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A comparison exercise between a wind LIDAR and anemometers mounted on a 30 m mast

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A comparison exercise between a wind LIDAR and anemometers mounted on a 30 m mast

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ABSTRACT

This report describes the results of a side-by-side comparison of a ZephIR wind LIDAR with anemometers mounted on a 30 m meteorological mast at an open-field site. The work was done as part of a refinery wind study and is novel in the use of wind LIDAR to obtain measurements of speed and direction at heights below 40 m. Good agreement was found for heights between 11 m and 30 m. This is important for dispersion of released gases on refineries and such data are difficult to obtain with traditional methods because of the need to anchor a tall mast. Profiles obtained from the LIDAR were consistent with stable atmospheric conditions.

KEYWORDS

Wind LIDAR, Wind Profile, Atmospheric Stability, Meteorology, Measurement

INTERNET

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SUMMARY

Information on wind speed and direction over a refinery site is important for dispersion calculations and the interpretation of remote sensing data. Obtaining wind data information at heights above 3 m is generally difficult on an operating site because of the difficulty in raising and installing tall masts safely. Therefore, wind data taken from a remote location are usually used. Concawe was interested to partner a portable anemometer with a wind LIDAR to examine refinery wind fields in situ (for further information on wind LIDARs see Appendix B). A ZephIR wind LIDAR, supplied by KONA, was chosen as the specifications for this LIDAR say that it can obtain data at heights as low as 10 m above the instrument and the system is mobile. Information on wind from heights of 10 to 100 m inside a refinery site would be very useful. At lower heights portable anemometers can be used.

No information beyond specification was available on the performance of the ZephIR wind LIDAR. As a first step to renting the LIDAR for use in a refinery Concawe asked the supplier, KONA, that it be set up against a traditional vertical anemometer array to test the performance at low heights. The resulting campaign was not a full validation study; the data comparison ran for 3 days over which time only a small range of meteorological conditions were sampled. Nevertheless, the data comparison is of intrinsic interest and Concawe believe it to be novel and of sufficient value to be reported separately.

The wind LIDAR was installed alongside a reference meteorological mast set in farmland in Ireland. The mast was fitted with anemometers at heights of 11, 20 and 30 m. The LIDAR was supplied with a portable anemometer operating at 2 m height above ground which was included in the LIDAR data set. Data were compared on ten-minute averaged time periods. This is relevant to both dispersion modelling calculations and to the interpretation of remote sensing data which inter-alia assumes a steady dispersing plume.

No statistical analysis was carried out on the difference in shape of the vertical profile between mast data and the lidar over the overlapping heights. Correlation of wind speed at the specific heights showed that agreement in wind speed measurements was very good. The ratio of lidar wind speed to anemometer wind speed was 0.9935 (R^2 = 0.87) at 11 m, 0.987 (R^2=0.9254) at 20 m and 0.9826 (R^2 = 0.9483) at 30 m. The LIDAR measurement is a path-averaged measurement and the anemometer a point measurement so the height comparison is nominal.

Wind directions differed consistently between the lidar and mast data with an off-set of 8 ° ± 5° between the two. A typical accuracy for setting North is ±5 ° so opposite alignment errors on each instrument could account for this but the importance of verifying agreement of direction between the lidar and a reference measurement is underlined.

Variability in wind-direction and wind-speed as measured using wind-persistence was largest near to the ground and decreased with height. The LIDAR measurement at 11 m and 20 m height were much more variable than at higher elevations.

To investigate the shape of the LIDAR wind profiles they were compared with specimen theoretical profiles. No attempt at deriving stability parameters was made, and there was no independent check on atmospheric stability but the shape of the profiles were overall consistent with those of a stable atmospheric boundary layer.

This comparison exercise, essentially a blind test, gives confidence to the manufacturer's specifications for the LIDAR and shaped the planning of the full wind

study at a refinery, the results of which are reported separately [1]. That report also discusses the practical issues encountered with using a wind LIDAR on a mobile platform in a refinery environment.

1. INTRODUCTION

The wind field over a refinery is complex due to interactions of the wind with buildings, tanks and process structures. Investigating the wind field using traditional in-situ measurements is difficult. Large height meteorological masts need anchoring for stability and positioning is problematic. Reference wind information is therefore obtained either from reference masts mounted in remote parts of the refinery where they are away from structures, cables, underground hazards, etc., or from the nearest meteorological station which may be far away. This gives cause to uncertainty about their representativeness.

Wind LIDAR technology was first developed to provide information on wind fields in the upper part of the boundary layer (above 200 m). The evaluation of sites for wind farms needs information at ~ 100 m height (large turbines) down to 40 m height (small turbines) and has pushed the development of instruments that work at these lower heights. The usual minimum height requirement for a wind LIDAR is a standardised 39 m height providing on-axis data for small wind turbines. The ZephIR wind LIDAR is specified to provide data as low as 10 m above the instrument which is a key reference height for wind data to be used in dispersion studies. Concawe decided to use this type of LIDAR as part of a refinery wind field study. As part of the rental agreement and training package with Kona, Concawe asked that the LIDAR be set up to run against a set of anemometers mounted on a reference mast. This was not a thorough validation of the LIDAR but it filled a data comparison gap at heights from 11 to 30 m.

This report provides the observations made in the period 27/09/2016 to 29/09/2016. The LIDAR was run to sample at approximately 20 s intervals and the data averaged to give 10-minute values. This is a standard averaging time for wind use in atmospheric dispersion calculations and in the interpretation of sensing data. The averaged data comprised wind-vector and wind speed. Persistence was calculated as the ratio of the modulus of the wind-vector to the (scalar) wind-speed. This measures variability in wind-direction.

The anemometer data (from AMMONIT 3D anemometers– see Appendix C) were averaged to 10-minute intervals using the on-board data-logging system. Wind-speed and wind-direction were output from the preconfigured logging system. It was not possible to extract persistence from the mast data using the pre-configured system.

Time series of vertical wind speed and direction profiles were obtained giving a time-series of nearly 100 consecutive 10-minute periods where data from both instrument systems were logged. These data are presented in Appendix A.

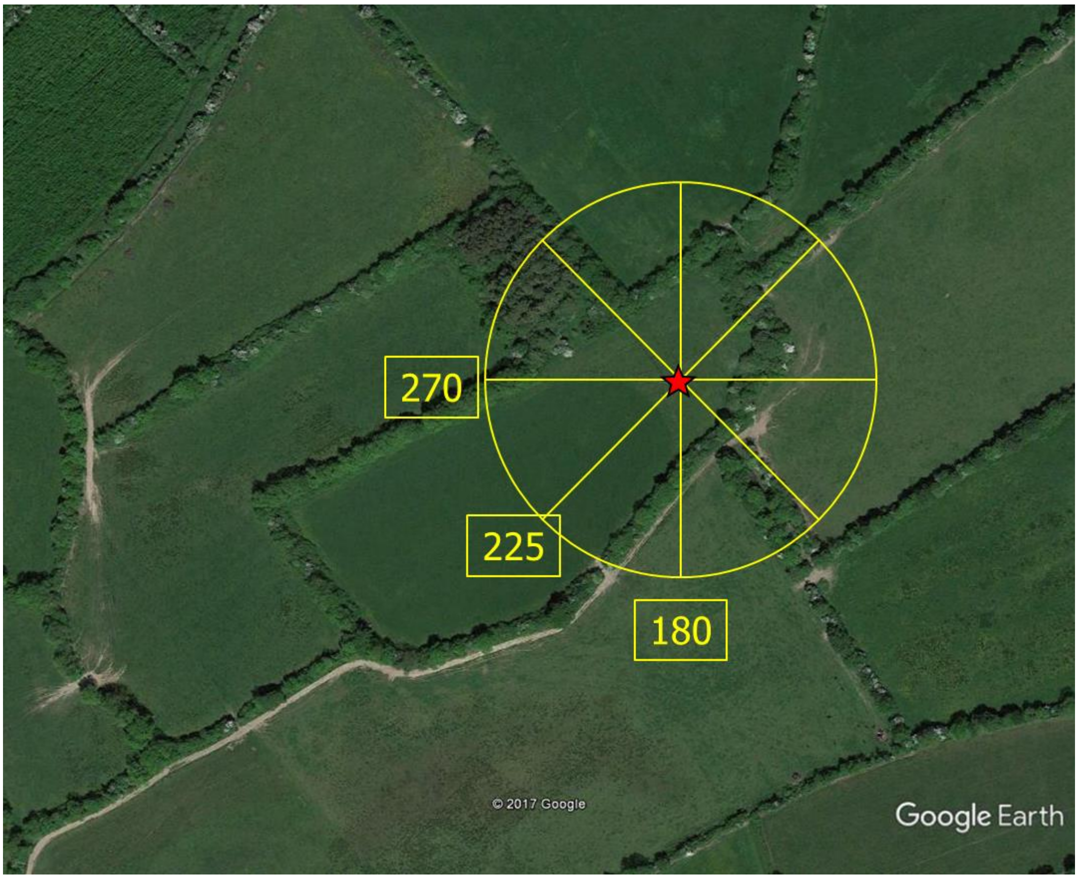
The general shape of the wind profiles was for a stable boundary layer which is credible for the location. Some example theoretical profiles for stable atmospheres were calculated and presented against the data to give a visual impression of measured vs expected profiles. No attempt was made to fit profiles numerically to derive stability parameters and there was no independent measure of atmospheric stability.

2. METHODOLOGY

The data comparison was carried out at a farmland site in Ireland, (latitude= 53.64 degrees, longitude = -6.89 degrees) where an 80 m meteorological mast is installed.

The location is shown in **Figure 1**.

Figure 1 Location of meteorological mast showing local topography.



For wind directions between 220 and 260 degrees the mast has an upwind fetch of ~ 500 m over smooth terrain and would be expected to experience a relatively well-developed surface boundary layer with a surface roughness length of a few centimetres in value. A typical value for farmland with regular hedge boundaries would be about 0.05 m.

The wind profile in the boundary layer over uniform roughness is of the theoretical form:

$$U(z) = \frac{u_*}{\kappa}\left(log\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right)\right)$$

Where u_* is the friction velocity, κ von Karman's constant (0.4), z_0 the roughness length and $\Psi\left(\frac{z}{L}\right)$ is a function that represents the effect of atmospheric stability on the profile. The parameter L is the Monin-Obukhov length and represents the distance over which mechanically generated turbulence due to friction at the surface dominates how buoyancy forces augment (L > 0) or suppress (L < 0) turbulence. For a stable boundary layer $\Psi\left(\frac{z}{L}\right) = -5\frac{z}{L}$ and $\Psi\left(\frac{z}{L}\right) \rightarrow 0\ as\ |L| \rightarrow \infty$ which condition represents the neutrally stratified boundary layer.

In this evaluation of the LIDAR some profiles with L having value 50 (very stable), 158 (moderately stable) and 500 (slightly stable) have been added to the data comparison for illustrative purposes. The middle value of L is the geometric mean of the other values and chosen to space the profiles. No special meaning attaches to its value.

The value of u_* was fixed by forcing the illustrative profiles to go through the measured 20 m height wind value from the anemometer array.

Data provided from Kona comprised ten-minute values of wind speed and direction from both the LIDAR (at heights 11, 20, 35, 39, 40, 50, 60, 65, 80 and 100 m) and the anemometer array (at heights 11, 20 and 30 m). Additionally, output from a sonic anemometer co-located with the LIDAR at a height of 2 m was provided and has been added to the LIDAR profile.

Raw LIDAR soundings were also given. These are at approximately 20 second intervals but the time-step of the LIDAR output can vary because the deconvolution of the data is dependent on the signal to noise ratio obtained. If the signal is weak then the sampling time step increases.

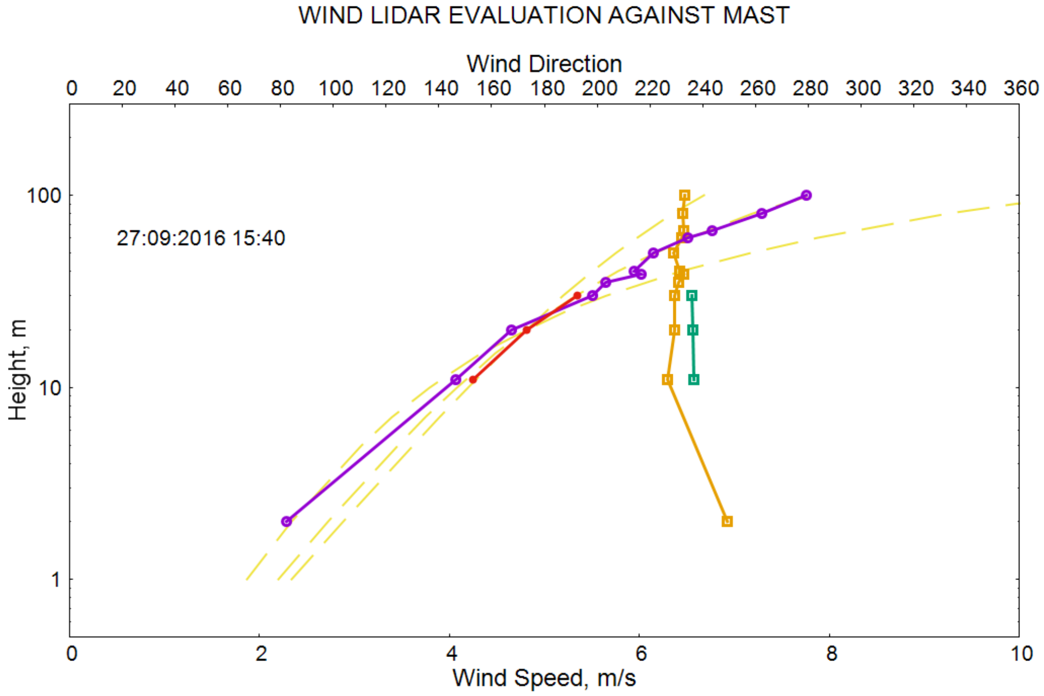
Evaluation of the raw LIDAR data showed that the averaging procedure used was to take a predefined 10-minute interval, count the records obtained in that interval, then carry out averaging of those records and report at the time of the interval start. Averaging of circular variables requires making the average of the components (u, v) from each measurement and from these obtain the average wind direction and the average wind speed in that direction (modulus of the wind vector). The data reported as 10-minute averages comprised the correctly calculated wind direction together with the average scalar wind speed, i.e. the average of the wind speed as measured and not the length of the wind vector. It is assumed that the anemometer data, which were only reported at 10-minute intervals, have been subjected to the same treatment. Therefore, the comparisons here are of scalar wind speed and vector wind direction. It would be preferable to compare vector rather than scalar wind speeds but the difference is small in stable conditions as will be shown in the results section.

3. RESULTS

The data comparison is made by co-plotting the LIDAR and anemometer profiles on a graph where height is shown as the y-axis and the dependent variables on the x-axis. An example plot is shown in **Figure 2**. The wind speed and direction are plotted against the logarithm of height. The wind variation with height in a neutrally stratified boundary layer would appear as a straight line in this case.

As described in the Methodology (Section 2) three examples of stable boundary layer wind profiles have been shown for illustration (yellow dashed lines). No fitting has taken place but the profiles are forced to go through the anemometer measurement at 20 m height to provide alignment. The most stable profile is the most curved. In this example, the LIDAR wind profile shown in purple closely follows the middle example profile. The 2-meter height datum on the LIDAR profile comes from an anemometer fitted to the LIDAR. It is included in the LIDAR profile for illustrative purposes and because it was co-located. It could equally have been plotted as a fourth anemometer height.

Figure 2 An example of evaluation of wind LIDAR against conventional wind monitors. The purple line is the wind speed profile with wind speed on the lower x-axis and height on the y-axis. The red line is wind speed from the mast. The three dashed yellow curves are example theoretical wind profiles corresponding to neutral, slightly stable and more stable conditions. The orange line represents wind direction obtained from the LIDAR as the upper x-axis against height and the green line is the wind direction taken from the mast.



A full set of the 10-minute profiles is given in Appendix A. The main features of the time series are very good agreement between the LIDAR and the anemometer data for wind speed at all three heights. Further, the LIDAR wind profile from 11 to 100 m is a credible shape for a boundary layer profile in all cases. Although the time series is limited to some 16 hours due to a data logging failure on the morning of September 8th a range of wind speeds and wind directions were experienced and the agreement was good across these.

The pointwise comparison of wind speed is shown in the following three figures for the nominal heights of 11 m, 20 m, and 30 m respectively. The agreement is very close to linear, allowing that wind speed increases with height the LIDAR values are slightly smaller than the anemometer values. Scatter decreases with height with variance measured as R^2 increasing from 0.87 at 10 m to 0.95 at greater heights. Although this shows a wider variation at 11 m height it is seen below that, in this stable boundary layer, the atmospheric turbulence (as measured by the persistence) also decreases with height. The performance of the LIDAR at 11 m is therefore commendable.

Figure 3 Correlation between LIDAR wind speed and the nearest anemometer at 11 m height above ground.

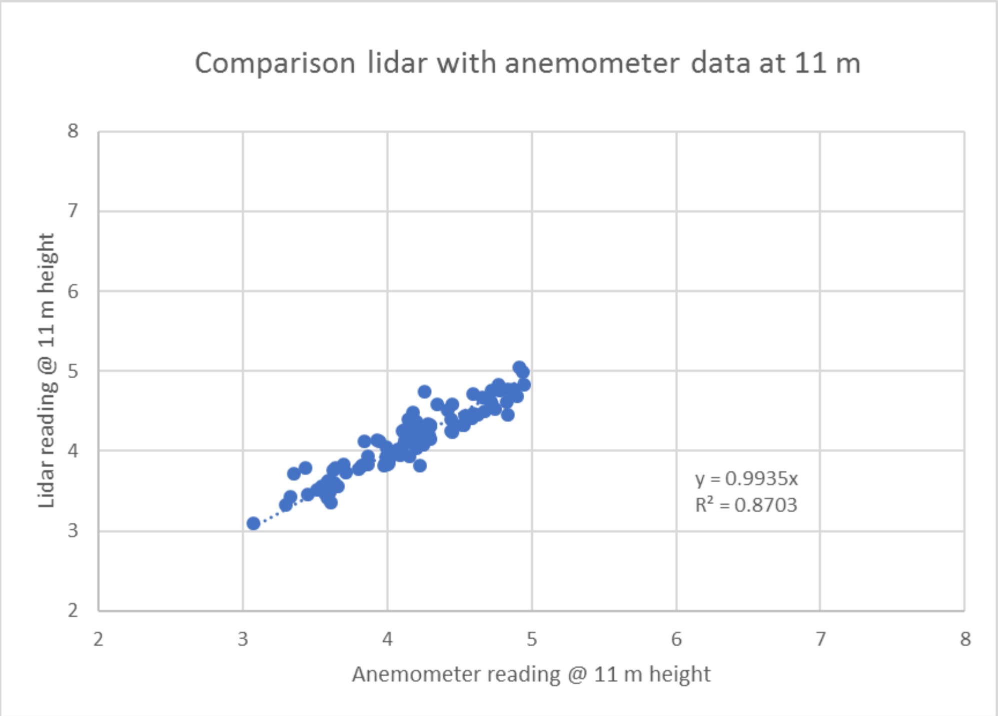


Figure 4 Correlation between LIDAR wind speed and the nearest anemometer at 20 m height above ground.

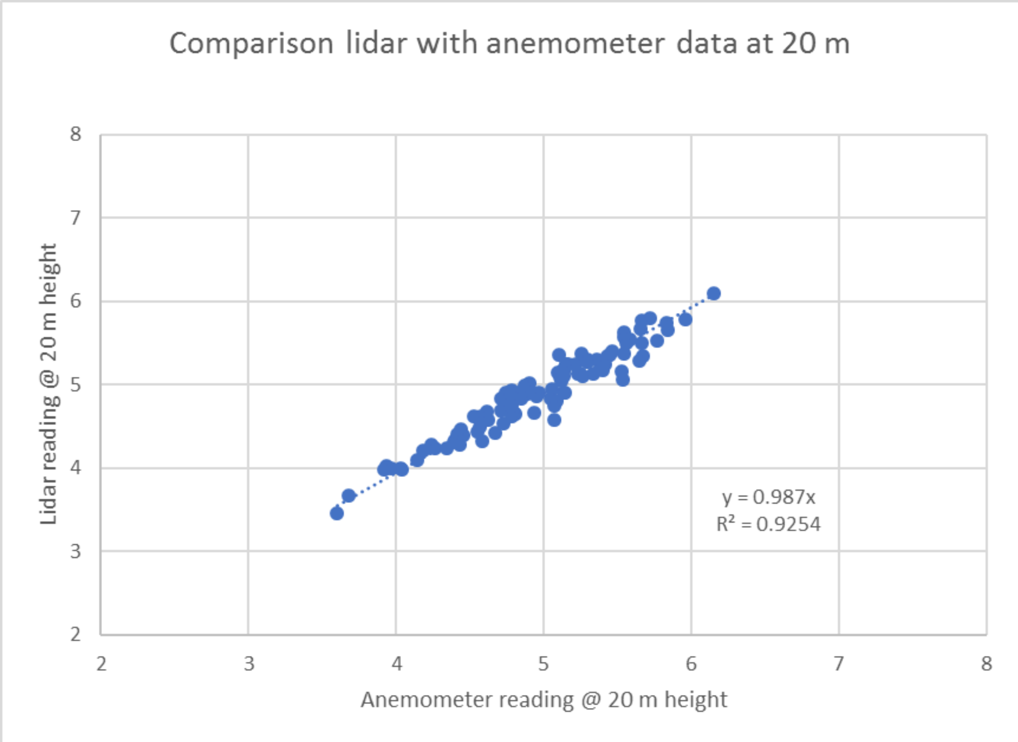
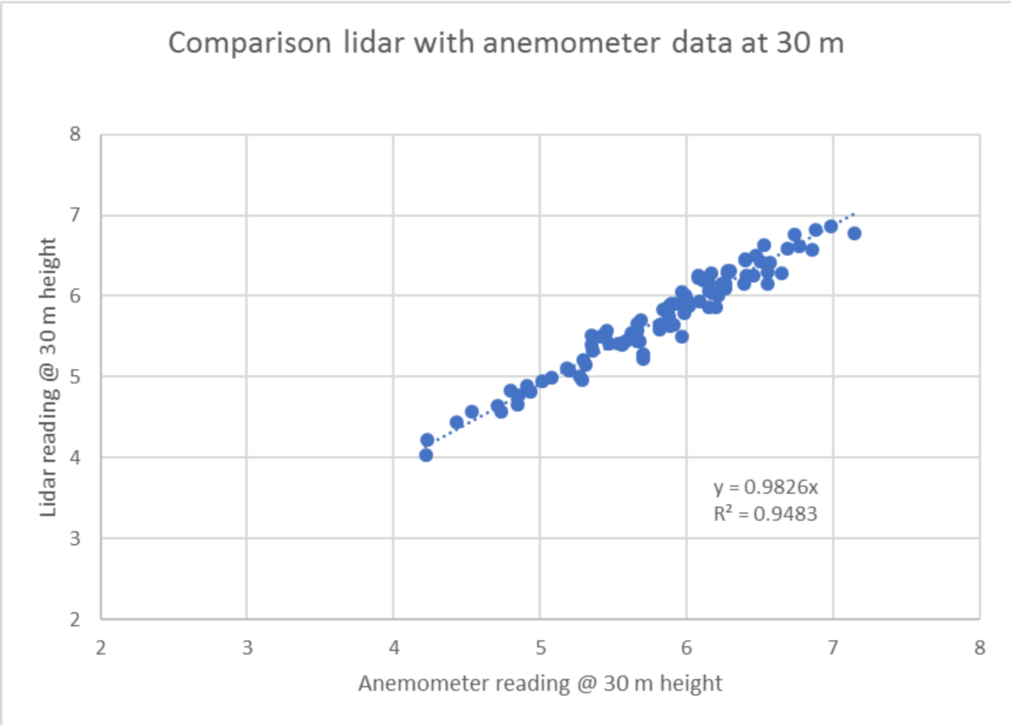
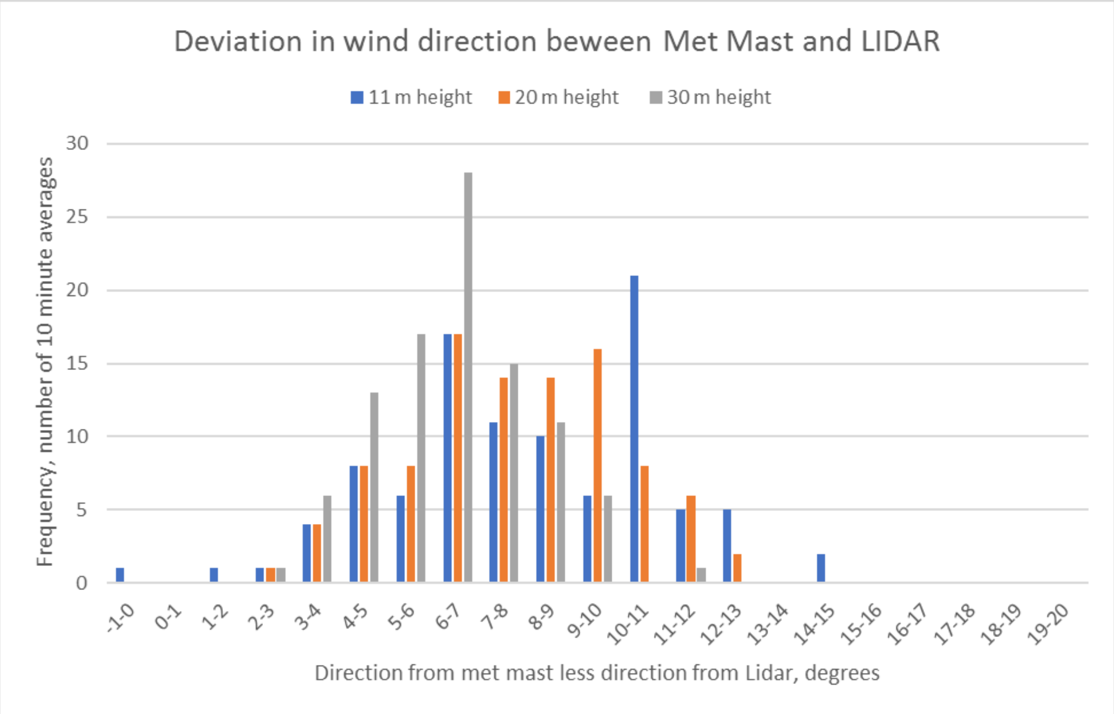


Figure 5 Correlation between LIDAR wind speed and the nearest anemometer at 30 m above ground.



There is a consistent but variable difference in wind direction between the LIDAR and mast measurements. Over the 100 or so data sets the average wind direction difference at 11 m is 8 degrees, at 20 m it is 7.8 degrees and at 30 m it is 6.4 degrees. The spread of values around these averages decreases slightly as the height increases, from a standard deviation of 2.8 at 11 m to 1.7 degrees at 30 m. The difference in direction is small and likely shows a North calibration offset on one or other of the instruments. It is unfortunate not to have the time-resolved anemometer data to examine the variability in wind speed that they measured over the 10-minute periods.

Figure 6 Difference in wind direction determined between LIDAR and mast.



The variability in wind direction with height decreases rapidly in the LIDAR data. This can be shown by plotting time-series of persistence for the reported data heights as shown in **Figure 7** and **Figure 8**. Persistence is the ratio of the length of the wind vector to the scalar wind speed. If there is no change in wind direction in the averaging period, the persistence has value 1. If the wind is completely variable so that it blows equally in all directions over the averaging period, it has value 0.

Here persistence has lowest value for the 11 m output and decreases systematically with height to very low values at 100 m. The value is always close to 1 (smallest value at 06:20 on the 28/09 was 0.93). These data are all supportive of a stable boundary layer indicated by the LIDAR wind profile.

Figure 7 Time series of persistence as a function of height.

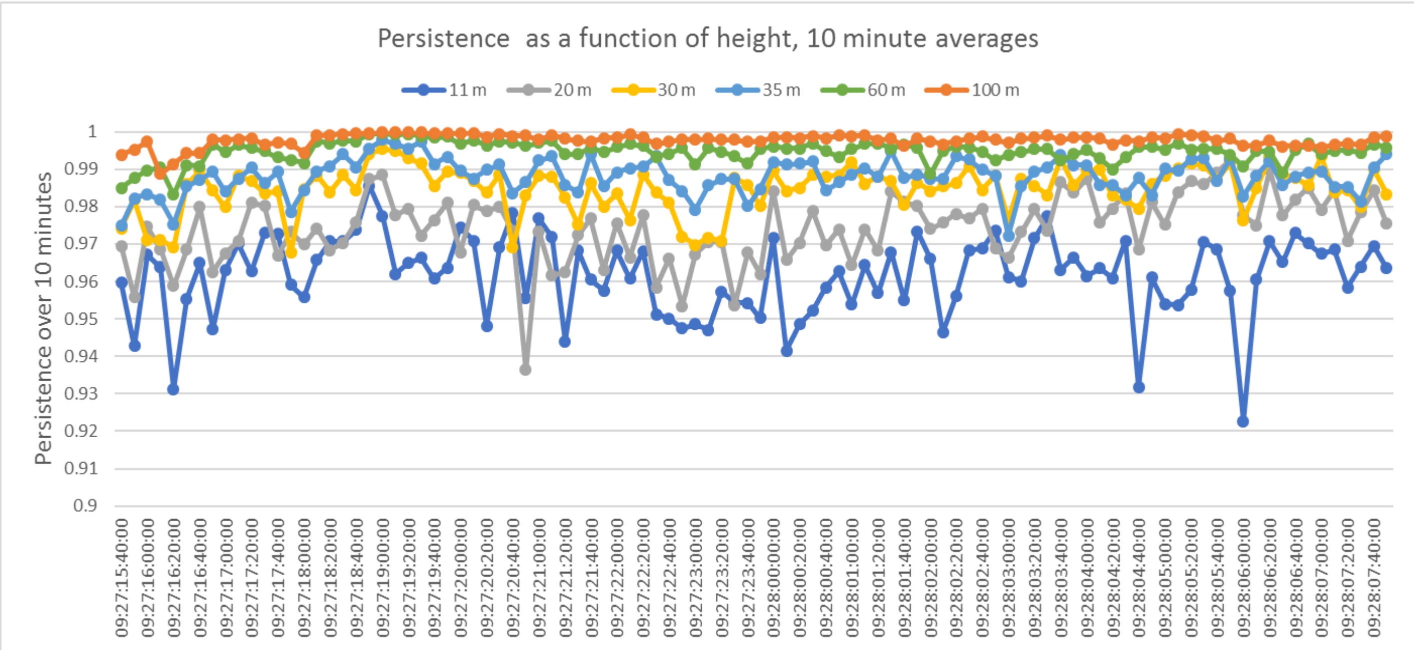
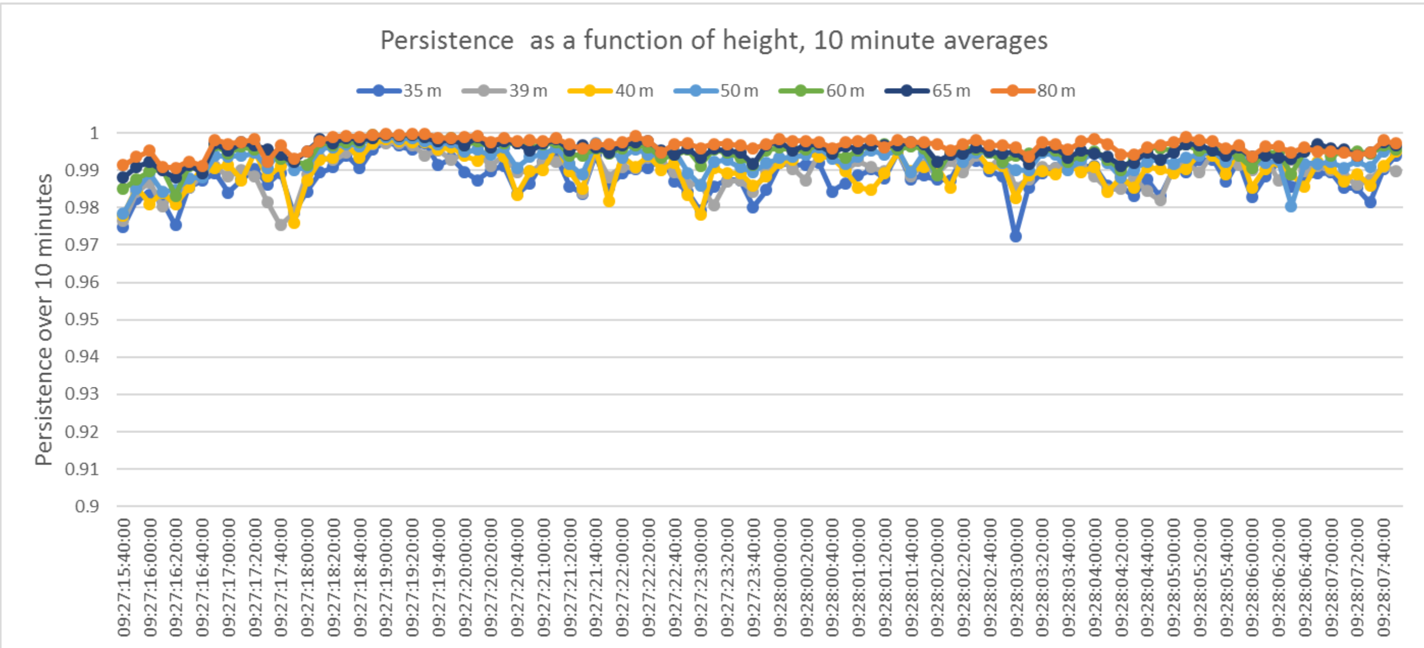


Figure 8 Time series of persistence as a function of height.



4. CONCLUSIONS

Time series of vertical wind profiles obtained from a ZephIR wind LIDAR have been compared to anemometer data on a meteorological mast. These data were obtained as a verification activity to assess whether the ZephIR LIDAR could resolve wind data at heights as low as 10 m before it was deployed on a refinery study. The test was not part of targeted validation. Nevertheless, this is thought to be the first published comparison of a wind LIDAR operated to give information below ~40 m, which is the minimum reference height for application in wind-farm site assessment.

The agreement between the LIDAR and anemometer data was very good. The scalar wind speed averaged over 10 minutes was in excellent agreement. There was a consistent offset in wind direction of a few (< 8) degrees to which North alignment errors may have contributed. In terms of deployment for dispersion modelling or the interpretation of remote sensing data an error of a few degrees is not that significant compared with other uncertainties. Verification of North alignment should be an important quality assurance step for wind measurements.

Interestingly the whole shape of the vertical profile obtained (11 – 100 m) was very consistent with theoretical profiles of the stable atmospheric boundary layer. This lends credibility to the results. Derivative data looking at the change in turbulence with height support fully the credibility of the measurement.

The ZephIR wind LIDAR therefore seemed to be a very useful tool for examining the variation in wind profiles across a refinery site. The results of such a study are described in a companion report [1]. That report also discusses the practical issues encountered with using a wind LIDAR on a mobile platform in a refinery environment.

5. REFERENCES

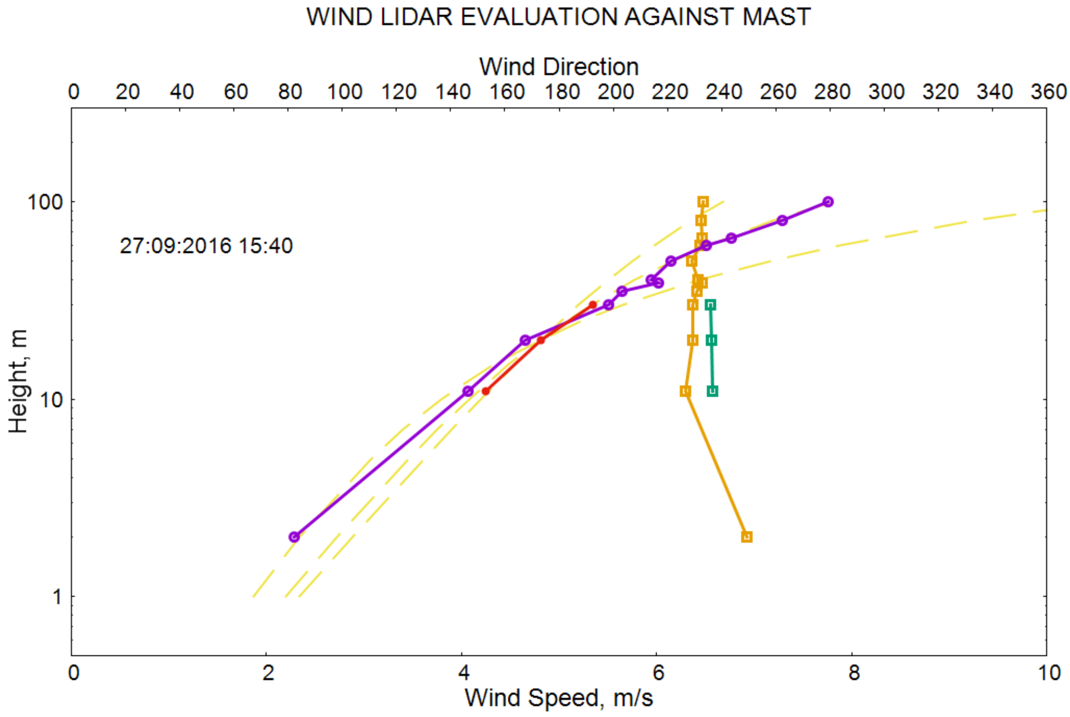
1. Concawe (2019): A study of wind flow around a refinery. Report No. 12/19. Brussels: Concawe.

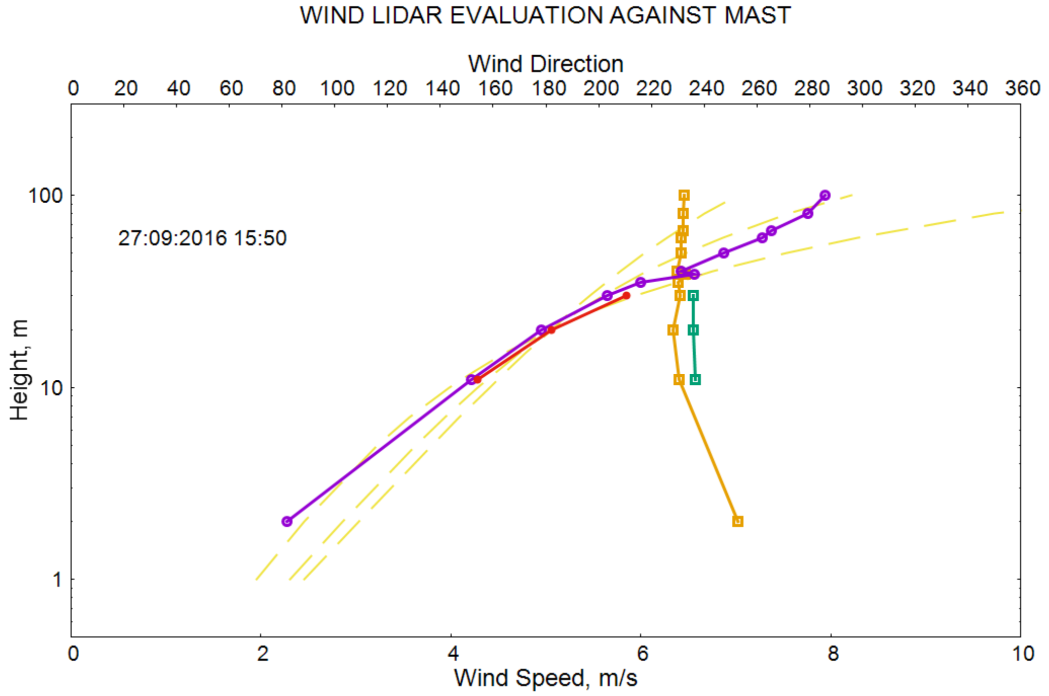
2. National Renewable Energy Laboratory (NREL) (2015): Remote Sensing of Complex Flows by Doppler Wind Lidar: Issues and Preliminary Recommendations. Technical Report, NREL/TP-5000-64634.

