UNIVERSITY OF WARSAW

WIND PROFILING WITH DOPPLER LIDAR

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Geophysical Laboratory I

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Abstract

In this Geophysics Laboratory, we focus towards understanding the nature of data obtained from a Doppler Lidar system. Such a system utilises the concept of Doppler shift to calculate line of sight wind speed of aerosols/particulate matter in the atmosphere. We use the data collected over a day at an urban site in Warsaw, Poland. The data consists of wind vector profiles with values in the categories of direction, speed and the directional components within the atmospheric boundary layer. We seek to filter and process the data, along with understanding the wind vector patterns and their nature.

Contents

1 Introduction

1.1 Aerosols

While walking on a street or strolling across the road, we often come across small and light flying objects. Pollen, pollution and dust are some of the most commonly experienced objects. Some of these can be seen within naked eyes, while others can only be visualized with the help of a microscope. Our atmosphere consists of so many of these type of particles. These are called aerosols[1] and play a significant role in many different types of phenomena on earth. With growing effects of climate change[2] and corresponding factors it has therefore become important to assess and understand the impact of these aerosol particles on our health and daily activities [3].

1.2 Remote Sensing

A lot of times, we need to collect and analyse data from a location without actually being physically present in that region. The process of remote sensing[4] provides the benefit of measuring/recording data from the location in a proper way using various devices. Satellites, drones and so many other devices provides this useful feature. The principle of remote sensing involves measuring the reflected and emitted radiation from the target object in its nearby regions. The emitted radiation could be electromagnetic in nature or could be gravity field as well. In terms of remote sensing instruments, there are two categories

- Passive remote sensors[4] - These kind of sensors record electromagnetic radiation emitted or reflected from the target in focus. They just record the changes occuring. Photometers and radiometers comprise these kind of sensors.
- Active remote sensors[4] - Devices working on the principle of active remote sensing, shoot self generated waves toward the target or the location in focus. The wave that is reflected back to the system is then recorded and analysed. Radar and lidar(being used in this geophysics laboratory work) are common examples of such types of remote sensing devices.

1.3 Doppler Lidar

Doppler Lidar as the name suggests, works on the principle of Doppler effect. Consider yourself standing at a traffic stop, from time to time you will find some vehicles honking/making sirens while passing through the crossing. The siren/sound will completely change while moving towards the place you are standing and by the time it has left the position where you are standing, the effect of the sound received by you would be entirely different. This phenomena where we are experiencing change in sound, involves change in the frequency emitted by object/source as observed/receiver by the receiver. It also applies when both the receiver and the source are in relative motion with each other. The relative speed of the source can be calculated by measuring the difference in frequency. Doppler Lidar systems use these mechanisms to send radiation with frequency f_0 to the atmosphere. The shift in the frequency is measured by detecting the backscattered radiation that is scatted by the aerosols (assumed to move with air with velocity v) in the atmosphere. In the equation[4] below, c denotes the velocity of light and v_r being the the velocity component along the line of sight.

$$f = f_0 + \Delta f = f_0(1 + 2v_r/c) \tag{1}$$

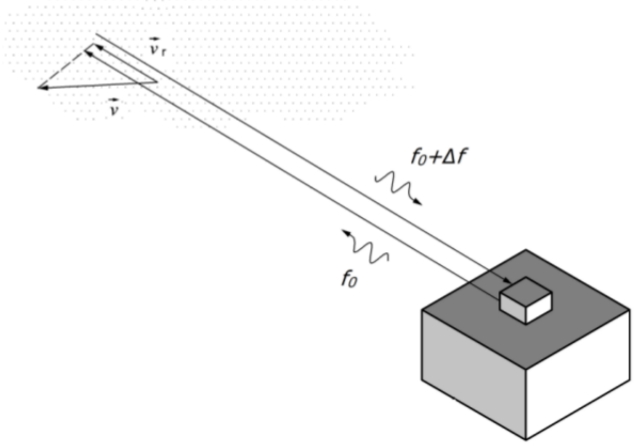

Figure 1: Mechanism of Doppler Lidar[4]

By using the process of demodulation[5] of the detected signal, the frequency shift is measured. The process involves mixing the light from Local Oscillator (LO)[4] with that of the backscattered radiation from the doppler lidar. The amplitude of the new signal oscillations at the frequency as that of the 2 beams. The doppler shift is then measured by the modulation frequency from this new mixed signal. Let us consider the field depicted in the following equation[4] which is monochromatic and backscattered in nature, A is the amplitude, f the frequency, t being time, and ϕ is the arbitrary phase.

$$E = A\cos(2\pi ft + \phi) \tag{2}$$

The frequency f is give by $f = f_0 + \Delta f$, where Δf is the doppler shift and f_0 frequency of the outgoing pulse. The following equation[4] represents the LO field, where f_{LO} is known as the LO frequency:

$$E_{LO} = A_{LO}\cos(2\pi f_{LO}t + \phi_{LO}) \tag{3}$$

Therefore, after all the superposition has taken place, the photodetector in the lidar, detects irradiance[5], as represented by the following equation[4]

$$I \propto (E + E_{LO})^2 = E^2 + E_{LO}^2 + AA_{LO}\cos(2\pi f_+ t + \phi_+) + AA_{LO}\cos(2\pi\delta ft + \delta\phi) \tag{4}$$

where + represents the superposition of the backscattered and the LO frequencies/phases, and the signal[4] given off by the photo-detector is as:

$$s(t) \propto \cos(2\pi\delta ft + \delta\phi) \tag{5}$$

where $\delta f = f - f_{LO} = \Delta + f_0 - f_{LO}$. The raw detected signal is given by the above equation. If we know the frequency difference between the outgoing pulse and the LO, we can easily calculate the shift of the backscattered radiation.

The Doppler lidar also produces Signal-to-Noise- ratio (SNR), which is the ratio of the desired signal to that of the unwanted signal or the background. We will see in the data analysis later, how filtering data based on this produces considerable difference in our understanding and visualization of wind components.

