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Design of the American Wake Experiment (AWAKEN) field campaign

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Abstract. The American WAKE experimeNt (AWAKEN) is a multi-institutional collaborative field campaign, starting in March 2022, that will gather an unprecedented data set including both atmospheric observations and wind plant operational data. This comprehensive data set will be used to characterize the wind plant performance and turbine loading in different operational and atmospheric conditions and validate the use of different wind plant control strategies and simulation frameworks. An extensive field campaign like AWAKEN requires proper coordination and long-term planning to be successful. In this paper, we review the major activities planned during AWAKEN to provide information for current and future project partners. Specifically, we provide information about the project sites, their planned instruments, and how these will relate to the scientific objectives of the overall AWAKEN project.

1. Introduction

The American WAKE experimeNt (AWAKEN) is a collaborative wake observation and model validation field campaign funded by the U.S. Department of Energy (DOE). The AWAKEN field campaign is scheduled to run from March 2022 to October 2023. The goal of AWAKEN is to better understand the interaction between wind plants and their surrounding environment through coordinated field observations and simulations under different atmospheric conditions (1). These observations aim to look at not only individual turbine wakes but also the wakes produced behind an entire wind plant and other wind plant-atmosphere interactions. Wake interactions are among the least understood physical phenomena in wind plants and add uncertainty to the power predictions, both within a single wind plant and between adjacent plants. The project will generate detailed data sets on wind plant wakes, their interactions with the atmosphere, and their influences on cloud formation and dynamics. The collected observational data set will be used to evaluate the performance and efficiency of operational wind plants and validate numerical models.

AWAKEN will take place in the southern Great Plains of the U.S. Midwest, a location that offers a variety of atmospheric phenomena of interest for wind energy applications. In the southern Great Plains, the gradual west-to-east terrain slope can create diurnal horizontal temperature gradients (2), and a significant number of low-level jet events, particularly in the summertime, have also been observed. Additionally, significant diurnal variations of geostrophic wind up to 6 m s^{-1} have been observed in this region (3; 4) due to diurnal heating and cooling on sloping terrain and the oscillation of the horizontal pressure gradient.

Since 2012, a number of wind plants have been developed in northern Oklahoma, in a region around a large number of instruments which now constitute the DOE Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) observatory. The ARM facility has the world's largest and most extensive climate research facility, operating since 1989, with instruments that can also be configured to measure the impacts of nearby wind plants for the science goals of the AWAKEN project. The ARM sites and the nearby wind plants are presented in Fig. 1. Considering the climatology, terrain, density of the wind plants, and current ARM instrumentation, researchers of the AWAKEN team will deploy additional instruments in this region. Five wind plants (King Plains, Armadillo Flats, Breckenridge, Chisholm View, and Thunder Ranch) have been chosen for the AWAKEN field campaign to evaluate the targeted science objectives. The AWAKEN team has identified 16 instrument sites for this project (Fig. 1). This document describes the preferred instrument locations for the field campaign and also the reasoning behind their placement as well as some details around operating behavior. First, a short summary of the AWAKEN site is provided, followed by a description of by the science goals of the AWAKEN project. Next, we discuss the suite of instruments to be used in AWAKEN and their placement related to the project objectives. Finally, general remarks and future perspectives about the AWAKEN project plan are provided in the Conclusions.

2. Site characterization

The AWAKEN team has examined observations from existing ARM instruments to understand the wind characteristics and the climatology of the northern Oklahoma location. Fig. 2a shows the wind rose, obtained from 3 years of wind observations at a height of 91 m from a lidar deployed at the ARM central facility (ARM SGP site C1). At this site, the wind comes predominantly from the south, with strong seasonal variability (5). The seasonal distributions of wind direction are provided in Fig. 2b. In the winter, wind frequently comes from both the south and the north, showing a bimodal distribution. During the summer months, the winds come more consistently from the south. Wind speed and wind direction of the atmospheric boundary layer (ABL) are also cleanly characterized in terms of atmospheric stability. In the stable ABL, wind directions are dominantly from the south and southeast, and from the south and southwest in unstable conditions (5). Therefore, the AWAKEN project will primarily consider the winds coming from both southwest and southeast directions.

