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SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

WIND DATA LOGGING AND VALIDATION USING TELECOMMUNICATION BASE STATION INFRASTRUCTURE

BY

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This project report is my original work and it has not been presented for a degree in any other University or any other award.

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DEDICATION

Dedications to Life, My Origins, My Love.

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ABSTRACT

Meteorological stations form the basic units for the existing wind monitoring network in Kenya. Siting of a typical Greenfield mobile telecommunication Base Station (BS) has traditionally followed similar principles to siting a conventional meteorological station. The current BS is however more secure containing passive infrastructure including tower, stable power supply and provides stable wireless connectivity which are critical components for a functional wind monitoring station. The validity of wind data logged utilizing the existing mobile infrastructure is investigated here. Wind monitoring instrumentation is set up on Kibiko BS similar to the one at Kibiko meteorological station and data is collected in parallel from both stations and analysed. Results indicate similar wind roses and time series with a correlation coefficient of 0.87 for a month's data between the two stations. Regression analysis on collected data returns a roughness class of 3.4 against a value of about 3 obtained through using existing literature. Results are strongly indicative that through simple application of existing literature existing BTS stations could provide complete infrastructure to log wind data as valid as a conventional meteorological station.

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LIST OF ABBREVIATIONS AND ACRONYMS

EDGE: Enhanced Data rates for Global Evolution or Enhanced GPRS

BS: Base station. A base station is a radio transmitter/receiver, including an antenna, used in a mobile telecommunications network. The base station maintains the communication between the network and the mobile users through a radio link. In **GSM** it's referred to as BTS: Base Transceiver Station and Node B in UMTS

CAK: Communication Authority of Kenya.

DTMs: Digital Terrain Models

FDD: Frequency Division Duplex

FiT: Feed-in Tariff

GPRS: General Packet Radio Service

GSM: Global System of Mobile telecommunications.

HSDPA: High Speed Downlink Packet Access

HSPA: High Speed Packet Access

HSUPA: High Speed Uplink Packet Access

LAN: Local Area Network.

NMC: Network Management Centers

PDP: Packet Data Protocol

R'98/R'99: Release 98/Release 99

STRM: Shuttle Radar Topography Mission

TI: Turbulence Intensity

UMTS: Universal Mobile Telecommunication System

UTRAN: UMTS Terrestrial Radio Access Network

W-CDMA: Wideband Code Division Multiple Access.

WECS: Wind Energy Conversion Systems

2G: 2nd Generation mobile telecommunication system

3G: 3rd Generation mobile telecommunication system

3GPP: 3rd Generation Partnership Project

SSE Error Sum of Squares

SSTO Total Sum of Squares.

SSR Regression Sum of Squares.

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LIST OF SYMBOLS USED

Engineering Symbols

u Speed.

ρ Density.

A Area.

μ_p Efficiency Factor of a wind turbine.

Z_0 Roughness Length

z Height above ground

V Velocity

L Monnin-Obkhov Length

q Heat flux

$^\circ K$ kelvins

$^\circ C$ degree Celsius

T Absolute temperature in ˚K=273+˚C

Ψ Correction factor for different stability conditions of the atmosphere.

α wind shear exponent coefficient

Statistical Symbols

β_0 regression line parameter for the *y-intercept*.

β_1 regression line parameter for the slope.

N (0, σ2) normally distributed, with mean 0 and variance σ^2.

ε_i Independent N (0, σ^2).

b_1 Point estimator

X_i known constant, level of predictor variable in the i^{th} trial

Y_i observed response i^{th} trial.

$\bar{Y}$ Mean of Y_i observations.

$\hat{y}$ ordinate of the estimated regression line

$\bar{X}$ Mean of X_i observations.

σ Standard deviation (σ^2 Variance)

E{Y} the mean of the probability distribution of Y, for given X.

f_i the density of an observation Y_i

CHAPTER ONE

1 INTRODUCTION

Wind power has been acclaimed as one with the most potential and techno-economical viability among the renewable sources of energy in Kenya [1]. Research indicates that among the current principle sources of renewable energy, wind energy leads in terms of the relatively lower capital cost and gestation period required to commission wind electrical power systems [2].

Wind energy utilization however requires two vital technical components: one is in relation to the wind resource available and the other is related to the engineering or performance characteristics of commercially available wind electric turbines [3]. Insufficient wind regime data has been cited as the main barrier affecting the exploitation of wind energy resources in Kenya [1]. The wind industry largely depends on data logged on Kenya's 34 conventional meteorological stations and the Ministry of energy has a plan to set up 53 wind masts to collect site specific data [4]. The expansive, remote, southern and northern Kenya is not yet fully explored as attributed to the prohibitive costs in exploration capital infrastructure [1].

Kenya's mobile telecommunication network has however conquered the remotest northern and southern regions [5]. Its network employs thousands of base stations with towers equipped with secure power supply, access roads and security. These stations are rapidly expanding to satisfy the high demand for voice and data services supported by a high revenue base of the mobile telecommunication industry [6].

The possibility of utilizing this mobile infrastructure as a swift and economic alternative for area wind resource evaluation is of interest to this project. Emphasis will be laid on how this data could compare to the one logged using a conventional meteorological station.

1.1 Statement of the Problem

The current (2012) 34 synoptic meteorological stations in Kenya were solely established to log data for the agricultural, aviation and marine industries [7] . Investors in the wind energy industry however require more accurate site representative data than what the current scattered meteorological stations can offer. There is an urgent need to set up new meteorological stations but this has proved to be not only capital intensive but also very costly to maintain [8].

Kenya's mobile telecommunication industry has maintained an upward trend with an annual growth of over 4.7 percent both in the number of mobile subscribers and mobile penetration standing [6]. The number of mobile subscribers in Kenya currently stands at 36.1 million with mobile penetration of 88.1 percent [6]. Planning of every new BS is in accordance to the radio and transmission objectives which overlap in many aspects as setting up a meteorological station.

The purpose of this project is to investigate the inherent properties of the mobile telecommunication infrastructure that could support reliable logging of wind data and to analyse if the quality of data logged using existing mobile infrastructure matches the one that could have been logged using a conventional meteorological station.

1.2 Justification of the problem

Wind energy has been identified as the leading alternative source of energy required to power the Kenyan economy towards achieving vision 2030 and the government has invited private sector to invest in the wind industry [4]. Insufficient wind regime data has however hampered investment in wind energy [4]. Using the already established and well maintained telecommunication infrastructure to log wind data will be a swift and economic alternative to provide area specific data required by investors in the wind energy industry.

1.3 Objectives of the Study

1.3.1 General Objective

To investigate the intrinsic properties of the mobile telecommunication infrastructure in relation to a conventional wind monitoring station and to find out how wind data logged using the existing mobile infrastructure compares to a conventional meteorological station.

1.3.2 Specific Objectives

The specific objectives of the study were:

A. To research the wind energy industry's wind data logging requirements and the provisions of the current meteorological stations in Kenya.
B. To analyse how the radio and transmission planning strategies for the mobile telecommunication industry affect the location of the BS.
C. To identify a BS station that shares a common wind current with a nearby conventional meteorological station and set up a data logger using the BS infrastructure to record concurrent wind measurements with the meteorological station.
D. To analyse wind data logged on the BS in comparison with the one logged on the nearby meteorological station and evaluate its quality by regression and correlation models.

1.4 Research questions:

The following research questions guided the study:

A. What are the current data quality thresholds for the wind energy industry and are there any weaknesses faced by the current meteorological stations in meeting them?
B. How is the current mobile BS suited to log wind data and how could their potential weaknesses be alleviated to meet the wind industry standards.
C. What is the correlation coefficient between the data collected using the BTS and the concurrent one logged using the conventional meteorological station?

1.5 Research Report Organization

In order to meet the objectives outlined in section 1.3.2 a systematic approach in research, identification and analysis was employed. This could be summarized in the flowchart in Figure 1-1-1

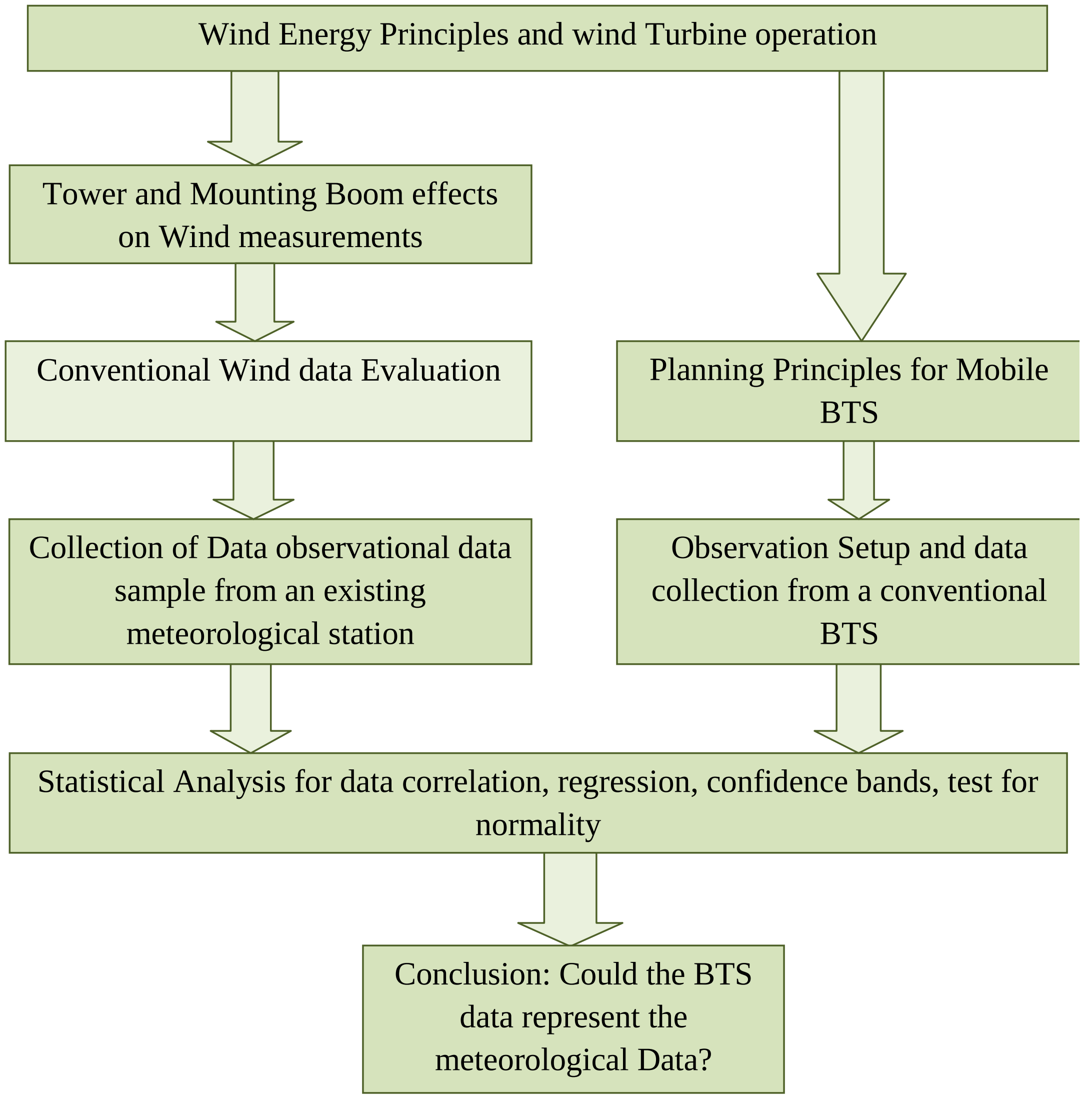


Figure 1-1-1: A flowchart summary of the research thesis organisation

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Wind Energy Resource Evaluation.

Wind resource evaluation is the key technical prerequisite toward exploitation of wind energy [3]. There is no other branch in meteorology, science or technology where the importance of minimal uncertainty required in wind speed measurement is as great as in wind energy [9].

The mechanical properties behind wind turbines and the how the current meteorological stations record these properties will be described first before wind energy resource evaluation is discussed.

2.1.1 Mechanical Properties of Wind Energy

Wind turbines extract kinetic energy from wind, whose magnitude largely depends on the velocity of wind. In a wind of speed u_0 and density ρ, a turbine intercepting a cross-section A of wind front will produce power given by equation (2-1) [10].

$$P_T = \mu_p A \frac{\rho u_0^3}{2} \qquad \textbf{(2-1)}$$

Where μ_p is efficiency factor called the *"power coefficient"*; which has a maximum value of $\mu_{p(max)} = 0.59$ called the Betz Limit[1]). Modern large wind turbines achieve peak values for C_P in the range of 0.45 to 0.50, about 75% to 85% of the theoretically possible maximum [10].

[1] Betz limit is the maximum possible energy that may be derived by means of an infinitely thin rotor from a fluid flowing at a certain speed.

From equation (1), whereas doubling A will produce twice the power, a doubling of wind speed produces 8 times the power. The power coefficient C_P also varies with wind speed for individual machines. Since wind speeds above average are less likely than those below, optimum design for a particular site is quite complex, given that power has to be supplied for extended periods [11].

Wind Energy Conversion Systems (WECS) have their maximum rated power given for a specific wind speed. Commonly this rated wind speed is about $12ms^{-1}$ [11].

Given this high dependability of wind energy on wind speed, respective wind data logging points have to be stationed strategically away from any obstructions to give clearly representative data.

2.1.1.1 Wind Direction

This is reported by the direction from which it originates, and is usually reported in cardinal directions or in azimuth degrees [10]. This information is particularly important when selecting a site for a wind machine in hilly sites, near structures or in arrays of several machines where shielding could occur.

2.1.1.2 Wind Shear.

This is the vertical Variation of Wind Speed. It's useful during comparison of wind data logged a varying anemometer heights [10]. A wind velocity profile in the surface boundary layer is a logarithmic function of height; the slope of the log profile for wind velocity is a function of friction velocity and the zero intercept is a function of the roughness length [12] as shown in equation (2-2) below [13]:

$$V(z) = \frac{V_{fr}}{k}\left[\ln\left(\frac{z}{Z_0}\right) - \psi\left(\frac{z}{L}\right)\right] \qquad (2\text{-}2)$$

Where: V_{fr} is the friction velocity=0.4 is the von Karman constant, L is the Monin-Obukhov length, Zo is the roughness length.

The Monin-Obukhov L is a scaling parameter which depends upon the heat flux at the ground surface q_0 and is given by equation (2-3).

$$L = \frac{T_0}{k.g} \frac{c_p V^3{}_{fr}}{q_0} \tag{2-3}$$

Where: T_0 is the ground surface absolute temperature in Kelvins, (°K=273+°C), q_0 is the ground surface heat flux, Cp is the heat capacity of the air at constant pressure, g is the gravity's acceleration.

Different correction factors are suggested for stable and unstable conditions as illustrated in equations (2-4) and (2-5).

$$\psi_{unstable} \frac{z}{L} = \left(1 - 16\frac{z}{L}\right)^{1/4} - 1 \tag{2-4}$$

For unstable conditions

$$\psi_{stable} \frac{z}{L} = 4.7\frac{z}{L} \tag{2-5}$$

Under stable conditions

In neutral conditions, the Monin-Obukhov length L is infinite in magnitude and the correction term vanishes.

If we know the wind speed on one height, we can compute it at other height by taking the ratios, thereby eliminating the need to assess the friction velocity as shown in equation (2-6).

$$V(z) = V(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\alpha} = V(Z_{ref})\left(\frac{\ln\frac{z}{Z_0}}{\ln\frac{z_{ref}}{Z_0}}\right) \quad (2\text{-}6)$$

Where $V(z)$ denotes the wind speed at height z, V_{ref} is the wind speed at height z_{ref}; Z_0 is the roughness length and α is the wind shear exponent coefficient.

The roughness length (Z_0) is a parameter for roughness of a terrain, which is a measure of terrain roughness as "seen by" the surface wind. Z_0 is the level at which the logarithmic wind profile has zero wind speed. The roughness class is defined in terms of the roughness length in meters Z_0, according to equation (2-7) [13]

$$RC = 1.699823015 + \frac{\ln Z_0}{\ln 150} \quad (2\text{-}7)$$

For $Z_0 \leq 0.03$

$$RC = 3.912489289 + \frac{\ln Z_0}{\ln 3.3333} \quad (2\text{-}8)$$

Table 2-1: Typical values of roughness length and class [13].

Roughness Class RC	**Roughness Length, Z_0, m**	**Landscape**
0	0.0002	Water surface
0.5	0.0024	Completely open terrain, such us concrete runways in airport, mowed grass
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings only softly rounded hills
1.5	0.055	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 1250m
2	0.1	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500m
2.5	0.2	Agricultural land with many houses, shrubs and plants, or 8 meter tall sheltering hedgerows within a distance of about 250m
3	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows and very rough and uneven terrain
3.5	0.8	Larger cities with tall buildings
4	1.6	Very large cities with very tall buildings and skyscrapers

for $Z_0 > 0.03$

We can use **equation** (2-6) to solve directly for roughness length as shown in **equation** (2-9). The formula assumes neutral atmospheric stability conditions under which the ground surface is neither heated nor cooled compared with the air temperature [13].

$$\ln z_o = \frac{u_2 \ln z_1 - u_1 \ln z_2}{u_2 - u_1} \qquad \textbf{(2-9)}$$

2.1.2 **Wind Energy Resource Evaluation.**

Several approaches for investigation are given depending on magnitude of the area to be represented [14]. This can be summarized as:

a) Preliminary Area Identification: This process screens a relatively large region (e.g., state or utility service territory) for suitable wind resource areas based on information such as airport wind data, topography, flagged trees, and other indicators. At this stage new wind measurement sites can be selected.
b) Area Wind Resource Evaluation: This stage applies to wind measurement programs to characterize the wind resource in a defined area or set of areas where wind power development is being considered. The most common aim is to justify site specific investigations after verifying that sufficient wind resources exist within the area.
c) Micro-Siting: Its main objective is to quantify the small-scale variability of the wind resource over the terrain of interest. Ultimately, micro-siting is used to position one or more wind turbines on a parcel of land to maximize the overall energy output of the wind plant.

