

AWAKEN Dual-Doppler Lidar (ADDLidar) Field Campaign Report

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December 2024



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How to cite this document:

Newsom, R, R Krishnamurthy, C Kaul, D Chand, and M Pekour. 2024.
AWAKEN Dual-Doppler Lidar (ADDLidar) Field Campaign Report. U.S.
Department of Energy, Atmospheric Radiation Measurement user facility,
Richland, Washington. DOE/SC-ARM-24-035.

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

ADDLidar	AWAKEN Dual-Doppler Lidar
ARM	Atmospheric Radiation Measurement
AWAKEN	American Wake Experiment
NREL	National Renewable Energy Laboratory
RHI	range height indicator
SGP	Southern Great Plains

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1.0 Summary

The AWAKEN Dual-Doppler Lidar (ADDLidar) experiment was conducted as part of the larger AWAKEN field campaign (<https://www.nrel.gov/wind/awaken.html>). The American Wake Experiment (AWAKEN) is an international, multi-institutional wind energy field campaign that was conducted from May 2022 to 2024, in the vicinity of the King Plains wind farm in north central Oklahoma. The goal of AWAKEN was to provide observations to better understand interactions between wind turbines in a wind farm and the interactions between the wind farm as a whole and the atmosphere.

The focus of the ADDLidar campaign was to provide height-resolved measurements of wind speed and direction at key locations upwind of the wind farm to characterize the inflow and possible blockage effects upwind of the farm. Specifically, dual-Doppler scanning methods were employed to create a number of so-called virtual towers (Calhoun et al 2006, Debnath et al. 2017, Fernando et al. 2019, Hill et al. 2010, Newman et al. 2016, Newsom et al. 2008, 2015) upwind of the farm.

The ADDLidar campaign involved the deployment of two U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility scanning Doppler lidars (S/N 236 and 237) to AWAKEN sites A4 (36.361894° , -97.356352°) and A7 (36.347259° , -97.389968°). Both sites are located approximately 29 km south of the ARM Southern Great Plains (SGP) observatory C1 site, as shown in Figure 1. These sites were chosen for their close proximity to the most southerly row of turbines in the King Plains wind farm.