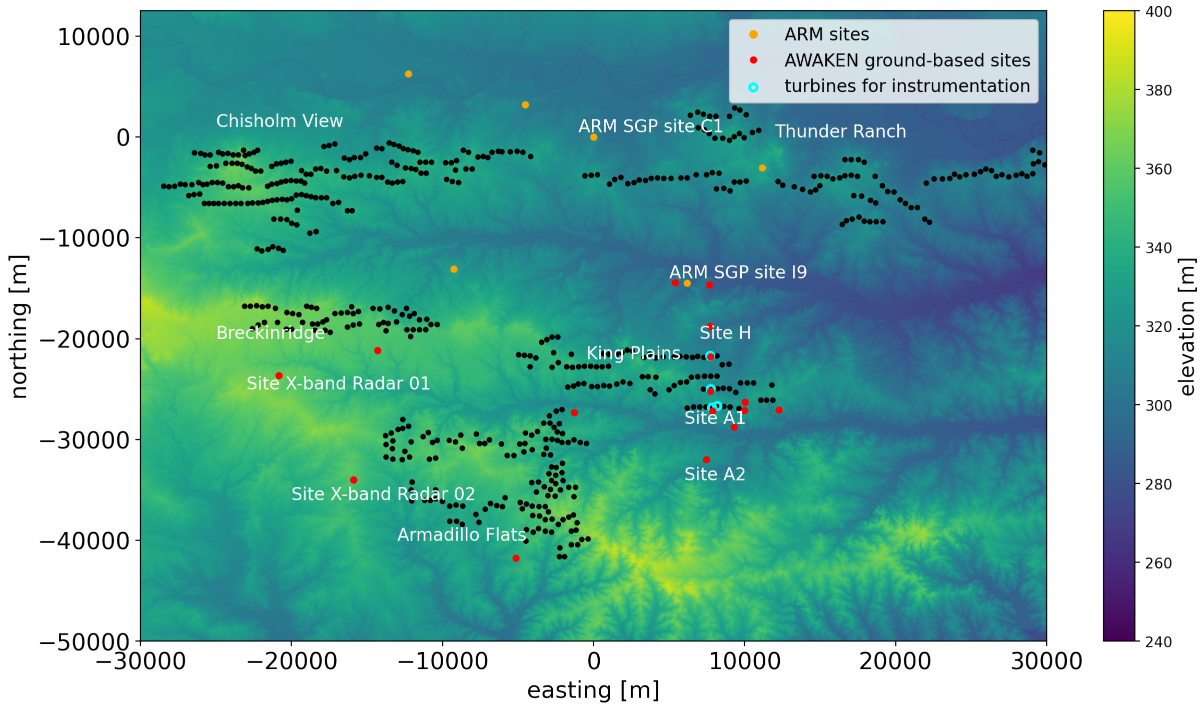

Figure 1: Map of the existing ARM sites and the additional AWAKEN-specific sites created at the SGP location. In the map, the origin of the coordinates is at 36.6073°N, 97.4876°W.