2.1.2.1 Setting up a Wind Monitoring Station.

Analysis of topographical maps and analysis of historical wind records are a reliable means in streamlining the siting process [14]. Field surveys and ranking of candidates based on their estimated wind resource and overall development potential follows. The following should be observed when choosing an exact location for the monitoring tower:

a. The tower should be positioned as far away as possible from nearby obstructions to wind flow obstructions. If sensors must be near an obstruction, they should be at a horizontal distance no closer than 10 times the obstruction height in the prevailing wind direction [14].
b. The selected location should be as representative as possible of the general location
c. The tower height should be high enough to support the following monitoring levels:

- **40 m:** This height represents the approximate hub height of most utility-scale wind turbines.
- **25 m:** This level approximates the minimum height reached by the blade tip portion of a rotating turbine rotor and will help define the wind regime encountered by a typical turbine rotor over its swept area.
- **10 m:** This is the universally standard meteorological measurement height.

In addition, the tower should be equipped with lightening protectors, be structurally stable to minimize wind-induced vibration, meet local aviation standards and be secured against vandalism and unauthorized tower climbing.

2.1.2.2 Measurement Parameters

The main purpose of the monitoring program is to collect wind speed, wind direction, and air temperature data. These nominal parameters are recommended to obtain the basic information needed to evaluate resource-related wind energy feasibility issues. Optional parameters could include solar irradiation, vertical wind speed, barometric pressure and change in temperature with height to give more detailed information in the assessment.

Recorded parameters are internal functions of the data logger represented as average, standard deviation, minimum and maximum. Standard deviation is the true population standard deviation of the one or two seconds' samples within each averaging intervals and should be recorded for wind speed and direction [14]. This is useful in determining atmospheric stability, turbulence and for pointing our erroneous values during validation.

2.1.2.3 Data loggers

Data loggers can be grouped by their method of data transfer, either in-field or remote. Data recording should be serial in nature with a designated by a respective time and date stamp [14].

Modern data loggers rely on good network connectivity to allow a user to call into the logger and view live data at the site, as well as to download data site conditions and even to change data collection parameters or to program new alarms, all remotely from the user's computer [15].

2.1.2.4 Data storage devices

Data loggers employ their internal memory to store serial data. It's this data that is referenced by their internal algorithms while calculating and recording the desired data. The data could be stored in volatile and non-volatile memory. Data is conveyed to a central monitoring station where it's stored permanently via the network.

2.1.2.5 Power supplies

All electronic data logger systems require a main power source that is sized to meet the total power requirements of the system. A backup power supply should be included to minimize chances of data loss caused by power failure.

2.1.3 **Wind Data Monitoring by the Local Meteorological Stations in Kenya.**

Currently the Kenya Meteorological Department (KMD) operates and maintains 36 synoptic stations [8] as shown in Figure 2-2-1. Their main aim is to observe and record all the surface meteorological data [16]. These observations include: rainfall, temperature, wind speed and direction, relative humidity, solar radiation, clouds, atmospheric pressure, sun shine hours, evaporation and visibility. These stations have been in existence long enough and can be used to study past climatic conditions that could be used to predict future climatic patterns [8]

2.1.3.1 Challenges facing utilization of the current meteorological stations for wind energy monitoring

The following are among the main challenges [8]:

a. Meteorological stations are not distributed evenly well enough to capture small scale climate conditions that could be influence by small scale topographical variations, etc. which demands enhanced detail in wind resource monitoring.
b. The current wind monitoring stations are designed to record at a height of 10m. Wind energy monitoring requires wind to be monitored simultaneously at multiple heights i.e. 50m, 30m and 10m [14], for wind shear calculations.
c. The meteorological department is having maintenance and technical challenges to run its multiple stations and taking it long time to fix failed equipment [8].
d. There is lack of necessary infrastructure such us electricity and access roads in some of the stations.

- There is reported insecurity in some areas where observatory stations are

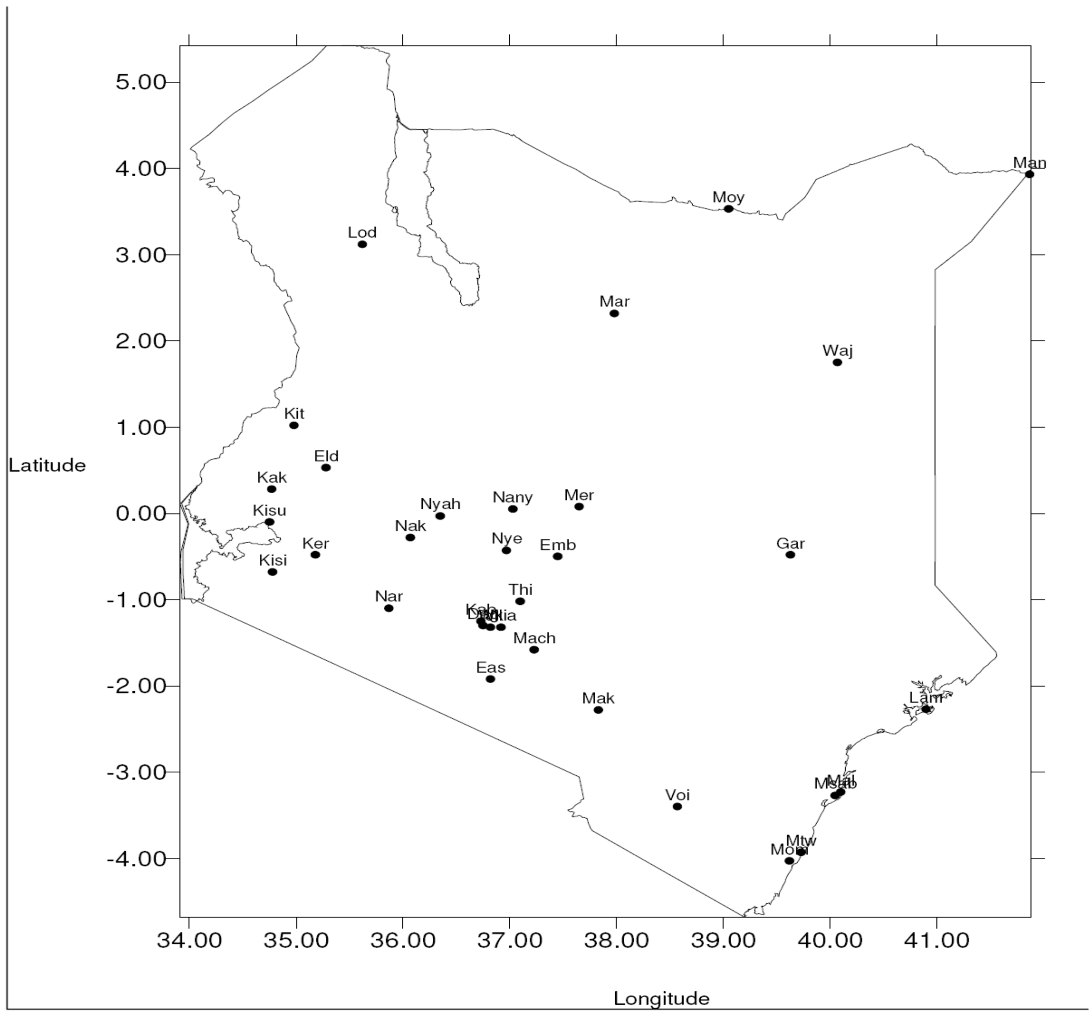


Figure 2-2-1: Geographic distribution of surface observing stations in Kenya.

located.

2.2 The Wind Energy Industry in Kenya

2.2.1 Installed Capacity and Energy Projections

Development projects recommended under vision 2030 are projected to increase energy demand from the current 1526MW (2012) to 21599MW (2031) and Kenya is obligated to generate more energy at lower cost [17]. New renewable energy sources are expected to be exploited among which wind energy expected to inject a leading 2036MW to the national grid. Wind energy installed capacity currently stands at 5.45MW [18].

The Kenya government is calling upon the private sector to invest in wind power for electricity generation [4].

2.2.2 The Wind Atlas.

The ministry of energy developed the wind atlas in 2008 using data from available meteorological stations [19]. Aided with development partners, the ministry also aspires to augment this information by installing 53 wind masts and data loggers to collect site-specific data [1].

Kenya is lagging behind its National Energy Policy implementation that requires the Cabinet Secretary to have already commenced a countrywide survey and a resource assessment of all renewable energy resources within the first twelve months of coming into force of this Act (2014)[20].

2.3 Tower and Mounting Boom Effect on Measured Parameters

It has been proved that when an anemometer is mounted in the wake of a tower then its indication will not be a true indication on the free field wind speed. This disturbance is unacceptable and it’s recommended to avoid mast and boom distortions greater than 0.5% [9].

The tower top is indisputably the preferred location for the reference anemometer for wind power performance evaluation. The anemometer should further be vertically separated from the tower top by no less than the separation recommended for that tower type for horizontal booms.

Meteorological masts can either be of cylindrical or lattice construction and the required vertical or horizontal (in case of boom mounting) separation of the anemometer from the tower is subject to the tower type and solidity [9]. For cylindrical towers, the separation should be no less than 8.5 mast diameters in order to achieve less 0.5% distortion.

Calculation is not straight forward in case of Lattice towers and recommendations here are based upon the combination of actuator disc and Navier-Stokes theory and analysis [21]. Flow distortion is a function of the assumed thrust coefficient C_T, which in turn depends upon the porosity of the mast and the drag on the individual members

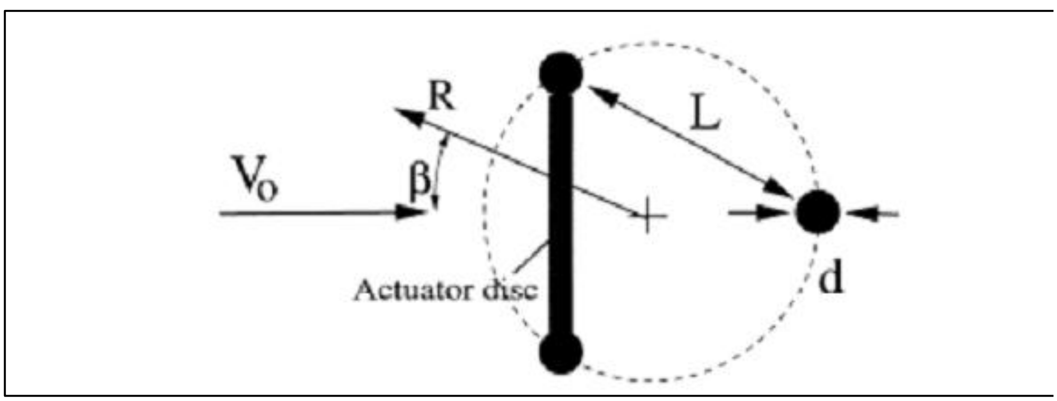


Figure 2-2-2: Representation of a 2 dimensional lattice mast showing the major geometrical parameters and the system for describing nearby points in space.

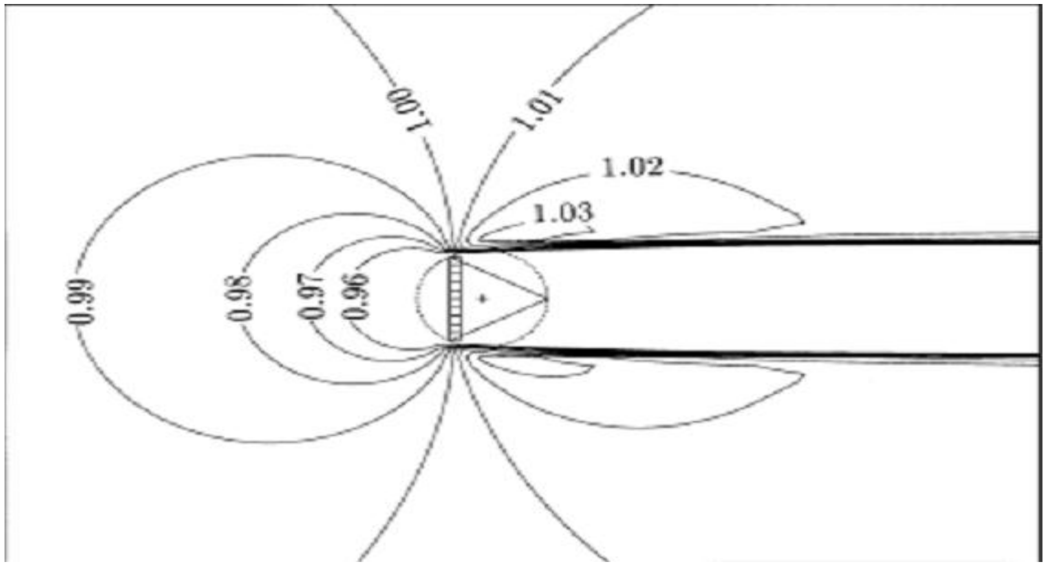


Figure 2-2-3: Iso-speed plot, with local speed normalized by free-field wind speed, of flow round a triangular lattice mast; analysis by 2 dimensional Navier-Stokes computation and actuator disc theory and a CT of 0.486.

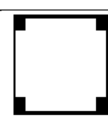
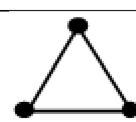
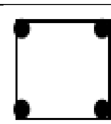
It can be noted from Figure 2-2-3 that there is very minimal flow distortion at 90° to the flow direction making it the most appropriate location for a side boom in unidirectional wind climates.

Curve fitting procedures suggest the centreline velocity deficit, Δ, for a Lattice mast face on to the wind can be evaluated as shown in equation (2-10).

$$\Delta = (0.126C_T - 0.006)\left(\frac{L}{R} - 0.08\right) \quad \textbf{(2-10)}$$

This expression should be used as the basis for evaluating the mast to anemometer separation required for a desired maximum flow distortion and a given tower C_T.

Table 2-2: Estimation of Thrust Coefficient CT for a Lattice tower

Type of Tower	**Plan Section**	**Expression for C_T**	**Valid Range**
Square cross section, members with sharp edges		$4.4(1-t)t$	$0.1 < t < 0.5$
Triangular cross section, round members		$2.1(1-t)t$	$0.1 < t < 0.3$
Square cross section, round members		$2.6(1-t)t$	$0.1 < t < 0.3$

C_T can be estimated from local building codes [9].

If t is defined as the ratio of the projected area of all structural members on the side of the tower to the total exposed area, C_T can be evaluated as shown in Table 2-2 [21]

2.4 Cellular Mobile Telecommunication infrastructure

Kenya has an elaborate mobile telecommunication infrastructure that is well spread into the interior parts of the country, and more extensive than her main road network (Figure 2-4). Safaricom alone has over 3000 BTSs (Safaricom Radio Network and Optimisation Department site Data for the year 2014). CAK has

Picture 2-1: Luterere site between Kainuk and Lokichar (Turkana County) with access road and wind turbines. (Picture taken by researcher during his normal work)

drafted guidelines on telecommunication mast construction with respect to the Civil Aviation Authority [22].

2.4.1 BS Access and Security

With over seven years experience working the telecommunication industry I have noted that the security organisation of the telecommunication infrastructure is efficient and reliable. Every BS site has intrusion alarms at the entrance, smoke and fire alarms, diesel generator operation alarms, rectifier and battery monitoring alarms among others that are installed to ensure seamless service of the network. The site alarms are routed over to central and regional NMC (Network Management Centres) using dedicated channels on the GSM network. Any site access request has to be approved before a CRQ is issued by the NMC under a distinct code, and access to every site is monitored on call, SMS and key. Armed security is accessible once signaled by the NMC to deter any unauthorised access and some sites have permanent resident security on site

Telecommunication companies have also invested heavily in access infrastructure like roads to ensure every site can be accessed easily by road anytime. They have Field Officers FOs distributed in all the network geographical regions for technical support in case remote assistance is needed.

