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Field evaluation of remote wind sensing technologies: Shore-based and buoy mounted LIDAR systems

EXECUTIVE SUMMARY:
In developing a national energy strategy, the United States has a number of objectives, including increasing economic growth, improving environmental quality, and enhancing national energy security. Wind power contributes to these objectives through the deployment of clean, affordable and reliable domestic energy. To achieve U.S. wind generation objectives, the Wind and Water Power Program within the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) instituted the U.S. Offshore Wind: Removing Market Barriers Program in FY 2011. Accurate and comprehensive information on offshore wind resource characteristics across a range of spatial and temporal scales is one market barrier that needs to be addressed through advanced research in remote sensing technologies.

There is a pressing need for reliable offshore wind-speed measurements to assess the availability of the potential wind energy resource in terms of power production and to identify any frequently occurring spatial variability in the offshore wind resource that may impact the operational reliability and lifetime of wind turbines and their components and to provide a verification program to validate the "bankability" of the output of these alternative technologies for use by finance institutions for the financing of offshore wind farm construction. The application of emerging remote sensing technologies is viewed as a means to cost-effectively meet the data needs of the offshore wind industry. In particular, scanning and buoy mounted LIDAR have been proposed as a means to obtain accurate offshore wind data at multiple locations without the high cost and regulatory hurdles associated with the construction of offshore meteorological towers. However; before these remote sensing technologies can be accepted the validity of the measured data must be evaluated to ensure their accuracy.

The research conducted under this grant utilized existing instrumentation platforms that created a unique coastal ocean test-bed in the Mid-Atlantic for the evaluation of LIDAR-based wind measurement systems to validate the accuracy of remotely measured wind data in marine applications. The test-bed was used to systematically evaluate the capability of emerging scanning LIDAR and buoy mounted vertically profiling LIDAR byevaluating a fixed scanning LIDAR against two land-based 50 meter high meteorological masts fitted with research quality cup-vane anemometers and one buoy mounted vertically profiling LIDAR . Initially, the experiment was designed to more robustly evaluate both the scanning and buoy mounted vertically profiling LIDAR by: (1) Assessing the vertically profiling LIDAR statically on land and floating in a sheltered bay against a co-located 60 meter high meteorological mast fitted with a research quality cup-vane anemometers; (2) Assessing co-located data collected by both the scanning LIDAR and the vertically profiling LIDAR located on land and in the bay and (3) Offshore field evaluation of both LIDAR platforms through a comparison of the fixed scanning LIDAR data and data obtained by the buoy mounted LIDAR located 10 miles offshore.
The research plan was developed with "go" – "no go" decision points between platform and configuration tests. Poor comparisons between data collected by the scanning LIDAR and the two land-based 50 meter high meteorological masts during the first phase of the research resulted

in significant changes to the research plan. These changes were designed to identify possible environmental conditions in the urban coastal zone that could influence the scanning LIDAR data. It is important to note that the scanning LIDAR data comparison to the fixed meteorological masts are representative of overland wind data analysis. No analysis of over ocean scanning LIDAR data was conducted during this study and any conclusions drawn from the present research must be confined to overland LIDAR measurements only. During the course of the experiment co-located scanning LIDAR data was collected over two WindCube vertically profiling LIDARs; one located on a coastal dock 6 km inland and one located on an ocean pier located 9 km north of the LIDAR. Co-located vertical wind profiles collected by the pier located WindCube and the buoy mounted profiling LIDAR were also collected during the course of the experiment. Comparison and assessment of the WindCube data and the scanning and buoy mounted LIDAR data have not been conducted; however, the data is available for future analysis.

PROJECT OBJECTIVE: The objective of the research was to systematically evaluate the capability of both scanning and vertically profiling Light Detection and Ranging (LIDAR) based wind measurement systems to accurately measure 3D wind fields. Once validated, data collected by both LIDAR systems can be used to assess the temporal and spatial variability of the offshore wind resource in the Mid-Atlantic east of New Jersey.