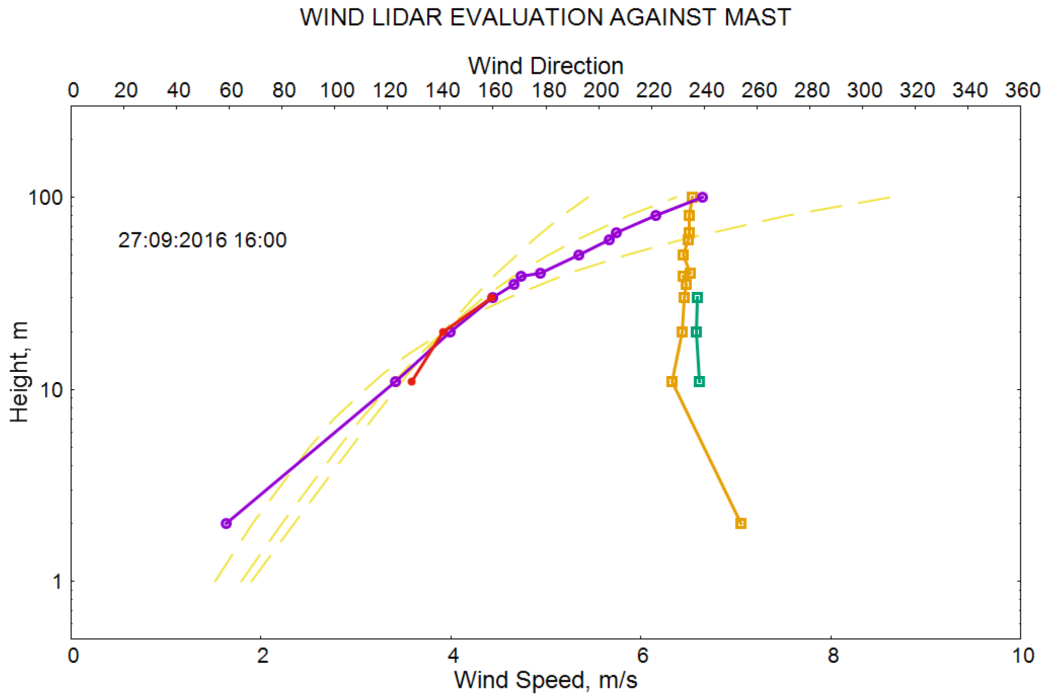
APPENDICES

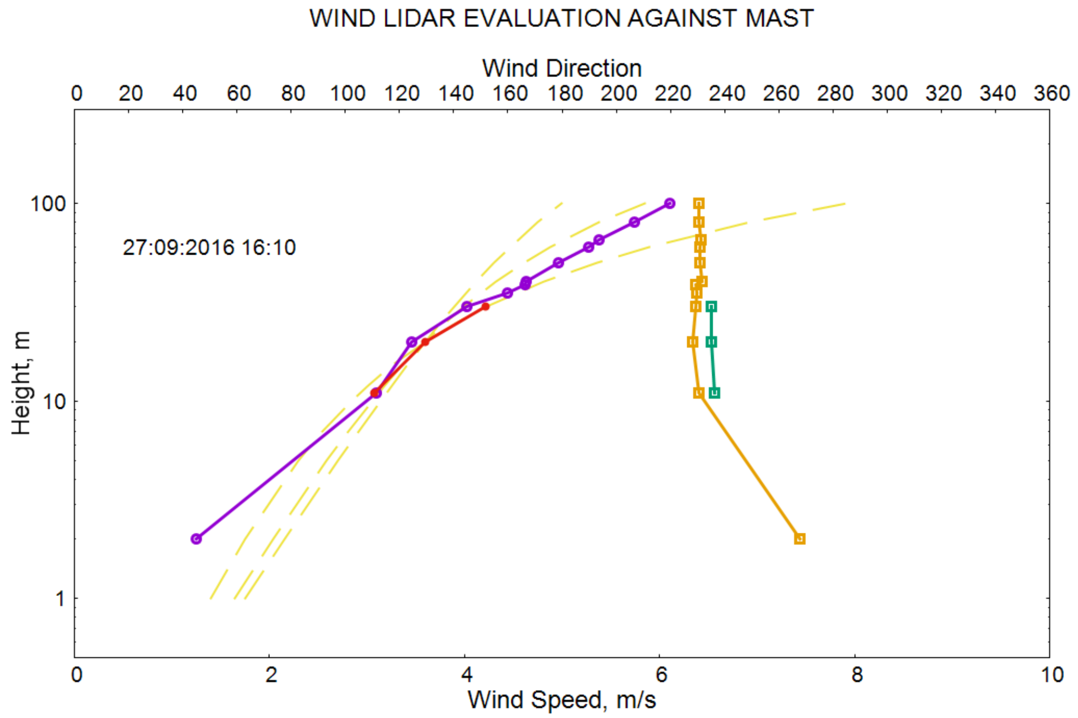
APPENDIX A – TIME SERIES OF DATA

This appendix contains the time-series of data provided from the comparison. Note the logarithmic scale exaggerates the LIDAR profile extended from the lowest LIDAR measurement point (11 m) to the reading of the anemometer (2 m) situated on the instrument. The guide profiles are for illustrative purposes only to give an impression of the shape of profile to be expected.




WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360
Height, m
100
10
1
27:09:2016 15:50
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360
Height, m
100
10
1
27:09:2016 16:00
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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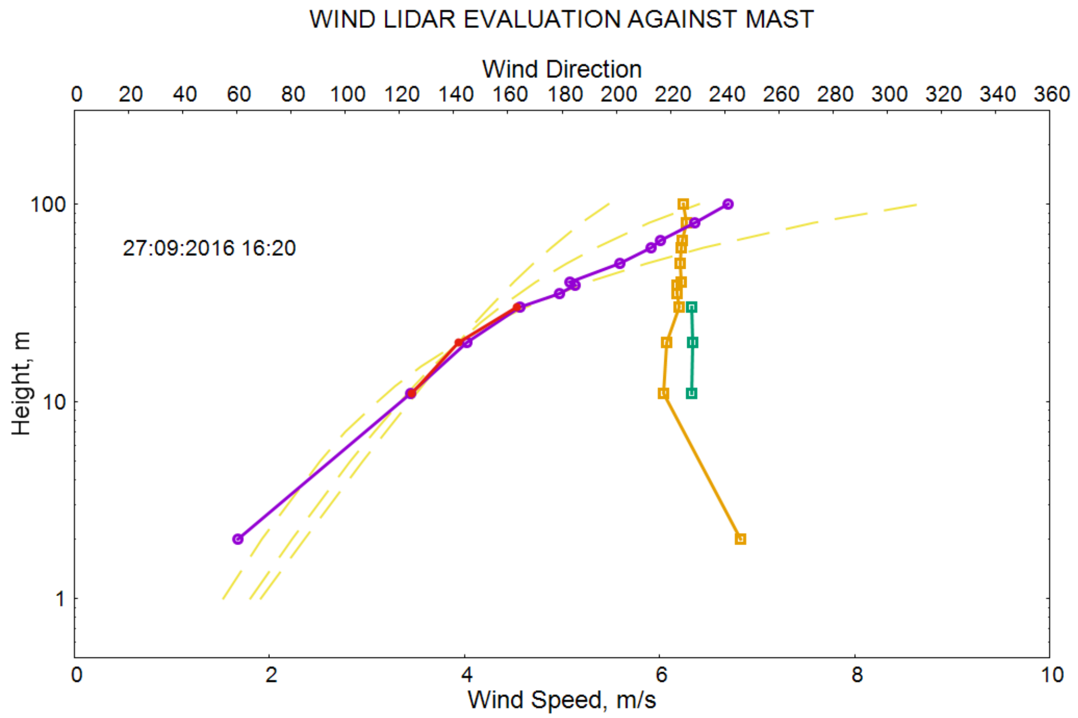
100
10
1
27:09:2016 16:10
Height, m
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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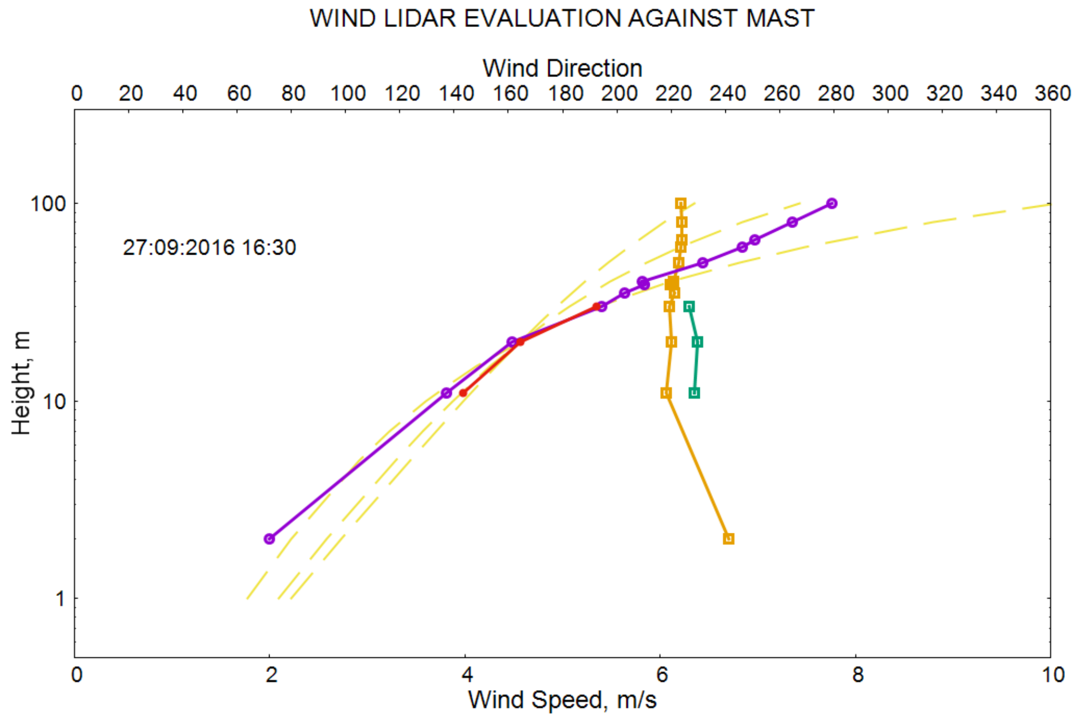
100
10
1
27:09:2016 16:20
Height, m
0 2 4 6 8 10
Wind Speed, m/s



WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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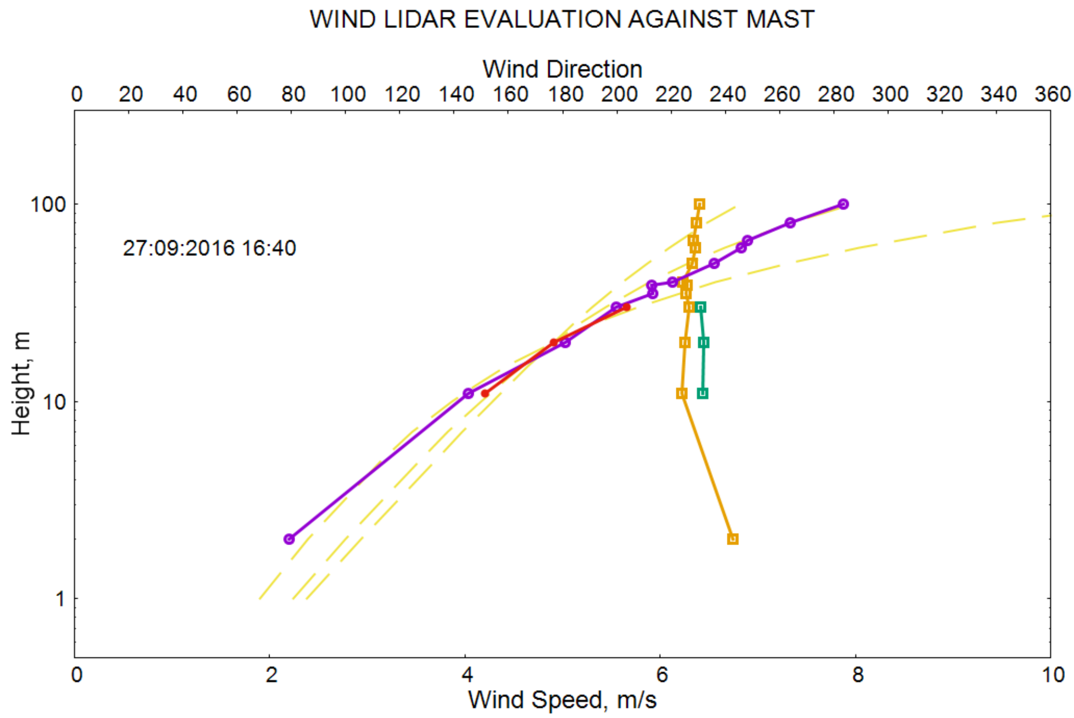
27:09:2016 16:30
Height, m
100
10
1
0 2 4 6 8 10
Wind Speed, m/s



WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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27:09:2016 16:40
Height, m
100
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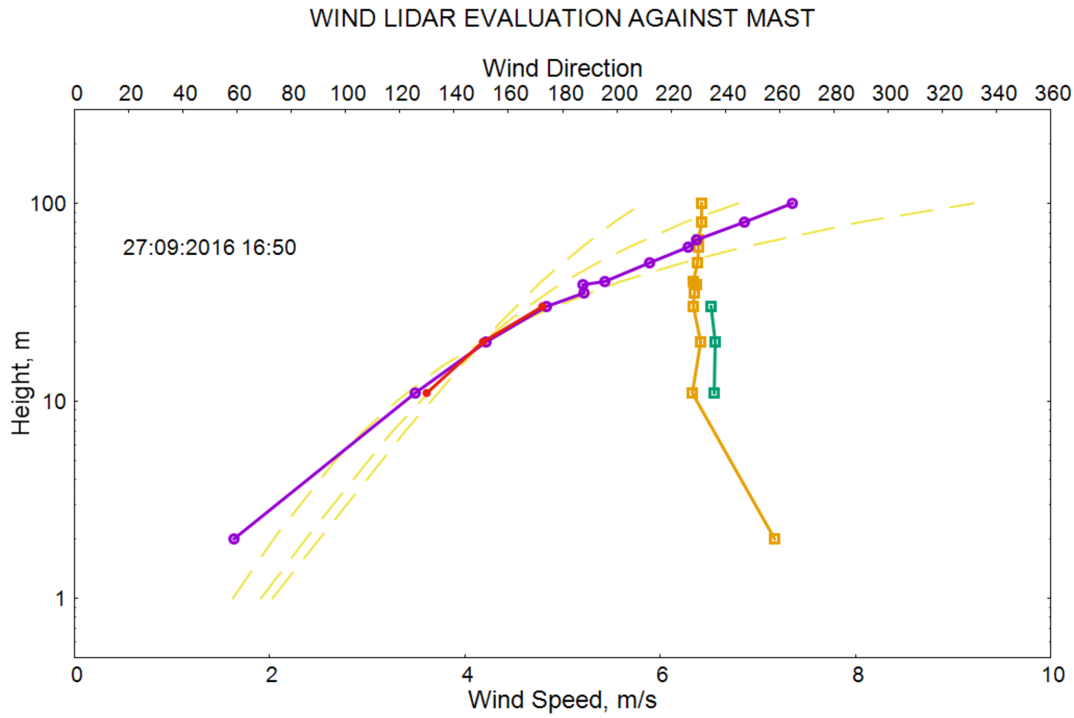
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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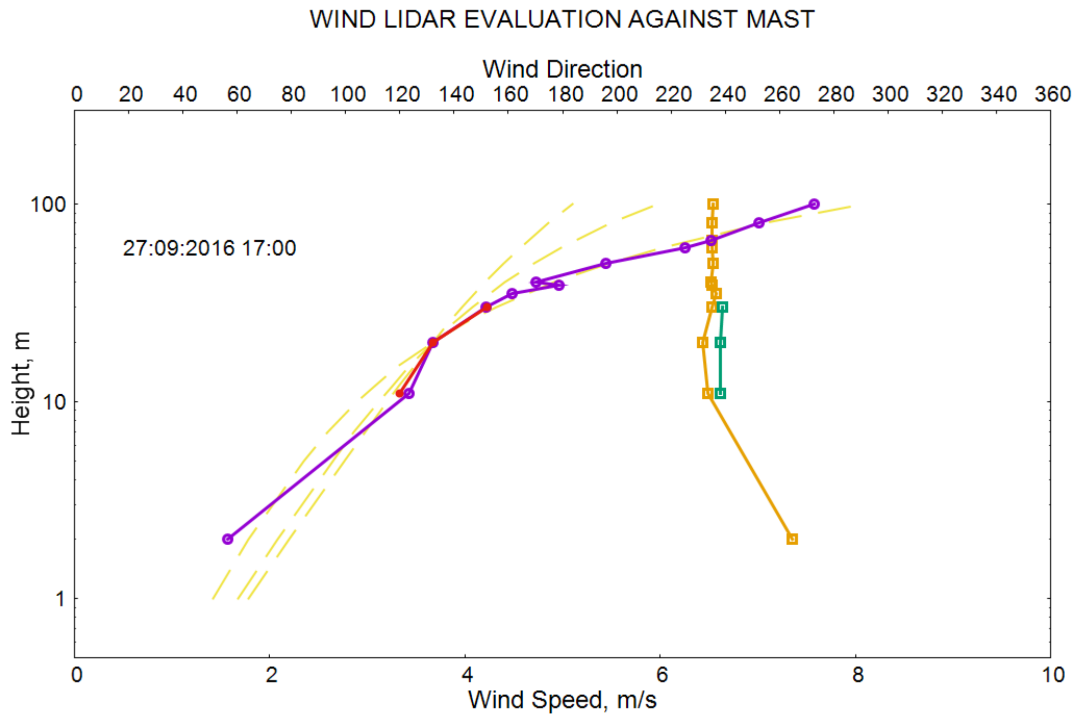
27:09:2016 16:50
Height, m
100
10
1
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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27:09:2016 17:00
Height, m
100
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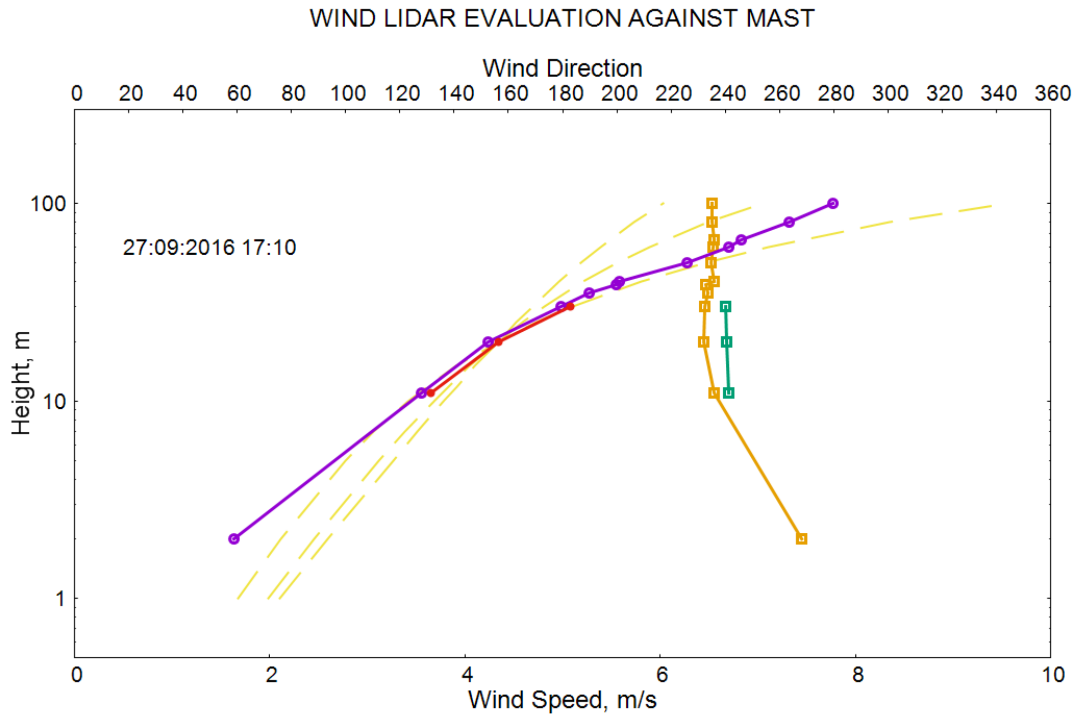
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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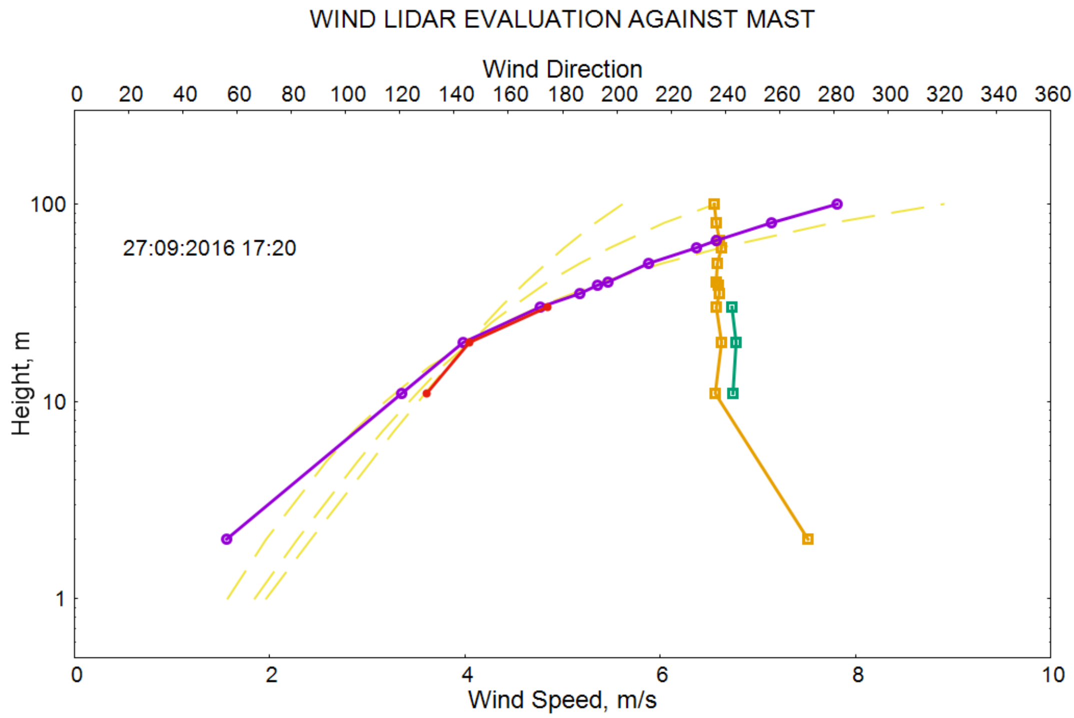
Height, m
100
10
1
27:09:2016 17:10
0 2 4 6 8 10
Wind Speed, m/s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Wind Direction
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Height, m
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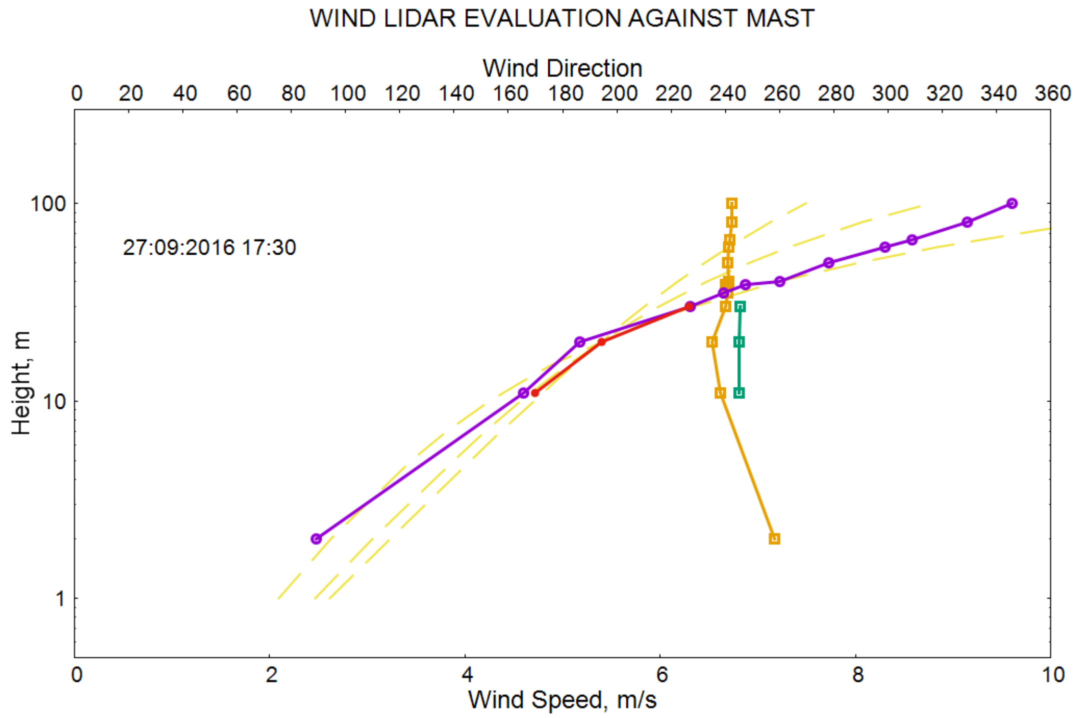
10
1
27:09:2016 17:20
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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100
10
1
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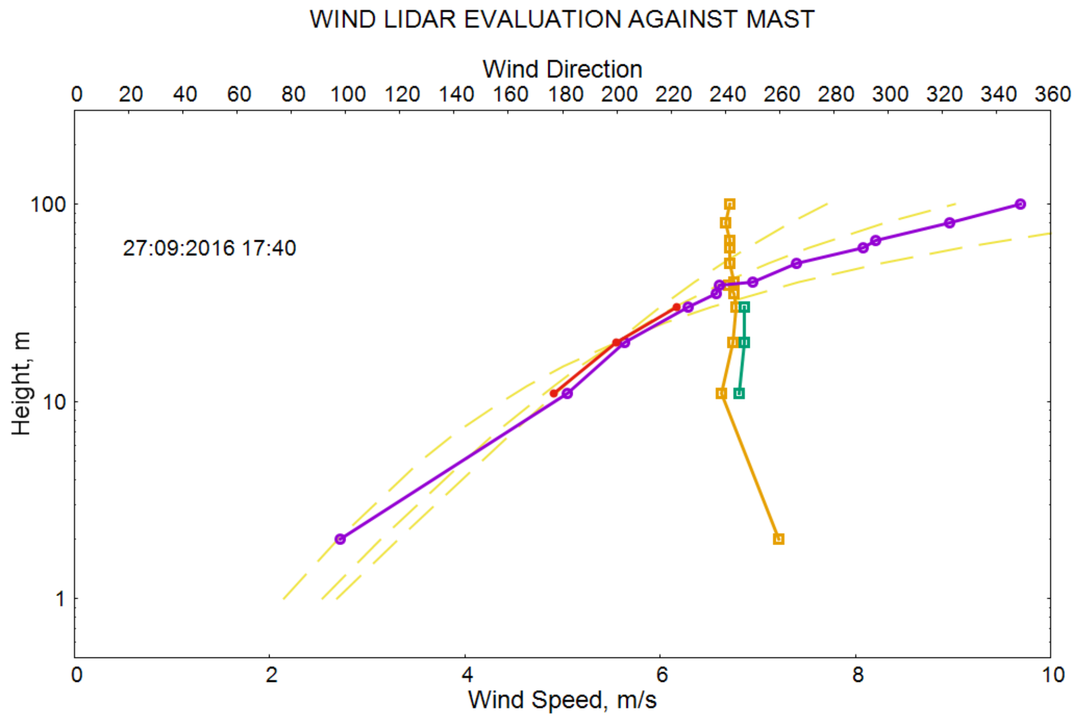
Height, m
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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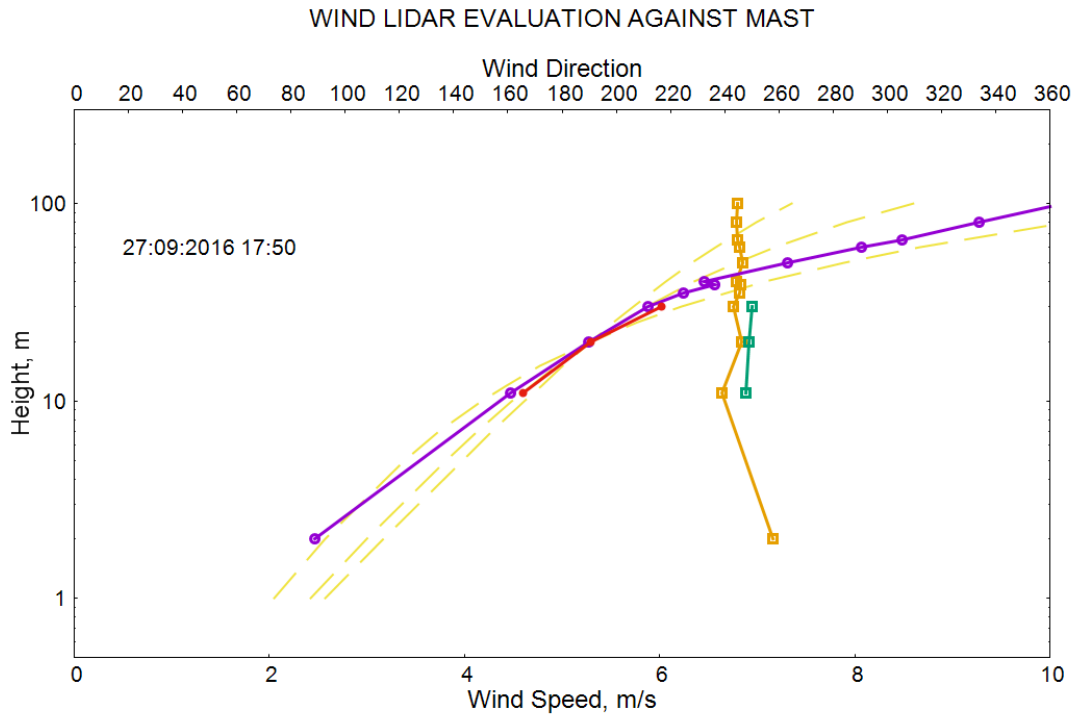
100
10
1
27:09:2016 17:40
Height, m
0 2 4 6 8 10
Wind Speed, m/s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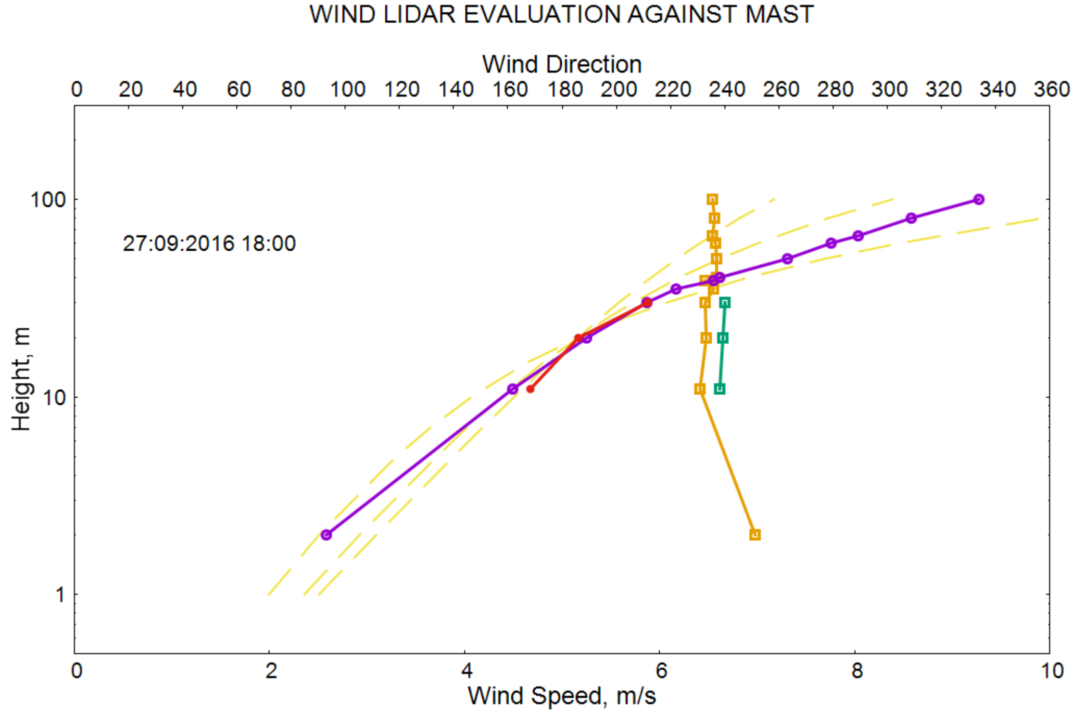
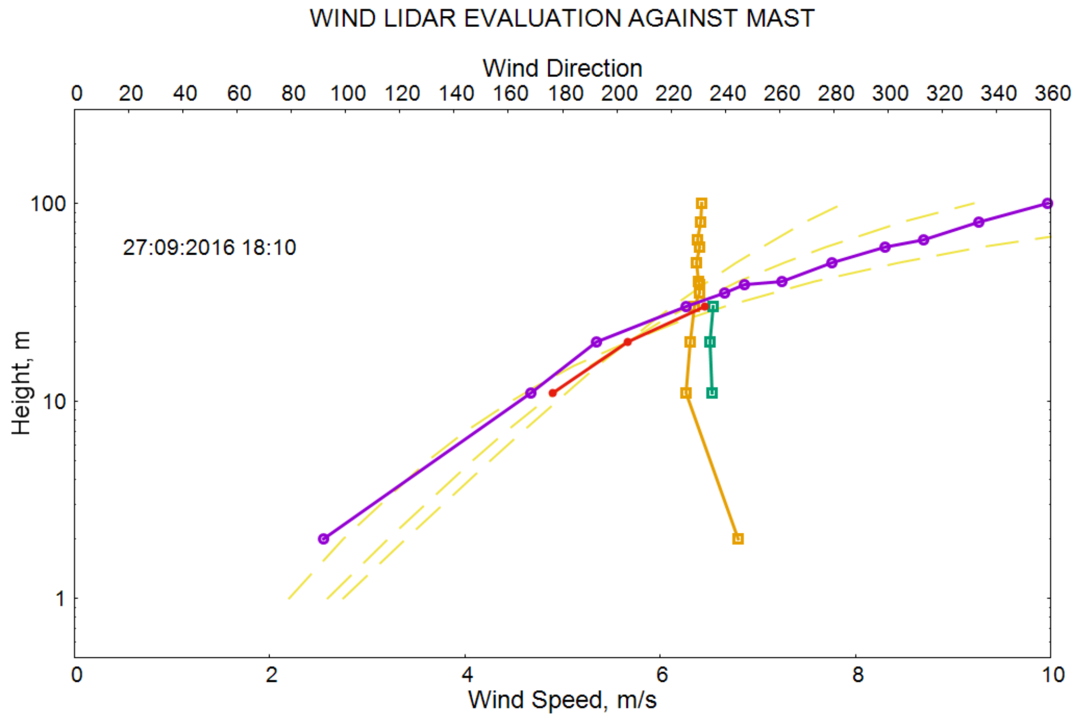
Height, m
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
27:09:2016 18:00
Height, m
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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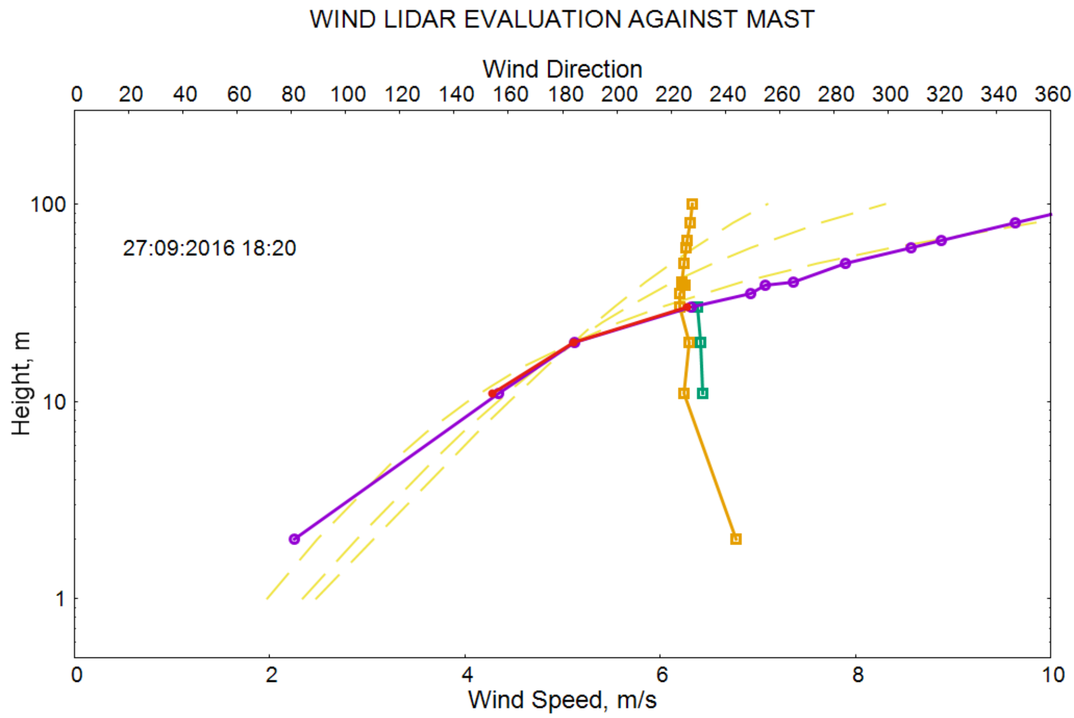
27:09:2016 18:10
Height, m
100
10
1
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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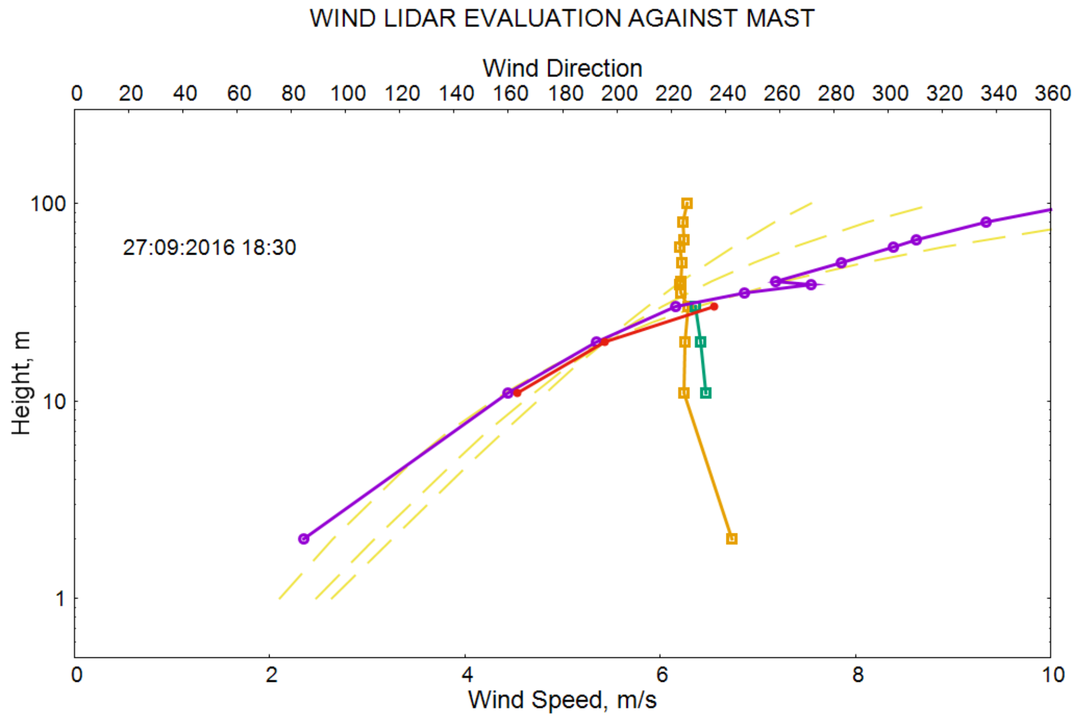
27:09:2016 18:20
Height, m
100
10
1
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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27:09:2016 18:30
Height, m
100
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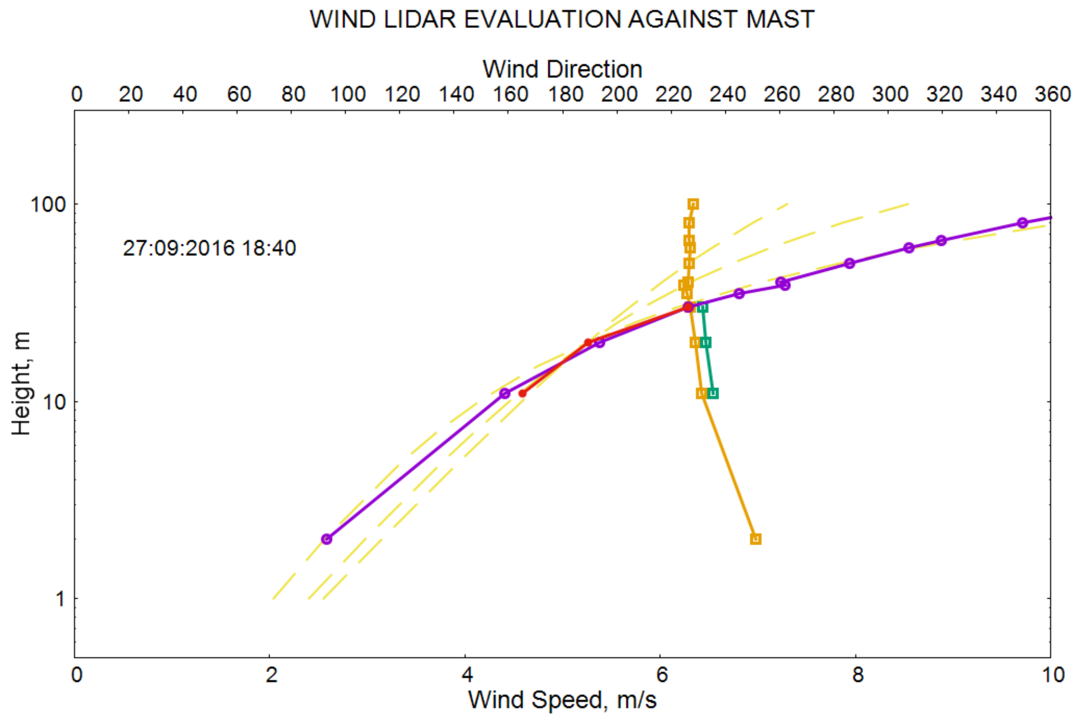
Wind Speed, m/s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Wind Direction
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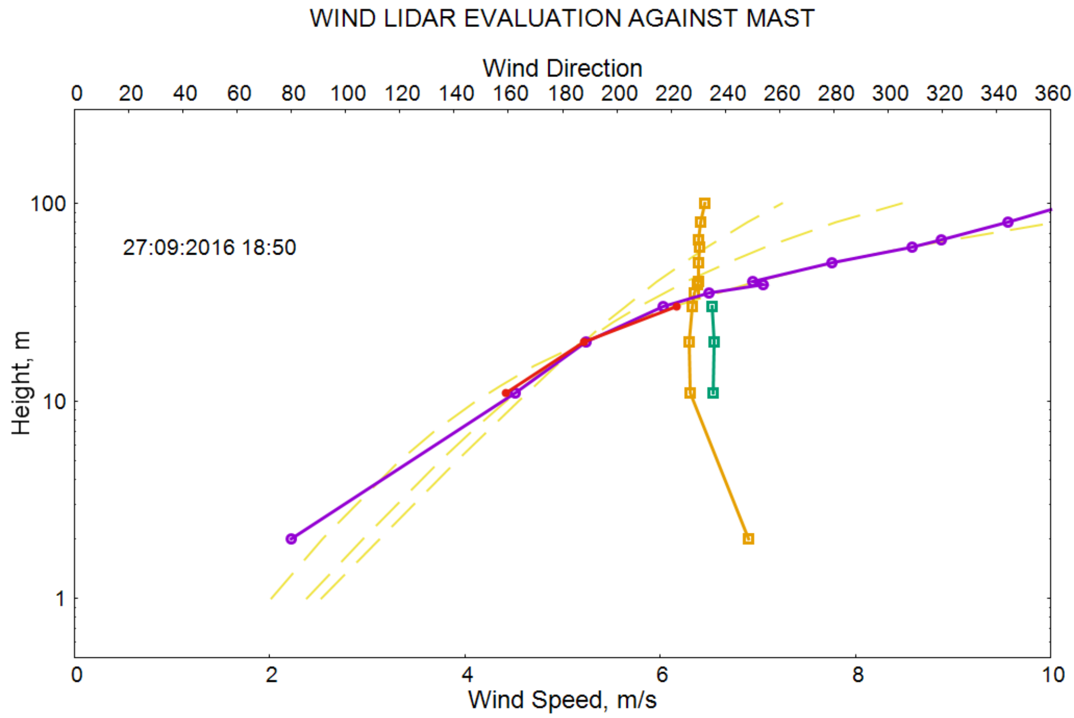
Wind Speed, m/s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Wind Direction
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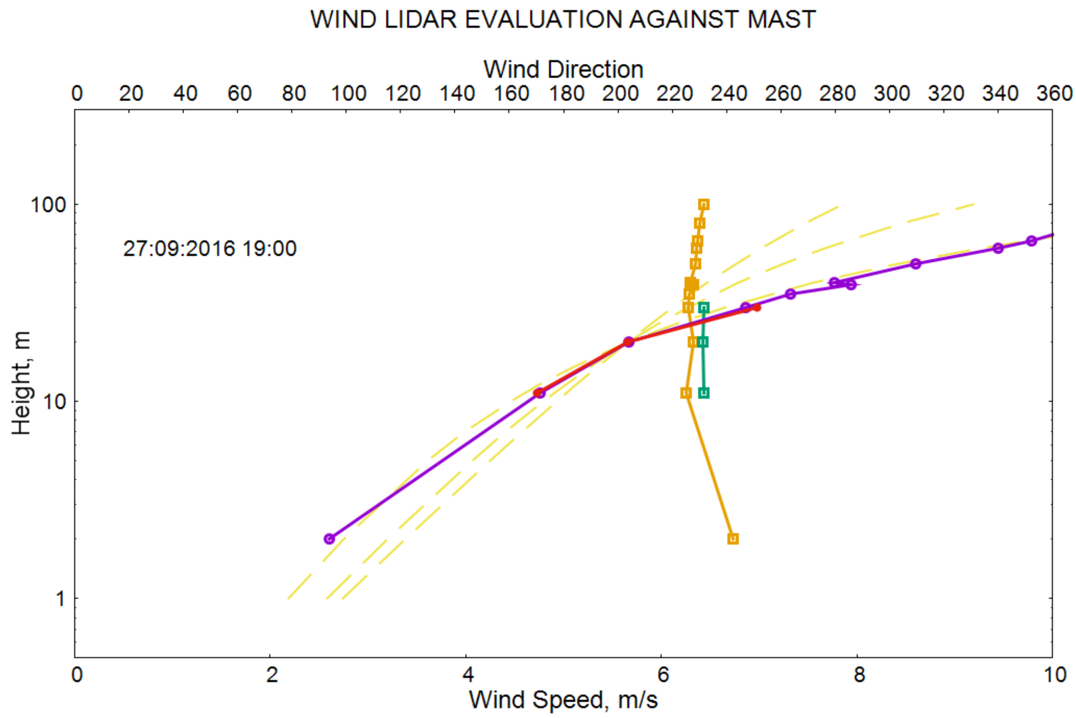
Wind Speed, m/s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Wind Direction
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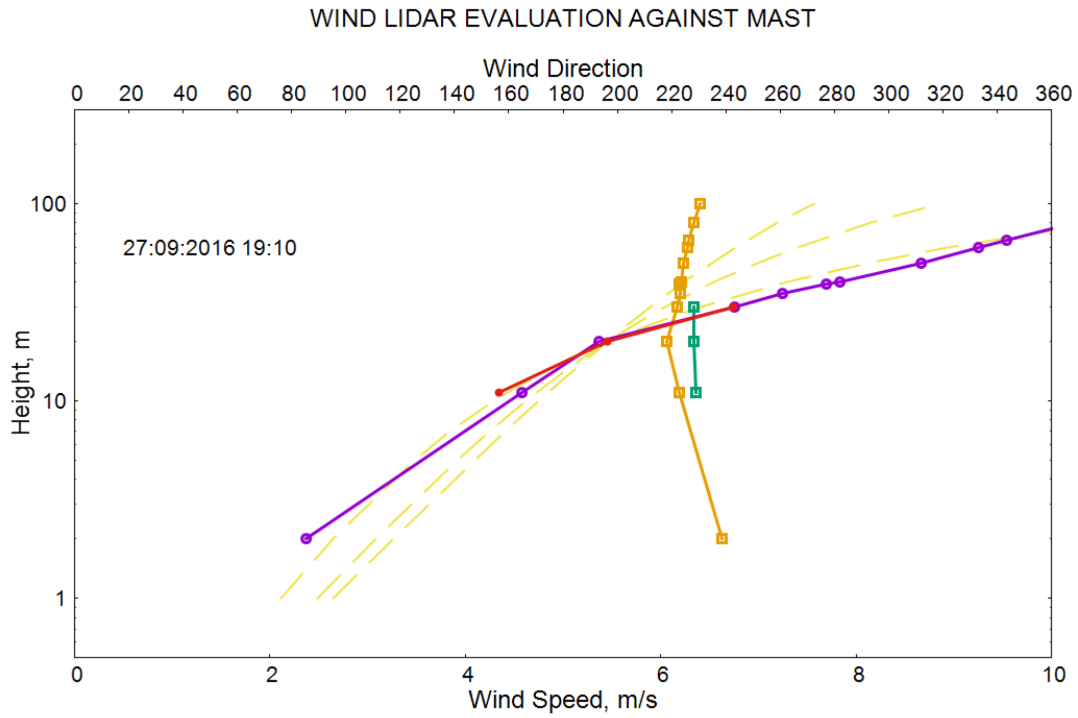
Wind Speed, m/s



