

# Emerging mobile Micropulsed-Doppler Lidar technology for Wind Energy Research

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**Abstract:** The development of a Micropulsed Doppler (MD) Lidar and deployment of this compact system on mobile air-borne, ship-borne, and truck-borne platforms opened a new opportunity to characterize the dynamics of large-scale, complex wind flows in the atmospheric boundary layer in all regions, from urban areas to remote locations in complex terrain. Traditional in-situ or stationary profiling observations cannot provide the flexible combination of spatial and temporal coverage fully available from mobile lidars.

The Atmospheric Remote Sensing (ARS) group at the Chemical Sciences Laboratory (CSL) of the National Oceanic and Atmospheric Administration (NOAA) successfully operated mobile Doppler lidars from various platforms providing unique measurements to characterize ocean and atmospheric processes, to study the complex flow of winds around wildland fires, and to understand the effect of a large wind farm on wind flows under different atmospheric conditions.

## 1. Introduction

Stationary Doppler lidars provide high-quality measurements of wind and turbulence profiles from the surface up to several hundred meters aloft in the boundary layer. They have proven to be powerful remote sensing instruments.

The Atmospheric Remote Sensing (ARS) group at the Chemical Sciences Laboratory (CSL) of the National Oceanic and Atmospheric Administration (NOAA) uses both commercial Doppler lidars and lidars developed within the group for various applications from the understanding of wind flow modified by the wind turbine (Banta et al, 2015) to the evaluation and improvement of weather prediction models (Pichugina et al, 2022). Lidar development at ARS goes back decades, with continuous engineering updates and the design of new versions to meet research objectives.

The growing requirements for compact lidar configurations that can be deployed on any moving platform led to the development of a new system, the state-of-the-art Micropulsed Doppler (MD) lidar, a compact and robust

Doppler lidar system with increased sensitivity compared to commercially available systems.

The goal of an MD deployment in the smaller space was achieved by a unique design of a master oscillator power amplifier (MOPA) microjoule-class pulsed coherent Doppler lidar system in two physically separated modules: the transceiver and the data acquisition system connected by an umbilical cable (Shroeder et al., 2020). This design, along with the significant decrease in the weight and the size of both modules, enables deployments of these systems on small aircraft and pick-up truck platforms that are otherwise inaccessible by commercial and research instruments of similar design.

The development of an MD lidar and deployment of this compact system on mobile airborne, shipborne, and truck-borne platforms opened a new opportunity to characterize the dynamics of large-scale, complex wind flows in the atmospheric boundary layer in all regions, from urban areas to remote/inaccessible locations in complex terrain. Traditional in situ or stationary profiling observations cannot

provide the flexible combination of spatial and temporal coverage that is fully capable with mobile lidars.

Measurements from a mobile platform face many challenges, such as an accelerating reference frame and vibration while in motion, that require thoughtful hardware design and data processing methods. A significant obstacle to obtaining accurate wind profiles from the high-precision lidar measurements using these techniques is compensating for the pointing error and along-beam velocity due to platform motions. To accomplish this, the mobile lidar systems utilize a Motion Compensation frame, which allows the calculation and removal of the platform motion projected into the line-of-sight velocity measurement in real-time, and the Pointing Stabilization, which allows measurements of the platform orientation and actively stabilizes the orientation of the lidar beam in the world frame.

The vertical, spatial, and temporal variability of wind flows obtained from mobile lidar systems during several recent experiments has been used for various air quality and weather applications, including understanding the dynamics of wildfire plumes, studying urban heat islands, assessing air quality around gas/ oil facilities, and characterizing the boundary layer dynamics around/within wind farms.

The results obtained from recent experiments illustrate the high precision and excellent pointing accuracy of measurements from the ground, airborne, and shipborne deployments and clearly illustrate success in developing a fully capable mobile Doppler lidar for environmental studies. The synergy between ground-based and aircraft-based mobile lidar systems provides a unique opportunity to characterize atmospheric processes and to study wildfire plume transport (Carroll et al., 2023; Strobach et al., 2023). The flexible combination of spatial and temporal coverage of aircraft-based mobile lidar measurements provides an advantage over traditional in situ or stationary profiling observations to study the air quality of large urban areas.

## 2. Measurements during the American Wake Experiment (AWAKEN)

The AWAKEN is a U.S. Department of Energy (DoE) project led by the National Renewable Energy Laboratory (NREL). It is a multi-

institutional, long-term (2022-2024) study in the U.S. Midwest aiming to understand the interaction between wind farms and their surrounding environment and improve the performance of wake models (Moriarty et al, 2020) and <https://openei.org/wiki/AWAKEN>.

Participating organizations deployed various in-situ and remote-sensing instruments to the study area, including 13 stationary scanning Doppler lidars and 7 wind-profiling lidars.

In Aug-Sep 2023, the latest version of the truck-based lidar system (Fig. 1), the Pickup-based Mobile Atmospheric Sounder (PUMAS), participated in the AWAKEN to study the spatial structure of the horizontal wind and turbulence fields near wind farms in north-central Oklahoma.