1.4 Wind Vector Field

The wind has direction and intensity at all times, depending on time and space. Thereby, a three dimensional vector field such that , $\vec{U}(x, y, z, t) = (u, v, w)$. For analysing/calculating the particular position of a wind at any time, we need three vector components. In this laboratory, we are using a doppler lidar system, which however measures only the projection of the wind vector along the laser beam line of sight (LOS), also called the radial velocity v_r. But, if we, assume the wind to be a stationary and horizontally homogeneous field, such that $\vec{U}(x, y, z, t) \sim \vec{U}(z)$, we can then estimate the wind vectors from consecutive radial measurements from the doppler lidar. The measured radial velocity, v_r by mesured with a beam at a certain elevation angle ϕ and azimuth θ (with respect to North direction) shows a sine-like behaviour as depicted in the following equation[5]

$$v_r(z) = u(z)\sin\theta\cos\phi + v(z)\cos\theta\cos\phi + w(z)\sin\phi \tag{6}$$

1.5 Scanning Technique

Doppler lidars measure profiles of the LOS wind velocity, where the lidar systems are vertically aligned and therefore, the components of the vertical wind velocity are easily obtained. To generate components for the horizontal wind, the beams from the lidars have to be tilted out of the vertical. The horizontal wind thus produces a LOS component to the lidar signal, and with appropriate scanning schemes the three-dimensional wind vector can be inferred. There are two most common scanning techniques[6] used. VAD Scanning method and DBS scan. In our analysis of aerosols using Doppler Lidar, we have utilised the VAD scan method.

1.5.1 VAD Technique

Velocity-azimuth display or the VAD[5] scanning technique involves scanning of the required area in a way such that the tip of the cone lies at the lidar scanner and the velocity signal is displayed as a function of azimuth angle for a given height/distance.

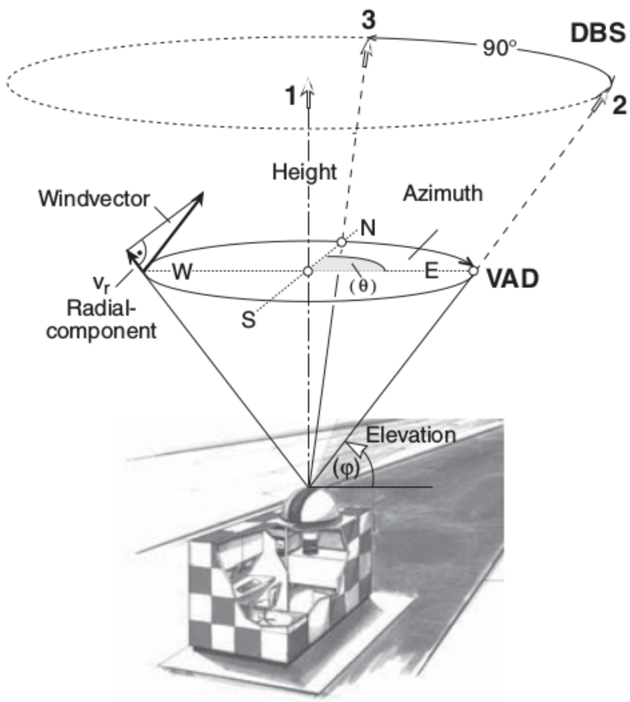

Figure 2: Doppler lidar scanning techniques[5]

If we consider the atmosphere to be ideal and assuming the obtained LOS component shows a sine-like behavior given by the equation[5]

$$v_r = -u \sin\theta \cos\phi - v \cos\theta \cos\phi - w \sin\phi \tag{7}$$

u denotes the west-east component, v the north-south component, w the vertical component, θ the azimuth angle, clockwise from north and ϕ the elevation angle and fitting it to the following function

$$v_r = a + b\cos(\theta - \theta_{max}) \tag{8}$$

we can then calculate the 3d wind vector

$$\mathbf{u} = (u, v, w) = (-b \sin\theta_{max}/\cos\phi, -b\cos\theta_{max}/\cos\phi, -a/\sin\phi) \tag{9}$$

where, a denotes the offset, b the amplitude and θ_{max} is the phase shift. Therefore, the horizontal wind speed u_{hor} and horizontal wind direction dd becomes

$$\begin{aligned} u_{hor} &= (u^2 + v^2)^{1/2} = b/\cos\phi \\ dd &= \theta_{max} \end{aligned} \tag{10}$$

vertical wind velocity w(positive for wind up)

$$w = -a \sin\phi \tag{11}$$

Therfore, total wind speed is

$$|\mathbf{u}| = (u^2 + v^2 + w^2)^{1/2} \tag{12}$$

Each single height, consists of a separate sine fit, when dealing with results for a VAD scan. Therefore, by utilising the values a, b, θ_{max}, we obtain the values - u, v, w for each height interval.

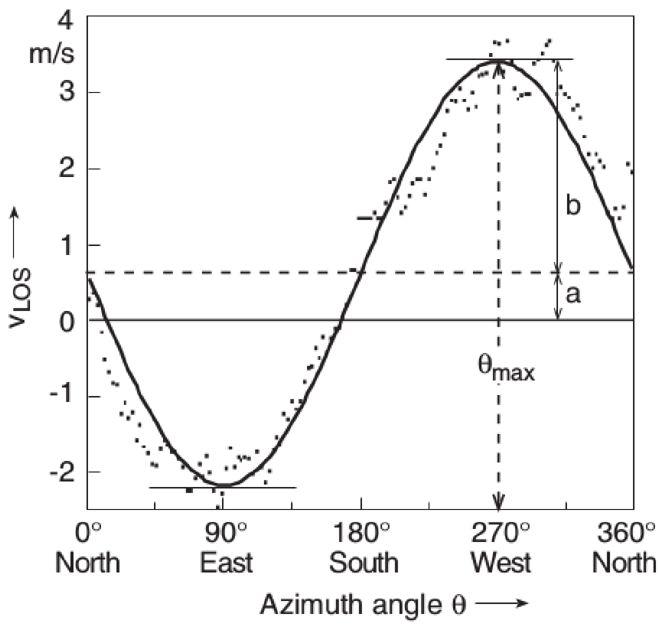

Figure 3: Curve Fit of the radial wind velocity obtained from the VAD technique[5]

Emission	
Wavelength(nm)	1550
Pulse Duration(ns)	180
Pulse Repetition Rate, PRR(kHz)	10
Reception Optics	
Lens diameter(cm) Lens divergence	7.5 3
Detection	
Detection type Range resolution (m) Sampling frequency (MHz) Velocity resolution Nyquist velocity	Heterodyne 30 50 0.0382 19

Table 1: Technical details of the main optical elements of the Doppler lidar system [4]

2 Instrument - Doppler Lidar System

In this report, the vertical profiles of wind were obtained using the measurements of the Doppler lidar Stream Line (Halo Photonics, Figure 4). Table 1, provides a description of the main instrumental features. The instrument has been operating at 30 m vertical resolution and an effective range from 90 m to 6000-9000 m.