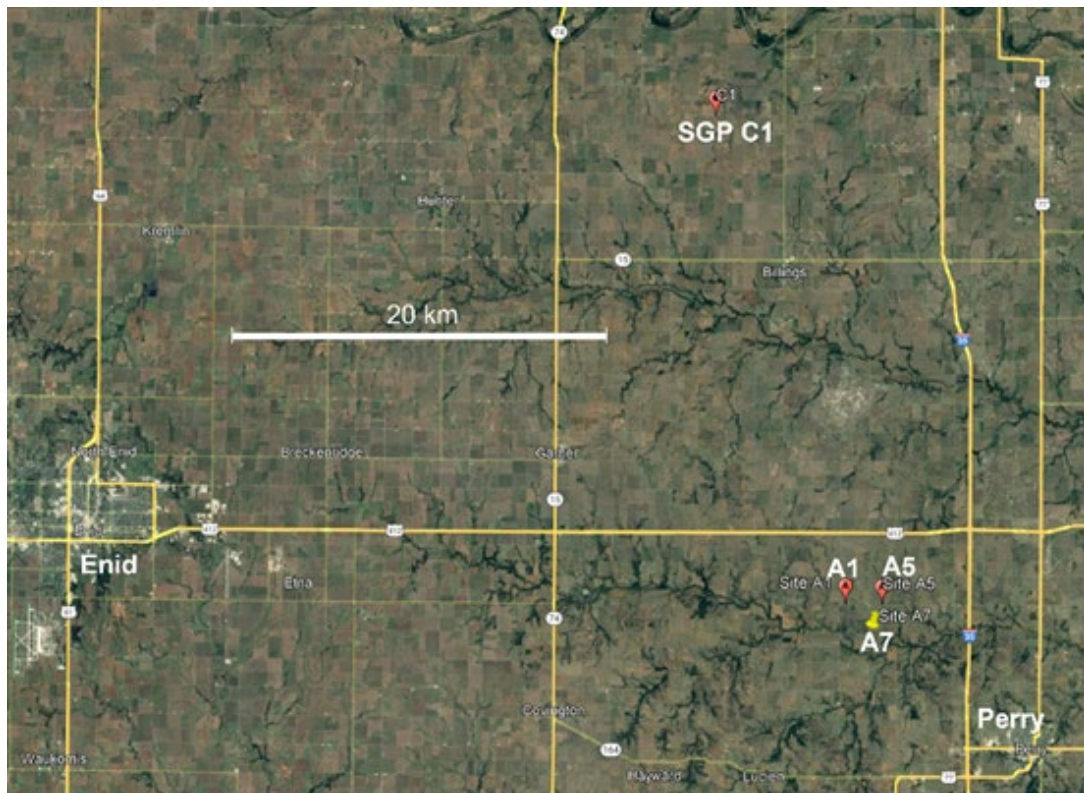


Figure 1. AWAKEN sites A1, A5, and A7 are located approximately 29 km south of the SGP C1.

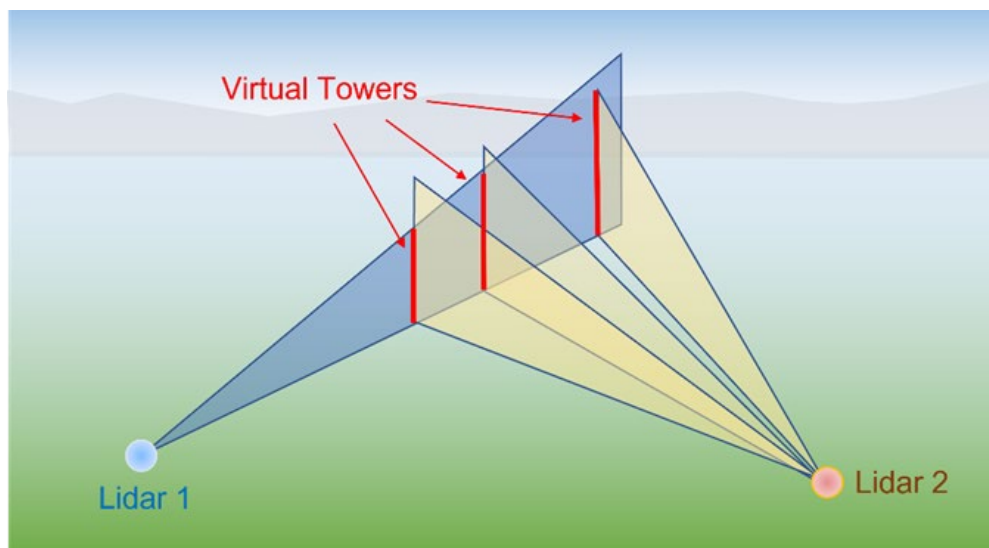


Figure 2. Illustration of the asynchronous dual-Doppler performed during the ADDLidar campaign. The first lidar continuously repeats a single range height indicator (RHI) scan, while the second lidar executes a continuous sequence of three RHI scans. The scans intersect along vertical profiles, which we refer to as virtual towers.

1.1 Deployment

On 10 November 2022, the 236 and 237 (Halo XR+) lidars were transported from the SGP warehouse to AWAKEN sites A5 and A7. The systems were deployed atop rented shipping containers at sites A5 and A7, as shown in Figure 3. SGP staff provided valuable support lifting the lidars in place with their telehandler. Also, the National Renewable Energy Laboratory (NREL) provided basic infrastructure at each of the sites, including security fencing and power.

