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USE OF MAST AND REMOTE SENSING DATA FOR WIND RESOURCE ASSESSMENT IN KENYA.

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Abstract: The main goal of this study was to characterize the winds at Lake Turkana wind energy site using both mast and Doppler LIDAR measurements. The methods used to achieve this objective include the Advanced LIDAR data volume processing technique (ALVPT), time series, correlation and error analysis. Data was collected at 3 masts: Kalkumpei, Nyiru and Sirima using cup anemometers and wind vanes for the entire year, 2009. The Doppler Lidar collected data for 2 weeks from 11th to 24th July 2009. The annual average wind speed at the 3 masts is: 10.44m/s, 10.75m/s & 11.10m/s respectively while the predominant wind direction is south east. Comparison between mast and Lidar measurements was computed during LIDAR data period. The difference between Doppler LIDAR and mast wind speed means is small, the mean standard deviations for both instruments are in close agreement - 0.33, 0.05 & 0.47 and the Correlation is 0.9, 0.6 & 0.73 for Kalkumpei, Nyiru and Sirima respectively.

The windspeed derived from Doppler LIDAR datawasoutputintoa20kmby20kmgriddomainandoverlayedona digitalterrainmodel to create a wind atlas map. This map provides a useful productthat can be used to evaluate Wind Atlas Analysis and Application Program (WAsP) generated wind atlases. LIDAR being mobile has shown great potential to assess winds accurately at any particular site for a range of heights over an area of ~ 200 km^2 and with high radial resolution [~150 m]. Use of Doppler LIDAR for wind assessment is still maturing. Equipment configuration and software changes especially the ALVPT may affect measurement quality and accuracy of retrieved wind speed and direction.

Keywords: LIDAR measurements, mast measurements, resource assessment, wind energy.

Introduction

Kenya has experienced a steady increase in energy demand over the past decade which is linked to both the rising population and the expanding economy. According to 2009 national census, the Kenyan population is around 38 million and only 28% has access to electricity (Kirai, 2009). Over the years Kenya has relied on petroleum imports and hydropower to meets it’s ever increasing domestic and commercial energy requirements (Oludhe, 2008), but the frequent droughts thought to be caused by climate change have led to critical power shortages particularly in years when the droughts are more pronounced like 1999 – 2002 (Oludhe, 2008, Kirai, 2009, Muthuri et al., 2009).

Renewable energy resources particularly wind energy are progressively being investigated for electricity generation with negligible emissions of greenhouse gases (Theuri, 2008). The wind energy resource is naturally a function of the climate system because electricity is generated by the wind turbines which are moved by the winds. Therefore, the prospect of wind energy power generation will increase the resilience of Kenya’s power generation vis-à-vis potential climate risk variations.

The region of study is north-western Kenya where the winds are generated by a low level jet called the Turkana Channel jet. The jet stream is created by the much bigger East African low level jet. The Turkana Channel jet blows lasting through the year from the South East through the valley between the East African and the Ethiopian Highlands extending from the Ocean to the deserts in Sudan (Kinuthia, 1992). The wind is enhanced locally between Mt. Kulal (2300 m ASL) and the Mt Nyiru Range (2750 m ASL). Due to thermal effects, the wind decreases around mid-day and is at full force during the night (Kinuthia, 1992).

Both Kinuthia and Asnani (1982) and Kinuthia (1992) observed that, throughout the year, the NE and SE monsoon near the equator branches off from the Indian Ocean, enters the Turkana channel and intensifies, maintaining an average speed of 10ms^{-1} (Figure 1). Their observations showed quite distinct low-level jet in the channel (Turkana easterly low-level jet) that persists throughout the year. They further hypothesized that the configuration of the Ethiopian highlands and the East African highlands could be playing a critical role in the development and maintenance of the Turkana low-level jet through the orographic channeling effect.