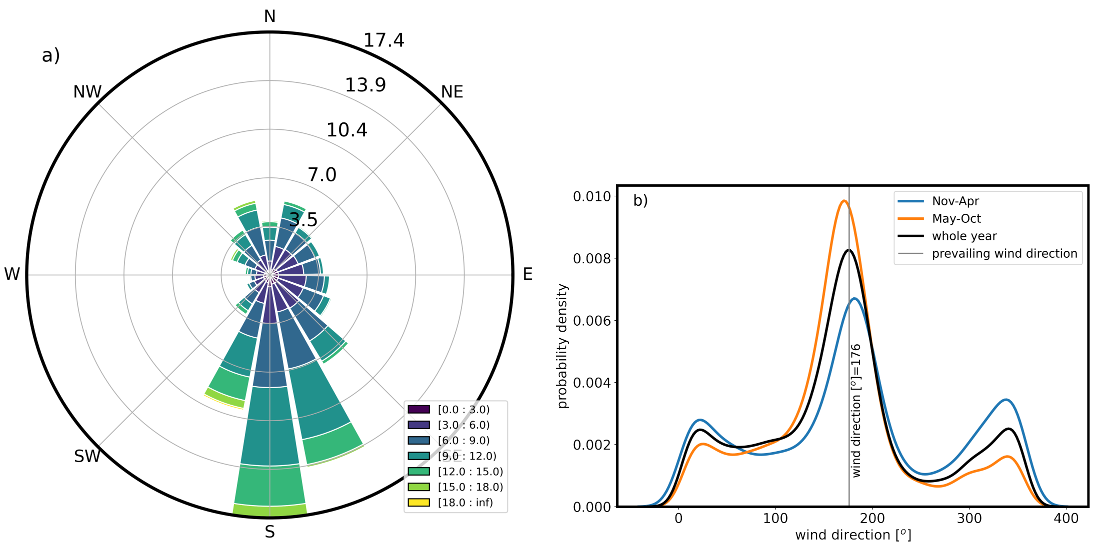

Figure 2: Wind rose at 91-m height (left), and seasonal variability of wind direction at 91-m height at ARM SGP site C1 (right).

3. Objectives of the field campaign

The objective of the AWAKEN project is to relate wind plant aerodynamics and performance to atmospheric physics. The target physical processes are organized into four main categories:

(i) Wind turbine-to-turbine and wind plant-to-plant interactions;

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(ii) Upstream blockage and flow acceleration around the side of wind plants;

(iii) Turbulent transport mechanisms (e.g., momentum flux, heat flux) within and near wind plants, and internal boundary layer above wind plants;

(iv) Control and loading of turbines under different atmospheric and wind plant operating conditions.

Each objective requires different instruments, experimental strategies and measurement capabilities. To begin, the AWAKEN team will leverage the existing ARM instrumentation to increase the measurement capabilities, in terms of data availability and spatio-temporal coverage, of the AWAKEN field campaign. In addition to the instruments permanently located at the ARM SGP site, ARM will also be providing one of their mobile facilities for the AWAKEN project. The list of the ARM Mobile Facility (AMF-3) instruments that have been approved for the AWAKEN project is provided in Table 1. Additional information and documents about the ARM instruments can be found at https://www.arm.gov/capabilities/instruments.

Table 1: ARM instruments, and their approved locations and quantities for the AWAKEN project.

Instrument	Site A1	Site A2	Site H	Site I9
Ceilometer			✓	
Doppler lidar	✓	✓	✓	
Eddy correlation flux station	✓		✓	
Infrared thermometer	✓(2)			
Laser disdrometer				✓
Microwave radiometer	✓		✓	
Met station	✓			
Automatic weather station			✓	
Micropulse lidar	✓			
Multifilter rotating shadowband radiometer	✓			
Radar wind profiler				✓
Sky radiometers (SKYRAD)	✓			
Ground radiometers (GNDRAD)	✓			
Sonde system			✓	
Thermodynamic profiler, AERI	✓		✓	
Total sky imager	✓			
Tipping bucket rain gauge				✓

Furthermore, the instrumentation suite will be augmented by instruments coming from additional partners, including DOE national laboratories, research institutions, universities, and wind industry partners. A summary list of the partner institutions with their instrument categories are provided in Table 2. The broad categories of the instruments coming to the AWAKEN project are meteorological (met) towers or met stations, scanning lidar, profiling lidar, X-band radar, radar wind profiler, thermodynamic profiler, radiosonde, surface flux station, microwave radiometer, precipitation measurement sensors such as disdrometers, and load measurement sensors. Finally, the CLAMPS facility (CLAMPS stands for Collaborative Lower Atmospheric Mobile Profiling System) is a package of instruments with a Doppler lidar, a microwave radiometer (MWR), and an atmospheric emitted radiance interferometer (AERI).

Table 2: Partnership with different institutions, and the category of instruments participating in the AWAKEN project.

