Identification of Low-Level Jets from AWAKEN Lidar Data

ATOC 5770 – Final Project

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Spring 2023

**Introduction:**

The AWAKEN program is a landmark international campaign to collect measurements of wake interactions within wind power plants, spearheaded by the National Renewable Energy Lab (Moriarty et al., 2020). The motivation for this campaign is the poorly understood effect that wake interactions have within wind plants, which leads to significant and unpredictable power and financial losses. High-fidelity, long duration data will be gathered in north-central Oklahoma, an area important and relevant for near-term wind energy developments in the U.S. Great Plains. This data is critical for the development and validation of models which will in turn inform wind development projects and ultimately reduce the cost of wind energy.

This project uses doppler lidar data from the AWAKEN project to find and classify LLJs in the region. LLJs can have a significant effect on wind farm power production and operations and are therefore an important phenomenon to understand and quantify. We utilize data from a doppler lidar located at site H, which is in the immediate vicinity of turbines in the King Plains wind farm.

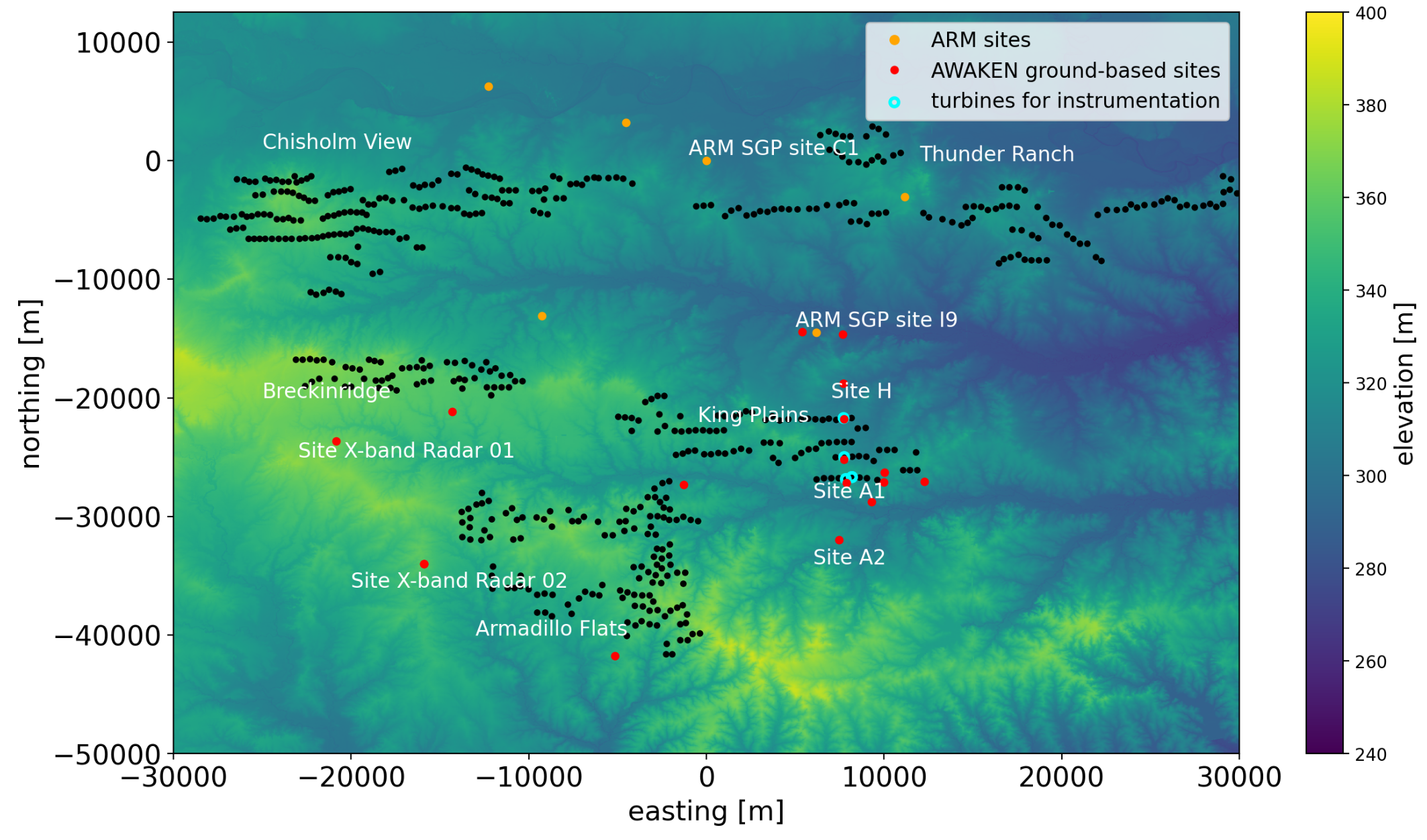


Figure : The AWAKEN field experiment layout. In this work, doppler lidar data from site H is used to identify LLJs in the region. Figure adapted from (Debnath et al., 2022)

**Related Work:**

While wind farm technology has seen rapid growth and improvement, there still exist several problems to overcome over several scales of space and time. Improved understanding of the physics of atmospheric flow and interaction with wind turbines has been identified as a grand challenge in wind energy research (Veers et al., 2019). Improved understanding of atmospheric flows will inform techniques to maximize the efficiency and therefore cost effectiveness of wind plants.

Diurnal low-level jets (LLJs) are an impactful weather event found around the world, driving the transportation of moisture, pollutants, dust, and other airborne substances for thousands of kilometers, all within the atmospheric boundary layer (Rife et al., 2010). These phenomena also impact wind farms, as modern turbines reach heights where LLJs commonly occur. LLJs can increase power output but can also cause damage to wind turbines. The Great Plains region of the United States experiences strong nocturnal LLJs during the warm season, which can be hundreds of kilometers wide and thousands of kilometers long. As this region is also home to much of our wind power resources, understanding LLJs is of great importance.