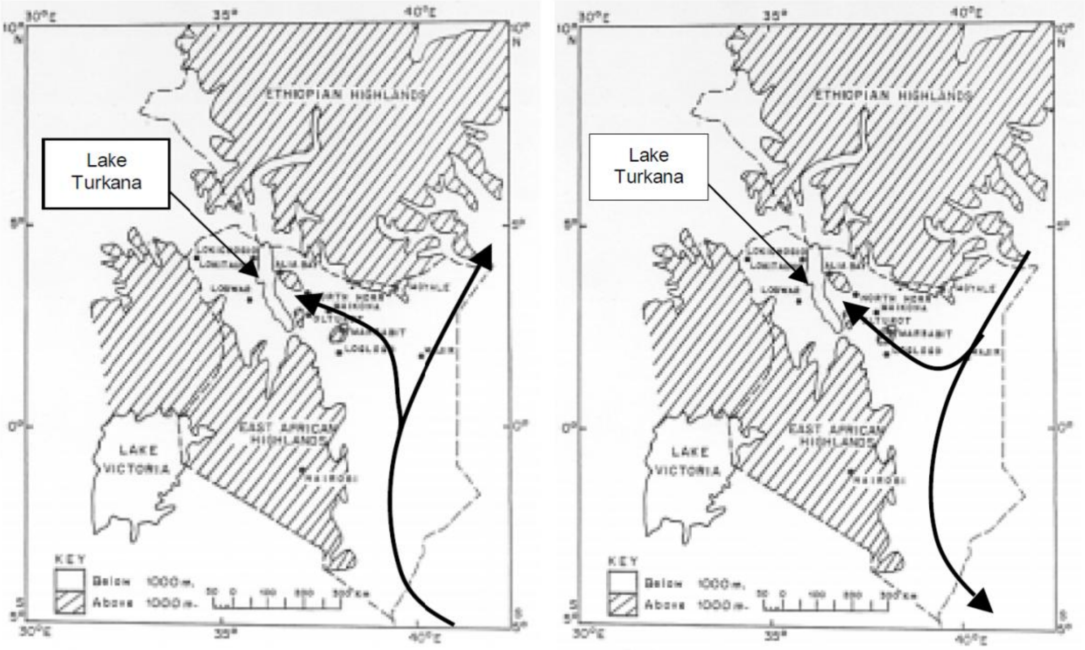

Figure 1: A simplified model showing the cross-equatorial monsoon flow diverting into the Turkana channel during (a) northern summer, and (b) northern winter (Indeje, 2000).

Resource assessment using Mast measurements

Conventional site assessment process relies on the use of meteorological towers and wind speed and direction sensors in order to evaluate the wind resource at a site. The most common wind speed and direction sensors are cup anemometers and wind vanes. The Wind Resource Assessment Handbook (Baily, 1997) provides a detailed description of many aspects of the site assessment process, especially a method of evaluating the wind resource at a site.

Wind resource measurement campaigns are almost always carried for at least one year; this is uniformly recommended in reputable site assessment manuals (Baily, 1997, Gardner et al., 2004). This practice is accepted primarily because of seasonal variations in the wind resource. The most common type of anemometer used for wind energy site assessment is the cup anemometer (Manwell et al., 2002.). The performance of a cup anemometer is determined by a variety of factors, including its size and weight, bearing friction, and cup design (Manwell et al., 2002., Pedersen and Paulson, 1999). The accuracy of a cup anemometer is generally assumed to be approximately 0.1 m/s (1-2% of the mean wind speed), based on wind tunnel tests by (Pedersen, 2004, Westermann, 2003, RISØ., 2004).

There are several factors which influence the accuracy of a power estimates using meteorological mast measurements. These factors are broadly classified into six categories: Wind Speed Measurement Uncertainty (Baily, 1997); Long-term Resource Estimation Uncertainty (Gardner et al., 2004, McCaa, 2006, Oliver, 2006, Moon and Miler, 2005); Wind Resource Variability Uncertainty(McCaa, 2006, Moon and Miler, 2005); Site Assessment Uncertainty (Feuquay et al., 2005, Livingston and Anderson, 2004, Oliver, 2006, Brower, 2006); Topographic Effects (Oliver, 2006 and Brower, 2006) and Wind Shear Model Uncertainty (Livingston and Anderson, 2004).

Resource Assessment using Remote Sensing Devices

With the constantly expanding advancement of physically bigger wind turbines (both in hub height and rotor diameter), the requirement for taller and taller masts (and several masts for the bigger sites now being developed) is adding both significant cost and danger to ventures, especially those in the early stages, preceding financing. At the same time, the current practice of basing power performance measurements on a solitary, hub-height wind speed measurement gets to be instinctively more suspect for such huge rotor swept areas. Recent numerical studies (Wagner R. et al., 2007) demonstrate that the relationship between measured electrical power and wind speed increases if the wind speed is based on a weighted mean of the wind speed profile over the entire rotor rather than on a single point measurement. Here, remote sensing is positioned to assume a significant role.

LIDAR systems are ground-based wind speed measurement devices that utilize electromagnetic radiation to measure the wind speed. The use of LIDARs for wind resource assessment is a more recent development (Albers, 2006). Until recently, making wind speed measurement using LIDARs was restrictively expensive (Huffaker R. M. et al., 1970). Suitable lasers were expensive, extensive and required intricate cooling systems. The optical frameworks were based on conventional optical-benches and were intrinsically hard to keep aligned. Moreover it was hard to get a sufficient acquisition rate while keeping these early frameworks eye-safe. All these limits were cleared aside by the rise of sufficiently coherent lasers.