Institutions	Instruments	Quantity
École Polytechnique Fédérale de Lausanne (EPFL)	Scanning lidar	3
Lawrence Livermore National Laboratory (LLNL)	Scanning lidar	1
	Profiling lidar	3
National Oceanic and Atmospheric Administration (NOAA)	CLAMPS facility	1
	Mobile lidar	1
National Renewable Energy Laboratory (NREL)	Scanning lidar	4
	Profiling lidar	1
	Nacelle-mounted commercial lidar	1
	Thermodynamic profiler, ASSIST-II	3
	X-band radar	1
	Load sensors	9
Pacific Northwest National Laboratory (PNNL)	Scanning lidar	1
	Met station	7
	Sonic anemometer	3
	Laser disdrometer	5
Sandia National Laboratories (SNL)	90-m tall meteorological tower	1
Texas Tech University	X-band radar	1
University of Colorado at Boulder	Profiling lidar	2
The University of Oklahoma	CLAMPS facility	1
University of Texas at Dallas	Scanning lidar	2
	Met station	1

4. Methodology

4.1. Process overview

The wide variety of instruments will provide unprecedented insight into the physical processes of interest but will also increase the complexity of the field deployment process (6; 7). Researchers have considered several factors to determine the optimal deployment strategy for the instruments with regard to each scientific objective (Fig. 3). First, the capabilities of the instruments are identified and connected to a particular scientific phenomenon. The most relevant parameters to characterize the capabilities of an instrument are its measurement range, probe length, temporal resolution, spatial resolution, and data availability as a function of the atmospheric conditions. Before assigning an instrument to a particular scientific goal, the coordination capability of the instrument with other instruments is checked. Logistical constraints, such as power supply, land use restrictions, and local terrain are used to finalize the locations. Once a preliminary layout of all available instruments is created, the measurement designs are evaluated with virtual instrumentation in NREL's large-eddy simulation tool SOWFA (Simulator fOr Wind Farm Applications) (8; 9) and mid-fidelity tool FAST.plant (10). Simulations are used to test

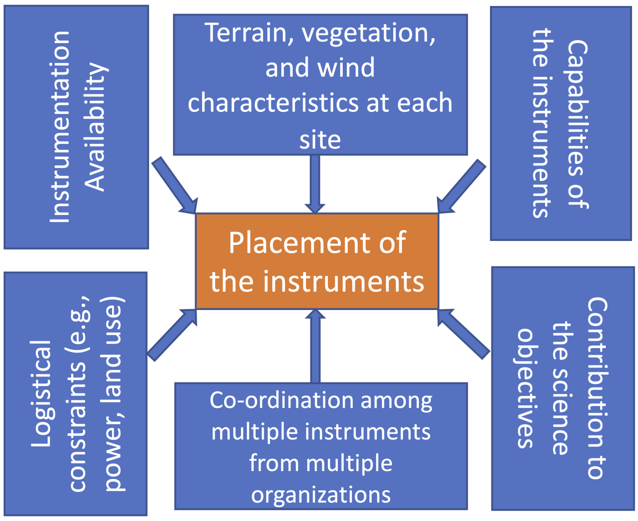

Figure 3: Criteria used to determine the optimal deployment strategy for the instruments of the AWAKEN field campaign.

instrument accuracy using different retrieval algorithms, whose results will be subject of a future publication.

