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Wind measurement comparison of Doppler lidar with wind cup and L band sounding radar

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Abstract: Wind-profiling lidars are now regularly used in boundary-layer meteorology and in applications such as vertical wind field measurement. In order to verify the accuracy of the Doppler wind lidar, the major domestic Doppler wind lidar manufacturers were organized to compare the Minute-level average wind speed and direction data measured by the lidars to which measured by meteorological gradient tower and L band Sounding radar in Shenzhen and Zhangjiakou, respectively. The result of comparison with the wind cup on the meteorological gradient tower is in good agreement, the correlation coefficient of wind speed is close to or higher than 90%, and the maximum standard deviation of the wind direction is about 7 ° except the inflection point. When the L-band sounding radar is used as a reference for the lidar equipment which joint the comparison. The system difference and standard deviation of daily wind speed and direction vary greatly, and the reliability is poor. At the same time, it was founded that compared with the 1-minute average data, when the 10-minute average data were used for comparison, the system deviation and standard deviation were reduced. That mean the results were more stable and reliable. The comparison results show that the technical indicators of several domestic lidar equipment are equivalent to windcube indicators made by Vaisala and complying with the World Meteorological Organization's requirements for the Coherent Doppler Lidar indicator for near-term weather forecasts. It shows the lidars are reliable to obtain wind speed and direction parameters at different altitudes in real time.

Keywords: Lidar, Wind direction, Wind speed, Detection, Comparison, Reliability

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Introduction

Considering the poor structural stability, high cost of construction and site constraints, the traditional wind tower can just detect the wind field in low height and has limited detection range (Matthew et al., 2020). Although the observation height of some modern wind measuring equipment such as Doppler wind profiler is up to 8 km, it has limitations in practical application due to its low near-ground resolution. Doppler lidar (hereinafter referred to as "lidar") can obtain three-dimensional wind field information in clear and dry atmosphere with high time and space resolution. Its detection accuracy is high and can be used to continuously observe at different altitudes. At present, it has become one of the most effective means to measure the atmospheric wind field as well as a wide range of applications in environmental protection, aerospace flight support, wind power and national defense (Antuñano et al., 2017).

As a new technology, the reliability of lidar wind measurement should be verified by a series of comparative tests before it been used. In recent years, various experts have carried out a series of correlation comparison work in different places using wind lidar. E.Päschke et al compared wind lidar measurements with independent reference data from a collocated operational radar wind profiler running in a four-beam Doppler beam swinging mode and winds from operational radiosonde measurements. The intercomparing results reveal a particularly good agreement between the Doppler lidar and the radar wind profiler, with root mean square errors ranging between 0.5 and 0.7 m/s^{-1} for wind speed and between 5 and 10° for wind direction. The median of the half-hourly averaged wind speed for the intercomparing data set is 8.2 m/ s^{-1}, with a lower quartile of 5.4 m/ s^{-1} and an upper quartile of 11.6 m/s^{-1}(Päschke et al., 2015). To verify their detection performance, the synchronous observation data of three-type wind lidars were analyzed at Hangzhou National Reference Climate Station by using the data of sounding observation and L-band stationary wind profiler as the reference (Qin et al., 2019). Two types of uncertainties in this process are investigated and confirmed in simulation by David Schlipf et al. They found the uncertainty caused by model errors for the longitudinal wind is larger than the uncertainty caused by measurement errors and show an approach how to model uncertainties in wind field reconstruction (David et al., 2020). To quantify the errors of Wind-profiling lidars expected from violation horizontal homogeneity, J. K. Lundquist et al simulated inhomogeneous flow in the atmospheric boundary layer, notably stably stratified flow past a wind turbine, with a mean wind speed of 6.5 m s^{-1} at the turbine hub-height of 80 m. By three rotor

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diameters downwind, DBS-based assessments of wake wind speed deficits based on the stream-wise velocity can be relied on even within the near wake within 1.0 m s^{-1}, and the cross-stream velocity error is reduced to 8% while vertical velocity estimates are compromised (Lundquist et al.,2015).

In order to test the wind measurement accuracy of Doppler wind lidar and ensure its practicability and reliability, several domestic manufacturers were organized to carry out wind comparative observation by Doppler wind lidar equipment in the observation field of Shenzhen National Climate Observatory and Zhangjiakou Meteorological Bureau of Hebei Province during November 2019 to January 2020. The experiment will use the data of the wind cup on the national climate observation typhoon tower in Shenzhen and the data of L-band radiosonde radar of Zhangjiakou Meteorological Bureau as the standard.