The performance of LIDARs for wind resource assessment appears to be very promising. While there is not a great deal of experience with the use of LIDARs, preliminary evaluations of the ZephIR LIDAR show a high level of performance. The evaluations of the ZephIR from three separate institutions compare the LIDAR wind speed measurements to cup anemometer wind speed measurements from a meteorological tower, and the results indicate very high correlation coefficients (~0.99) between the measurements, with average errors less than 1% (Albers, 2006, Smith et al., 2006, Jaynes et al., 2007).

A pulsed Doppler LIDAR intended for wind energy applications ('Windcube') was introduced to the wind energy industry in 2007. Albers et al. provided details regarding a measurement campaign including both the ZephIR and Windcube, in even landscape at a northern German test Centre. Both LIDARs performed well, with data availabilities more than 96% at 124 m elevation and LIDAR-cup standard deviation errors of 0.24 m/s (Windcube) and 0.3 m/s (ZephIR). (Anderson, 2004) compressed various other Windcube measurement campaigns. Against cup anemometers, these indicated linear regression slopes in flat terrain of 0.99–1.01; insignificant counterbalances (<0.2 m/s); and standard deviation errors of ~0.2 m/s.

The WindTracer LIDAR manufactured by US Defence Company Lockheed Martin Coherent Technologies was used in this to collect wind data at the wind farm site. The WindTracer is an infrared Doppler LIDAR and utilizes a 1.6 μm laser source which is eye safe. The WindTracer operates in the following way. A pulse of laser light is produced and released into the atmosphere. As the light travels away from the system, small portions of the light are reflected back to the system by very small particles in the air called aerosols. This reflected light is detected and recorded.

By analyzing the difference in time between when the pulse of light left the laser and when the reflected light returned, a distance to the particle that reflected the light can be determined. In addition, by measuring the frequency of the original pulse and the frequency of the reflected light, a shift in frequency can be measured (called a Doppler shift). The Doppler shift is induced by the component of the velocity of the particle directly towards or away from the laser. By analyzing the frequency shift, a direct measurement of the radial component of velocity of the aerosol particle is made.

There are several factors which influence the accuracy of using LIDAR for wind resource assessment. Some can be tied to uncertainties in the hardware, for example uncertainties in the cone angle, while others are spurred by atmospheric effects, like rain or clouds. These factors are broadly grouped into two: Uncertainties connected to errors in LIDAR hardware and Uncertainties connected to atmospheric phenomena (Petter Lindelöw-Marsden., 2009).

Results

Three masts equipped with cup anemometers and wind vanes recorded wind data for the entire 2009 calendar year.WindTracer LIDAR deployed at the site between 11th July and 25th July 2009 also recorded wind data.

The measured mean annual wind speed for Kalkumpei at 38.5 m is 10.44 m/s while the mean wind direction at 39m is 117.25° respectively. The mean annual temperature is 28.3°c. The measured mean annual wind speed for Nyiru at 46 m is 10.75 m/s while the mean wind direction at 49 m is 121.21°. The mean annual temperature was not computed because 4 months (June, July, August and September) data were missing. The measured mean annual wind speed for Sirima at 38 m is 11.10 m/s while the mean wind direction at 40 m is 110.73°. The mean annual temperature is 28.0°c.

Figure 2 and 3 shows the monthly mean wind speed variation and temperature for the three respectively. The period between June and October has the highest mean wind speed hence the prime period for electricity generation. The windiest month is August with mean wind speed varying between 11.86 m/s and 12.42 m/s for Kalkumpei, Nyiru and Sirima mast locations. December records the least mean wind speed varying between 8.79 m/s and 9.31 m/s for the 3 mast locations.