4.2. Science goals and corresponding instruments

(i) Plant-to-plant interactions:
Plant-to-plant interactions of wakes are considered among three wind plants: Armadillo Flats, King Plains, and Breckinridge, due to their close proximity in the dominant southerly wind direction. The wake of Armadillo Flats will interact with the King Plains and Breckinridge wind plants for wind directions from the southwest (or south) and southeast, respectively. Plant-to-plant interactions will be measured using long-range remote sensing instruments, mainly X-band radars (see Fig. 4a), to the north and west sides of the Kings Plains wind plant. X-band radars have a range of 32 km depending on the atmospheric conditions and will be able to observe large-scale wake interactions among the three wind plants. The radars will be scanning at multiple elevation angles to retrieve wind speeds at hub height and above using the dual-Doppler strategy. The wind plant wake of an individual wind plant (King Plains) under different atmospheric conditions will be observed using long-range, nacelle-mounted scanning lidars, shown in Fig. 4b. Four turbines in the King Plains wind plant will be equipped with a total of five nacelle-mounted lidars, including two long-range scanning lidars that will measure up to 10–12 km upstream and downstream of King Plains (see Fig. 4b). The scanning lidar on a turbine in the southernmost row will be forward-facing, and the lidar on the turbine of the northernmost row will be rearward-facing. Both scanning lidars will be scanning a $\pm 45°$ azimuth sector with $0°$ elevation angle from the nacelles. For a southwest wind direction, the long-range scanning lidar of the southernmost row can be reoriented to capture the wake interaction between the Armadillo Flats and King Plains wind plants.

(ii) Blockage and speedups:
The power extraction and associated thrust force of a wind turbine induces a pressure field that reduces the velocity upstream of the rotor and creates speedups around the rotor. Aggregating these effects in a wind plant leads to upstream flow blockage that can reduce production of the wind plant as a whole. The blockage and possible speedups brought about

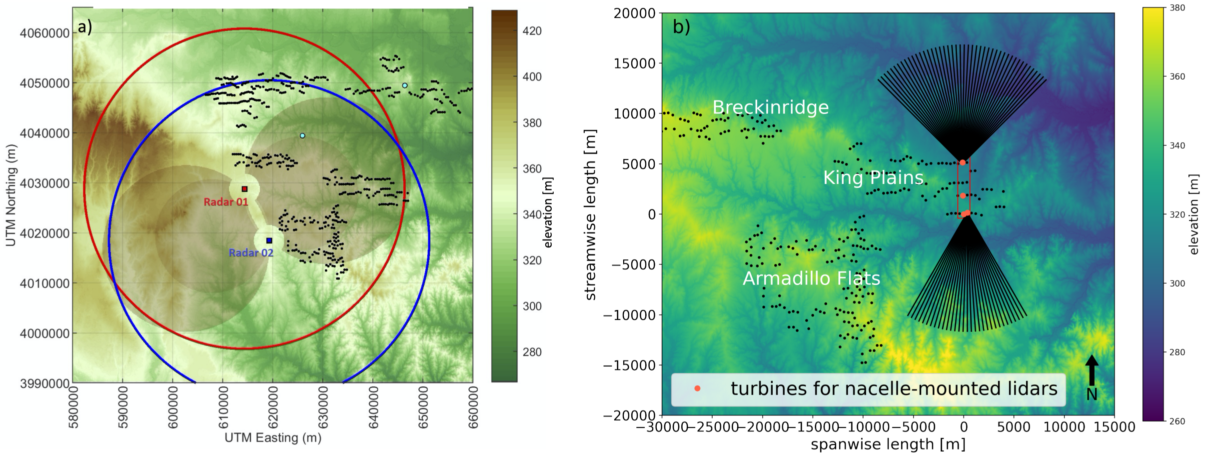

Figure 4: (a) Two X-band radars and their coverage areas and (b) nacelle-mounted lidars planned to measure downstream and upstream of King Plains wind plant.

by the wind plant will be measured in the AWAKEN project with multiple remote sensing instruments. Considering the dominant southerly flow, two forward-facing Doppler lidars will be placed on turbine nacelles in the southernmost row, shown in Fig. 4b. A WindCube Nacelle forward-facing lidar will measure incoming wind speeds over a range of 50 m to 400 m upstream of the turbine and will focus on blockage near the turbine. A scanning lidar can measure from 150 m to 10–12 km and will focus further upstream to characterize the atmospheric flow approaching the wind plant and eventual speedups occurring at the sides.