1 Comparison methods

1.1 Principle of wind measurement by Doppler lidar

The laser beam emitted from lidar is scattered by aerosol particles and atmospheric molecules in the atmosphere, and the backscattered light returns to the lidar receiving telescope along the emission direction (Augere et al., 2019). The relative direction (wind direction) of atmospheric molecular motion can be calculated by using four beam scanning synthesis. Due to the action of wind or the movement of atmospheric particles, it will cause to Doppler frequency shift which relative to the radial wind speed between received optical signal and emitted laser. The relationship between the Doppler frequency shift and the radial wind speed can be calculated as follows:

$$v_r = {}^{\lambda}/_{2} \times \Delta_v \qquad (1)$$

Where v_r is the radial wind speed, λ is the laser wavelength, and Δv is the Doppler frequency shift which can be measured by frequency meter (Baron et al., 2017).

1.2 Placement of comparison equipment

At the Shenzhen National Climate Observatory, the wind lidar and the weather gradient tower should be placed adjacent to each other in the same atmospheric environment, and should not be affected by turbulence or other obstacles in their measurement range. In Zhangjiakou Meteorological Bureau, the distance between the wind lidar and the L-band sounding radar deployment is greater than 50 m but less than 200 m. The ground altitude difference is less than 1 m to ensure that there are no large vegetation and obstacles around.

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1.3 Data Acquisition

When compared with the Shenzhen Meteorological Gradient Tower, the data during the period due to the influence of the weather gradient tower and the wind cup failure of the Lidar and Meteorological Gradient Tower were excluded, and the minute level (1 minute, 1 minute, 2 minutes and 10 minutes) wind speed and wind direction average data, and save the second interval data participating in the average. At Zhangjiakou Meteorological Bureau, the gross errors caused by various reasons are also eliminated, the 1-minute data of the lidar is obtained for comparison with the second-level data of the L-band sounding radar, and the average second interval data is saved

1.4 Data Comparison Method

After obtaining the wind field data of the corresponding altitude in the same period, the system deviations and standard deviations of the compared wind lidar data and the meteorological gradient tower or L-band detection radar results are calculated according to the following formula (2) and formula (3):

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (2) \qquad\qquad s = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \qquad (3)$$

The correlation coefficient between the measured wind data of the lidar and the true value (weather gradient tower wind cup or L-band sounding radar data) is calculated by formula (4):

$$\gamma_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i-1}^{n}(x_i-\bar{x})^2 \times \sum_{i-1}^{n}(y_i-\bar{y})^2}} \qquad (4)$$

where x_i represents the wind speed and direction data measured by the wind lidar, $\overline{x}$ is the average value; y_i represents the wind speed and direction data obtained by the meteorological gradient tower wind cup or L-band sounding radar, $\bar{y}$ is their average value, and n is the number of comparison data.

2 Comparison and analysis of meteorological gradient tower data

The Doppler wind measurement lidar equipment produced by domestic manufacturers and Finland VAISALA has carried out wind speed comparison observation tests in two batches at the Shenzhen National Climate Observatory. Each lidar can leave the field after 15 days of comparison. After converting the detection height of the wind cup data and the lidar data of the meteorological gradient tower to the same coordinate system (such as the station center coordinate height or altitude), select the meteorological gradient tower data and the lidar data to have the same

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detection height value as a comparable comparison Detection height. Calculate the system deviation, standard deviation and correlation coefficient according to the aforementioned method, and draw the average wind speed, wind direction time series graph and scatter plot of each layer of meteorological gradient tower and lidar participating in the comparison.

2.1 Wind speed comparison results

Figures 1 to 4 below are the minute-level (1 minute and 10 minutes) average wind speed scatter plots of individual manufacturers' lidars and weather gradient towers at four levels. The horizontal axis is the minute-level average wind speed of each lidar.

