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Innovative Technologies to Investigate Fine-Scale Wind Flow

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Abstract

Scientists and engineers understand the need to observe and predict the structure of the atmosphere at relatively small scales. While the importance of characterizing the lower atmosphere is ubiquitously recognized, historical progress has been stymied. Texas Tech University (TTU) has developed several new observation technologies to help fill this identified need. These technologies include two high-resolution mobile research Doppler radars capable of resolving relevant information from clear-air and precipitating atmospheres, and a small tower technology termed StickNet which allows rapid deployment of dense instrument arrays to make near-surface measurements of highly transient atmospheric phenomena.

Introduction

Wind engineers have spent many years defining the structure of atmospheric turbulence using in-situ anemometers; they now recognize the need to examine the spatial continuity of their assumptions, document the spatial context and intermittency of coherent turbulence, and record and understand the micro-scale structure of extreme events. The understanding of fine-scale motions within extreme events has a direct effect on our ability to engineer resistant structures. At the same time, these same small-scale motions are important in maximizing power output from wind turbines and mitigating fatigue loads which could detrimentally impact the wind power industry in the coming decades. Atmospheric scientists have also developed a growing respect for the influence of fine-scale structures on larger scaled atmospheric events. There are a host of atmospheric phenomena such as tornadogenesis and convective initiation, rich in dynamical complexity, that are dependent on small-scale atmospheric motions relatively close to the ground.

The major impediment in lower atmospheric research is the inability to accurately observe the three-dimensional wind flow with adequate spatial and temporal resolution, especially for phenomena which are highly transient (e.g. thunderstorms). Hence, assumptions about the characteristics of the lower atmosphere persist in engineering design, wind power analyses, and atmospheric modelling efforts. TTU has developed several observation technologies to help fill this identified need. These technologies include two high-resolution mobile research Doppler radars capable of resolving relevant information from clear-air and precipitating atmospheres, and a small tower technology termed StickNet which allows rapid deployment of dense instrument arrays to make near-surface measurements of highly transient atmospheric phenomena.

StickNet

Over the previous decade, TTU has developed or shared in the development of various observational assets to observe the structure of the lower atmosphere. These include the West Texas Mesonet (Schroeder et al. 2005), mobile mesonet platforms (Straka et al. 1996), the Shared Mobile Atmospheric Research and Teaching radars (Biggerstaff et al. 2005), multiple portable instrumented towers used largely for landfalling hurricane research (Schroeder and Smith 2003), and a 200 m tower meteorological tower. The use of these observational assets has enabled a wealth of research, but fundamental needs remained.

Providing detailed, near-surface observations within thunderstorms provides a challenge which could not be met with the existing facilities. Thunderstorms are a highly transient event, and the inability to effectively predict the location of a thunderstorm updraft or mesocyclone even one hour before its passage complicates deployment of a dense observational network. Mobile mesonets can effectively be used in and near thunderstorm events to gather scientifically relevant information, but hazards (e.g., hail and tornadoes) often limit their widespread deployment in the most critical areas. Deploying a dense network of instrumented towers offers an alternative, but the long lead time required for deployment of the traditional 10 m towers made them ineffective for thunderstorm applications.

At the same time, acquiring information from the near-surface region of landfalling hurricanes is also of interest to many given the dismal performance of operational automated weather observing systems (Blessings and Masters 2005) in the United States. Several institutions, including TTU, have maintained programs to collect meteorological information from landfalling hurricanes using deployed towers and/or research radars since the late 1990's, but Hurricane Katrina's landfall in 2005 continued to underscore a fundamental problem. Specifically, even with the efforts to deploy ruggedized instrumented towers, the near-surface wind field was still inadequately sampled. In Katrina, only a few observations were collected from the eyewall region. This relative dearth of data at landfall leads to increased uncertainty of storm intensity and adversely impacts all post-storm activities (e.g. emergency response, evaluation of structural performance relative to design standards, etc.) and research. Recognizing the combined thunderstorm and hurricane observational needs, TTU worked to develop a new observational platform called StickNet.

Working with graduate students in the Wind Science and Engineering and Atmospheric Science programs at TTU, the StickNet platforms were developed through iterative design projects in several Atmospheric Science graduate courses. The StickNet platforms are portable, versatile, rapidly-deployable probes (Figure 1A) that measure standard atmospheric state variables at sampling frequencies up to 10 Hz. The StickNet monitoring platforms, and associated infrastructure, have been developed using a variety of funding mechanisms totalling over $500,000 US since 2005. However, individual probes are relatively inexpensive (~$10,000 US), enhancing the ability to place at least some of the platforms into precarious, and therefore scientifically unique, situations. Twelve of these compact units are packed into one small covered trailer as shown in Figure 1B. When these compact units are coupled with short deployment timelines, and years of field experience, it allows for the acquisition of high-resolution temporal wind information at previously un-imagined spatial resolutions.

Figure 1. A third generation type “A” StickNet observational platform deployed in the thunderstorm configuration (A) and associated transport trailer (B).