(iii) Internal boundary layer above wind plants:
As the wind turbines extract energy from the atmospheric flow, they produce a wake region with lower momentum and higher turbulence intensity. Consequently, the wind accelerates around the wind turbine to balance the mass and momentum. A wind plant creates extra surface roughness to the lower surface of the atmospheric boundary layer due to the downstream low wind speed flow and turbulence, and therefore creates an internal boundary layer within and above the wind plant (11). The internal boundary layer above the wind plant will be captured through the coordinate scans of two lidars. Specifically, two scanning lidars located upstream and downstream of King Plains wind plant will create a dual-Doppler scan pattern to retrieve streamwise and vertical components of wind flow to provide ABL flow above the King Plains wind plant. The scanning pattern of the lidars and estimated errors of the targeted retrievals from the scanning pattern are provided in Fig. 5b,c (refer to Stawiarski *et al.* (12) for detailed information).

(iv) Atmospheric boundary layer profiles:
The AWAKEN team is interested in measuring the wind profile up to the ABL height. Depending on the atmospheric conditions, the ABL height can extend up to a couple of kilometers above ground level. Commercial profiling lidars are limited to 300 m in height; therefore, long-range scanning lidars will be used to measure the ABL profile. Four scanning lidars will be used to measure the ABL profiles upstream and downstream of the King Plains wind plant. The scanning lidars will be performing high-elevation velocity-azimuth display and vertical scans to retrieve the three components of the wind field up to a couple of kilometers with 30-m vertical resolution. The sites where the atmospheric boundary layer profiles will be measured by different scanning and commercial profiling lidars are shown in Fig. 6. Dual-Doppler scanning strategy will be used to create multiple virtual towers

to the south of the King Plains wind farm. Considering the scope of the article, detail information about the virtual towers that will be created by two Halo XR+ scanning lidars is not provided. In addition to the lidars, a 915-MHz radar wind profiler at ARM SGP site I9 will measure wind speed profile from a height of 150 m to a couple of kilometers, depending on the atmospheric conditions.

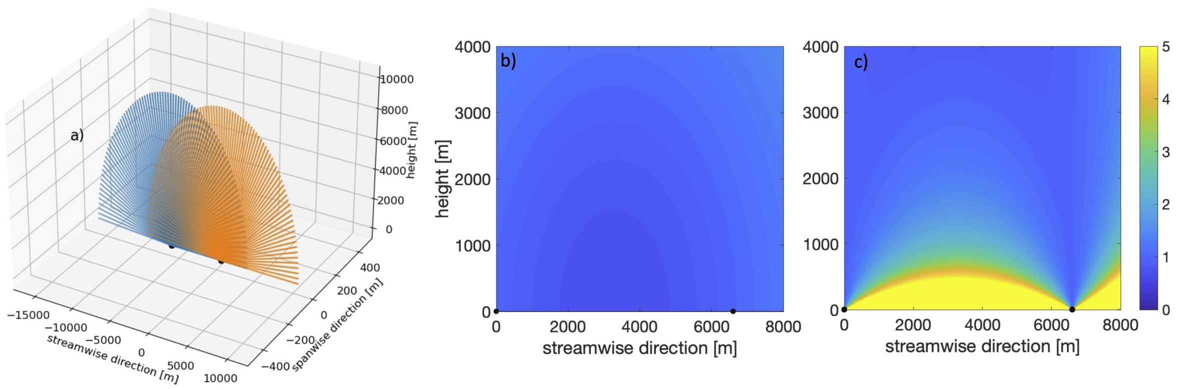

Figure 5: (a) Ground-based lidars with co-planar scan to retrieve wind profiles above the King Plains wind plant. Error magnifications due to the retrieval of (b) the streamwise component and (c) the vertical component according to (12).