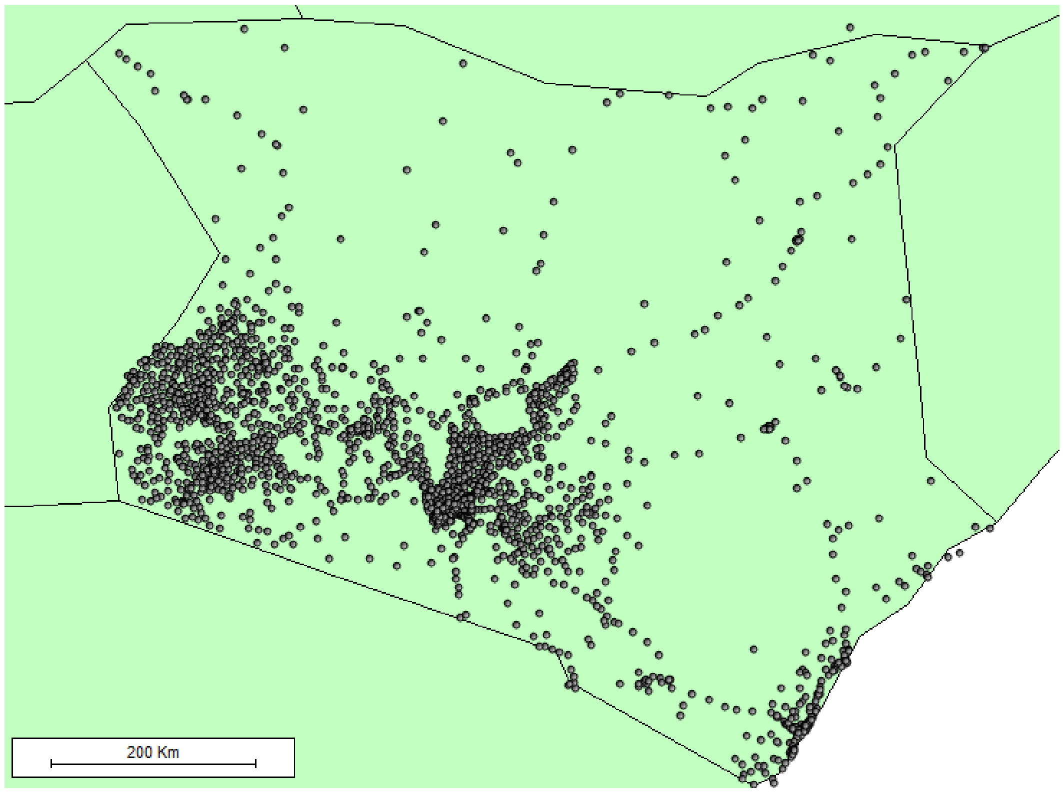


Figure 2-4: Kenya's Mobile infrastructure (BS) Stations as at mid 2014 (Courtesy Safaricom Kenya and Actix)

Infrastructure primarily consists of Active infrastructure and Passive infrastructure. Passive infrastructure includes: Steel tower, BS shelter, Power supply, Generators, Batteries, Air-conditioners, Fire extinguishers, while active contains network elements (radiating equipment)

2.4.2 Transmission and Radio Planning for New BS

Modern radio systems operate well beyond the 100MHz Range where radio waves travel a direct path from the transmitter to the receiver [23]. During planning and design, suitable candidates are identified and ranked following a criteria similar to the one used in wind site selection for a wind monitoring station.

2.4.2.1 Radio Planning

The primary objective of the radio planning is to provide quality cellular coverage at the least cost [24]. A site must therefore serve a specific clutter and be away from physical obstructions for minimum loss of signal power between the transmitter and receiver.

A typical outdoor macro-cell should be mounted above medium rooftop level with heights of all surrounding buildings below base station antenna height [25].

2.4.2.2 Microwave transmission planning

Telecommunications backhaul links have traditionally relied upon microwave transmission because of its reliability, cost-effectiveness and speed of rollout [26]. A clear line of sight is required between two transmitting antennas. During link planning, there is a general tendency to use high masts to obtain good Fresnel zone clearance from terrain. The need to get good Fresnel clearance is because of k-factor variation [27]. Designers will typically aim for up to 4th Fresnel zone clearance assuming a k-factor of 0.9 or less.[28]

Transmission planning employs terrain study computer tools using DTMs e.g.STRM databases and technical site visits to ensure there are no obstacles on the transmission paths. In light of the above design constraints, chosen nominal candidates for the planned sites are often located on hills or places with little obstruction from buildings and vegetation.

2.4.3 Mobile Signal Strength and Quality

The mobile signal strength is a key component for estimation the Quality of Service QoS for mobile communication network [5]. Mobile data communication heavily depends on excellent signal strength for excellent service.

The Communications Authority of Kenya is mandated to conduct annual QoS assessment across all the mobile operators in Kenya and to enforce compliance to its standards upon the mobile service operators. The latest report by CAK indicates compliance across all operators in signal strength [5].

Mobile signal strength is strongest near the radiating antenna and it degrades as the signal propagates through space [23]. The mobile strength is therefore strongest inside the BS and instruments depending on mobile signal strength for transmission like data loggers are expected to enjoy quality service when located inside the BS.

2.4.4 Cellular data services

Based on specifications in Release 97(R'97), GPRS typically reached speeds of 40Kbps in the downlink and 14Kbps in the uplink by aggregating GSM time slots into one bearer [29]. Enhancements in Releases R'98 and R'99 meant that GPRS could theoretically reach downlink speeds of up to 171Kbps.

The next advance in GSM radio access technology was EDGE with increase in data speeds to 384Kbps placed EDGE as an early pre-taste of 3G, although it was labelled 2.75G by industry watchers. EDGE Evolution with Improved spectral efficiency and reduced latencies down to 100ms has increased throughput speeds to 1.3Mbps in the downlink and 653Kbps in the uplink

HSDPA, offering download speeds potentially in excess of 10 Mbit/s, and an uplink equivalent undergoes continuous development in Kenya, and the LTE exercise has extended the radio technology to keep UMTS™ highly competitive to potential rival technologies, with data rates approaching 100 Mbit/s currently [30].

2G network technology is widespread in Kenya because it's the oldest (as compared to 3G and LTE) and is the most preferred for providing widest coverage in sparsely populated areas (GSM 900). From experience, virtually every outdoor mobile telecommunication site in Kenya has 2G network. Most data loggers have

GPRS capability that can enable them to utilize the GSM (GPRS/EDGE) network for data transmission [15]

2.4.5 Collocation Concept

Telecom operators’ aggressive pursuit of lean business models has led to an evolution, with many now turning to tower sharing as a viable option. Tower sharing has been a feature in the Americas and Europe over the past decade [31] and has already been implemented in Kenya [22]. Eaton Towers for instance has entered a sales agreement with Airtel Kenya and Telkom Kenya [32] to manage its towers and passive infrastructure. Eaton Towers is expected to focus on leasing tower space to anyone wishing to install wireless communication equipment [33].

By 2007, [34] 44% of states in the world mandated collocation while 74% permitted infrastructural sharing for mobile operators. Kenya has an existing elaborate policy on collocation for the existing cellular infrastructure as stipulated in CAK guidelines for telecommunication site rollout [22].

Environmental concerns have constrained tower construction in places like game parks and conservation sites. With fewer places to erect towers and the growing demand for telecommunication service and wind energy data logging facilities, sharing the existing physical infrastructure appears to be a more practical way to go.

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CHAPTER THREE

3 RESEARCH METHODOLOGY

3.1 Observational Study Design

Unlike experimental studies, random assignments to factor levels to experimental units do not occur in observational studies [35]. Factor levels in this study were S1 (Wind Speed at the meteorological station) and S2 (wind speed at the mobile telecommunication site). Random assignments to S1 and S2 were not possible since the research had no control over the prevailing wind speeds at both stations. The study could thus be termed as purely observational and research interest was in the study of relationships between the factors.[35].

3.1.1 Selection of Sample Size

Readings were to be taken concurrently from S1 and S2, and their wind speeds were to be compared. The requirements for this study called for a minimum sample size with a power of 90%, using a two sided test at 1% level that could explain a difference of 0.1 meters per second (between the measured wind speeds at S1 and S2) in a distribution with a standard deviation of 0.8 meters per second. The following R function call was used:

```
> power.t.test(delta=0.2, sd=1.3, sig.level = 0.01, power=0.9)
    Two-sample t test power calculation
            n = 1258.968
        delta = 0.2
           sd = 1.3
    sig.level = 0.01
        power = 0.9
  alternative = two.sided
 NOTE: n is number in *each* group
```

Computation using R statistical software gave a minimum sample size of 1259. This calculation had assumed the industry's maximum error allowable of 5% and average wind speed of 5 meters per second translating to 10 minutes sample data running continuously for 8.74 days.

Data loggers in industry samples data every one or two seconds and then their internal algorithms process this data and stores on ten minute basis. The algorithms work on stored data and present it as average, standard deviation, maximum, and minimum value. The data logger to be used was to be similar with the meteorological one to ensure they recorded similar wind parameters at the same time interval.

This study was not for prediction and thus a timeframe of one month was chosen in order to collect continuous ten minute sample data for analysis which could approximate to 4320 samples for a 30 days month. The 4320 samples were far above the minimum sample size of 1259 to cater for any data validation losses and data collection risks.

3.2 How the selected study area was justified.

A typical location choice could have been S1 and S2 to be located at the same point, but this is mutually exclusive; all meteorological stations in Kenya are established and managed independently from the mobile BS.

A practical option was to first study local wind patterns and chooses an existing meteorological station that lies in a common prevailing wind current with an existing BS. For valid analysis of relationship between the collected wind data, the site selected was supposed to have on record average wind speeds above 3.5 metres per second which is the minimum operational speed of commercial scale wind turbines [36].

Kibiko area was chosen because it lies in the wind corridor running from Kilimambogo hills to Ngong hills [37] and has Safaricom's Kibiko BS and

KMD's Kibiko meteorological station. Ngong hills terrain funnels and accelerates winds around Kibiko before winds pass over and are dispersed in the Rift Valley on the western side. This area has recorded good wind conditions for investment in wind energy [38]. Kengen has installed 5.3 MW Wind station nearby and had

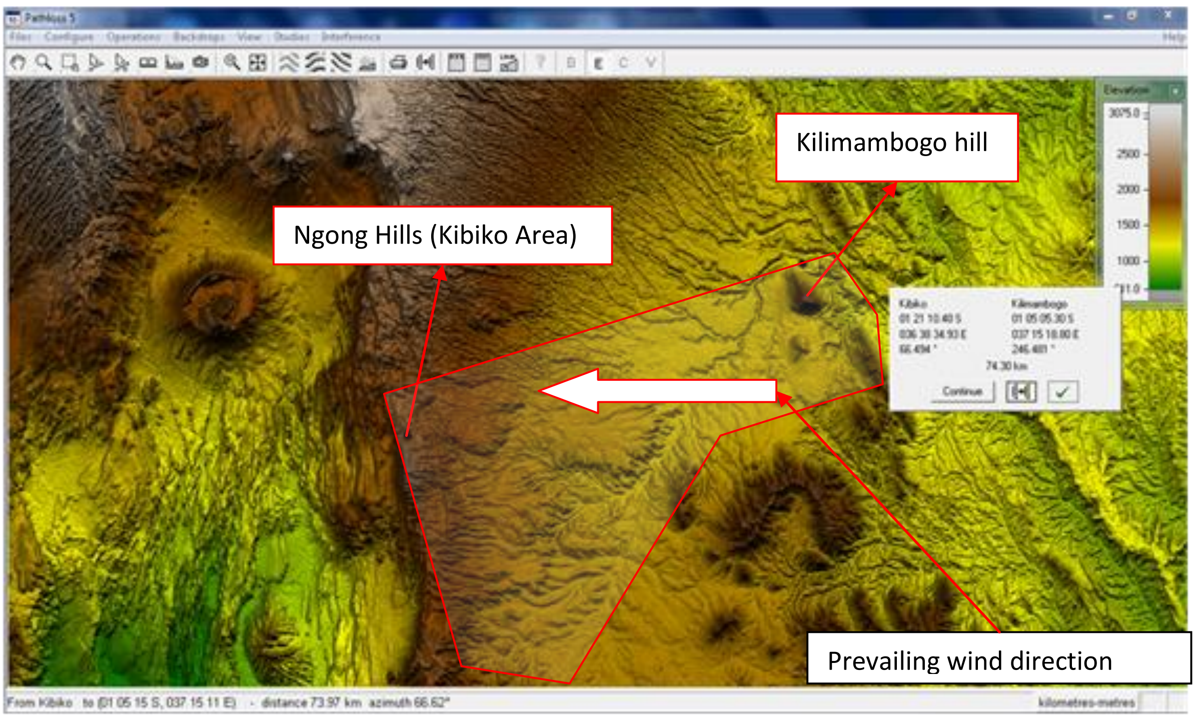


Figure 3-3-1: Pathloss-5 terrain view of the kilimambogo Hill-Ngong hills wind

commissioned an additional 20MW with a recorded load factor of 36% [39].

3.2.1 Reference station-Ngong Meteorological station (S2).

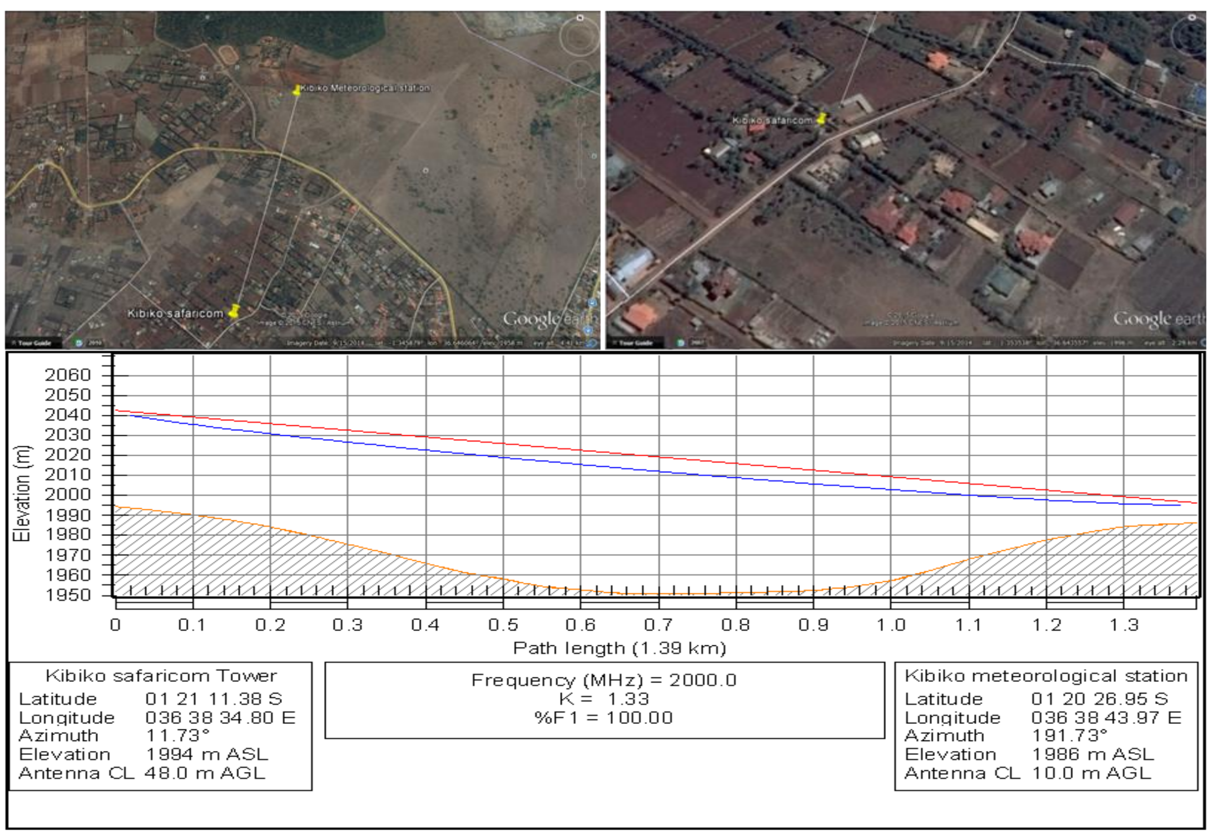
Location details are as follows: 01 20 26.95S, 036 38 43.97E, and altitude of 1986m. The data logger uses a private transmission network to convey results to the central meteorological headquarters and also their staffs take measurements on hardcopies at hourly intervals. Besides wind, the meteorological station houses other basic meteorological instruments.

S2 could be clearly observed from S1 ground level and prevailing winds pass S1 before reaching S2 Figure 3-3-1 .

3.2.2 **Target Station-Kibiko Safaricom BS (S2)**

location details: coordinates 36.367553°E, 0.62275°S, and altitude of 1998m above level. Anemometer was mounted at 50m standing slightly higher from the tower top on a fabricated bracket. The station is located 1.39km, on a bearing of 191° away from the reference site.S1 could be seen clearly ten meters ground level above at S2.

The target station has an indoor shelter with a secure power supply and sensitive equipment. Site is on 24h/7day surveillance on hired security services with a



Picture3-1: Top is Kibiko Area arial view from google earth, bottom is the terrain profile as generated by Pathloss5.

telemetric alarm system to deter vandalism, fire, flooding, power failure etc. It is supplied by utility power, standby generator and a battery back-up system to keep on essential loads connected even during mains and generator failure.

3.3 Preliminary Arrangements before Observation

Following the request approval from Safaricom and the Kenya Meteorogical department, permission was granted for research at Kibiko BTS station and Kibiko meteorological stations respectively. Netsol Kenya company being my employer and Safaricom site maintenance contractor at Kibiko site facilitated my access to S2. The KMD staff supported me in setting up the leased data logger and access to meteorological data and services.