Figure 4: Doppler lidar system[7]

3 Data

The data files obtained from the Doppler Lidar system are in netcdf format. It has large number of attributes and variables, with each of the values associated with a particular time and height. Figure 3 shows the general outlook of the values that we need to utilise for this laboratory work.

time	height	u	v	w	wind_speed	wind_direction	R_squared	mean_snr
	14.095389	0.077628	-0.089937	0.162686	0.118805	319.201080	0.995608	0.002488
	42.286167	-0.292972	0.035971	-3.131866	0.295172	96.999748	0.999990	0.029492
0.035556	**70.476944**	19.405523	-1.075329	7.555077	19.435295	273.171722	0.993510	0.890416
	98.667725	2.756088	3.166335	0.210140	4.197821	221.037445	0.997622	1.100812
	126.858505	4.187781	4.071055	0.176254	5.840462	225.809738	0.998134	1.059273
...	**...**	...	...	...	...	...	...	...
	9260.670898	5.748781	6.958433	-11.049571	9.025977	219.562164	0.997901	1.002329
	9288.861328	-36.106884	17.837549	-2.823414	40.272636	116.290329	0.904760	1.002720
23.957085	**9317.052734**	-6.831859	-16.622639	-8.863403	17.971823	22.342527	0.991480	1.000503
	9345.243164	-3.914443	-19.700989	-9.412493	20.086111	11.237894	0.992982	1.002226
	9373.433594	-4.791733	-7.778895	-4.721473	9.136296	31.632715	0.951799	1.002431

Figure 5: Values of the dataset

3.1 Data Analysis

To analyse the data, one can use any programming language or software. For my convenience, I have used python and visualized the code in pandas dataframe.

- We first filter all of our data using the SNR limit of 1.006 and R^2 in limit of 0.95.
- We then plot vertical profiles of 3D wind components (u, v, w) at a particular time.
- We plot horizontal wind components (wind speed and direction) for the given time.
- We further plot time evolution of components at a selected height.
- We plot time-height evolution of horizontal wind speed, wind direction and vertical wind component.

time	height	u	v	w	wind_speed	wind_direction	R_squared	mean_snr
	98.667725	2.756088	3.166335	0.210140	4.197821	221.037445	0.997622	1.100812
	126.858505	4.187781	4.071055	0.176254	5.840462	225.809738	0.998134	1.059273
0.035556	**155.049286**	4.921351	4.358400	0.132180	6.573839	228.471558	0.999139	1.025466
	183.240067	5.452626	4.488103	0.145748	7.062167	230.541916	0.999491	1.013218
	211.430847	5.502176	4.599914	0.122026	7.171691	230.103790	0.998991	1.007181
...	**...**	...	...	...	...	...	...	...
	239.621613	3.711231	9.040781	-0.976161	9.772868	202.318100	0.999891	1.037424
	267.812408	4.688043	9.356037	-0.989721	10.464854	206.614136	0.999937	1.027107
23.618750	**296.003174**	5.394883	9.669534	-0.982937	11.072699	209.158279	0.999901	1.019742
	324.193939	6.196064	9.616165	-1.047337	11.439487	212.795227	0.999860	1.012300
	352.384735	6.834667	9.793531	-1.043958	11.942610	214.910248	0.999844	1.006246

Figure 6: Values of the dataset after filtering

4 Figures and Discussion

4.1 Vertical Wind Components vs Height

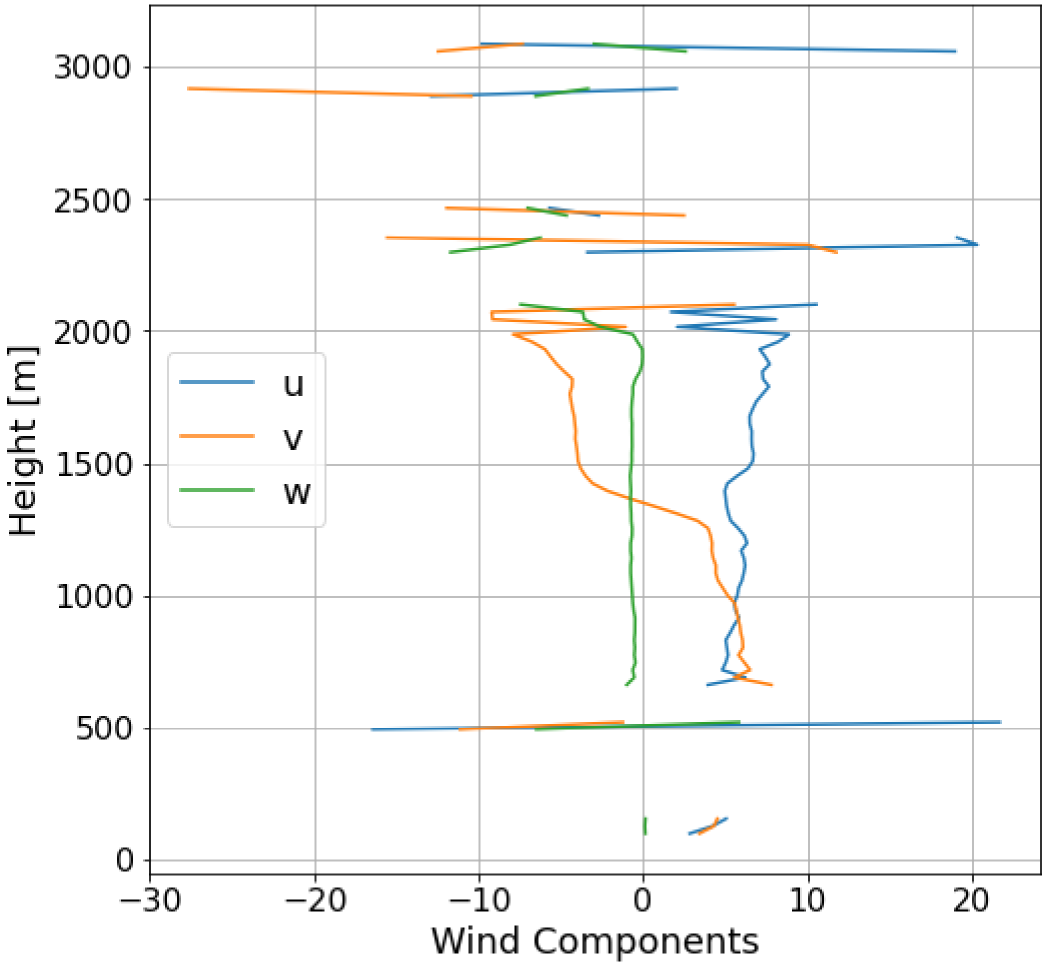

Figure 7: Variation of Vertical Wind Components with Height

- As we can infer from the above figure, the values of the wind components have a constant distribution of magnitude at height of 500ms, 2400ms and around 3000ms. From around 700ms to 2000ms, the wind components mostly have a magnitude within a range of -10 to 10.

- Interestingly, the distribution of wind component u is more widely spread as compared to v and w components. It's almost stationary/uniform in nature.