The mobile lidar system (Fig. 1) included a motion-stabilization frame, a lidar head, an all-sky camera, and a sensor for in-situ temperature ( $T^{\circ}$ ) measurements and wind speed. The electronics rack was located in the back of the cabin (Fig. 1b), and the real-time display was located in the front of the cabin (Fig. 1c).

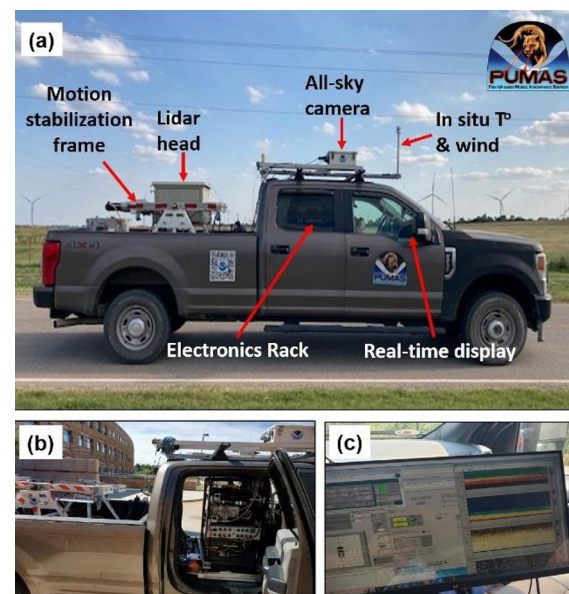


Fig. 1. Picture of a truck-based lidar system-PUMAS with indicated sub-systems.

To support the AWAKEN science objectives, PUMAS provided continuous motion-compensated measurements of 3-D wind flow and turbulence profiles driving on highways and dirt roads within wind farms. Two motion-stabilized lidar beams - vertically pointed and conically scanning with  $\pm 15^{\circ}$  of zenith - provided simultaneous profiles of horizontal wind vectors and vertical velocity statistics

from 60 m AGL to the top of the atmospheric boundary layer. Data were obtained with a temporal resolution of 1-4 Hz and an along-beam resolution of 30 m. Wind speed profiles were obtained with an along-path resolution of 300-600 m, while vertical velocity profiles were obtained every 10-30 m. Along-path resolution depends on the driving speed and the road conditions. However, it can be modified by hardware settings or the vehicle's driving speed. Considering the predominant wind direction forecasts, the driving transects for each day were designed to sample waked and free flows at various distances from the wind turbine cluster.

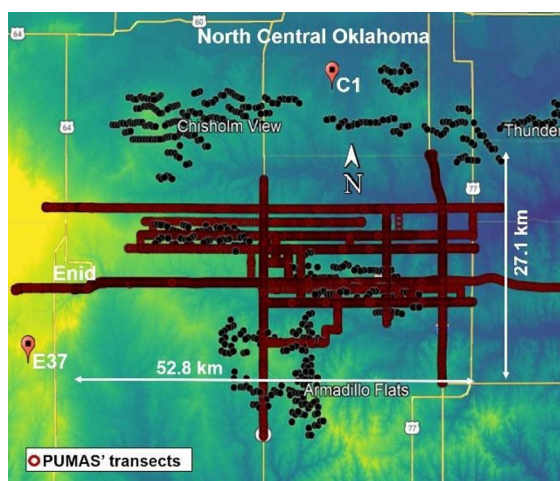


Fig. 2. PUMAS driving transects around wind farms in north-central Oklahoma.

The terrain elevation map (Fig.2) shows wind turbines (black dots) in the research area of North-Central Oklahoma. Dark red symbols show transects covered by PUMAS during the 20 days of its AWAKEN measurement period. Transects were repeated several times during 4-5 hours of measurements each day. Dark red circles represent wind speed profile measurement. At the beginning and end of each transect, 5-minute measurements were often made from a stationary position to use these data for system performance evaluation. Sometimes, stationary data were taken for an hour or longer for future comparison with the AWAKEN stationary Doppler lidars.

White circles in Fig. 2 indicate research sites of the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP). Long-time measurements from the various ARM instruments provide additional information on wind and turbulence in the surrounding area ([www.arm.gov/capabilities/observatories/sgp](http://www.arm.gov/capabilities/observatories/sgp)).

Samples of mobile lidar measurements along the transect segment on Breckenridge Rd on Sep 5 are shown in Fig. 3. Weaker winds ( $<10 \text{ m s}^{-1}$ ) can be seen below 200 m for the predominant SSW wind direction (Fig. 3a). Above this height winds became much stronger ( $\geq 20 \text{ m s}^{-1}$ ) with the episodes of Low-Level Jet ( $\sim 30 \text{ m s}^{-1}$ ). A curtain of the vertical-velocity (Fig. 3b) shows a variable flow structure with updraft and downdraft motions. The combination of the horizontal and vertical wind profiles of 3-D wind flow (Fig. 3c) is shown from the south point of view for better visualization.

