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Title: Evaluation of Tower Shadowing on Anemometer Measurements at Los Alamos National Laboratory

Author(s): Bruggeman, David Alan

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Evaluation of Tower Shadowing on Anemometer Measurements at Los Alamos National Laboratory

Los Alamos
NATIONAL LABORATORY
EST. 1943

Author: David Bruggeman, EPC-CP

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ACRONYMS AND ABBREVIATIONS

AGL	Above ground level
ANS	American National Standard
ANSI	American National Standards Institute
KLAM	Los Alamos County Airport
LANL	Los Alamos National Laboratory
TA	Technical Area

1.0 INTRODUCTION

Wind velocity is measured using various types of anemometers including cup, propeller, and sonic anemometers. For operational applications, anemometers are commonly mounted on top of a meteorology tower or mounted at multiple heights on an instrument boom that is attached to a tower. Meteorology towers are typically an open-lattice or cylindrical structure. Lattice towers allow wind to flow through compared with cylindrical towers that force air around the structure. In-situ wind measurements can be precise if the instruments or structures supporting the instruments do not distort the wind field. Wind tunnel and field studies concluded similar flow characteristics introduced by a meteorology tower; wind speed decreases upwind of the tower, increases around the tower, and decreases downwind in the wake of the tower (e.g., Dabberdt 1968; Lubitz 2009; Fabre et al. 2014). The under prediction of local wind speeds in the wake of the tower is known as tower shadowing. An anemometer mounted on top of a tower is ideal to avoid tower shadowing since the tower structure would not be upwind in any direction. However, anemometers mounted at multiple levels can be significantly affected by the wake of a tower.

Several studies analyzed tower shadowing from lattice towers. Cermak and Horn (1968) used a wind tunnel to determine wind speeds decreased in the wake of the tower up to 37% within a 30° sector, measured at a distance of two tower diameters away from the tower. At Brookhaven National Laboratory, wind speeds measured in the wake of the tower at less than a tower diameter from the tower decreased up to 35% across a 60° sector (Dabberdt 1968). Barthlott and Fiedler (2002) concluded a mean decrease of 19% and a maximum decrease of 36% over a 40° sector measured at 2.6 tower diameters.

The measurement error introduced by tower shadowing can be reduced by the orientation of the instrument boom and extending the anemometer horizontally further from the tower. ANSI/ANS-3.11-2015 recommends wind sensors should be oriented toward the prevailing wind direction and mounted at a distance at least twice the width of a tower. Vegetation, buildings, or other obstructions can also interfere with wind measurements. It is suggested the anemometer and obstruction should be separated by at least 10 times the obstruction height, and the obstructions should not exceed one-half the height of the wind measurement (ANSI 2010). Vegetation across Los Alamos National Laboratory (LANL), including juniper, piñon-juniper, and ponderosa pine, that does not meet the ANSI/ANS-3.11-2015 standard is trimmed or removed.

The objective of this study is to evaluate the effect of tower shadowing from the meteorology towers at LANL during 2014. This study is in response to the Department of Energy Meteorological Coordinating Council visit in 2015 that recommended an evaluation of any biases in the wind data introduced by the tower and boom alignment at all meteorology towers.

2.0 BACKGROUND

2.1 Site Description

Los Alamos is located in north-central New Mexico. LANL is situated on the Pajarito Plateau, which includes complex terrain and several east-to-west oriented canyons. There are five meteorology observation towers, four across the Pajarito Plateau and one in Mortandad Canyon, to observe the local meteorology across LANL (Fig. 1).

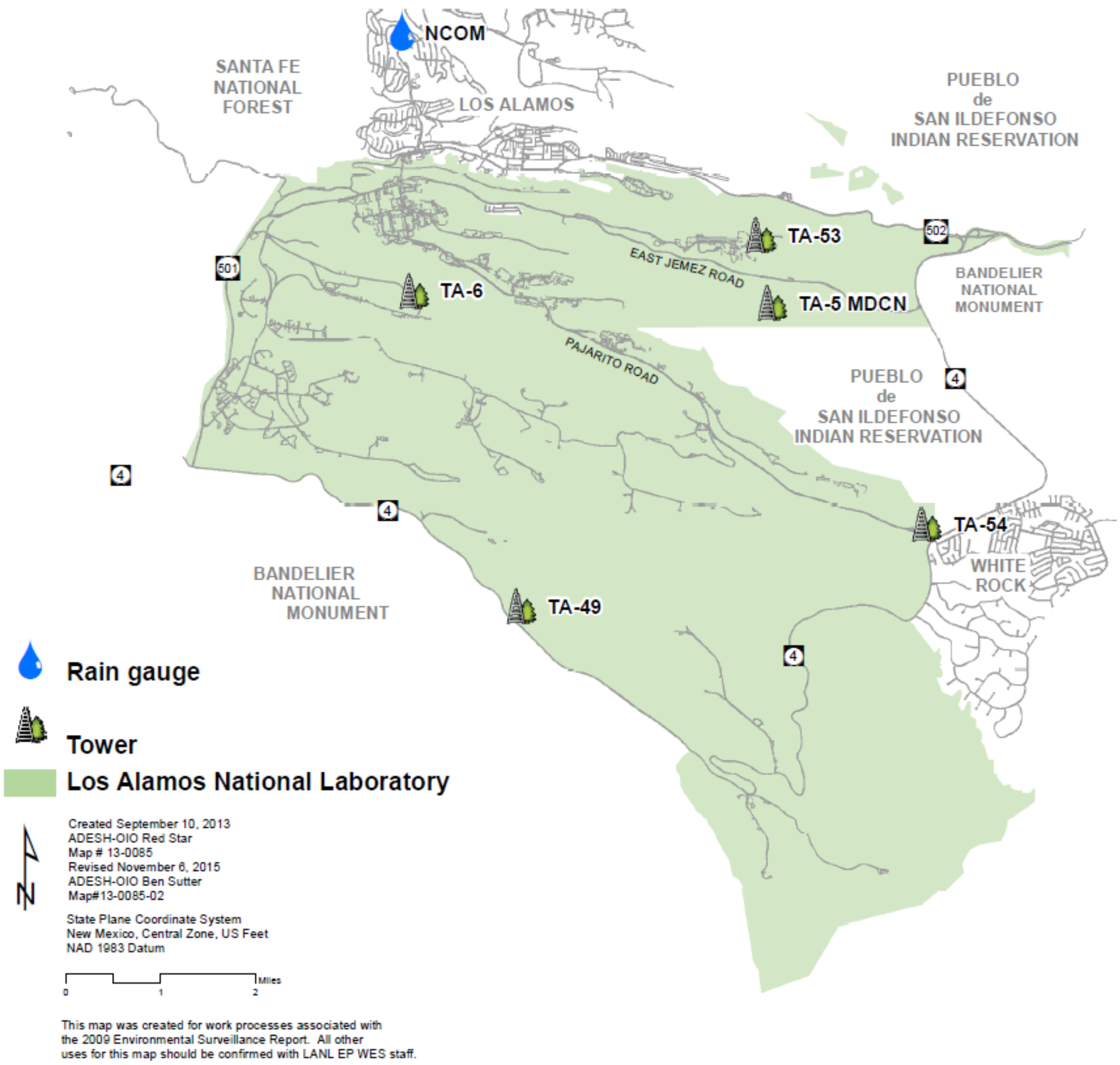

Fig. 1: Meteorological monitoring towers at Los Alamos National Laboratory

2.2 Meteorology Towers

The five meteorology tower sites measure meteorological variables including temperature, insolation, wind speed and direction, vertical wind speed, relative humidity, and precipitation. The tower structures are a triangular open-lattice construction manufactured by ROHN Products, LLC. The towers are fitted with propeller anemometers that measure horizontal and vertical wind data. The Technical Area (TA) 06 tower is the largest on-site tower, a model 80 guyed tower with four levels and width of 41 inches. The TA-49, TA-53, and TA-54 towers are model 55G guyed towers with three levels and width of 17 inches. The lower three levels are at heights of 11.5, 23, and 46 m above ground level (AGL). The fourth level at TA-06 is at a height of 92 m AGL. A view of the TA-53 meteorology tower and instrument boom mounted with a horizontal and vertical propeller anemometer and thermistor is shown in Fig. 2. The TA-05 tower is located in Mortandad Canyon with an anemometer mounted on top of the tower at 10 m. The top-mounted anemometer at TA-05 is out of the tower wake and will not be analyzed in this study.