- The negative values indicate the wind components are in a direction opposite to that of the doppler lidar.

4.2 Time vs Vertical Wind Components

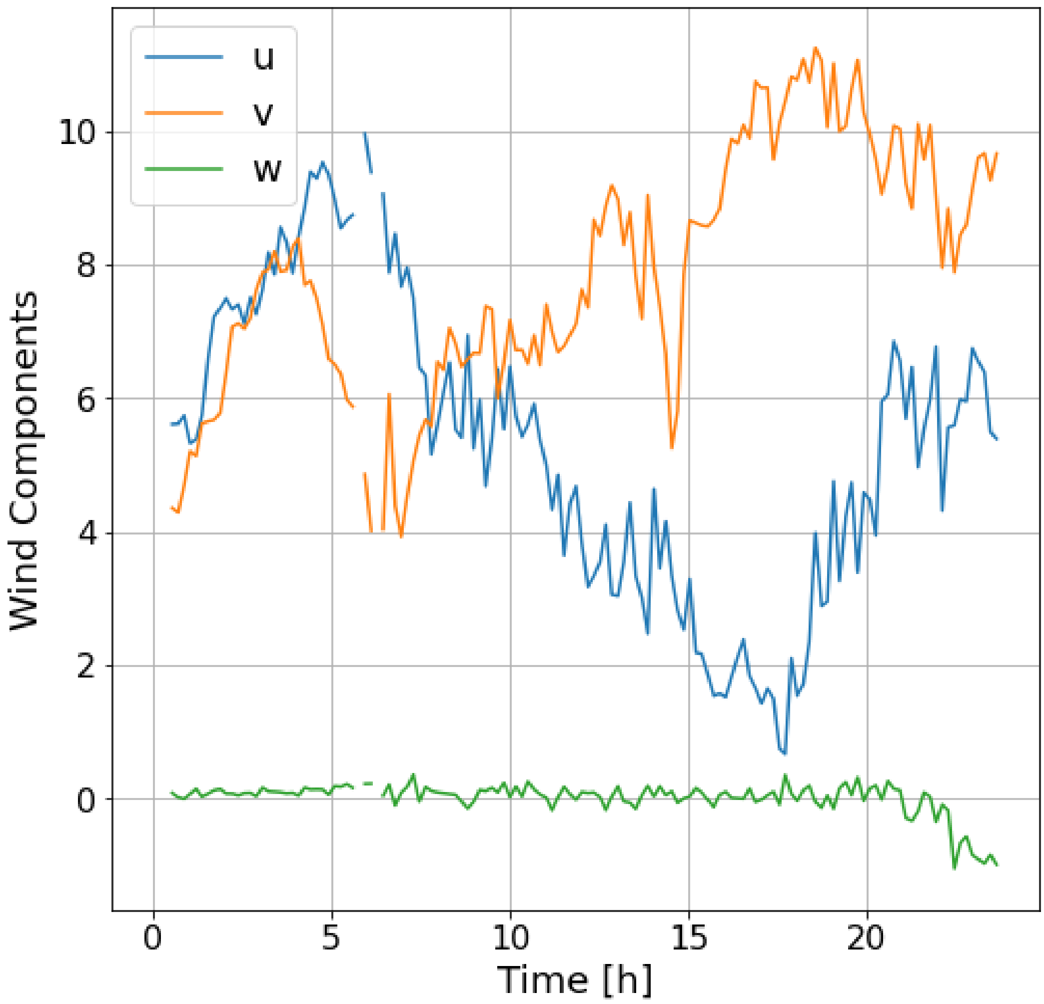

Figure 8: Variation of Vertical Wind Components with Time

- The wind component w varies around the magnitude 0. Therefore there isn't much variation ir it could be that it is uniform with no change in direction except after 20 hours.
- Components u and v vary in a complimentary manner to each other as they rise and fall with time completely opposite to each other even though their initial rise is almost similar.