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Wind Direction
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Height, m
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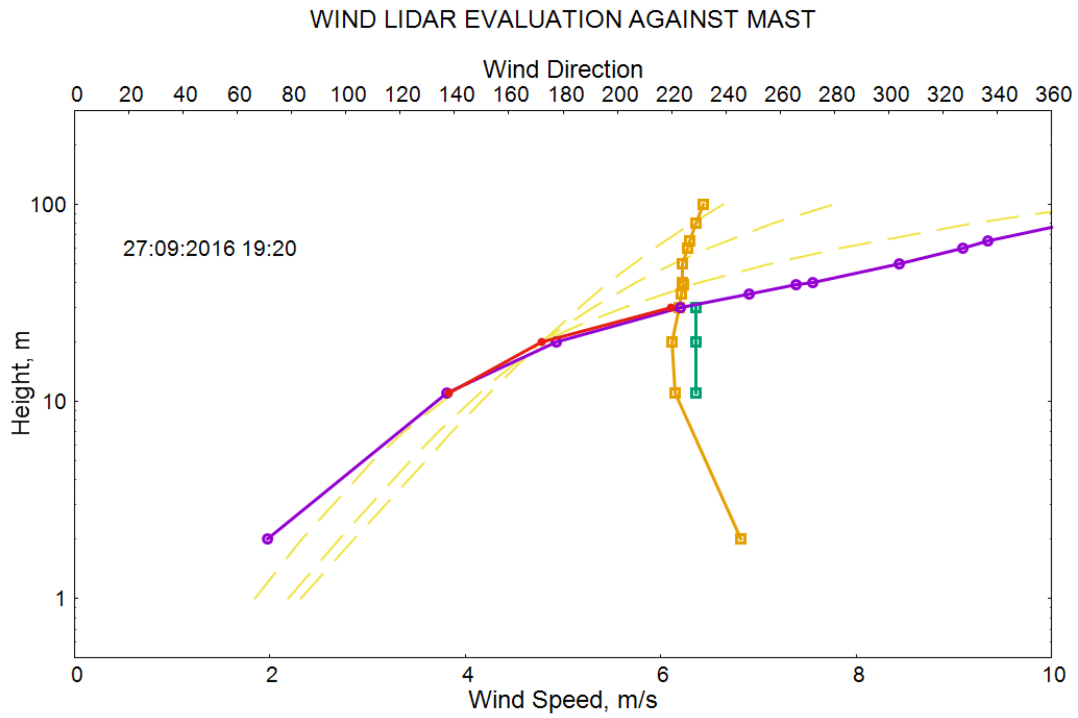
Wind Speed, m/s



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Wind Direction
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Height, m
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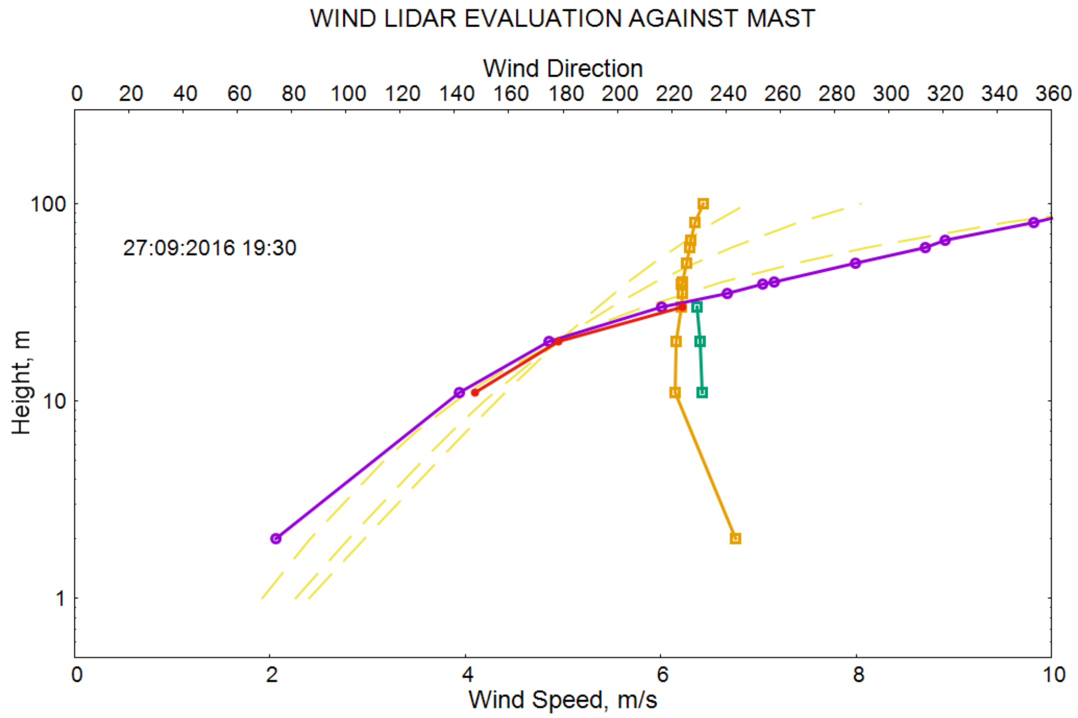
Wind Speed, m/s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Wind Direction
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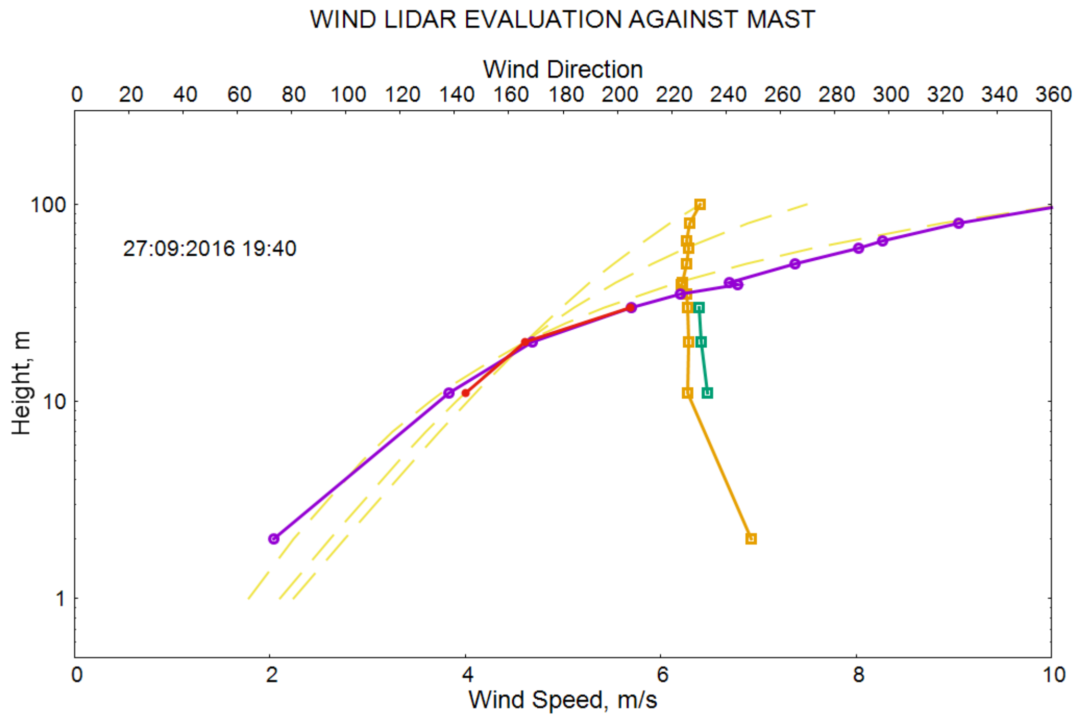
Wind Speed, m/s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Wind Direction
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Height, m
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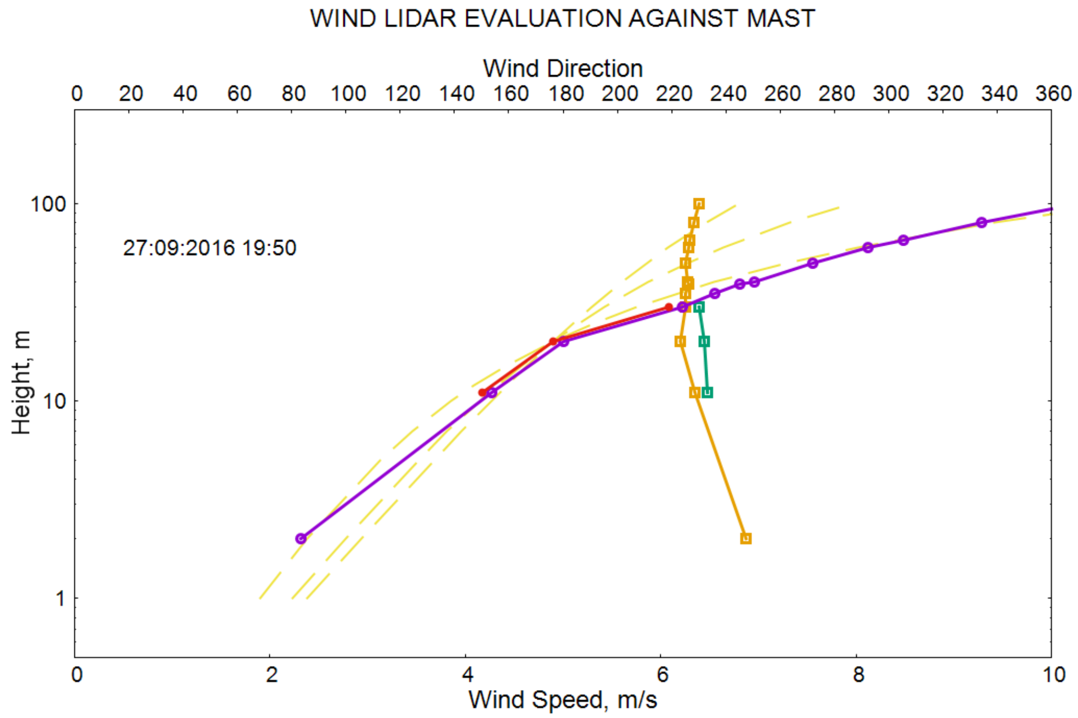
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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Height, m
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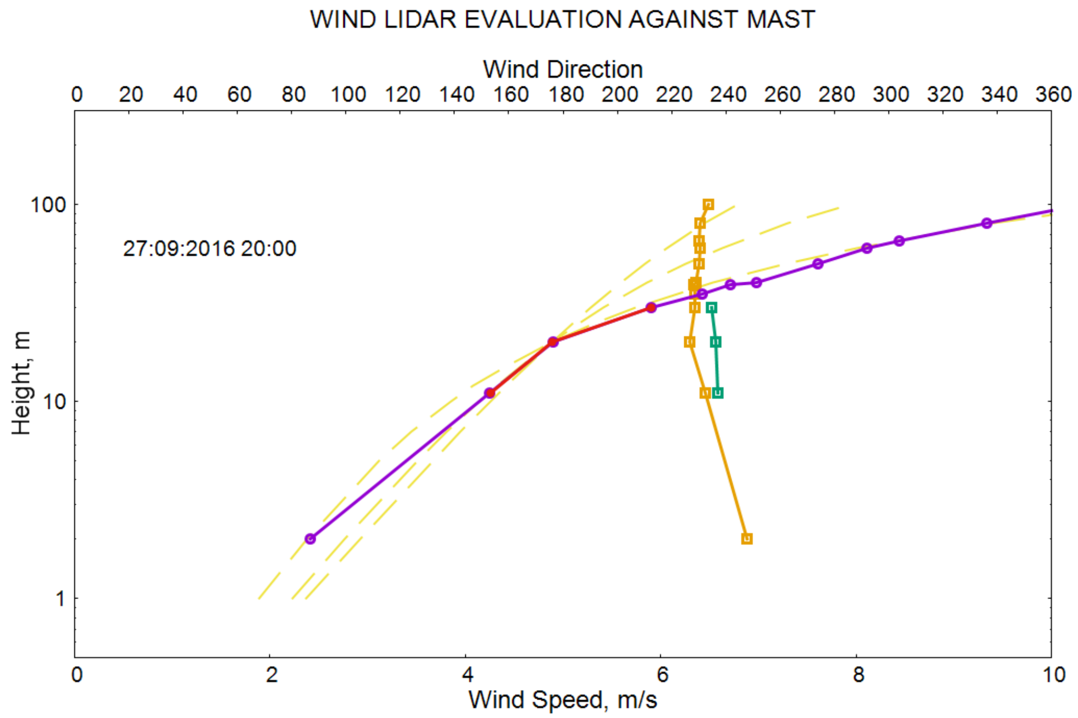
Wind Speed, m/s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Wind Direction
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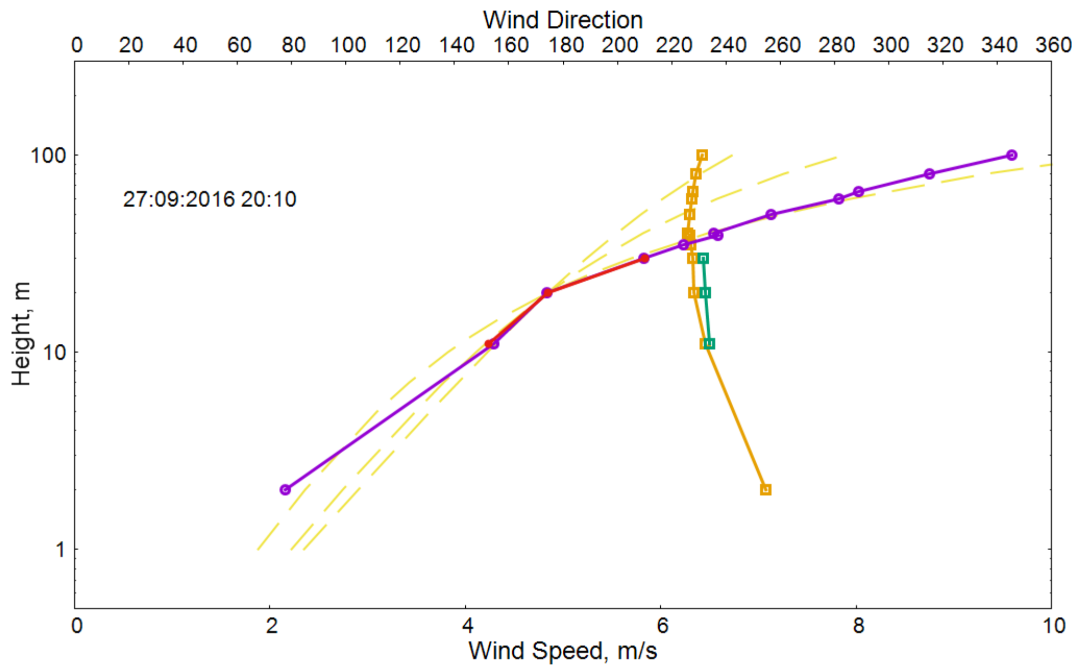
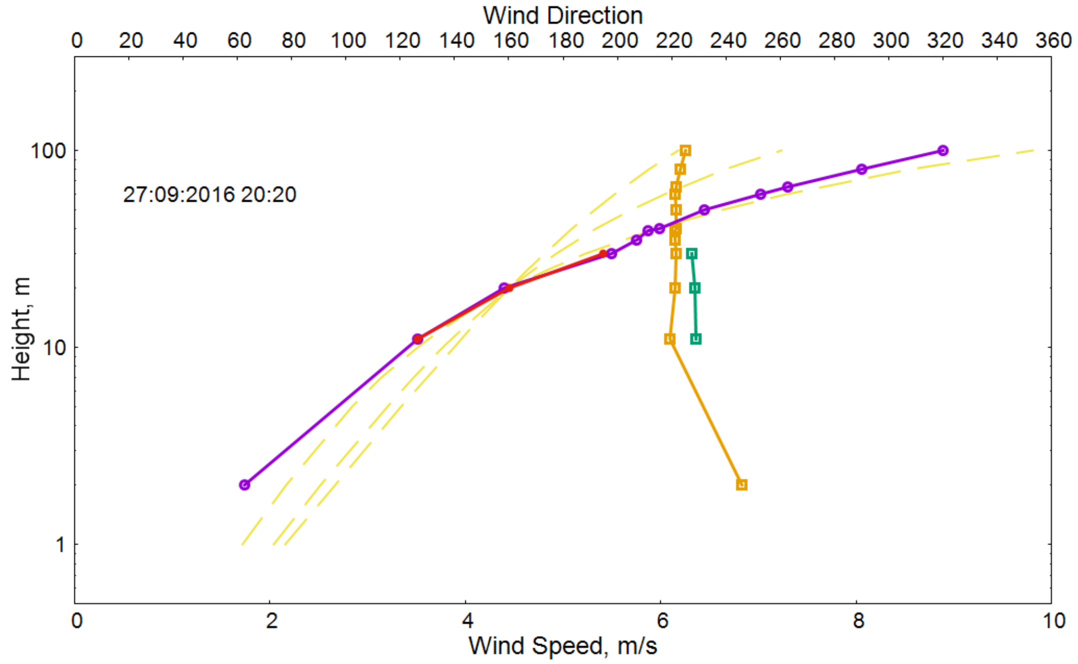
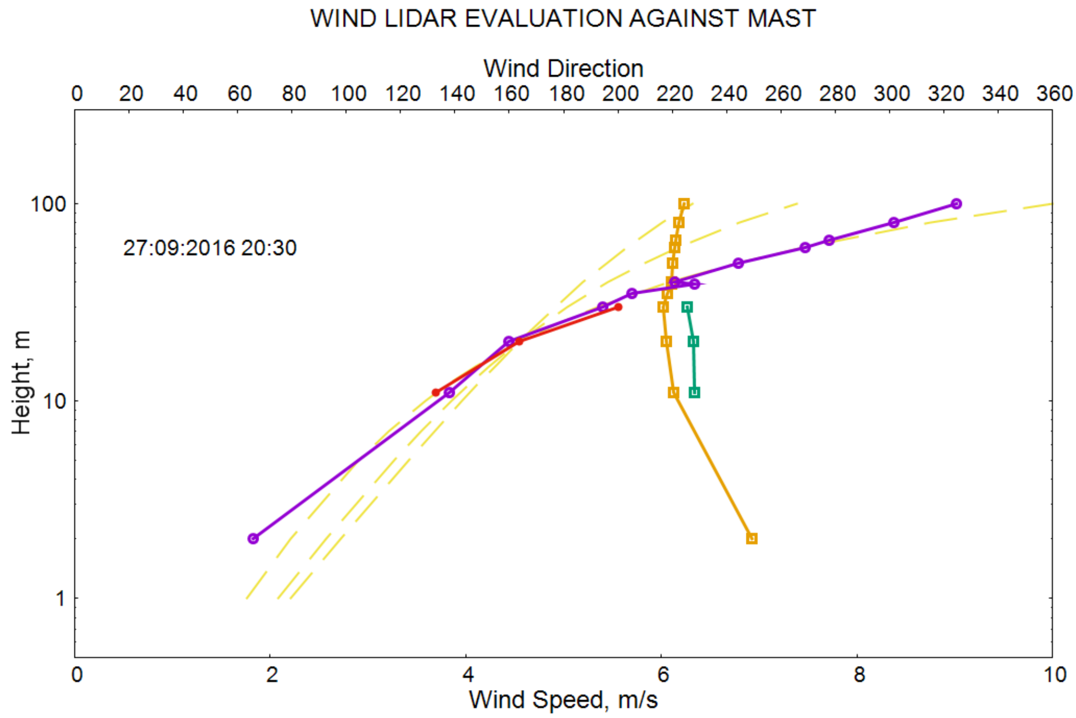
Wind Speed, m/s