PROJECT GOALS: The *goal* of the research project was to address the technical and commercial challenges of the offshore wind energy industry by validating and assessing cost-effective, over ocean wind resource characterization technologies. The *objective* was to systematically evaluate the capability of both scanning and vertically profiling LIDARs to accurately measure 3D wind fields through comparison with fixed met masts and intercomparison among LIDAR platforms. Once validated, data collected by both buoy mounted vertically profiling LIDARs and shore-based, pulsed horizontally scanning LIDARs can be used to accurately assess offshore wind resources and to quantify the spatial and temporal variability in the offshore wind fields. To achieve the final goal, a series of sub-goals were to be met:

1. Validation of the use of a fixed scanning LIDAR for the remote sensing of spatial and temporal wind vectors through an intercomparison of measurements obtained with research grade anemometers mounted on meteorological masts located 3, 6, and 12 miles from the location of the scanning LIDAR.
2. Validation of the use of a buoy mounted vertically profiling LIDAR for the measurement of over ocean vertical wind profiles through:
    a. an intercomparison of co-located wind measurements obtained with research grade anemometers mounted on a 60m meteorological mast with the LIDAR located on land, and
    b. an intercomparison of co-located wind measurements obtained with research grade anemometers mounted on a 60m meteorological mast with the LIDAR mounted on the buoy and floating adjacent to the meteorological mast.
3. Evaluation of data obtained in an offshore field evaluation of both LIDAR systems to assess the capability of each instrument in characterizing the offshore wind resource under varying atmospheric conditions.

Work toward achieving the 3 sub-goals was to be conducted through 3 research project campaigns that each spanned one-year in duration. As indicated above, due to the negative results obtained during the first campaign focused on sub-goal 1, the research plan was significantly changed to focus on identifying the possible environmental conditions negatively affecting the scanning LIDAR data. Additionally, the meteorological mast to be constructed 3 miles from the scanning LIDAR as part of the research never received an construction permit over the course of the study, hampering efforts to collect near field comparison data. Due to the significant changes in the research plan over the duration of the project, the results of the Field Evaluation are detailed in the following sections by Budget Period.

Goal Status: Budget Period 1 (**FY2011-2012**): Fixed scanning LIDAR coastal wind measurement evaluation.

The purpose of the FY2011-2012 effort is to collect volumetric wind data with a scanning pulsed Doppler LIDAR to retrieve vector velocities for the validation of coastal scanning LIDAR in comparison to standard anemometer towers located within the coastal zone. Three tasks are being pursued in this budget period: (1) Data collection; (2) Validation Analysis; and (3) Data Assessment. Prior to the authorization to proceed with the present research, Fishermen's Energy purchased, leased and installed the instrument platforms necessary for the proposed research. The focus of the 1st annual period of research was to evaluate the condition of the existing instrument platforms, fine tune the measurement platforms, and develop the protocol for collecting, processing and transferring the data to Garrad Hassan and NREL for validation and assessment. A major effort to achieving the first quarter goals was a meeting of the Project PIs and collaborators was held on August 1, 2012 at the Fishermen's Energy Office in Atlantic City, NJ to discuss the overall objectives of the research and develop a plan to meet the year one milestones. Following the meeting, site visits were made to each of the instrument platforms and an assessment was made regarding the present state of the instrument network.

I. Task 1: Data Collection

The objective of the data collection task is to obtain measurements of scanning pulsed Doppler LIDAR with co-located standard anemometer data over portions of all four seasons and during specific events (e.g., coastal low pressure system passage). These data are necessary to evaluate the performance of the scanning LIDAR with varying atmospheric aerosol levels over broad sampling ranges (5 to 20 km).

Major activities:

Research Instrument Evaluation: Prior to the collection of research quality data, all of the instrument platforms were deployed and assessed to ensure that they would meet the standards for research quality wind measurements. Figure 1 present a location map of the study area and the locations of the instrument platforms.