Design and Construction

The design specifications for the StickNet platforms were based primarily on the scientific and engineering needs to acquire research-grade meteorological measurements from hazardous regions within thunderstorms and hurricanes. Given the highly transient nature of a thunderstorm event, the platforms were to support rapid deployment in order to allow the critical regions of the storm to be predictably sampled with a dense instrument array. At the same time, given the potentially long lasting winds of a hurricane, the platforms were to support data collection for several days without interruption. Measurements were to include wind speed and direction at a height of at least 2 m, temperature, relative humidity, and barometric pressure. The sampling rate was expected to be 1 Hz or greater. Additionally, the platforms were required to record information such as position (latitude and longitude), orientation (bearing with respect to magnetic or true north) and time (allowing synchronization of the internal clock controlling the data acquisition system). The monitoring units were to support data collection for a period of up to four days, and maintain stability in 55 m s^{-1} sustained wind speeds. Beyond the individual platform requirements, there were also system requirements. The individual platforms were to collapse down, enabling the transport of 12 or more units within one covered trailer. The trailer was to support data and power networks, allowing data download and battery recharge of all platforms while in motion. Finally, a communications system for each platform was to be designed to enable real-time transfer of data to end-users.

The development of the current StickNet fleet occurred in three main phases. The initial idea was conceived in 2004, and student design projects resulted in two unique prototype systems in 2005 (Schroeder and Weiss 2008). The two prototype designs were constructed during the fall of 2005 and tested in thunderstorm environments the following spring. Based on the initial testing, a second design iteration occurred during summer 2006, which was followed by mass construction of 20 additional units in the fall of 2006 and spring of 2007. The first full scale testing of the units and the associated logistical plans for the thunderstorm environment occurred in spring 2007. A third design phase occurred in 2010 when half of the StickNet fleet were upgraded to provide real-time telemetry and enhance reliability. Currently, there are 24 fully functioning StickNet platforms which are transported using two small covered trailers. Half of the fleet maintains the real-time data transmission capability. There are plans to upgrade the remaining 12 units to include real-time telemetry, and TTU maintains interest in expanding the fleet to 48 in the coming years.

The initial development of two prototype systems still permeates through the current platform inventory. The main difference between the two prototypes is the chosen instrumentation, with the 20 “A” probes maintaining a RM Young 05103V Wind Monitor (propeller vane anemometer), RM Young 41382 temperature/relative humidity sensor, and Vaisala PTB101B barometric pressure sensor, while the four “B” probes incorporate the Vaisala WXT510 Weather Transmitter (all-in-one instrument), which includes a sonic anemometer and an acoustical precipitation sensor useful for denoting periods of rain and hail fall. The initial StickNet inventory maintained 12 of each prototype, but the WXT510 Weather Transmitter was deemed unreliable through the initial years of deployment and a larger percentage of “A” probes was slowly introduced.

The modified engineering tripod and mast system, internal battery, GPS receiver, compass, voltage boost regulator and controller module are common to both prototypes, but the instrumentation differences across the two prototypes require slightly different data acquisition components. All communications on the "B" probes (to/from the Vaisala WXT-510 Weather Transmitter, GPS receiver and compass) employ a serial RS-232 protocol, while the suite of meteorological instruments employed by the “A” probes provide analog output. Hence, the "A" probes require an additional analog-to-digital module, but result in higher sampling rates. The enclosed components of an edition three "A" StickNet probe are shown in Figure 2.

All StickNet platforms use a custom software application developed using National Instruments (NI) LabVIEW. The application controls data acquisition and storage functionality, but also completes a number of other tasks. Upon deployment, the StickNet systems are switched on by the user. The unit immediately seeks to provide a satellite lock for the GPS receiver, while at the same time reading the compass to record platform orientation. Once the positioning information is acquired, the system clock is updated using the newly acquired GPS information and a brief instrument test is performed. Upon completion of the entire warm-up cycle, the external LED indicator provides the user feedback that the data acquisition has started.

The third generation StickNet platforms provide real-time data telemetry utilizing an Internet In Motion 2000Z Cell Router and four port Cell Router platform. The device is an industrial Internet Protocol (IP) router that provides broadband wireless communications using both dynamic and static IP networks. The router provides a Linux 2.6 OS that employs an in-house shell script to retrieve the meteorological observations (wind speed, wind direction, temperature, pressure and relative humidity) measured by the StickNet platform instrumentation and collected/stored on the NI controller. A Netgear ProSafe five-port Ethernet switch is used to bridge the gap between the NI controller and the Cell Router platform. Once the data has been acquired by the router, a secure shell network protocol is used to securely channel the data over to server at TTU. The real-time meteorological observations are then displayed and disseminated to major stakeholders and various government entities via a website.