WIND LIDAR EVALUATION AGAINST MAST



WIND LIDAR EVALUATION AGAINST MAST




WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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Height, m
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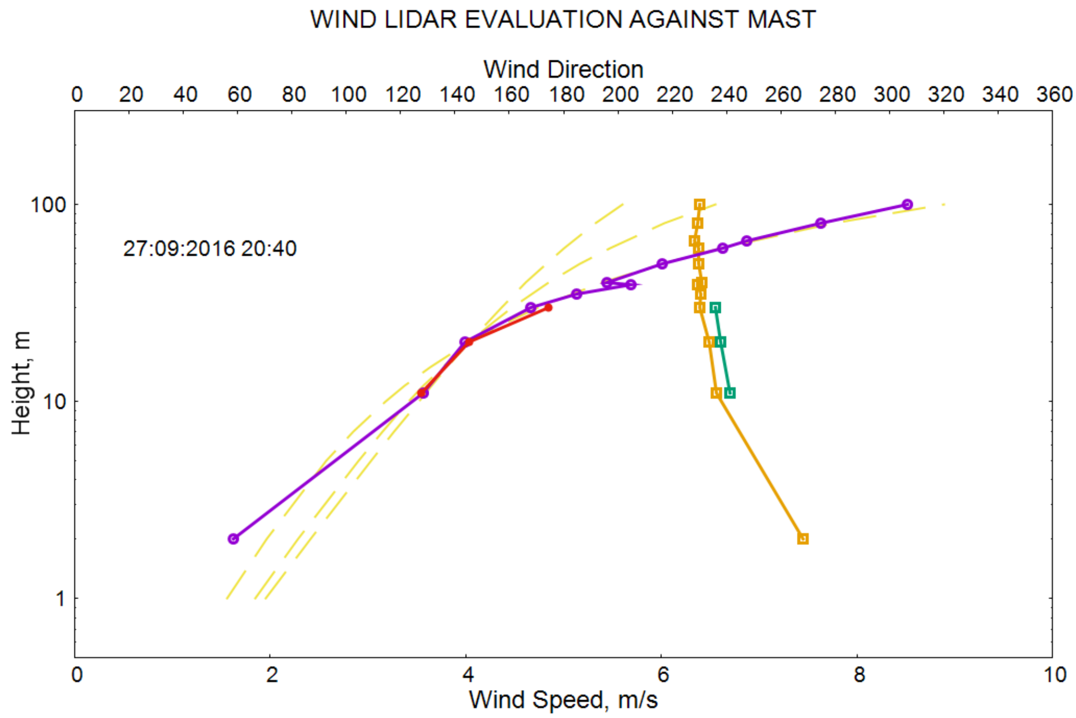
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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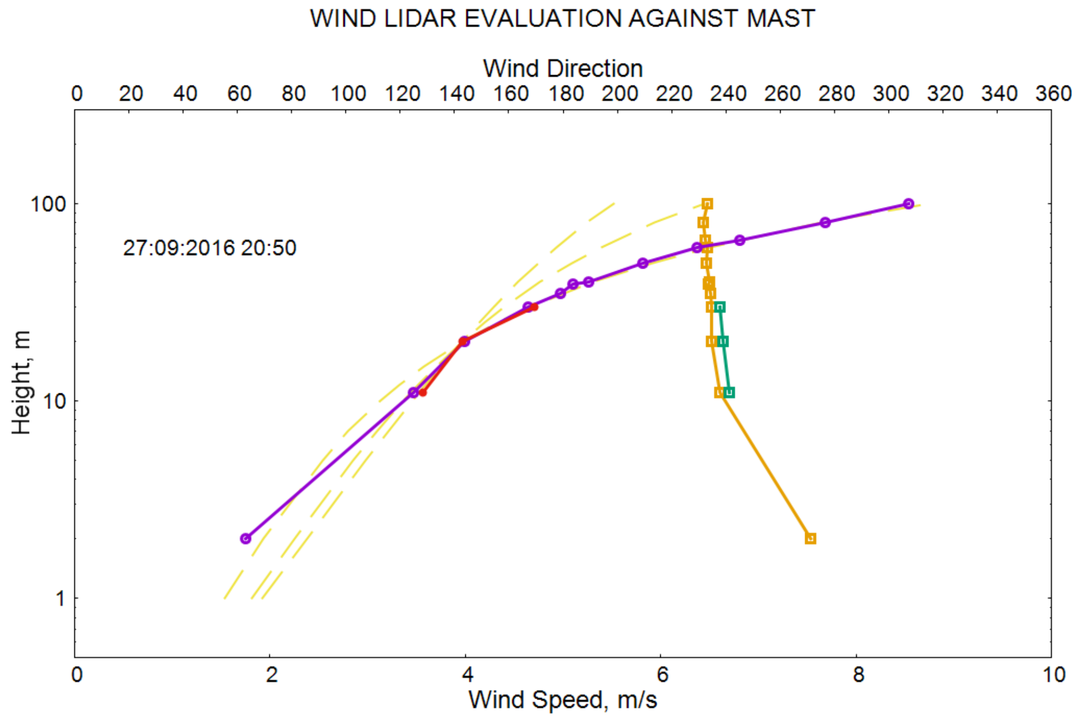
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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Height, m
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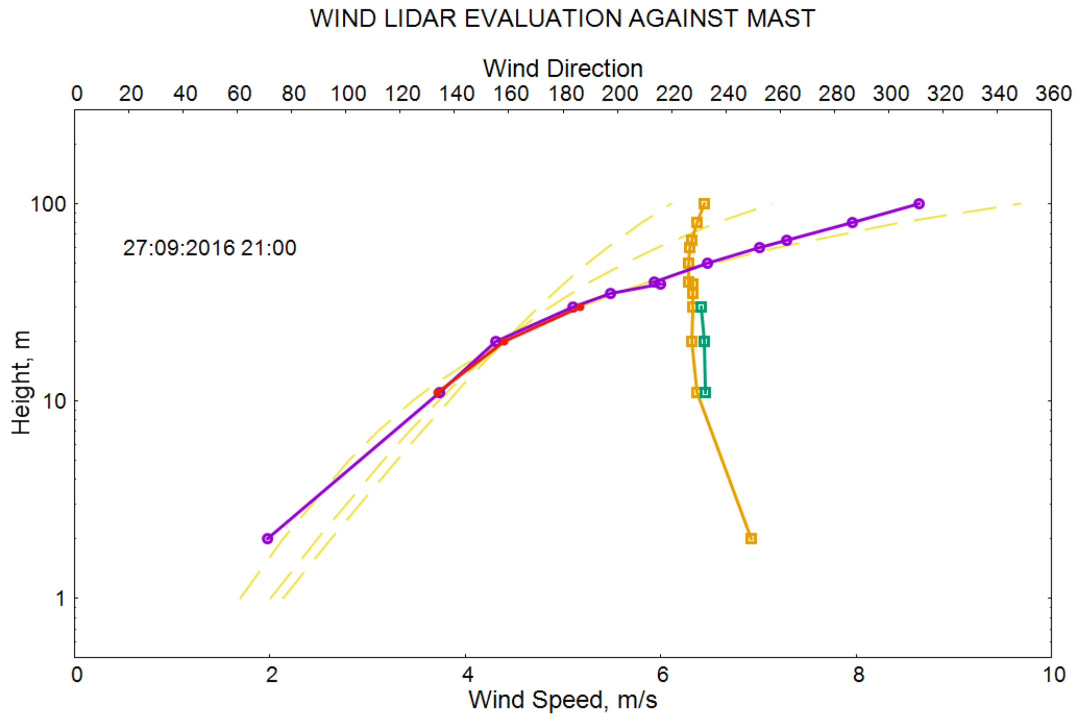
Wind Speed, m/s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Height, m
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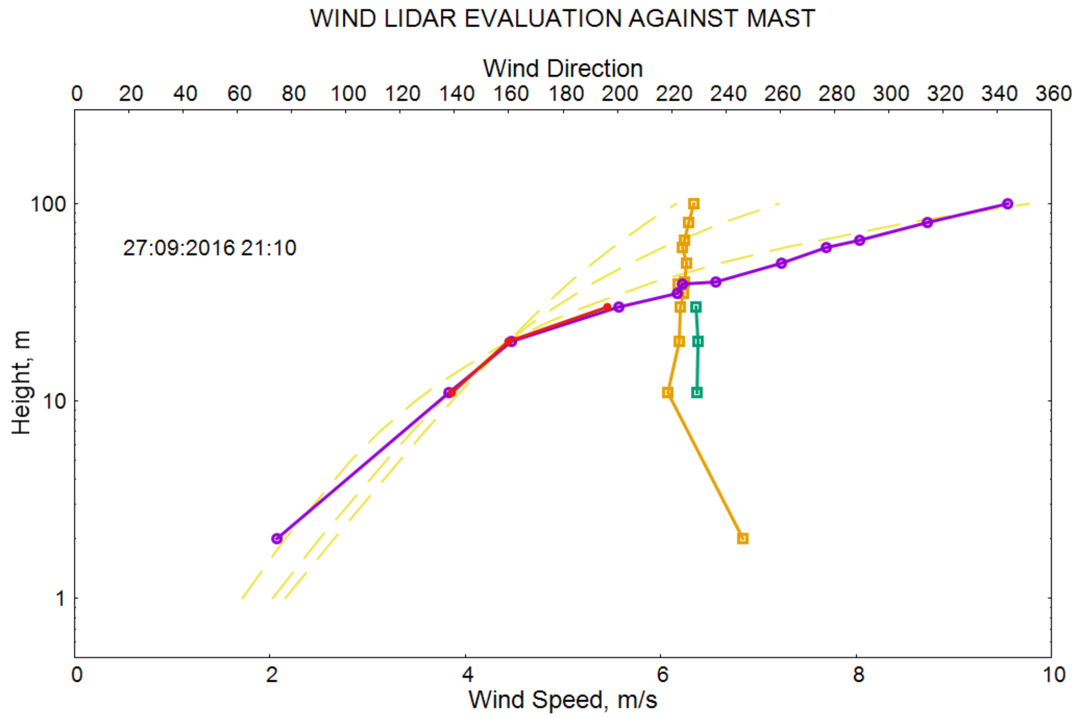
Wind Speed, m/s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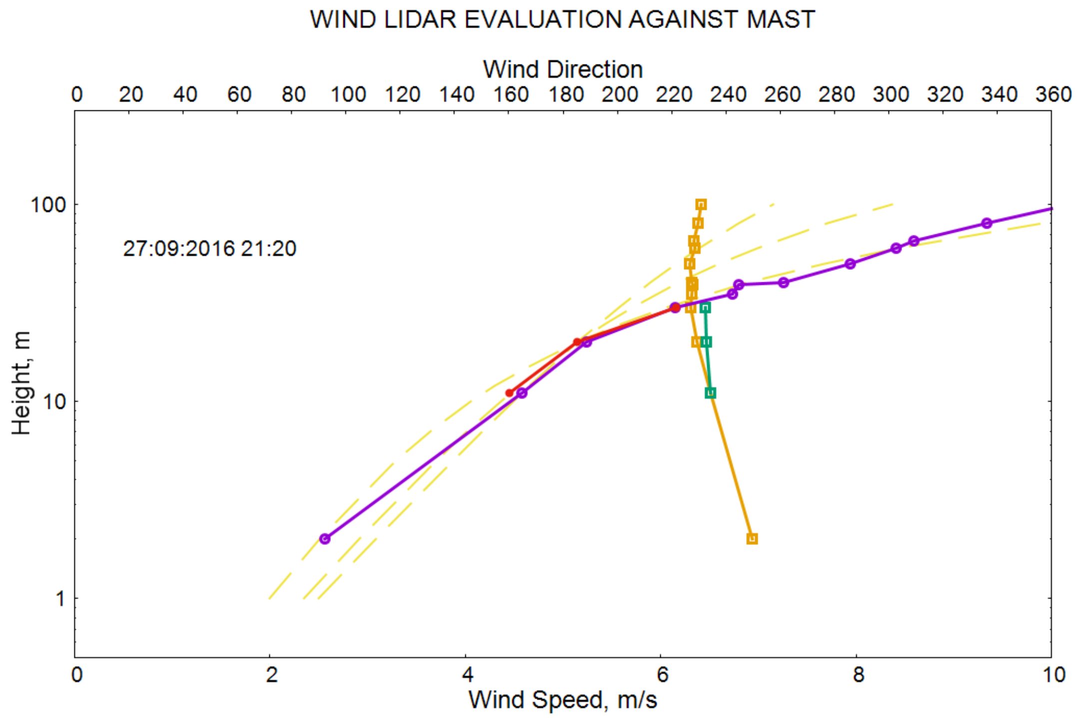
Wind Speed, m/s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Wind Direction
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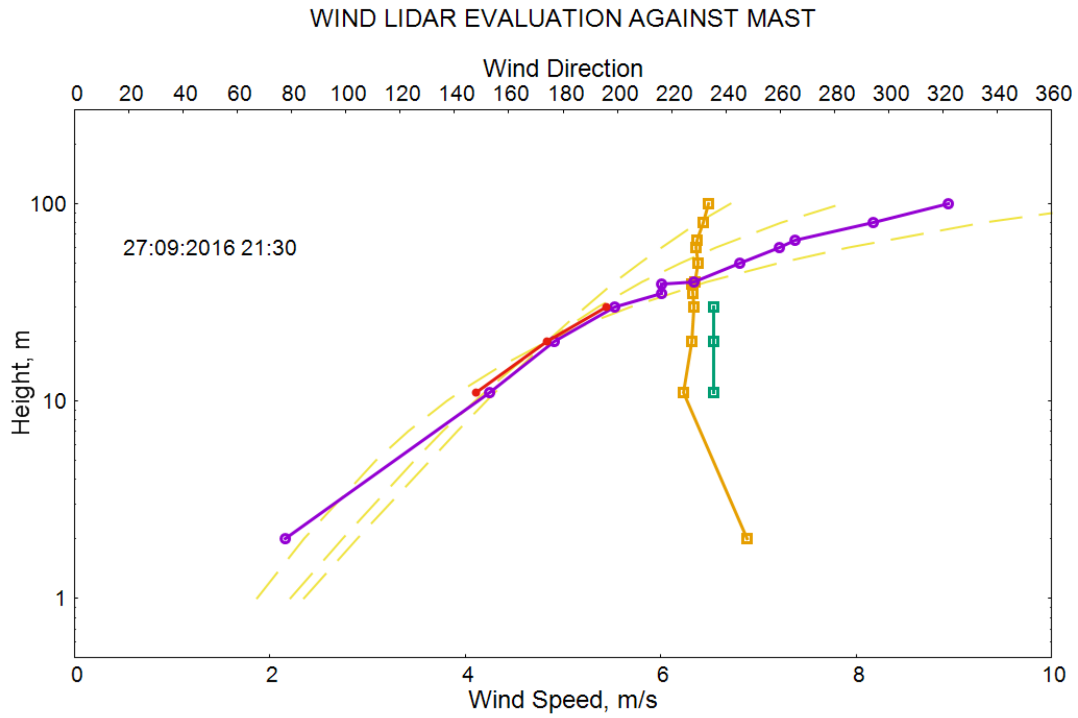
Wind Speed, m/s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Wind Direction
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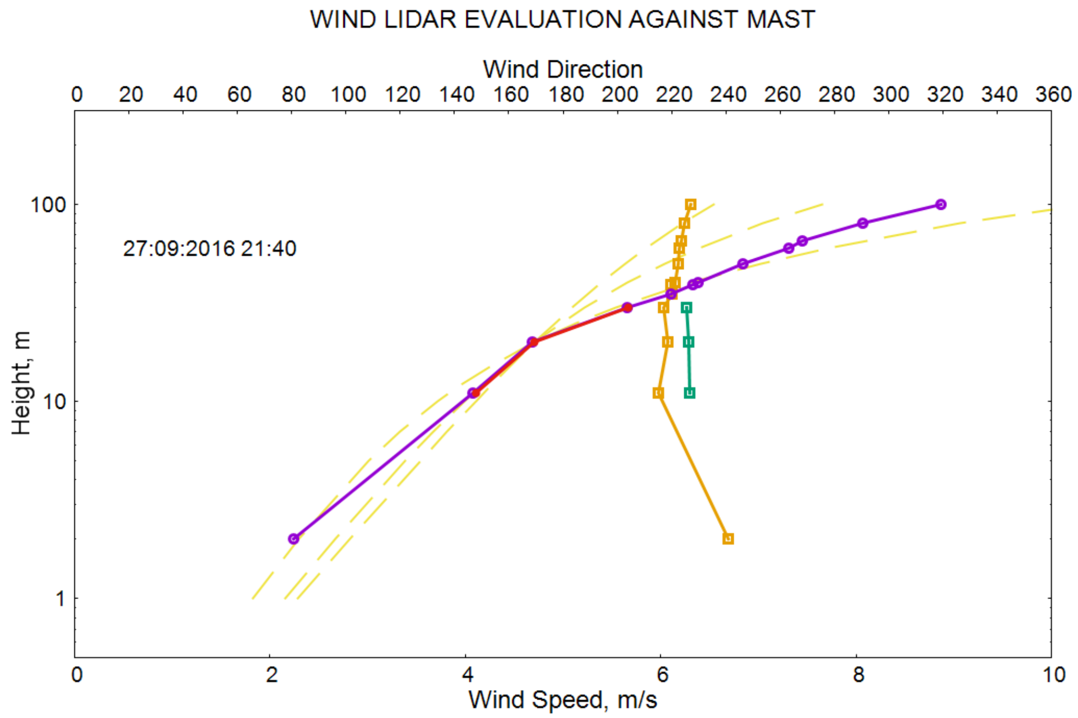
Wind Speed, m/s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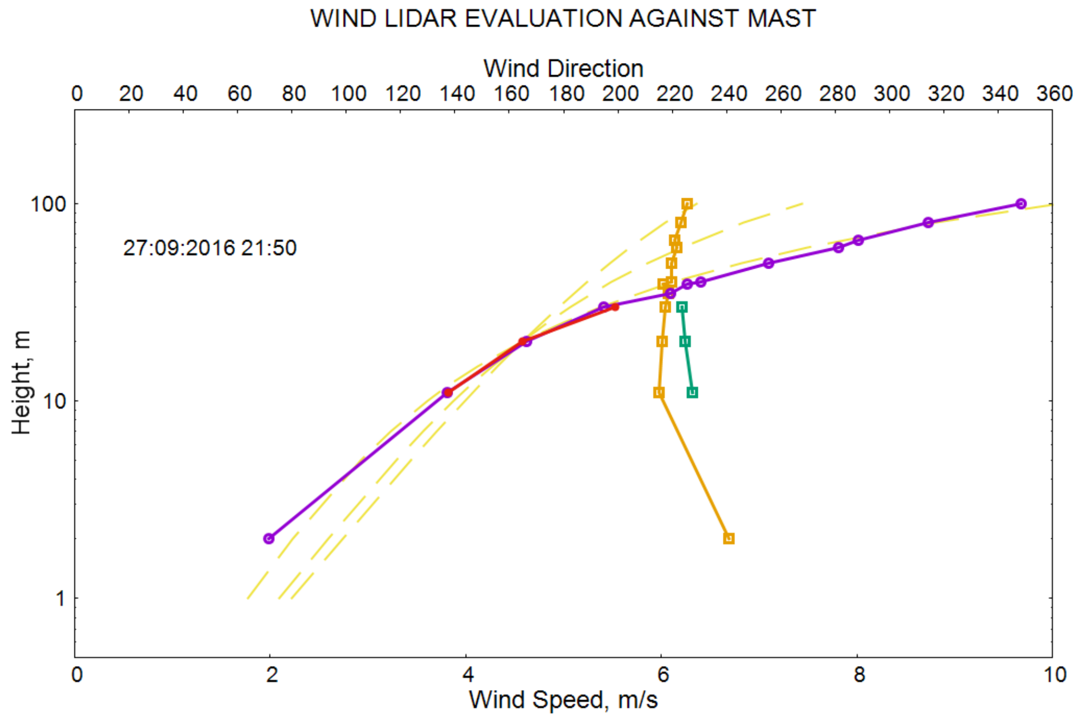
Wind Speed, m/s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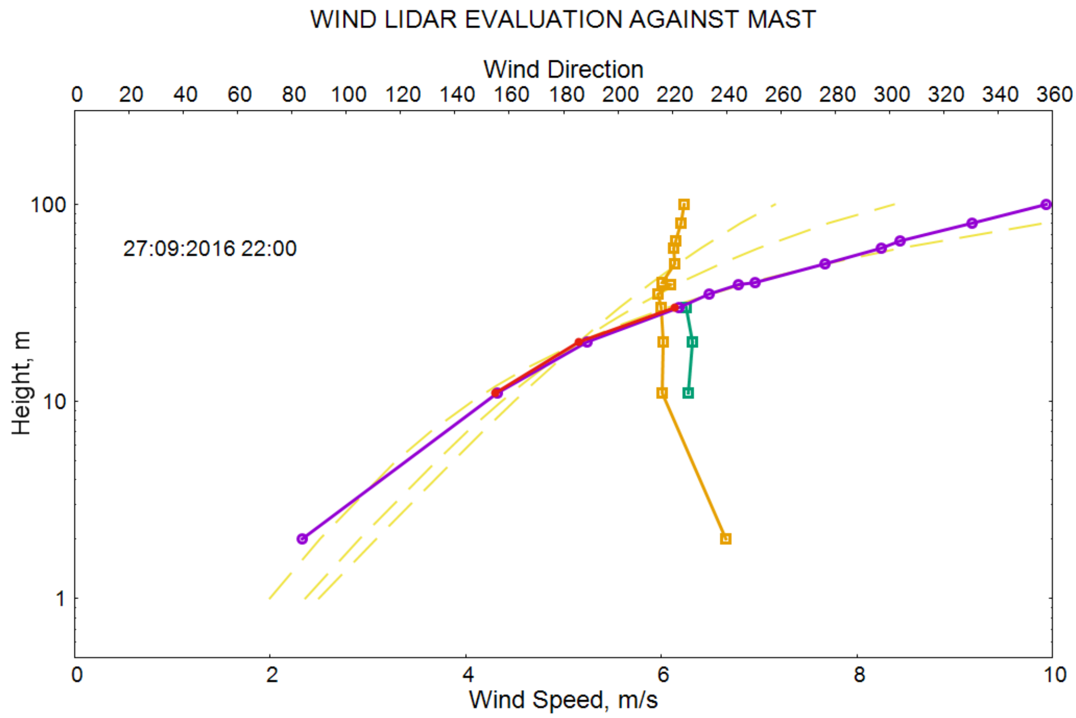
Wind Speed, m/s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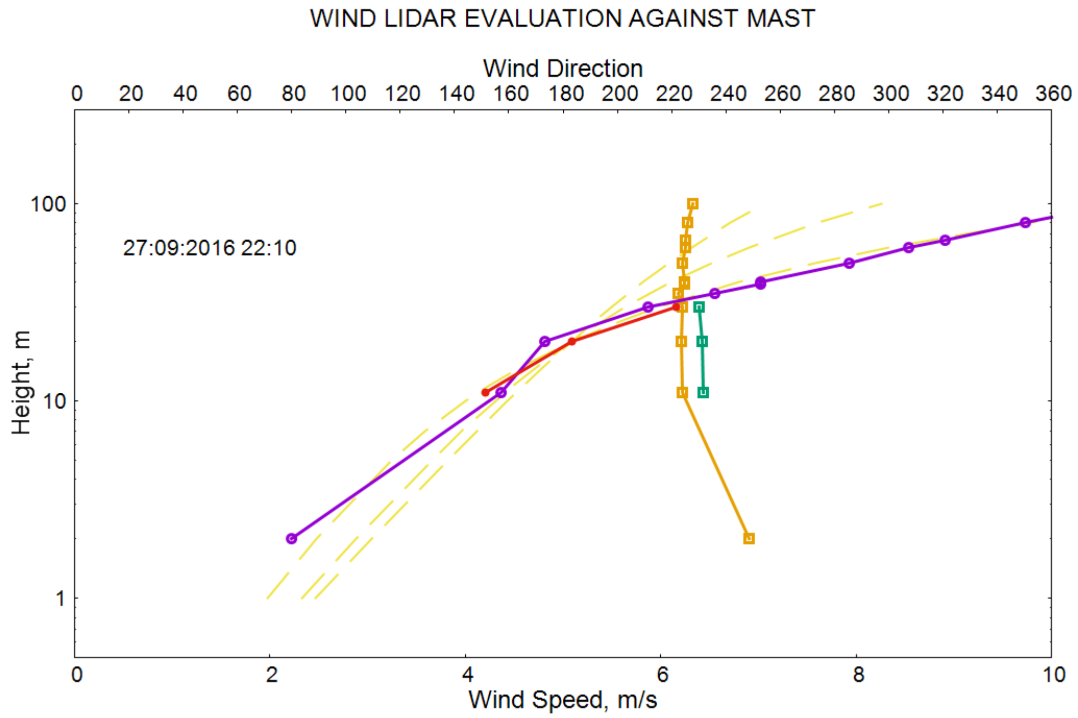
Wind Speed, m/s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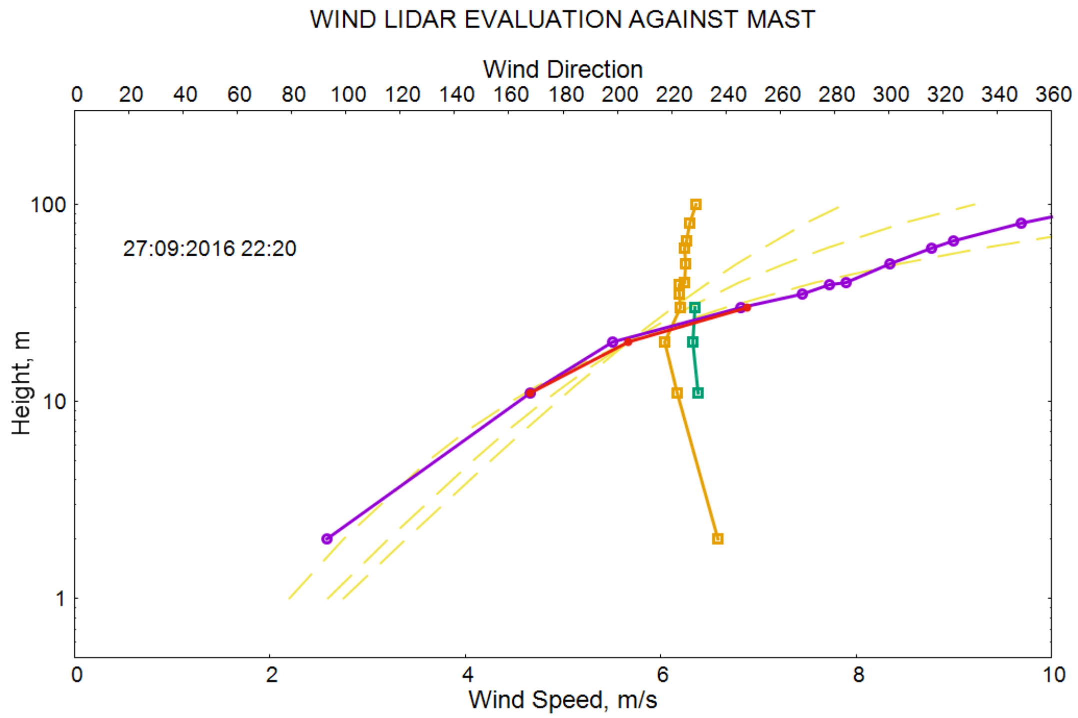
Wind Speed, m/s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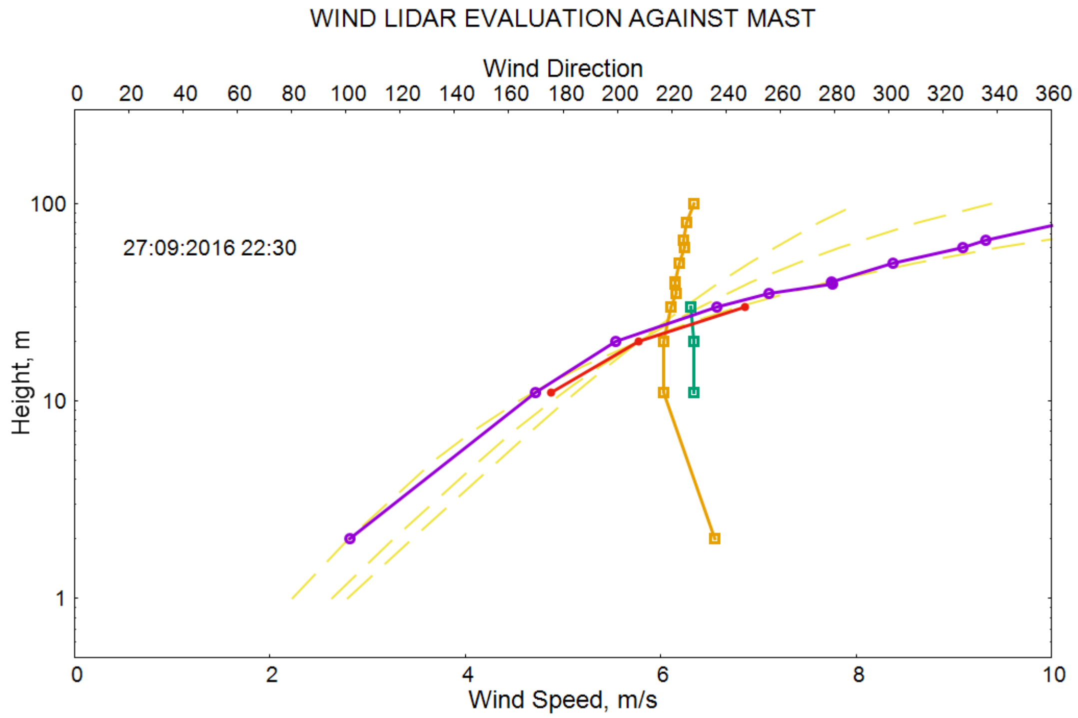
Wind Speed, m/s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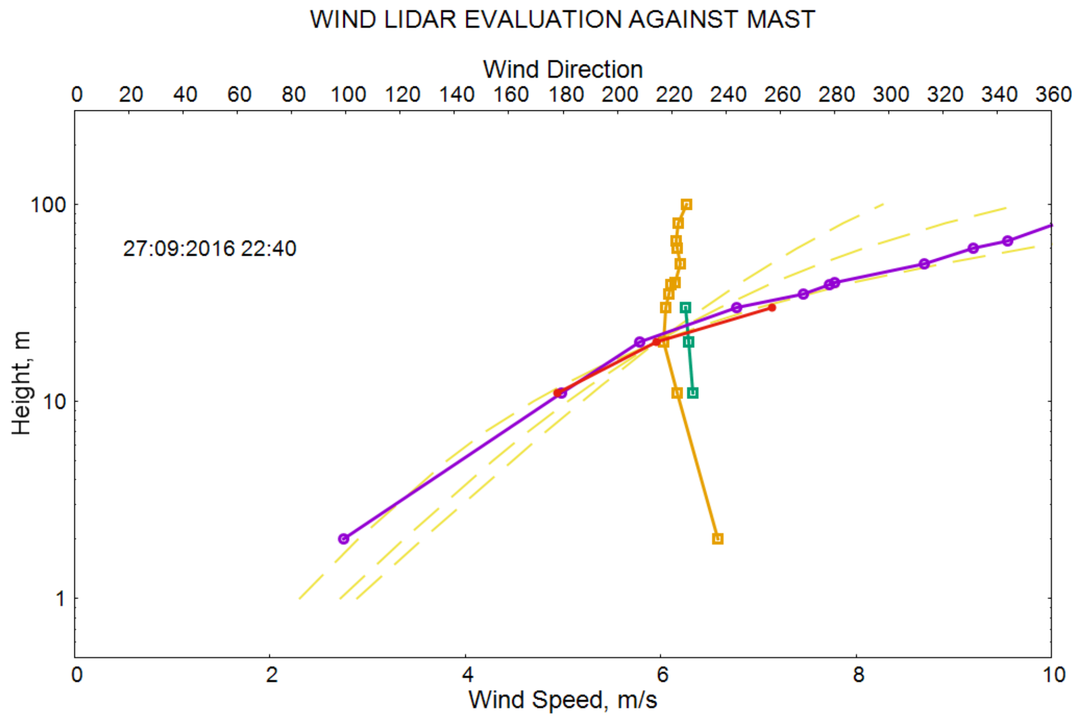
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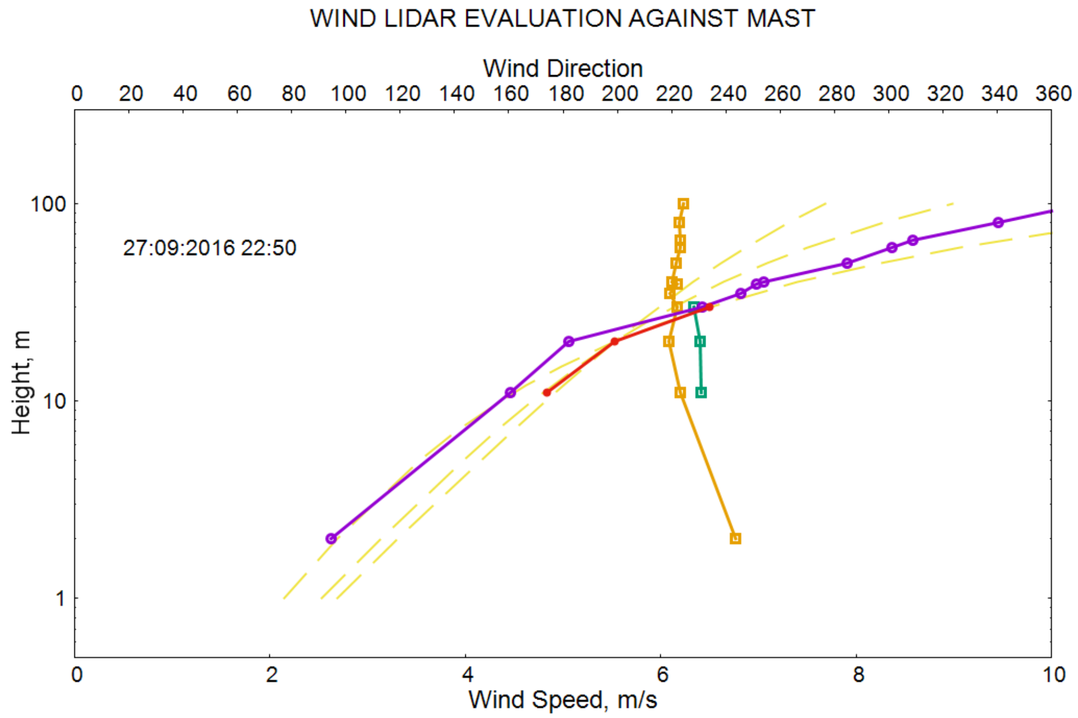
Wind Speed, m/s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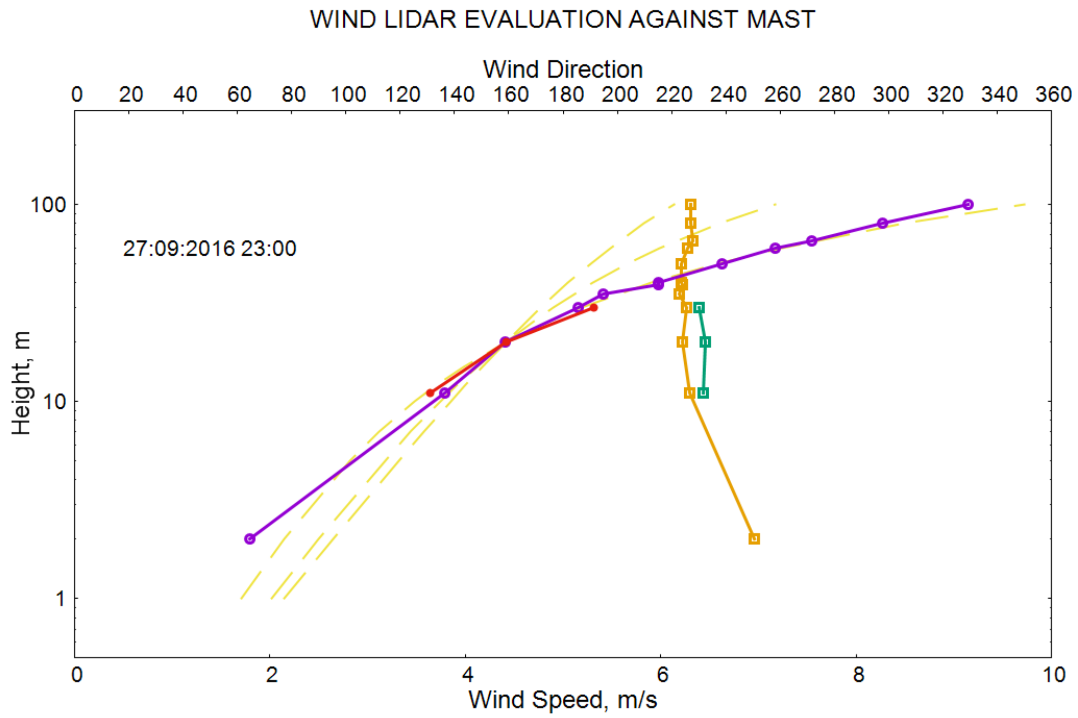
Wind Speed, m/s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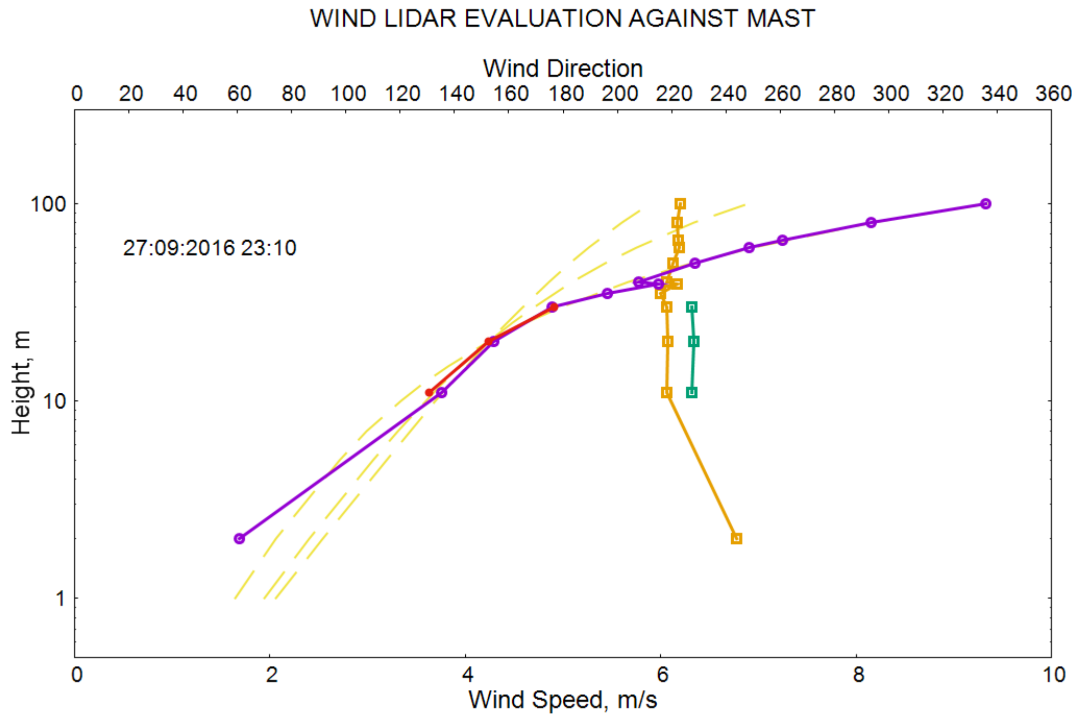
Wind Speed, m/s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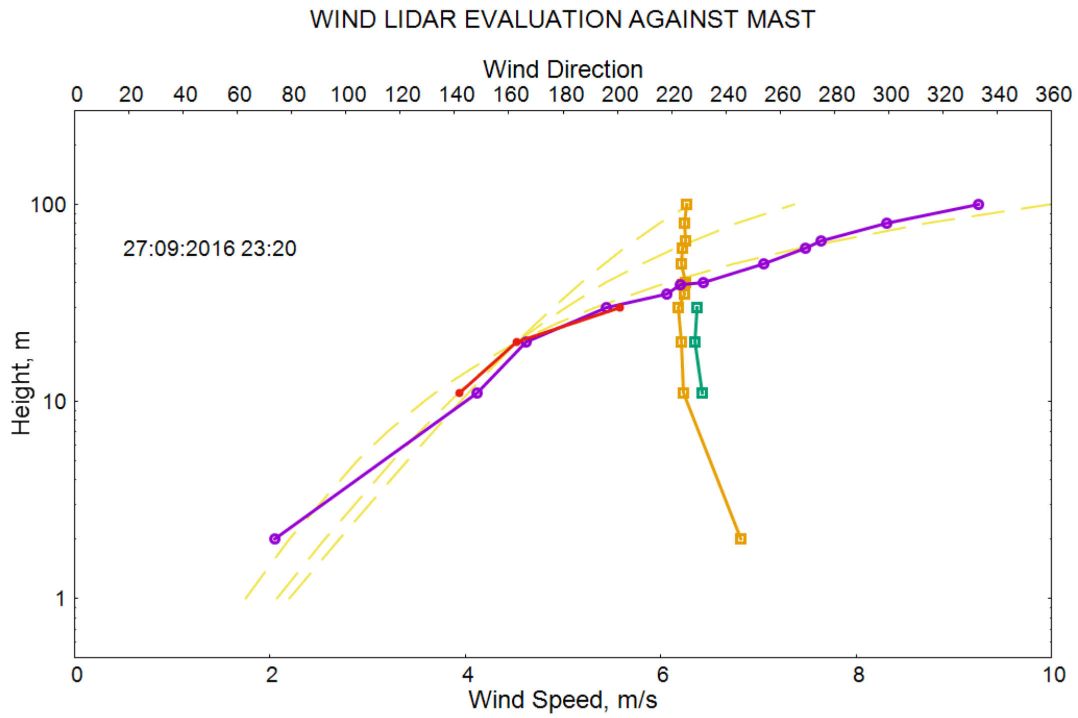
Wind Speed, m/s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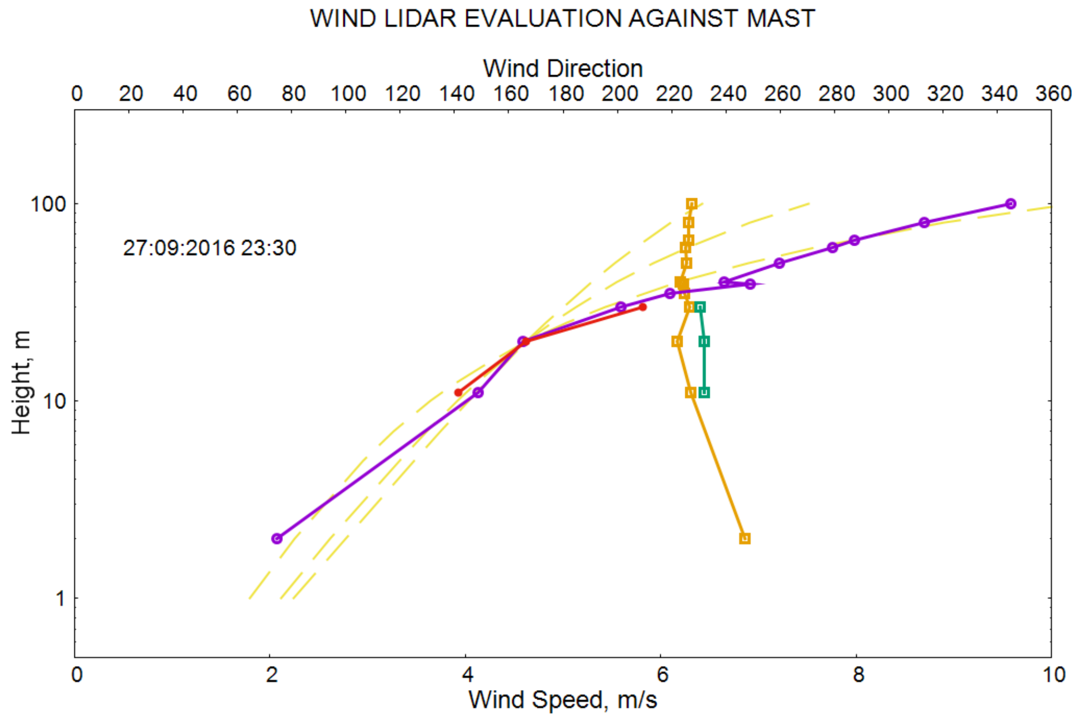
Wind Speed, m/s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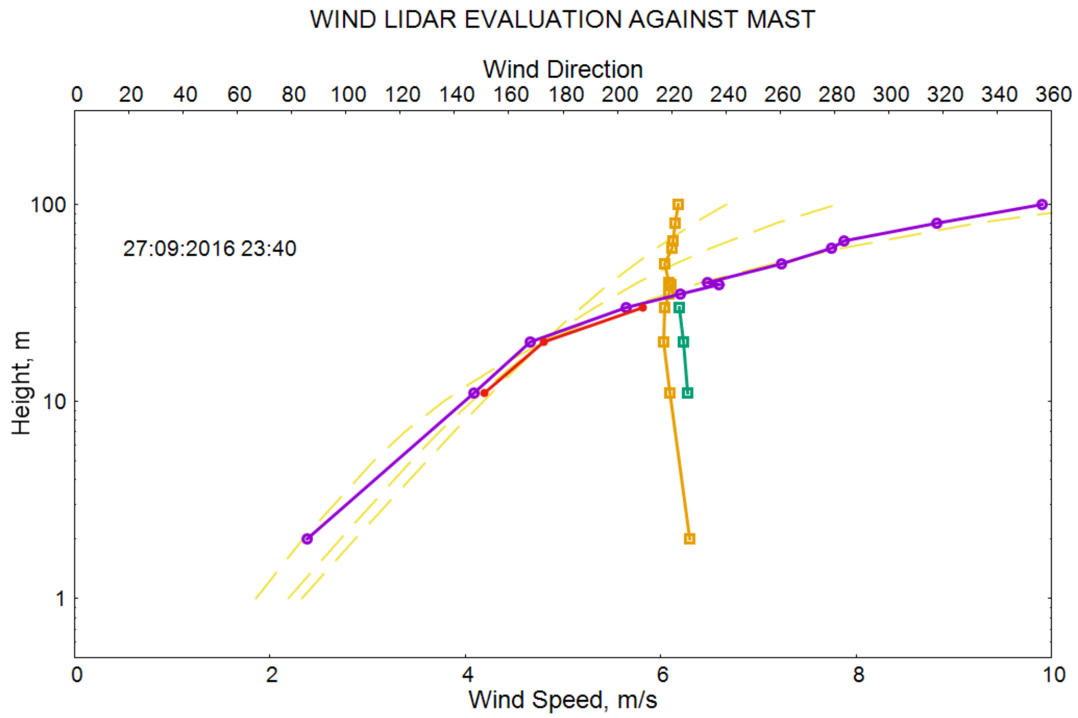
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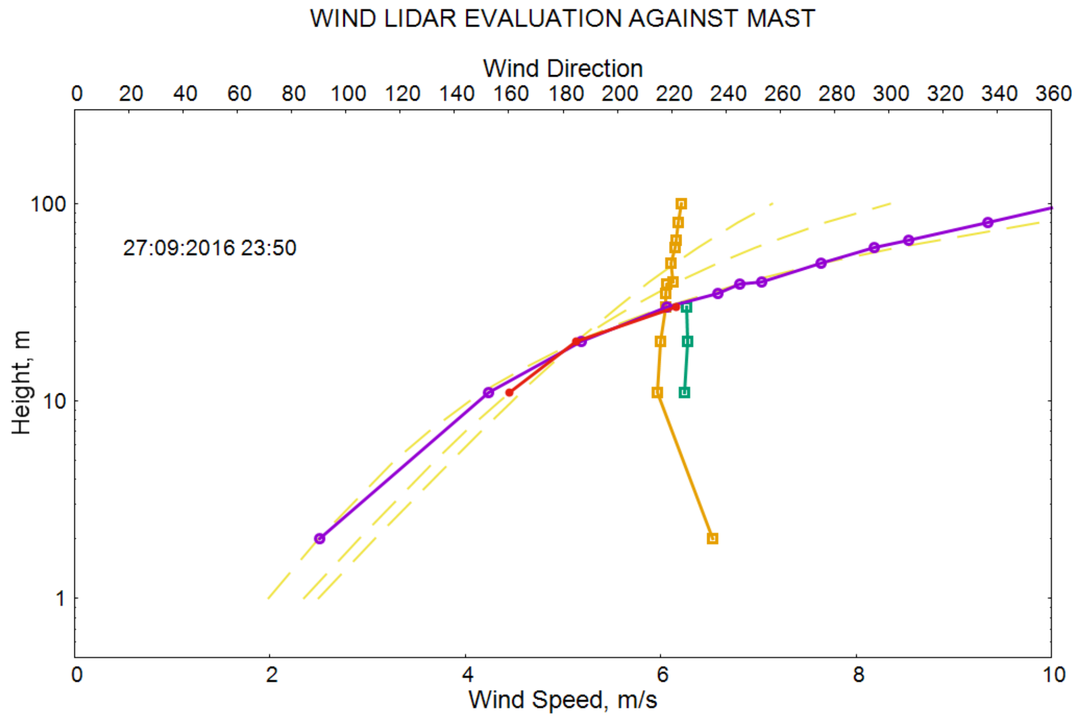
Wind Speed, m/s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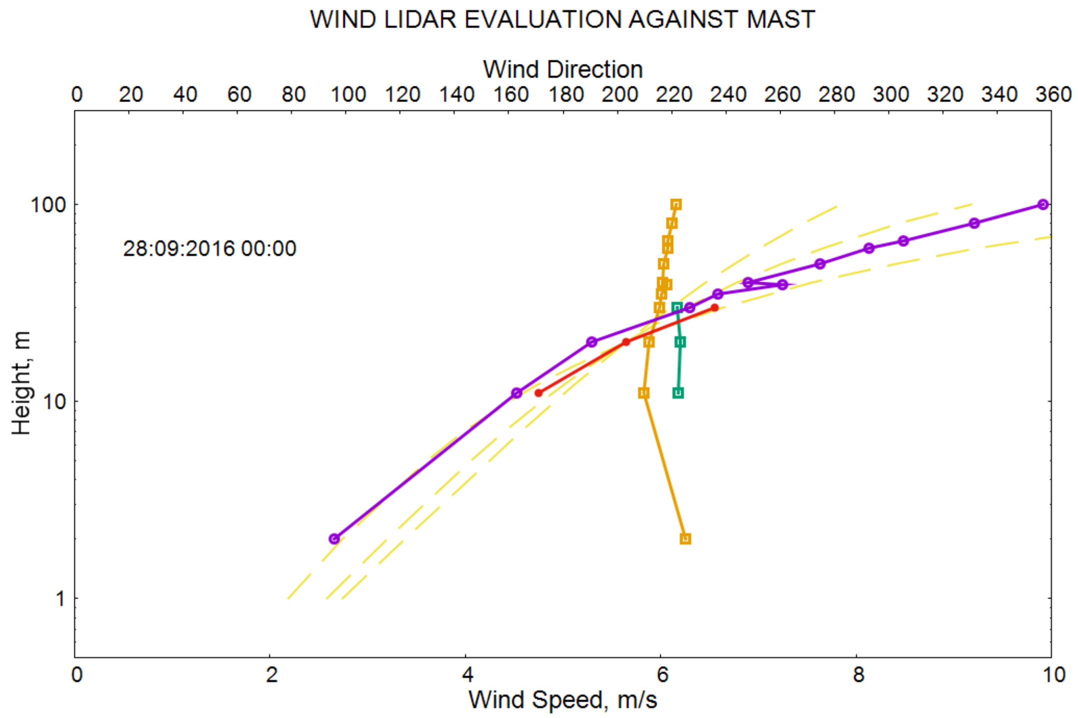
Wind Speed, m/s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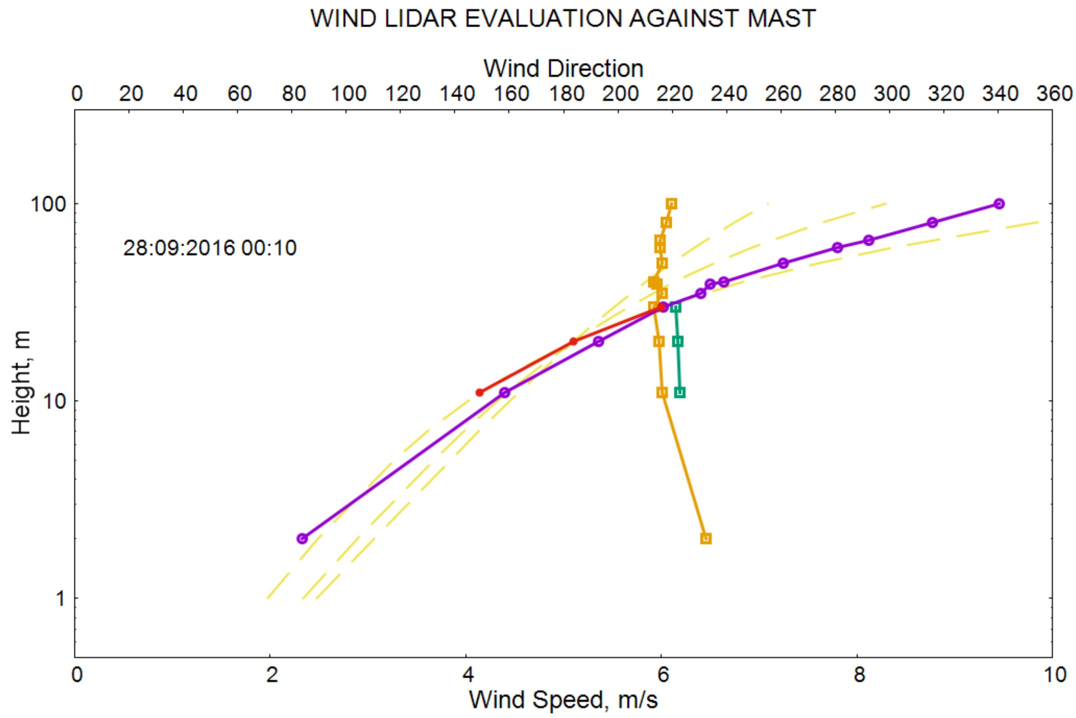
Wind Speed, m/s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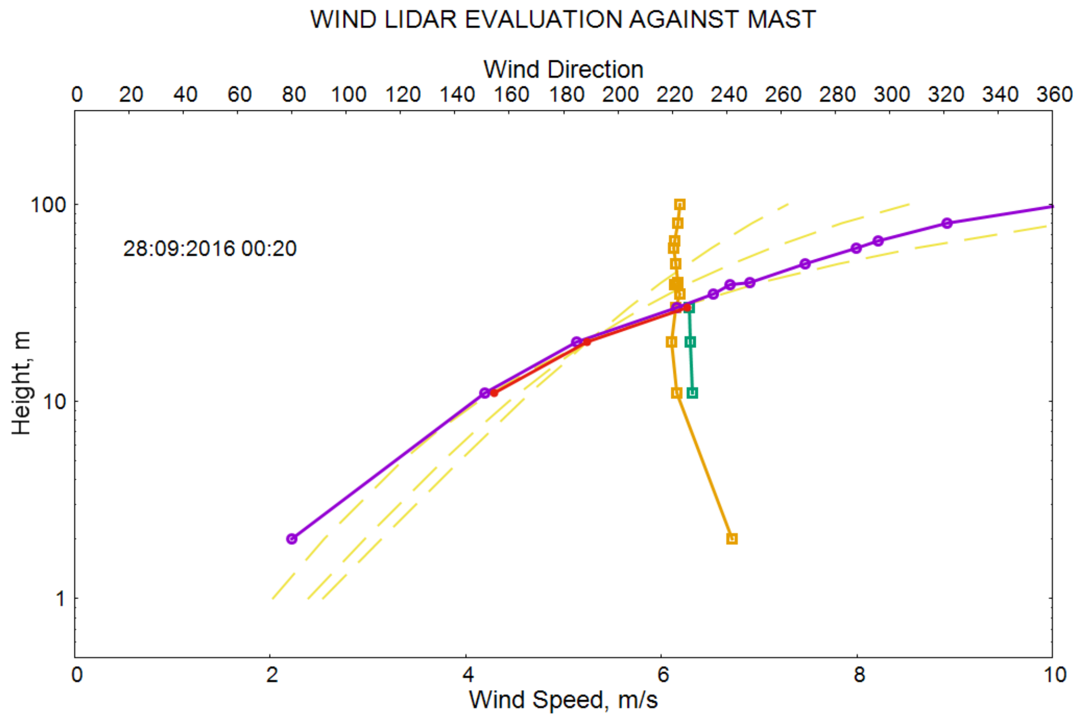
Wind Speed, m/s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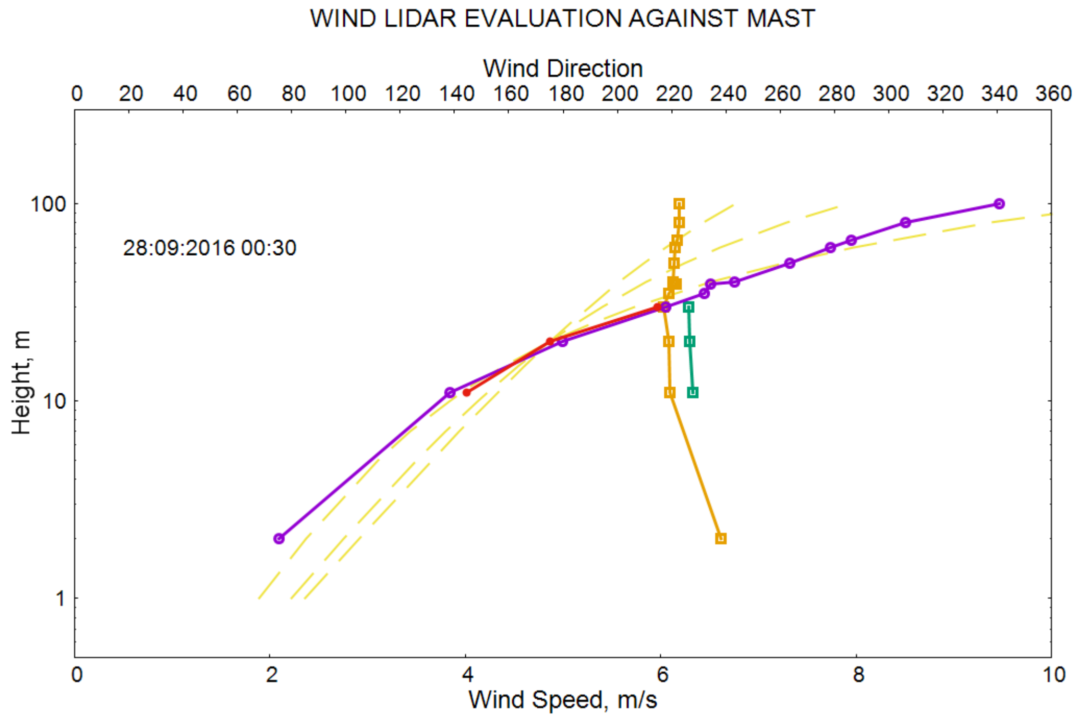
Wind Speed, m/s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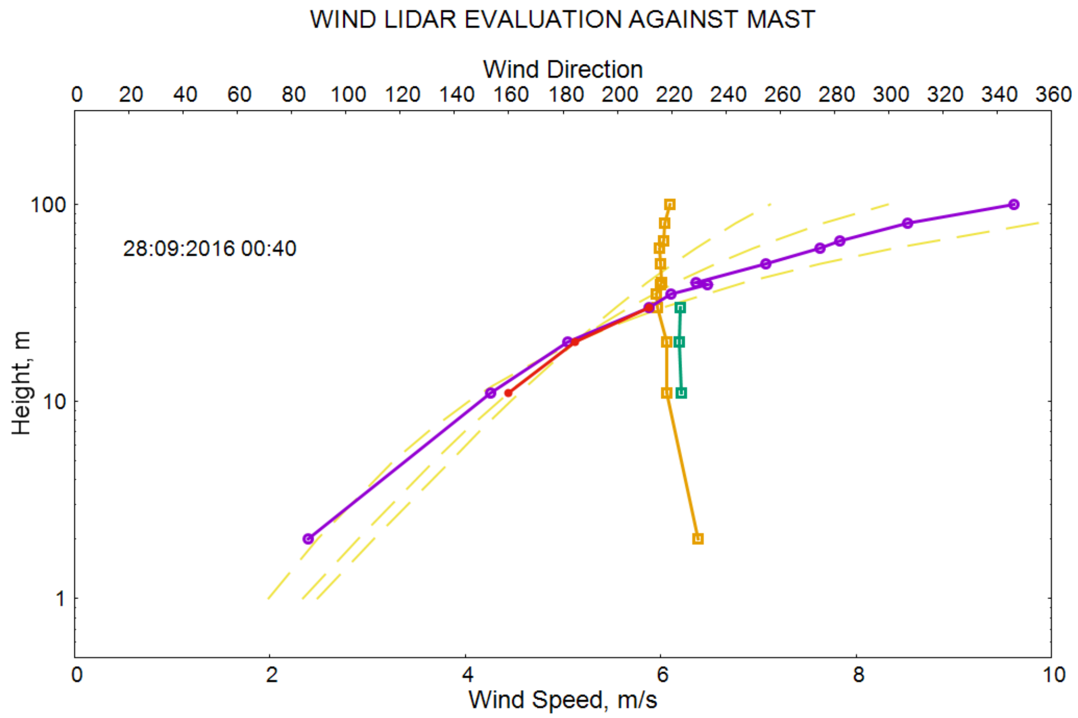
Wind Speed, m/s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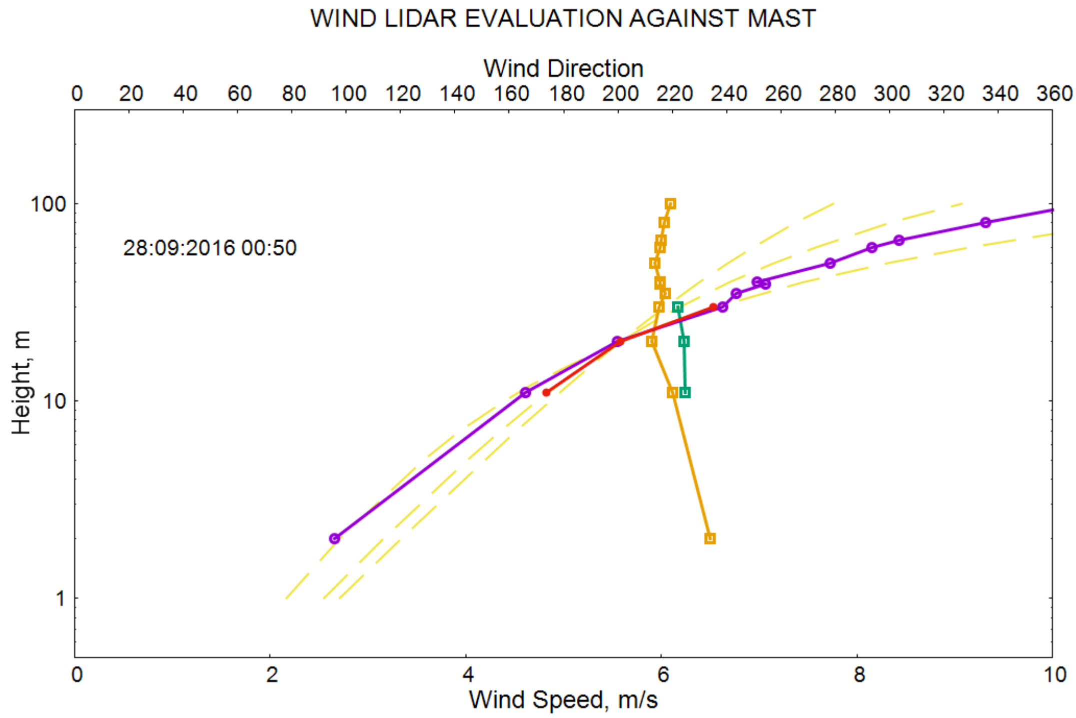
Wind Speed, m/s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Wind Direction
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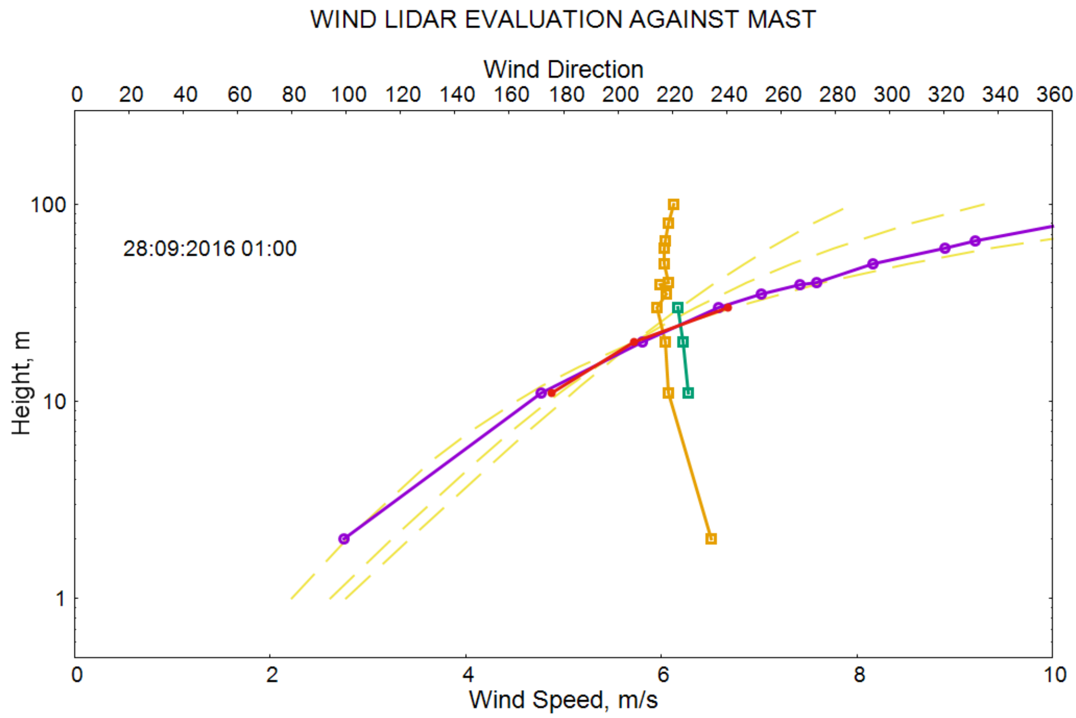
Wind Speed, m/s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Wind Direction
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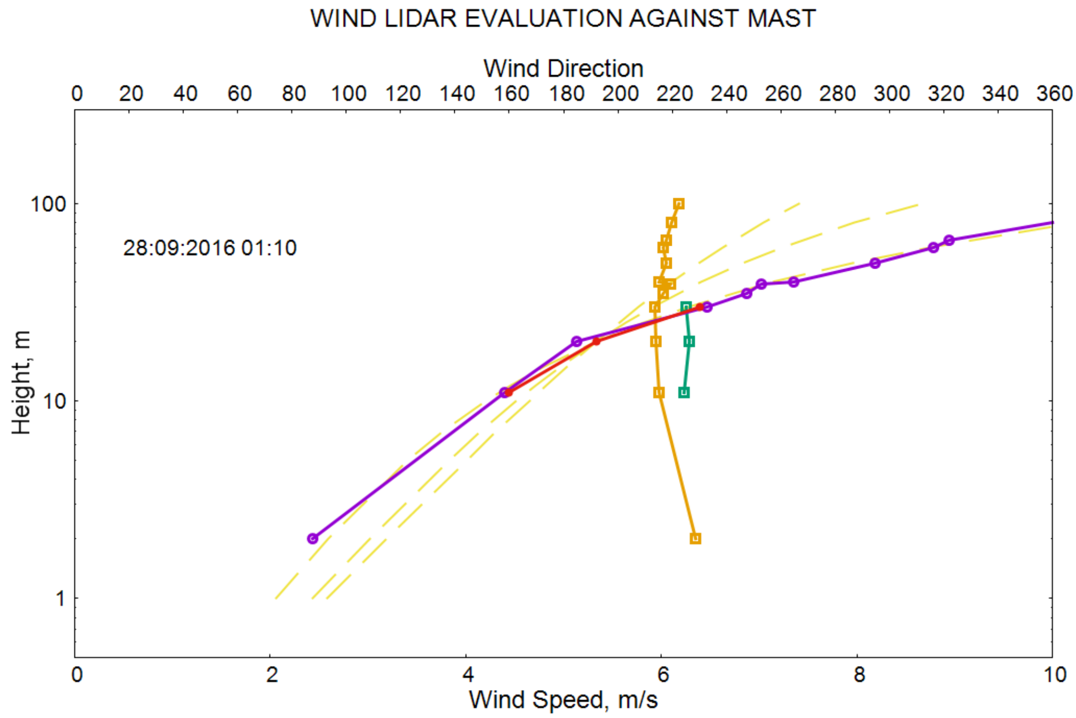
Wind Speed, m/s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Wind Direction
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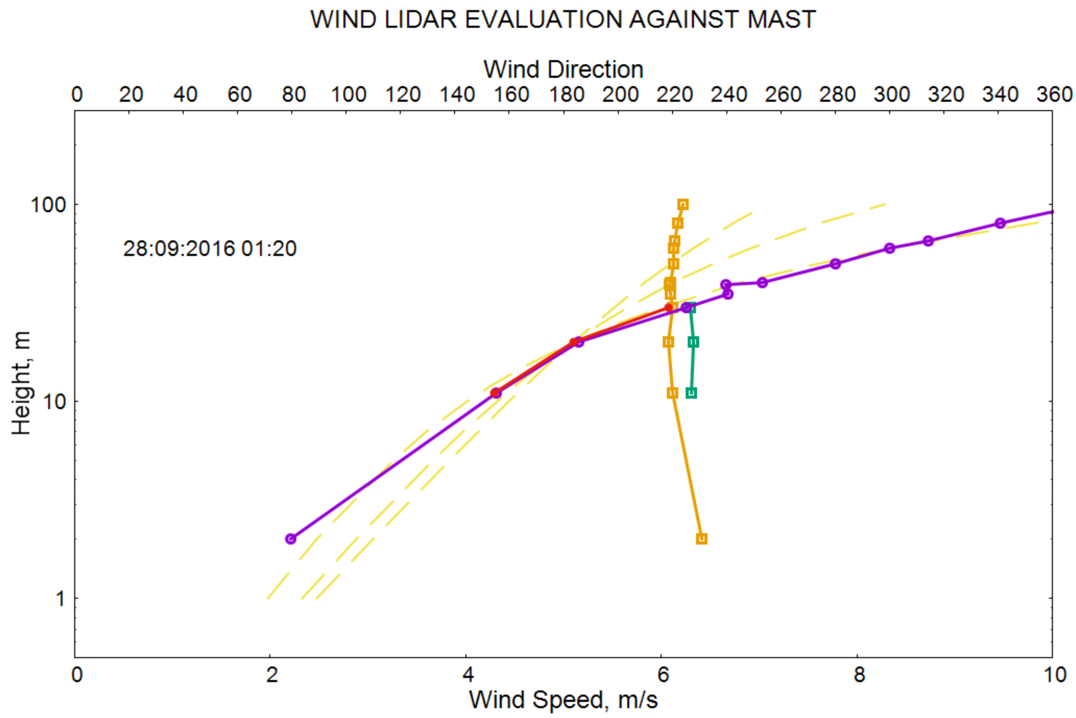
Wind Speed, m/s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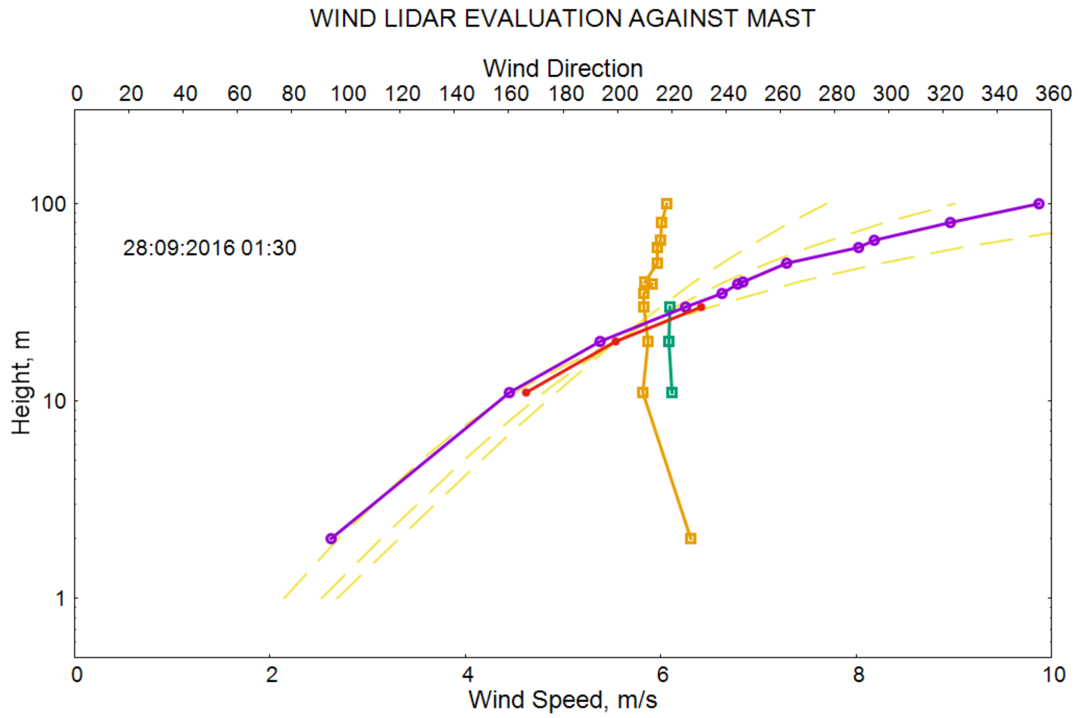
Wind Speed, m/s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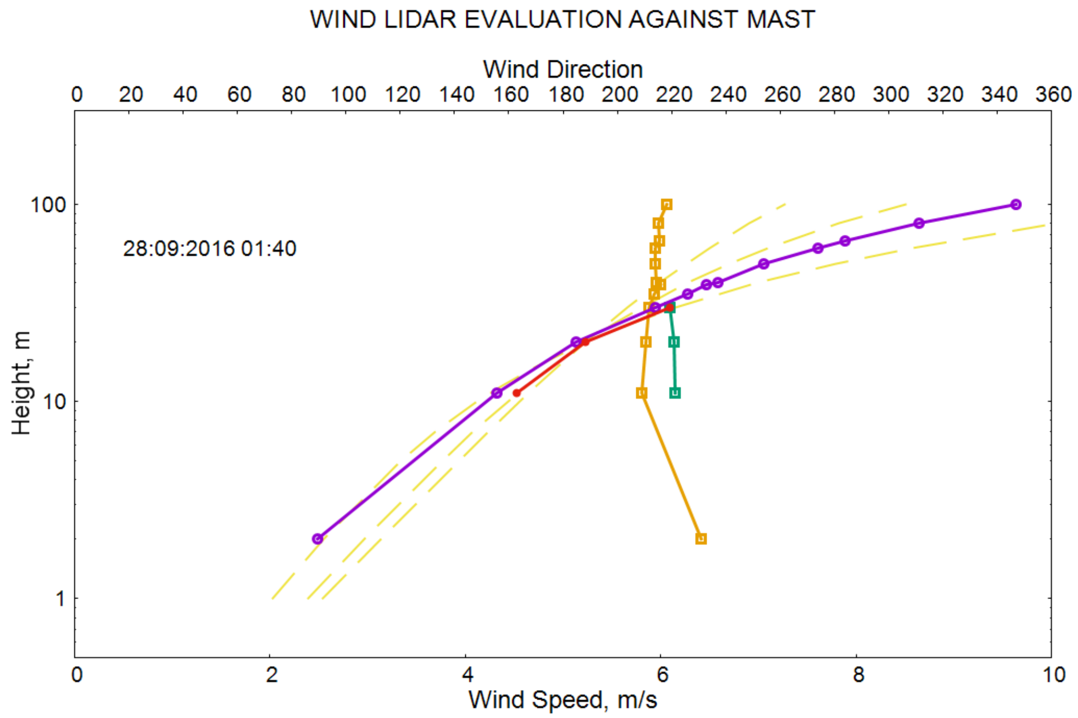
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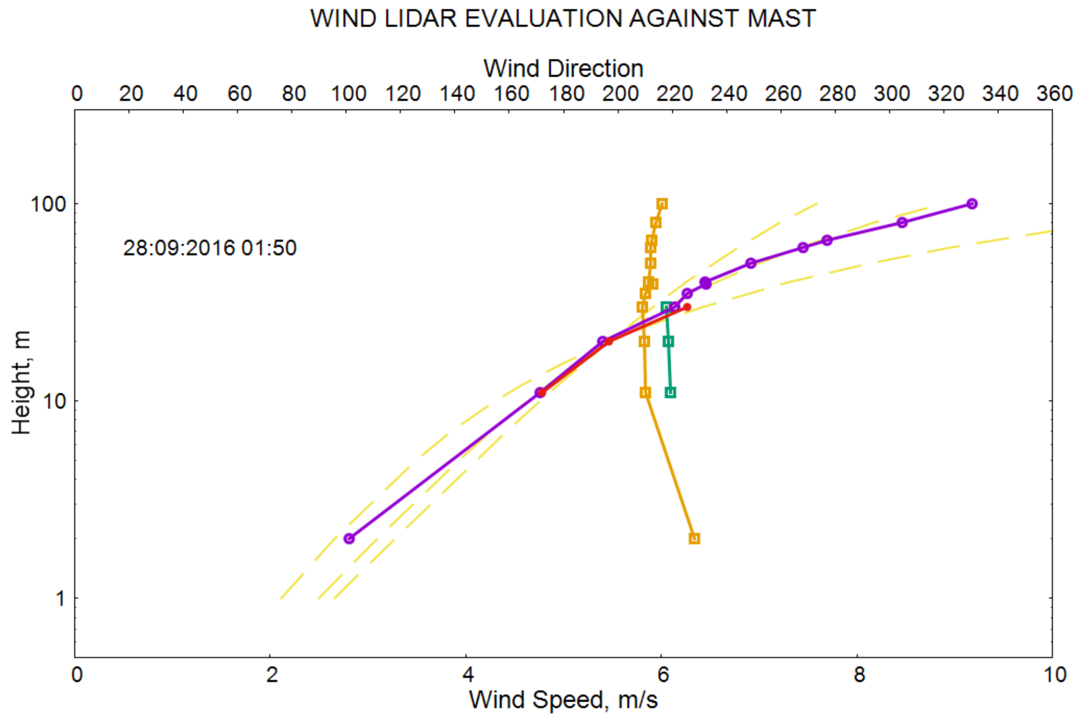
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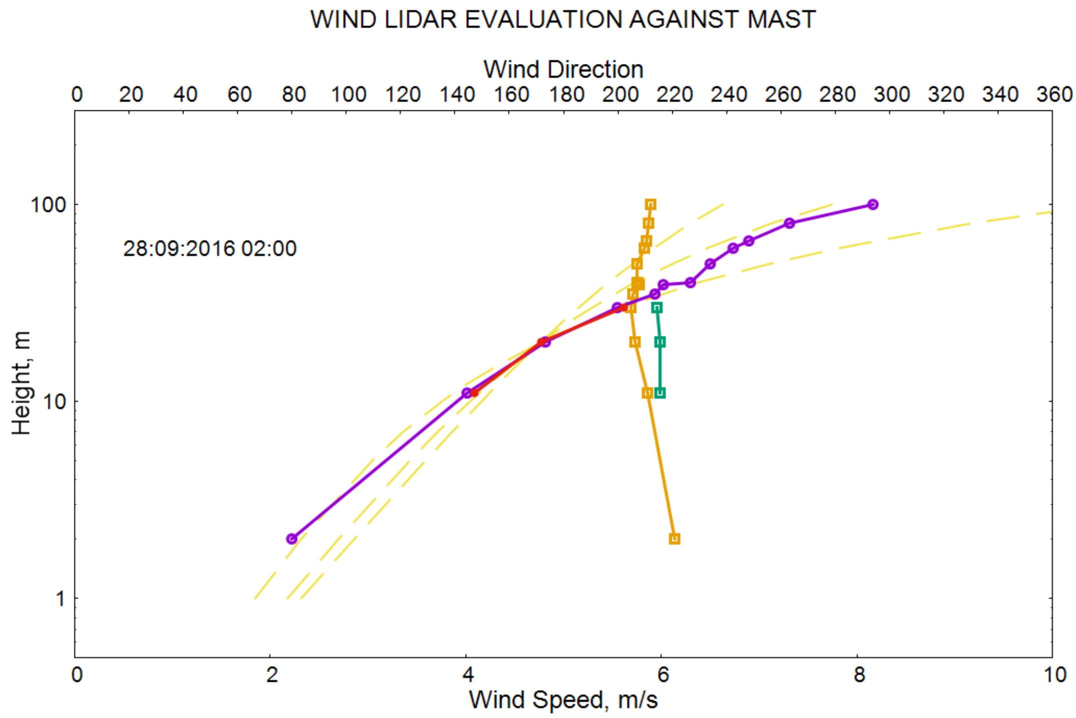
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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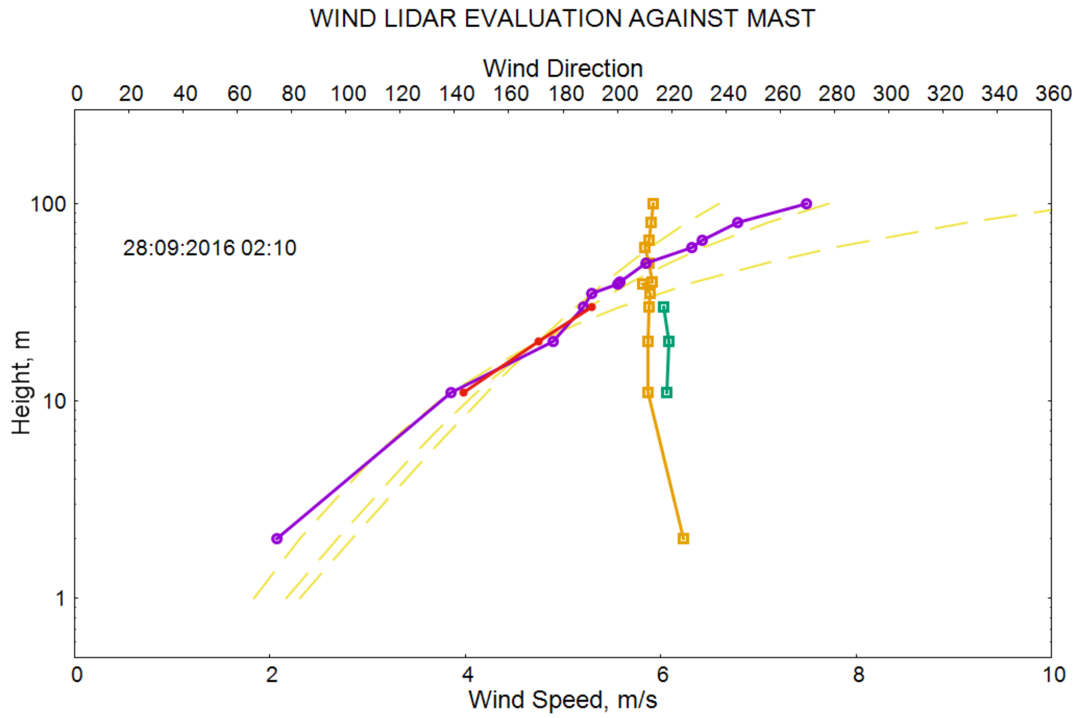
28:09:2016 02:00
Height, m
100
10
1
0 2 4 6 8 10
Wind Speed, m/s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Wind Direction
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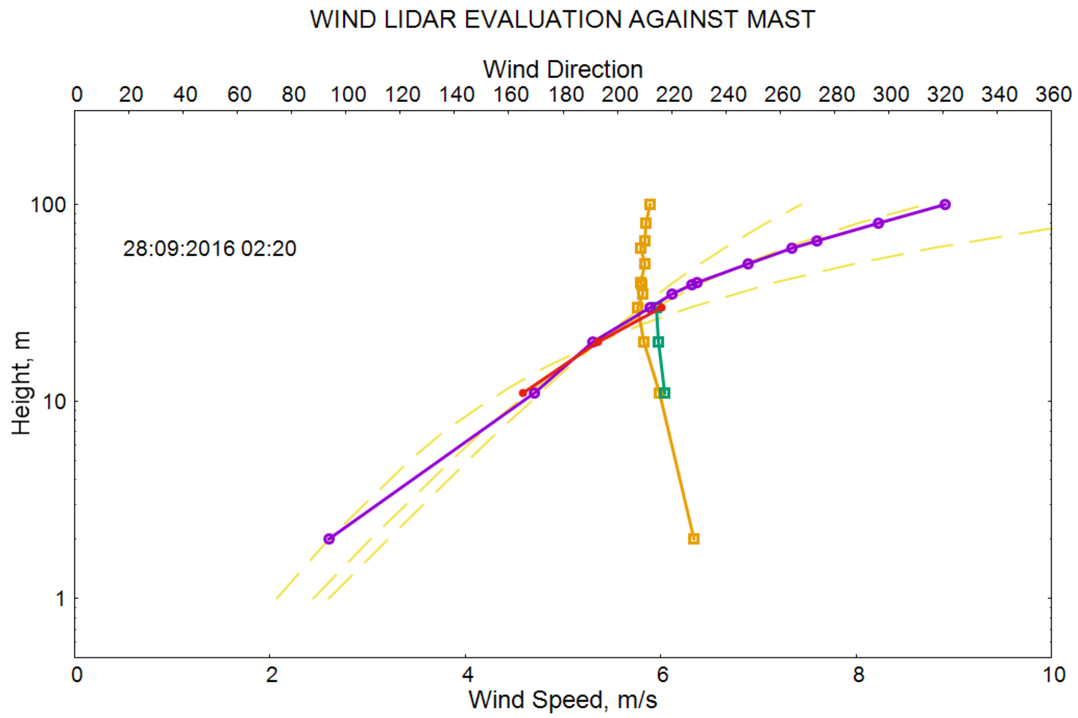
Wind Speed, m/s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Wind Direction
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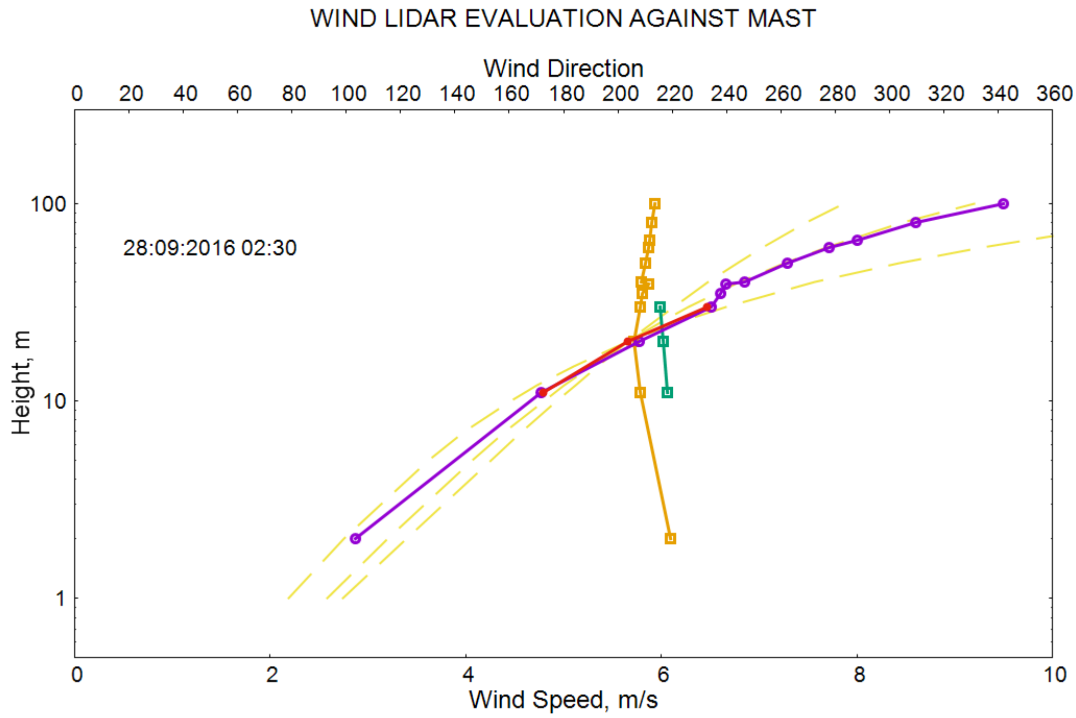
100
28:09:2016 02:20
Height, m
10
1
0 2 4 6 8 10
Wind Speed, m/s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Wind Direction
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100
10
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Height, m
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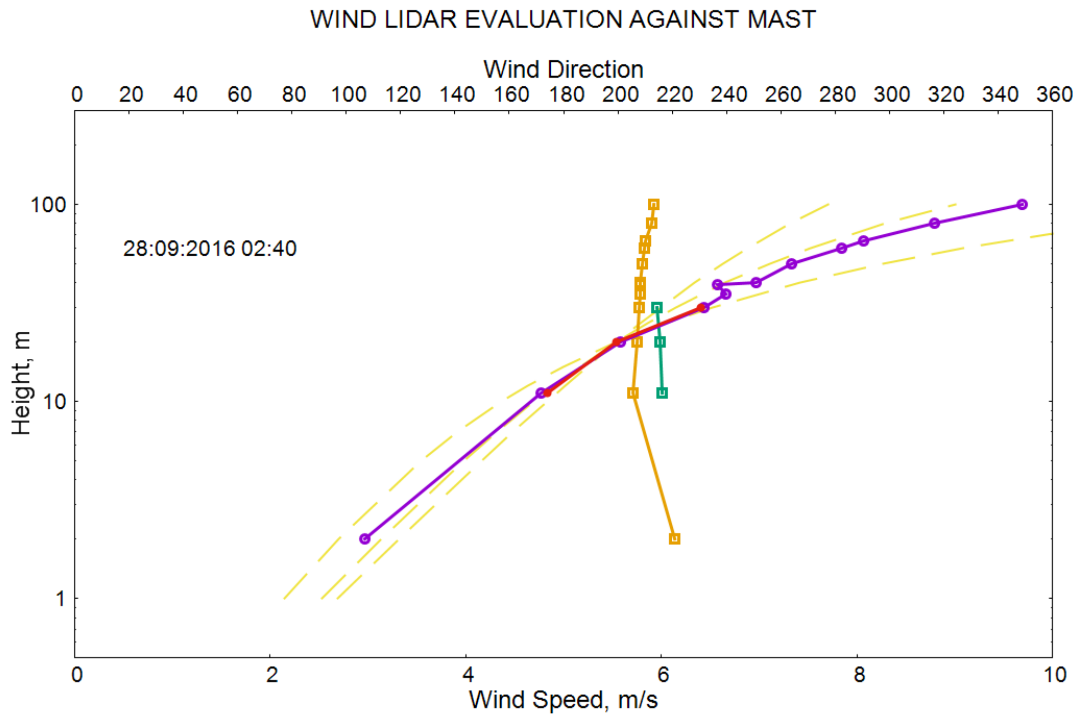
Wind Speed, m/s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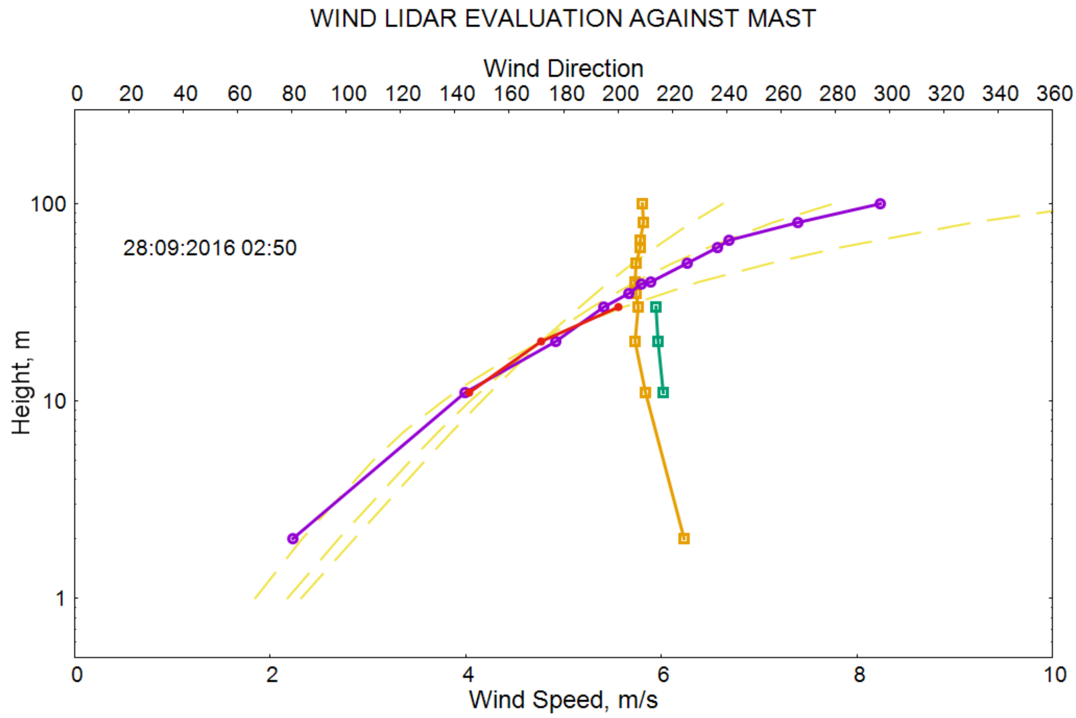
Wind Speed, m/s