a

b

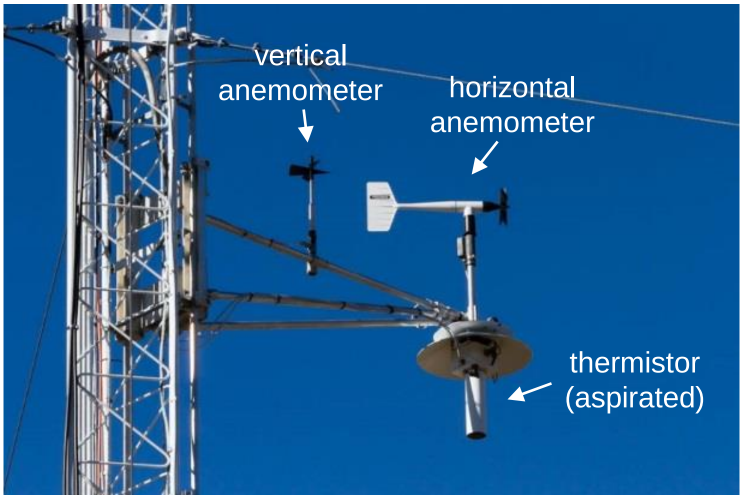

Fig. 2: View of the (a) TA-53 meteorological tower and (b) detail of anemometers, thermistor, and boom

2.3 Instrument Booms

The horizontal instrument booms support a horizontal and vertical anemometer manufactured by the R. M. Young Company. The booms are attached to an elevator system that provides a means of lowering the booms for servicing. A diagram of the instrument boom, horizontal anemometer, and tower dimensions at TA-06 is shown in Fig. 3a and the remaining towers in Fig. 3b. The horizontal propeller anemometers are mounted on the end of the boom at a distance exceeding twice the tower width and are designed to rotate to allow the propeller to face into the wind. At TA-06, the anemometer is mounted at a distance of 2.34 tower diameters away from the tower and the remaining towers have anemometers mounted at 4.24 tower diameters away. Based on the boom lengths and width of the towers, the TA-06 anemometers face into the tower over a 24° sector compared with the other anemometers at the smaller towers that face into the tower over a 13° sector.

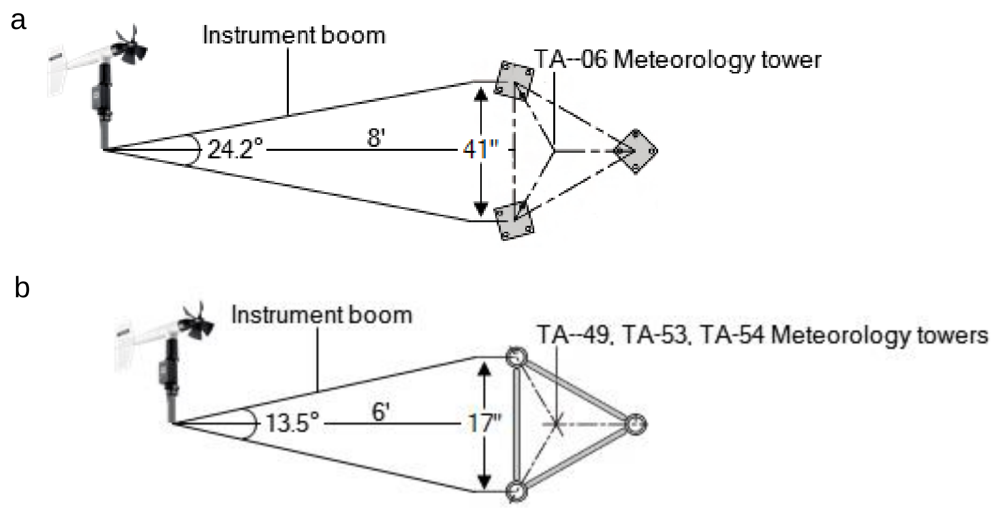

Fig. 3: Dimensions of the meteorology tower and instrument boom for (a) TA-06 and (b) TA-49, TA-53, and TA-54

Table 1 shows the approximate angle and compass direction for the instrument booms on all meteorology towers and Fig. 4 shows a map of the boom orientations across LANL. The anemometers face into the center of the tower at 180° from the directions in Table 1. While there is no documentation on the reasoning for the current boom angles, it is assumed the booms were oriented into the prevailing wind direction. At TA-49, the tower was prefabricated with the booms and their orientations were not altered. The TA-06, TA-53, and TA-54 booms are generally oriented to the west and TA-49 booms are oriented to the south. The level 1 booms at all towers point in a different direction from the upper levels, with level 1 at a larger angle. TA-06 and TA-54 have a much larger angle between level 1 and the upper levels compared with the other towers that have an angle difference of 2°. The towers located in the west (TA-06 and TA-49) have booms directed to the southwest, and the eastern towers have booms directed to the west and northwest.

Table 1: Approximate angle and compass direction the instrument booms extend out from the meteorology towers (measurements made by Alan Madsen and Sean Dolan of the LANL Environmental Stewardship Services Group)

	TA-06	**TA-49**	**TA-53**	**TA-54**
Level 1	264° (W)	203° (SSW)	282° (WNW)	290° (WNW)
Level 2	250° (WSW)	201° (SSW)	280° (W)	267° (W)
Level 3	250° (WSW)	201° (SSW)	280° (W)	267° (W)
Level 4	250° (WSW)	N/A*	N/A	N/A

* N/A = not available.

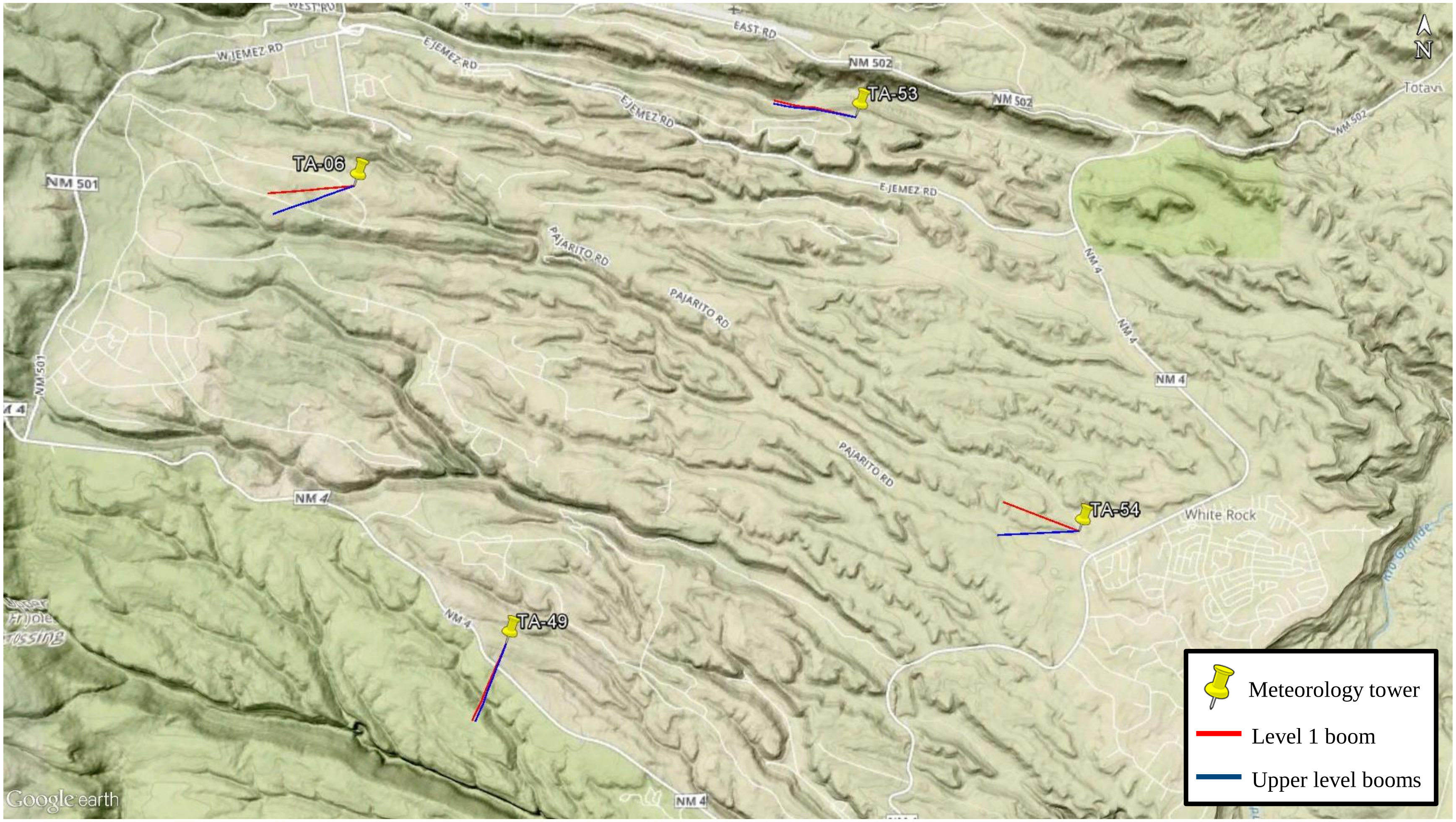

Fig. 4: Direction of the instrument booms at the meteorology towers. Boom lengths not to scale