One of the first studies of LLJs in the U.S. Great Plains was conducted and presented in (Bonner, 1968). The author used two years of radiosonde data from 46 weather stations to identify hundreds of cases of nocturnal LLJs using a criterion developed therein. The diurnal variation and oscillation of the LLJ was observed throughout the year, although most often in spring and late summer. This landmark study provided substantial proof of the prominence and massive scales of LLJs in the region which significantly impact the local climate.

A more recent climatology of LLJs in the Great Plains of the United States provided more detail on general trends in the region (Walters et al., 2008). This study combined forty years of twice-daily radiosonde observations from 36 weather stations across the Great Plains. The authors were able to identify several characteristics of LLJs which vary based on seasonality and location. While this paper helped provide a broad description of LLJs in the region, the authors conclude that much remains to be documented and understood.

Other works have studied LLJs in the U.S. Great Plains using lidar measurements. In 2013, researchers deployed profiling and scanning lidars to collect data which was used to detect LLJs in central Iowa as part of the CWEX-13 field campaign (Vanderwende et al., 2015). The authors detailed a systematic procedure for computing wind profiles from the scanning lidar and using these profiles to detect and classify LLJs. LLJs were consistently identified, with peak windspeeds around 250-500m at the observation site, heights relevant to modern wind turbines. The authors also investigated the ability of various numerical weather models (and ensembles of said models) to predict LLJs in the area, demonstrating good performance. The LLJ classification procedure will be used in the proposed project to detect LLJs during the AWAKEN experiment.

Data from the CWEX-13 campaign was also used to characterize and study wake interactions from multiple turbines (Bodini et al., 2017). Again, a systematic procedure for identifying wakes from lidar measurements was presented. The researchers investigated both geometric and gaussian mixture models for the horizontal wind profile (downwind, perpendicular to the row of turbines). It was shown (for the first time, experimentally) that wind veer directly effects wakes by stretching them, resulting in angular changes in wake centerlines as a function of height. This phenomenon was observed to be greater for outer turbines.

Lidar data can also be paired with in situ tower sensors and radiosondes to rigorously measure and characterize turbulence in the ABL. This sensor combination for ABL sensing was demonstrated in the CASES-99 campaign in southeast Kansas (Blumen et al., 2001). This is important as LLJs can create sufficient mechanical forcing to induce turbulence and subsequent Kelvin-Helmholtz instability (KHI) billows. Richardson numbers of 0.13 were observed in the atmospheric layer that experienced KHI, which aligned with theory. These observations were essential in validating KHI and turbulence simulations.