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Wind Direction
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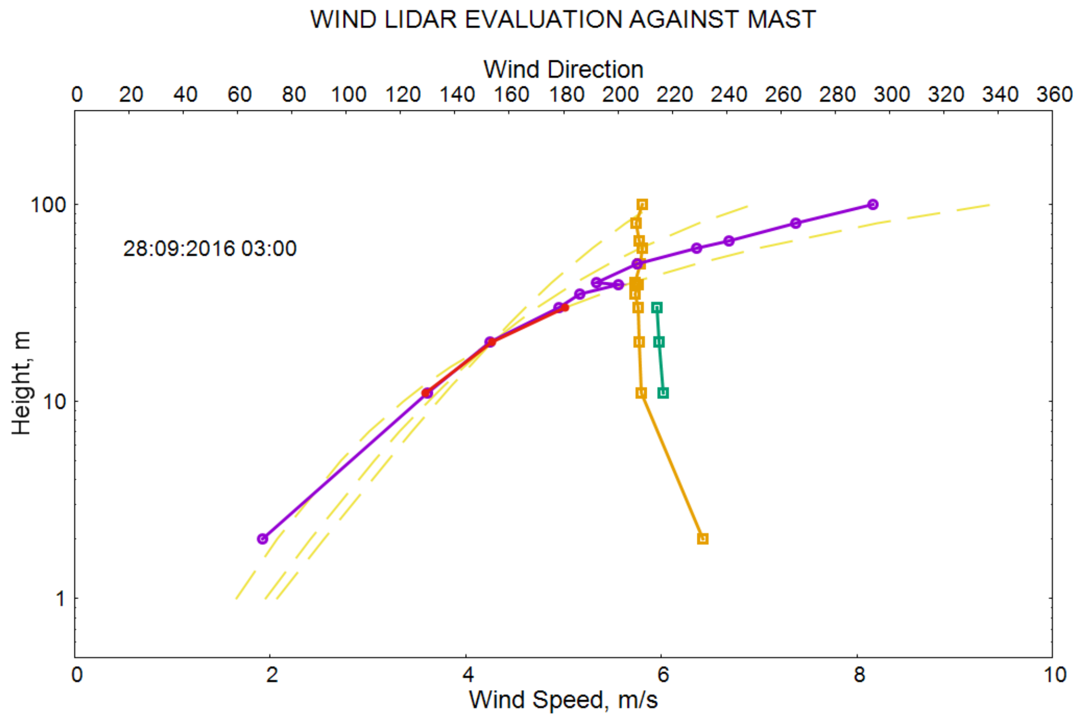
Wind Speed, m/s