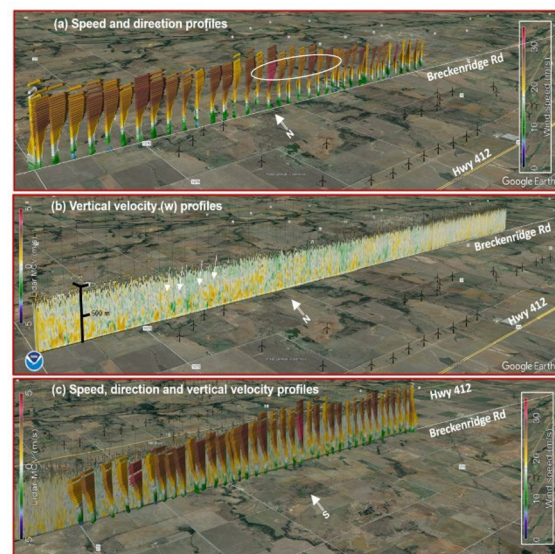


Figure 3. Samples of PUMAS measurements on Sep 5 at 12:47:52-13:03:35 UTC.

These unique measurements offer insight for the first time not only into the temporal and vertical variability of wind flows as it is available from stationary scanning lidars but also reveal the spatial variability of simultaneously measured characteristics of the horizontal and vertical structure of wind flows modified by operating wind turbines.

The high temporal ( $\sim 20 \text{ sec}$ ) and vertical (30 m) resolution of vertical velocity profiles yield unique information about the extent and strengths of the vertical-velocity motions, including thermal updrafts and turbulence at the cloud base.

In addition to observing the signature of wakes along the driving transect, the data are used to estimate wake dynamics at various distances from the wind turbines. Samples of PUMAS' transects during eight hours of measurements

on Sep. 7 from 16:42 UTC to 00:07 UTC are shown in Fig. 4 under SE wind directions.

For the south-easterly winds predominant for this period, the transects were performed to capture turbine outflow, driving on the roads in the east-west or west-east directions. Data from the south-north/north-south transects were used for the referenced flow undisturbed by turbines.

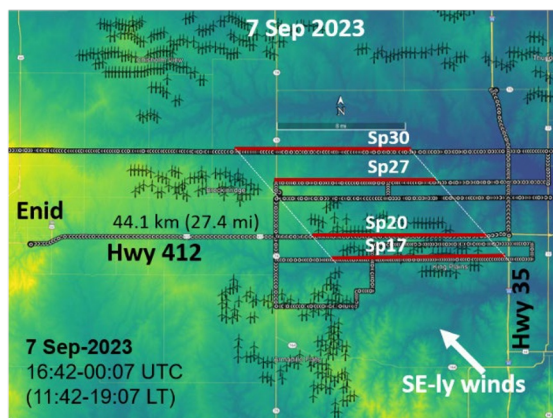


Figure 4. PUMAS' transects on 7 September.

Measurements from four west-east transects of similar length, located within the turbine cluster (Sp17 and Sp20), at 1.6 km (Sp27) and 4.8 km (Sp30) from the top turbines indicate the variability of wind speed (Fig.5).

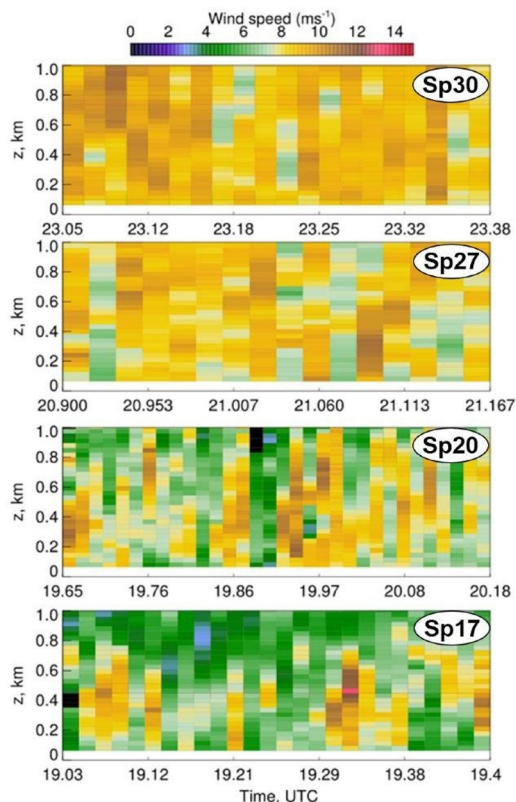


Fig. 5. The variability of wind flows at different distances within/from turbine clusters.

Fig. 5 shows stronger wind speeds farther from wind turbines (Sp30) compared to wind speeds close to turbines (Sp17, Sp20).

The data from mobile lidar will also complement the AWAKEN instrumentation to understand the effect of a large wind farm on wind flows under different background wind conditions and stratification. Measurements can be used as additional information for evaluating wind simulation by models and improving wake model prediction accuracy.

Overall, high-frequency, simultaneous measurements of the horizontal and vertical winds provide a new approach to characterize dynamic processes critical for the wind farm wake analysis

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