2.4 Los Alamos Wind Climatology

Wind patterns at Los Alamos vary with time of day, season, and height above ground level as a result of local terrain features. Annual average surface winds are generally light, measuring nearly 3 m s^{-1} (7 mph). Above the surface, wind speeds generally increase with increasing height. Average daytime winds are typically from the south as a result of upslope and up-valley winds, and nighttime winds are typically from the west caused by cold-air drainage down the Pajarito Plateau. Wind speeds are lowest during the morning and increase to a maximum during midafternoon. Winds during the winter typically are from the north and northeast, and during the summer are from the south with the onset of the southwest monsoon. The strongest winds in Los Alamos typically occur during the spring as a result of intense storms commonly passing through the southern and central Rocky Mountains (Bowen 1990).

3.0 METHODOLOGY

3.1 Meteorology Data Source

Wind speed and direction data from the meteorology towers at 15-minute increments during 2014 were obtained online from the Weather Machine at http://weather.lanl.gov/. The wind data completeness during 2014 met the ANSI 2015 standard of 90% completeness. The data completeness for wind speed exceeded 98% at TA-06, TA-49, and TA-53. The data completeness for wind direction at TA-06, TA-53, and TA-54 exceeded 98% with the exception of level 1 at TA-06 at 94% as a result of a failed calibration test in three wind directions. TA-54 data completeness for wind speed and direction was 91% as a result of various calibrations and upgrades (Dewart et al. 2015).

3.2 Calculating Frequency and Speed

Average wind speed and wind direction frequencies were calculated in the 16 primary compass directions (22.5° sectors). The speed and frequency calculations are depicted with wind roses. Wind roses depict the frequency of wind direction from the 16 compass directions and the frequency of wind speed ranges. Wind roses can indicate the dominant wind direction and direction of the strongest wind speeds.

In order to identify the segment of wind directions the tower could be distorting the wind field, the annual average wind speed at all towers at level 1 is calculated for all wind directions between ± 90° from the center of the towers. For example, at TA-06 level 1, the center of the tower in relation to the anemometer is at 84°, and therefore the annual average wind speeds are calculated at all directions between 354° and 174°.

3.3 Wind Reference Data

A comparison of the upstream and downstream flows around a tower can determine the magnitude of decreasing wind speeds as a result of tower shadowing. The wind data measured in the wake of the tower are the downstream velocities, but there are no anemometers located in the upstream flow before the wind encounters the tower. Thus, there is no local reference to compare the upstream and downstream flows. The National Weather Service measures wind data at the Los Alamos County Airport (KLAM) on top of a 10 m tower located 1.2 km northwest of TA-53. KLAM wind data is used as large-scale wind reference data that is located on Pajarito Plateau and avoids tower wake effects.

4.0 RESULTS

The 2014 wind roses for the meteorology towers are shown in Figs. 5–8 by level. For example, at TA-06 level 1, the most frequent wind direction was from the south at over 10% of the time. The wind speeds range from 0 m s^{-1} to 2.5 m s^{-1} approximately 3% of the time, 2.5 m s^{-1} to 5 m s^{-1} approximately 6% of the time, 5 m s^{-1} to 7.5 m s^{-1} approximately 2% of the time, and 7.5 m s^{-1} to 10 m s^{-1} less than 1% of the time. The red line represents the direction the anemometer faces into the center of the tower. Tables 2–5 show the numerical values from the wind roses. The annual average wind speeds from ± 90° from the center of the towers are shown in Figs. 9–12.

The results at TA-06, TA-53, and TA-54 were similar in the wake of the towers; the winds occurred at near the lowest frequencies and measured near the lowest wind speeds. The wind roses at all levels show the highest wind speeds and wind direction frequencies occurred from the west and southwest and the lowest occurred from the east and southeast. At TA-06, the anemometers were in the wake of the tower at an average frequency of 2.98%, the lowest frequency of all the towers. The average wind speed at all levels at TA-54 was 1.77 m s^{-1}, the lowest speed of all the towers. The annual average wind speeds in the wake of the TA-06, TA-53, and TA-54 towers showed a decrease of approximately 1 m s^{-1} over an approximately 130° sector with local maximums at nearly ±90° from the center of the tower (Figs. 9, 11, 12). At a smaller scale, wind speeds around the TA-06, TA-53, and TA-54 tower wakes did not significantly decrease.

The wind direction frequency and wind speed at TA-49 in the wake of the tower was significantly different from the other sites. The anemometers were in the wake of the tower at an average frequency of 5.56%, the highest frequency and nearly 2% more often than the other sites. The average wind speed coming from the tower at all levels was the highest of all the sites at 2.88 m s^{-1} (approximately 1 m s^{-1} faster). Unlike the other sites, the lowest wind speeds were not from the tower and there was not a decrease in annual average wind speed in the wake of the tower over a large sector (Fig. 10), but rather the lowest speeds were measured from the east-southeast. This suggests tower shadowing did not occur at TA-49.

Figure 13 shows the wind data from KLAM and represents the ambient flow that is not distorted by tower wake effects. Similar to the winds shown in the tower data, the highest wind speeds occurred from the west and southwest, and the lowest wind speeds occurred in the east (approximately 40° to 160°).

These results suggest the decreasing wind speeds observed in the tower wakes at TA-06, TA-53, and TA-54 are a result of the low ambient wind speeds from the east. Since the TA-49 anemometers are not in the wake of the tower at low ambient wind speeds, tower shadowing would be easier to identify at TA-49 compared with the other sites. As stated above, the TA-49 annual average wind speed did not show a wind deficit in the wake of the tower and therefore tower shadowing does not influence the wind data at TA-49. Since the size of the tower and instrument boom lengths at TA-49 are similar to TA-53 and TA-54, it can be assumed tower shadowing is not a factor at any of the sites.