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Wind Direction
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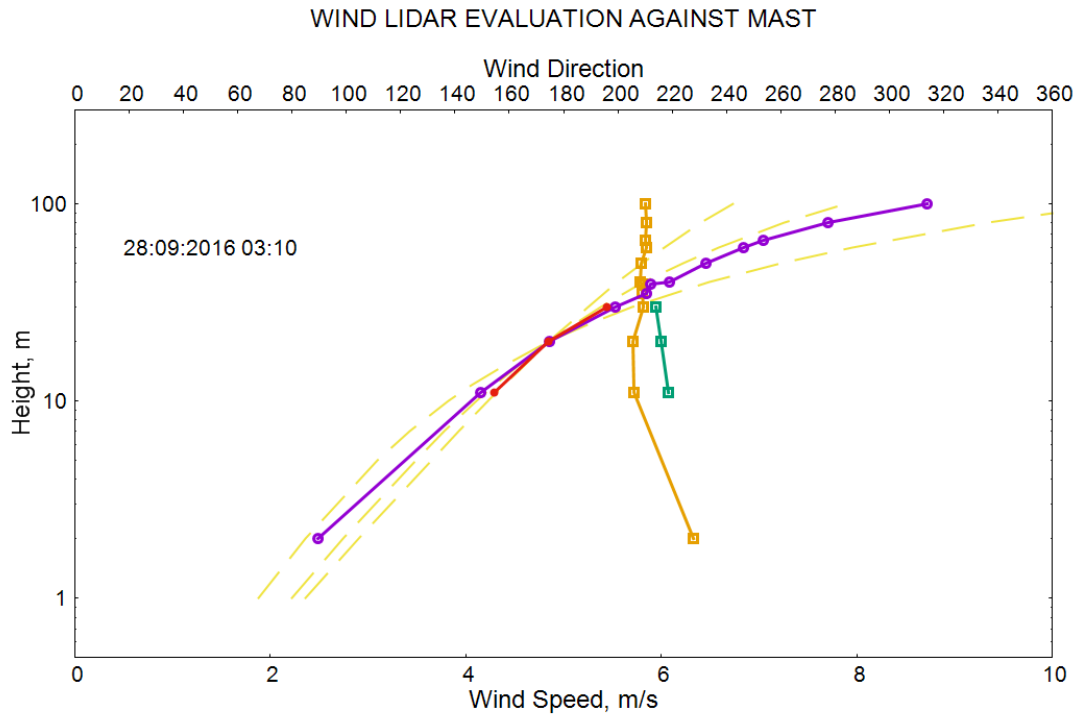
Wind Speed, m/s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Wind Direction
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Height, m
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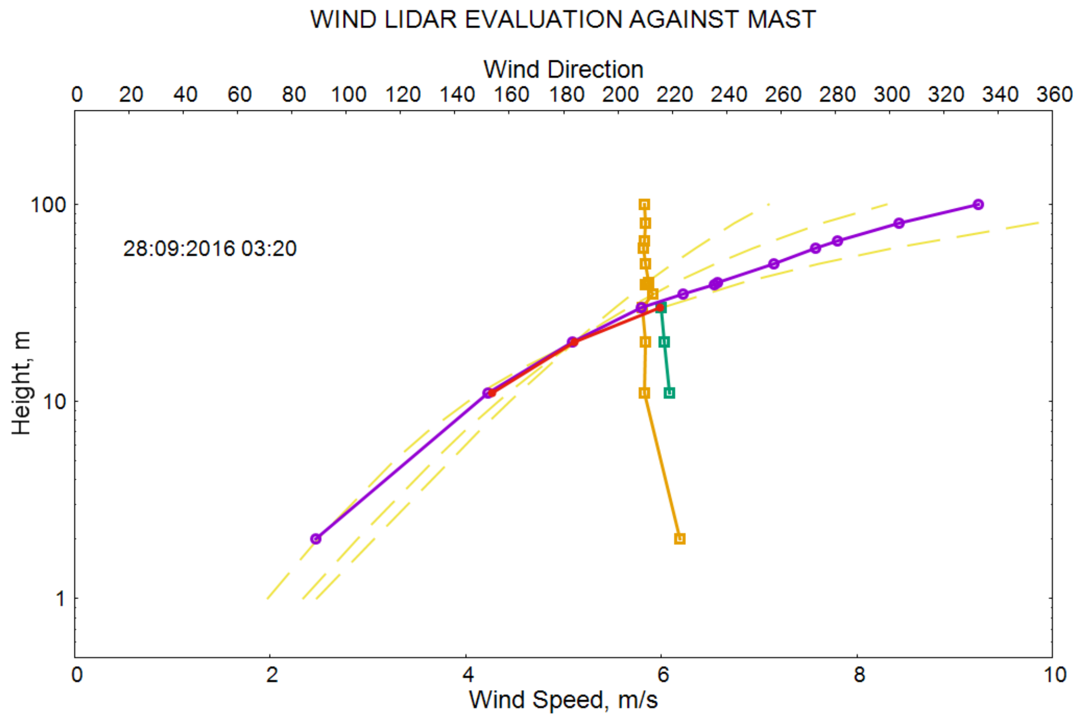
Wind Speed, m/s
0 2 4 6 8 10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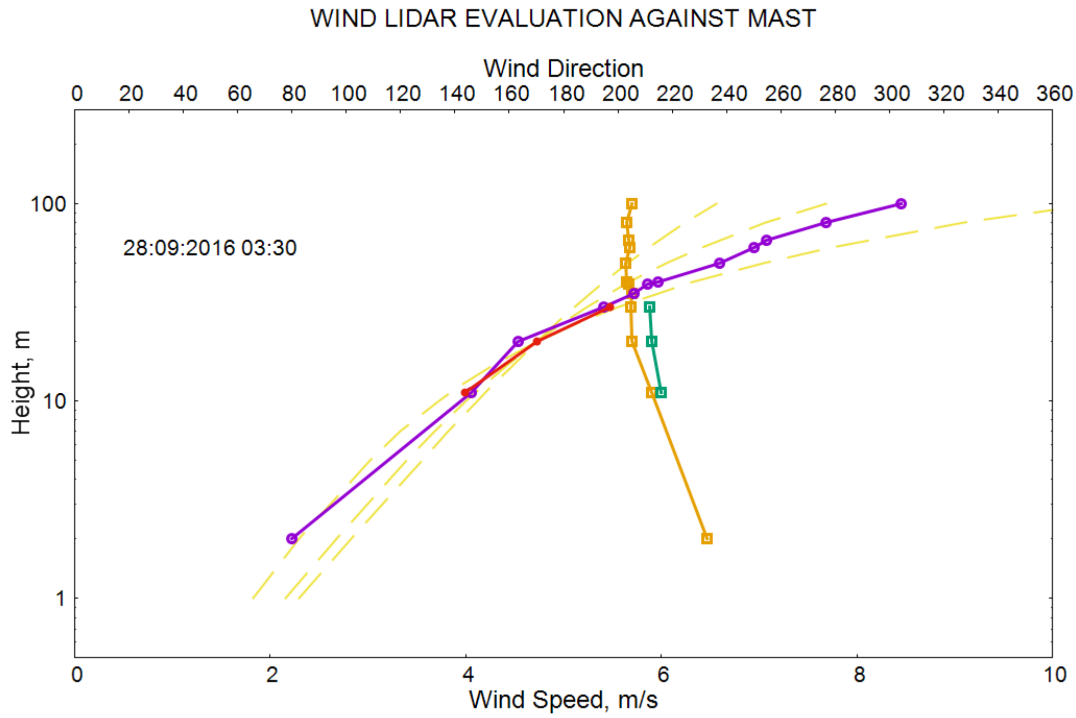
Wind Speed, m/s
0 2 4 6 8 10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Wind Direction
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Height, m
100
10
1
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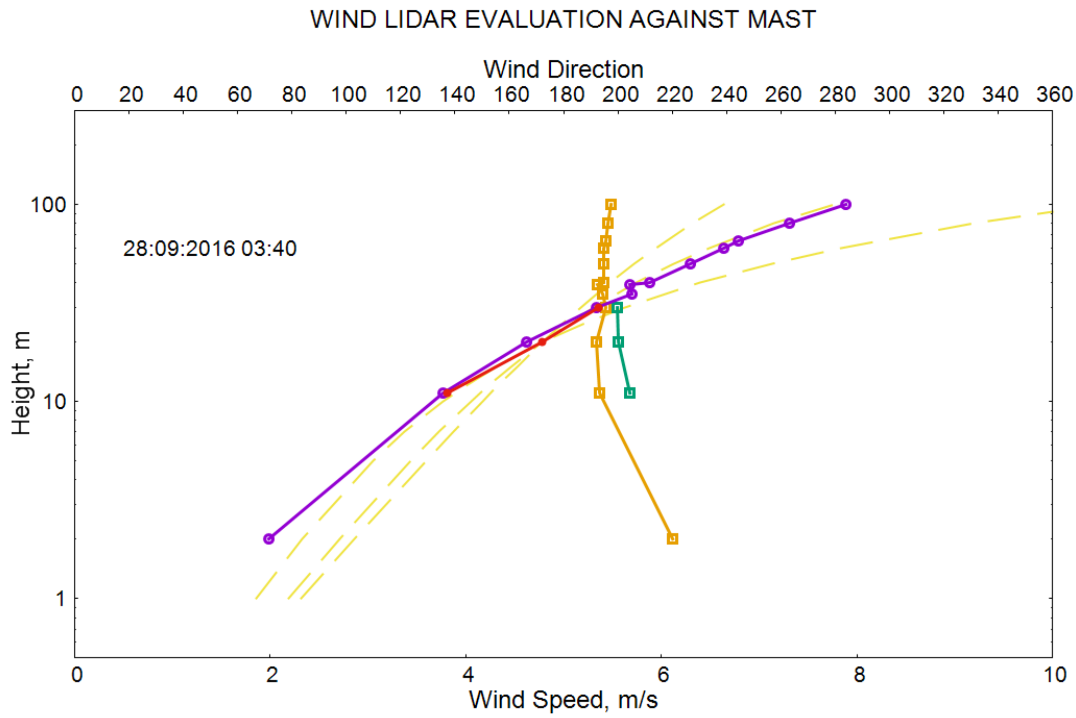
Wind Speed, m/s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Wind Direction
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Height, m
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10
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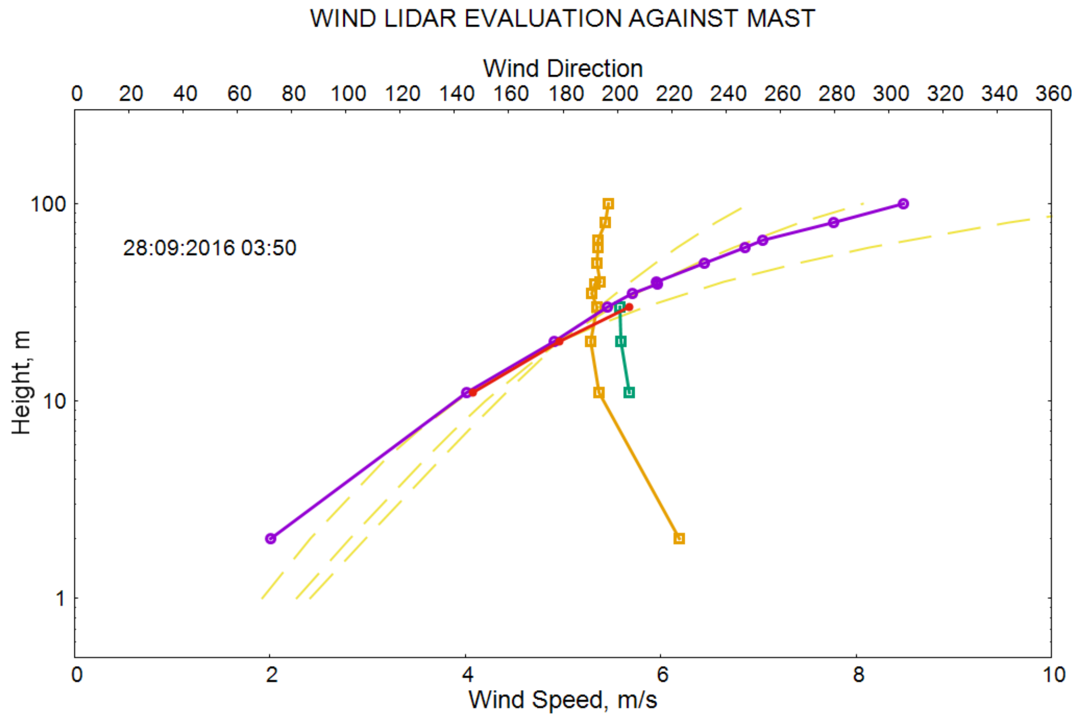
0 2 4 6 8 10
Wind Speed, m/s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Wind Direction
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Height, m
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10
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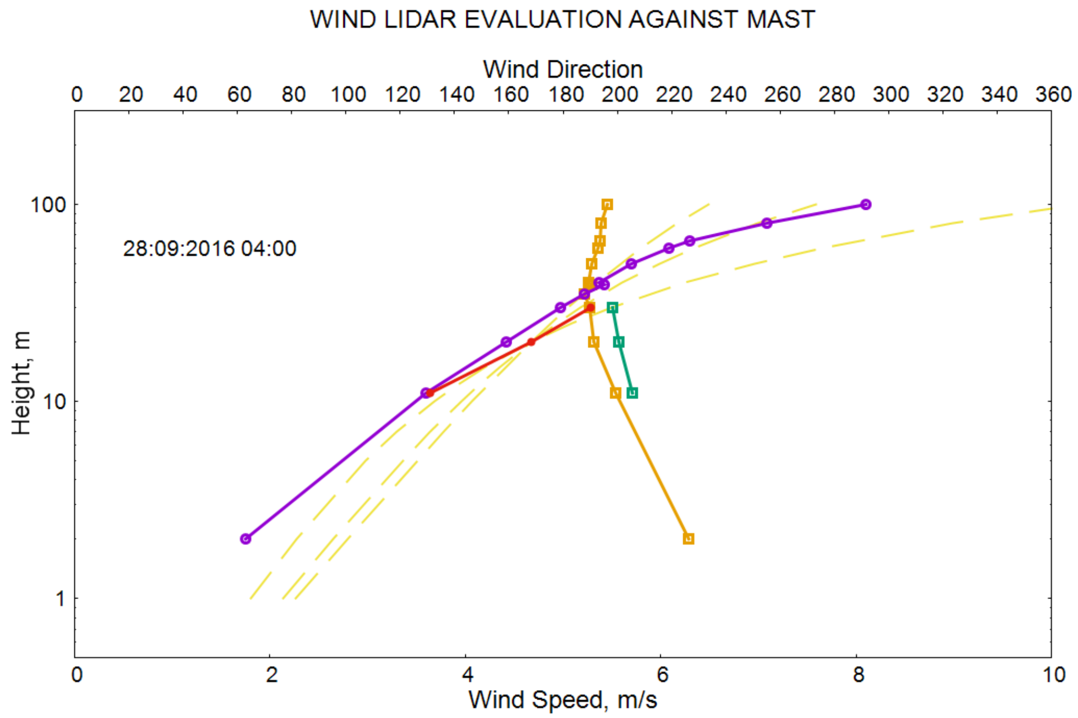
28:09:2016 03:50
0 2 4 6 8 10
Wind Speed, m/s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Wind Direction
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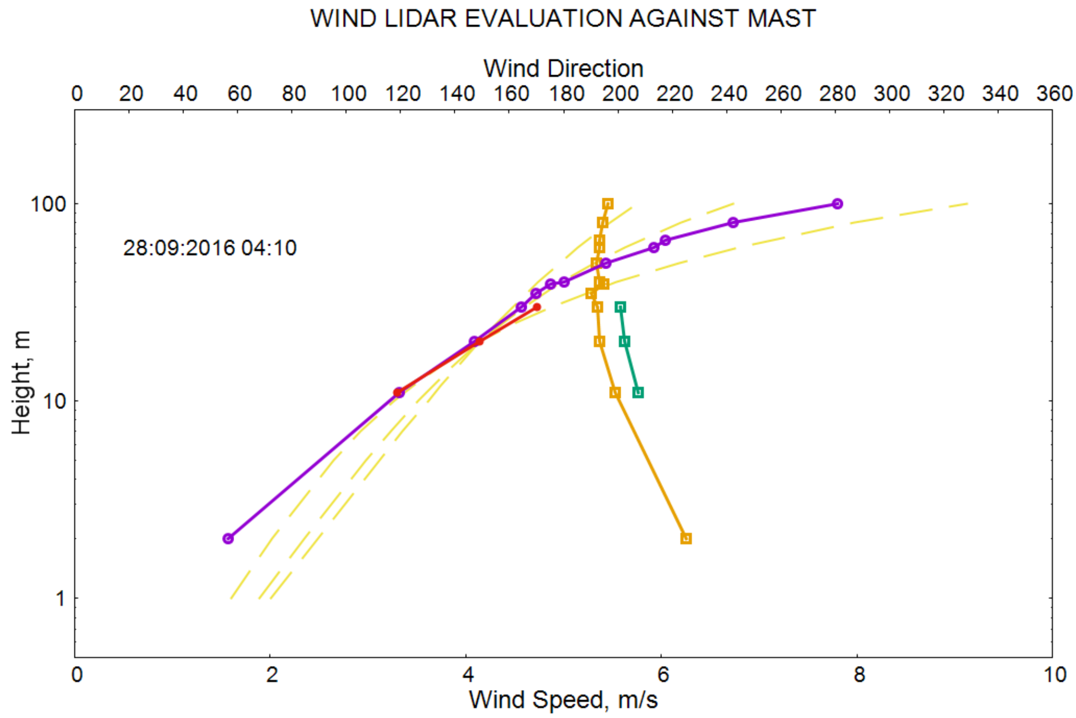
Wind Speed, m/s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Height, m
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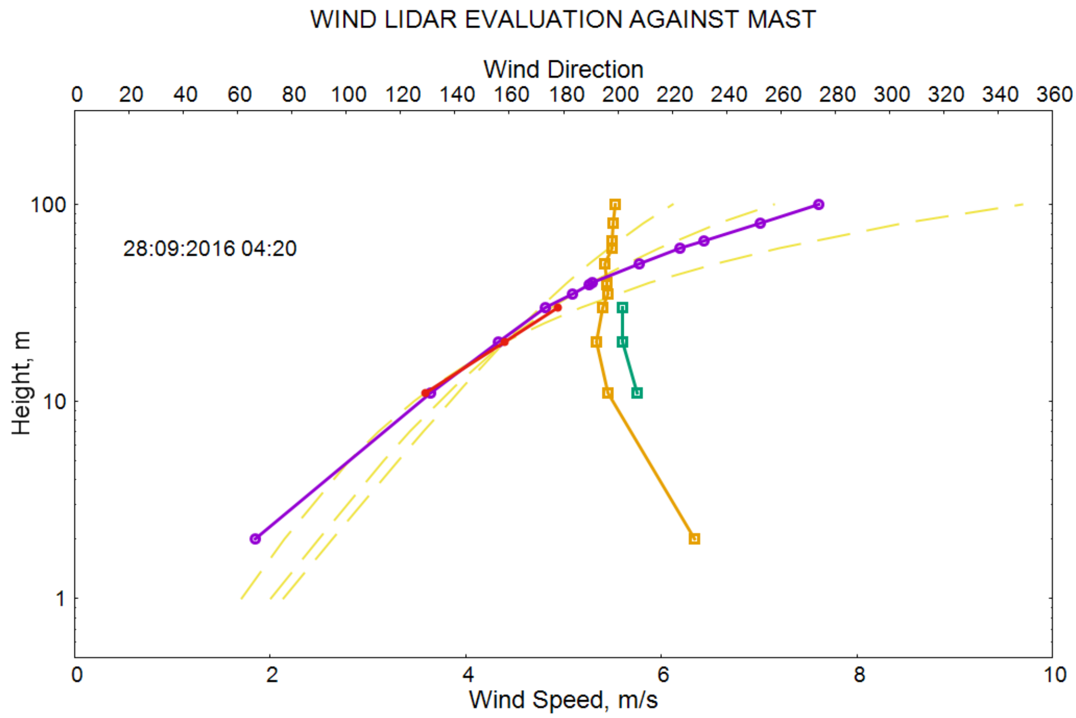
28:09:2016 04:10
0 2 4 6 8 10
Wind Speed, m/s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Wind Direction
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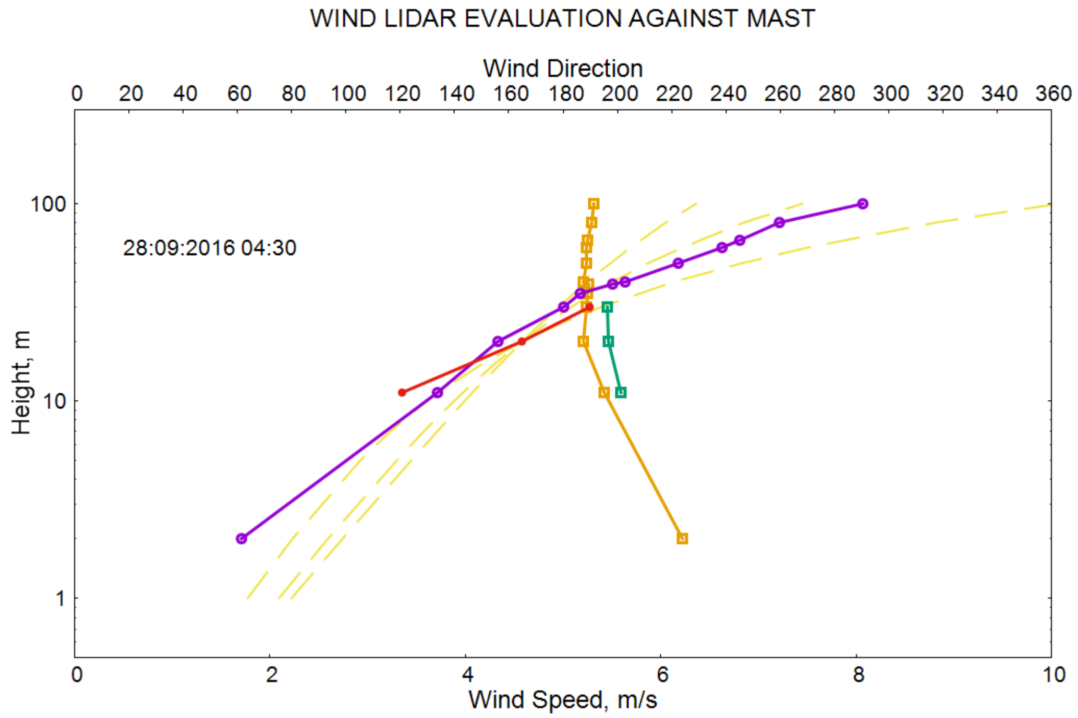
Wind Speed, m/s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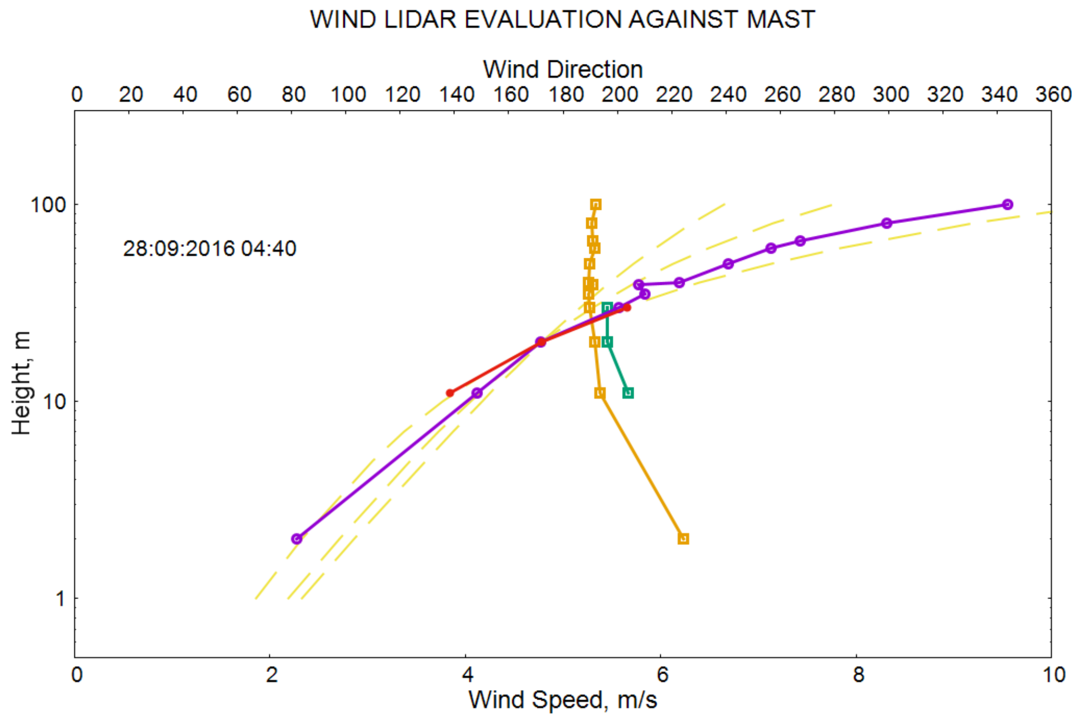
Wind Speed, m/s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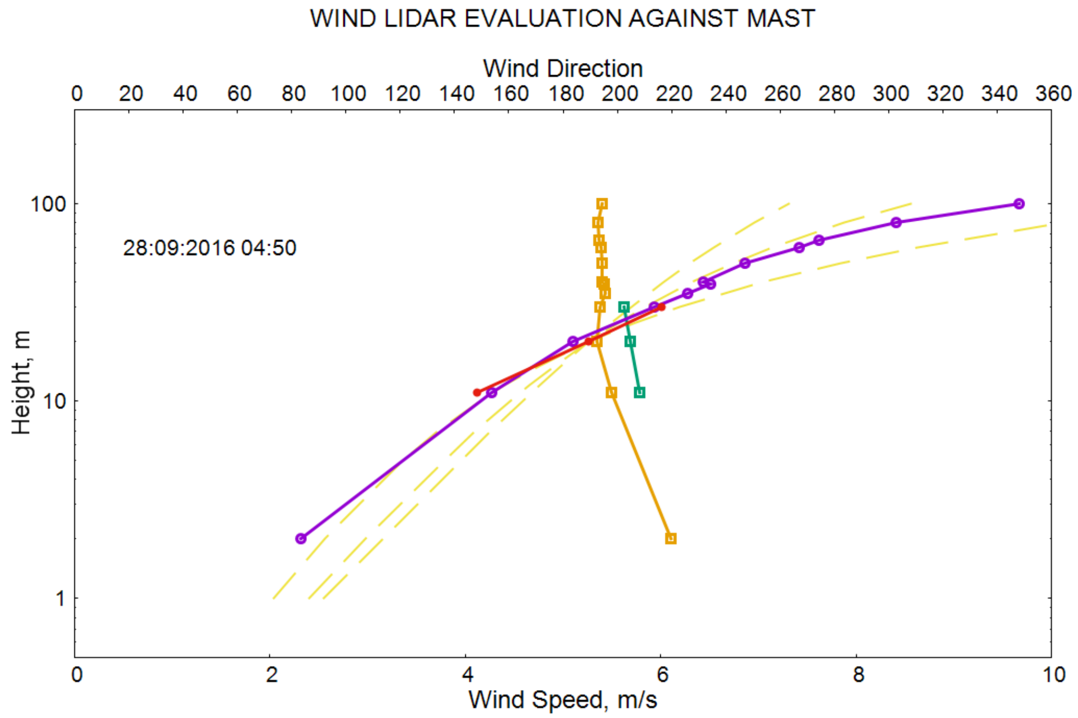
Wind Speed, m/s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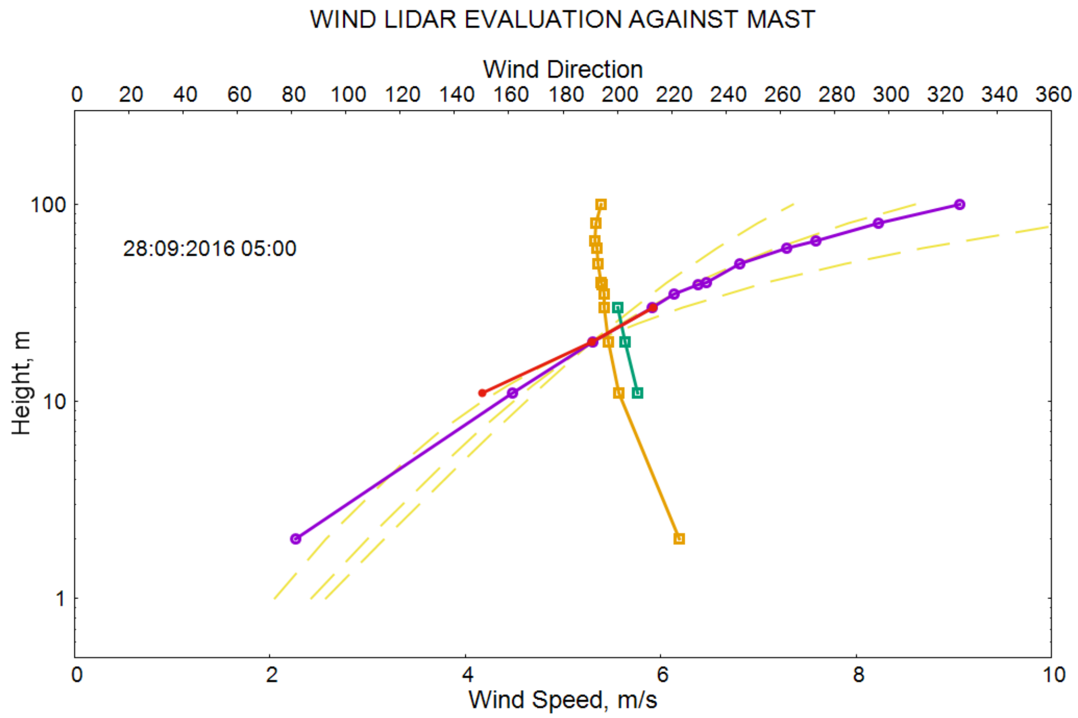
Wind Speed, m/s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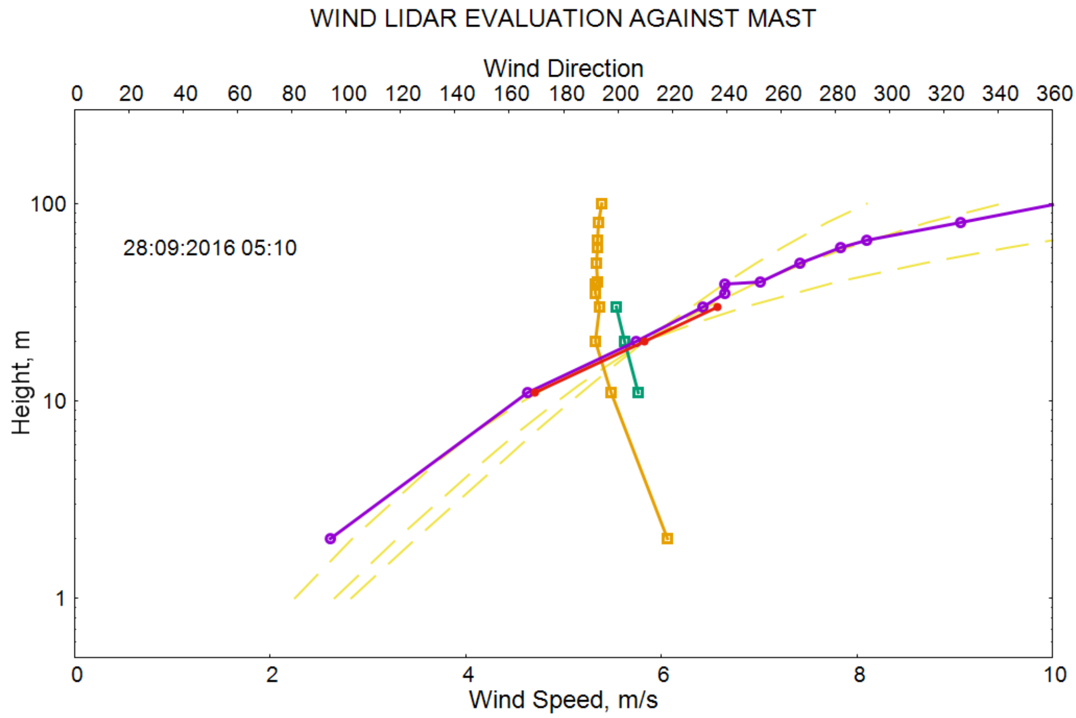
Wind Speed, m/s