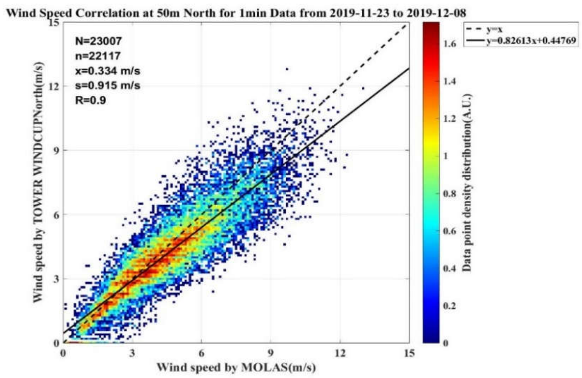

Fig.1 Average wind speed at 50 meters height in 1 minutes

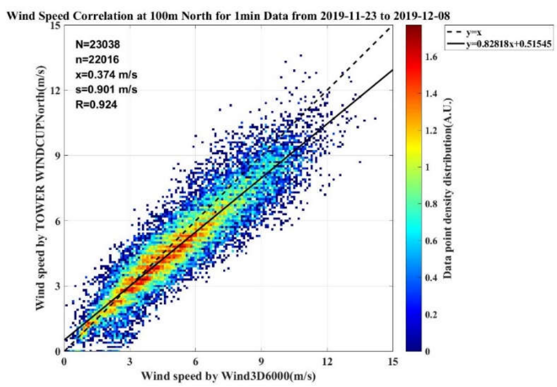

Fig.2 Average wind speed at 100 meters height in 1 minutes

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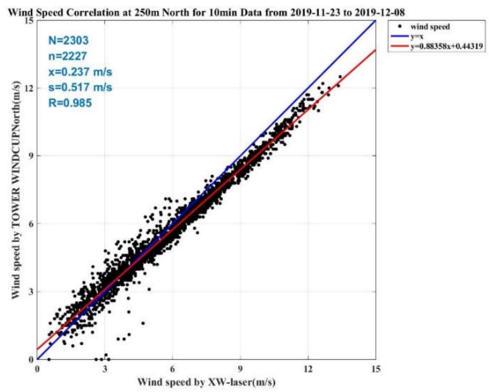

Fig.3 Average wind speed at 250 meters in 10 minutes

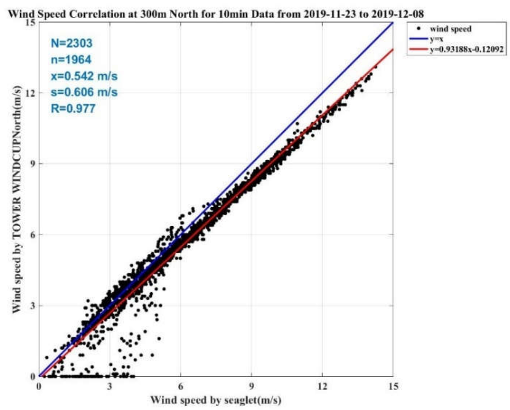

Fig.4 Average wind speed at 300 meters in 10 minutes

The vertical axis represents the wind speed measured by the wind cup at the corresponding height of the meteorological gradient tower. The solid lines in Figures 1 and 2 and the red lines in Figures 3 and 4 are the fitting straight lines between the average wind speed of the lidar and the wind speed measured by the meteorological gradient tower wind cup, which is given by formula (5):

$$y = a + bx \qquad (5)$$

Among them, the slope b and intercept a is calculated by formula (6) and (7) respectively:

$$b = \frac{\sum_{j=1,i=1}^{m,n}(x_{j,i}-\bar{x})(y_{j,i}-\bar{y})}{\sum_{j=1,i=1}^{m,n}(x_{j,i}-\bar{x})^2} \qquad (6)$$

$$a = \bar{y} - b\bar{x} \qquad (7)$$

Where: $x_{j,i}$ is the i-th measured result of the compared lidar at the j-th tested wind

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speed point; $y_{j,i}$ represent the i-th data measured by wind cup in meteorological gradient tower at the j-th tested wind speed point ; $\bar{y}$ is the average value of the four levels of the meteorological gradient tower; $\bar{x}$ means the average value of the lidar measurement results at all levels in a certain period of time; m and n are the number of test point and the number of measure data at each test point.

One minute and ten minutes average wind speed of certain domestic lidars and Finnish Vaisala Windcube lidars at four altitudes of 50 m, 100 m, 250 m, and 300 m respectively were compared to which measured by wind cup in meteorological gradient. Table 1 below selects correlation coefficient, system deviation and standard deviation. Meanwhile, the combined standard deviation and system deviation at the 4 levels were calculated at the same time.