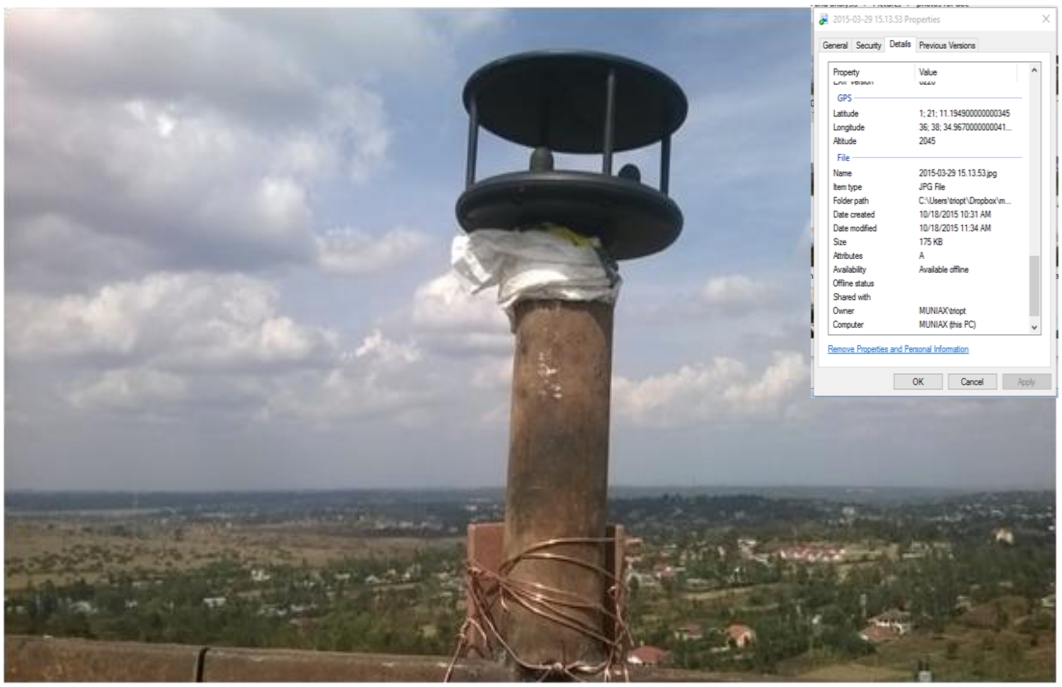
S1 was visited first to take note of its wind measurement plan in order to have a similar setup arranged for S2. Similar data loggers were to be employed with similar anemometers in order to normalize the random errors. It wasn't mandatory to have measurements taken at the same height in order to have flexibility in choosing the best mounting position at S2. However the heights were to be noted for analysis purposes that were to employ the wind shear calculations.

The prevailing wind direction for the area was noted using previous measurements recorded at S1. This would be useful in selecting the mounting position of anemometer on S1 tower to minimize tower effects on measurements.

3.4 Observation Setup

S1 uses a SUTRON data logger housed inside its shelter as shown in and connected by a cable to an ultrasonic anemometer mounted ten metres on a lattice tower. The data logger automatically recorded wind measurements at ten seconds intervals. Communication between the data logger to the KMD was though a LAN.

The meteorological technical staff offered guidance in the selection of a similar [anemometer and data logger from their store to be installed at S2. A metallic bracket was fabricated by help of a local welder to mount the anemometer on top of the fifty metre S2 tower as shown in Picture 3-2 . The anemometer was mounted on top of the tower and inclined to the true north; its magnetic compass reading being compensated by the local declination angle. Care was taken to avoid mounting the anemometer in the wake of the lightning arrestor to the prevailing wind direction which could distort measurements. The data logger was securely



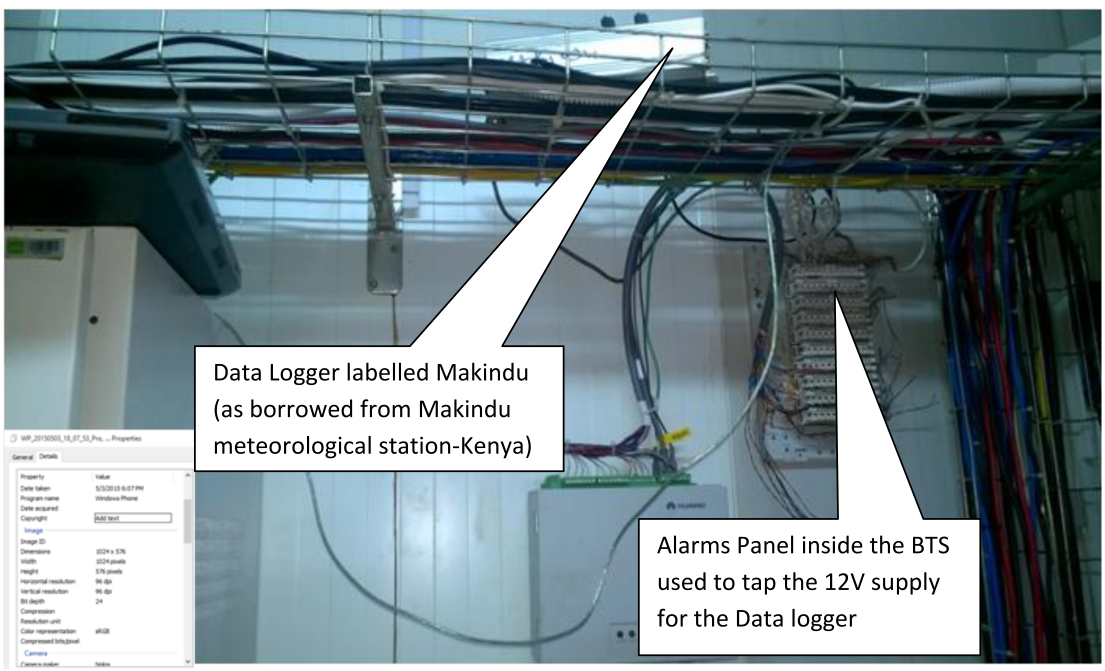
Picture 3-2: Mounted anemometer ready to take measurements, inset; picture details.

anchored inside the BS shelter and supplied by twelve volts secure power supplied from the alarms panel. Data was collected for duration of one month running in concurrence to the proposed BS wind data logger.

3.5 Data collection

3.5.1 Estimation of the Roughness Class of BS Environment

Estimation of the roughness class of the BS environment was done by analysing the immediate surrounding within a kilometre. Attention was given to obstacles within 100m and panoramic pictures were taken at the ground level in six



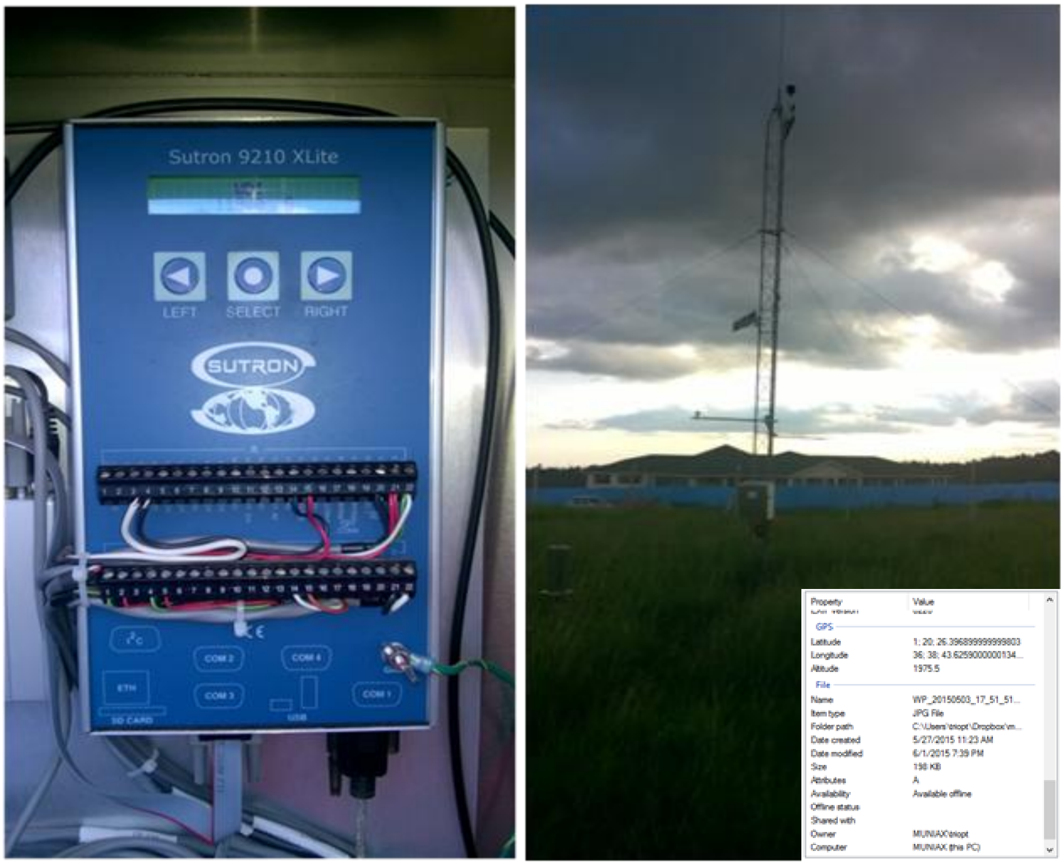
Picture3-3: Data logger placed securely inside the BTS cable-run, powered from the alarms panel.

principle directions as shown in Picture 3-4, length and width of tower members.

3.5.2 Data retrieval from the stations

Mobile telecommunication network service is capable of supporting modern data loggers employing GPRS and UMTS service for data transmission. The KMD currently employs its internal network for transmission of logged data to the central station alongside manual data recording by resident staff. This experiment was set up in line with the current set up of the KMD and therefore didn’t explore this option of data transmission for easy comparability of results.

Picture 3-4: Panoramic Pictures taken at S1 (Ground Level)



Picture 3-6: Sutron 9210 XLite data logger used at the Kibiko meteorological station; Kibiko meteorological station 10 metres high mast for wind measurement.

Recorded data was retrieved from the S1 at three days interval and S2 after a month. This was so because S1 data logger could keep data for three months and S2 data logger could keep data only for 3 days. This was confirmed to have no

04-01-0750_04-03-1840 - Notepad

File Edit Format View Help

04/01/2015	07:50:00	WSI	11.2	knots	G
04/01/2015	07:50:00	WSA	9	knots	G
04/01/2015	07:50:00	WDA	84.9		G
04/01/2015	07:50:00	GUST	11.3	knots	G
04/01/2015	07:50:00	GUSTDIR	75		G
04/01/2015	07:50:00	AT	215.7	C	G
04/01/2015	07:50:00	RH	100	%	G
04/01/2015	07:50:00	HRSSUN	0.17	hr	G
04/01/2015	07:50:00	SOLRAD	26338	WH/m2	G
04/01/2015	07:50:00	DP	0	C	B
04/01/2015	07:50:00	BARO	0	hPa	B
04/01/2015	07:50:00	QFE	0		B
04/01/2015	07:50:00	QNH	0		B
04/01/2015	07:50:00	QFF	0		B
04/01/2015	08:00:00	ATMIN	215.7	C	G
04/01/2015	08:00:00	ATMAX	216.2	C	G
04/01/2015	08:00:00	RAIN	0	mm	G
04/01/2015	08:00:00	WSI	11.6	knots	G
04/01/2015	08:00:00	WDI	89		G
04/01/2015	08:00:00	WSA	10	knots	G
04/01/2015	08:00:00	WDA	84.9		G
04/01/2015	08:00:00	GUST	12.5	knots	G
04/01/2015	08:00:00	GUSTDIR	89		G
04/01/2015	08:00:00	AT	215.8	C	G
04/01/2015	08:00:00	RH	100	%	G
04/01/2015	08:00:00	DP	0	C	B
04/01/2015	08:00:00	HRSSUN	0.17	hr	G
04/01/2015	08:00:00	SOLRAD	26599	WH/m2	G
04/01/2015	08:00:00	BATTERY	13.1	V	G

Picture 3-5: Sample data from S2

effect to other data logger's operations. The data logger was connected to the laptop via the serial communication port using software provided by the meteorological department staff. Data was transferred from the data logger to the laptop for further analysis.

3.5.3 Data output

Data output was in ***ASCII*** format with measurements for Gust speed, Gust direction, Average (10minutes) Wind Speed and direction and instantaneous wind speed. A sample raw data output is displayed in Picture 3-5.

3.5.4 Data processing

Table 3-1: Processed, combined and matched data from S1 and S2

Data Logged at S2							Data Logged at S1					
DATE TIME	GUST	GUSTDIR	WDI	WSI	WSA	WDA	GUST	GUSTDIR	WDI	WSI	WSA	WDA
04/01/2015 08:00:00	12.5	89	89	11.6	10	84.9	9.3	111	96	7.9	6.6	100.3
04/01/2015 08:10:00	12.9	97	93	10.6	11	96	12.1	111	118	10.9	7.1	100.4
04/01/2015 08:20:00	13.7	103	103	8.2	11.3	99.7	12.1	112	112	8	7.4	101.1
04/01/2015 08:30:00	11.7	97	79	9.1	9.9	95.8	11	104	93	5.8	6.8	93.9
04/01/2015 08:40:00	12.7	88	87	9.5	9.5	83.5	11.7	104	71	9.1	6.4	96.3
04/01/2015 08:50:00	11.4	79	83	9.1	9.5	81.5	9.6	84	90	6.6	5.1	89
04/01/2015 09:00:00	10	103	98	7.3	7.6	96.2	10.2	84	115	5.9	6.1	95.8
04/01/2015 09:10:00	11.1	88	82	9.7	9.1	71.2	9.7	87	71	5	6.2	86.5
04/01/2015 09:20:00	12.7	76	70	10.8	10	79.8	11.4	108	71	5.6	6.4	88.6
04/01/2015 09:30:00	13.5	78	74	7.8	9.6	73.6	10.1	118	82	8.1	6.8	92.1
04/01/2015 09:40:00	12.1	83	96	11.1	8.4	67.8	9.7	86	103	5.2	6.9	85.8
04/01/2015 09:50:00	15.3	116	103	11	11.5	102	9.1	99	108	8.1	6.7	77.8
04/01/2015 10:00:00	13.6	110	79	7.8	10.4	84.2	11.1	109	103	9	7.7	89.2

The ***ASCII*** raw data was converted into ***Microsoft Excel©,*** filtered to remove unnecessary data and organized into columns for easier analysis as shown in Table 3-1.

Analysed data was reconverted into ASCII format for easier analysis using **R** software[2]© and ***windrose***©[3].

[2] R: powerful statistical software. Visit official website, https://www.r-project.org.

CHAPTER FOUR

4 RESULTS AND ANALYSIS

R statistical software and the Wind-Rose software were chosen to aid in data analysis. R was applied in analysis of central tendencies and statistical inferences but Wind-rose was chosen for graphical display of data especially wind roses.

4.1 Roughness Class Estimation by Assessment of Local Obstacles

Kibiko BTS is in a suburb surrounding agricultural land with many or tall sheltering hedgerows and very rough and uneven terrain. This approximates to a Roughness class of 3 and roughness Length of 0.4 m according to Table 2-1. Using **equation (8)** to calculate corresponding β_1 gives 1.5.

4.2 Time series Plots for wind speed and wind direction.

Time series plot using the recorded data was plotted for combined series using Wind-Rose software as shown in Figure 4-4-2.

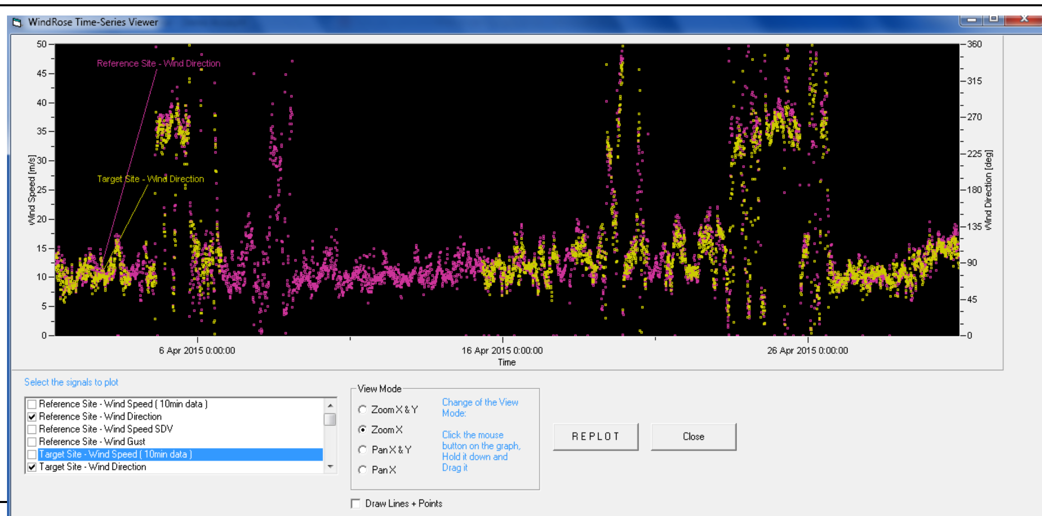


Figure 4-4.2 Wind direction time series plot (WindRose software).

[3] WindRose: wind data analysis and correlation software. Visit official website, http://www.windrose.gr.