Several other works and analyses on LLJs and shear-flow instability spurred from the CASES-99 campaign in southeastern Kansas. Researchers investigated a shear-flow instability which occurred over 30 minutes below a LLJ maximum (Newsom & Banta, 2003). It was shown that the observed instability was caused by an increase in shear due to flow slowing below the LLJ, while the speed and height of the LLJ remained essentially constant. The authors state it is not clear what caused this reduction in windspeed below the LLJ. The lowest Richardson number observed during this event was approximately 0.1, indicating a turbulent environment. The authors were able to rigorously characterize the KHI wave characteristics, including wavelength, phase speed, and amplitude.

CASES-99 data was also used to characterize individual LLJ occurrences and trends with respect to topography, time of night, and spatial distribution (Banta et al., 2002). The site of study frequently saw LLJs at or below 100m AGL, which would certainty impact modern wind turbines. LLJs were found and classified using a relatively simple procedure which was heavily informed by visual inspection. It was shown, for this site, that higher sites tended to have higher windspeeds, and that LLJs tend to not be terrain following (i.e., they tend to have near constant MSL altitude).

**Methods:**

To identify LLJs, this work implements a slightly modified version of the procedure developed in prior work (Vanderwende et al., 2015). The identification of LLJs from lidar measurements is done in three steps:

1. Initial quality assurance of wind speed and direction measurements at each bin.
2. Calculation of wind speed and direction profiles from Lidar radial velocity measurements.
3. Identification and classification of LLJs using wind speed profiles.

Wind speed and direction profiles at each altitude were found using a commonly used technique known as velocity azimuth display (VAD). VAD assumes a homogenous flow over the course of a 360-degree azimuth scan. As the Lidar is sweeping the azimuth angles, the radial velocity measurement axis will move in and out of alignment with the horizontal wind vector, resulting in a sinusoidal velocity profile. Using nonlinear least squares, the following function was fit to data at each available altitude bin:

Where is the radial wind speed, is the azimuth angle of the measurement, and are all parameters to be fit. The fitted parameters are then used to derive the horizontal wind speed and direction using:

Where is the beam elevation angle from horizontal. To filter out wind speed and direction datapoint which are poorly fit to the sinusoidal model, we calculate the commonly used value as:

Where is the sum of squares of the residuals, while is the total sum of squares. A threshold of 0.7 was place on this metric, as described in (Vanderwende et al., 2015). If a lower value was found, then the wind speed and direction measurement for that altitude was rejected. See the appendix for examples of valid/invalid VAD fits and their corresponding values.

This procedure can be run for each radial range bin from the Lidar profile. As we know the range and elevation angle of the lidar beam (in this work, 60 [deg]), we can derive the AGL altitude via:

The final step is to classify LLJs based on criteria originally proposed in (Bonner, 1968), then modified by (Whiteman et al., 1997) and (Song et al., 2005). There are two criteria that a wind profile must fulfill to be classified as a LLJ. First, the profile must contain a maximum windspeed above a windspeed threshold, and this maximum windspeed must occur below a height threshold. While Song/Vanderwende impose a 2km threshold, we observed consistently valid data only below 1km in the data available. We therefore placed a height threshold at 1km, and only considered profiles below that threshold. Maximum LLJ nose height observed at 688m, further justifying this choice.

The second criteria involves a threshold on the reduction of wind speed above the LLJ nose. This shear value must meet a certain threshold for LLJ classification. In (Whiteman et al., 1997), four jet intensity levels (0-3) are specified as a function of maximum windspeed and shear, with thresholds provided in the following table:

|  |  |  |
| --- | --- | --- |
| LLJ Category | Max windspeed [m/s] | Upper shear [m/s] |
| LLJ-0 |  |  |
| LLJ-1 |  |  |
| LLJ-2 |  |  |
| LLJ-3 |  |  |

**Results and Discussion:**

Data used in this project was acquired through the DOE’s Atmosphere to Electron website (Shi et al.), and can be found at <https://a2e.energy.gov/ds/awaken/arm.lidar.sgp_s6.ppi.b1> . Unfortunately, only a limited amount of data was able to be acquired from the A2E site via the link above. Email correspondence with A2E administrators was limited, so this project examines a limited dataset primarily composed of measurements taken between Nov 9, 2022, and Nov 17, 2022. Lidar measurements are available at approximately 30-minute intervals throughout this time period. Measurement azimuth angles ranged from 0 – 360 degrees, at 30-degree intervals. Measurement elevation angles were 20 and 60-degrees. In this work, only measurements at 60-degree elevation were used, however the code could be easily modified to incorporate measurements at 20 degrees elevation.A picture containing shape

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Figure : Elevation and azimuth angles at which measurements are taken by the AWAKEN Site H Doppler Lidar.