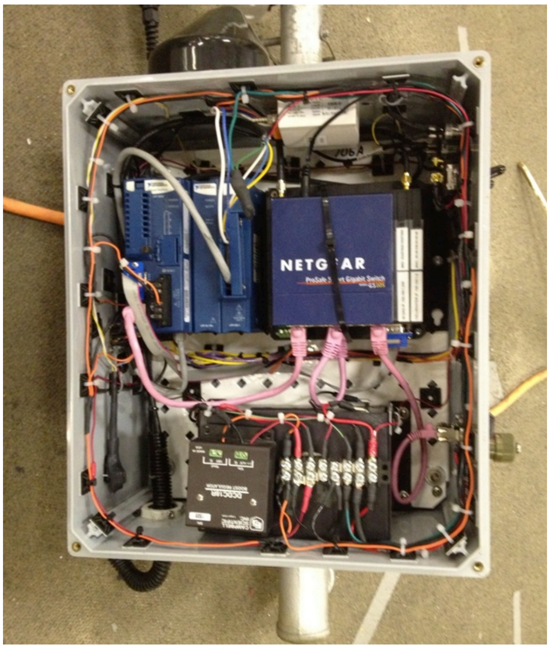

Figure 2. A third generation type “A” StickNet probe enclosure and its components.

To accommodate required deployment timelines of less than 120 seconds for thunderstorm applications, but retain enough power for hurricane applications, two separate deployment configurations were developed. For thunderstorm applications, an internal battery provides data acquisition for approximately 18 hours, while the hurricane configuration employs an external battery. The external battery allows unit functionality for a period of seven days and also adds approximately 36 kg (80 lbs) of deadweight to the unit, which is useful for stabilization in high winds. For a thunderstorm application, the unit is anchored using three 46 cm (18 inch) stakes driven perpendicular to each leg into the ground. For hurricane deployments, these stakes are coupled with an earth screw anchor which is tethered to the center of the unit. The dead weight of a fully deployed unit using the hurricane configuration is approximately 64 kg (140 lbs). Initial engineering studies and field testing indicates the primary failure mechanism for the thunderstorm configuration is bending of the driven stake, not failure of the tripod itself. The thunderstorm configuration is estimated to resist winds of approximately 62.5 m s^{-1} (three-second gust), while the hurricane configuration would resist substantially more but has never been formally estimated. To date, the highest wind speeds recorded by the system was a wind gust of 53 m s^{-1} which occurred in Hurricane Ike. The deployment timeline for thunderstorm applications is approximately 60-120 seconds, while the additional battery and anchoring provided for hurricanes results in a slightly longer deployment timeline of approximately 180-300 seconds for hurricane applications.

Deployment Logistics

For hurricane deployments, two trucks pull the small covered trailers into the impacted region about 48 hours prior to the expected landfall. Starting about 18-30 hours prior to landfall, a course array of StickNet deployments is completed. A secondary deployment phase occurs 0-12 hours before landfall, during which a fine-scale array is nested within the course array in the region where the maximum winds are expected. While the majority of the deployments are devoted to providing coverage of the wind speeds in the landfall region, some deployments are dedicated to specific scientific objectives. In particular, there has been a significant effort to position the StickNet probes as close to the coastal interface as possible, given the inherent research interest in marine exposure and the change in wind speeds along and just inland from the coast. This experimental plan requires monitoring the expected storm surge levels closely and using this data coupled with elevation information to make intelligent deployment decisions. One major advantage of a StickNet platform over the historically employed trailer mounted 10 m towers is the ability to deploy StickNet probes in precarious situations on foot. This advantage has been used countless times to place StickNet platforms on sand dunes right along the coast as shown in Figure 3. Upon completion of the deployment effort, 24 StickNet units are deployed in about one day by four trained individuals using two vehicles.

For thunderstorm deployments, two additional pickup trucks are employed to reduce the deployment timeline of all 24 platforms to an hour. Each additional vehicle transports five StickNet units in the bed of the truck using custom mounting and bracing systems (Figure 4). The inclusion of two additional trucks (which do not tow trailers) enhances the team’s ability to make quick decisions (and turnarounds) as the most dangerous part of the storm approaches. During the second iteration of the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) project (2009-2010), the StickNet fleet was dedicated to making observations from the areas within and near the low-level mesocyclone in an attempt to document the local kinematic and thermodynamic fields. One and two-road idealized experimental plans were developed, such as that shown in Figure 5. In this case, the teams place themselves about 75 minutes in front of the updraft and low level mesocyclone (found in the rear portion of the storm). About 60 minutes before the updraft is estimated to cross the westernmost road, the field coordinator announces the first estimated crossing point, “A1”, and a truck pulling a trailer starts to deploy a course array working north to south on the westernmost road. A short time later, an estimated crossing point on the easternmost road (“B1”) is announced and another truck/trailer starts the deployment of second course array. As the storm updraft continues to progress towards the deployment array and the confidence in the crossing points increases, the deployment of fine-scale arrays is initiated using the vehicles which are not towing trailers. By this time, the course array deployments are typically completed and the trailers are being moved south of the storm to protect them against any threatening winds associated with the rear flank downdraft and gust front, while the remaining StickNet platforms are placed immediately in front of the most crucial portion of the storm. At any time during the deployment process, the field coordinator may update the crossing points and shift the remaining deployments northward or southward (“A2” or “B2”). Upon completion of the deployment effort, 20-24 StickNet units are deployed in about one hour by 12 trained individuals using four vehicles.

