightarrow \ln\left[-\ln\left(1-CW(U_e)\right)\right] = k.\ln U_e - k.\ln c \qquad (**)$$

The expression (**) is linear in the variable $\ln U_e$, cumulative histogram values from the empirical dataset to produce a series of values of $CW(U_e)$. A series of values for $CW(U_e)$ produced from the normalised cumulative histogram values of wind speeds less than each U_e from the dataset. When $\ln\left[-\ln\left(1-CW(U_e)\right)\right]$ is plotted for various values of $\ln U_e$ a first order line of best fit will have a slope equal to the scale parameter k.

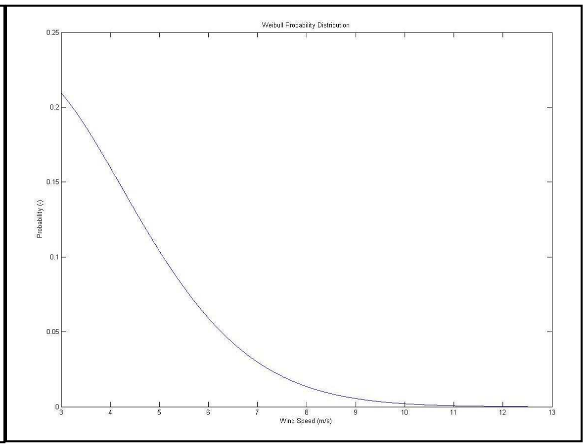
This value of k may then be substituted into (*) to determine a value for c. With values for k and c, the fitted Weibull curve for each data set is fully specified.

v. Method for estimating turbine output

Turbine energy output may be theoretically estimated by combining information represented by a manufacturer's power curve and a site specific wind probability density function.

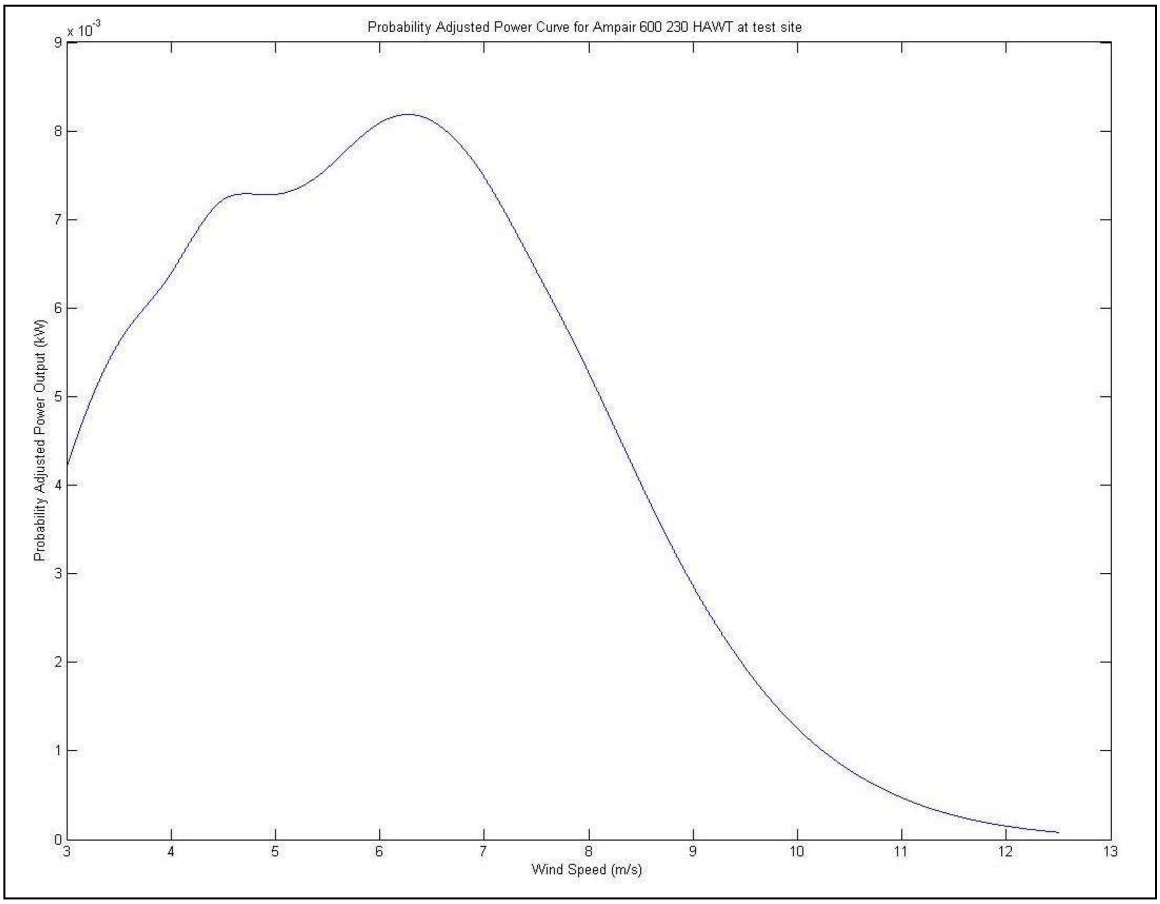


Turbine Power Curve



Weibull Prob Density Function

To do so, a probability adjusted power curve may be obtained by multiplying the power obtained at each speed on a manufacturer's power curve by the probability of that speed occurring as determined from the Weibull curve. The resulting curve looks as shown below:



Probability Adjusted Power Curve

An estimate of energy production may be produced by integrating the probability adjusted power curve over all speeds and multiplying by a time period (to produce an energy estimate with units of kWh). Care should be taken so that the time period used for the estimation is consistent with the likely wind speed distribution contained in the Weibull curve.

vi. Windmaster programming and variables recorded

Schedule Length	Variable	Description	Units
1 Minute	ST	Sonic Temperature	(ºC)
1 and 10 Minutes	Umax	Maximum U gust	(m/s)
	Umin	Minimum U gust	(m/s)
	Uave	Average U Component is Positive from south,	(m/s)
	Vmax	Maximum V gust	(m/s)
	Vmin	Minimum V gust	(m/s)
	Vave	Average V Component is Positive from west	(m/s)
	Wmax	Maximum W gust	(m/s)
	Wmin	Minimum W gust	(m/s)
	Wave	Average W Component W is Positive from the ground	(m/s)
	AveWD	Average horizontal wind direction	(º true)
	SDWD	Standard Deviation of horizontal wind direction	(º circ)
	TIU	Turbulence intensity in the U direction	(-)
	TIV	Turbulence intensity in the V direction	(-)
	TIW	Turbulence intensity in the W direction	(-)
	3DV	Average 3D wind velocity	(m/s)
	SD3DV	Standard Deviation of 3D wind velocity	(m/s)
	TI3D	3D Turbulence Intensity	(-)