4.3 Time vs Horizontal Wind Components

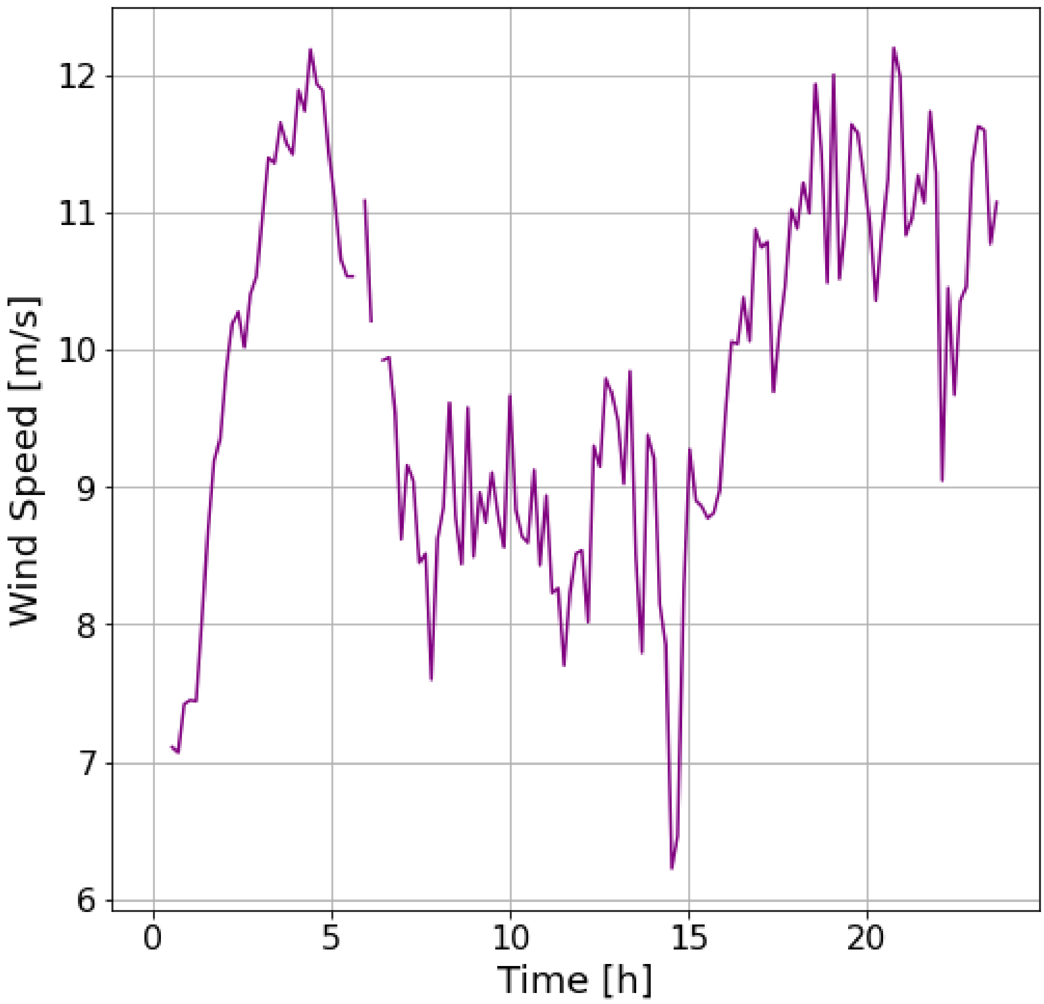

Figure 9: Variation of Horizontal Wind Speed vs Time

- The wind speed in the above figure rises from 7 m/s to around 12 m/s and then starts dropping to around 8 m/s in the first 10 hours. However, it fluctuates between a speed difference 9 m/s to 8 m/s and then undergoes a long fall for a short time period of 1 hour at 6 m/s.
- The wind speed increases from a little above 6 m/s and continues on again till 12 m/s. Thus the peak speed of the wind is 12 m/s as we can from both the peaks.

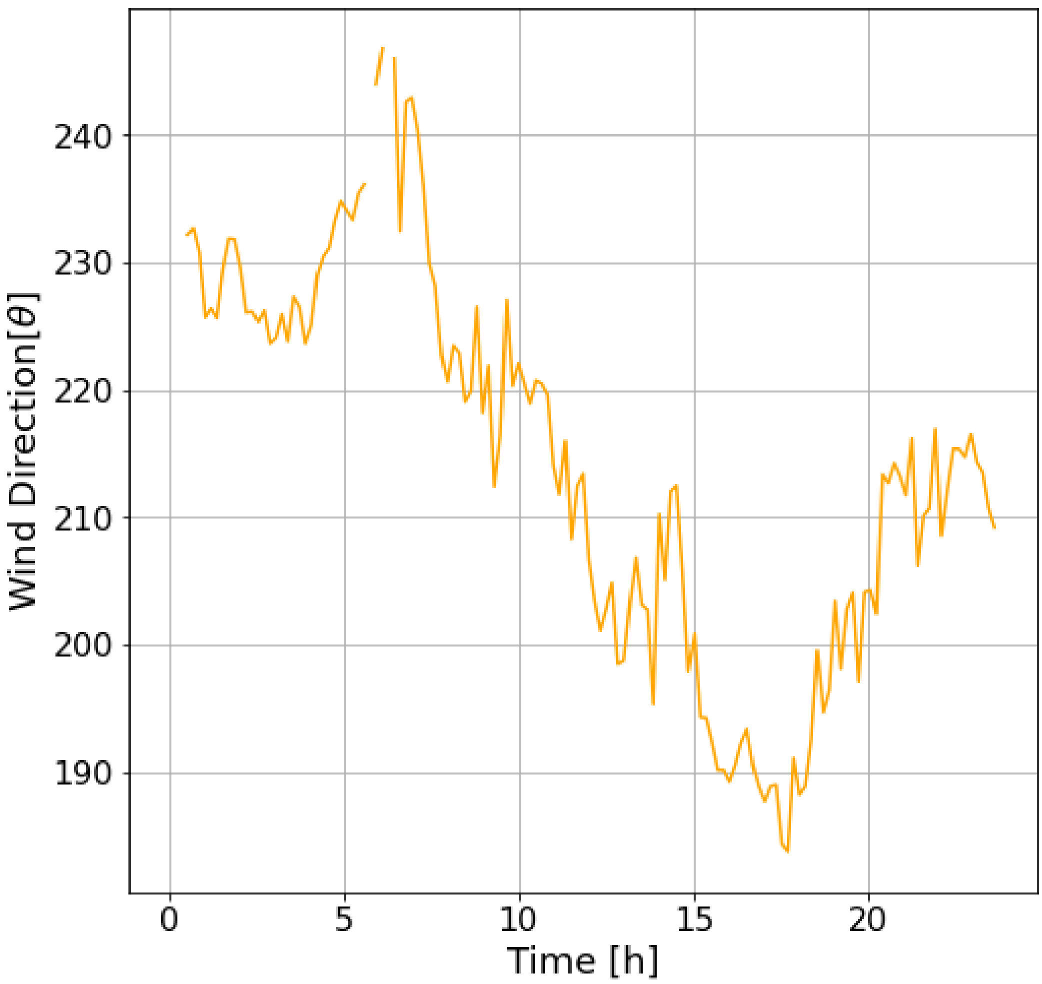

Figure 10: Variation of Horizontal Wind Direction vs Time

- The wind direction is varying rapidly with time as we see in the above diagram.
- This also means there is quite a significant amount of wind activity, which could be turbulent in nature, this is very evident by the sharp peaks during each rise and fall of the values. If the curves would have been smooth, then it meant the movement is uniform. However, the sharp peaks present clearly showcase that the wind rapidly and abruptly changes direction.