Analysis of the time series plots for the 10 minutes average shows a close positive correlation between the reference wind speed and target wind speed. Wind direction of the target site is almost the same as wind direction of the reference site as shown in

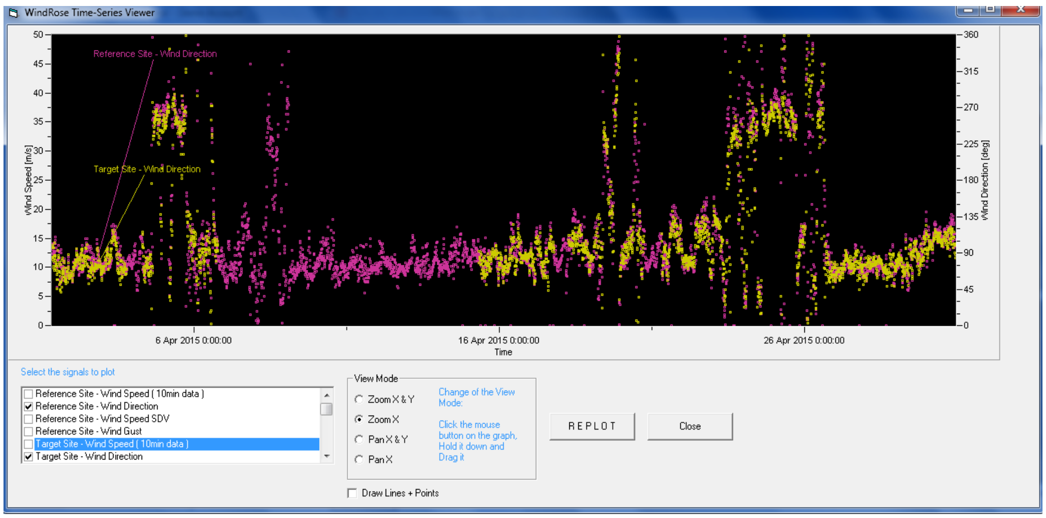


Figure 4-4.2.

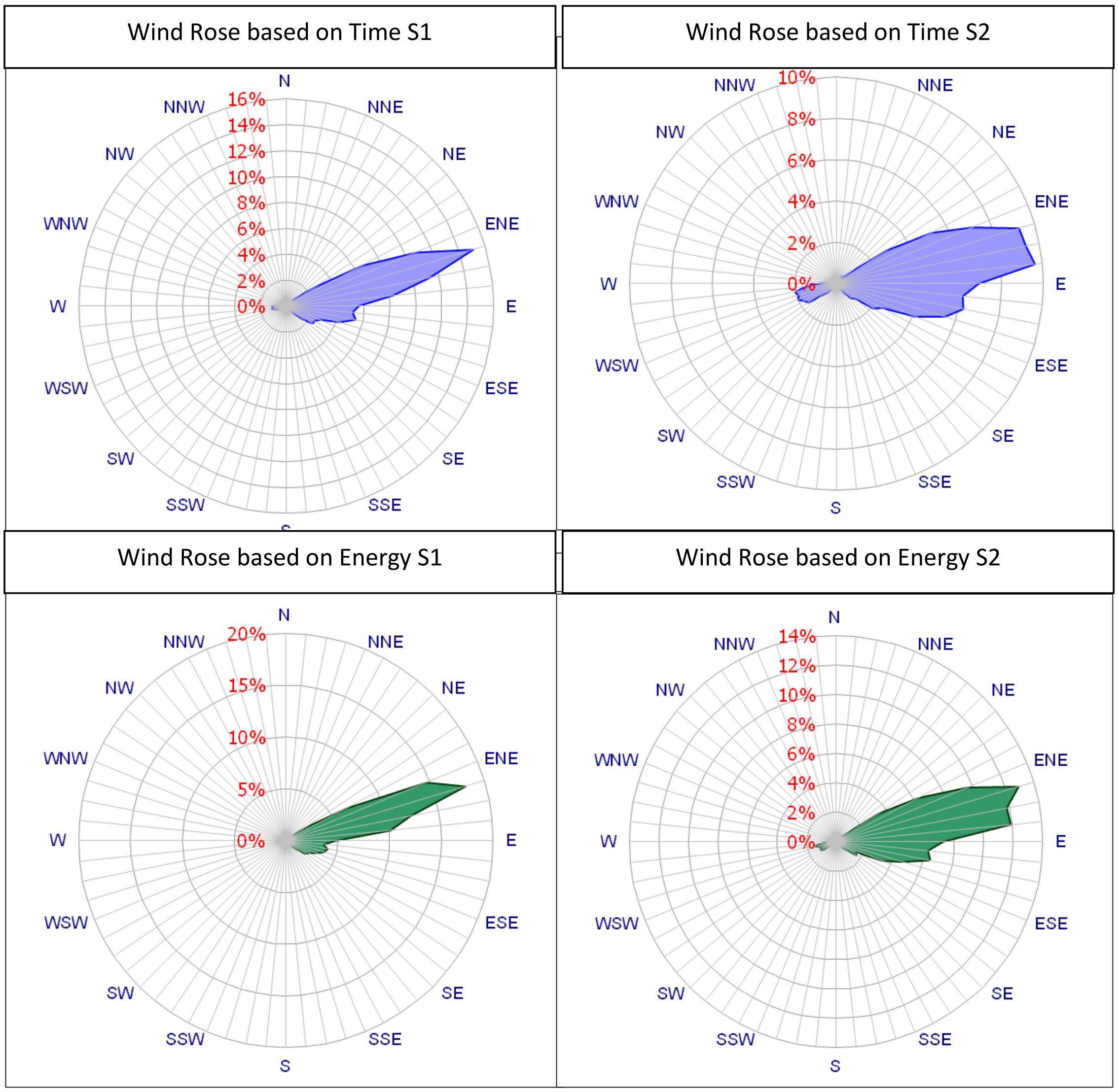


Figure 4-1: Wind Roses

4.3 Wind Rose Plots.

Results yielded similar wind roses for analysis based on time and energy (Figure 4-1). Wind roses based on energy was more directional as compared to the one based on time. This is so because the one based on energy filters out some data below the wind turbine cut-in wind speed. S2 wind rose had a small plot on the W and WSW direction because the S2 tower is high enough above the relief obstacles so as to capture winds from this direction.

The best sector in wind energy was ENE-73.1° at the reference site and ENE-78.7° at the target site. Plots based on energy and time returned exactly similar wind roses. The data indicates the respective sites have directional prevailing winds in the month of April at 42% and 37%. This is of particular interest for wind turbine placement.

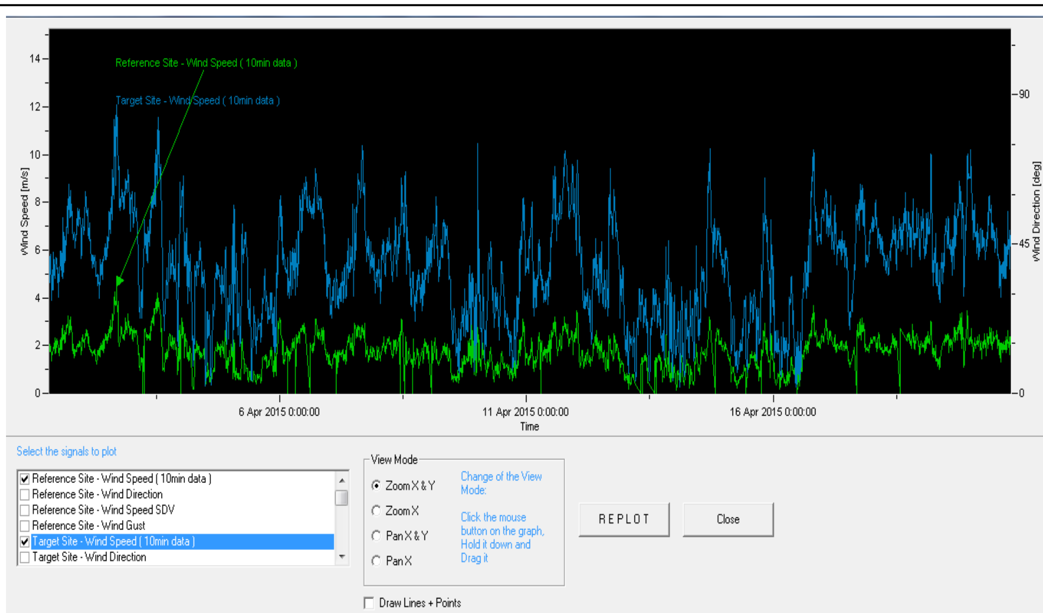


Figure 4-4-2: Time Series plot (using WindRose Software)

4.4 Statistical Inferences

This observation model was treated as a bivariate correlation model and therefore applied ordinary regression techniques for analysis (as described in section A-2-6). Wind speed results in R statistical software were in Knots and were converted to meters per second using a standard unit converter.

4.4.1 Box-Plot

A "box-plot" or more descriptively a "box and whiskers plot" is a graphical summary of a distribution [40]. Figure 4-4-3 shows box-plots for recorded wind speed average at S1 and S2 plotted using R software.

```
> par(mfrow=c(1,2))
> boxplot(WSAS1,WSAS2,col = "bisque",main="Boxplot of Wind Speed at S1 and S2",names=c("Wind Speed S1","Wind Speed S2"),ylab="Wind Speed in Knots")
> boxplot(WDAS1,WDAS2,col = "bisque",main="Boxplot of Average Wind Direction at S1 and S2",names=c("Wind Direction S1","Wind Direction S2"),ylab="Wind Direction in Degrees")
```

It's evident from the boxplots that the average wind speed at S2 is higher than that at S1 but the average wind direction is almost the same. This is because anemometer at S2 was higher (50 meters) that S1 (10 meters).

Table 4-1: Analysis Using R Software.

Site	Mean Wind Speed(m/s)	Correlation coefficient	General regression coefficients of wind speed		Standard deviation	Multiple R squared
S1	3.43		Intercept 0	Multiplier 1.53	1.34	0.97
S2	5.33				2.08	

4.4.2 General statistical results

The general statistical parameters were computed using wind-rose and R software and represented in Table 4-2 and Table 4-1 respectively.

4.4.3 Residuals and normal QQ-Plot

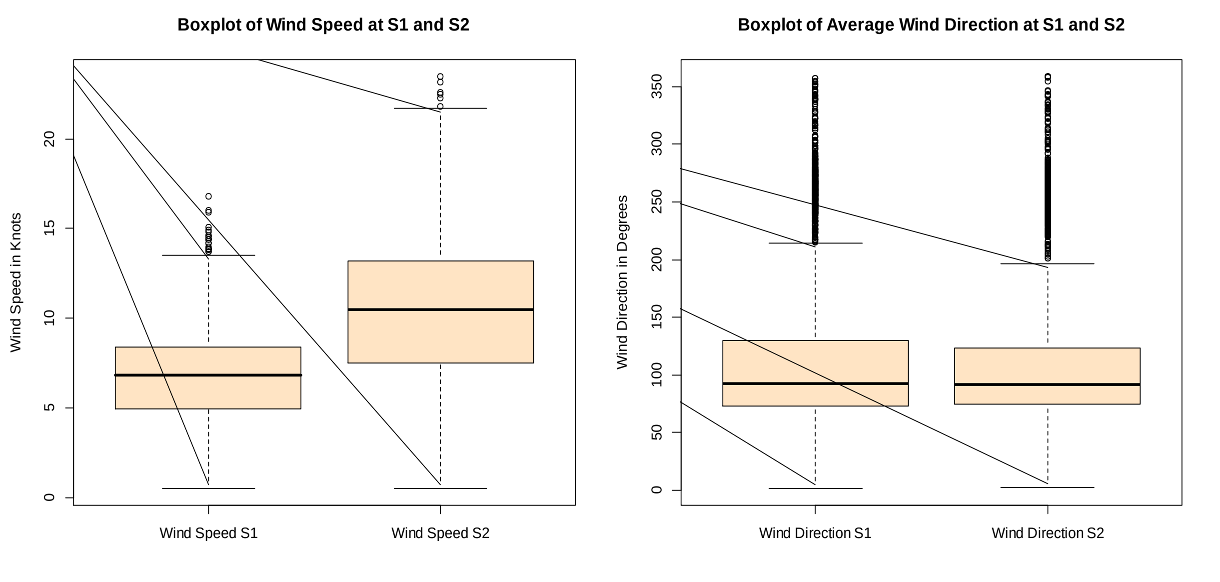


Figure 4-4-3: Box Plot for Wind Speed at S1(1) and S2(2).

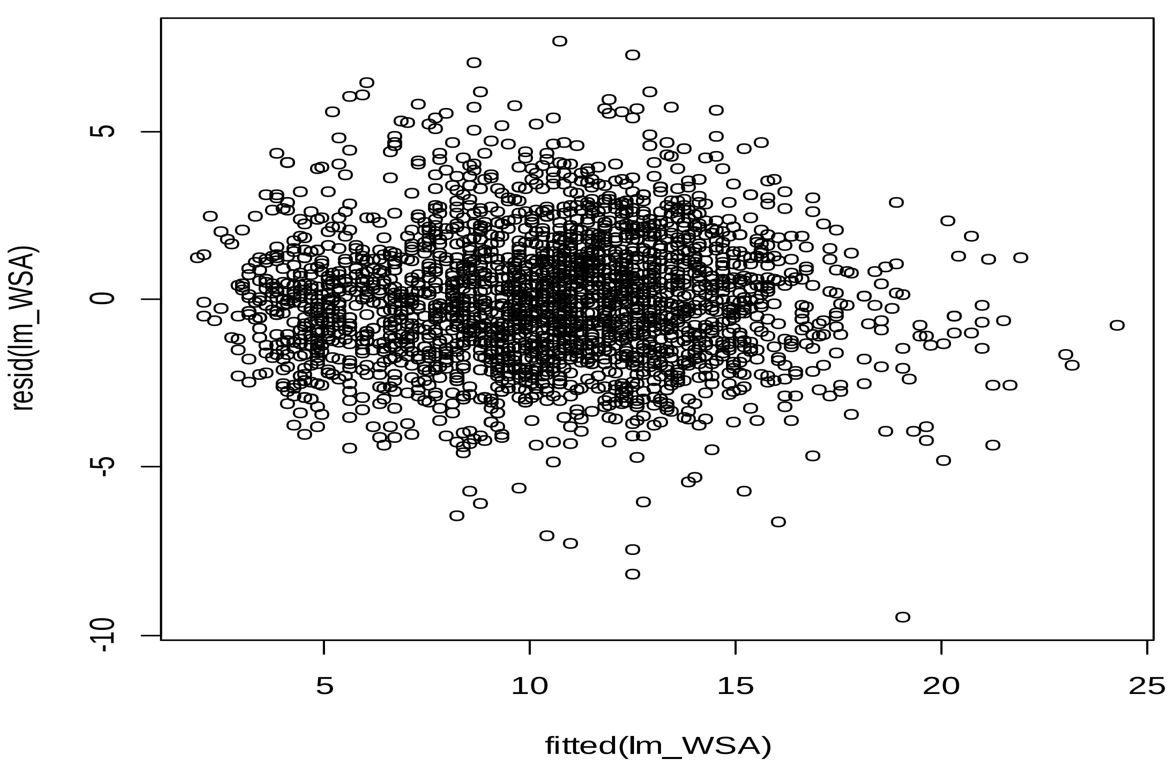


Figure 4-4-4: a plot of residuals verses fitted values.

The main purpose of ploting a normal Q-Q (Quantile verses Quantile) plot is that in this way we could expect to obtain a straight line if data come from a normal distribution with any mean and standard deviation. The Q-Q plots were generated for average wind speed and direction for S1 and S2 using R (Figure 4-4-5) and approximates to a symmetrical distribution of error terms but with heavy tails[35]. The distortion in the middle of normal QQ plots for wind direction was due to the 360° to 0° discontinuity. An interesting observation here is that the normal QQ plot for S2 wind speed data yields more normal distribution of errors as compared to S1.

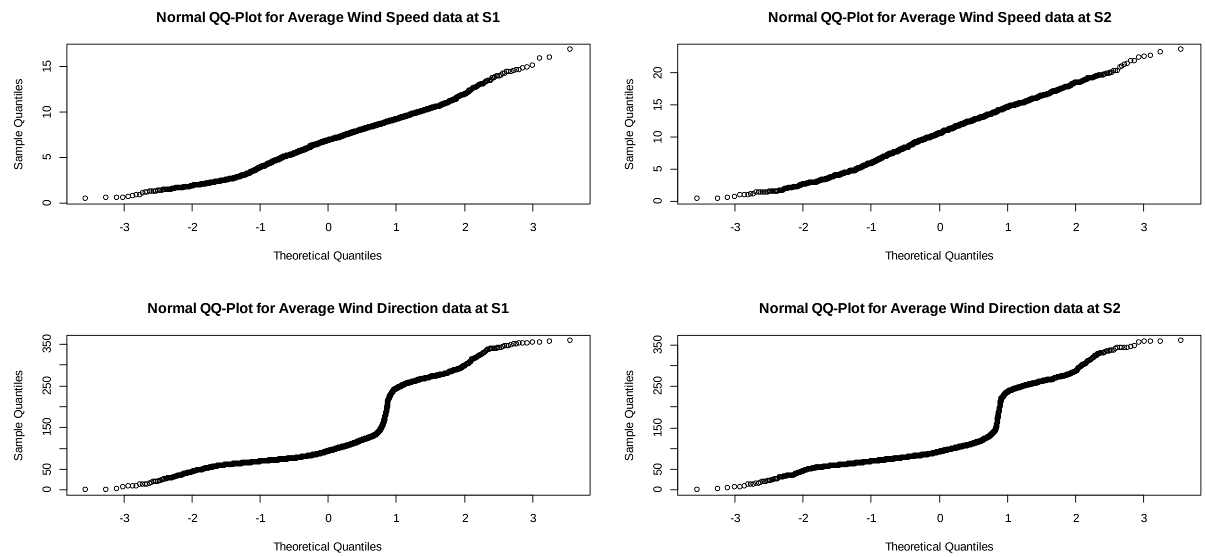


Figure 4-4-5: Normal QQ plots.