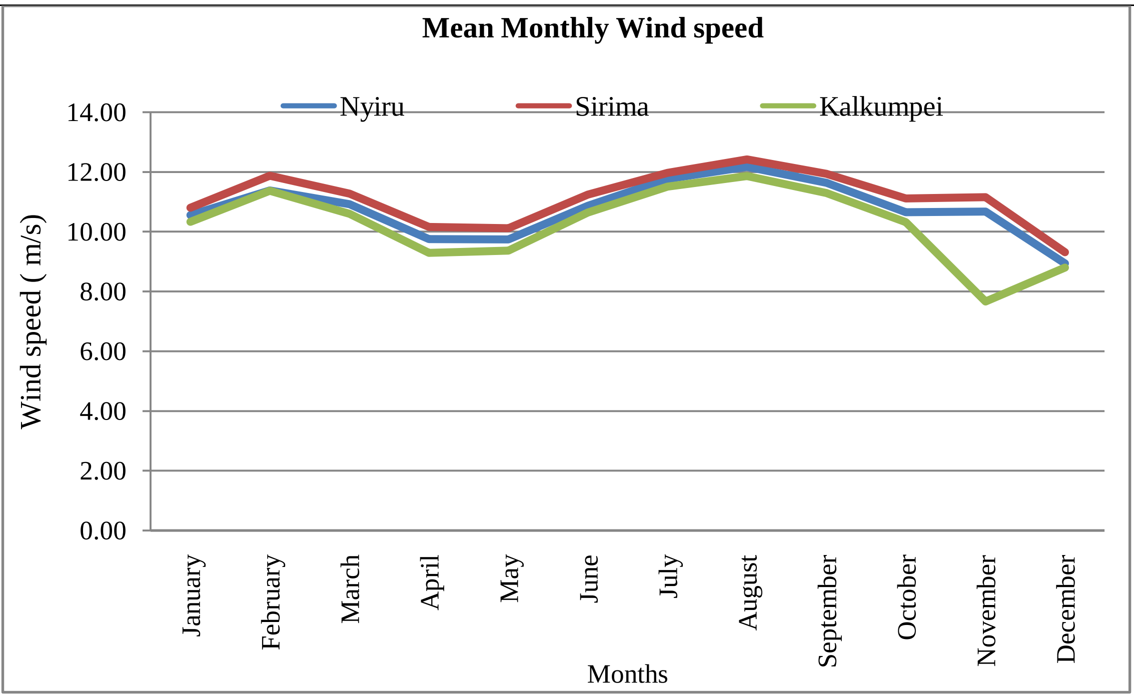

Figure 2: Mean monthly wind speed variation for Kalkumpei, Nyiru and Sirima mast locations.

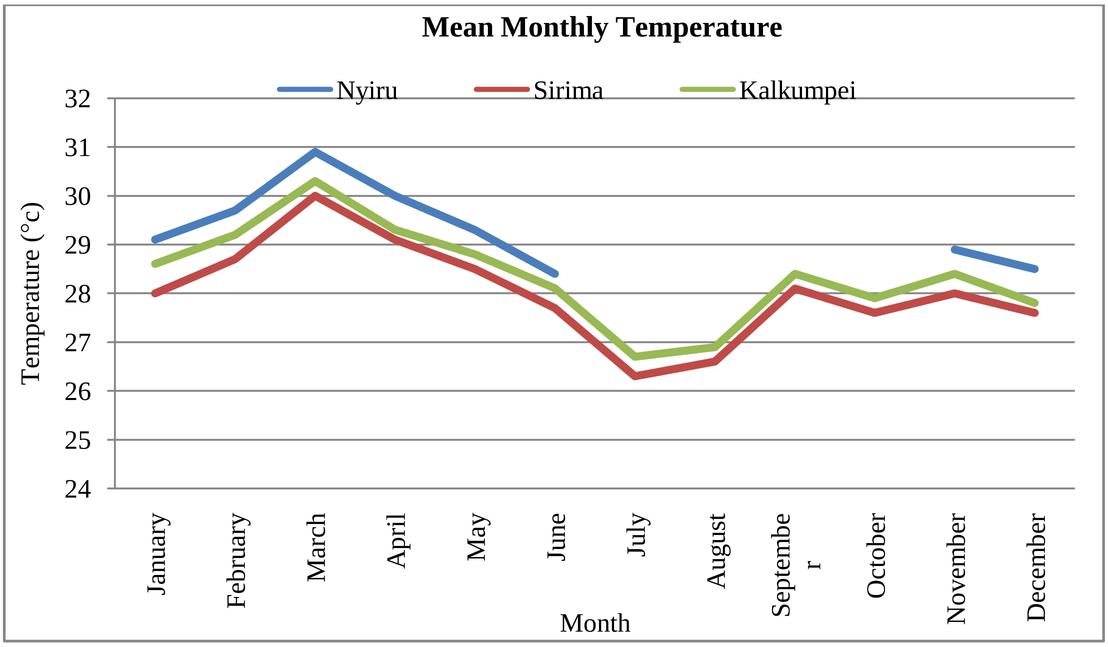

Figure 3: Mean monthly Temperature variation for Kalkumpei, Nyiru and Sirima mast locations.

Figure 4 shows the annual diurnal variation in wind speed at Kalkumpei, Nyiru and Sirima. High wind speeds are experienced during morning hours from midnight to around 11am.