4.4 Time-Height evolution of the Wind Components

4.4.1 Vertical Wind Component - U

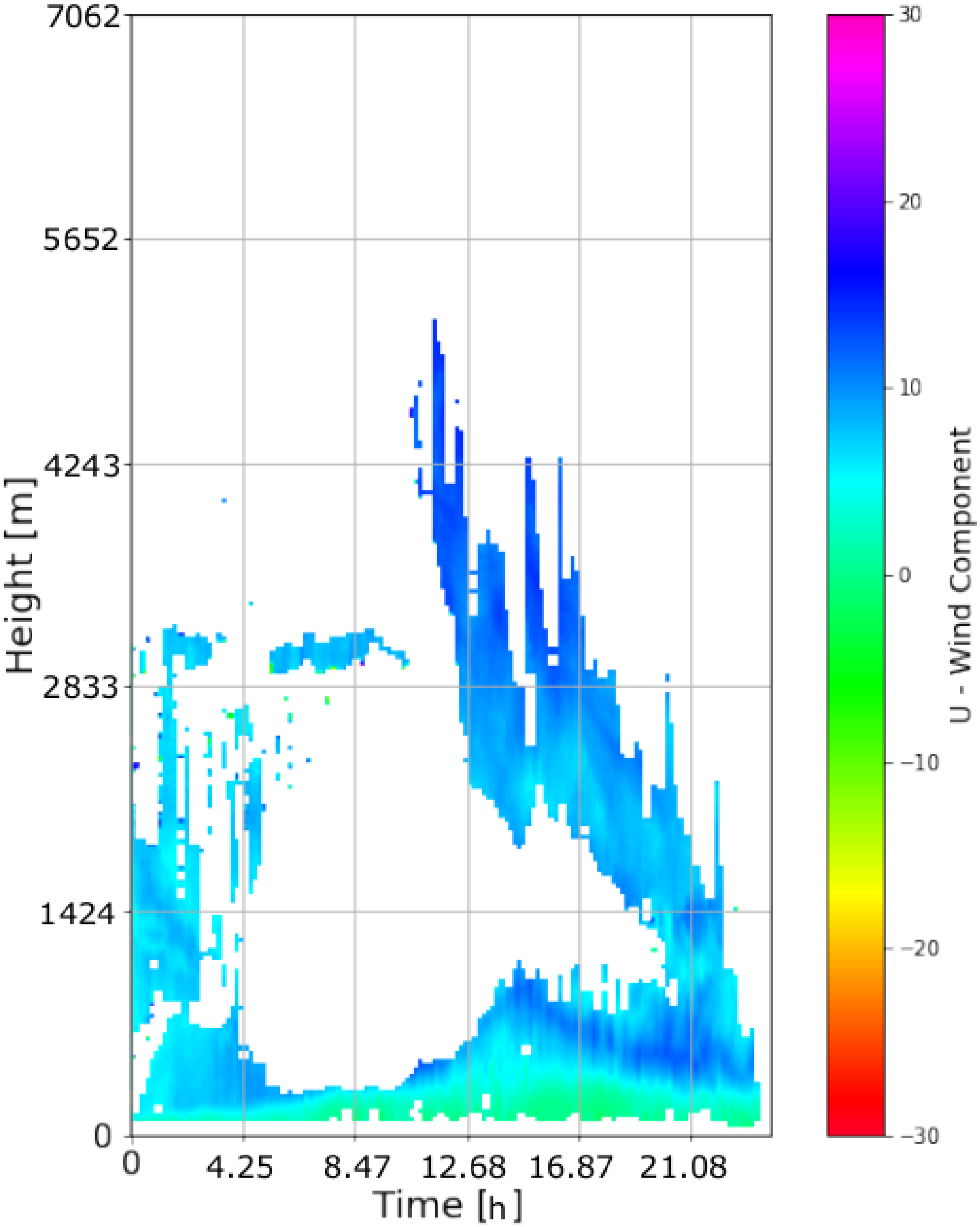

Figure 11: Variation of U wind component

- The majority values of the U component lies in the direction towards the doppler lidar since all the values are in positive range as shows by its time-height evolution.
- Only a small amount of U components lies in the range of 30 m/s and that too for quite some considerable amount of time.

4.4.2 Vertical Wind Component - V

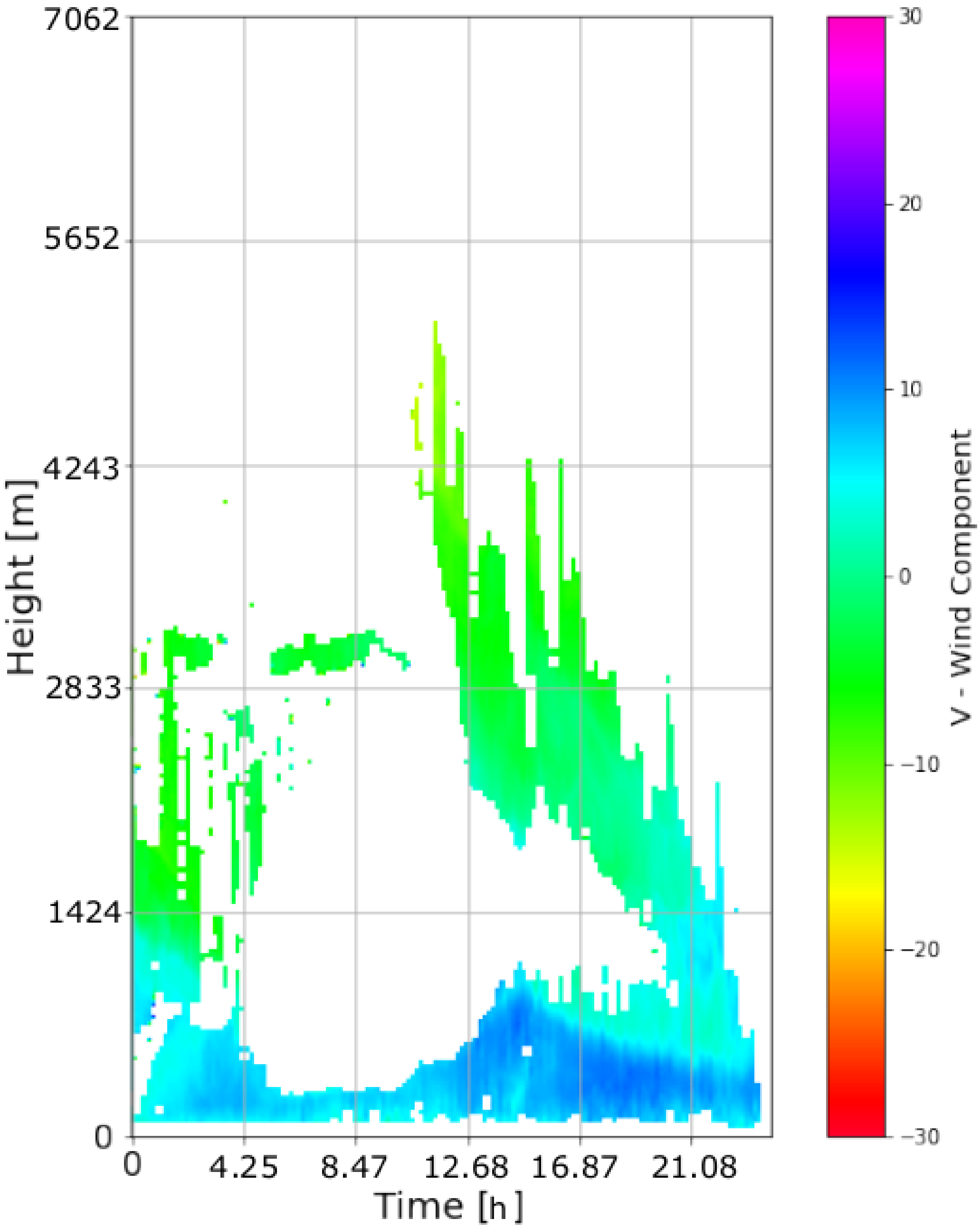

Figure 12: Variation of V wind component

- The values of the V component lying in the direction opposite to that of the doppler lidar is more in intensity as compared to the U component in figure 11. This is depicted by light green shade in the above diagram.
- However, the overall intensity towards the doppler lidar is much less and lies only till the value of 10.