Table 1 The comparison results of minute-level wind speed data at each altitude

Altitude		50m		100m		250m		300m		Combined result	
Lidar Number		1 min	10 min	1 min	10 min	1 min	10 min	1 min	10 min	1 min	10 min
1	Correlation coefficient	0.9	0.98	0.93	0.99	0.95	0.99	0.95	0.99		
	System deviation	0.334	0.286	0.335	0.282	0.497	0.431	0.517	0.441	0.4207	0.36
	Standard deviation	0.915	0.405	0.85	0.395	0.845	0.491	0.914	0.484	0.881	0.45
2	Correlation coefficient	0.897	0.984	0.924	0.988	0.952	0.993	0.946	0.981		
	System deviation	0.347	0.298	0.374	0.32	0.488	0.421	0.513	0.46	0.431	0.374
	Standard deviation	0.932	0.414	0.901	0.445	0.885	0.51	0.956	0.579	0.918	0.491
3	Correlation coefficient	0.897	0.984	0.924	0.988	0.952	0.993	0.946	0.981		
	System deviation	0.347	0.298	0.374	0.32	0.488	0.421	0.513	0.46	0.431	0.374
	Standard deviation	0.932	0.414	0.901	0.445	0.885	0.51	0.956	0.579	0.918	0.491
4	Correlation coefficient	0.892	0.984	0.921	0.937	0.949	0.868	0.944	0.885		
	System deviation	0.335	0.282	0.357	-0.235	0.549	-0.249	0.579	-0.299	0.455	-0.241
	Standard deviation	0.907	0.4	0.871	0.555	0.874	0.953	0.951	0.932	0.901	0.759

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Vaisala Windcube	Correlation coefficient	0.884	0.96	0.898	0.958	0.914	0.959				
	System deviation	-0.075	-0.136	-0.012	-0.084	0.054	-0.004			-0.00825	-0.056
	Standard deviation	0.725	0.397	0.743	0.451	0.797	0.532			0.654	0.401

It can be seen from the above table that the correlation coefficient of the measured wind speed between wind lidars and wind cup is near to 90% which means is well consistent. In terms of accuracy, the standard deviation of the wind speed for one-minute average data is about 1 m/s, and the standard deviation of 10-min average data is greatly reduced to less than 0.5 m/s. The technical indicators of several domestic wind lidars are equivalent to those of Finland's Vaisala Windcube, also in line with the World Meteorological Organization's indicator requirements for coherent Doppler lidar for near-weather forecasting (Evgeniya et al., 2010).

2.2 Wind direction comparison analysis

The minute-level average wind direction of wind lidars and wind cup at the four levels are drawn. The comparison results of the average wind direction data of a certain lidar at the minute level are listed in Fig. 5 to Fig. 8 below:

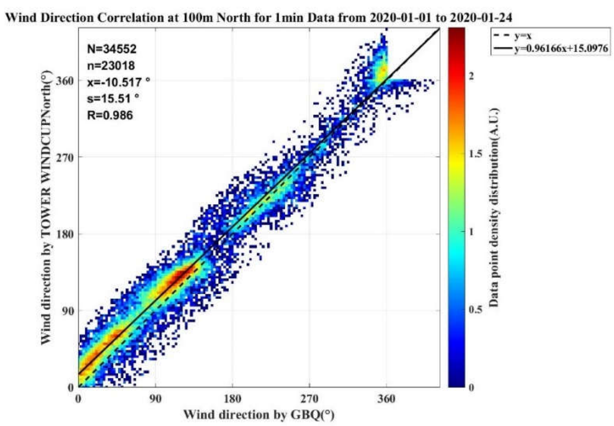

Fig.5 Average wind direction at 50 meters height in 1 minutes

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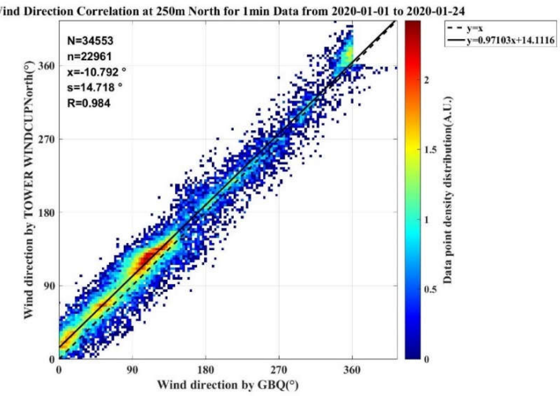