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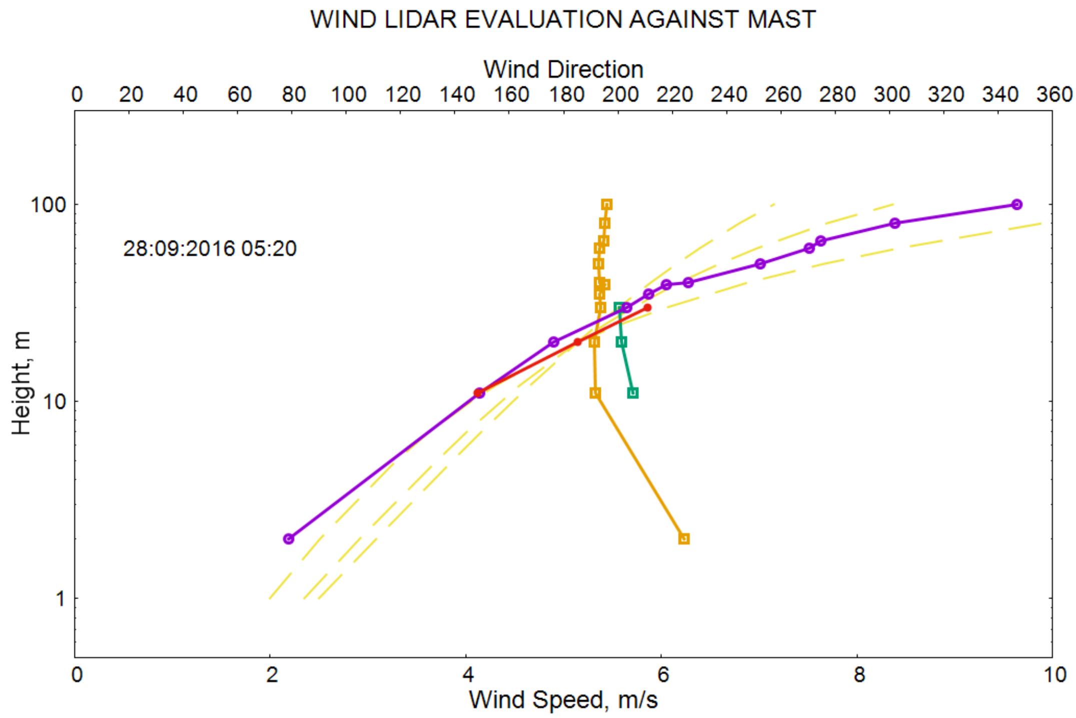
Wind Speed, m/s



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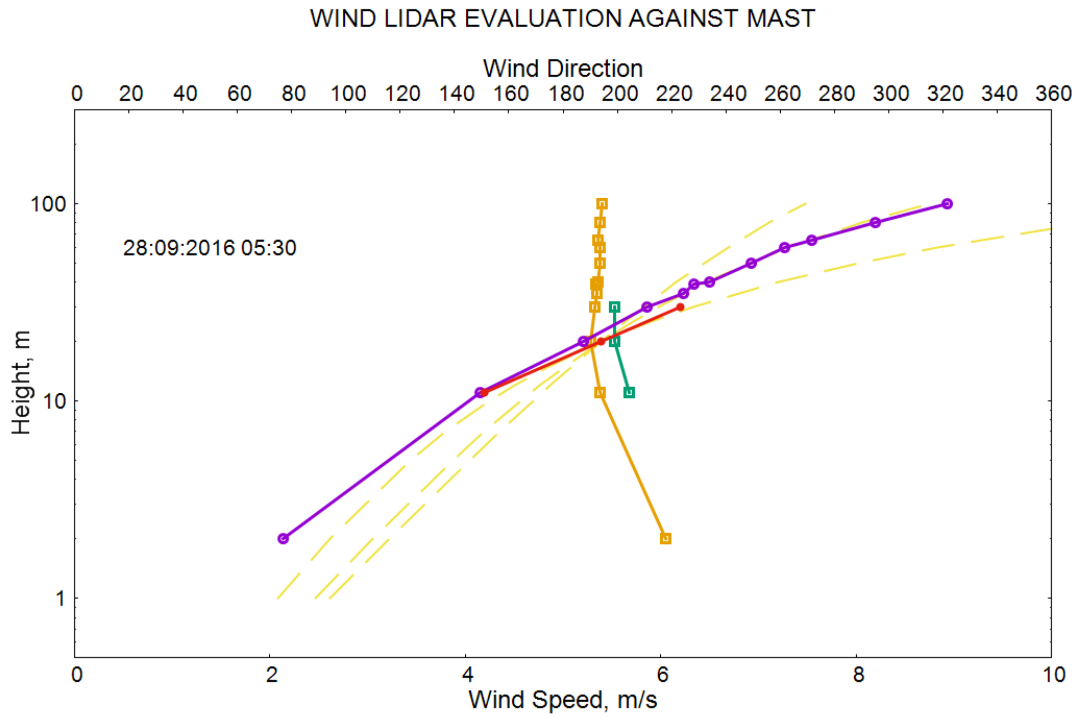
Wind Speed, m/s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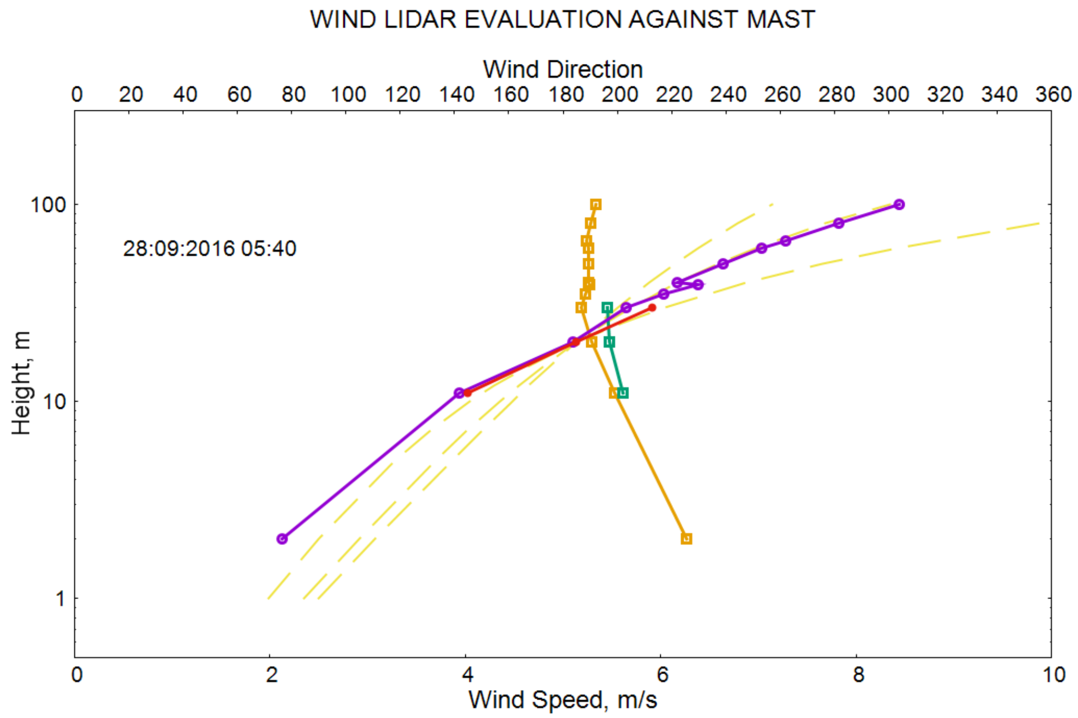
Wind Speed, m/s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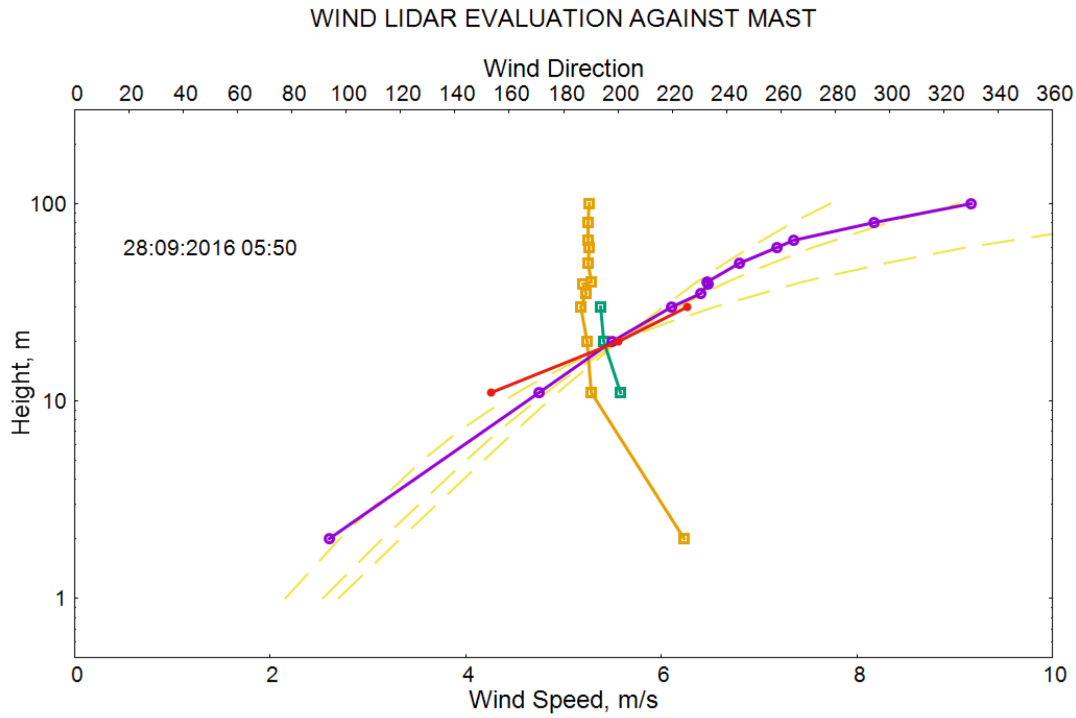
Wind Speed, m/s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Wind Direction
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Height, m
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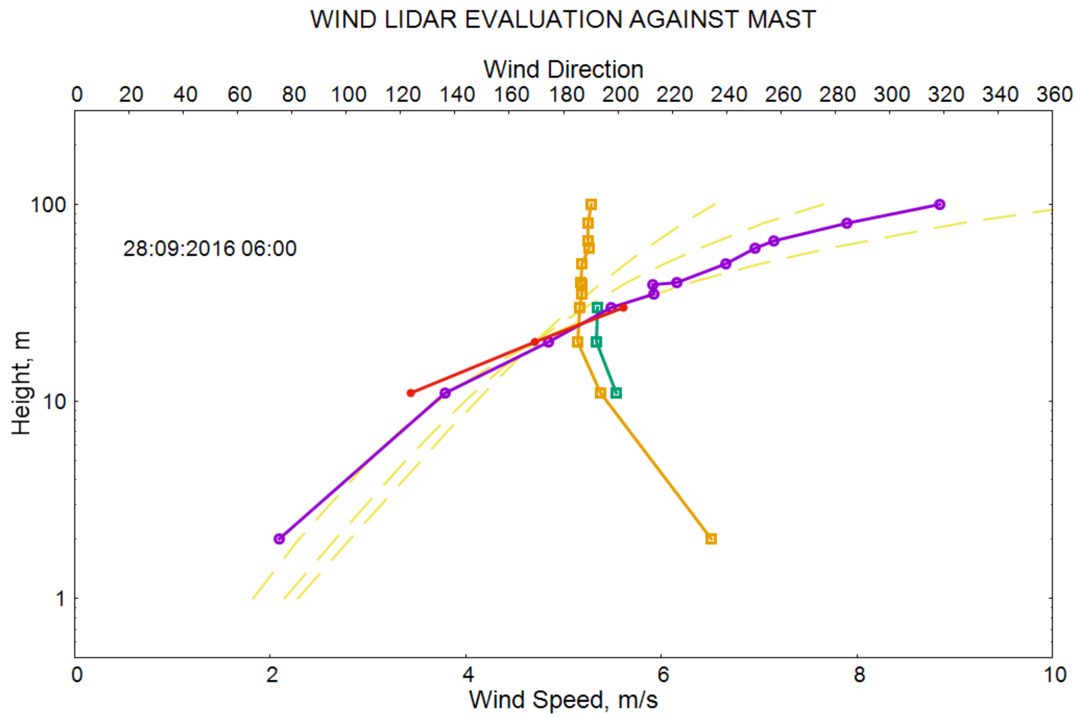
Wind Speed, m/s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Wind Direction
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28:09:2016 06:00
Height, m
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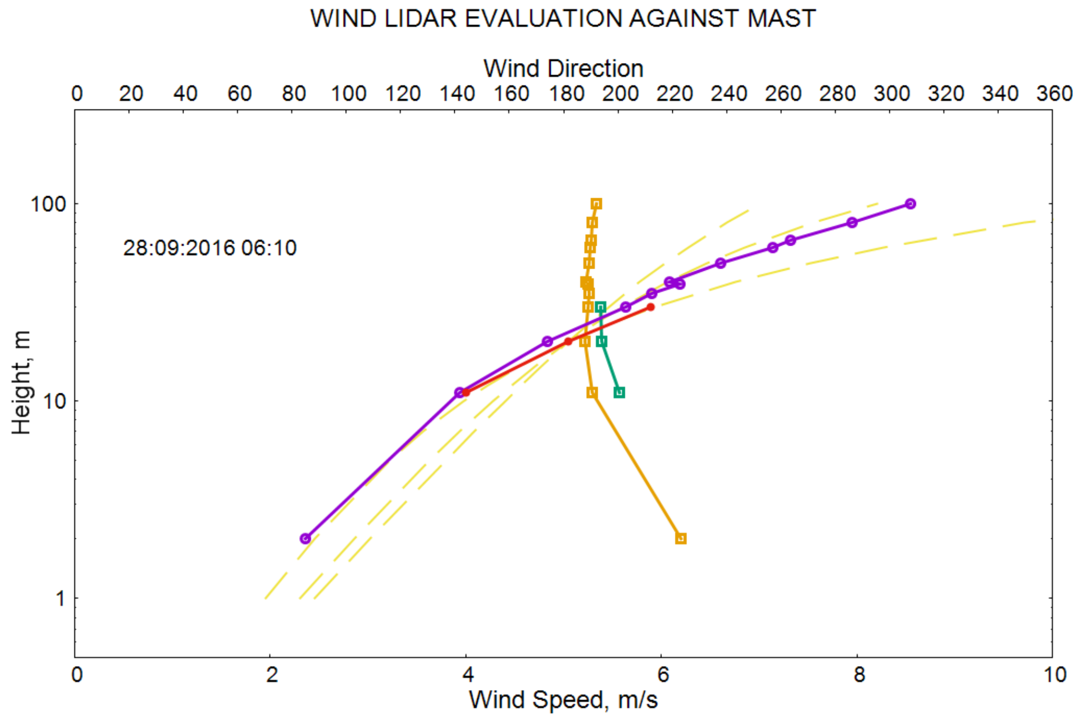
Wind Speed, m/s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Wind Direction
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Height, m
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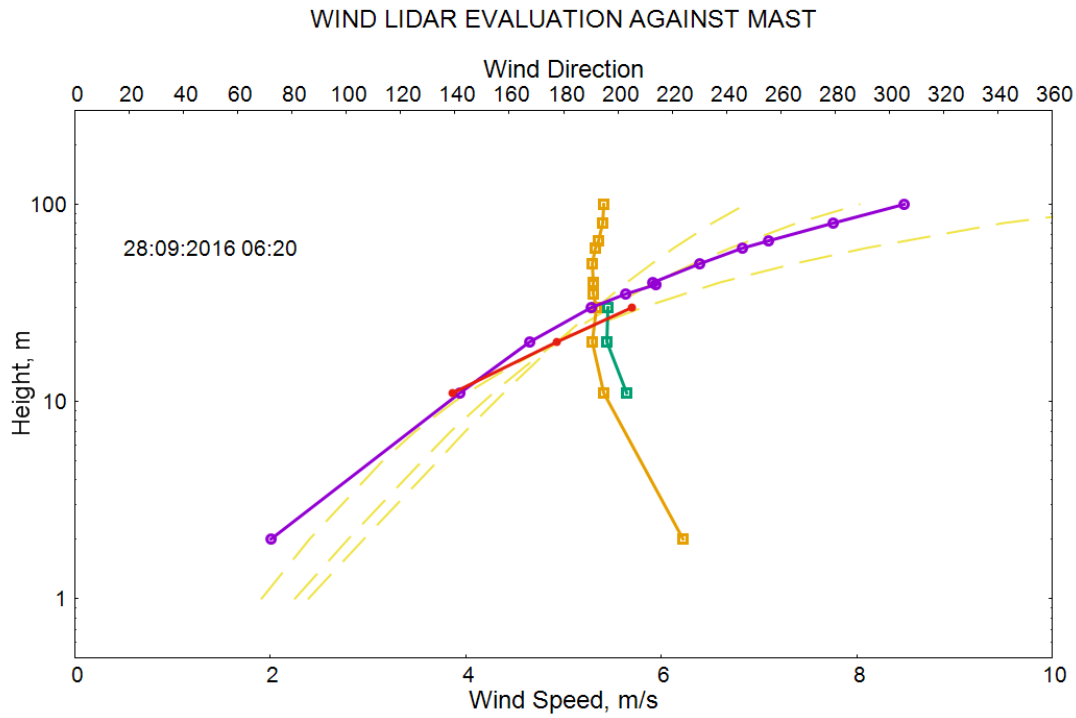
Wind Speed, m/s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Wind Direction
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Height, m
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10
1
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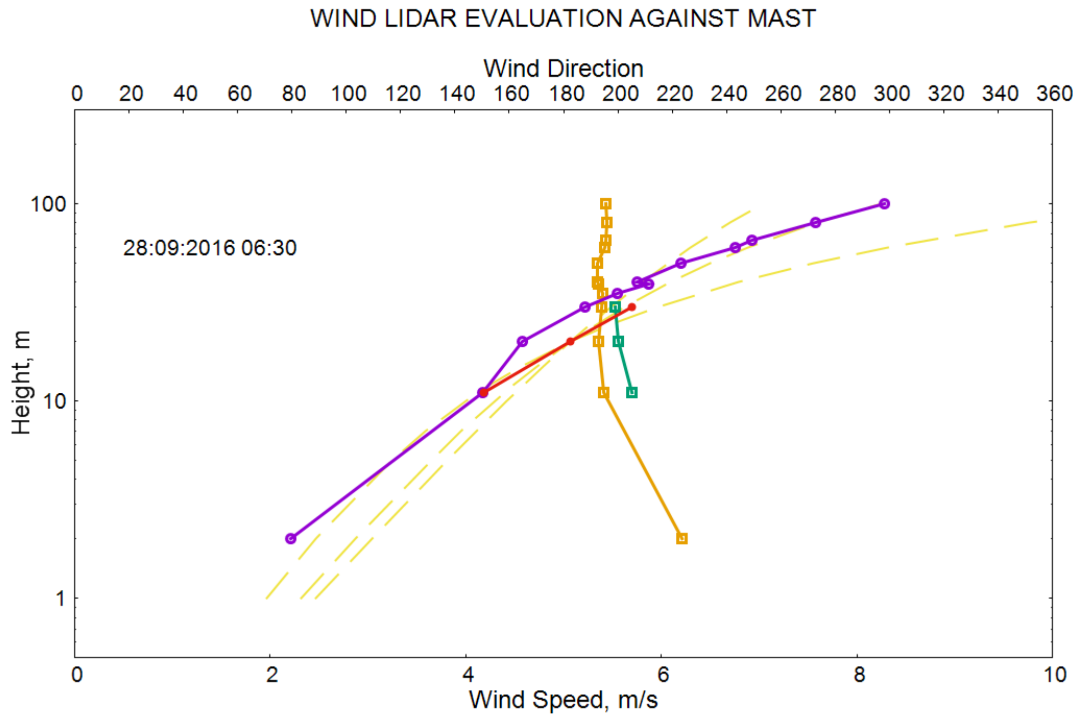
Wind Speed, m/s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Wind Direction
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Height, m
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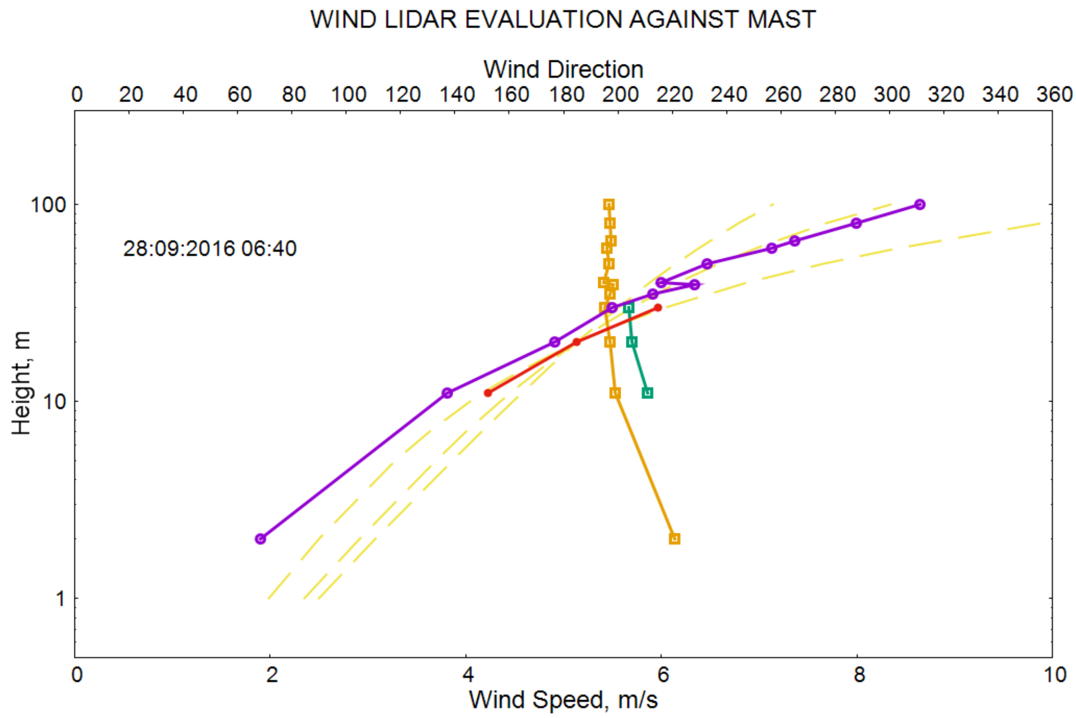
Wind Speed, m/s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Wind Direction
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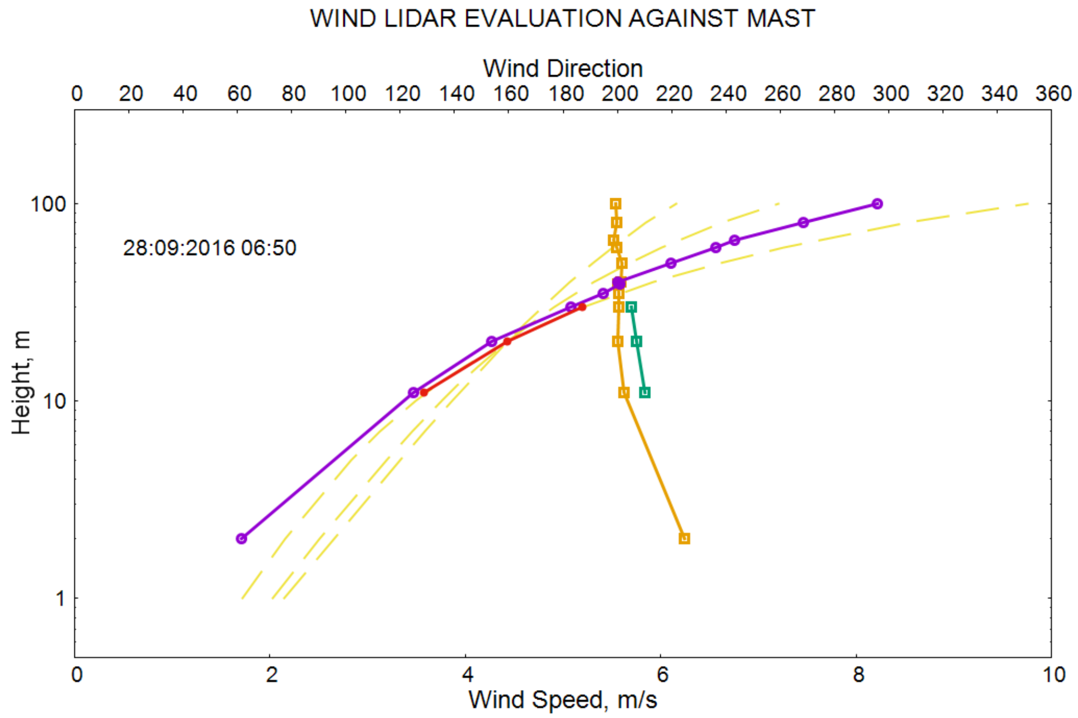
Wind Speed, m/s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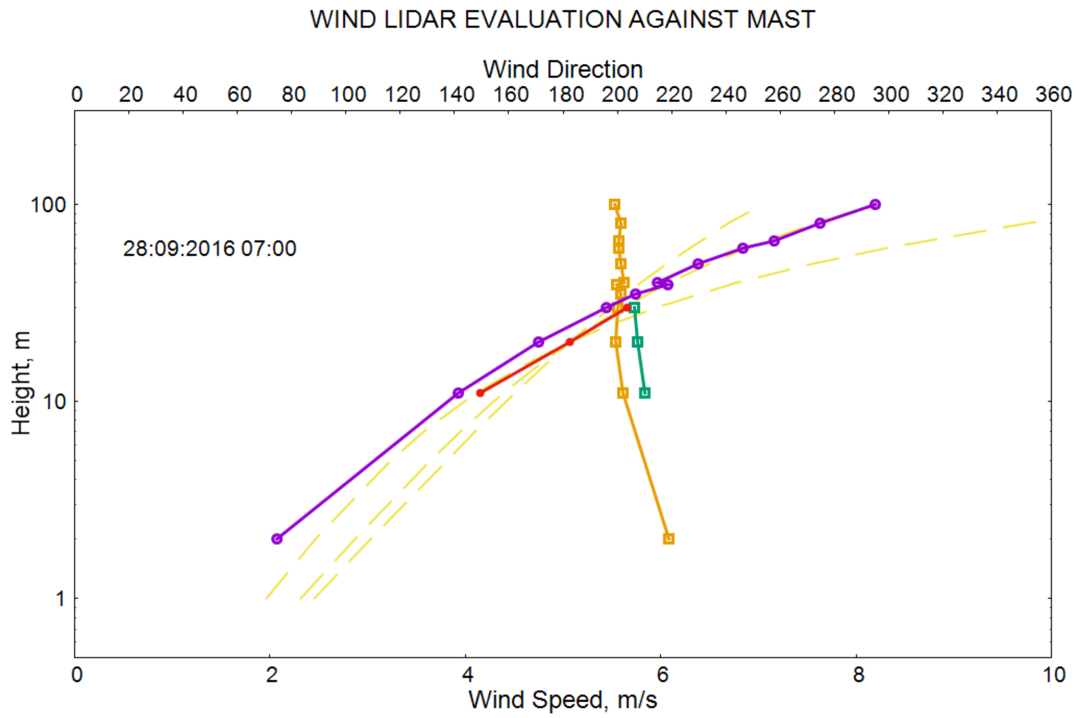
Wind Speed, m/s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Wind Direction
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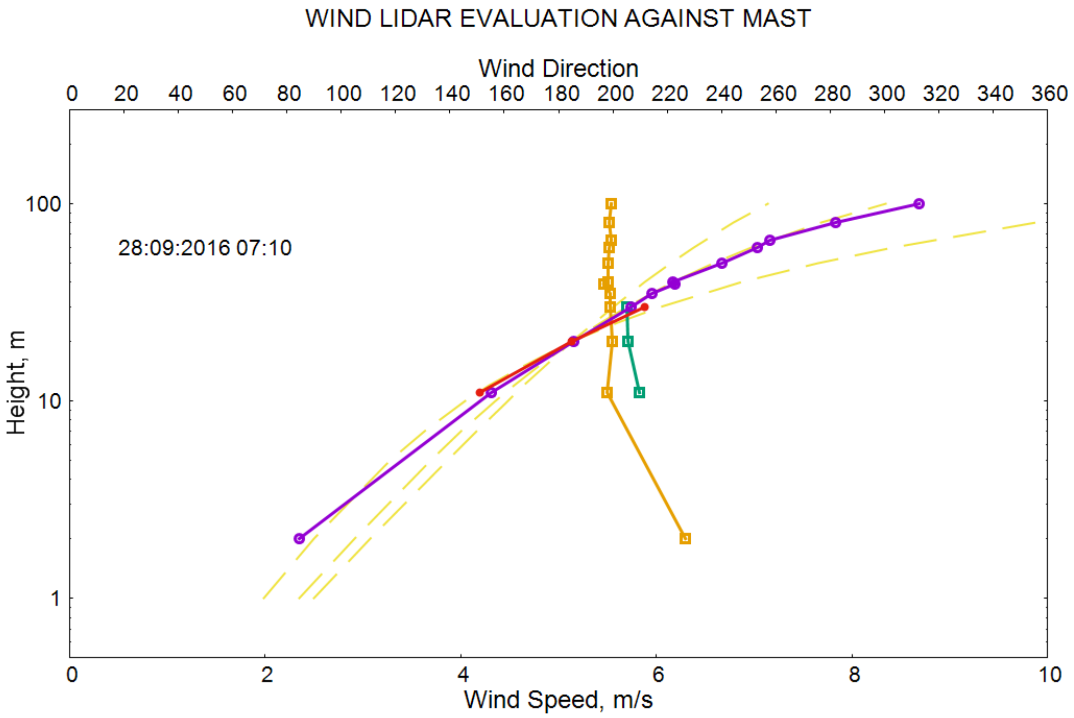
Wind Speed, m/s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Height, m
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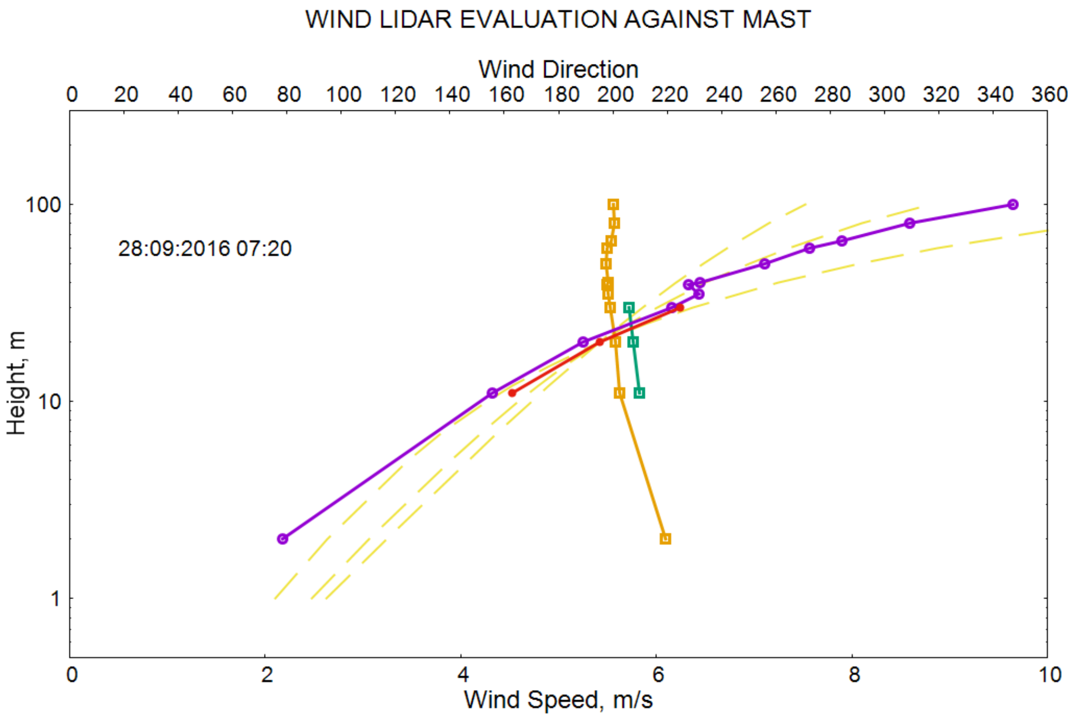
Wind Speed, m/s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Height, m
100
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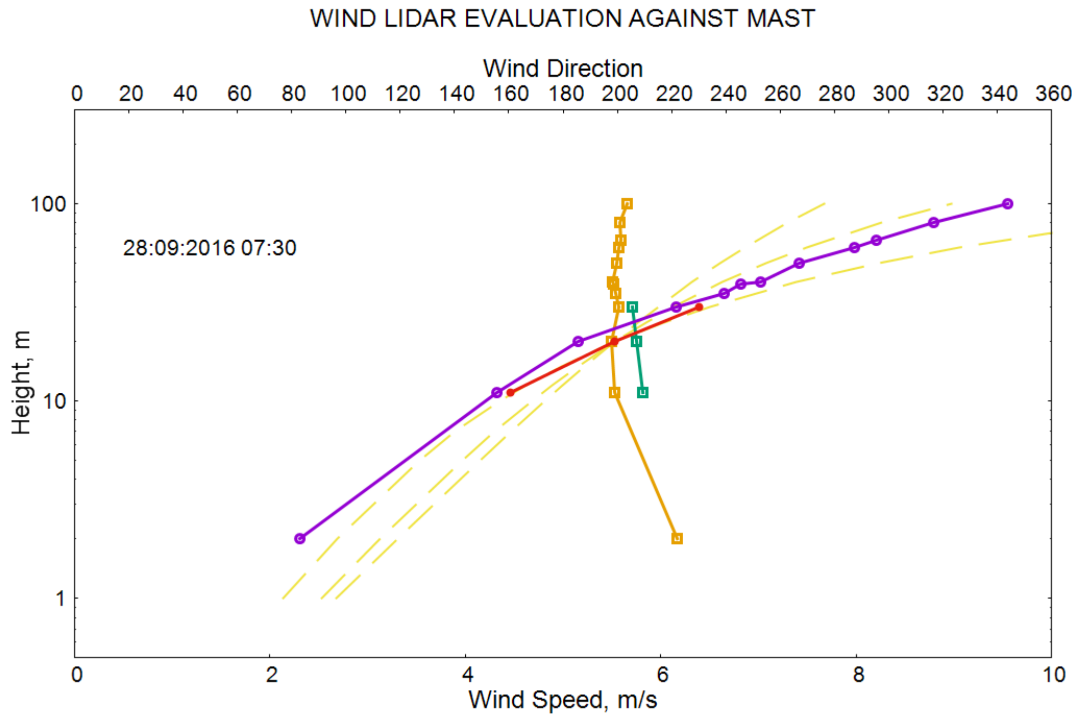
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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Height, m
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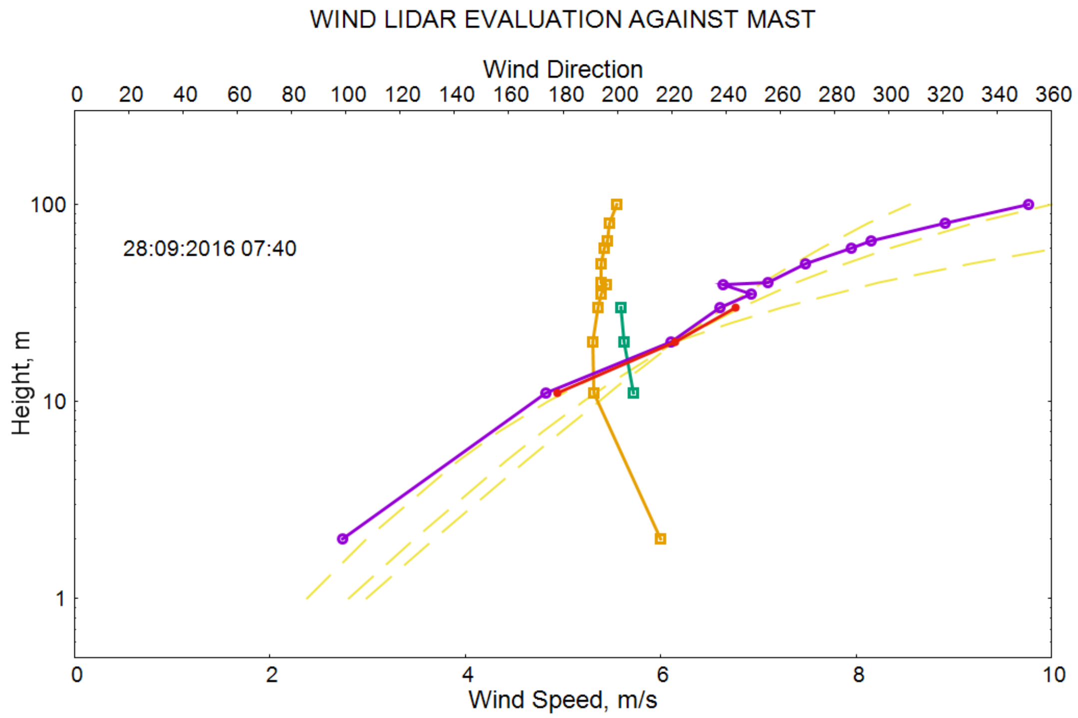
28:09:2016 07:30
0 2 4 6 8 10
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
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Height, m
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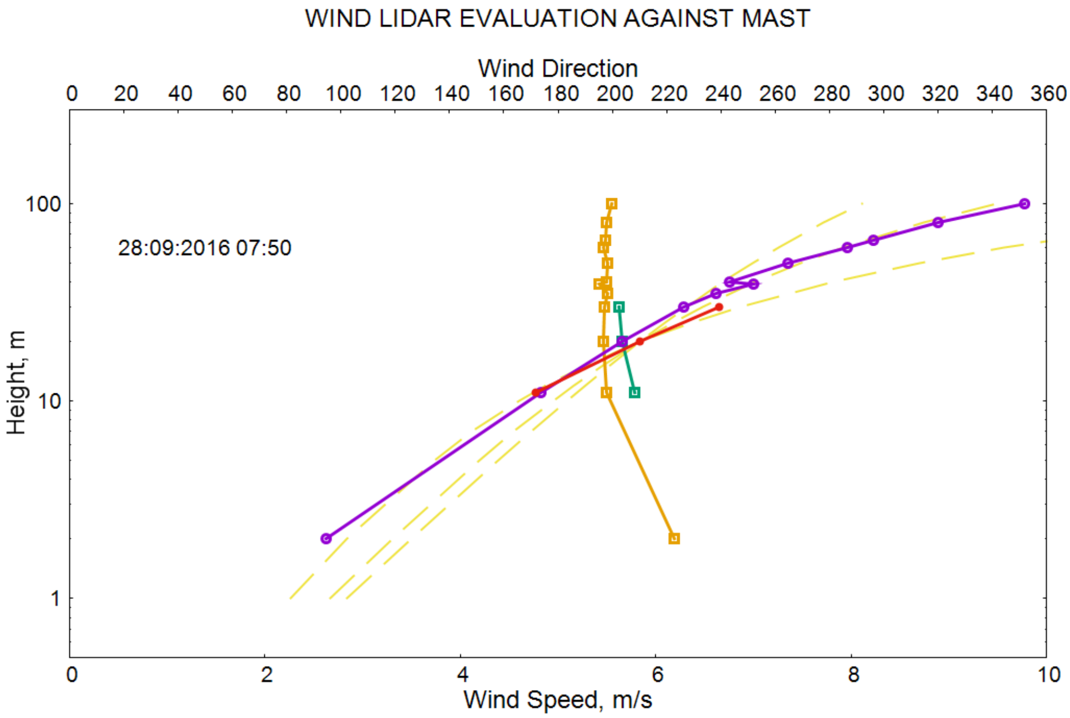
Wind Speed, m/s


WIND LIDAR EVALUATION AGAINST MAST
Wind Direction
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360
28:09:2016 07:50
Height, m
100
10
1
0 2 4 6 8 10
Wind Speed, m/s

APPENDIX B – THE WIND LIDAR TECHNIQUE

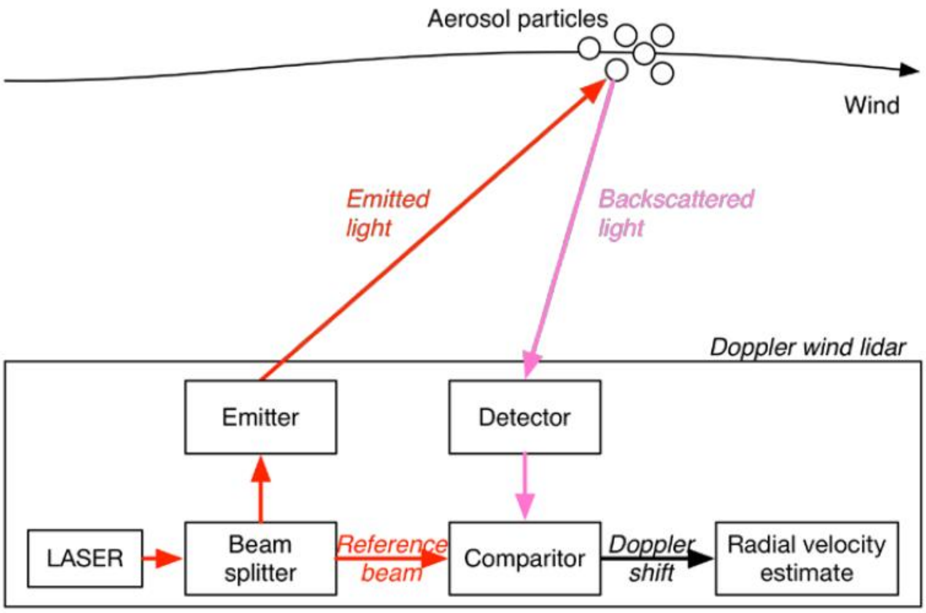
In the last few years, the LIDAR (Light Detection And Ranging) remote sensing technique has become a reasonable and flexible alternative method to replace the standard wind measurements (e.g., cup or sonic anemometers, vanes) used on a meteorological mast.