Figure 3. StickNet probe 0108A deployed on a sand dune for Hurricane Irene (2011).

Figure 4. Five StickNet units mounted in the back of a pick-up truck for thunderstorm operations.

Deployment and Data Examples

The StickNet platforms have contributed to thunderstorm field campaigns every year since 2007, and have also been deployed along the United States southern and eastern coasts for Hurricanes Dolly, Gustav and Ike in 2008 and Hurricane Irene in 2011.

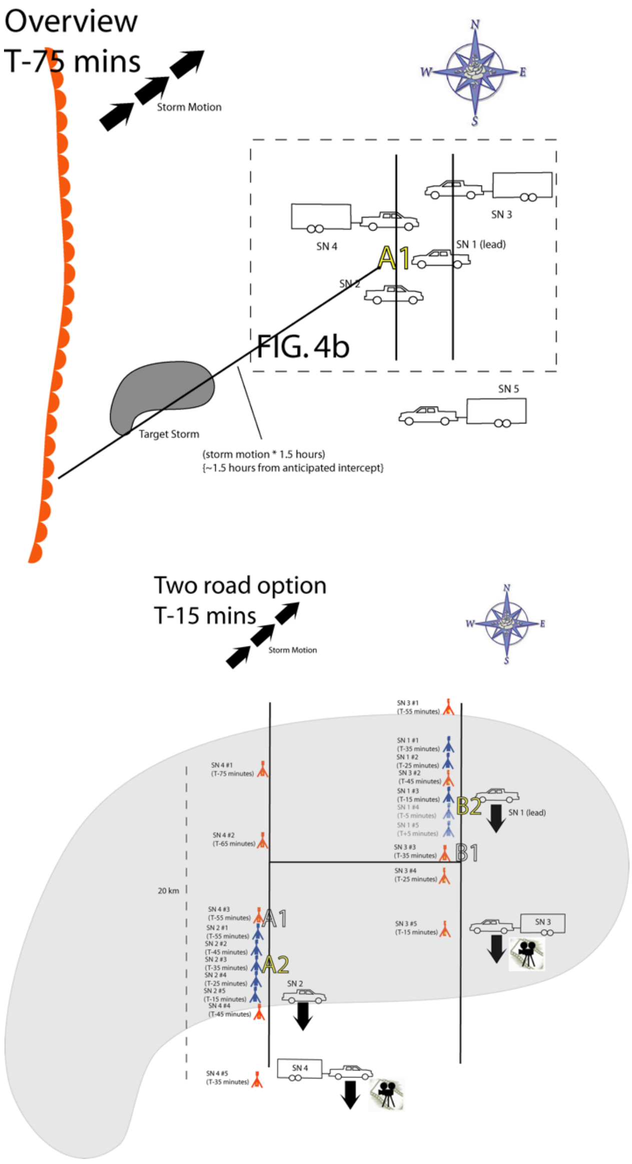

Figure 5. An overview (top) and detailed schematic (bottom) of a typical StickNet deployment strategy. The orange probes denote the coarse array; blue probes indicate the fine array. Center positions “A2” and "B2" are indicated with yellow text indicating the most recently announced center point. Downward arrows denote motion of deployment vehicles. Shading represents typical coverage of rainfall associated with the target storm.

An example of StickNet deployment made for a supercell thunderstorm along a single road oriented northwest to southeast near Perryton, Texas on 23 May 2007 (Skinner et al. 2011) is illustrated in Figure 6. The deployment array is overlaid with radar imagery provided by Shared Mobile Atmospheric Research and Teaching radar, which indicates that the array sampled the forward and rear flank downdraft regions of the supercell thunderstorm with the low-level mesocyclone passing through the northern portion of the array. A tornado was confirmed to the west of the array, but the storm cycled as it approached the road and the tornado decayed prior to reaching the StickNet array. Some examples of the collected wind speed and direction time histories are shown in Figure 7.

Another deployment example (Figure 8) is included from Hurricane Irene (2011), in which all 24 StickNet platforms were deployed along the Outer Banks of North Carolina. This particular deployment was the first time half of the StickNet platforms transmitted data in real-time, which lead to the integration of the data into the NOAA Hurricane Research Division H*Wind product and various National Weather Service products.

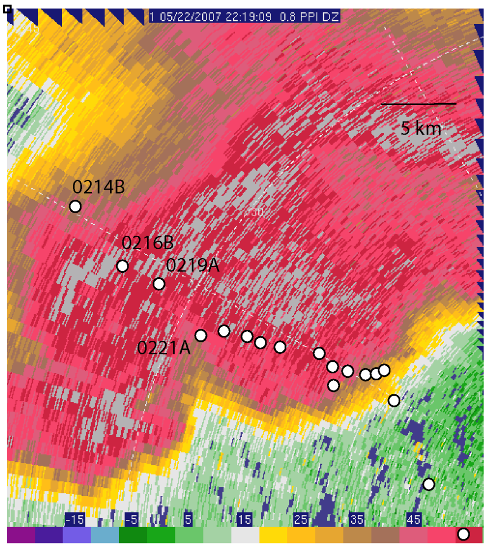

Figure 6. Coordinated StickNet deployment for a supercell thunderstorm on 23 May 2007. StickNet locations are indicated with a white dot and overlaid on the reflectivity data field acquired courtesy of the National Severe Storms Laboratory using a SMART radar. Four specific StickNet platforms are identified in the image; data from these four probes are illustrated in Figure 7.