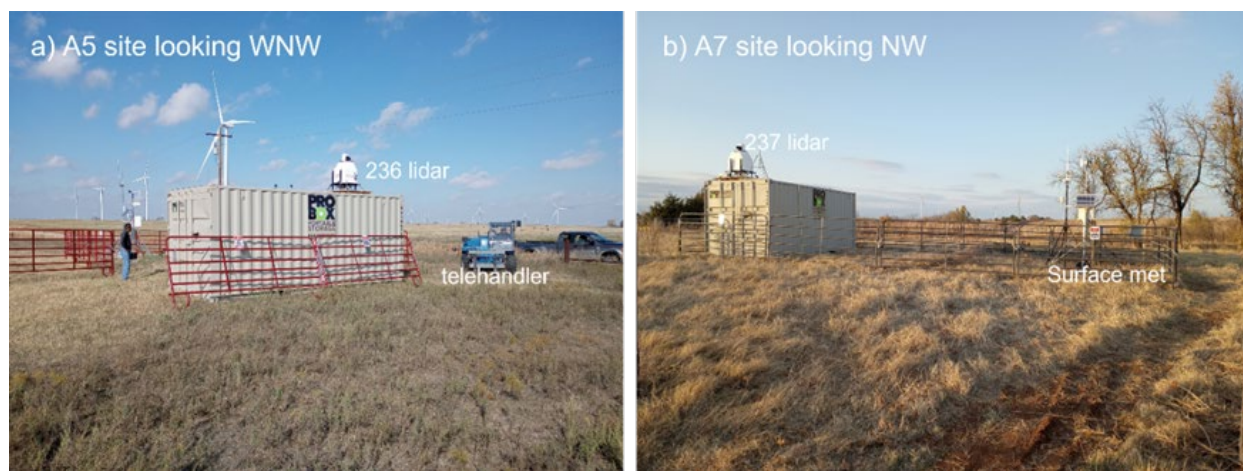


Figure 3. AWAKEN sites a) A5, and b) A7.

The 236 and 237 lidars were removed from A5 and A7 and returned to ARM on May 17, 2023. The ARM systems were replaced with two other (Halo XR+) lidars from Pacific Northwest National Laboratory and Lawrence Livermore National Laboratory to continue the virtual tower experiment into the fall of 2023.

1.2 Dual-Doppler Configuration

Figure 2 shows the geometry of the dual-Doppler set-up. During the course of the campaign, two slightly different configurations were used. For both configurations the A7 lidar scanned continuously in a single direction, while the A5 lidar executed a continuous sequence of three RHI scans.

Configuration A (Figure 4a) was used from 10 November 2022 until 31 January 2023, and Configuration B (Figure 4b) was used from 15 February 2022 until the end of campaign. For Configuration A, the virtual towers are labeled V01 through V03, and for Configuration B, the virtual towers are labeled V04 through V06. We note that for Configuration B, V04 was collocated with site A1 (SGP S4) in order to facilitate comparisons with additional lidar measurements located at that site. Table 1 lists the range and heading angles from the lidars to all virtual towers. Both lidars were operated with 30-m range gates, one-second pulse integration times, and the same scan rate ($\sim 0.5^\circ \text{ s}^{-1}$), resulting in a nominal angular resolution of about 0.5° . Also, for a given configuration both lidars scanned the same elevation range. For Configuration A, the elevation range was from 0 to 10 deg. For Configuration B, the upper elevation limit was extended to 12° , which in turn extended the maximum heights of the virtual towers compared to Configuration A. For both configurations, the time to scan a single RHI was the same for both lidars. The final temporal resolution of the virtual tower data is determined by scan repeat time of the A5 lidar. For Configuration A, the scan repeat time was 3 minutes and 14 seconds, and for Configuration B, the scan repeat time was 3 minutes and 25 seconds.