A wind LIDAR is a wind measurement device (**Figure B1**) which relies on the Doppler effect – a slight change in frequency of the backscattered light – caused by moving air-borne particles passing through a laser beam emitted from the device. A typical size of a wind LIDAR is approximately 900 x 900 x 1000 mm, while it weighs around 50-60 kg.

Figure B1 Image of a typical wind LIDAR device.

In detail, an infrared beam of coherent radiation emitted by the wind LIDAR illuminates natural aerosols (particles of dust, pollen, droplets, etc.) in the atmosphere, and a small fraction of the light is backscattered into a receiver. Motion of the target particles along the beam direction leads to a change in the light's frequency through the Doppler shift effect. This frequency shift is accurately measured by mixing the return signal with a portion of the original beam, and sensing the resulting beats at the different frequency on a photodetector and can be used to estimate the speed of the particles. Because those particles are of the order of 1 µm in size, they are assumed to act as tracers and thus move at the same speed as the wind. **Figure B2** presents a schematic description of a Doppler wind LIDAR system.

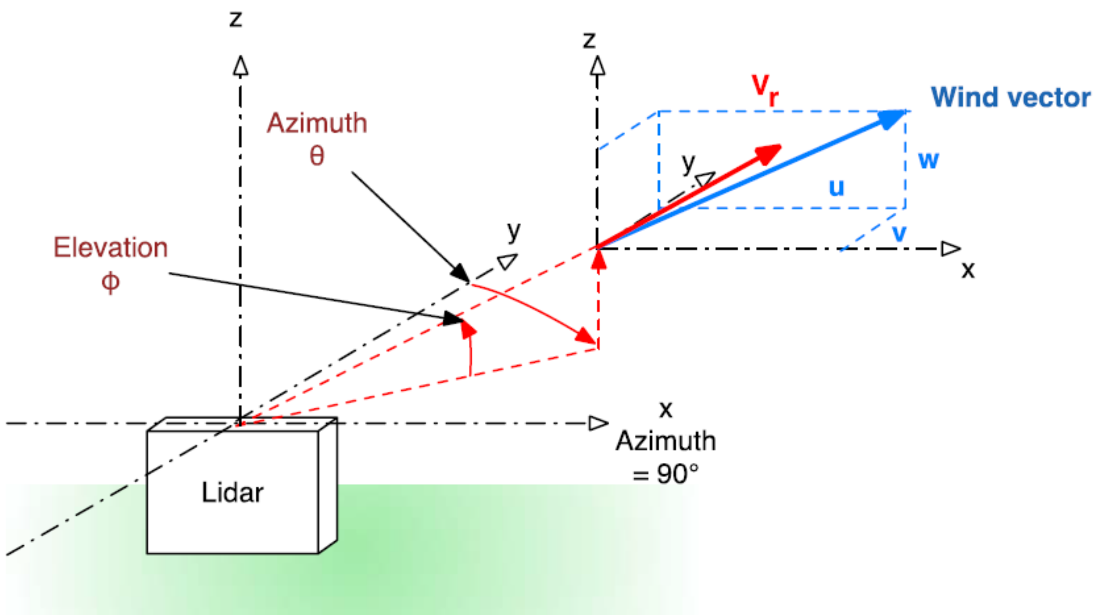
Figure B2 Schematic representation of a Doppler wind LIDAR system [2].



Typically, a LIDAR scans its beam through a sequence of beam orientations, defined in terms of their azimuth angle θ and elevation angle φ. The orientation of the lines of sight relative to the wind direction in the probe volume determines the magnitude of the projection of the wind velocity vector onto the line of sight. As a result, this measurement yields a radial velocity (**Figure B3**). Several radial velocity measurements can be combined and analysed using assumptions about the flow properties. Wind parameters are typically extracted from the radial velocity data acquired during each individual scan, but can also be built up from longer time series. Some assumptions allow the wind in the measurement volume to be quantified; others are more qualitative. The aim of most of these methods is to understand the wind field, which is the spatial variation of the horizontal and vertical wind speeds, along with the wind direction. These could be in a vertical profile or over an area. Point values of the wind speed and direction are termed wind vectors.

The region where the radial velocity is acquired is termed the probe and has a characteristic probe length along which radial velocities are measured. Because the beam has a finite width, the radial measurement is made in a probe volume. The volume within which these individual probe volumes are distributed for the purposes of a measurement of one or more wind parameters is termed the measurement volume. The measurement volume is defined by the scan geometry, which is the arrangement of lines of sight along which LIDAR emissions occur.

Figure B3 Illustration of the relationship between the wind vector and the radial velocity observed by a LIDAR [2].



Wind LIDARs can be classified into two different categories based on their measurement principles:

a) *Continuous Wave (CW) LIDARs*

A CW LIDAR focuses a continuous transmitted laser beam at a measurement height and there determines, also continuously, the Doppler shift in the detected backscatter from that particular height. The measurement ranges (measurement heights) as well as the spatial resolution of a CW LIDAR measurement is controlled by the focal properties of the telescope. The shorter the measurement distance, and the bigger the aperture (lens), the better defined is a CW LIDAR range definition and its radial measurement confinement. Typically, CW LIDARs can measure radial wind speeds at ranges from 10 m up to 200 m, and wind vectors at heights up to 150 m.

b) *Pulsed LIDARs*

A pulsed LIDAR transmits a sequence of many short pulses, typical 30 m in effective length, and then it detects the Doppler shift in the backscattered light from each pulse as they propagate with the speed of light. While a CW LIDAR measures from one height at a time, a pulsed LIDAR measures wind speeds from several range-gated distances simultaneously, typically at up to 10 range gates at a time.

The pulsed LIDAR's spatial resolution, in contrast to the CW LIDAR, is independent of the measurement range. The pulse width and the distance the pulse travels while the LIDAR samples the detected backscatter control its resolution. The spatial resolution in the beam direction of a pulsed LIDAR can reach up to 30 - 40 m.

Wind LIDARs evaluated for the purposes of this study

Generally, the most important specifications to consider when selecting a wind LIDAR are the height and wind speed range. The majority of LIDARs have been developed for the wind farm industry aiming to replace the need for tall masts. Hence, a typical LIDAR is not designed to measure below 30 m. Additionally, another important factor to consider in relation to a refinery wind survey is the mobility of the LIDAR device.

The following table compares the technical specifications for potential wind LIDARs examined for the objective of the Concawe refinery wind study:

Table B1 Technical specifications of the wind LIDARs examined for the objective of the Concawe refinery wind study.

Technical Specifications	Wind LIDARS		
	ZephIR	**Galion**	**WindCube v.2**
Type	Continuous	Continuous	Pulsed
Supplier	KONA	SgurrEnergy	Oldbaum
Range	10 – 200 m.	10 – 250 m	40 – 200 m
Heights measured	10 (user configurable)	15+ (user configurable)	12 (user configurable)
Spatial resolution	User configurable **	24 m	N/A
Averaging period	User defined (1 s standard)	N/A[1]	1 s
Sampling rate	50 Hz	100 MHz	100 MHz
Scanning cone angle	30°	N/A	N/A
Speed accuracy variation	< 0.5% *	N/A	0.1 m/s
Speed range	< 1 m/s to 70 m/s	0 m/s to >70 m/s	0 m/s to 60 m/s
Direction accuracy variation	< 0.5°	N/A	2.0°
Data	10 minute averaging	N/A	10 minute averaging
Laser classification	Class 1	Class 1	Class 1
Compliance	Full CE accreditation	Full CE accreditation	Full CE accreditation
Power consumption	69 Watts	130 Watts	45 Watts
Weight	55 kg	85 kg	45 kg (21 kg transport case)
Mobile?	**YES**	**Yes, but with constraints** (Will need to be turned off and on each time it is moved).	N/A

*As measured against a calibrated moving target

** The distance needed for the first measurement is 10 meters. The resolution can be adjusted as needed for the next measurement points.

[1] N/A: "Not Available"

Based on the information in Table B1, it was concluded that the ZephIR LIDAR was the most well suited device to meet the objectives and needs of the Concawe refinery wind study, based on its height range, wind speed range, mobility and other favourable specifications.

APPENDIX C – ANEMOMETER DESCRIPTION AND CALIBRATION DATA

The following section presents a brief description of the anemometer used in this study as well as data from the different calibrations performed on the anemometer used in this study. The data have been taken from the official calibration certificates of the anemometer.

Anemometer description

The anemometer used for in this study was the Ultrasonic Anemometer Thies 3D (**Figure C1**). The Ultrasonic Anemometer 3D is designed to measure the horizontal and vertical components of wind velocity, wind direction and acoustic virtual temperature in 3 dimensions. It consists of 6 ultrasonic transformers, in pairs facing each other at a distance of 200 mm. The three resulting measurement paths are vertical in relation to each other. The transformers function both as acoustic transmitters and receivers.

In comparison to cup anemometers, the measuring principle provides for inertia-free measurement of rapidly changing variables with maximum precision and accuracy, while all calculations are carried out by a high-capacity digital-signal-processor (DSP). The anemometer is maintenance-free, wearless and equipped with heating for extreme winter conditions.

Figure C1 Image of the Ultrasonic Anemometer Thies 3D used in this study.

Table C1 Technical specifications of the Ultrasonic Anemometer Thies 3D used in this study.

Wind Speed	
Measuring Range	0 – 65 m/s
Accuracy	≤ 5m/s: ± 0.1 m/s rms (root mean square over 360º) > 5 m/s - ≤ 65 m/s: 1% - 2% rms of measured value
Resolution	0.01-0.1 m/s
Wind Direction	
Measuring Range	Azimuth: 0º - 360º Elevation: -90º - +90º
Accuracy	> 1m/s - ≤ 35 m/s: 1º > 35m/s - ≤ 65 m/s: 2º
Resolution	1º
Acoustic Virtual Temperature	
Measuring Range	-40 – +70 ºC
Accuracy	± 0.5 K
Resolution	0.1 K

Calibration Data

a) Calibration mark: 1623511/D-K-15140-01-00/09-2016

Calibration Object	3D Sonic Anemometer
Manufacturer	Thies Clima D-37083 Göttingen
Type	4.3830.22.503
Serial number	03160050
Customer	Ammonit Measurement GmbH D-10997 Berlin
Order No.	L 24151
Project No	VT160883
Date of Calibration	12.09.2016

Calibration procedure	• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA Based on following standards: • MEASNET: Anemometer calibration procedure • IEC 61400-12-1: Power performance measurements of electricity producing wind turbines • IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 3966: Measurement of fluid in closed conduits • ISO 16622: Meteorology – Sonic anemometers / thermometers
Place of calibration	Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel
Test conditions	Wind tunnel area: 10000 cm^2 Anemometer frontal area: 270 cm^2 Diameter of mounting pipe: 48 mm Blockage ration[1]: 0.027 [-] Software version: 7.64 [1] Due to the special construction of the test section no blockage correction is necessary
Ambient conditions	Air temperature: 23.3 °C ± 0.1 °C Air pressure: 1017.6 hPa ± 0.3 hPa Relative humidity: 64.5% ± 2.0%
Measurement uncertainty	The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%. The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische-Bundesanstalt) standard for flow speed. It is realised by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2%, k=2)
Additional remarks	Orientation: 0°

Calibration Result

Sensor v_hor (m/s)	Sensor dir (deg)	Sensor v_vert (m/s)	Tunnel speed (m/s)	Uncertainty (k=2) (m/s)
4.033	357.382	0.052	3.973	0.050
6.059	357.421	0.062	5.964	0.050
8.076	357.400	0.070	7.948	0.050
10.149	357.336	0.070	9.987	0.050
12.317	357.285	0.080	12.124	0.050
14.342	357.259	0.085	14.120	0.050
16.292	357.216	0.093	16.056	0.050
15.362	357.231	0.089	15.133	0.050
13.307	357.300	0.083	13.105	0.050
11.238	357.341	0.076	11.067	0.050
9.098	357.377	0.068	8.963	0.050
7.118	357.409	0.064	7.017	0.050
4.988	357.421	0.055	4.926	0.050

Statistical Analysis

Slope: 0.98477 (m/s)/(m/s) ± 0.00050 (m/s)/(m/s)
Offset: 0.0016 m/s ± 0.005 m/s
Standard error (Y): 0.007 m/s
Correlation coefficient: 0.999999

Remarks Serial number

The calibrated sensor complies with the demanded linearity of MEASNET

Graphical representation of the result

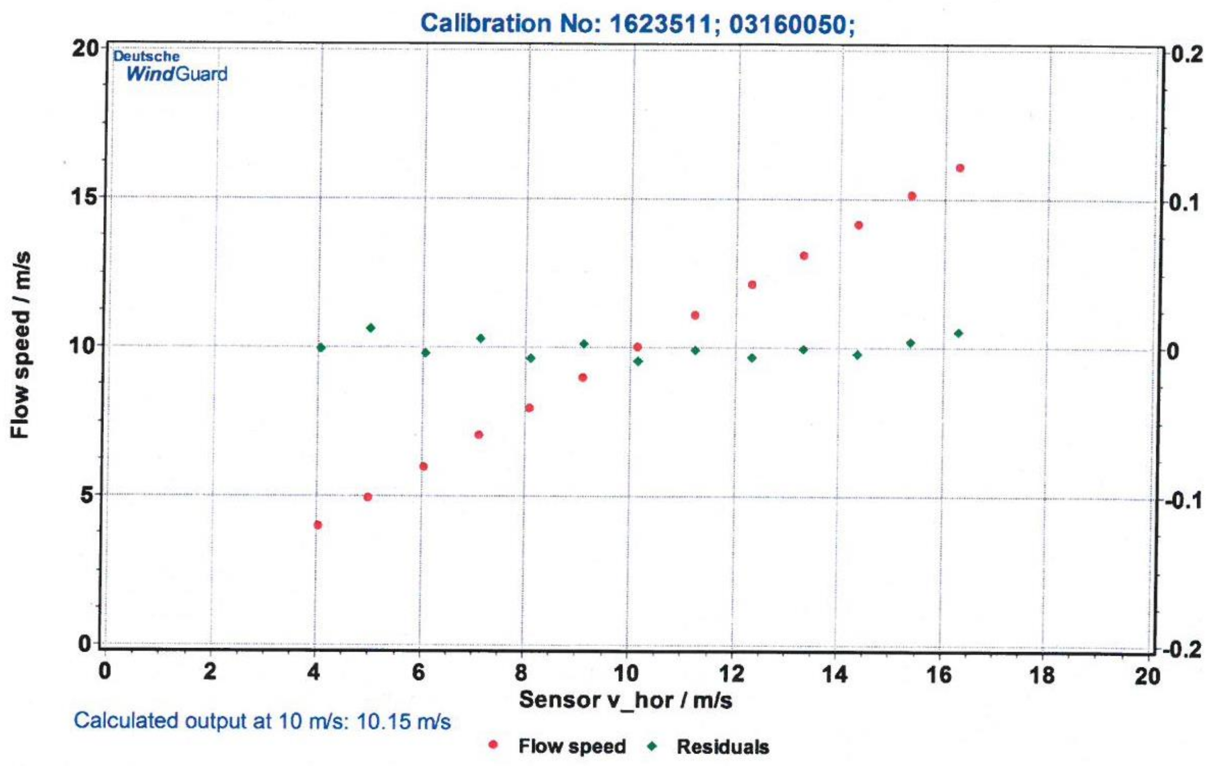


Photo of the measurement setup

Sensor configuration during calibration

!00AA00003	!00GU00000	!00WM00000
!00AB00003	!00HC00017	!00WN00002
!00AC00003	!00HL00275	!00XI00000
!00AG00000	!00HH00280	!000UT\02@12,08,03,00,00,00@, @13,08,03,00,00,0
!00AM00002	!00HT00001	
!00AN00000	!00ID00000	
!00AR00060	!00MA00013	
!00AU00050	!00MD00005	
!00AV00001	!00NC00000	
!00AY00000	!00OR00100	
!00AZ00000	!00OS00000	
!00BL00308	!00PC00007	
!00BH00000	!00PR00050	
!00BP00100	!00PT00048	
!00BR00007	!00RC00536	
!00BS00100	!00RD00005	
!00BT00000	!00RF00120	
!00BX00007	!00SC00000	
!00BY00000	!00SH00316	
!00BZ00000	!00SL00050	
!00CA59907	!00SM00000	
!00CB01000	!00SV00312	
!00CI00000	!00TA508052	
!00CO00000	!00TB00002	
!00CY00000	!00TC00001	
!00CZ00000	!00TF00001	
!00DE00000	!00TT00000	
!00DM00000	!00UM00000	
!00DU19818	!00UN00002	
!00DV19878	!00VC01088	
!00DW19859	!00VM00000	
!00EI00000	!00VN00001	
!00FB00000	!00VT00001	

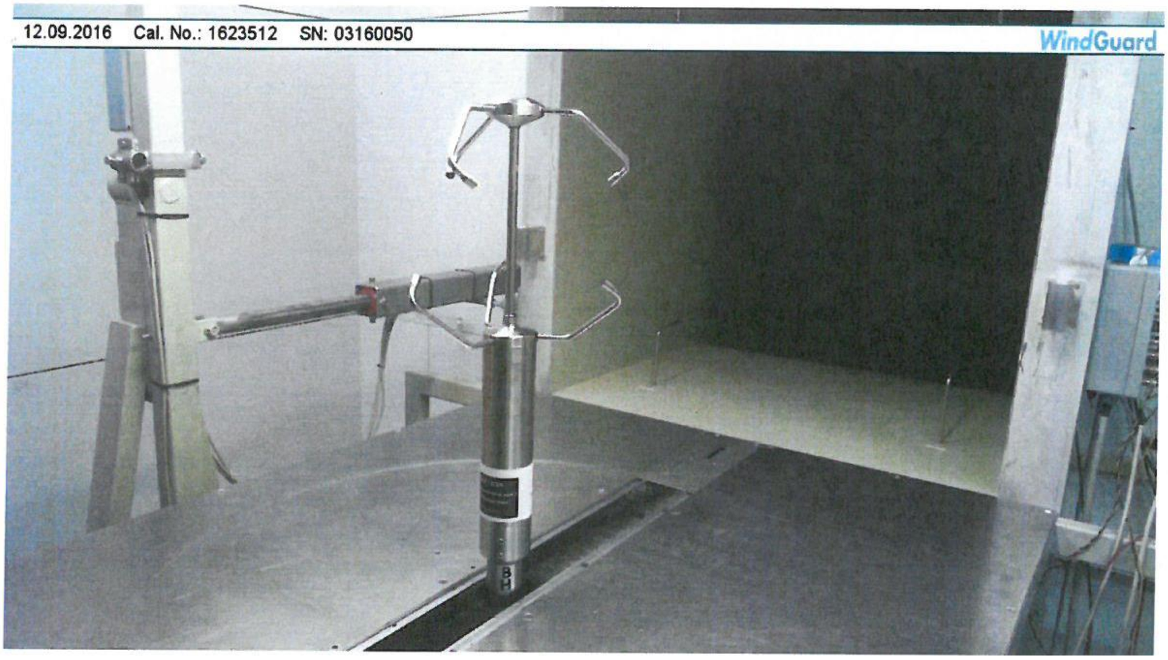
b) Calibration mark: 1623512/D-K-15140-01-00/09-2016

Calibration Object	3D Sonic Anemometer
Manufacturer	Thies Clima D-37083 Göttingen
Type	4.3830.22.503
Serial number	03160050
Customer	Ammonit Measurement GmbH D-10997 Berlin
Order No.	L 24151
Project No	VT160883
Date of Calibration	12.09.2016
Calibration procedure	• Deutsche WindGuard Wind Tunnel Services: QM-KL-OAK-VA • Based on following standards: • IEC 61400-12-1: Power performance measurements of electricity producing wind turbines • ASTM D 5096-2: Determining the Performance of a Cup Anemometer or Propeller Anemometer • ISO 16622: Meteorology – Sonic anemometers/thermometers
Place of calibration	Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel
Test conditions	Wind tunnel area: 10000 cm^2 Anemometer frontal area: 270 cm^2 Diameter of mounting pipe: 48 mm Blockage ration[1]: 0.027 [-] Software version: 7.64 [1] Due to the special construction of the test section no blockage correction is necessary
Ambient conditions	Air temperature: 23.5 ºC ± 0.1 ºC Air pressure: 1017.5 hPa ± 0.3 hPa Relative humidity: 64.6% ± 2.0%
Measurement uncertainty	The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%. The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische-Bundesanstalt) standard for flow speed. It is realised by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2%, k=2)
Additional remarks	Orientation: 0º

Calibration Result

Bin	Tilt angle (deg)	Sensor v_hor (m/s)	Sensor dir (deg)	Sensor v_vert (m/s)	Flow speed (m/s)
1	-30.02	6.822	357.130	-3.878	7.893
2	-28.01	6.978	357.239	-3.623	7.894
3	-26.03	7.096	357.170	-3.397	7.894
4	-24.00	7.214	357.353	-3.141	7.893
5	-22.00	7.311	357.422	-2.893	7.893
6	-20.00	7.410	357.423	-2.636	7.893
7	-18.00	7.501	357.421	-2.370	7.892
8	-16.00	7.594	357.206	-2.091	7.892
9	-14.00	7.681	357.139	-1.821	7.895
10	-12.01	7.762	357.138	-1.551	7.895
11	-10.01	7.833	357.138	-1.277	7.897
12	-8.01	7.890	357.138	-1.003	7.895
13	-6.00	7.937	357.138	-0.730	7.896
14	-4.25	7.973	357.184	-0.492	7.897
15	-2.99	7.992	357.388	-0.323	7.895
16	-2.00	8.006	357.400	-0.190	7.898
17	-1.00	8.019	357.420	-0.055	7.898
18	-0.01	8.026	357.383	0.076	7.898
19	0.99	8.031	357.399	0.214	7.899
20	2.00	8.035	357.406	0.357	7.900
21	3.00	8.035	357.419	0.494	7.897
22	4.25	8.031	357.422	0.673	7.900
23	6.01	8.021	357.423	0.923	7.903
24	8.00	7.996	357.423	1.197	7.903
25	10.00	7.963	357.427	1.472	7.907
26	11.99	7.923	357.514	1.767	7.909
27	13.99	7.840	357.659	2.073	7.910
28	15.99	7.696	357.710	2.360	7.907
29	18.00	7.584	357.792	2.625	7.906
30	19.99	7.496	357.921	2.876	7.904
31	22.00	7.393	357.984	3.126	7.902
32	23.99	7.297	357.978	3.359	7.900
33	26.00	7.187	358.029	3.610	7.901
34	27.99	7.084	357.996	3.836	7.899
35	30.05	6.961	358.045	4.071	7.897

Photo of the measurement setup



Sensor configuration during calibration

!00AA00003	!00GU00000	!00WM00000
!00AB00003	!00HC00017	!00WN00002
!00AC00003	!00HL00275	!00XI00000
!00AG00000	!00HH00280	!000UT\02@12,08,03,00,00,00@, @13,08,03,00,00,0
!00AM00002	!00HT00001	
!00AN00000	!00ID00000	
!00AR00060	!00MA00013	
!00AU00050	!00MD00005	
!00AV00001	!00NC00000	
!00AY00000	!00OR00100	
!00AZ00000	!00OS00000	
!00BL00308	!00PC00007	
!00BH00000	!00PR00050	
!00BP00100	!00PT00048	
!00BR00007	!00RC00536	
!00BS00100	!00RD00005	
!00BT00000	!00RF00120	

Sensor configuration during calibration (cont'd)

!00BX00007	!00SC00000
!00BY00000	!00SH00316
!00BZ00000	!00SL00050
!00CA59907	!00SM00000
!00CB01000	!00SV00312
!00CI00000	!00TA508052
!00CO00000	!00TB00002
!00CY00000	!00TC00001
!00CZ00000	!00TF00001
!00DE00000	!00TT00000
!00DM00000	!00UM00000
!00DU19818	!00UN00002
!00DV19878	!00VC01088
!00DW19859	!00VM00000
!00EI00000	!00VN00001
!00FB00000	!00VT00001

c) Calibration mark: 1623513/D-K-15140-01-00/09-2016

Calibration Object	3D Sonic Anemometer
Manufacturer	Thies Clima D-37083 Göttingen
Type	4.3830.22.503
Serial number	03160050
Customer	Ammonit Measurement GmbH D-10997 Berlin
Order No.	L 24151
Project No	VT160883
Date of Calibration	12.09.2016

Calibration procedure	• Deutsche WindGuard Wind Tunnel Services: QM-KL-WRK-VA Based on following standards: • IEC 61400-12-1: Power performance measurements of electricity producing wind turbines • IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 16622: Meteorology – Sonic anemometers/thermometers • ASTM D 5366-96: Standard Test Method of Measuring the Dynamic Performance of Wind Vanes
Place of calibration	Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel
Test conditions	Wind tunnel area: 10000 cm^2 Anemometer frontal area: 270 cm^2 Diameter of mounting pipe: 48 mm Blockage ration[1]: 0.027 [-] Software version: 7.64 [1] Due to the special construction of the test section no blockage correction is necessary
Ambient conditions	Air temperature: 23.7 °C ± 0.1 °C Air pressure: 1017.4 hPa ± 0.3 hPa Relative humidity: 64.6% ± 2.0%
Measurement uncertainty	The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%. The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische-Bundesanstalt) standard for flow speed. It is realised by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2%, k=2)
Additional remarks	-

Calibration Result

Bin	Flow dir (deg)	Sensor dir (deg)	Sensor v_hor (m/s)	Sensor v_vert (m/s)	Unc (deg)	Flow speed (m/s)
1	5.05	1.905	8.085	0.070	0.8	7.953
2	10.08	7.063	8.088	0.061	0.8	7.952
3	15.07	11.924	8.091	0.068	0.8	7.954
4	20.09	16.713	8.070	0.059	0.8	7.951
5	25.09	21.593	8.096	0.050	0.8	7.952
6	30.09	26.222	8.114	0.011	0.8	7.951
7	35.02	31.219	8.086	0.049	0.8	7.950
8	40.04	36.361	8.053	0.087	0.8	7.952
9	45.05	41.597	8.026	0.116	0.8	7.952
10	50.08	46.906	8.005	0.125	0.8	7.950
11	55.07	52.176	7.987	0.123	0.8	7.950
12	60.02	57.479	7.974	0.124	0.8	7.949
13	64.59	62.066	7.974	0.100	0.8	7.951
14	69.97	67.372	7.971	0.059	0.8	7.949
15	74.96	72.184	7.968	0.015	0.8	7.946
16	80.02	77.778	7.988	0.049	0.8	7.949
17	84.99	82.803	8.002	0.044	0.8	7.952
18	89.99	87.770	8.023	0.046	0.8	7.954
19	94.95	92.487	8.036	0.057	0.8	7.953
20	99.96	97.518	8.054	0.071	0.8	7.948
21	105.00	102.334	8.039	0.073	0.8	7.951
22	110.04	107.093	8.049	0.035	0.8	7.953
23	115.06	112.081	8.051	0.015	0.8	7.951
24	119.99	116.926	8.063	0.019	0.8	7.948
25	125.00	121.859	8.071	0.025	0.8	7.948
26	130.03	126.971	8.076	0.024	0.8	7.951
27	135.00	131.834	8.074	0.034	0.8	7.954
28	140.02	136.639	8.048	0.023	0.8	7.950
29	145.00	141.600	8.069	0.023	0.8	7.944
30	150.05	146.336	8.092	-0.007	0.8	7.953
31	155.04	151.316	8.069	0.022	0.8	7.953
32	160.06	156.628	8.031	0.081	0.8	7.950
33	165.03	161.696	8.010	0.088	0.8	7.950
34	170.05	166.879	7.995	0.094	0.8	7.952
35	175.08	172.172	7.977	0.104	0.8	7.951

Bin	Flow dir (deg)	Sensor dir (deg)	Sensor v_hor (m/s)	Sensor v_vert (m/s)	Unc (deg)	Flow speed (m/s)
36	180.04	177.412	7.968	0.104	0.8	7.952
37	185.05	182.346	7.966	0.099	0.8	7.947
38	190.04	187.057	7.974	0.060	0.8	7.954
39	195.06	192.166	7.976	0.045	0.8	7.947
40	200.09	197.263	7.985	0.035	0.8	7.949
41	205.07	202.380	8.008	0.043	0.8	7.952
`42	210.03	207.407	8.033	0.060	0.8	7.954
43	214.91	212.227	8.048	0.071	0.8	7.952
44	219.94	217.186	8.065	0.086	0.8	7.953
45	225.01	222.343	8.055	0.103	0.8	7.951
46	229.93	227.208	8.071	0.072	0.8	7.957
47	234.94	232.134	8.077	0.056	0.8	7.953
48	239.96	236.983	8.092	0.056	0.8	7.953
49	244.98	241.938	8.095	0.067	0.8	7.953
50	249.99	247.000	8.093	0.065	0.8	7.954
51	254.95	251.841	8.095	0.072	0.8	7.956
52	259.96	256.678	8.059	0.068	0.8	7.953
53	264.99	261.403	8.092	0.044	0.8	7.950
54	269.89	266.241	8.097	0.037	0.8	7.951
55	274.94	271.083	8.077	0.077	0.8	7.955
56	279.93	275.972	8.043	0.093	0.8	7.951
57	284.94	281.399	8.003	0.143	0.8	7.950
58	289.94	286.564	7.986	0.146	0.8	7.949
59	294.96	291.860	7.964	0.153	0.8	7.948
60	300.00	297.248	7.956	0.159	0.8	7.950
61	304.96	302.167	7.956	0.129	0.8	7.950
62	309.97	307.178	7.962	0.102	0.8	7.950
63	314.94	312.096	7.965	0.059	0.8	7.953
64	320.00	317.240	7.962	0.031	0.8	7.950
65	325.02	322.536	7.983	0.041	0.8	7.953
66	330.00	327.801	8.023	0.078	0.8	7.957
67	334.99	332.763	8.038	0.099	0.8	7.947
68	339.95	337.705	8.063	0.112	0.8	7.954
69	344.95	342.650	8.034	0.116	0.8	7.954
70	349.98	347.501	8.049	0.076	0.8	7.951
71	354.95	352.442	8.056	0.063	0.8	7.951

Statistical Analysis

Slope: 1.00095 deg/deg

Offset: -3.1432 deg

Graphical representation of the result

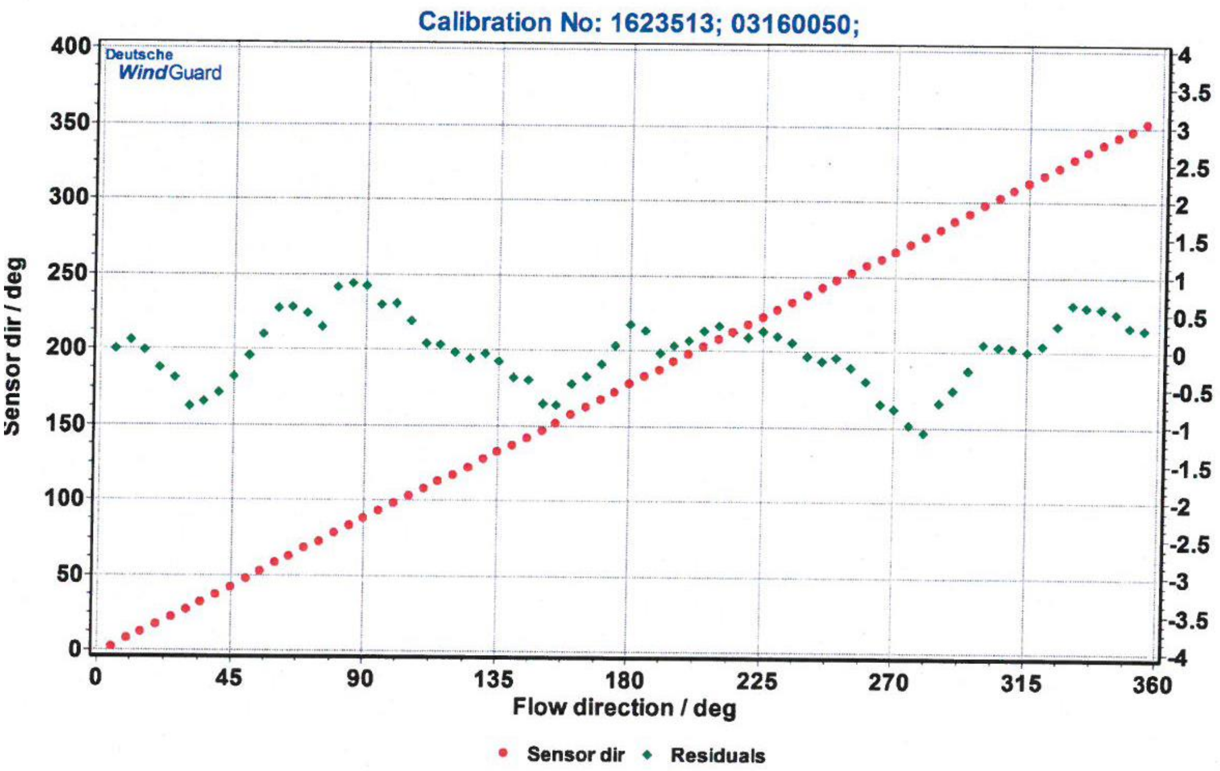
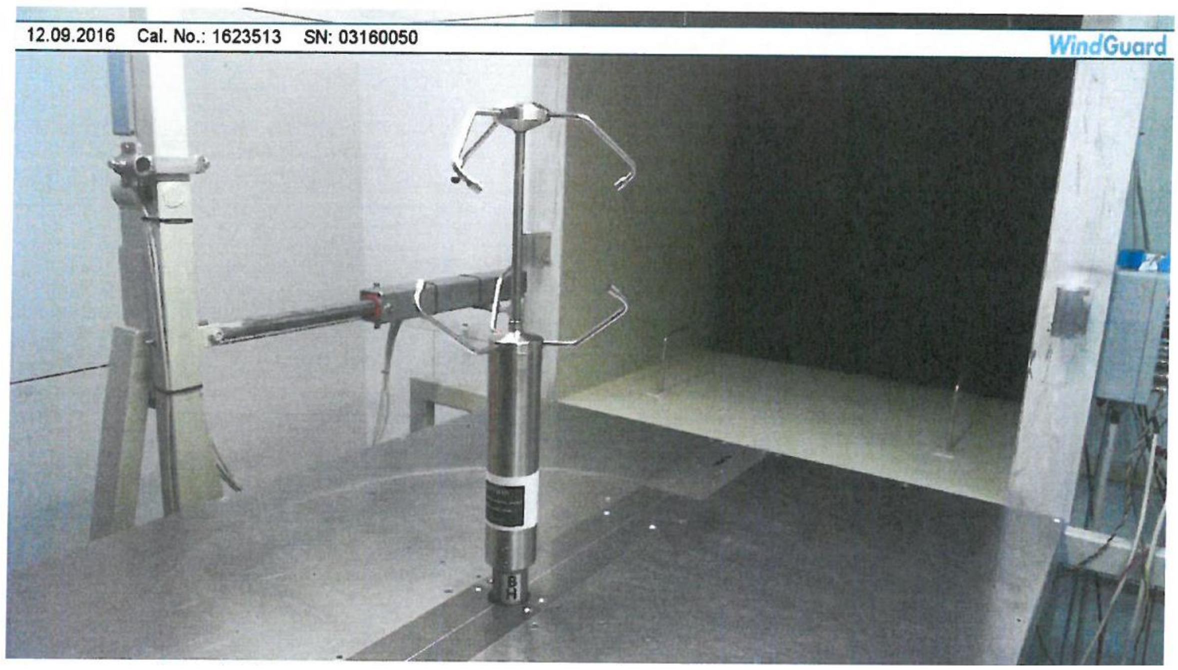


Photo of the measurement setup



Sensor configuration during calibration

!00AA00003	!00GU00000	!00WM00000
!00AB00003	!00HC00017	!00WN00002
!00AC00003	!00HL00275	!00XI00000
!00AG00000	!00HH00280	!000UT\02@12,08,03,00,00,00@, @13,08,03,00,00,0
!00AM00002	!00HT00001	
!00AN00000	!00ID00000	
!00AR00060	!00MA00013	
!00AU00050	!00MD00005	
!00AV00001	!00NC00000	
!00AY00000	!00OR00100	
!00AZ00000	!00OS00000	
!00BL00308	!00PC00007	
!00BH00000	!00PR00050	
!00BP00100	!00PT00048	
!00BR00007	!00RC00536	
!00BS00100	!00RD00005	
!00BT00000	!00RF00120	
!00BX00007	!00SC00000	
!00BY00000	!00SH00316	
!00BZ00000	!00SL00050	
!00CA59907	!00SM00000	
!00CB01000	!00SV00312	
!00CI00000	!00TA508052	
!00CO00000	!00TB00002	
!00CY00000	!00TC00001	
!00CZ00000	!00TF00001	
!00DE00000	!00TT00000	
!00DM00000	!00UM00000	
!00DU19818	!00UN00002	
!00DV19878	!00VC01088	
!00DW19859	!00VM00000	
!00EI00000	!00VN00001	
!00FB00000	!00VT00001	

Environmental Science for European Refining

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