4.4.3 Vertical Wind Component - W

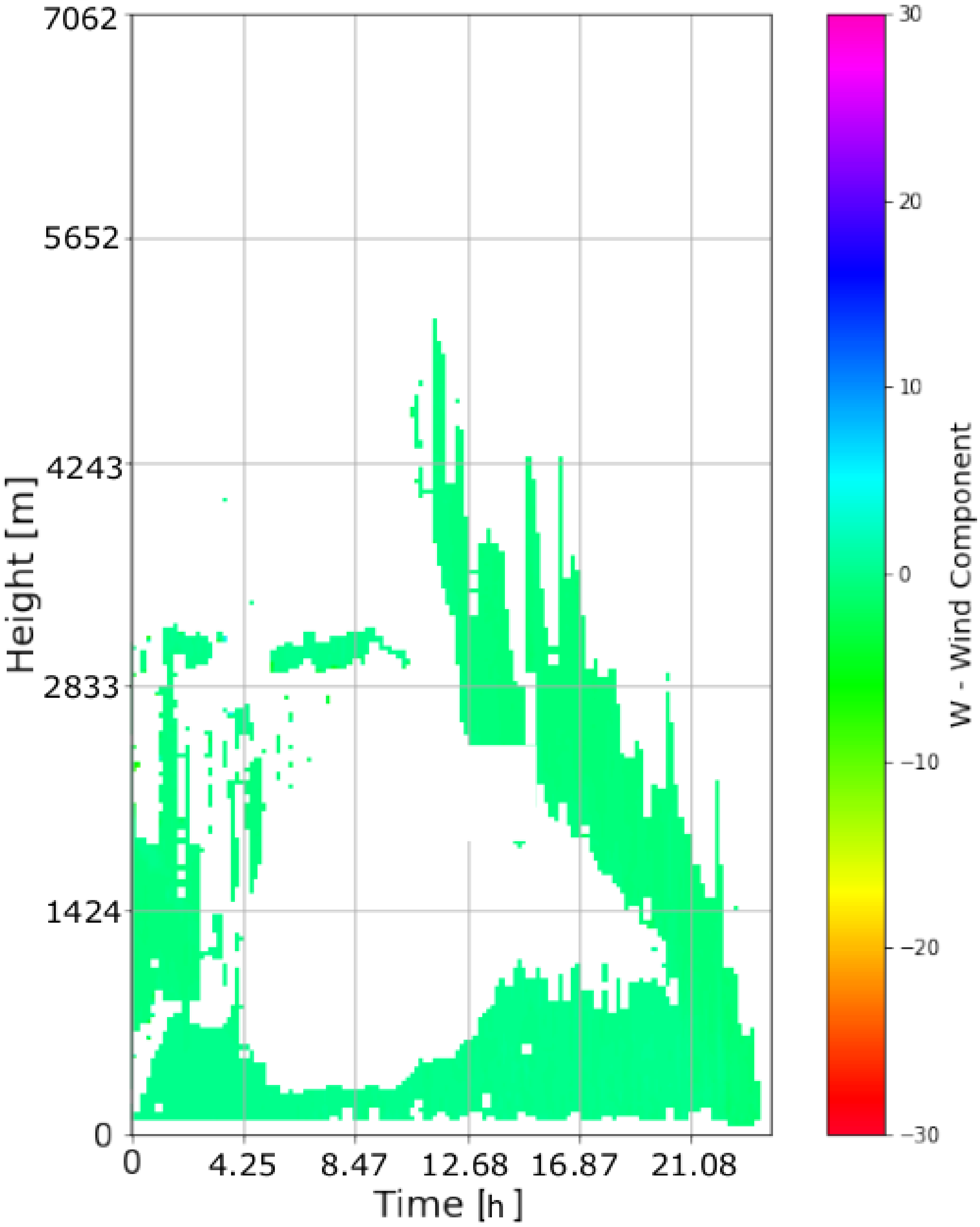

Figure 13: Variation of W wind component

- The W wind component rarely varies in its magnitude. This was evident even in the previous figure 8. The values strictly lies around 0 and there is almost no variation at all.