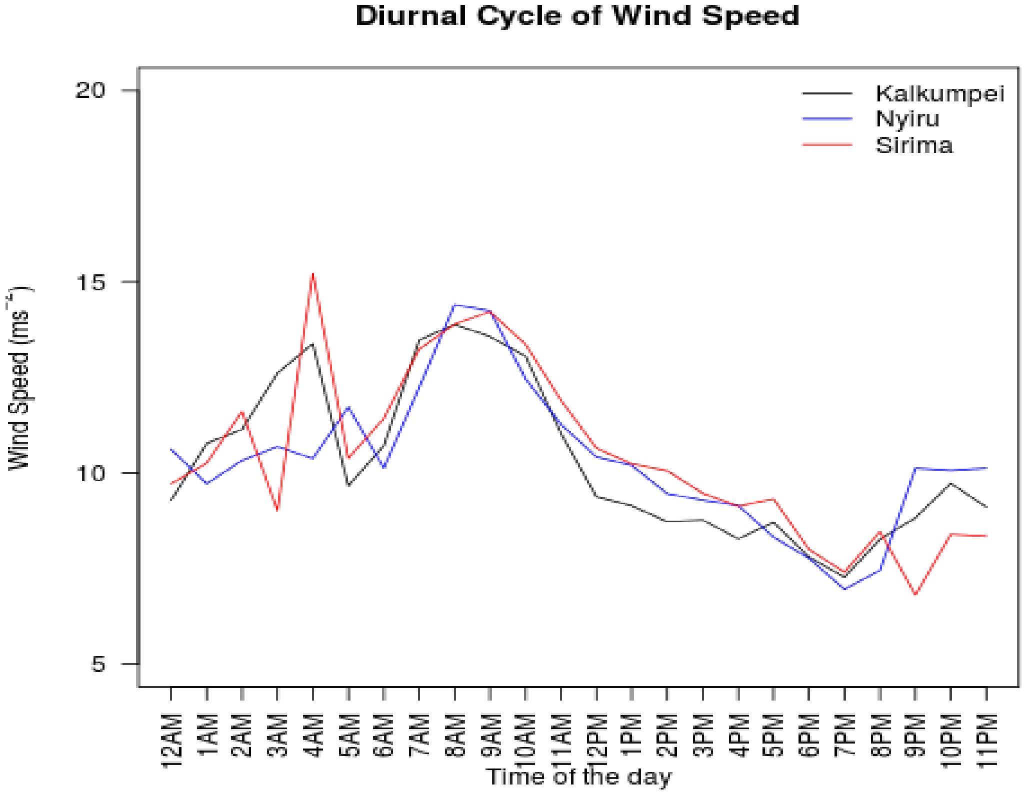

Figure 4: Annual Diurnal variation in wind speed for 2009 at the three mast locations.

An advanced LIDAR data volume processing technique developed by a research group based in Perth, Western Australia was used to retrieve the wind vectors. The technique categorizes the available LIDAR data into several conical layers and subsequently subdivides each layer into many small analysis volumes. The fundamental theory of this technique was derived from the general Doppler radar data processing scheme called Volume Velocity Processing (VVP). This type of scheme is considered to be a more straightforward way of resolving wind velocity directly from the LIDAR radial velocity data (Boccippio, 1995, Koscielny et al., 1982, Crook N.A. et al., 2005, Hannon S. et al., 2008).

The LIDAR analysed wind speed is compared to masts measurements at three locations from 11th July to 24th July 2009 after removal of poor quality LIDAR data. Each LIDAR scanning volume is composed of several 360° PPI scans, which approximately take 9~10 minutes duration, ranging from -1° to 1° elevations. These analysed time series of wind speed values are compared to the mast 10 minutes averaged measurements. It is shown that the differences between the two means (mast and LIDAR 45 meter level wind speed) are small and the standard deviations from the mean in both instruments are in close agreement. The standard deviation is the time series of wind speed deviation of each instrument to its own mean. It represents the degree of variability of the time series wind speed data.

Table 1: Mean wind speeds, mean difference and standard deviations (11th to 24th July 2009)

Mast locations	Height	Mean (m/s)	Mean Difference (m/s)	Standard Deviation (m/s)
Kalkumpei	Mast (38 m)	11.03	0.33	1.90
	LIDAR (45 m)	10.70		1.65
Nyiru	Mast (46 m)	11.19	0.05	1.92
	LIDAR (45 m)	11.23		1.79
Sirima	Mast (38 m)	11.43	0.47	1.71
	LIDAR (45 m)	10.95		1.72

Table 2: RMSE, Correlation coefficient and MAE between LIDAR and Mast data (11th to 24th July 2009)

	RMSE	Correlation	MAE
Kalkumpei	0.94	0.90	0.42
Nyiru	1.52	0.60	0.91
Sirima	1.10	0.73	0.94

The time series plots for the three mast locations are presented in Figure 5; Figure 6 and Figure 7 below. It can be seen that the LIDAR and mast measurements are in close alignment with the mean wind differences between two different instruments less than 0.5 m/s.