In all, three LLJ events were classified within the data between Nov. 9 2023 – Nov. 17 2023. These events occurred on the 10th, 13th, and 14th and are discussed below.

Nov. 10 2022 Event:

Around 10pm on Nov. 10 2022, a LLJ was detected by the doppler radar. Initially a class 1, the LLJ continued to develop until reading class 3 around 1:30am. Peak windspeeds reached over 23 m/s. As the LLJ developed, it rose from an initial height of 454m to 668m. Winds were approximately northernly during the entire event. See Figure 6 in the appendix for an example windspeed profile of during this event.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Time** | **LLJ Class** | **Nose Height [m]** | **Lower Shear [m/s]** | **Upper Shear [m/s]** | **Max. WS [m/s]** | **Wind Direction** |
| **2022-11-10 22:00:21** | 1 | 454.663337 | 4.601808777 | 10.55404499 | 12.95283 | 176.7562436 |
| **2022-11-10 22:30:03** | 1 | 532.6056233 | 3.867046732 | 12.07945204 | 15.41556521 | 180.7124451 |
| **2022-11-10 23:00:21** | 2 | 558.5863854 | 6.025352242 | 16.34717396 | 18.07030274 | 196.5659101 |
| **2022-11-10 23:30:03** | 2 | 558.5863854 | 7.495610134 | 15.88868941 | 18.58005714 | 194.1341738 |
| **2022-11-11 00:00:21** | 2 | 584.5671476 | 9.822115216 | 13.42602505 | 19.02541787 | 203.6872044 |
| **2022-11-11 00:30:04** | 2 | 636.5286718 | 8.717689058 | 13.16037807 | 19.11994452 | 199.9794563 |
| **2022-11-11 01:00:21** | 2 | 558.5863854 | 8.63195144 | 10.25600529 | 19.72596607 | 200.959821 |
| **2022-11-11 01:30:04** | 3 | 610.5479097 | 9.717245651 | 10.56671086 | 20.88689615 | 199.7955867 |
| **2022-11-11 02:00:21** | 3 | 636.5286718 | 12.48339243 | 12.42361126 | 23.05240182 | 205.9217827 |
| **2022-11-11 02:30:03** | 3 | 662.5094339 | 12.85571116 | 10.72432557 | 22.29127604 | 203.6517274 |
| **2022-11-11 03:00:21** | 3 | 688.490196 | 13.1093258 | 10.69020153 | 21.75783284 | 202.9095342 |

Nov. 13 2022 Event:

A weaker LLJ was detected on Nov. 13, 2022. This LLJ originated around 7:30 am, and persisted sporadically until noon. Maximum windspeeds reached just under 12 m/s, with winds originating from the southeast. The reason for sporadic classification was profiles were on the cusp of being classified as LLJ-0 (see Figures 7 and 8 in the Appendix). This event also occurred at a very low altitude of just 168m maximum.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Time** | **LLJ Class** | **Nose Height [m]** | **Lower Shear [m/s]** | **Upper Shear [m/s]** | **Max. WS [m/s]** | **Wind Direction** |
| **2022-11-13 07:30:03** | 0 | 142.8941916 | 1.682225047 | 7.380649528 | 10.59391871 | 286.5586739 |
| **2022-11-13 08:00:21** | 0 | 168.8749537 | 2.571314527 | 6.286773148 | 10.15243509 | 296.6405771 |
| **2022-11-13 08:30:03** |  |  |  |  |  |  |
| **2022-11-13 09:00:21** | 0 | 168.8749537 | 3.375974004 | 5.54821507 | 10.26635965 | 300.1912165 |
| **2022-11-13 09:30:03** | 0 | 168.8749537 | 3.442992106 | 5.20865028 | 10.2530479 | 303.6054142 |
| **2022-11-13 10:00:20** |  |  |  |  |  |  |
| **2022-11-13 10:30:04** |  |  |  |  |  |  |
| **2022-11-13 11:00:21** |  |  |  |  |  |  |
| **2022-11-13 11:30:03** |  |  |  |  |  |  |
| **2022-11-13 12:00:21** | 0 | 168.8749537 | 7.896632323 | 5.320173178 | 11.95228575 | 308.4319953 |