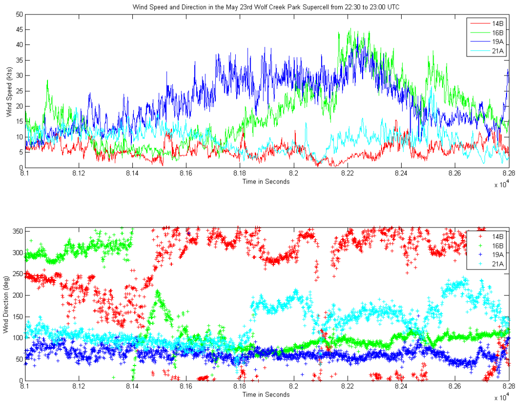

Figure 7. Wind speed and direction time histories acquired from StickNet probes 0214B, 0216B, 0219A and 0221A during the passage of a supercell thunderstorm on 23 May 2007.

Unlike the trailer mounted 10 m towers that TTU historically deployed to make hurricane observations, the ability to quickly adapt a StickNet array and place individual platforms into precarious situations without reservation has led to some scientifically relevant observations. TTU has historically aimed to deploy the majority of its observational assets in open exposure (often at airports). This effort was made to build a database with relatively consistent terrain conditions from which to study storm-scale interaction with the near-surface wind flow. However, the data collected by the StickNet platforms deployed along the coast where surge inundation has occurred, or in areas farther inland where fresh water flooding has occurred, yielded some interesting insights. In particular, based on the recorded time histories of turbulence intensity, the corresponding roughness lengths of the surrounding areas have been reduced following inundation. While this might be expected right along the coast, even open areas far inland can experience a drop in roughness and a corresponding increase in wind speed due to the impact of shallow water flooding.

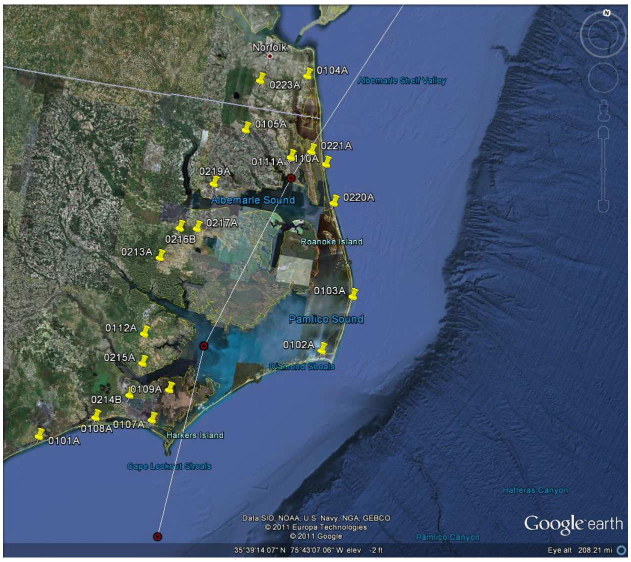

Figure 8. StickNet deployments completed for Hurricane Irene (2011). Hurricane Irene's track is also identified.

TTUKa Mobile Doppler Radars

While the StickNet technology provides a great platform to quickly deploy an adaptable observing network, the implementation of high-resolution radar or LIDAR technologies offers significant promise to make substantial contributions to the wind engineering and energy communities in the coming years. In 2006, TTU initiated the development of two mobile Ka-band Doppler radars. The TTUKa radars were to provide the ability for four-dimensional mapping of a wide spectrum of atmospheric phenomena with very-fine spatial resolution useful to both the atmospheric science and engineering communities. TTUKa1 is shown in Figure 9, while deployed nearby a supercell thunderstorm during the VORTEX2 project. The construction of both radars was completed in 2009 at a total cost of approximately $1.5M US.

There are several advantages of using two high-resolution mobile research radars for wind engineering applications. The mobile aspect allows the technology to be deployed near or within an event and/or location of interest (e.g. near the coast or within a wind farm). A coordinated deployment of two or more radars allows for dual Doppler synthesis of the acquired data which can yield four dimensional wind fields. Finally, one significant benefit of research radar is the ability to control the scanning strategies and focus observations within a specific atmospheric domain, and/or coordinate atypical scans to complete innovative research, which is not possible using an operational radar system.