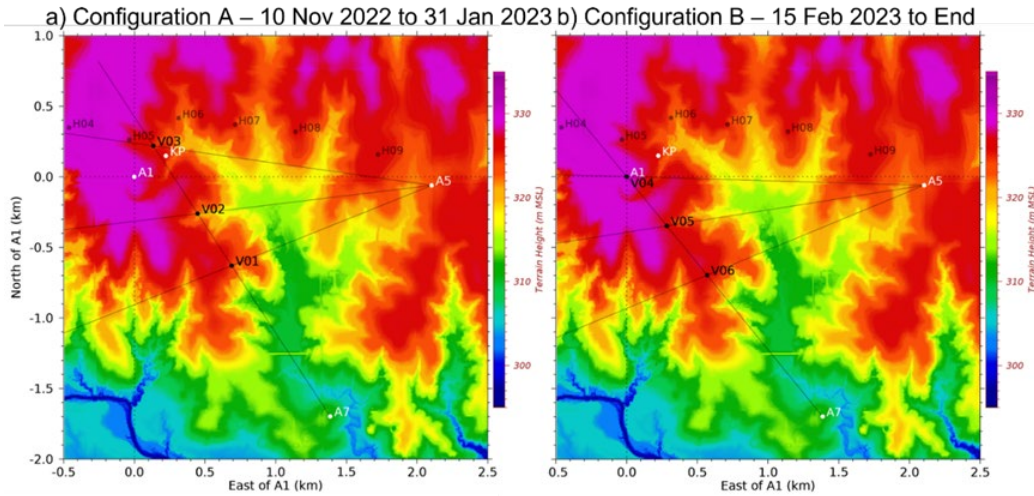


Figure 4. Aerial view of the experiment site showing a) Configuration A, and b) Configuration B. Black lines represent RHI scan directions, and colors show terrain altitude. Also shown are the locations of several wind turbines (H04 to H09).

Table 1. Headings, ϕ , and horizontal ranges, ρ , from the A5 and A7 to each of the virtual towers.

		V01	V02	V03	V04	V05	V06
A5	ϕ (deg)	248.10	263.10	278.10	271.66	261.02	247.48
	ρ (m)	1524	1667	1988	2104	1842	1661
A7	ϕ (deg)	326.87	326.87	326.87	320.77	320.77	320.77
	ρ (m)	1275	1715	2289	2192	1742	1292

1.3 Math

At a point of intersection between the two scans, the easting and northing components of the wind field can be expressed as

$$u = (u_{r2} \cos\phi_1 / \cos\theta_2 - u_{r1} \cos\phi_2 / \cos\theta_1) / \Delta, \quad (1)$$

and

$$v = (u_{r1} \sin\phi_2 / \cos\theta_1 - u_{r2} \sin\phi_1 / \cos\theta_2) / \Delta \quad (2)$$

where $\Delta = \sin\phi_2 \cos\phi_1 - \sin\phi_1 \cos\phi_2$, u_r is the radial velocity, ϕ is the azimuth, θ is the elevation, and the indices refer to the lidars (e.g., 1 for A5 and 2 for A7). Equations 1 and 2 assume that the vertical velocity contribution to measurements are negligible. This is a very good approximation given the scan geometry.

If we consider only the uncertainty in the radial velocity (disregarding pointing uncertainty) then the random uncertainties are given by

$$\delta u^2 = \left(\frac{\delta u_{r2} \cos\phi_1}{\cos\theta_2 \Delta} \right)^2 + \left(\frac{\delta u_{r1} \cos\phi_2}{\cos\theta_1 \Delta} \right)^2 \quad (3)$$

and

$$\delta v^2 = \left(\frac{\delta u_{r1} \cos\phi_2}{\cos\theta_1 \Delta} \right)^2 + \left(\frac{\delta u_{r2} \cos\phi_1}{\cos\theta_2 \Delta} \right)^2 \quad (4)$$

The random error in the radial velocity measurement, δu_r , is estimated from the variance of the four range gates nearest to the point of intersection of the beam, as illustrated in Figure 5. This provides estimates of δu_r for each radial velocity, and enables calculation of Equations 3 and 4.