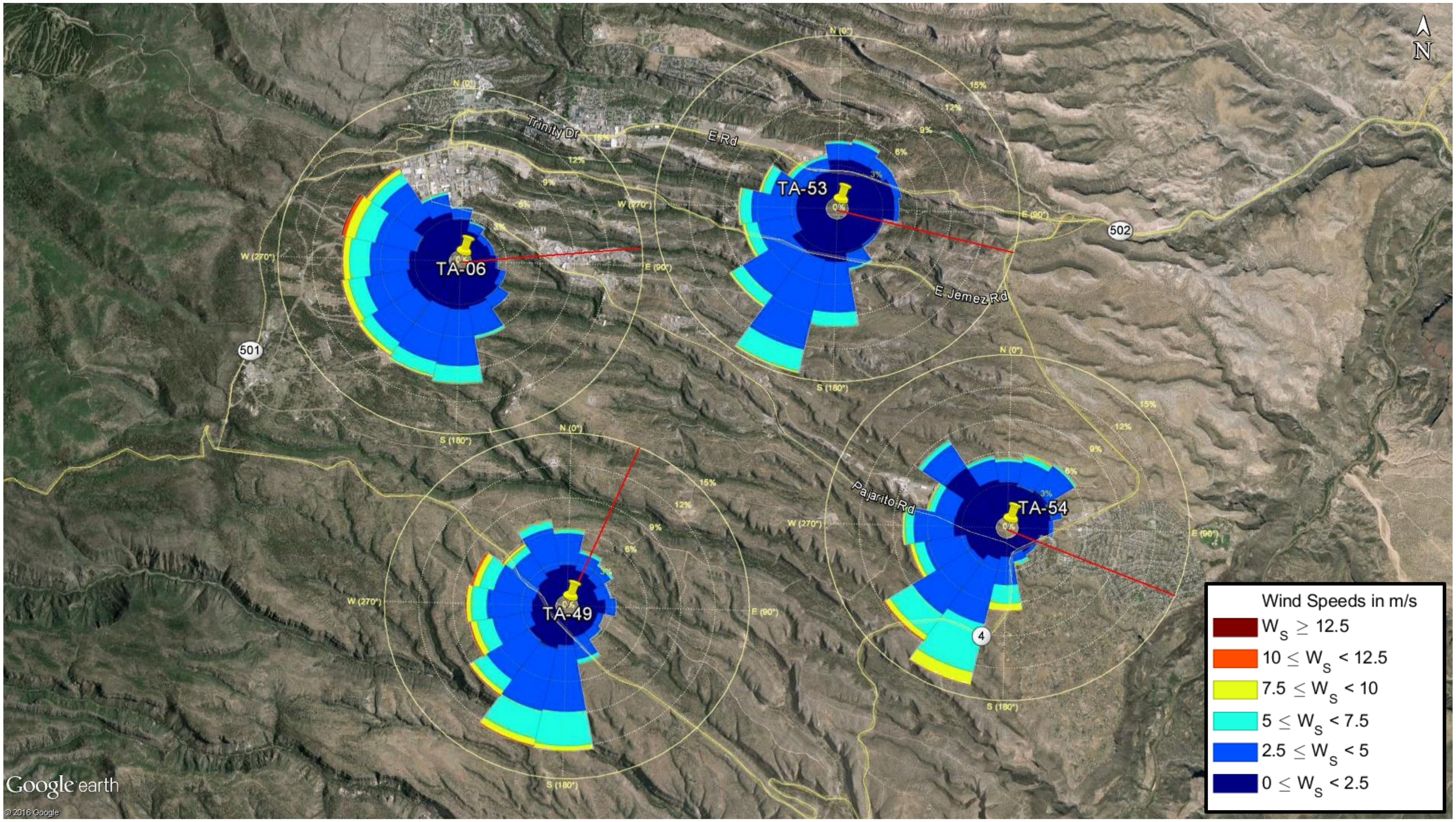

Fig. 5: Annual average wind roses during 2014 at level 1 with the direction the anemometer faces into the tower (red line)

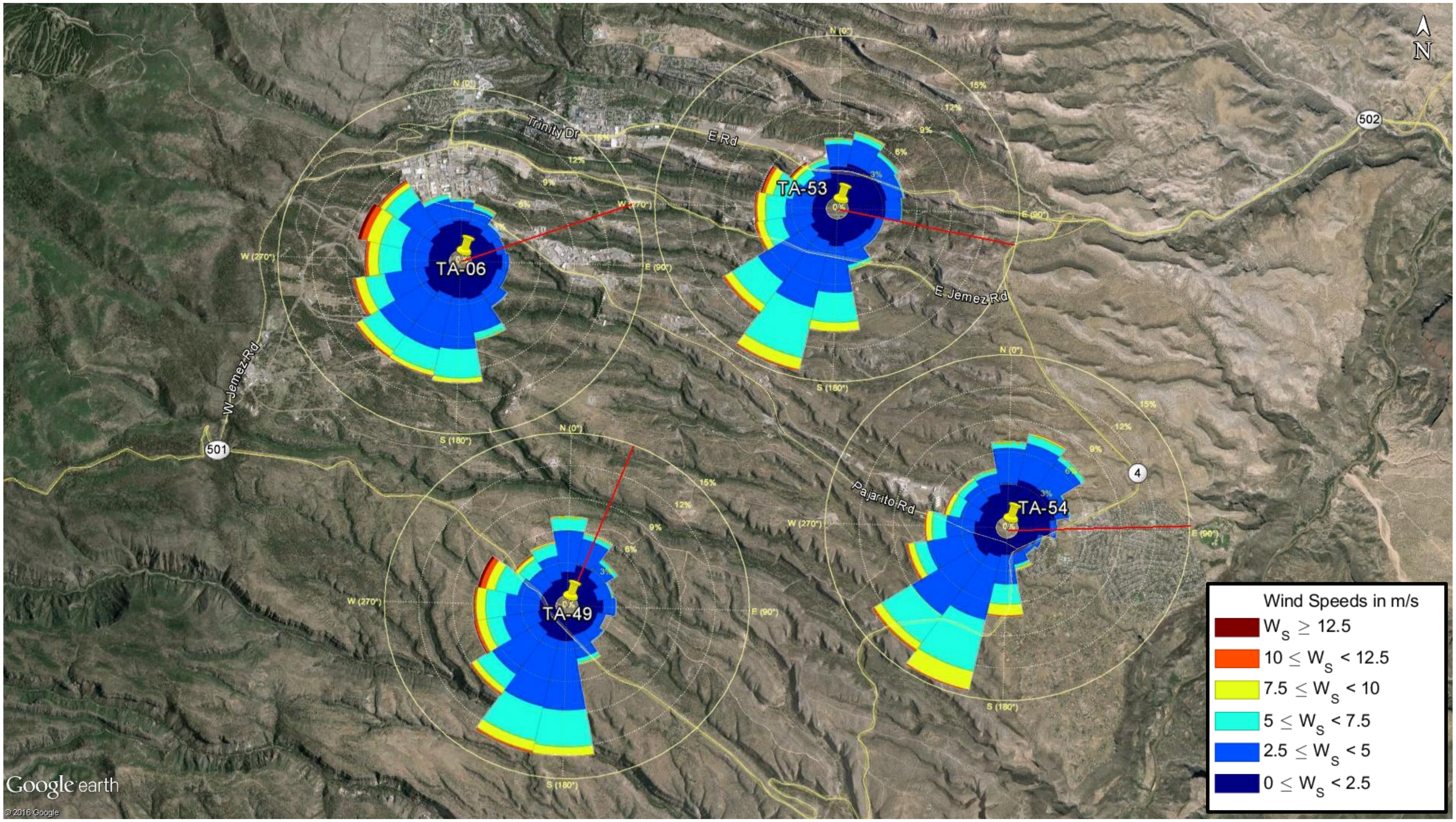

Fig. 6: Annual average wind roses during 2014 at level 2 with the direction the anemometer faces into the tower (red line)