Design and Construction

While integration activities occurred locally at TTU, the TTUKa radar systems include custom components manufactured from all across the world. A Vaisala/Sigmet RVP9 radar signal processor is mounted in a custom built rack, which resides in the rear portion of the cab on the driver's side, while the radar operator resides in the rear seat on the passenger's side. Power for the radar system is provided via a bed mounted MQ-Power, 7000 watt diesel generator which, when coupled with the 285 liter auxiliary fuel tank, allows radar operation for approximately 150 hours. The auxiliary tank also serves the Tri-Pac air conditioning unit, which cools the shock mounted transmitter and receiver case and also cools the cab. The radar, generator, and A/C unit as well as the auxiliary fuel tank are mounted on a Chevy C5500 crew cab truck, which has been modified to include a custom bed and appropriate hydraulics. A computer-assisted hydraulic levelling system is utilized in order to level the radar system prior to beginning operations. Onboard navigation and magnetically corrected compass systems provide location and orientation information, while remote starting systems for the generator and A/C units allow for full start-up without venturing outside the cab.

Figure 9. Photograph of TTUKa1 deployed nearby a supercell thunderstorm, showing the radome (rear), diesel generator (tan box) and auxiliary fuel tank (black box).

The TTUKa radars are the first research grade units in the Atmospheric Science community to utilize a non-linear frequency modulation pulse compression technique in the 35 GHz band (Ka-band). The TTUKa radars employ a fully coherent travelling wave tube amplifier and non-linear frequency modulation to suppress typical artifact range side lobes (Keeler et al. 1999). Pulse compression techniques achieve enhanced short pulse fine range resolution (~5 m) as well as increased received sensitivity due to the long pulse transmission (Puhakka et al. 2006). Relative to conventional non-modulated pulse transmission radar systems, pulse compression yields equally accurate velocity estimates while using considerably less pulses per estimate, allowing for the utilization of higher scan speeds. Further, increasing the number of pulses to equal that of conventional radar will yield a much higher quality and more sensitive measurement.

Additional specifications of the TTUKa radars are shown in Table 1. The radars operate using a wavelength of approximately 8.6 mm, and a half-power beam width of 0.49 degrees via a 1.3 m diameter parabolic reflector. A radome is used to protect the antenna and pedestal from hail and allow operations in extreme wind speeds upwards of 60 m s^{-1}. An additional upgrade is planned for 2012 to increase the reflector size and gain with the hope of enhancing measurements from non-precipitating atmospheres.

Deployment Logistics

The TTUKa radars can scan while in motion for surveillance, although most scientifically orientated deployments are done while the units are stationary. Once the vehicle is stopped, the truck can be levelled within approximately 60 seconds. Once a level radar horizon is achieved, scientifically relevant scanning can be started.

The TTUKa radar systems are typically deployed in a coordinated fashion to enable dual Doppler synthesis of the acquired radar data. While this strategy has historically been employed for many weather radar systems, the objective of the TTUKa radars is more focused on providing insight into high-resolution near-surface kinematics and not overall storm structure. Based on this objective and the fact that the 35 GHz band is highly susceptible to attenuation in heavy precipitation, deployment baselines (i.e. separation between the radars) is typically on the order of only 5 km.

Item	Specification
Transmit Frequency	34.86/35.06 GHz
Transmit Power	200 Watts Peak, 100 Watts Average
Transmitter Type	TWTA, 50% Duty cycle
Antenna Type	Cassegrain Feed, Epoxy Dielectric
Antenna Gain	50 dB
Antenna 3dB Beam Width	0.49 Degrees
Polarization	Linear, Horizontal
Waveguide	WR-28, Pressurized
PRF	Variable, up to 20 KHz
Pulse Width	4 Widths, Variable from 30 nsec to 20 usec
Gate Spacing	15.0 Meters
Receiver	Dual Block Up/Down Converter
IF Frequency	60 MHz
Pedestal System	Orbit AL-4016, 6 RPM max Axis Rotation Rate
DSP	Sigmet RVP-9 with Tx IF Modulator Rate
Modulation	Pulse, Linear FM Chirp, No-linear FM Chirp
Vehicle	Chevy C5500 Crewcab, Custom Bed
Platform Stabilization	Computer Assisted Hydraulic Levelling System

Table 1. Additional specifications of the TTUKa band radar systems.

Recent work within thunderstorms and hurricanes has concentrated on using coordinated range height indicator (RHI) scans (i.e. vertical scans over a range of elevation angles at a constant azimuth) to generate vertical profiles of wind speed and direction. Using the deployment strategy for a linear thunderstorm complex as shown in Figure 10, the southern radar performs a RHI scan northward, while the eastern radar performs a RHI scan westward. The two scans intersect near the intersection of the road network and over the coordinated StickNet array. Since an RHI scan takes approximately five seconds to complete, the radar data is synthesized to document the evolving nature of the wind profile as the thunderstorm outflow passes. This same strategy can be used to collect wind profiles from specific locations (e.g. near the coast in a landfalling tropical cyclone).

Deployment and Data Examples

The first TTUKa radar was deployed in 2009 for the VORTEX2 project, while both TTUKa radars were deployed in 2010 for the same project. In 2011, both radars were deployed for the Severe Convective OUtflow in Thunderstorms (SCOUT) project in the spring and then Hurricane Irene in the summer. Significant effort has also recently been made to employ the radars to document wind turbine wake flow.