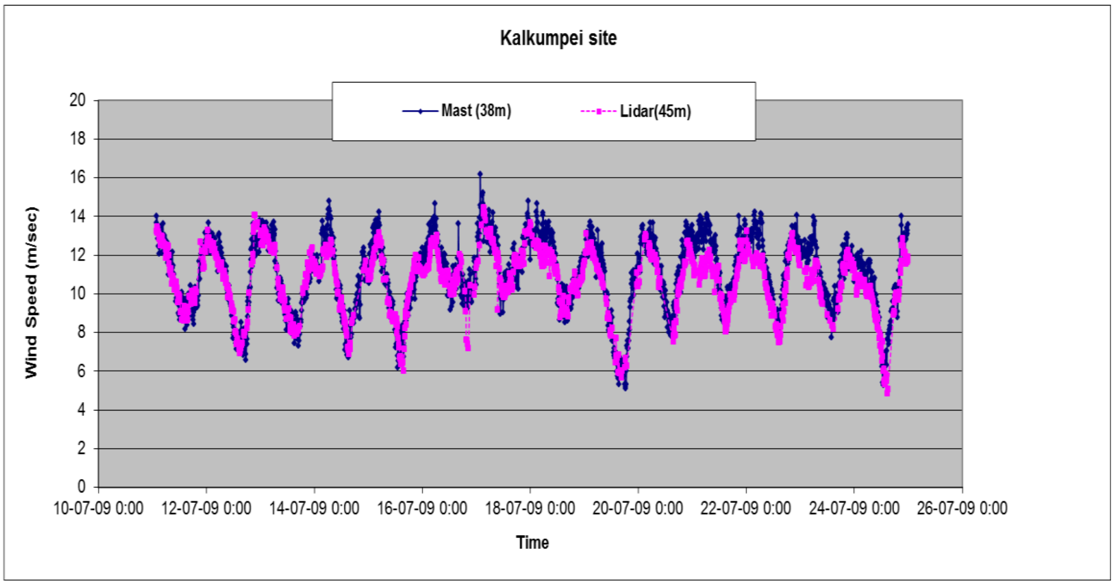

Figure 5: Comparison of LIDAR analyzed and Mast wind speed at Kalkumpei.

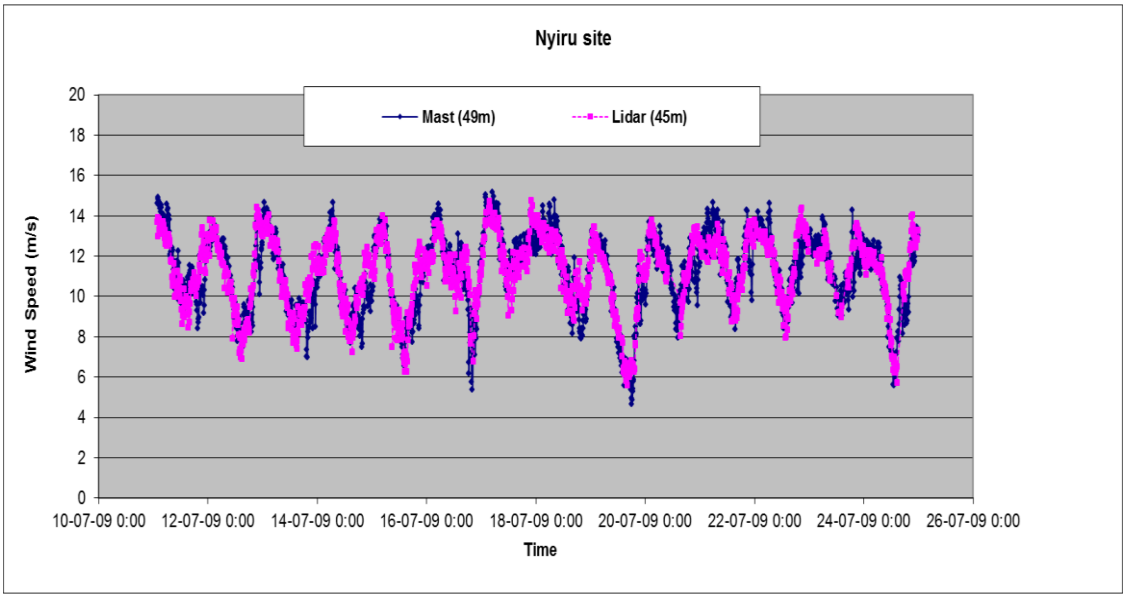

Figure 6: Comparison of LIDAR analyzed and Mast wind speed at Nyiru.