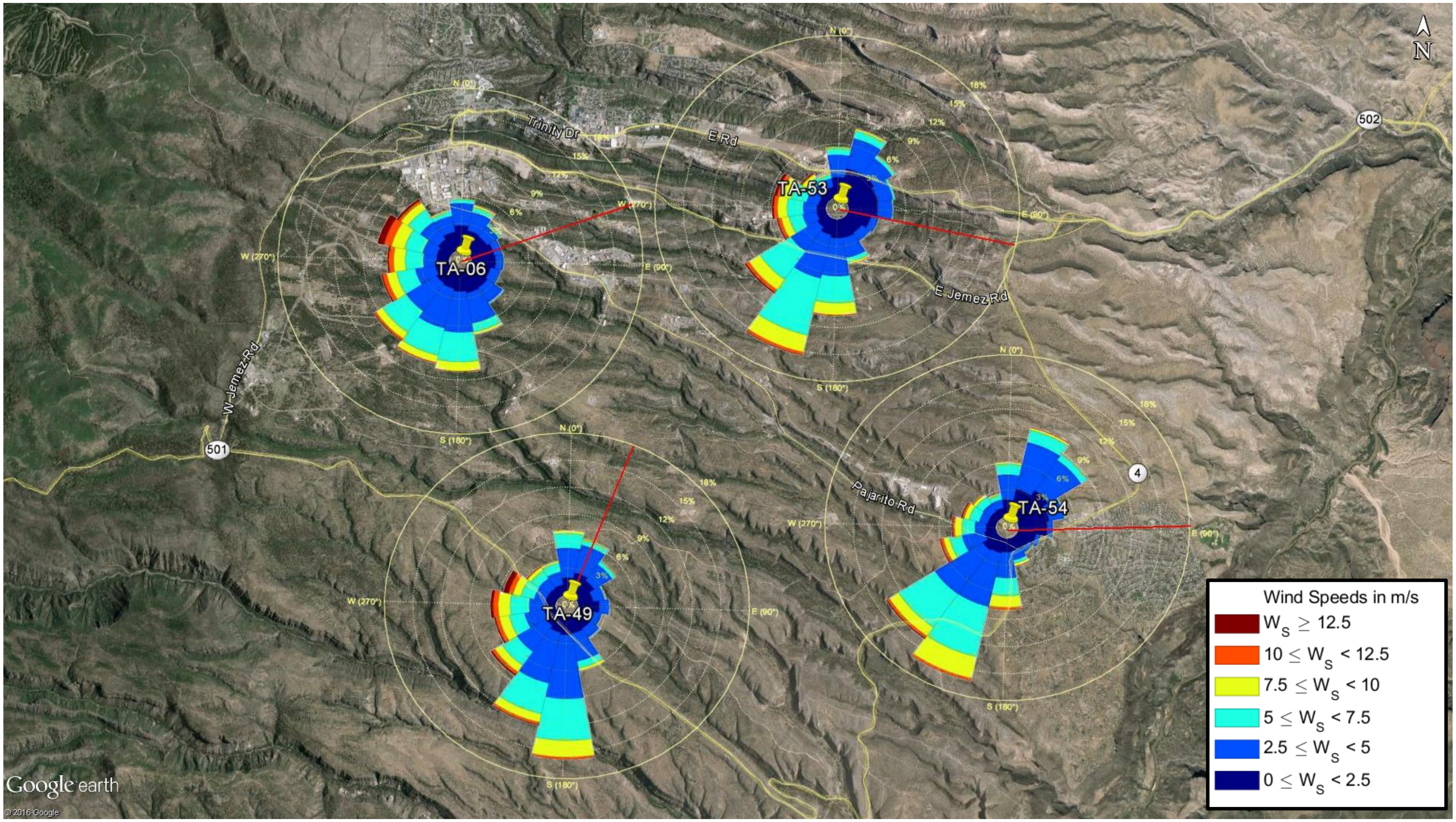

Fig. 7: Annual average wind roses during 2014 at level 3 with the direction the anemometer faces into the tower (red line)

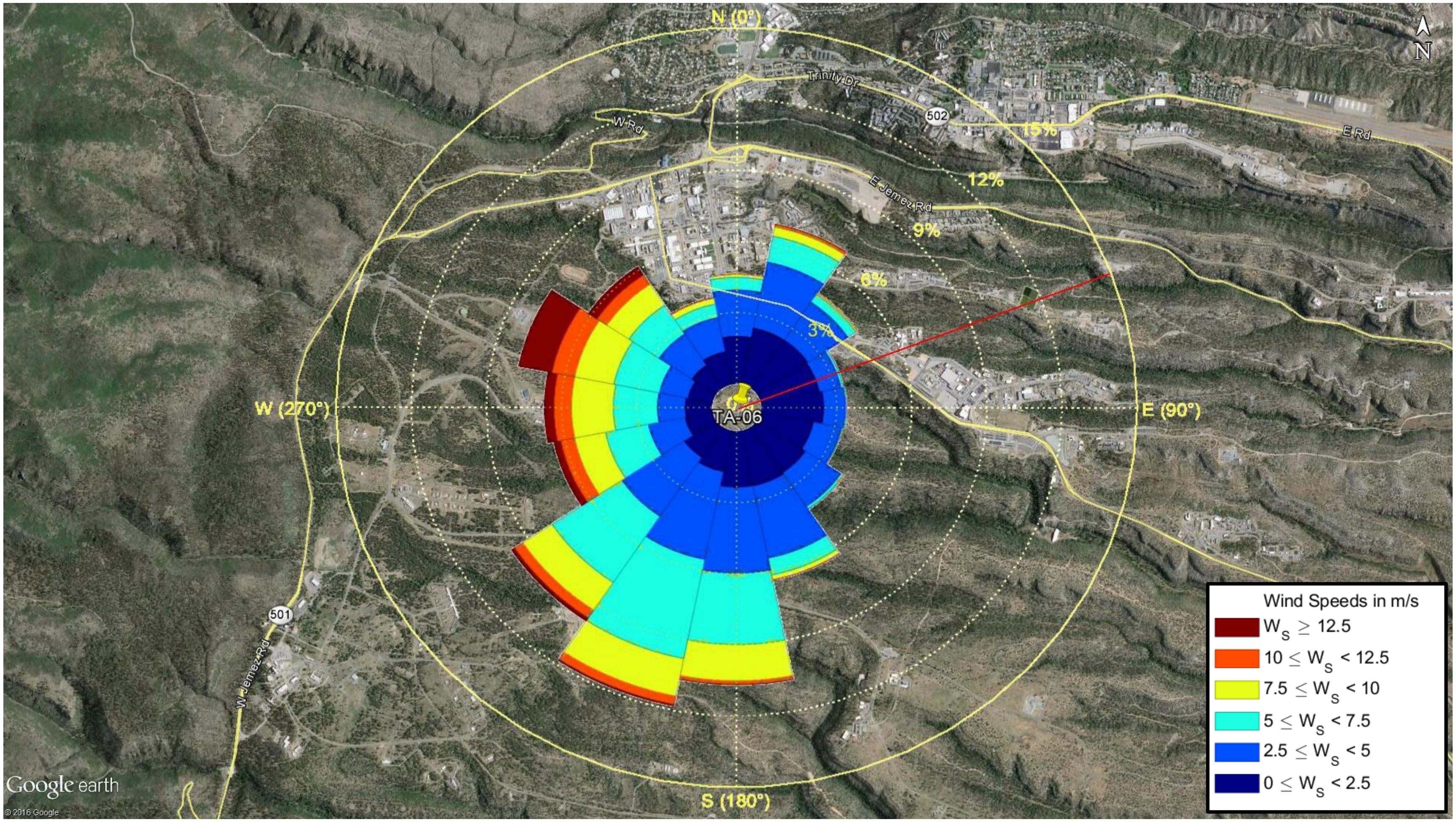

Fig. 8: Annual average wind roses at TA-06 during 2014 at level 4 with the direction the anemometer faces into the tower (red line)

Table 2: Annual average wind direction frequencies and wind speeds from 22.5° sector intervals at TA-06 during 2014. Highlighted sector represents the direction the anemometer was in the wake of the tower

		Level 1		Level 2		Level 3		Level 4	
From (°)	**To (°)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**
11.25	**33.75**	2.74	2.31	4.44	2.77	5.20	3.14	6.88	3.68
33.75	**56.25**	2.04	2.01	3.33	2.39	3.85	2.56	4.79	2.75
56.25	**78.75**	2.07	1.77	3.04	1.96	3.27	1.99	3.34	2.06
78.75	**101.25**	2.28	1.63	3.26	1.79	3.34	1.94	3.38	1.97
101.25	**123.75**	3.10	1.81	3.24	2.07	3.17	2.20	3.30	2.21
123.75	**146.25**	4.19	2.06	4.06	2.36	4.39	2.51	4.14	2.45
146.25	**168.75**	6.27	2.58	6.43	3.05	7.07	3.45	6.40	3.23
168.75	**191.25**	10.34	3.26	10.27	4.03	11.04	4.48	10.67	4.70
191.25	**213.75**	9.96	3.26	9.90	3.94	10.45	4.49	11.81	5.20
213.75	**236.25**	9.71	3.31	9.91	3.96	9.63	4.68	9.81	5.38
236.25	**258.75**	9.57	3.48	8.60	4.33	7.24	5.26	6.44	6.05
258.75	**281.25**	9.35	3.60	7.40	4.78	6.48	5.73	6.68	6.67
281.25	**303.75**	9.71	4.22	8.22	5.39	7.72	6.61	7.88	7.93
303.75	**326.25**	9.13	3.27	7.85	4.12	6.93	4.96	6.12	6.04
326.25	**348.75**	5.51	2.36	5.31	2.83	4.55	3.09	3.73	3.60
348.75	**11.25**	4.01	2.13	4.76	2.51	5.68	2.77	4.61	3.06

Table 3: Annual average wind direction frequencies and wind speeds from 22.5° sector intervals at TA-49 during 2014. Highlighted sector represents the direction the anemometer was in the wake of the tower