1.4 Data Processing

Computation of the virtual towers is a two-step process. In the first step, vertical profiles are extracted from all the scans and saved to disk. This is essentially a data reduction step, and requires interpolating the scans along a vertical profile at a fixed horizontal distance from the lidar as illustrated in Figure 5. In the second step, the individual profiles are temporally sorted, georeferenced, and interpolated to a common height grid. The resolution of the height grid was chosen to be 10 m, and the interpolation was done using an exponential weighting function. The true vertical resolution of the virtual tower data varies from tower to tower and degrades slightly with height, but never exceeds 10 m. The exponential weighting function does a good job at handling the variable vertical resolution.

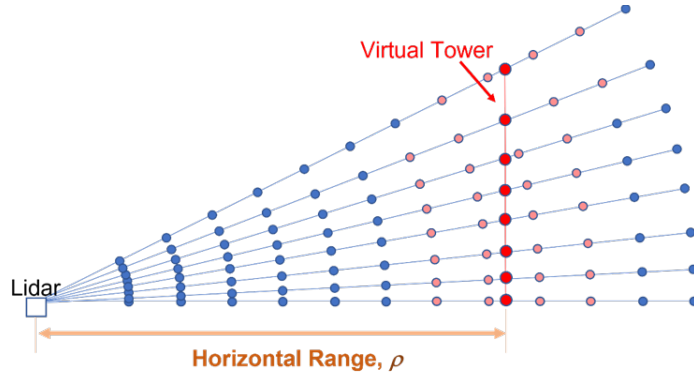


Figure 5. Radial velocity measurements are linearly interpolated along each beam in the RHI scan to form a profile (red) at a given horizontal range from the lidar. The uncertainty in the measurement is estimated from the variance in the four nearest range gates (pink points).

2.0 Results

Preliminary results from the ADDLidar campaign are summarized in Figures 6 through 9. These figures show comparisons between the virtual tower #3 (V03) and a profiling lidar deployed at the A1 site (SGP S4). The profiling lidar at A1 (ZephIR) is owned and operated by Lawrence Livermore National Laboratory. This system has a height range from about 40 m up to about 250 m AGL. By contrast, the height range for V03 was from ~10 m to about 350 m. We note that periods with poor signal have been masked out.

6 through 9 show good overall agreement between the preliminary results from V03 and the profiling lidar based at site A1. There are some important differences to note. The ZephIR data represents a 10-min average, taken every 10 min, whereas the virtual tower represents a ~1-min average taken every ~3.5 min. Quantitative comparison will require matching temporal and vertical resolutions. Nevertheless, the preliminary results shown in 6 through 9 confirm that the dual-Doppler data processing algorithms are working correctly.

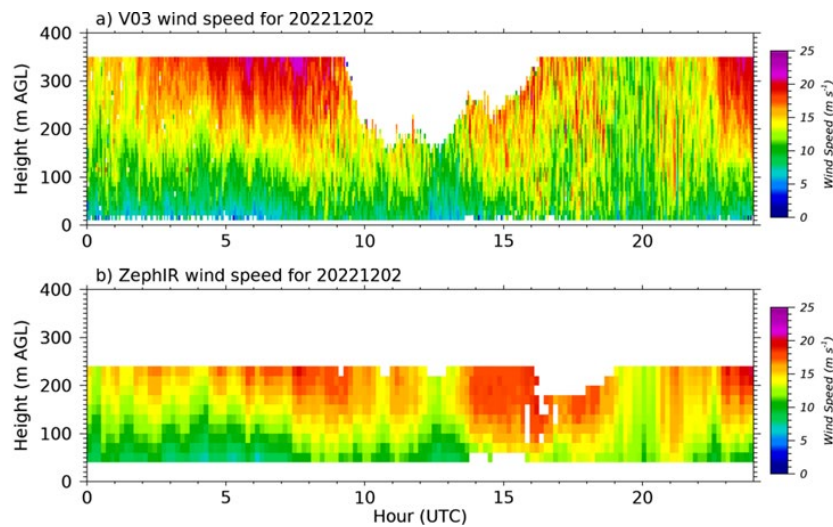


Figure 6. Comparison of wind speeds from a) V03 and b) the ZephIR profiling lidar at AWAKEN site A1 (ARM facility S4) on 2 December 2022.