The residuals plot in Figure 4-4-4 tests the adequacy of the regression model used. Residuals are concentrated around zero with few outliers. The model is therefore adequete enough to demonstrate that wind speeds at S1 have a positive correlation with wind speeds at S2.

4.4.4 **Regression Plots and Analysis**

The linear regression model for wind speed and wind direction returned the results as shown in Table 4-1 and Table 4-2. The plot is shown in Figure 4-4-6. Regression computation using R used function (*lm(formula = WSA_S2 ~ WSA_S1 - 1))* as illustrated in the appendix forced the regression line to pass though the origin since we expect wind speed at S2 to be zero when wind speed at S1 is zero in

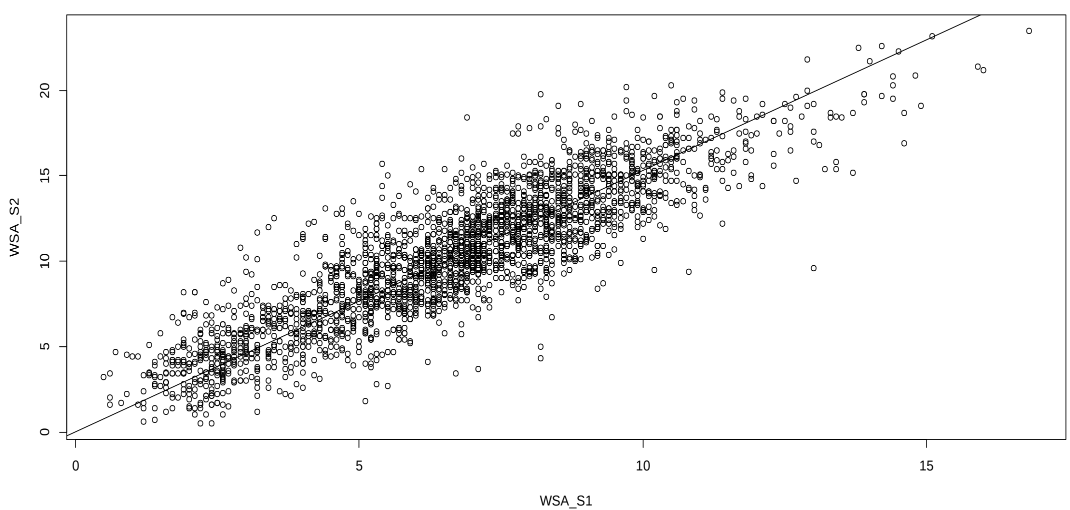


Figure 4-4-6: Regression line Plot of wind speed average S2(WSA_S2) against wind speed average S1(WSA_S1) using R statistical software.

Table 4-2: Analysis Using WindRose.

Number of Data	**Data start at**	**Data End at**	**Mean wind speed (m/s)**	**No concurrent data sets**	**Correlation coefficient**	**Prediction uncertainty for S2 using S1 (m/s)**	**General regression coefficients of wind speed**		**R^2**
4109(S1)	4/1/2015 7:50:00 AM	4/30/2015 10:50:00 PM	3.31	2615	0.852	0.9	1.364	0.636	0.723
2764(S2)	4/1/2015 8:00:00	4/30/2015 10:50:00	5.21						

reality.

4.4.5 Tolerance Limits, Confidence and Prediction bands.

Narrow band (confidence bands) describes uncertainity about the regression line itself while the wide band (prediction band) describes uncertainity about future observations [40] as plotted in Figure 4-4-8. The tolerance package for R as described by [41] was used to compute and plot tolerance limits and plot as shown in Figure 4-4-7. The R code below was used for plotting tolerance limits.

```
> out<-regtol.int(reg=lm(WSAS2~WSAS1-1),side=2,alpha=0.05,P=0.95)
> plottol(out,WSAS1,WSAS2,side="two",x.lab="Wind Speed at S1(Knots)",y.lab="Wind Speed at S2(Knots)")
[1] "NOTE: A regression through the origin is fitted!"
```

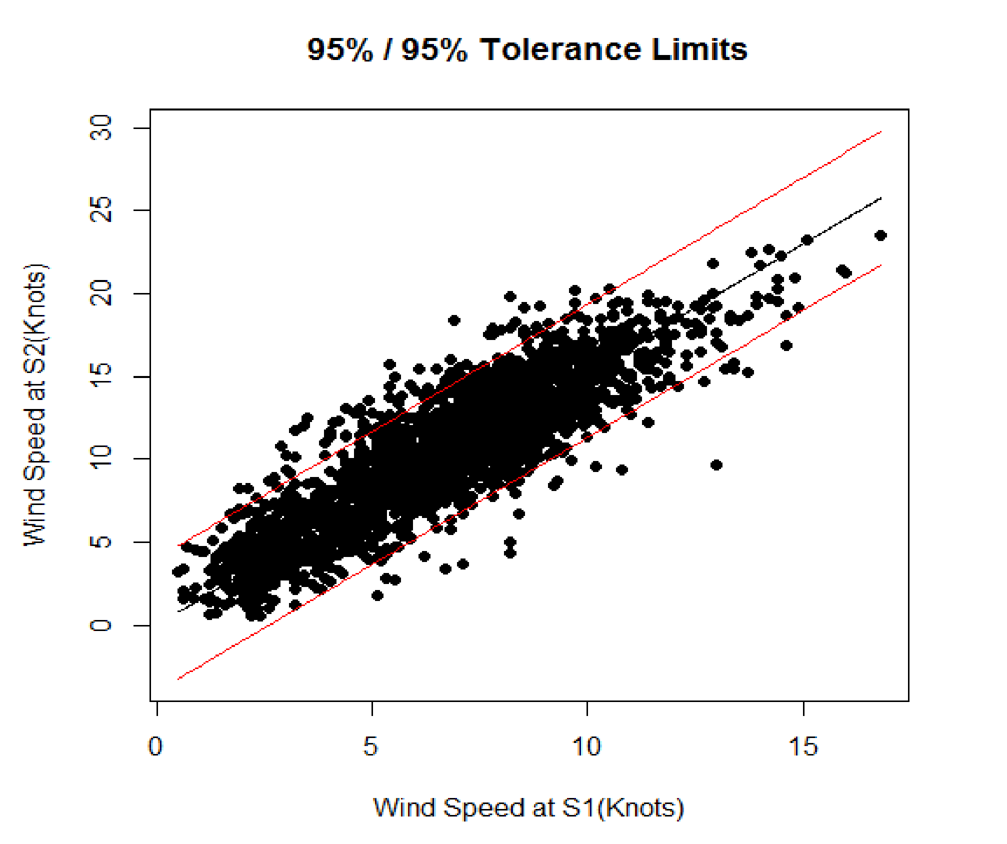


Figure 4-4-7: Tolerance Intervals

With a confidence level of 95%, 95% of average wind speed samples of S2

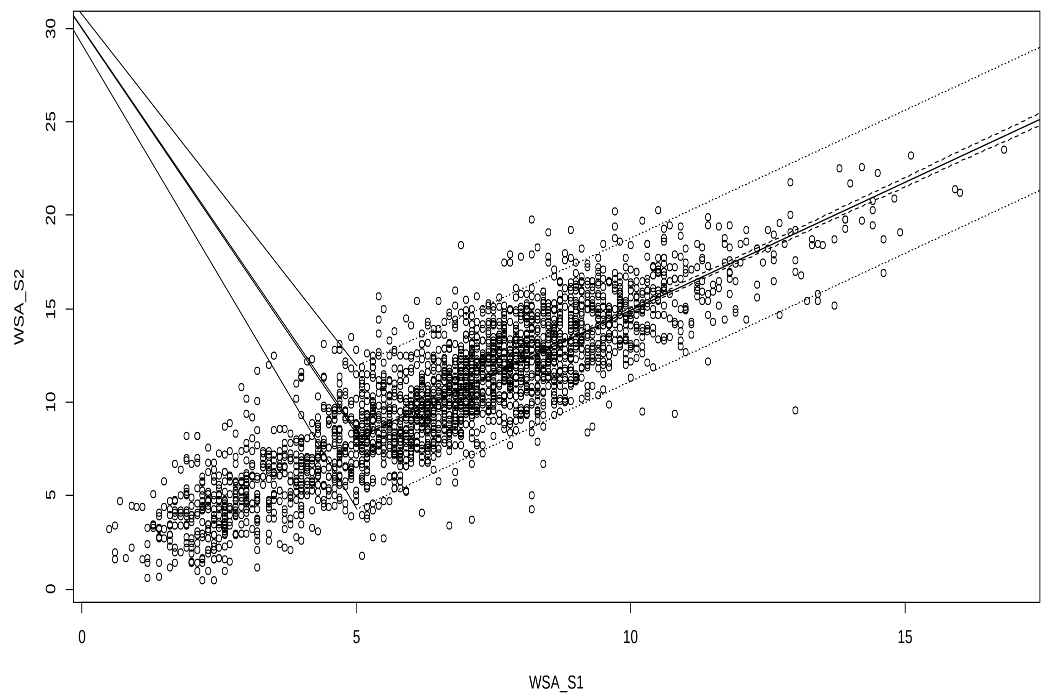


Figure 4-4-8: Plot with confidence and prediction bands.

(plotted in Figure 4-4-7 (between red lines)) could be predicted using data recorded from S1 by applying the linear model. The regression line fits perfectly with very narrow confidence bands as shown in Figure 4-4-8. Majority of observations could also be predicted by the given model. Wind speeds above 6 and 8 meters per second at S1 and S2 respectively perfectly fall within the prediction bands.

4.4.6 **Correlation analysis**

Analysis using WindRose software gave a general correlation coefficient of 0.852 and R software gave a Person's correlation coefficient of 0.87. Further analysis using R software returned the same Spearman's correlation[4]. Slight difference between WindRose and R software could be attributed to the fact that WindRose ignored calms (wind speed values below 2 meters per second) during correlation calculation.The following R function call was used for correlations calculation:

```
cor.test(WSA_S1,WSA_S2)

        Pearson's product-moment correlation

data:  WSA_S1 and WSA_S2
t = 93.6024, df = 2614, p-value < 2.2e-16
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.8685007 0.8861337
sample estimates:
      cor
0.8776138
> cor.test(WSA_S1,WSA_S2,method="spearman")

        Spearman's rank correlation rho
data:  WSA_S1 and WSA_S2
S = 386539036, p-value < 2.2e-16
alternative hypothesis: true rho is not equal to 0
sample estimates:
      rho
0.8704518

Warning message:
In cor.test.default(WSA_S1, WSA_S2, method = "spearman") :
  Cannot compute exact p-values with ties
```

Correlation coefficient was further analysed per wind direction bin using WindRose software and gave results presented on Table 4-3. NE (34°-56°) and WNW direction (281°-304°) returned the largest correlation coefficients (0.9) because the target site is on a bearing of 11° from the reference site (Figure 3-3-1); winds blowing from this direction were expected to have a similar effect at both stations just like in the same tunnel. Similarly SSW winds returned the lowest

[4] Spearman's correlation have the advantage of not depending on the normal distribution and, indeed, being invariant to monotone transformations of the coordinates [40]

correlation due to shadowing effect of the Ngong hills and could not be experience especially at S1.

A comparison for mean direction of S1 (Reference site) and mean direction of S2 (Target site) as shown on Table 4-3 shows a very tight correlation in wind direction especially in sector NE.

Table 4-3: WindRose Correlation results per direction (U > 2 m/s for both sites)

Direction of Ref. Site	From	To	Number of data	Mean Direction of Ref. Site	Mean Direction of Target Site	Corr. Coeff. of wind speed	Ref. site Mean wind speed	Target site Mean wind speed
NNE	11.25	33.75						
NE	33.75	56.25	45	49	50	0.8928	3.32	4.79
ENE	56.25	78.75	739	70	73	0.8498	4.04	6.39
E	78.75	101.25	524	89	86	0.7567	3.78	6.13
ESE	101.25	123.75	359	112	105	0.7903	3.69	5.65
SE	123.75	146.25	139	131	116	0.6728	3.55	5.18
SSE	146.25	168.75	28	156	134	0.6329	3.53	4.83
S	168.75	191.25						
SSW	191.25	213.75						
SW	213.75	236.25	22	225	212	0.8033	2.86	3.23
WSW	236.25	258.75	97	250	244	0.8355	3.19	4.50
W	258.75	281.25	130	269	254	0.8423	3.45	5.04
WNW	281.25	303.75	24	289	272	0.9081	3.32	4.77
NW	303.75	326.25						
NNW	326.25	348.75						
N	348.75	11.25						

Note: Because of the 360°discontinuity, wind direction average cannot be a simple arithmetic mean of directions, but a resultant unit vector.

4.4.7 Significance tests for correlation coefficients

To test for the inequality of the means of the average wind speed samples at S1 and S2, unpaired t-test was used by

t.test(WSAS1,WSAS2)

Welch Two Sample t-test

```
data:  WSAS1 and WSAS2
t = -39.326, df = 4452.2, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -3.895250 -3.525316
sample estimates:
mean of x mean of y
 6.661812 10.372095
```

Which does indicate a significant difference assuming normality. Since both samples are assumed to have come from a normal populations, F test was used to test for equality of variances.

```
> var.test(WSAS1,WSAS2)

        F test to compare two variances

data:  WSAS1 and WSAS2
F = 0.41047, num df = 2615, denom df = 2615, p-value < 2.2e-16
alternative hypothesis: true ratio of variances is not equal to 1
95 percent confidence interval:
 0.3801773 0.4431825
sample estimates:
ratio of variances
         0.4104728
```

Which shows no evidence of a significant difference, and so we can use the classical t-test that assumes equality of variances

```
> t.test(WSAS1,WSAS2,var.equal=TRUE)

        Two Sample t-test

data:  WSAS1 and WSAS2
t = -39.326, df = 5230, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -3.895242 -3.525323
sample estimates:
mean of x mean of y
 6.661812 10.372095
```

Results from the t-tests yield almost the same results confirming the two populations were from a normal distribution.

4.4.8 Wind shear and roughness class computation.

Roughness Length and Roughness Class was calculated as presented on Table 4-4. This was applied to calculate α using regression coefficient β1 and β0. Letting u_1

Table 4-4: Computation summary for wind shear parameters using observational data.

Software	Mean Velocity		Regression parameters		Using Mean Velocity		Using Regression parameters	
	u_1	u_2	β_1	β_0	Z_0	α	Z_0	α
WindRose	3.31	5.21	1.36	0.636	0.59	3.47	0.536	3.39

to be Wind speed at S1 at height z1=10m and u_2 to be wind speed at S2 at height Z2=50m, assuming atmospheric stability conditions and that the wind phenomenon is instantaneous at both sites, respective parameters were calculated as shown in Table 4-4.

4.4.9 Assumptions adopted during analysis.

The observed wind phenomenon was assumed to be instantaneous at both stations under stable atmospheric conditions. These assumptions were made to simplify the analysis using standard formulas.

There is however an obvious time lag for observed wind phenomenon since S1 and S2 are located 1.2 kilometres apart. The data logger computes and stores data sampled within a ten minute averaging period, and taking the average wind speed of 3.31 meters at S1 means it takes about 6 minutes for a current of wind to move between S1 and S2. The standard averaging period therefore captures nearly 50% instantaneous wind phenomenon between the S1 and S2.

The atmospheric conditions are rarely stable and buoyancy forces usually predominate over shear forces [13]. During computation of various parameter in ratio between S1 and S2 is applied which simplifies the equation by cancelling out the frictional velocity terms.

The aim of this analysis was to establish association between explanatory factors (wind speed and direction) as observed on S1 and respective response variables as observed at S2.

Tower and mounting boom effects were ignored with reference to available literature. This was so because the anemometer was mounted on the tower top North Eastern direction tower leg (away from the wake of the lightening arrester) see Picture 4-1.

CHAPTER FIVE

5 CONCLUSION

Analysis summary for results of wind data collected in stations S1 and S2 shows similar wind roses. Recorded wind directions were almost the same with the same mean from time series, Box-plot and wind-rose plots. Results show that with a regression coefficient of 1.53, wind speed at S2 could be modelled as S1 passing through the origin with a correlation coefficient is 0.87. We can be 95% confident that 95% of predicted samples for S2 will lie within the tolerance limits. The regression model gives a RC (roughness class) of 3.4 by calculation compared to an approximate RC of 3 from available literature and observation of surrounding vegetation and obstacles at S2. Calculation of RC is however unnecessary where recorded wind speed at a given height is directly usable without transposing to a different height.

Wind data logged using BTS S2 could thus be representative of data that could logged using meteorological station S1. Under this project research, tower and mounting boom effects were eliminated by mounting the anemometer on top of the tower and away from the wake of the lightning arrest with respect to prevailing wind direction. In cases where the anemometer is mounted with these distortions, available literature on compensation of such effects will be applied.

5.1 Further Work

Time and resources limited the scope of this study to one pair of BS and meteorological station.

Further similar study can encompass a wider random selection of stations picked from wider extents for a more definitive conclusion. For the entire Kenya, locations could be picked randomly from each of the 47 counties for an initial study. Analysis of results from the counties could guide specialised setting up of more logging stations in regions of interest for wind energy evaluation.

This system could be incorporated in a computer program with a data base for real-time data collection and analysis. Results will be transmitted using the mobile network from the sensors located on distributed BS throughout stations of interest. This would be used as a fast and swift alternative to collect site specific wind data that will be very resourceful for government and investors in the wind industry.