Windmaster Data logger measurement program

```
BEGIN "Windmaster"

'************************************************************************
********************************************'
'
'************************************************************************
********************************************'
'
'************************************************************************
**********************************************'
'This script has been authored by Mike Bagot of the Alternative
Technology Association based on source code and advice provided by
'Dr Jonathan Whale of RISE
'************************************************************************
**********************************************'

'************************************************************************
********************************************'
'
'************************************************************************
********************************************'
'THIS PROGRAM IS DESIGNED TO OPERATE WITH THE WINDMASTER SET TO
'M2,U1,O2,L1,P6,B4,H1,NQ,E1,T1,S1,C2,A4,I1,J1,V1,X1,G0,K50
'
'
'************************************************************************
**********************************************'
```

```
RS100T 'statistical schedule definition = as rapidly as possible,
statistical schedule is used in all schedules 100T= 0.1 seconds

PS=RS422,19200,N,8,1,NOFC    'Define serial sensor port comms parameters.

'Schedule definition


RA("B:",DATA:OV:65MB)1serial"^BQ,"

1SERIAL("^BQ,%f[1CV],%f[2CV],%f[3CV],M,%f[4CV],%f[5CV]\\e")   '1 =serial
sensor port ' "\\e" clears input buffer


1CV("Wind Direction~degrees")
2CV("U-V Wind Magnitude~m/s")
3CV("W~m/s")
'4CV("SOS~m/s")
5CV(W)

7CV(W)=D2R(1CV)

8CV(W)=-1*2CV*(cos(7CV)*((1CV>=0)AND(1CV<90))-sin(7CV-
1.571)*((1CV>=90)AND(1CV<180))-sin(4.7123-
7CV)*((1CV>=180)AND(1CV<270))+sin(7CV-4.7123)*((1CV>=270)AND(1CV<360)))
'u
8CV("U~m/s")   '  The statement above uses wind magnitude and direction
to determine the U (positive when blowing from the South) component of
horizontal wind velocity

9CV(W)=-1*2CV*(sin(7CV)*((1CV>=0)AND(1CV<90))+cos(7CV-
1.571)*((1CV>=90)AND(1CV<180))-cos(4.7123-7CV)*((1CV>=180)AND(1CV<270))-
cos(7CV-4.7123)*((1CV>=270)AND(1CV<360)))
9CV("V~m/s")   '  The statement above uses wind magnitude and direction
to determine the V (positive when blowing from the West) component of
horizontal wind velocity


17CV(W)=17CV+sin(7CV) '1 minute accumulator sine of wine direction
18CV(W)=18CV+cos(7CV) '1 minute accumulator of cos of wind direction

30CV(W)=30CV+sin(7CV) '10 minute accumulator sine of wind direction
31CV(W)=31CV+cos(7CV) '10 minute accumulator of cos of wind direction


'(NUM)= number of samples
'(AV)= average of variable
'(MN)= maximum of variable set
'(MX)= minimum of variable set
'(SD)= standard deviation of variable set


'schedule definition  B (1 minute Schedule)
RB("B:",DATA:OV:1D)1M
5CV("ST~degC")
8CV(AV,=10CV,W)(SD,=11CV,W)(MX)(MN) 'U LABEL THESE using ("U")
10CV("1 min Average U~m/s")
9CV(AV,=12CV,W)(SD,=13CV,W)(MX)(MN) 'V LABEL THESE using ("V")
12CV("1 min Average V~m/s")
```

```
3CV(AV,=14CV,W)(SD,=15CV,W)(MX)(MN) 'W LABEL THESE using ("W")
14CV("1 min Average W~m/s")

3CV(NUM,=16CV,W)          '1 minute count number of samples
17CV(W)=17CV/16CV         'calc average sine of wine direction
18CV(W)=18CV/16CV         'calc average cosine of wind direction
16CV("1 minute sample count")
19CV(W)=atan(17CV/18CV)  'average wind direction
19CV(W)=R2D(19CV)+((17CV<0)AND(18CV>0))*360+((17CV>0)AND(18CV<0))*180+((1
7CV<0)AND(18CV<0))*180
' Correction above is to adjust for the range of tan: -90<atan(WD)<90,
uses quadrant of average sin/cosine to calculate

19CV("Ave 1 min WD~degrees")  'log average wind direction over 1 min

20CV(W)=SQRT(1.0-(18CV*18CV+17CV*17CV)) 'Yamartino Epsilon
21CV(W)=asin(20CV)*(1+(0.1547)*(20CV*20CV*20CV)) 'Yamartino estimate of
SD of wind direction

22CV(W)=R2D(21CV)    'Convert to degrees
22CV("StDev WD~degrees")

23CV("TI-U")=ABS(11CV/10CV) ' turbulence intensity in U direction
24CV("TI-V")=ABS(13CV/12CV) ' turbulence intensity in V direction
25CV("TI-W")=ABS(15CV/14CV) ' turbulence intensity in W direction

26CV("UVWmag_Average")=SQRT((10CV*10CV)+(12CV*12CV)+(14CV*14CV))
27CV("SIG UVW")=SQRT((1/3)*((11CV*11CV)+(13CV*13CV)+(15CV*15CV)))
28CV("TI")=27CV/26CV

16..18CV(W)=0  ' RESET THE 1 minute COUNTER AND SINE & COSINE TOTs

'schedule definition  C (10 minute Schedule)
RC("B:",DATA:OV:1D)10M

8CV(AV,=32CV,W)(SD,=33CV,W)(MX)(MN)        ' U LABEL THESE using ("U")
32CV("10 min Average U~m/s")
9CV(AV,=34CV,W)(SD,=35CV,W)(MX)(MN)        ' V LABEL THESE using ("V")
34CV("10 min Average V~m/s")
3CV(AV,=36CV,W)(SD,=37CV,W)(MX)(MN)        ' W LABEL THESE using ("W")
36CV("10 min Average W~m/s")

3CV(NUM,=29CV,W)               ' 10 minute count number of samples
30CV(W)=30CV/29CV              ' calc average sine of wine direction
31CV(W)=31CV/29CV              ' calc average cosine of wind direction
29CV("10 minute sample count")
38CV(W)=atan(30CV/31CV)        ' average wind direction
38CV(W)=R2D(38CV)+((30CV<0)AND(31CV>0))*360+((30CV>0)AND(31CV<0))*180+((3
0CV<0)AND(31CV<0))*180
' Correction above is to adjust for the range of tan: -90<atan(WD)<90,
uses quadrant of average sin/cosine to calculate

38CV("Ave 10 min WD~degrees") 'log average wind direction over 1 minute
period
39CV(W)=SQRT(1.0-(31CV*31CV+30CV*30CV))                  ' Yamartino
Epsilon
40CV(W)=asin(39CV)*(1+(0.1547)*(39CV*39CV*39CV))        ' Yamartino
estimate of SD of wind direction
```

```
41CV(W)=R2D(40CV)                                           ' Convert SD to
degrees
41CV("StDev WD~degrees")

42CV("TI-U")=ABS(33CV/32CV)                                 ' turbulence
intensity in U direction ?use abs here?
43CV("TI-V")=ABS(35CV/34CV)                                 ' turbulence
intensity in V direction
44CV("TI-W")=ABS(37CV/36CV)                                 ' turbulence
intensity in W direction

45CV("UVWmag_Average")=SQRT((32CV*32CV)+(34CV*34CV)+(36CV*36CV))
46CV("SIG UVW")=SQRT((1/3)*((33CV*33CV)+(35CV*35CV)+(37CV*37CV)))
47CV("TI")=46CV/45CV

29..31CV(W)=0  ' RESET THE 10 minute COUNTER AND SIN & COS RUNNING TOTS

'schedule definition  D (Daily archiving schedule)
RD1D DO{ARCHIVE*} 'Archives Data from all schedules at midnight and
overwrites existing files


END
LOGONB ' Enables logging on Schedule B
LOGONC ' Enables logging on Schedule C
G
```