Fig.6 Average wind direction at 100 meters height in 1 minutes

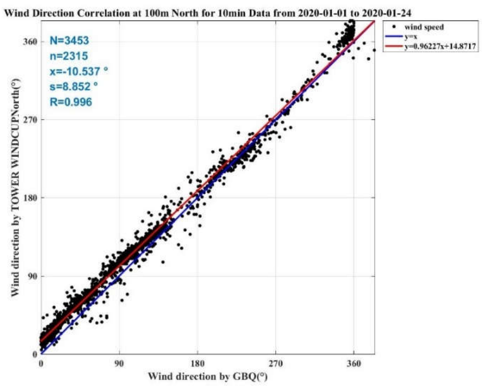

Fig.7 Average wind direction at 250 meters height in 10 minutes

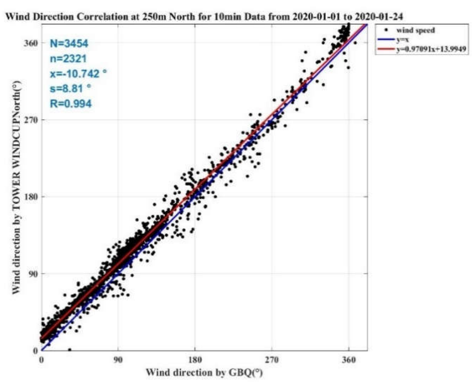

Fig.8 Average wind direction at 300 meters height in 10 minutes

where horizontal axis is the minute-level average wind speed of each lidar, and the

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vertical axis represents the wind speed measured by the wind cup at the corresponding height of the meteorological gradient tower. The minute-level average wind direction of certain domestic lidars and Finnish Vaisala Windcube lidars at four altitudes of 50 m, 100 m, 250 m, and 300 m respectively were compared to which measured by wind cup in meteorological gradient. Table 2 shows the correlation coefficient, system deviation and standard deviation as well as the combined standard deviation and system deviation at the 4 levels.

Table 2 The comparison results of minute-level wind speed data at each altitude

	Altitude	50m		100m		250m		300m		Combined result	
Lidar Number		1 min	10min	1 min	10min	1 min	10min	1 min	10min		
1	correlation coefficient	0.99	0.99	0.99	0.99	0.99	0.99	0.992	0.99		
	system deviation	-8.4	-8.2	-11.7	-11.7	-10. 3	-10.3	-7.6	-7.8	11.2	-9.8
	standard deviation	12.8	5.6	11. 5	5.3	10.6	5.7	9.7	5.77	-9.5	5.6
2	correlation coefficient	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99		
	system deviation	-11.0	-11.0	-15.21	-15.2	-13.4	-13.5	-10.6	-10.6	-12.58	-12.6
	standard deviation	13.4	5.9	12.6	5.7	11.4	6.1	10.6	6.1	11.9	5.9
3	correlation coefficient	0.99	0.99	0.99	0.99	0.988	0.99	0.989	0.99		
	system deviation	-8.4	-8.3	-12.7	-12.6	-11.607	-11.6	-8.99	-8.7	-10.4	-10.3
	standard deviation	13.9	7.4	12.2	6.5	11.552	6.7	10.81	6.8	12.1	6. 9
4	correlation coefficient	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.99		
	system deviation	-11.1	-11.1	-14.6	-14.6	-14.1	-14.3	-10.93	-10.9	-12.6	-12.7
	standard deviation	14.2	6. 1	13. 1	6.11	13.59	8. 1	12.7	7.88	13.4	7.08
5	correlation coefficient	0.95	0.96	0.94	0.95	0.91	0.92	0.91	0.91		
	system deviation	0.94	0.21	-3.2	-4.0	-2.74	-1.6	-0.27	1.03	-10.4	-1.1
	standard	34.8	25.6	32.7	25.5	34.0	29.4	33.9	30.4	12.1	27.8