Nov. 14 2022 Event:

The final LLJ event was detected on Nov. 13, 2022. This LLJ originated around 1:00 pm, and persisted just an hour until 2:00pm. Maximum windspeeds reached just under 14 m/s, with winds originating from the south.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Time** | **LLJ Class** | **Nose Height [m]** | **Lower Shear [m/s]** | **Upper Shear [m/s]** | **Max. WS [m/s]** | **Wind Direction** |
| **2022-11-14 13:00:21** | 0 | 532.6056233 | 5.67386484 | 5.535199332 | 13.85472968 | 360.7405744 |
| **2022-11-14 13:30:03** | 1 | 480.6440991 | 4.431470821 | 6.530675016 | 12.49415735 | 348.5196648 |
| **2022-11-14 14:00:21** | 1 | 532.6056233 | 6.168302845 | 6.375196483 | 13.41622806 | 355.3074378 |

**Conclusion and Future Work:**

This work used doppler lidar data to detect and classify low-level jets using the methods presented in (Vanderwende et al., 2015) and prior works. In total, 3 LLJ events were identified at site H of the AWAKEN experiment between Nov. 9 – 17, 2022. These LLJs were found within and around wind farms, thus may have distinct impacts on wind farm performance.

This project was limited in resources and therefore scope. There are several notable extensions that could readily be investigated. First, a study investigating the dependence of LLJ formation and severity as a function of atmospheric stability should be done. This project did not have temperature profile data available, making atmospheric stability calculations difficult. Second, it may be interesting to see how well an NWP model could predict the observed LLJs in the area. This could validate whether NWP models can be used for predictive control of wind farms. Third, an investigation into LLJ occurrence over a longer time period would be interesting and informative. The code developed in this project could be readily used to analyze a larger dataset, when it becomes available. Finally, the lidar measurements in this study were taken near the King Plains wind farm (Figure 1). An investigation into the effect of the wind farm on local LLJ formation should be conducted, as the wind farm likely influences our ability to detect local low-altitude LLJs when taking measurements down wind.

**Acknowledgements:**

The author acknowledges the code contributions from Daphne Quint and Prof. Julie Lundquist, which helped kick-start the project. All code to recreate the results can be found on GitHub at: <https://github.com/CamronAlexanderHirst/ATOC5770_LLJ> .

**Bibliography:**

Banta, R. M., Newsom, R. K., Lundquist, J. K., Pichugina, Y. L., Coulter, R. L., & Mahrt, L. (2002). Nocturnal Low-Level Jet Characteristics Over Kansas During Cases-99. *Boundary-Layer Meteorology*, *105*(2), 221–252. https://doi.org/10.1023/A:1019992330866

Blumen, W., Banta, R., Burns, S. P., Fritts, D. C., Newsom, R., Poulos, G. S., & Sun, J. (2001). Turbulence statistics of a Kelvin–Helmholtz billow event observed in the night-time boundary layer during the Cooperative Atmosphere–Surface Exchange Study field program. *Dynamics of Atmospheres and Oceans*, *34*(2–4), 189–204. https://doi.org/10.1016/S0377-0265(01)00067-7

Bodini, N., Zardi, D., & Lundquist, J. K. (2017). Three-dimensional structure of wind turbine wakes as measured by scanning lidar. *Atmospheric Measurement Techniques*, *10*(8), 2881–2896. https://doi.org/10.5194/amt-10-2881-2017

Bonner, W. D. (1968). CLIMATOLOGY OF THE LOW LEVEL JET. *Monthly Weather Review*, *96*(12), 833–850. https://doi.org/10.1175/1520-0493(1968)096<0833:COTLLJ>2.0.CO;2

Debnath, M., Scholbrock, A. K., Zalkind, D., Moriarty, P., Simley, E., Hamilton, N., Ivanov, C., Arthur, R. S., Barthelmie, R., Bodini, N., Brewer, A., Goldberger, L., Herges, T., Hirth, B., Valerio Iungo, G., Jager, D., Kaul, C., Klein, P., Krishnamurthy, R., … Wharton, S. (2022). Design of the American Wake Experiment (AWAKEN) field campaign. *Journal of Physics: Conference Series*, *2265*(2), 022058. https://doi.org/10.1088/1742-6596/2265/2/022058