(v) Thermodynamic profiles:
In addition to wind speed profiles, researchers will observe profiles of temperature and moisture (water vapor) in the AWAKEN field campaign. Influence of wind plants on the temperature and moisture throughout the ABL will be captured by five thermodynamic profilers strategically placed within the field campaign domain, as shown in Fig. 6. The thermodynamic profilers measure the radiance spectrum of the atmosphere, and the TROPOe (13) algorithm will be used to retrieve temperature and moisture profiles from up to 3 km with vertical resolution of approximately 60 m. Among five thermodynamic profilers, three are atmospheric sounder spectrometer for infrared spectral technology (ASSIST-II) systems, and two are atmospheric emitted radiance interferometer (AERI) systems. Considering the southerly wind direction, two thermodynamic profilers are placed upstream of the Armadillo and King Plains wind plants (one for each plant), and two are placed downstream of the same wind plants. Measurements of temperature and moisture profiles at different locations will provide a better understanding of the roles of atmospheric stability and mesoscale phenomena on the spatial variability of wind speed. In addition to the thermodynamic profilers, microwave radiometers, micro-pulse lidars, ceilometers, and skyrads are scheduled to measure different cloud properties such as liquid water content, cloud heights, and down-welling and up-welling radiation.

(vi) Surface turbulent fluxes:
Surface met stations provide near-surface wind speed and thermodynamic variables such as moisture, temperature, and pressure as well as turbulent fluxes of momentum and heat. Near-surface turbulent fluxes are important variables to characterize the evolution of the ABL under the influences of different atmospheric processes such as the diurnal cycle and baroclinicity. Measurements from the surface met stations will be used as boundary conditions for numerical simulations. A number of surface measurement stations distributed

in different locations of the AWAKEN field campaign domain (Fig. 6) will quantify the impact of wind turbines and wind plants on the surface layer properties of the ABL.

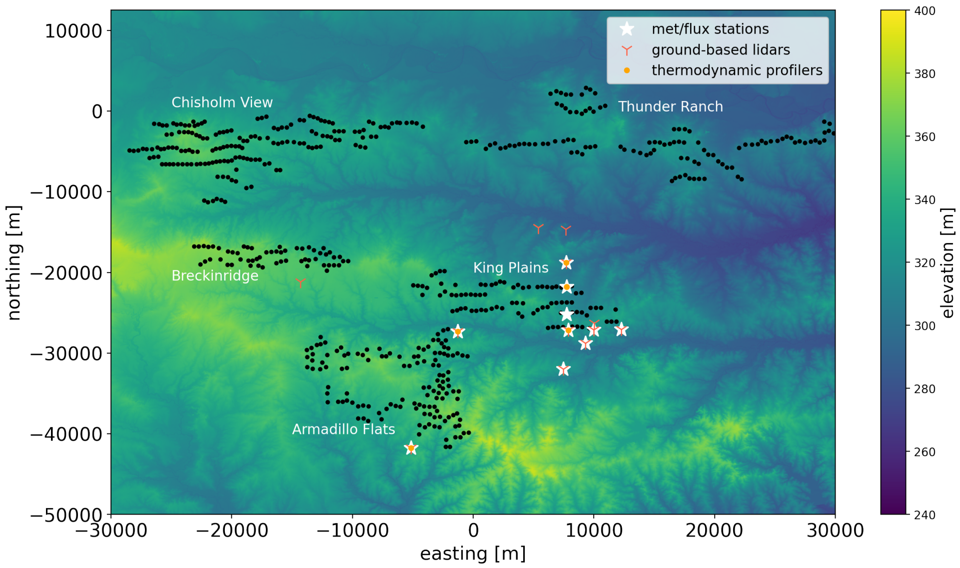

Figure 6: Locations of different set of instruments planned in the AWAKEN project.