		Level 1		Level 2		Level 3	
From (°)	**To (°)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**
11.25	**33.75**	4.30	2.65	5.91	2.89	6.48	3.11
33.75	**56.25**	3.81	2.56	4.24	2.74	4.89	2.89
56.25	**78.75**	2.90	2.37	3.15	2.55	2.91	2.48
78.75	**101.25**	3.31	2.10	3.32	2.27	3.29	2.24
101.25	**123.75**	2.30	1.94	2.47	2.09	2.57	2.23
123.75	**146.25**	2.67	2.19	2.95	2.36	3.11	2.54
146.25	**168.75**	4.45	2.92	4.48	3.12	6.10	3.52
168.75	**191.25**	12.38	4.00	12.90	4.27	15.78	4.80
191.25	**213.75**	12.29	3.97	12.93	4.38	12.37	4.67
213.75	**236.25**	9.15	3.63	9.06	4.10	8.25	4.89
236.25	**258.75**	7.66	3.89	7.25	4.56	6.53	5.40
258.75	**281.25**	7.87	3.80	7.17	4.68	6.81	6.03
281.25	**303.75**	7.58	4.12	8.22	5.39	7.72	6.61
303.75	**326.25**	5.86	3.48	7.85	4.12	6.93	4.96
326.25	**348.75**	7.11	3.23	5.31	2.83	4.55	3.09
348.75	**11.25**	6.37	2.85	4.76	2.51	5.68	2.77

Table 4: Annual average wind direction frequencies and wind speeds from 22.5° sector intervals at TA-53 during 2014. Highlighted sector represents the direction the anemometer was in the wake of the tower

		Level 1		Level 2		Level 3	
From (°)	**To (°)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**
11.25	**33.75**	5.55	2.68	6.27	2.81	7.87	3.11
33.75	**56.25**	4.82	2.21	5.35	2.45	6.06	2.57
56.25	**78.75**	4.70	1.92	4.96	2.16	4.96	2.31
78.75	**101.25**	4.40	1.85	4.67	2.08	4.66	2.20
101.25	**123.75**	3.20	1.76	3.19	1.94	3.27	2.00
123.75	**146.25**	3.22	1.95	3.25	2.14	3.14	2.35
146.25	**168.75**	4.75	2.66	4.78	2.91	5.11	3.22
168.75	**191.25**	9.91	3.69	10.38	4.21	10.67	4.64
191.25	**213.75**	14.57	4.15	14.40	4.67	15.50	5.29
213.75	**236.25**	10.17	3.85	10.90	4.46	10.30	5.42
236.25	**258.75**	7.41	4.03	6.36	4.63	5.25	5.49
258.75	**281.25**	7.67	3.94	6.25	4.84	5.66	5.83
281.25	**303.75**	5.99	3.86	5.85	5.15	5.57	6.22
303.75	**326.25**	4.37	3.47	4.08	4.38	3.53	4.91
326.25	**348.75**	4.04	2.82	3.77	3.08	2.81	3.41
348.75	**11.25**	5.23	2.58	5.53	2.76	5.63	3.21

Table 5: Annual average wind direction frequencies and wind speeds from 22.5° sector intervals at TA-54 during 2014. Highlighted sector represents the direction the anemometer was in the wake of the tower

		Level 1		Level 2		Level 3	
From (°)	**To (°)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**	**Wind Direction Frequency (%)**	**Average Speed (m/s)**
11.25	**33.75**	6.00	2.92	8.00	3.05	10.23	3.45
33.75	**56.25**	6.21	2.57	7.14	2.73	8.79	2.90
56.25	**78.75**	3.88	2.02	4.59	2.11	5.02	2.23
78.75	**101.25**	3.06	1.77	3.34	1.87	3.63	1.81
101.25	**123.75**	2.02	1.63	2.22	1.89	2.44	1.89
123.75	**146.25**	2.01	1.89	2.02	2.29	2.21	2.43
146.25	**168.75**	2.54	2.92	3.01	3.18	3.18	3.53
168.75	**191.25**	6.73	4.27	7.21	4.62	7.91	4.95
191.25	**213.75**	13.92	4.62	14.46	4.92	16.23	5.03
213.75	**236.25**	11.80	3.93	13.02	4.32	13.89	4.84
236.25	**258.75**	7.68	3.38	8.02	3.96	6.02	4.89
258.75	**281.25**	8.17	2.97	6.25	4.04	4.63	5.31
281.25	**303.75**	6.23	2.78	4.67	4.06	3.78	5.31
303.75	**326.25**	8.55	2.40	4.48	3.27	3.23	4.46
326.25	**348.75**	5.72	2.42	4.56	2.87	2.68	3.63
348.75	**11.25**	5.47	2.48	7.00	2.91	6.14	3.61

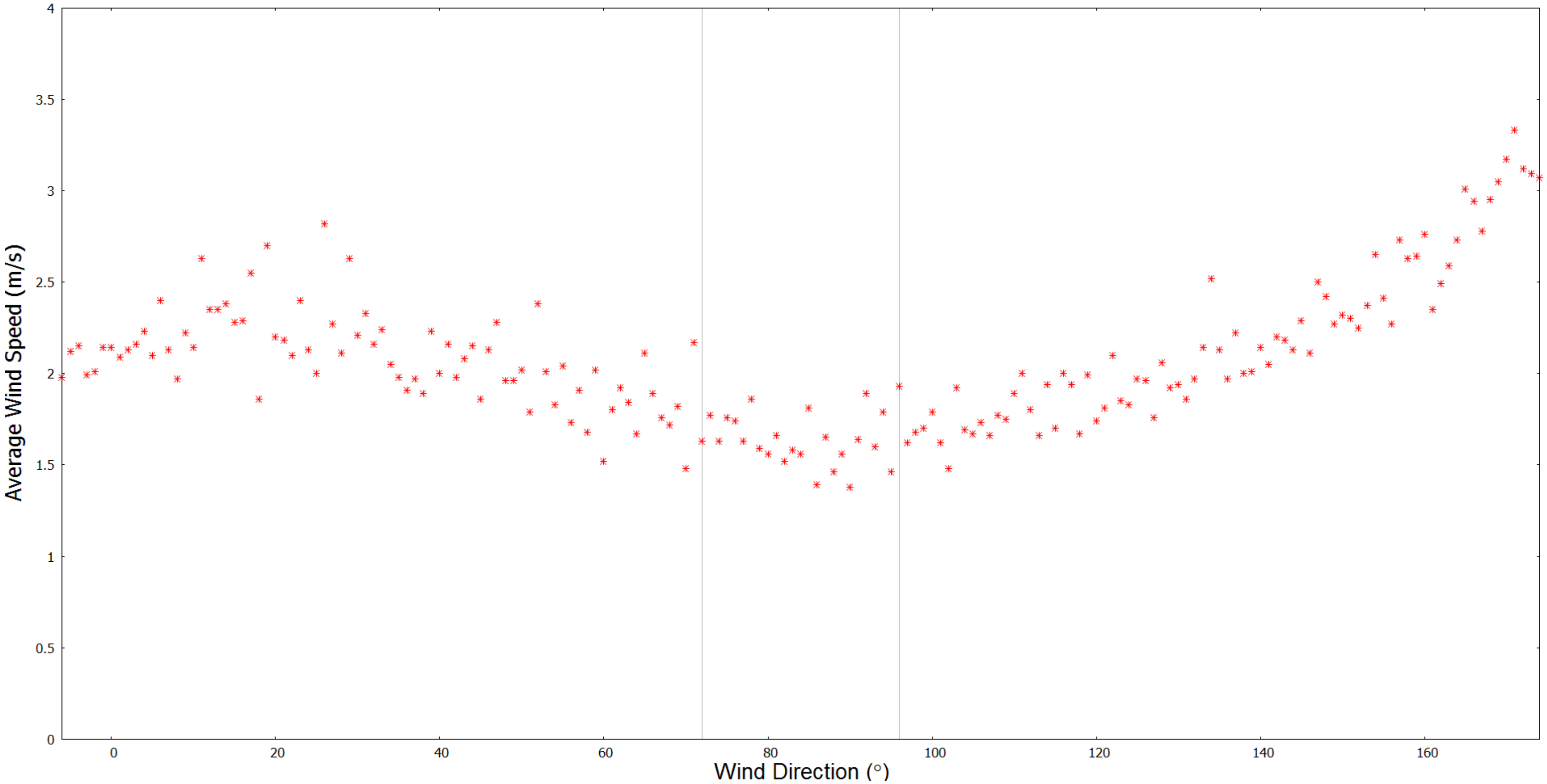

Fig. 9: Annual average wind speed at TA-06 from ± 90° from the center of the tower. Between the gray lines represents the region the anemometer faces into the tower