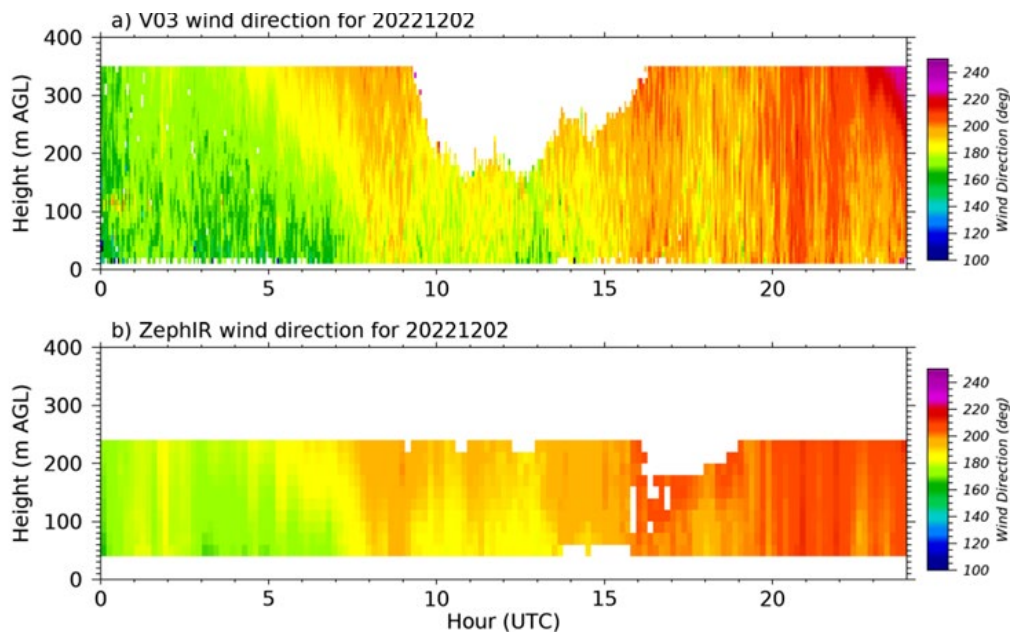


Figure 7. Comparison of wind directions from a) V03 and b) the ZephIR profiling lidar at AWAKEN site A1 (ARM facility S4) on 2 December 2022.