The TTUKa radar data acquired during project SCOUT are of interest to the wind engineering community, as project SCOUT was dedicated to making engineering-relevant observations from thunderstorm events to provide validation to ongoing numerical and experimental work world-wide. In these cases, short baseline coordinated RHI scans as illustrated in Figure 10 were the primary mode of operation, leading to the acquisition of vertical wind profiles such as that shown in Figure 11. The same deployment and scanning strategy was later used in Hurricane Irene to collect wind speed profiles just offshore (within a few kilometers) of the coast.

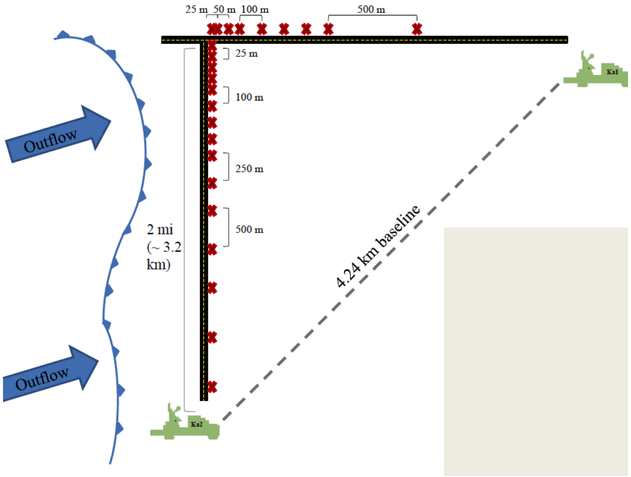

Figure 10. Project SCOUT deployment plan for the TTUKa radars. StickNet deployments are identified using the red X's.

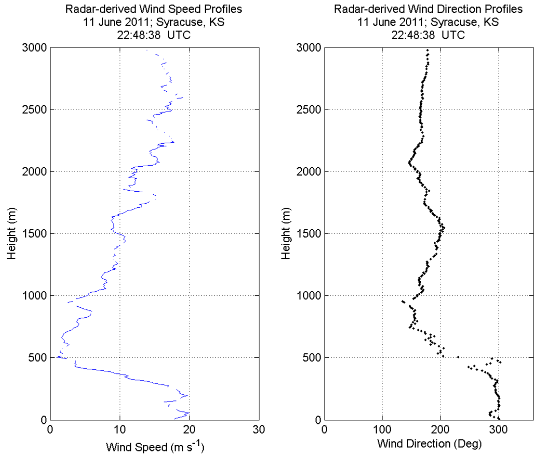

Figure 11. TTUKa radar derived vertical profiles of wind speed and direction obtained during a thunderstorm outflow event that occurred near Syracuse, Kansas on 11 June 2011.

Recent efforts have concentrated on using the TTUKa radars to document wind turbine wake flow. In these studies, the radars are located about 2-3 km in range from an operating megawatt wind turbine with a hub height of 80 m and a rotor diameter of 86 m. With the use of a 1.2° elevation angle plan position indicator (PPI) scan (i.e. horizontal scan) the radar volume is centered on the lowest portion of the rotor at the range of the wind turbine and then extends upward through the wake region for approximately 5 km downstream. While the acquired data has been synthesized, the single Doppler data is quite revealing. Figure 12 illustrates the radial velocity field acquired using a single PPI scan. In this case, the flow is all outbound from the radar within the reported sector, and hence the radial velocities are all positive. However, there is a distinct discontinuity in the radial velocity field at and beyond the turbine location (approximately 2.4 km in range). Behind the turbine, radial velocities are significantly lower providing easy documentation of the wake. Each PPI sector scan can be acquired in approximately five seconds, depending on the azimuthally range of the scan, and hence wake meandering can be easily tracked and visualized. In fact, the TTUKa radars have successfully documented turbine wakes over 25 rotor diameters downstream of the turbine.

Figure 13 shows the composite mean radial velocity and spectrum width assimilated from 25 repetitive RHI (vertical) scans through the plane of the turbine. The turbine is located at range = 2700 m and the influence of a meteorological tower can be seen at range = 2950 m. Mean radial velocity deficits found downwind of the turbine are greater than 35% of the upstream values. The enhanced spectrum width on the edge of the wake is likely associated with both the shear zone between the wake and ambient flow, as well as tip vortices.