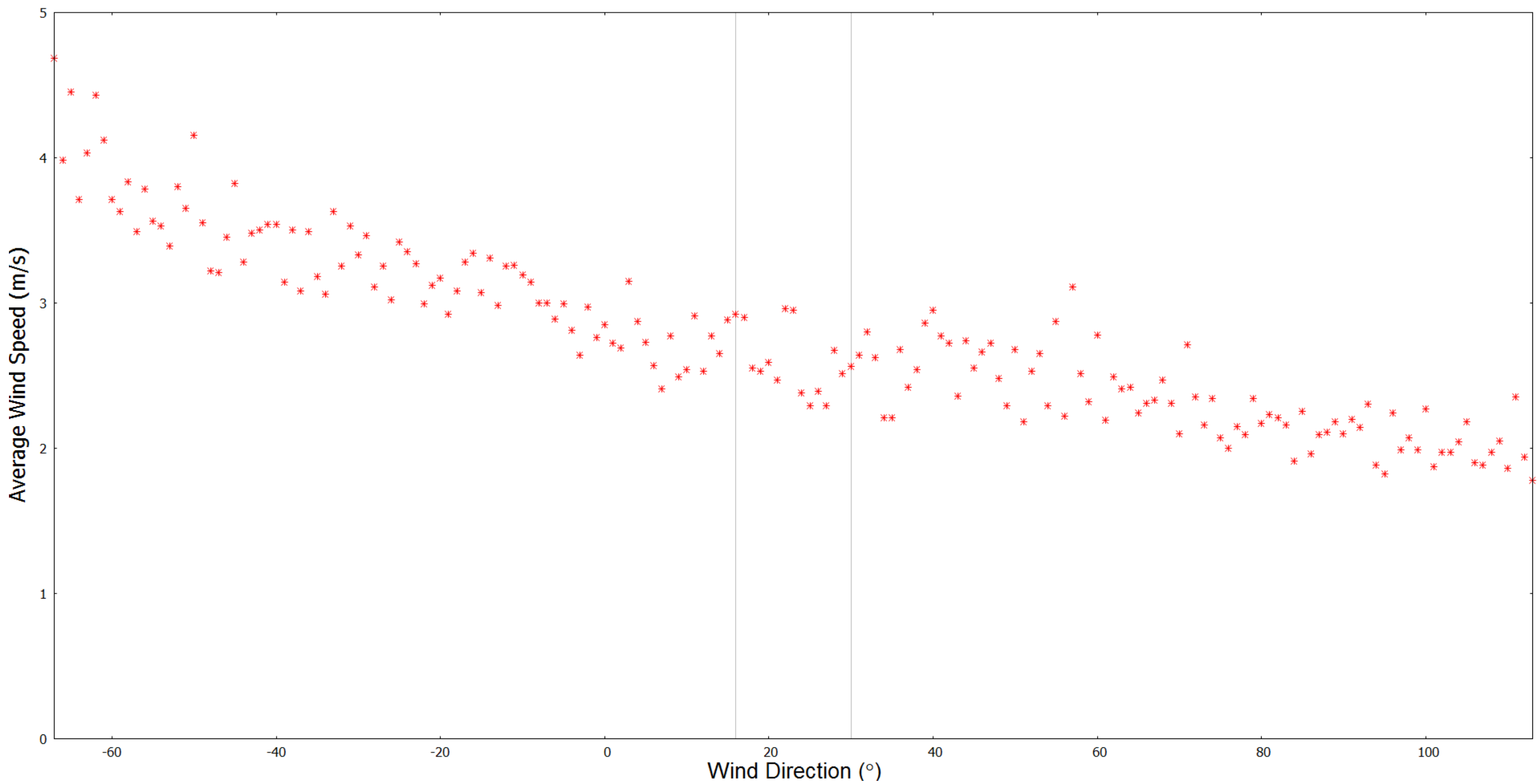

Fig. 10: Annual average wind speed at TA-49 from ± 90° from the center of the tower. Between the gray lines represents the region the anemometer faces into the tower

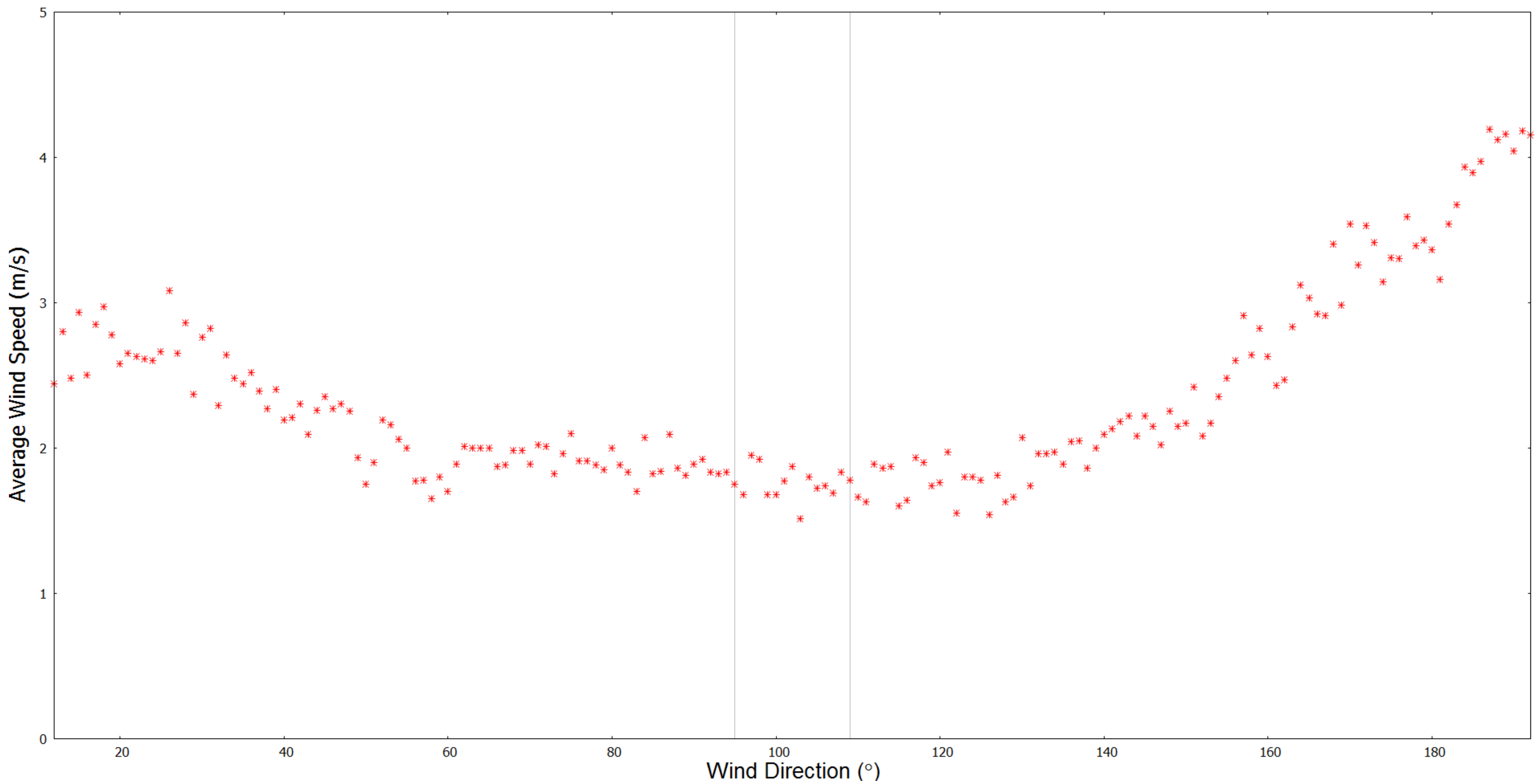

Fig. 11: Annual average wind speed at TA-53 from ± 90° from the center of the tower. Between the gray lines represents the region the anemometer faces into the tower