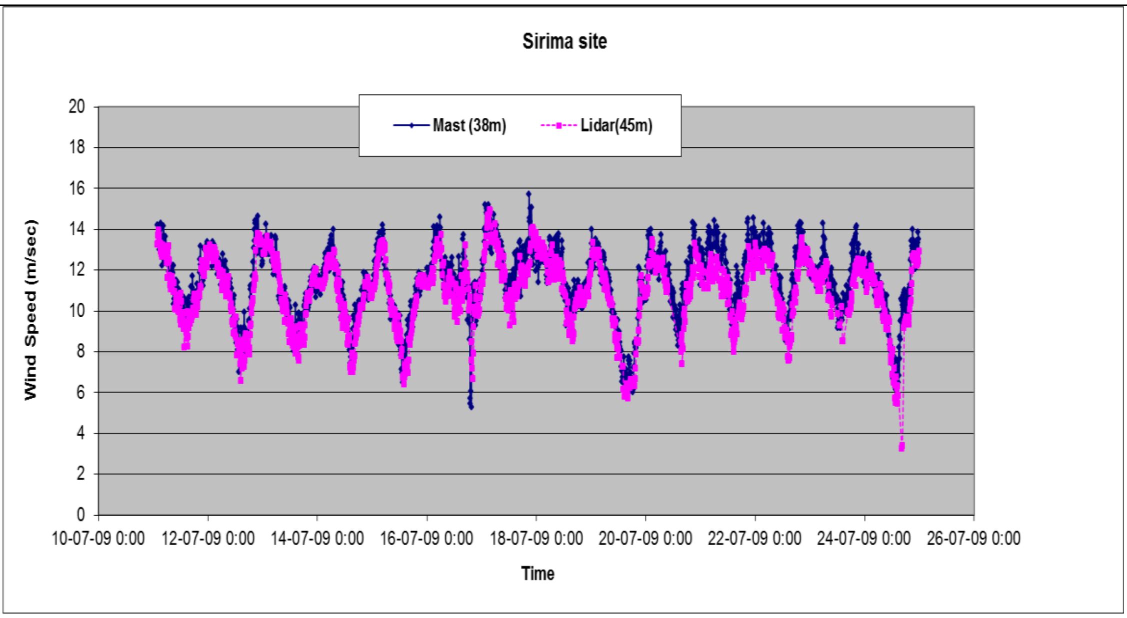

Figure 7: Comparison of LIDAR analyzed and Mast wind speed at Sirima.

Terrain-followingwindspeed plots

The derivedwindspeeddatawasoutputintoa20kmx20kmgriddomainandoverlaidona digitalterrainmodel.The datawasadjusted toremove bias arising fromanunevendistribution of 10minutesample periodswithinthedataset.
The resultantmap covers a geographic areaof 400square kilometresandcomprises approximately18,000datapointsalongthe45meterterrain-followingplane.Figure8and Figure 9containtwoplots,thefirstbeinga3Dimageofthewindfield;thesecondproviding the same information in2D, enhanced with terrainfollowingvector fields.
Themapsshowthattheaveragedtenminutewindspeedontherelatively flatlandscapetothe eastofthemeasurementdomainapproximately 6m/sec.Theaveragewindspeedgradually increasesastheflowmoveswesttoapproximately10m/sec neartheLIDARsite.Maximum velocitiesoccuronthehigherridgesonthewesternboundarywithwindspeedreachingover 14 m/sec.Windshadoweffectsfromtopography arealsoevidentinthemaps.

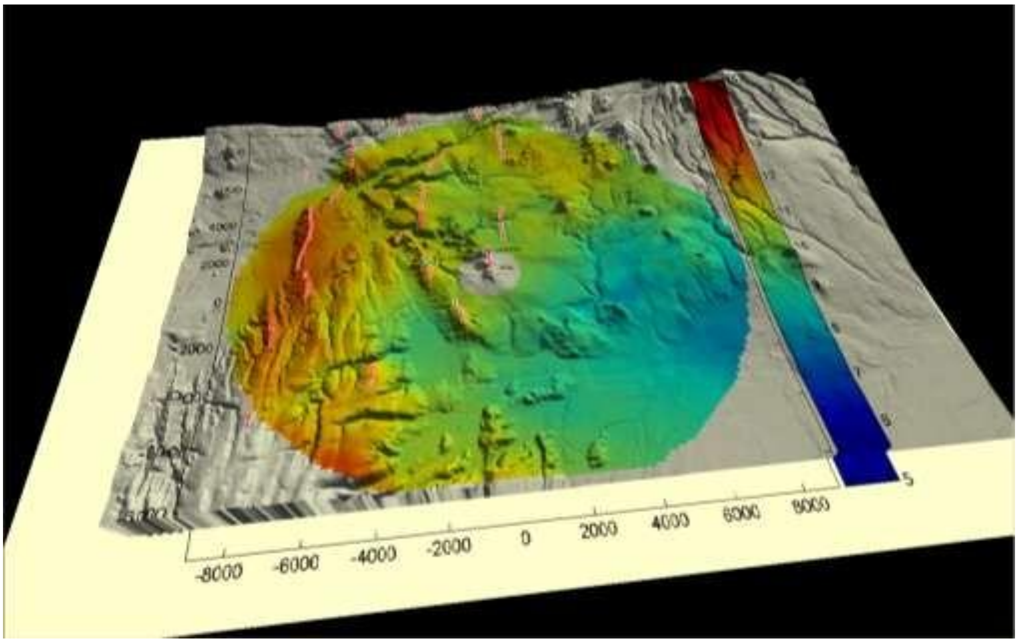

Figure 8: three dimensional horizontal wind speeds at Lake Turkana wind farm.