(vii) Control of wind turbines:
Two wind plant control strategies will be investigated as part of the AWAKEN experiment: 1) consensus control (14; 15), in which wind direction measurements from multiple wind turbines are combined to improve the estimation of local wind directions, and 2) wake steering (16; 17; 15), where upstream wind turbines are misaligned with the wind to deflect their wakes away from downstream turbines, increasing net wind plant power production. Researchers will implement these wind plant control strategies at the King Plains wind plant, which consists of 88 modern wind turbines with a rotor diameter (D) of 127 m and hub height of 88.5 m. The King Plains wind plant has advanced data acquisition and control systems that make it well-suited for implementing wind plant control algorithms. Although consensus control will likely be implemented throughout the wind plant, the wake steering portion of the experiment will initially be performed on a 3 $\times$ 4 array of wind turbines on the east side of the wind plant (indicated by a rectangular box of red color in Fig. 4b). This 12-turbine array—which includes several turbines with loads sensors and nacelle lidars installed—consists of three columns of four turbines each, oriented in the north-south direction (roughly corresponding to the predominant wind direction, as shown in Fig. 2) with turbine separations ranging from ~10 to 15.5 D within each column. The three columns are in turn spaced roughly 3–3.5 D apart in the east-west direction.
Consensus control is used to improve the accuracy of wind direction estimates at wind turbine locations compared to standard nacelle wind vane measurements, which measure turbulent flow behind the rotor, are limited to sampling the flow at a single point, and may suffer from poor calibration. Two consensus control methods will be considered in the project: 1) a simple weighted average of wind direction measurements from neighboring turbines (15), and 2) the consensus-based optimization algorithm using information from all turbines in the wind plant discussed by Annoni *et al.* (14). Replacing the turbines' wind vane measurements with more accurate consensus wind direction estimates is expected to increase energy capture through better alignment with the wind while also reducing yaw

travel, thereby improving yaw actuator reliability. Note that the reduction in yaw travel is expected to help balance the increase in yaw activity typically caused by wake steering control.

Wake steering will be implemented using an approach similar to the method described by Fleming *et al.* (17), in which low-pass-filtered wind speed and wind direction measurements are used as inputs to a yaw offset lookup table. To assess the impact of wake steering and consensus control on energy production and yaw travel, portions of the wind plant will be toggled hourly between control modes. Initial plans include toggling a subset of turbines on the west half of the wind plant between baseline and consensus control while toggling the 12-turbine array on the east side of the wind plant between baseline control and combined consensus and wake steering control. Finally, several turbines operating without wind plant control will be used as references to which the controlled turbines can be compared.

(viii) Turbine loads instrumentation:
Three wind turbines (three of four turbines shown in Fig. 4b) will be instrumented for mechanical loading for the AWAKEN field campaign. The turbines will be instrumented to measure tower bending, tower-top torque, low-speed shaft bending, low-speed shaft torque, and blade root bending using strain gauges. Additional sensors include an absolute yaw encoder to measure the turbine's yaw angle with respect to true north, an absolute encoder to measure rotor position, a proximity sensor to measure high-speed shaft speed, and sensors to independently measure turbine power. A National Instruments PXI-based data acquisition system (DAS) will synchronously record data from sensors at 50 Hz using GPS timestamps for all samples. Additionally, data from the wind turbine's supervisory control and data acquisition (SCADA) system will also be integrated into the DAS. The time-series data collected from these instruments can then be translated to component loading and used for ultimate load and fatigue analysis. In this experiment, the measurements will be used for model validation as well as a direct comparison of how wake steering affects turbine loads on a wind plant level.

5. Conclusions

Including the two radar sites, in total, 16 ground-based sites and 4 turbines have been identified for instrument deployment for the AWAKEN field campaign. The locations of the sites for all the instruments with respect to wind plants are provided in Fig. 1. Each site can have multiple instruments depending on the capabilities of the instruments and their contributions to the objectives of the campaign. The sites A1 and H are identified as primary inflow and downstream sites for the King Plains wind plant, with many more instruments than other sites to best quantify the impact of the wind plant on not only the wind speed and turbulence, but also other important atmospheric quantities such as energy flux, surface heat flux, temperature, and humidity profiles. Site A1 also contains a significant amount of ARM instrumentation focused on cloud observations, which is a science goal created in conjunction with the request for the ARM AMF-3 mobile facility to observe the potential impact of wind plants on cloud formation. The partnership among different institutions provided a set of instruments that will provide an unprecedented data set to understand the atmospheric and wind plant phenomena and validate numerical models. We plan to extend our partnership with many other institutions during the field campaign process so that wind industry organizations and research institutions can benefit from the AWAKEN field campaign. The non proprietary data sets will be publicly available after the field campaign.

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