Moriarty, P., Hamilton, N., Debnath, M., Herges, T., Isom, B., Lundquist, J., Maniaci, D., Naughton, B., Pauly, R., Roadman, J., Shaw, W., van Dam, J., & Wharton, S. (2020). *American WAKE experimeNt (AWAKEN)* (NREL/TP-5000-75789, 1659798, MainId:5894; p. NREL/TP-5000-75789, 1659798, MainId:5894). https://doi.org/10.2172/1659798

Newsom, R. K., & Banta, R. M. (2003). Shear-Flow Instability in the Stable Nocturnal Boundary Layer as Observed by Doppler Lidar during CASES-99. *Journal of the Atmospheric Sciences*, *60*(1), 16–33. https://doi.org/10.1175/1520-0469(2003)060<0016:SFIITS>2.0.CO;2

Rife, D. L., Pinto, J. O., Monaghan, A. J., Davis, C. A., & Hannan, J. R. (2010). Global Distribution and Characteristics of Diurnally Varying Low-Level Jets. *Journal of Climate*, *23*(19), 5041–5064. https://doi.org/10.1175/2010JCLI3514.1

Song, J., Liao, K., Coulter, R. L., & Lesht, B. M. (2005). Climatology of the Low-Level Jet at the Southern Great Plains Atmospheric Boundary Layer Experiments Site. *Journal of Applied Meteorology*, *44*(10), 1593–1606. https://doi.org/10.1175/JAM2294.1

Vanderwende, B. J., Lundquist, J. K., Rhodes, M. E., Takle, E. S., & Irvin, S. L. (2015). Observing and Simulating the Summertime Low-Level Jet in Central Iowa. *Monthly Weather Review*, *143*(6), 2319–2336. https://doi.org/10.1175/MWR-D-14-00325.1

Veers, P., Dykes, K., Lantz, E., Barth, S., Bottasso, C. L., Carlson, O., Clifton, A., Green, J., Green, P., Holttinen, H., Laird, D., Lehtomäki, V., Lundquist, J. K., Manwell, J., Marquis, M., Meneveau, C., Moriarty, P., Munduate, X., Muskulus, M., … Wiser, R. (2019). Grand challenges in the science of wind energy. *Science*, *366*(6464), eaau2027. https://doi.org/10.1126/science.aau2027

Walters, C. K., Winkler, J. A., Shadbolt, R. P., van Ravensway, J., & Bierly, G. D. (2008). A Long-Term Climatology of Southerly and Northerly Low-Level Jets for the Central United States. *Annals of the Association of American Geographers*, *98*(3), 521–552. https://doi.org/10.1080/00045600802046387

Whiteman, C. D., Bian, X., & Zhong, S. (1997). Low-Level Jet Climatology from Enhanced Rawinsonde Observations at a Site in the Southern Great Plains. *Journal of Applied Meteorology*, *36*(10), 1363–1376. https://doi.org/10.1175/1520-0450(1997)036<1363:LLJCFE>2.0.CO;2

**Appendix:**

Chart, line chart

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Figure : VAD Fit of Lidar scan on Nov. 11 2022 at 12m AGL. R-squared value does not meet the 0.7 threshold, therefore the windspeed and wind direction measurement was rejected.

Chart, line chart

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Figure : VAD Fit of Lidar scan on Nov. 11 2022 at 2325m AGL. R-squared value meets the 0.7 threshold, therefore the windspeed and wind direction measurement was accepted.

Chart, line chart

Description automatically generated

Figure : VAD Fit of Lidar scan on Nov. 11 2022 at 142m AGL. R-squared value meets the 0.7 threshold, therefore the windspeed and wind direction measurement was accepted.

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Figure : A windspeed profile taken on Nov 11 2022. This profile is a distinct example of LLJ formation, with maximum windspeed exceeding 22 m/s. This profile was classified as LLJ-3.