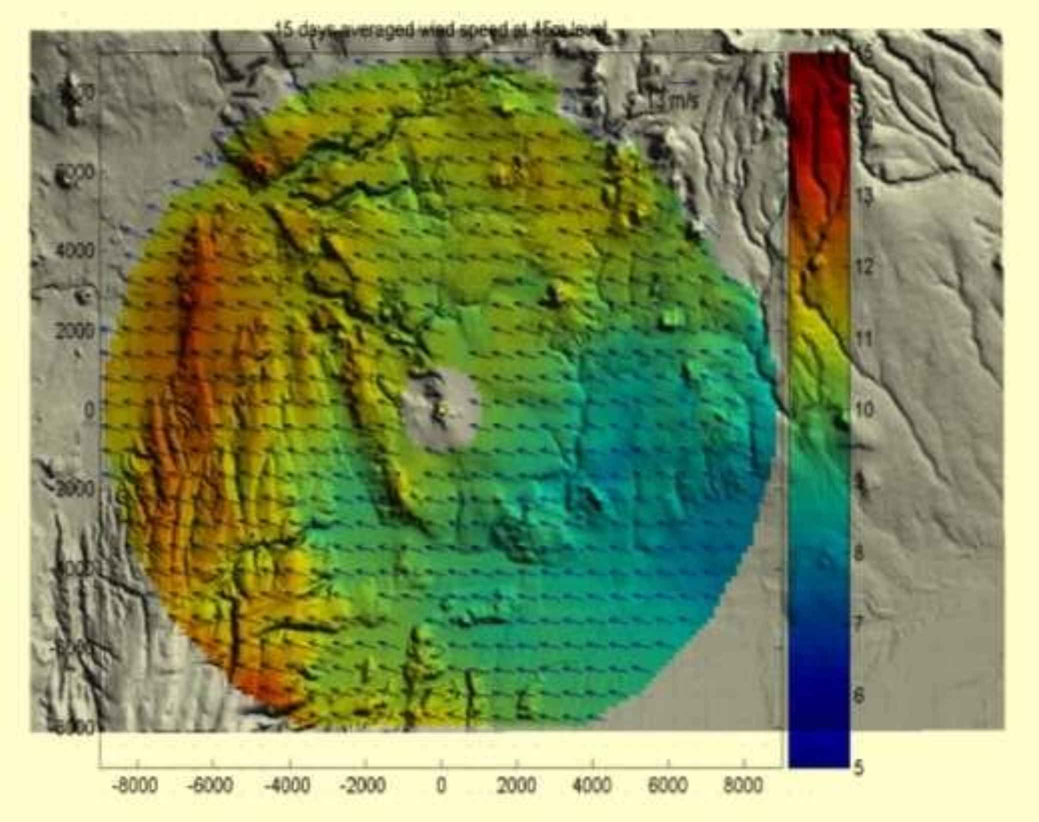

Figure 9: two dimensional horizontal wind speeds with terrain-following vector fields at Lake Turkana wind farm.

Conclusion

Analysis of wind speed data collected by mast mounted cup anemometers can show that the local winds are generally characterized by high annual mean wind speed with values over 10.3 m/s and relatively large diurnal variability. The mean diurnal cycle is characterized by stronger winds during night-time and early morning than during daytime.

Remote sensing measurements may be not quite the same as those of anemometry. Anemometers provide averages of point measurements of wind speed independent of wind direction (“scalar averages”). Doppler LIDAR measure average vertical, lateral and horizontal wind speeds. These are generally transformed to provide “vector averages” of wind speed. In turbulent conditions, vector averages are lower than scalar averages. These differences imply that remote sensing and anemometry may not provide the same wind speed values although each may be measuring accurately.

Results presented in figures 6, 7 and 8 shows outstanding agreement between the LIDAR and the anemometer wind speed measurements. The use of remote sensing technologies in wind resource assessment is still maturing. Equipment configuration and software changes particularly ALVPT may influence measurement quality and accuracy of retrieved wind speed and direction. In an energy assessment, remote sensing data may be used to evaluate: The accuracy of extrapolations from meteorological mast data; Hub-height wind speeds and Wind resource variability over the site.

Acknowledgements

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