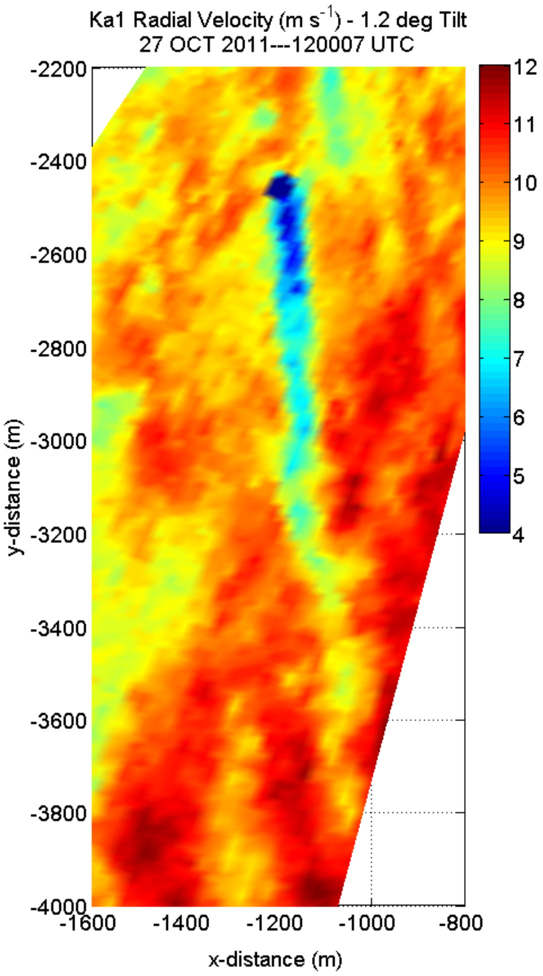

Figure 12. TTUKa PPI of radial velocity (m s^{-1}) showing a turbine wake.

By employing multiple PPI scans from different vantage points, it is possible to perform dual Doppler synthesis on the data to resolve the three dimensional flow and estimate true velocity deficits within the wake. Multiple PPI scans, using a selected set of elevation angles, are acquired from each TTUKa radar over a 1-2 minute time period. This information is gridded into a Cartesian coordinate system and then combined to resolve the three dimensional flow. Not unlike the single Doppler PPI radial velocity fields, the wake is easily evident in the synthesized data with velocity deficits reaching 45+% from the ambient flow within a few rotor diameters downstream of the turbine; deficits of 10-20% are still evident at 10 rotor diameters downstream. At the same time, vertical slices of gridded spectrum width, such as that observed 200 m downstream of the turbine and illustrated in Figure 14, indicate much higher turbulence values found on the edges of the wake with a relative "calm" in the middle of the wake itself.

Conclusions

Two technologies have been developed to document the detailed kinematics of the lower atmosphere. The first of these technologies is a small tower technology called StickNet, which allows the rapid assembly of a dense array of near-surface weather stations which can be used to document the wind field within landfalling tropical cyclones or obtain information from highly transient events such as thunderstorm outflows. The second technology is high-resolution, high-sensitivity mobile research radars, which operate in the 35 GHz band (Ka-band). These TTUKa radars can be deployed and scanned using innovative techniques of interest to the wind engineering and wind energy communities. These techniques can be used to document the evolving wind profiles within a thunderstorm outflows or wind turbine wakes.

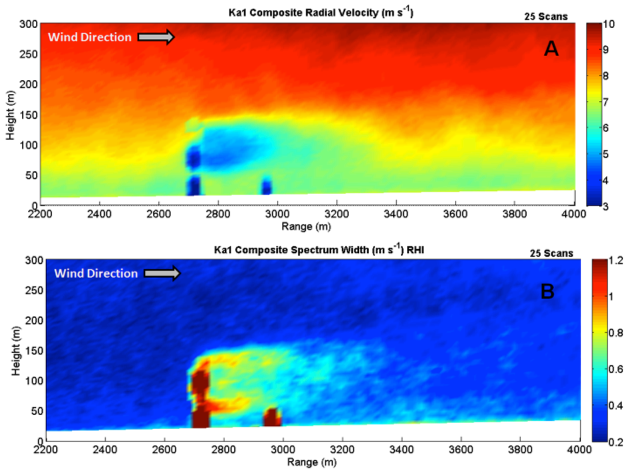

Figure 13. TTUKa1 composite RHI (A) radial velocity (m s^{-1}) and (B) spectrum width (m s^{-1}) for 25 successive scans.

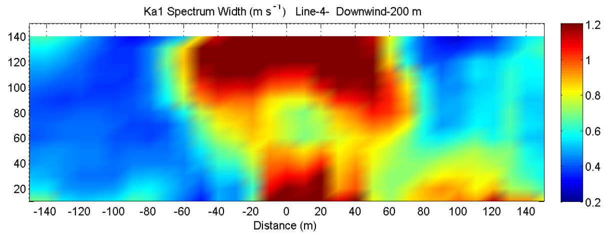

Figure 14. Vertical slice of TTUKa1 radar spectrum width located 200 m downwind from the turbine.

While considerable work remains to reconcile the volumetric measurements of a radar with point measurements of a traditional instrumented tower, the enhanced resolutions of short wavelength radars (and LIDAR systems) are likely to lead to new understandings of near-surface wind flow. Coupling TTUKa radar and StickNet technologies provides a unique opportunity to study specific atmospheric events or wind flows. Employing two radars to simultaneously sample the lower atmosphere will allow dual Doppler synthesis and the acquisition of three-dimensional wind fields, while the StickNet platforms maintain the ability to provide near-surface ground truth below the analyzed radar velocity fields.

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