It's further proposed the mobile telecommunication industry could enter into a symbiotic relationship with the wind energy industry on this platform. The telecommunication industry shall provide the infrastructure while the wind industry will pay pre-arranged fees.

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A APPENDICES

A-1 APPENDIX A: ANALYSIS GRAPHS.

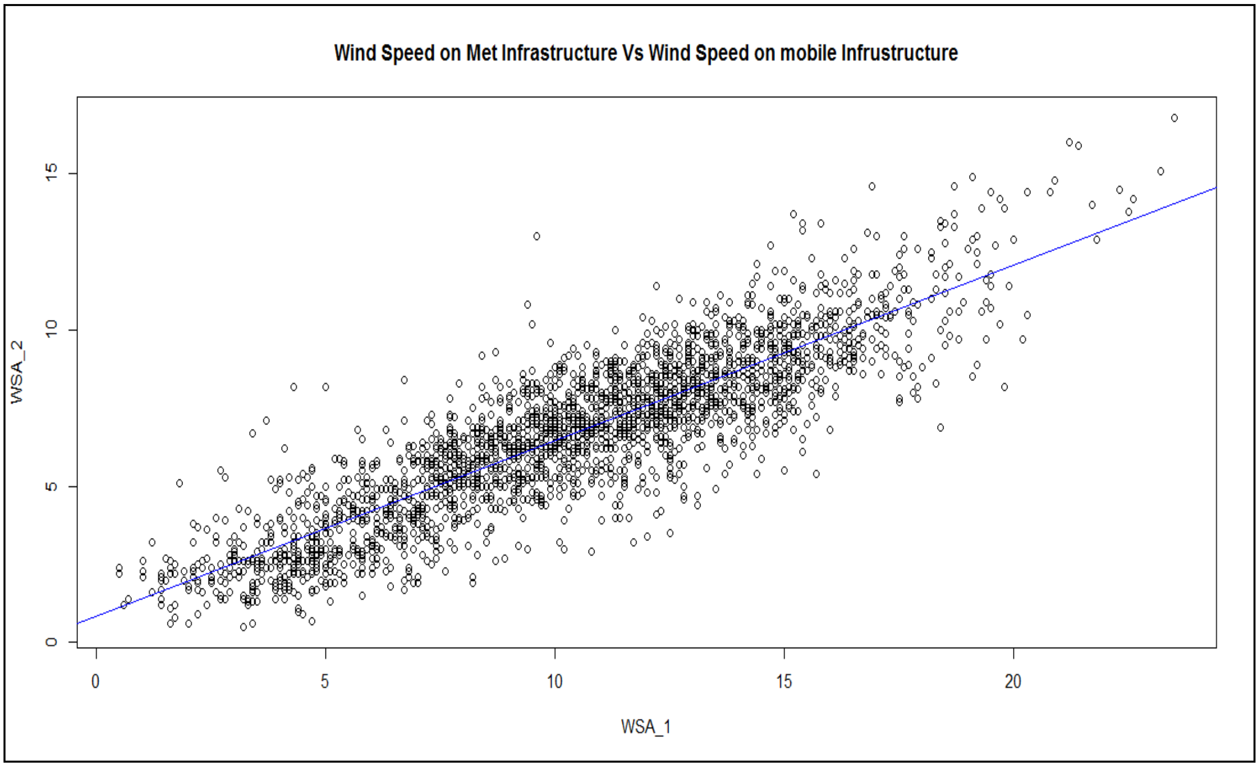


Figure A-1: Reference wind speed against target

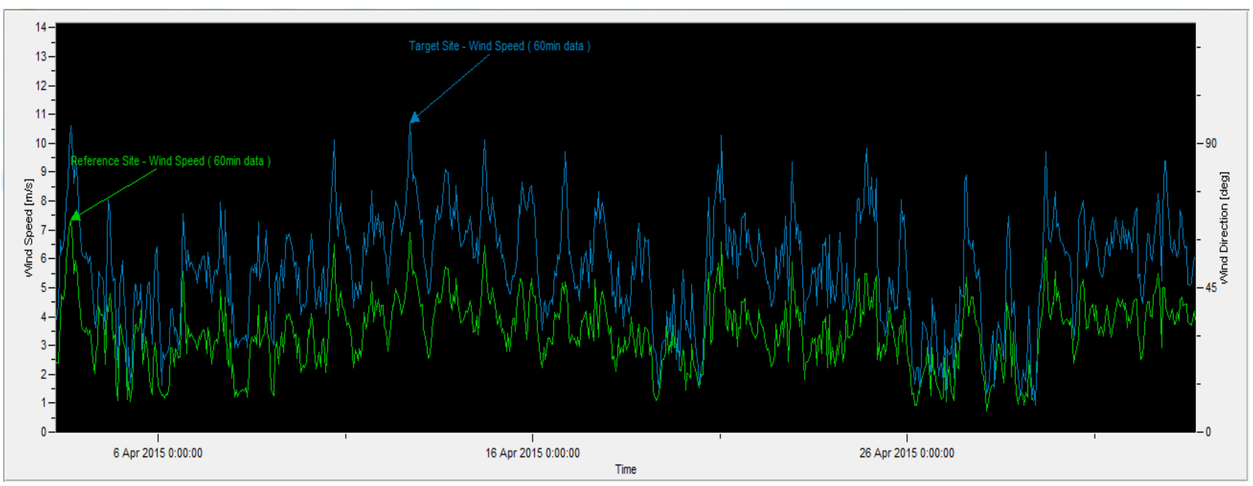


Figure A-2: Concurrent time series for wind speed at both the Reference site and Target site

A-2 APPENDIX B:

A-2-1 LINEAR REGRESSION.

Regression analysis is a statistical methodology that utilizes the relation between two or more quantitative variables so that a response or outcome variable can be predicted from the other, or others [35]. Only one predictor variable will be considered here but analysis with more predictor variables is explained in statistical literature [35].

The relationship between two variables could either be functional or statistical. A statistical relation unlike functional is not a perfect one and the observations do not exactly fall on the curve of relationship.

A-2-2 Estimation of the regression line

A regression line is a formal means of expressing two essential ingredients of a statistical relation: A tendency of the response variable *Y* to vary with the predictor variable X in a systematic fashion and a scattering of points around the curve of statistical relationship. These two characteristics are embodied in a regression model by postulating that: There is a probability distribution of *Y* for each level of X and the means of these probability distributions vary in some systematic fashion with X [35].

The need to reduce reality to manageable proportions when constructing models constrains the use of only a limited number of explanatory or predictor variables in a regression model for any situation of interest [35]. Regression serves for description, control and prediction. Existence of a statistical relation however doesn't imply causality. The normal error regression model is given as:

(A-1)

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i$$

Where Y_i is the observed response in the i_{th} trial, X_i is a known constant, the level of a predictor in the i_{th} trial, β_0 and β_1 are parameters and ε_i are independent $N(0,\sigma_2)$, $i=1,...,n$.

A-2-3 Estimation of Regression Function

GaussMarkov theorem, states: Under the conditions of regression model equation (A-1) the least squares estimators *bo* and b_l in equation (A-2)and (A-3) are unbiased and have minimum variance among all unbiased linear estimators [35].

(A-2)

$$b_1 = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sum (X_i - \bar{X})^2}$$

(A-3)

$$b_0 = \frac{1}{n}\left(\sum Y_i - b_1 \sum X_i\right) = \bar{Y} - b_1 \bar{X}$$

Estimation of parameters β_0 and β_1 uses the method of maximum likelihood (explained in Method of least -Squares). If the scope of some model were to be extended to X levels near zero, a model with a curvilinear regression function and some value of β_0 different from that for the linear regression function might well be required [35].

Equation (A-3) assumes the errors are normally distributed; uncorrelatedness of εi becomes a major assumption of the normal error model. Hence the outcome of in any other trial has no effect on the error term for any other trial whatsoever. This implies Yi are independent normal variables with mean $E\ \{Yi\} = \beta_0 + \beta_1 X_i$ with variance σ_2 as shown in equation (A-3) in the normality assumption in the model is justifiable in many situations because the error term frequently represent the effects of factors omitted from the model that affect the effect to some extent and that vary at random without reference to the variable X_i [35].

It can be shown as an extension of the GaussMarkov theorem that $\hat{Y}$ is an unbiased estimator of *E {Y}*, with minimum variance in the class of unbiased linear estimators, where $\hat{Y}_i$:

(A-4)

$$\hat{Y} = b_0 + b_1 X_i \ldots\ldots i = 1, \ldots, n$$

The fitted value for i_{th} case. Thus, the fitted value $\hat{Y}$ is to be viewed in distinction to the *observed value* Y_i.

A-2-4 Estimation of Error terms Variance σ2 and Residuals

The i_{th} residual, e_i, is the difference between the observed value Y_i and the corresponding fitted value $\hat{Y}_i$ i.e.:

(A-5)

$$e_i = Y_i - \widehat{Y}_i$$

Single population variance σ^2 is estimated by the sample variance S^2, which is given by: where the sum of squares is divided by the degrees of freedom associated with it. This number is (n-1) here, because one degree of freedom is lost by using $\overline{Y}$ as an estimate of the unknown population mean μ.

(A-6)

$$S^2 = \frac{\sum_{i=1}^{n} \left(Y_i - \overline{Y}\right)^2}{n-1}$$

Which is an unbiased estimator of the variance σ^2 of an infinite population. The sample variance is often called a mean square, because a sum of squares has been divided by the appropriate number of degrees of freedom [35].

For the regression model, the logic of estimation of σ^2 is same as for sampling from a single population but uses square of residuals instead (Error Sum of Squares denoted SSE). The SSE has (n-2) degrees of freedom associated with it. Two degrees of freedom are lost here because β0 and β1 had to be estimated in obtaining the estimated means $\hat{Y}_i$. The appropriate mean square denoted MSE is given by equation (A-7)[35].

(A-7)

$$SSE = \sum_{i=1}^{N}\left(Y_i - \bar{Y}\right)^2 = \sum_{i=1}^{n} e_i^{\ 2}$$

(A-8)

$$S^2 = MSE = \frac{\sum_{i=1}^{n} e_i^{\ 2}}{n-2}$$

A-2-5 Estimation of Normal Error Regression Parameters.

Method of maximum likelihood is used to estimate parameters $\beta_{0,}$ β_1 and $\sigma^2$when the functional form of the probability distribution of the error terms is specified. The product of densities viewed as a function of the unknown parameters is called the likelihood function *L(μ)*, and is given by[35]:

(A-9)

$$L(\mu) = \left[\frac{1}{sqrt(2\pi)\sigma}\right]^3 \prod_{n=i}^{n} \exp\left[-\frac{1}{2}\left(\frac{Y_i - \mu}{\sigma}\right)^2\right]$$

In general, the density of an observation Y_i for the normal error regression model equation (A-1) is as follows, utilizing the fact that $E\{Y_i\} = \beta_0 + \beta_1 X_i$ and $\sigma^2\{Y_i\} = \sigma^2$:

(A-10)

$$f_1 = \frac{1}{sqrt(2\pi)\sigma}\exp\left[-\frac{1}{2}\left(\frac{Y_i - \beta_o - \beta_1 X_1}{\sigma}\right)^2\right]$$

The likelihood function for n observations Y_1, Y2,...,Y_n is the product of individual densities in equation (A-10). The maximum likelihood estimators of $\beta_{0,}$ β_1 are the same estimators as those provided by the method of least squares. The maximum likelihood estimator σ^2 is biased, and ordinarily the unbiased estimator *MSE* as given in equation (A-7) is used [35].

A-2-6 Inferences in regression and correlation analysis

Inferences concerning β1 provide valuable information as to how much Xi affects Yi. Tests of particular interest maybe of the form:

H_0: $\beta_1=0$

Ha: $\beta_1 \neq 0$

It is also proved that the studentized statistic ***$(b_1-\beta_1)/s\{b_1\}$*** is distributed as t with n-2 degrees of freedom [35], thus tests concerning β_1 can be set up in ordinary fashion using the *t* distribution.

(A-11)

$$\frac{b_1-\beta_1}{s\{b_1\}} \sim t(n-2))$$

The 1-α confidence limits for β_1 are:

(A-12)

$$b_1 \pm t\left(1-\alpha/2; n-2\right)s\{b_1\}$$

The decision rule with Type 1 error test statistic for controlling the level of significance at α is:

(A-13)

$$\begin{aligned} & if\,[t^*] \leq t(1-\alpha/2; n-2), conclude...H_0 \\ & if\,[t^*] > t(1-\alpha/2; n-2), conclude...H_a \\ & where...t^* = \frac{b_1}{s\{b_1\}} \end{aligned}$$

A-2-7 Correlation and Regression in Wind data Analysis

The regression sum of squares (SSR) and the total sum of squares (SSTO) and interrelationship with SSE are given by [35]:

$$SSR = \sum\left(\widehat{Y}_i - \overline{Y}\right)^2$$

$$SSTO = \sum\left(Y_i - \overline{Y}\right)^2$$

$$SSTO = SSR + SSE$$

The goodness of fit line also referred to us the *coefficient of determination* R^2 is given by equation (A-14), the closer it is to 1 the greater is said to be the degree of linear association between X and Y. A measure of linear association between *Y* and X when both *Y* and X are random is the *coefficient of correlation.* This measure is the signed square root of R^2.

(A-14)

$R^2 = 1 - \frac{SSE}{SSM}$, where R is the goodness of fit, SSE is...and SSM is

(A-15)

$$SSE = \sum_{i=1}^{N} \left(Y_i - \overline{Y}\right)^2$$

(A-16)

$$SSE = \sum_{i=1}^{N} \left(Y_i - \hat{Y}\right)^2$$

$Where : \hat{y} = ax + b$ (a, b are the slope and offset of the best − line fit), $\overline{Y}$ is the time series (Y) mean, $\hat{y}$ is the ordinate of the estimated regression line.

We say that Y_I and Y_2 are *jointly normally distributed* if the density function of their joint distribution is that of the bivariate normal distribution. One principal use of a bivariate correlation model is to make conditional inferences regarding one variable, given the other variable. If a researcher has data that can be appropriately described as having been generated from a bivariate normal distribution and wishes to make inferences about Y_2, given a particular value of Y_I, the ordinary regression techniques will be applicable [35]. In such a case, conditional probability function for Y_1 for a given value of Y_2 will be applied as:

(A-17)

$$f(Y_1 / Y_2) = \frac{f(Y_1, Y_2)}{f_2(Y_2)}$$

Where $f\ (Y_1,\ Y_2)$ is the joint distribution function of Y_1 and Y_2, and $f_2\ (Y_2)$ is the marginal distribution function of Y_2. It can be shown that the conditional probability distribution of Y_I for any given value of $Y2$ is normal with mean $\alpha_{1/2}$ + $\beta_{12}Y2$ and standard deviation $\sigma_{l/2}$ and its density function is:

(A-18)

$$f(Y_1/Y_2) = \frac{1}{\sqrt{2\pi\sigma_{1/2}}}\exp\left[-\frac{1}{2}\left(\frac{Y_1-\alpha_{1/2}-\beta_{12}Y_2}{\sigma_{1/2}}\right)^2\right]$$

The parameters $\alpha_{1/2}$, β_{12}, and σ_{12} of the conditional probability distributions of Y_I are functions of the parameters of the joint probability distribution, as follows:

(A-19)

$$\alpha_{1/2} = \mu_1 - \mu_2\rho_{12}\frac{\sigma_1}{\sigma_2}$$

(A-20)

$$\beta_{12} = \sigma_{12}\frac{\sigma_1}{\sigma 2}$$

(A-21)

$$\sigma_{1/2}^2 = \sigma_1^2\left(1-\sigma_{12}^2\right)$$

The parameter $\alpha_{1/2}$ is the intercept of the line of regression of Y_I on Y_2, and the parameter β_{12} is the slope of this line. Thus we find that the conditional distribution of Y_1 given Y_2, is equivalent to the normal error regression model

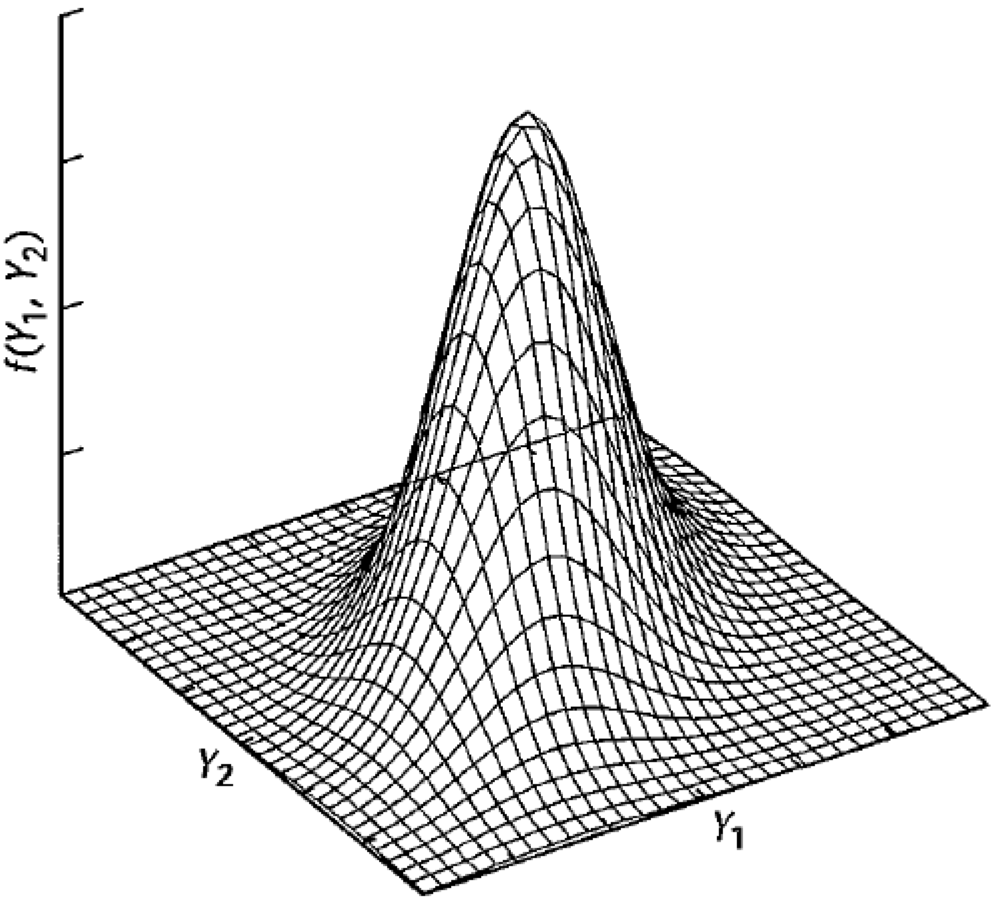


Figure A-3: Example of a bivariate normal distribution[35].