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	deviation										
6	correlation coefficient	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.99		
	system deviation	-10.0	-9.95	-13.9	-13.9	-12.3	-12.5	-9.82	-9.68	-11.0	-11.5
	standard deviation	13.3	5.75	12.2	5.77	11. 7	5.9	10.7	6.24	12.0	5.9
7	correlation coefficient	0.98	0.99	0.98	0.99	0.98	0.99	0.98	0.99		
	system deviation	-6.56	-6.74	-10.5	-10.5	-10.8	-10.7	-5.43	-5.17	-8.32	-8.3
	standard deviation	17.2	9.22	15.5	8.85	14.72	8.81	12.9	7.08	15.2	8.5
Vaisala Windcube	correlation coefficient	0.99	0.99	0.98	0.99	0.98	0.99				
	system deviation	-4.08	-4.21	-7.99	-8.16	-7.86	-7.8			-4.98	-5.0
	standard deviation	14.7	7.41	14.7	7.78	13.1	6.9			12.3	6.4

It can be seen from Table 2 that except for one lidar, the comparison between other devices and the wind cup is relatively consistent. For the 1-minute average data, the standard deviation of wind direction is close to or less than 15°, the standard deviation of 10-minute average wind directions are basically less than 7° which lower than the 1-minute average data. The technical indicators of most domestic lidar are equivalent to those of Finnish Vaisala Windcube and in line with the World Meteorological Organization's indicator requirements for coherent Doppler lidar for near-weather forecasting.

3 L-band radiosonde radar comparison

This time, the L-band sounding radar data of Zhangjiakou Meteorological Bureau was used as the standard value which is compared to the wind data of various wind lidars. By calculating the correlation coefficient, standard deviation and system error of wind data measured from those equipments, the operation reliability of the compared lidar were analyzed.

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3.1 Analysis of comparison results

Fig. 9 to Fig.11 shows the wind data of WindMast PBL lidar and L-band sounding radar from December 8, 2019 to December 24, 2019. It can be seen intuitively from the timing diagram that the wind speed and direction measured by this type of lidar and the L-band sounding radar have good consistency.

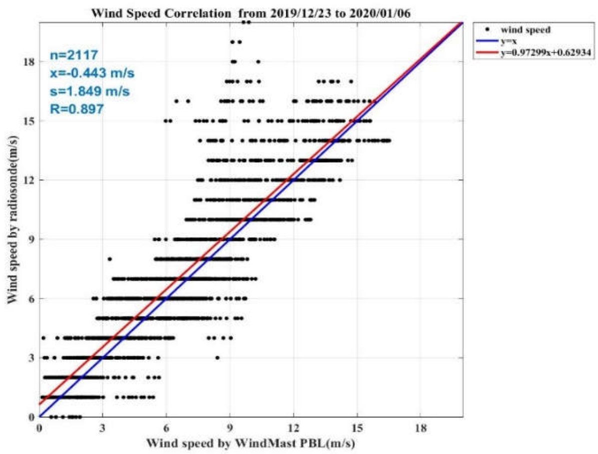

Fig.9 Wind speed

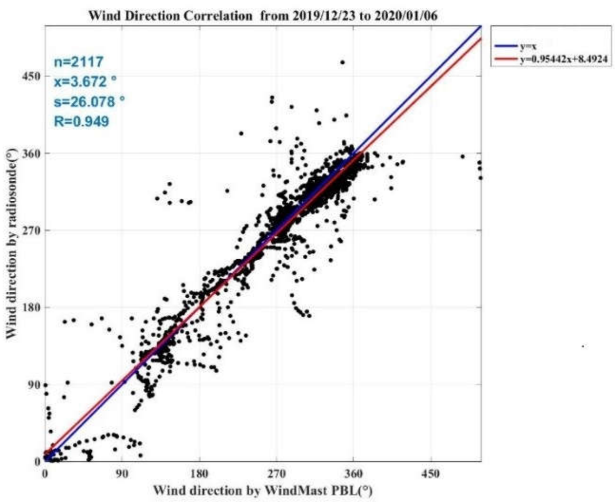

Fig.10 Wind direction

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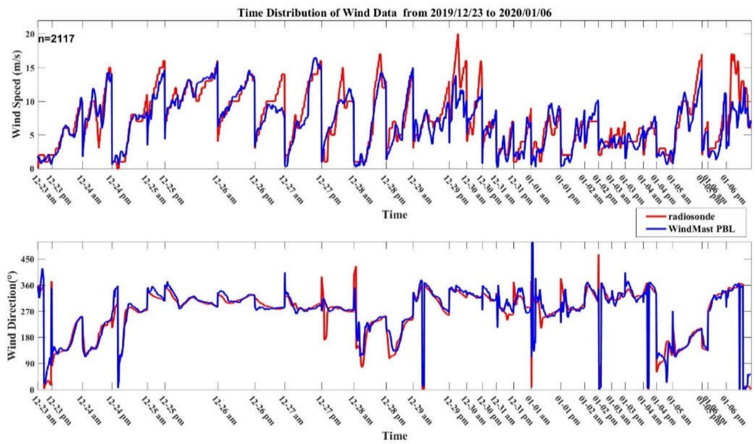

Fig.11 Comparison between WindMast PBL wind lidar and L-band sounding radar

Wind data of certain lidar were compared with L-band sounding radar. The system deviation, standard deviation and correlation coefficient were calculated and list in following table 3.