4.4.4 Horizontal Wind Component - Wind Direction

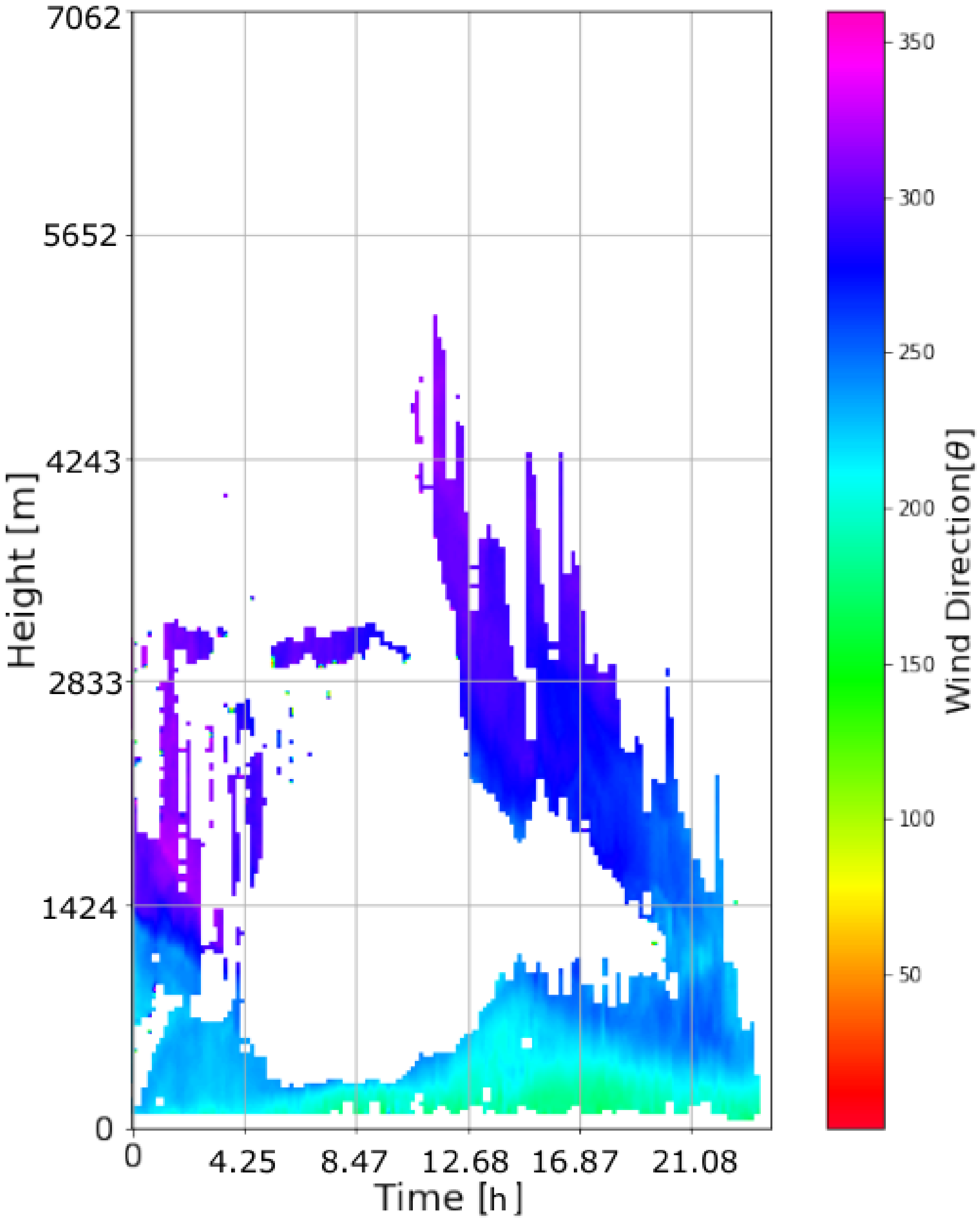

Figure 14: Variation of Wind Direction

- The wind direction stays constant at values of 200 degrees at a lower height of 50 ms, but with increasing height there is a slight variation of θ from 250 to about 350, which means there is more dynamics of the wind at higher altitude.

4.4.5 Horizontal Wind Component - Wind Speed

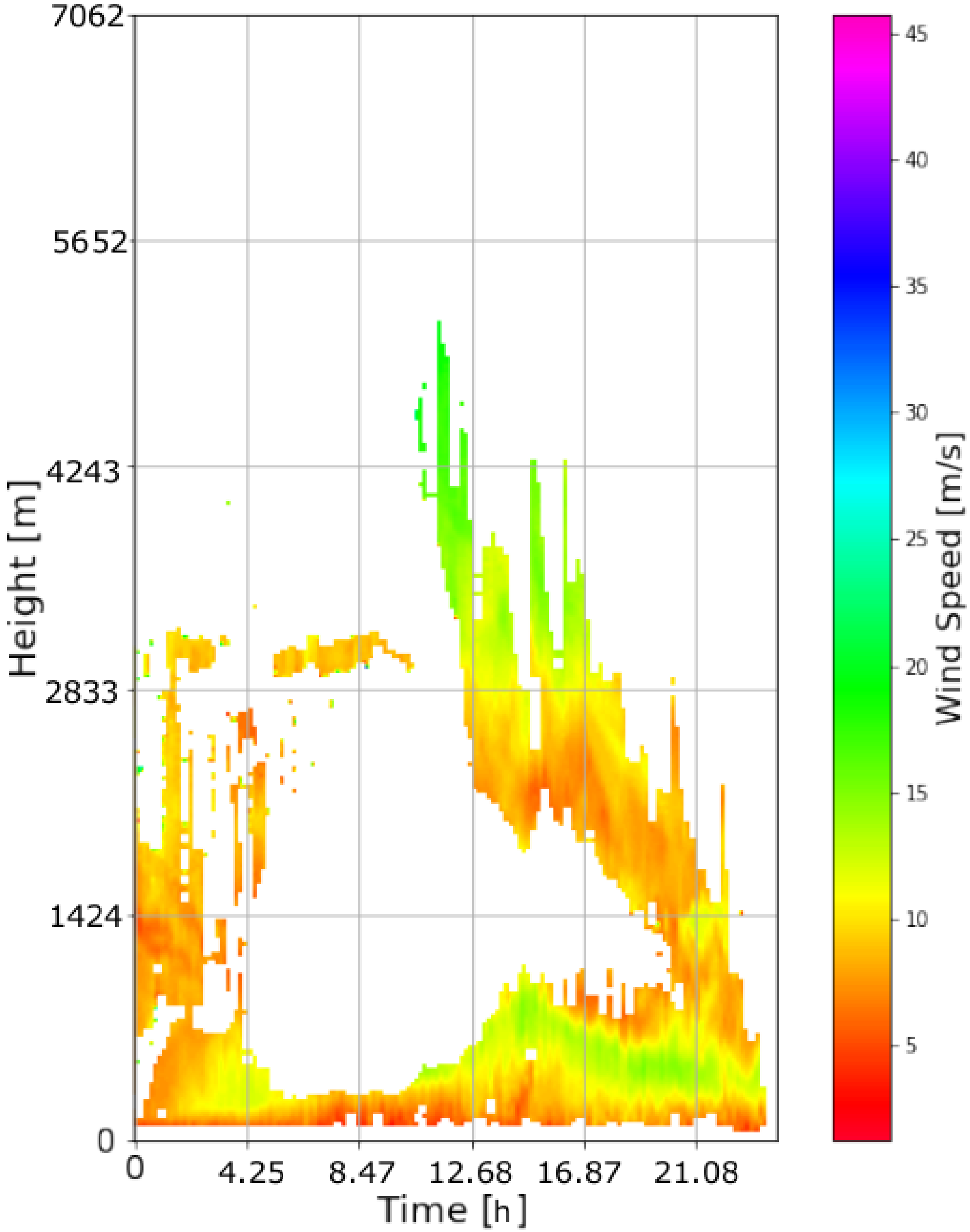

Figure 15: Variation of Wind Speed

- The wind speed varies in magnitude from around 5 m/s to upto 20 m/s. The time-height evolution clearly depicts that at higher heights the wind speeds seems to increase, but only for a very short amount of time.

5 Discussion

- We filtered the datasets obtained from doppler lidar with R^2 being above 0.96 and mean SNR being above 1.006. This creates some gaps in the plots, as given by the absence of pixels in the 3d plots. When we filter the dataset based on the particular threshold, there is removal of background noise from the dataset. But at the same time this process causes us to loose quite a significant amount of valuable signals, which is given by the absence and presence of pixels.

- Therefore, if we filter the dataset based on lower values of threshold, we can increase the efficiency of data availability and would have more better values for visualizing the properties of the vertical and horizontal wind components.

- There are various languages and softwares for visualizing netcdf files, python might not be a better choice for visualization. Working in MATLAB could produce more better plots as the libraries and orientation is much better and efficient.

6 Conclusion

Therefore, after analysing the data collected over a day at an urban site in Warsaw, Poland, we have the following basic conclusions.

- At higher heights, there seems to be more wind activity as depicted by figure 10, 14 and 15.

- The wind components, u and v have a complimentary relation with each other as depicted by figure 8, whereas component w is almost static in nature, with slight variation in direction towards doppler lidar as shown in figure 8 and 13.

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