.The density function of the bivariate normal distribution is given as:

(A-22)

$$f(Y_1Y_2) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho_{12}^2}} \exp\left\{\frac{1}{2(1-\rho_{12}^2)}\left[\left(\frac{Y_1-\mu_1}{\sigma_1}\right)^2 - 2\rho_{12}\left(\frac{Y_1-\mu_1}{\sigma_1}\right)\left(\frac{Y_2-\mu_2}{\sigma_2}\right) + \left(\frac{Y_2-\mu_2}{\sigma_2}\right)^2\right]\right\}$$

Where: μ_1 and σ_1 mean and standard deviation of the marginal distribution of Y_1, μ_2 and σ_2 mean and standard deviation of the marginal distribution of Y_2, ρ_{12} is *coefficient of correlation* between the random variables Y_I and Y_2.

(A-23)

$$\sigma_{12} = \rho\{Y_1, Y_2\} = \frac{\sigma_{12}}{\sigma_1\sigma_2}$$

Where σ_{12} is the covariance $\sigma\ \{Y_1, Y_2\}$ between Y_1 and Y_2 defined as:

(A-24)

$$\sigma_{12} = E\{(Y_1 - \mu_1)(Y_2 - \mu_2)\}$$

Marginal distribution for either Y_1 is normal with mean μ_1, and standard deviation σ_1 and Y_2 could be expressed in similar manner:

(A-25)

$$f(Y_1) = \frac{1}{\sqrt{2\pi\sigma_1}} \exp\left[-\frac{1}{2}\left(\frac{Y_1 - \mu_1}{\sigma^2} \right)^2 \right]$$

The random variables Y_1, Y_2 play symmetrical roles in bivariate normal probability distribution.

Correlation Coefficient

(A-26)

$$\rho = \sum_{i=1}^{N} \frac{(X1_i - \bar{X}1)(X2_i - \bar{X}2)}{\sigma_1 \sigma_2}$$

Where ρ is the correlation coefficient, $X1_1$, $X1_2 ... X1_n$ and $X2_1$, $X2_2 ... X2_n$ are the common data of the two independent time-series X1 and X2, with mean values: $\bar{X}1$, $\bar{X}2$ and standard deviations: σ_1, σ_2.

A-2-8 Experimental data

During data collection, control over the explanatory variable(s) consists of assigning a treatment to each of the experimental units by means of randomization. The reason is that randomization tends to balance out the effects of any other variables that might affect the response variable.

A-2-9 Limitations of Using the Correlation Coefficient.

As illustrated on Figure A-4.

A-2-10 Method of least -Squares

To find "good" estimators of the regression parameters β_0 and β_1, we employ the method of least squares. For the observations (X_i,Y_i) for each case, the method of least squares considers the deviation of Yi from its expected value:

(A-27)

$$\mathrm{Y_i} - (\beta_0 + \beta_1 X_i)$$

In particular, the method of least squares requires that we consider the sum of the n squared deviations. This criterion is denoted by Q:

(A-28)

$$Q = \sum_{i=1}^{n} \left(\mathrm{Y_i} - (\beta_0 + \beta_1 X_i)\right)^2$$

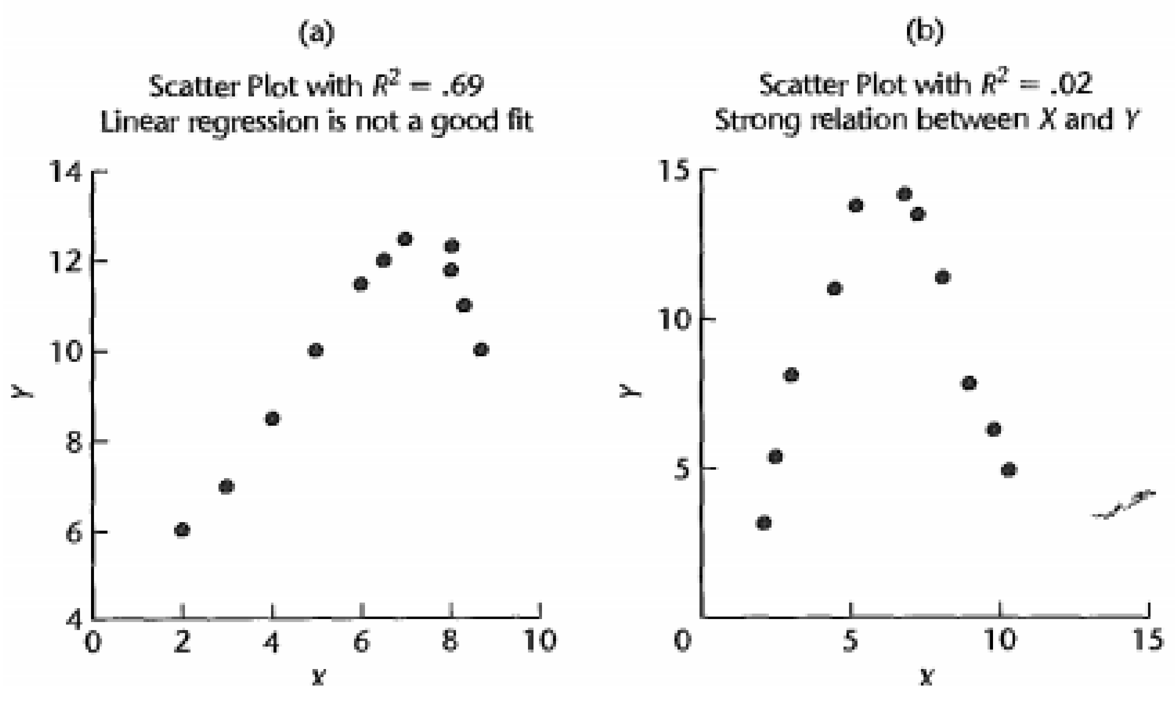


Figure A-4: illustrations of Two Misunderstandings about Coefficient of Determination.

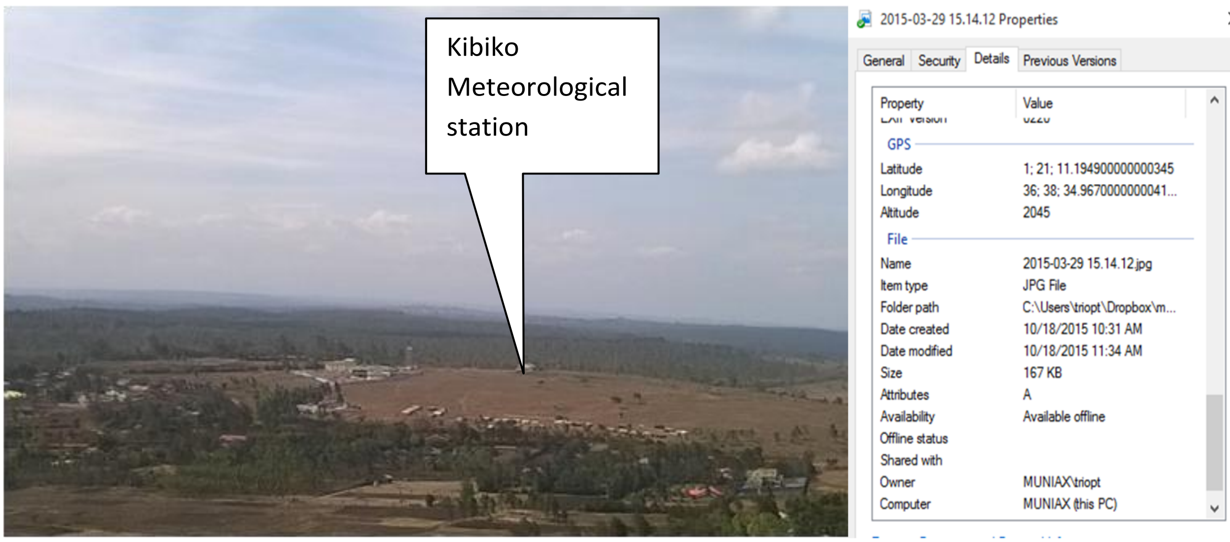
According to the method of least squares, the estimators of β_0 and β_1 are those values

b_0 and b_1 respectively, that minimize the criterion Q for the given sample observations

$(X_1\ Y_I), (X_2, Y_2), \ldots, (X_n, Y_n)$ [35].

A-3 APPENDIX C

A-3-1 : Photos Taken During Data Collection.



Picture A-2: Kibiko meteorological station as clearly observed from the BTS tower top.

Picture A-1: Kibiko BTS station secured with gate with key and remote log in using

Picture A-4: Kibiko meteorological station: Left transmission mast to communicate with the central meteorological station using private network. Right: Wind station and mast

Picture A-3: 12v maintenance-free Battery backup supply.

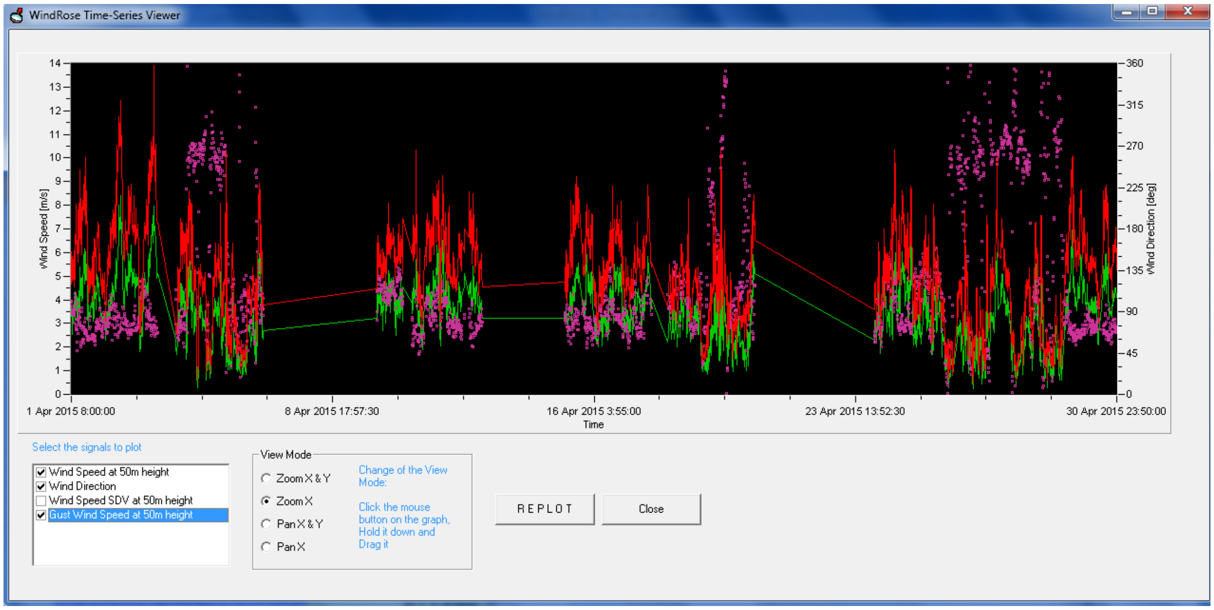


Figure A-6: WindRose time series plot for S1.

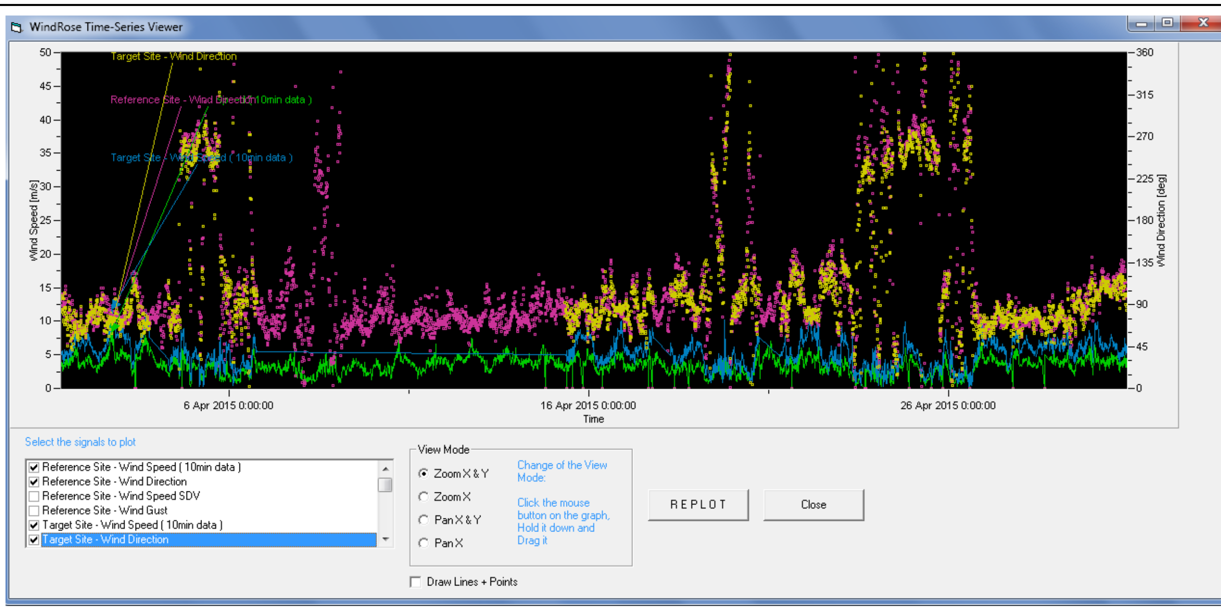


Figure A-5: Time series for S1 and S2 Wind Direction and Speed

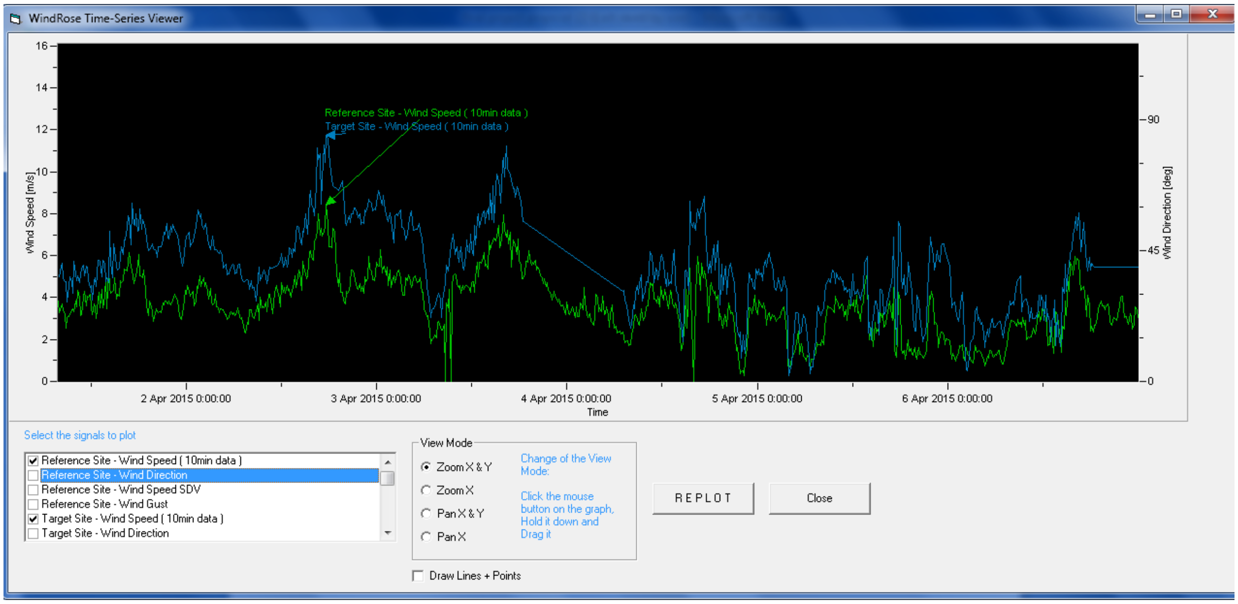


Figure A-7: Simple series courtesy of WindRose Software