Table 3 comparison results between wind lidars to L-band sounding radar

Lidar Number	Resolution (km)	Number of valid data	Blind spot (km)	Maximum detection height (km)	Wind speed			Wind direction		
					Correlation coefficient	system deviation (m/s)	standard deviation (m/s)	Correlation coefficient	system deviation (°)	standard deviation (°)
1	0.03	469	0.06	0.75	0.273	-0.352	10.86	0.924	7.759	38.025
2	0.03	1210	0.06	2.37	0.91	-0.637	1.78	0.951	-0.525	24.933
3	0.03	348	0.03	0.36	0.896	-0.27	1.561	0.876	-2.391	50.399
4	0.03	1172	0.06	1.23	0.887	-0.899	1.832	0.945	6.311	28.72
5	0.013/0.014	2401	0.051	2.44	0.926	-0.496	1.635	0.919	2.574	28.561
6	0.014	2117	0.056	2.43	0.897	-0.443	1.849	0.949	3.672	26.078
7	0.028	2414	0.046	3.71	0.91	-0.601	2.11	0.938	7.022	24.9
8	0.028	1791	0.038	2.829	0.906	-0.755	2.205	0.933	-3.479	28.138
9	0.03	1717	0.045	3.015	0.549	-0.543	7.162	0.935	-2.234	26.004
10	0.03	177	0.05	1.67	0.89	0.231	1.494	0.843	-10.024	53.832
11	0.03	925	0.04	2.12	0.547	-0.22	6.594	0.906	1.683	33.751

12	0.029	535	0.058	0.985	0.851	-0.536	2.208	0.884	4.834	45.472

As can be seen from that table, wind speed accuracy of six doppler wind lidars which participate in the comparison are less than 2 m/s and wind direction accuracy of seven lidars are less than 30°. Through relative comparison, it is possible to see the reliability of different manufacturers' lidars relatively. However, due to the accuracy and resolution limitations of the L-band sounding radar, the relative accuracy of data obtained by using it as a standard is much lower than that obtained from wind cup in the meteorological gradient tower.

3.2 Long-term reliability analysis of L-band sounding radar

In order to verify the reliability of L-band sounding radar for long-term Lidar calibration, different types of Lidars from two manufacturers were selected to compared with L-band sounding radar by analysis the wind data of 8 o'clock every night from December 8 to December 24. The system difference and standard deviation of wind speed and direction during the comparison are shown in Figure 12 and Figure 13.

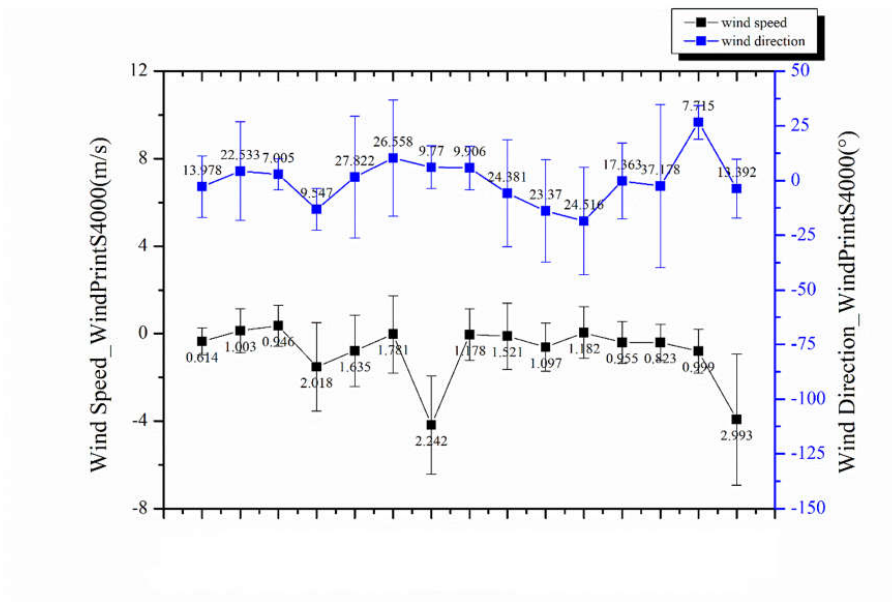

Fig.12 System deviation/standard deviation curve versus time of WindPrintS4000 wind Lidar