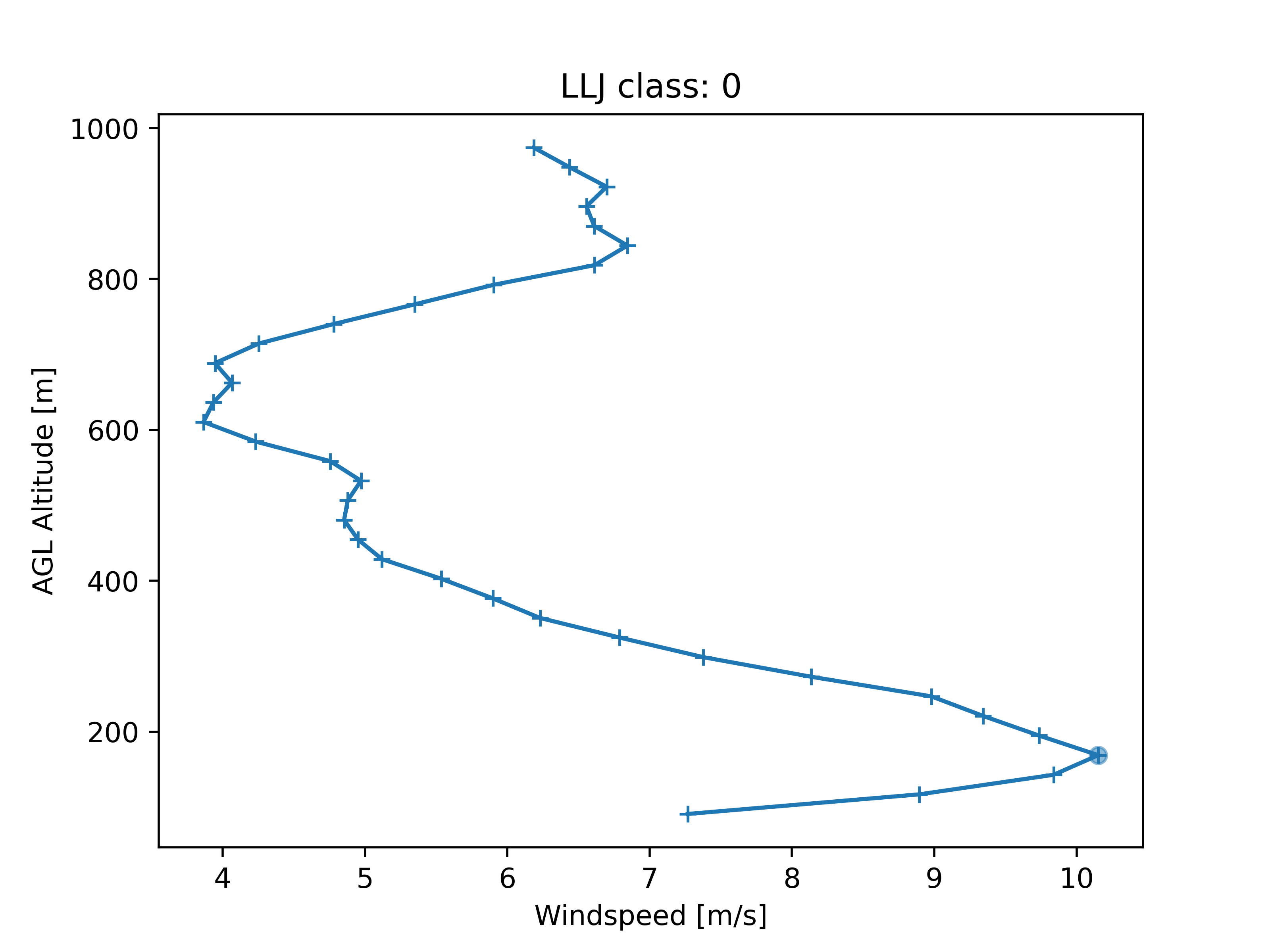


Figure : A windspeed profile taken at 8:00am on Nov 13, 2022. This profile met the windspeed threshold of 10 m/s to be classified as LLJ-0. Similar profiles resulted during the Nov 13 event, leading to sporadic LLJ identification.

Chart, line chart

Description automatically generated

Figure : A windspeed profile taken at 8:30am on Nov 13, 2022. This profile did not meet the windspeed threshold of 10 m/s to be classified as an LLJ. Similar profiles resulted during the Nov 13 event, leading to sporadic LLJ identification.

Chart, line chart

Description automatically generated

Figure : A windspeed profile taken on Nov. 14 2022. This profile did not meet the shear criteria to be classified as an LLJ.