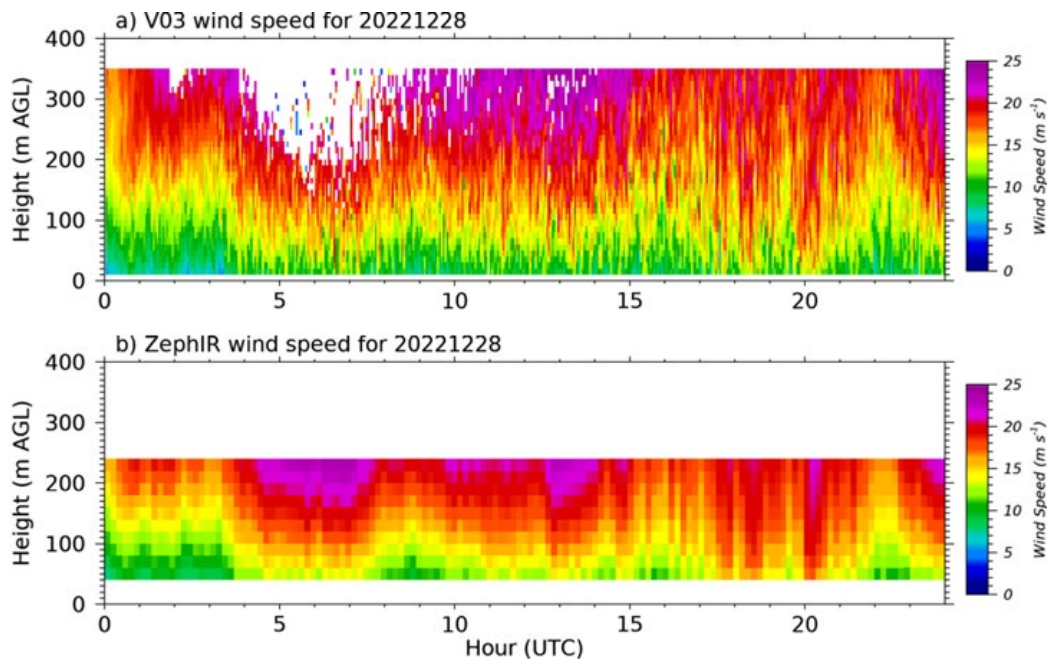


Figure 8. Comparison of wind speeds from a) V03 and b) the ZephIR profiling lidar at AWAKEN site A1 (ARM facility S4) on 28 December 2022.

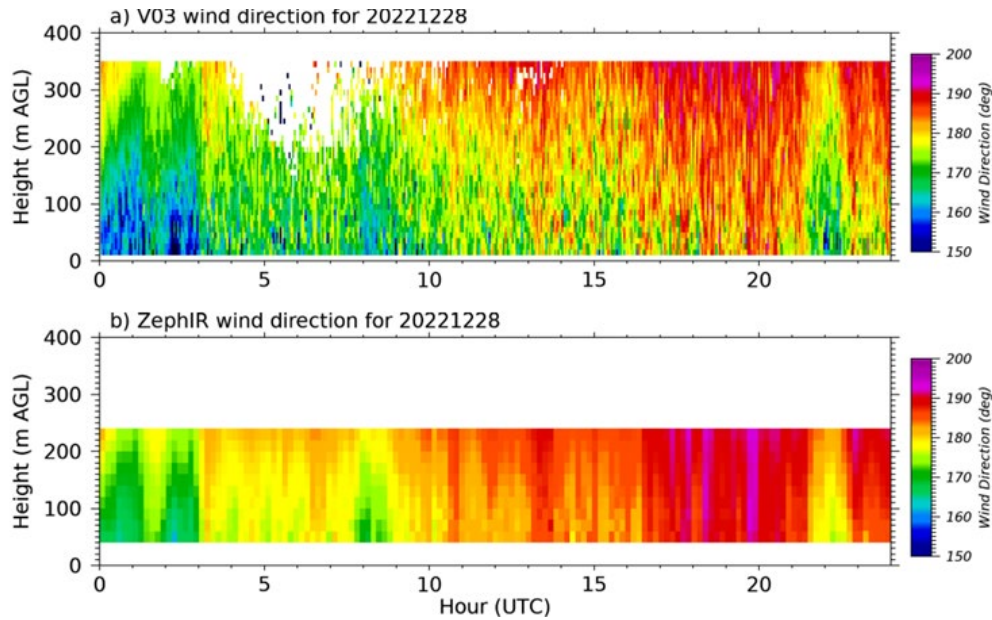


Figure 9. Comparison of wind directions from a) V03 and b) the ZephIR profiling lidar at AWAKEN site A1 (ARM facility S4) on 28 December 2022.

3.0 Publications and References

3.1 Publications

Results from the ADDLidar campaign will be published in relevant technical journals. Work is currently underway to develop a journal article that expands on the results and methods presented in this short report. Also, the derived wind fields will be used to characterize the inflow and assess the impact of blockage. We will target journals that focus on applied meteorology and wind energy science. Examples include *Wind Energy Science*, *Wind Energy*, *Wind Engineering*, *Atmospheric Measurement Techniques*, or the *Journal of Geophysical Research*.

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