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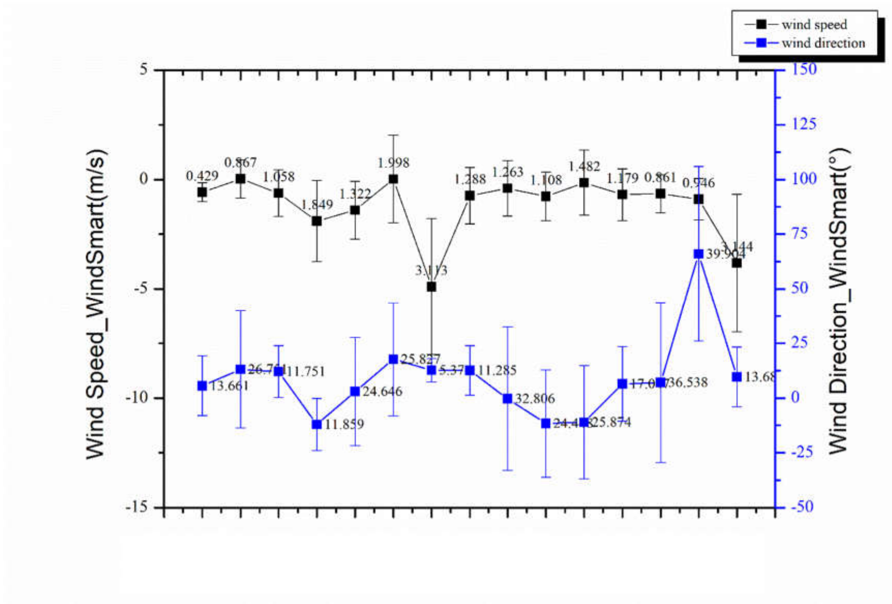

Fig.13 System deviation/standard deviation curve versus time of WindSmart wind Lidar

It can be seen from the above figures that when the L-band sounding radar is used as the standard for the joint comparison of wind lidar, the system difference as well as standard deviation of daily wind speed and wind direction vary greatly which means the result is not very reliable.

4 Conclusion

Through comparison, it is found that multiple Doppler wind lidar devices of various manufacturers are highly reliable, and they can perform unattended 7×24 hours continuous and stable operation. This work is of great significance for testing the accuracy of the Doppler wind lidar and improving the quality of the Doppler wind lidar.

Compared with the wind cup in Shenzhen Meteorological Gradient Tower, except for the large deviation of wind speed of one lidar, the wind speed comparison of other lidars and the wind cup is consistent. In terms of accuracy, the standard deviation of wind speed of 12 lidars are less than 1m/s for 1min average data, and the wind direction accuracy of 7 devices is less than 15°. For 10min average data, the standard deviation of wind speed and wind direction are obviously decline to 0.6 m/s and 7° respectively. The technical indicators of much domestic wind lidars are equivalent to those of Windcube wind lidar Produced by Vaisala factory in Finland and are in line with the

World Meteorological Organization's indicator requirements for coherent Doppler lidar for near-weather forecasting.

Among the 12 Doppler wind lidars that participated in the comparison with L-band sounding radars, wind speed accuracy of six lidars are less than 2 m/s, and seven of them have wind direction accuracy less than 30°. However, due to the accuracy and resolution limitations of the L-band sounding radar, the reliability of the data obtained by using it as a standard is seems to much lower than that of the wind cup in meteorological gradient tower.

Data availability. Relevant data can be obtained at https://pan.baidu.com/s/1VH12PQVfvJHrrnmqfbKVQw with extraction code ai3g or on request via email zhou_zizhong@sina.com directly.

Author contributions. ZZ processed the data, drew pictures and wrote the manuscript. ZB organized the comparison and review the manuscript.

Competing interests. The authors declare that there is no conflict of interest.

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