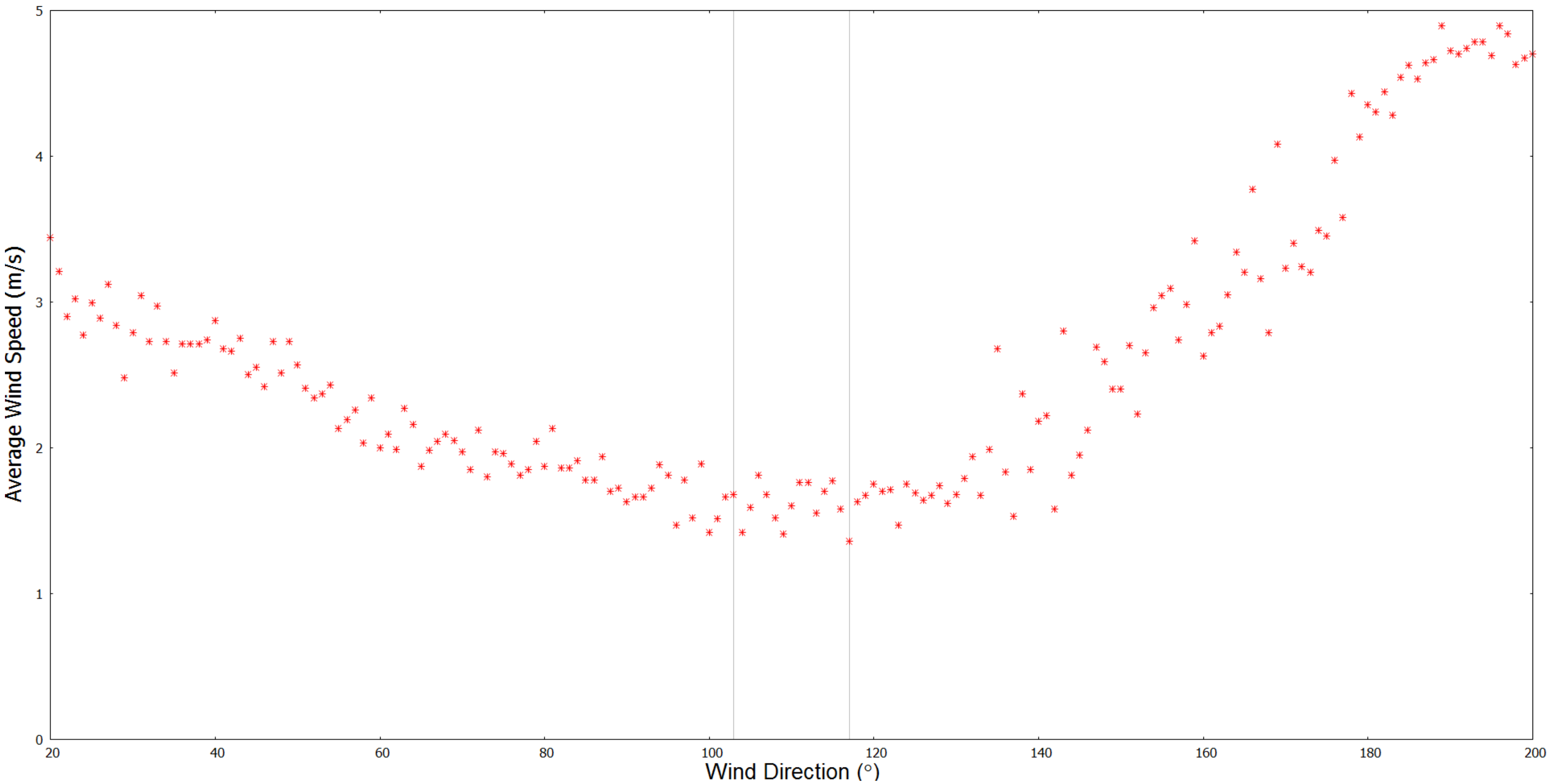

Fig. 12: Annual average wind speed at TA-54 from ± 90° from the center of the tower. Between the gray lines represents the region the anemometer faces into the tower

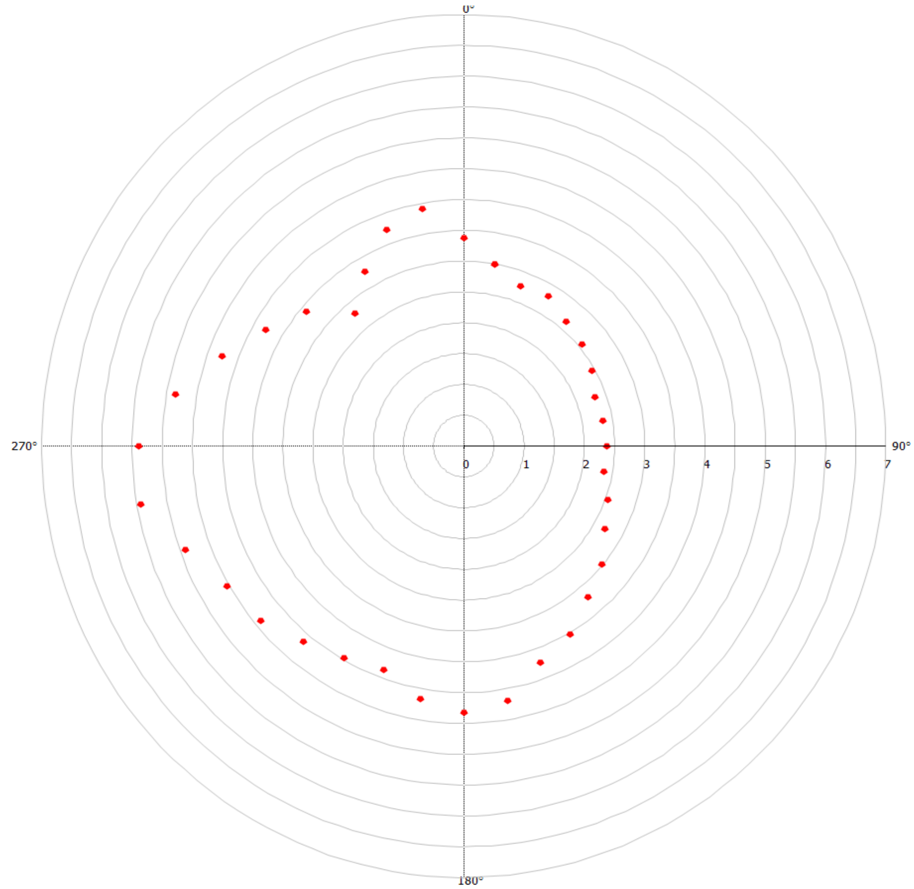

Fig. 13: Polar plot of annual average wind speed (m s^{-1}) vs. wind direction at KLAM in 2014

5.0 CONCLUSIONS

In previous studies meteorology towers have been shown to affect anemometer measurements located in the wake of the tower or tower shadow and therefore yield an under prediction of local wind speeds. The length and orientation of an instrument boom can influence the magnitude of tower shadowing. To minimize the impact of tower shadowing, the anemometer should be located further from the tower and the anemometer should be in the wake of the tower at a low frequency. Generally, the instrument booms at TA-06, TA-53, and TA-54 are oriented toward the west and at TA-49 toward the south. The anemometers mounted on the instrument booms at all the sites exceed the recommendation of twice the tower width. Wind roses of the meteorology towers at LANL during 2014 showed the anemometers were in the wake of the towers at low frequencies and measured near the lowest wind speeds, except for the TA-49 anemometers that were in the wake of the tower more frequently and measured higher wind speeds than the other sites. This was a result of the south orientation of the TA-49 booms. The annual average wind speeds at TA-06, TA-53, and TA-54 showed a distinct decrease in wind speeds in the wake of the tower over a 130° sector (toward the east). However, the TA-49 anemometers showed no decrease in wind speeds in the wake of the tower. Thus, tower shadowing did not occur at TA-49. Based on the KLAM wind data that is unaffected by tower wake effects, the ambient flow coming from the east (approximately 40° to 160°) measured lower wind speeds than surrounding directions. These results indicate the observed decreasing wind speeds at TA-06, TA-53, and TA-54 in the wake of the towers are not a result of tower shadowing, but rather from the ambient flow. This is supported by the low wind speeds measured in the east and southeast at all LANL sites and KLAM, lack of tower shadowing at TA-49 with similar tower and boom dimensions to TA-53 and TA-54, and lack of small-scale wind deficit in the wakes of all the towers.

The existing orientation of the instrument booms at TA-06, TA-53, and TA-54 are in favorable directions since the anemometers are in the wake of the tower at low frequencies and the occurrence of possible tower shadowing would be minimal. The booms at TA-49 could be oriented further to the west to reduce the occurrence of the anemometers in the wake of the tower. However, the results indicate the anemometers at all sites extend far enough from the towers to avoid tower shadowing.

A difficulty in this study was the inability to measure the local upwind flow of the towers to act as a reference of the flow unaffected by the towers. Previous studies used anemometers upwind of a tower or a wind tunnel to compare the upstream and downstream measurements. KLAM wind data helped determine the general trend of wind speeds from all directions. However, KLAM measurements are lower in resolution with wind direction in 10° sectors and wind speed in 0.5 m s^{-1} increments. A future study that would include the addition of an anemometer in the upstream flow that is not shadowed by a tower would likely yield similar results to this study.

6.0 REFERENCES

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