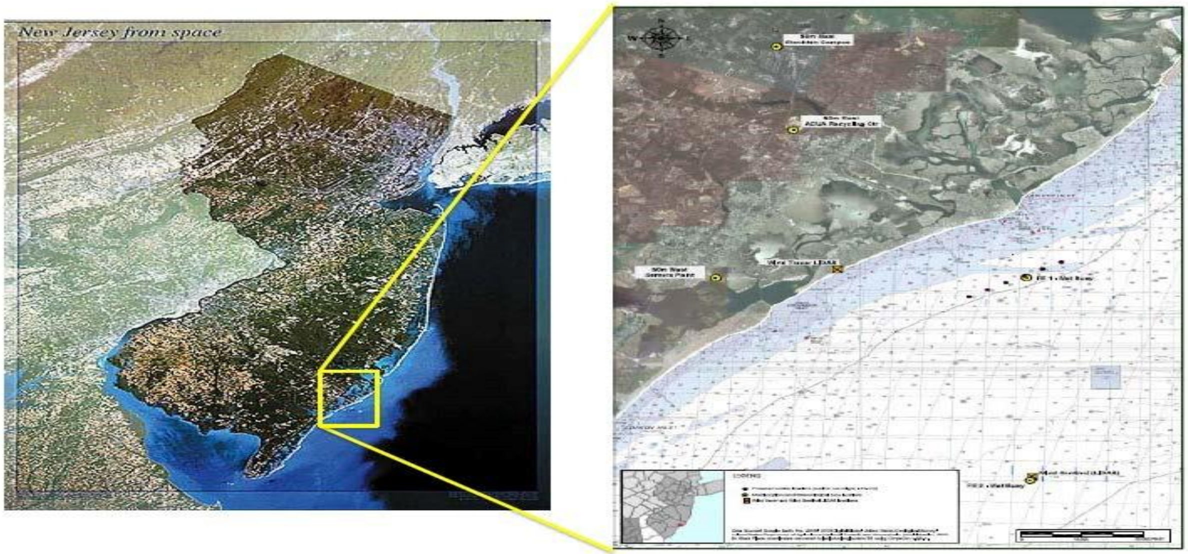


Figure 1:Location Map

The research site is located within the yellow box depicted on Figure 1. It is centered within a 12 mile radius of Margate, NJ. Margate is located along the southern NJ coast approximately 3 miles southwest of Atlantic City. The right panel of Figure 1 is a terrain/nautical chart indicating the location of the Scanning LIDAR, Meteorological Towers, and the two wind farm sites within which the buoy will be located. The location of Scanning LIDAR is indicated by the orange square on the coast. The 3-mile Met Mast is indicated by the yellow dot to the southwest of the Scanning LIDAR. The location of the 6- and 12-mile Met Masts are indicated by the yellow dots to the north of the Scanning LIDAR. The 3-mile wind farm site is indicated by the yellow dot located in the center of the figure, due east of the Scanning LIDAR, and the 12-mile site is indicated by the yellow dot in the lower right hand corner of the chart.

As of September 30, 2012 that status of the observation network is as follows:

1. Meteorological Masts
    a. Two of the three Met Masts are operational. Both the Stockton College 50m mast, located 12 miles from scanning LIDAR, and the Atlantic City Utility Authority 50m mast, located 6 miles from scanning LIDAR, are collecting and transmitting data.
    b. A field inspection of both 50m masts was conducted by engineers from Garrad Hassan in July 2012. The inspection report identified three deficiencies that required correcting prior to the collection of certifiable anemometer wind data. The identified deficiencies were: (1) anemometer boom orientation; (2) guy wire tension; and (3) wrapping of instrument cables along the mast. Arrangements have been made with the met masts operator at the Richard Stockton College of New Jersey to make the required corrections in October 2012.

c. The third Met Mast, located 3 miles from the scanning LIDAR, remains in the permit phase. This 60m tower is to be located 3 miles from the scanning LIDAR within the coastal marsh south of Atlantic City. Issues have been raised by the New Jersey Fish & Wildlife service over the impact of a guyed tower on migratory bird mortality. Fishermen's Energy personnel are currently addressing the concerns raised.

Figure 2: Photo of the 50m Met mast located at Richard Stockton College

2. Wind Tracer Scanning LIDAR
    a. The LIDAR was installed on top of Margate Towers, 9600 Atlantic Avenue, Margate, NJ in March 2012. The 11 story building is located along the Atlantic oceanfront. The WindTracer is located on top of the elevator shaft, 168 ft above MSL and has an unobstructed view of the Atlantic Ocean.
    b. Lockheed Martine technicians have configured, calibrated, and verified that the system is operating correctly.
    c. The LIDAR is presently sampling a test pattern over a proposed windfarm lease site located three miles east of Absecon Inlet, Atlantic City.
    d. The data is being transferred to Lockheed Martin for processing and analysis of the raw data files.

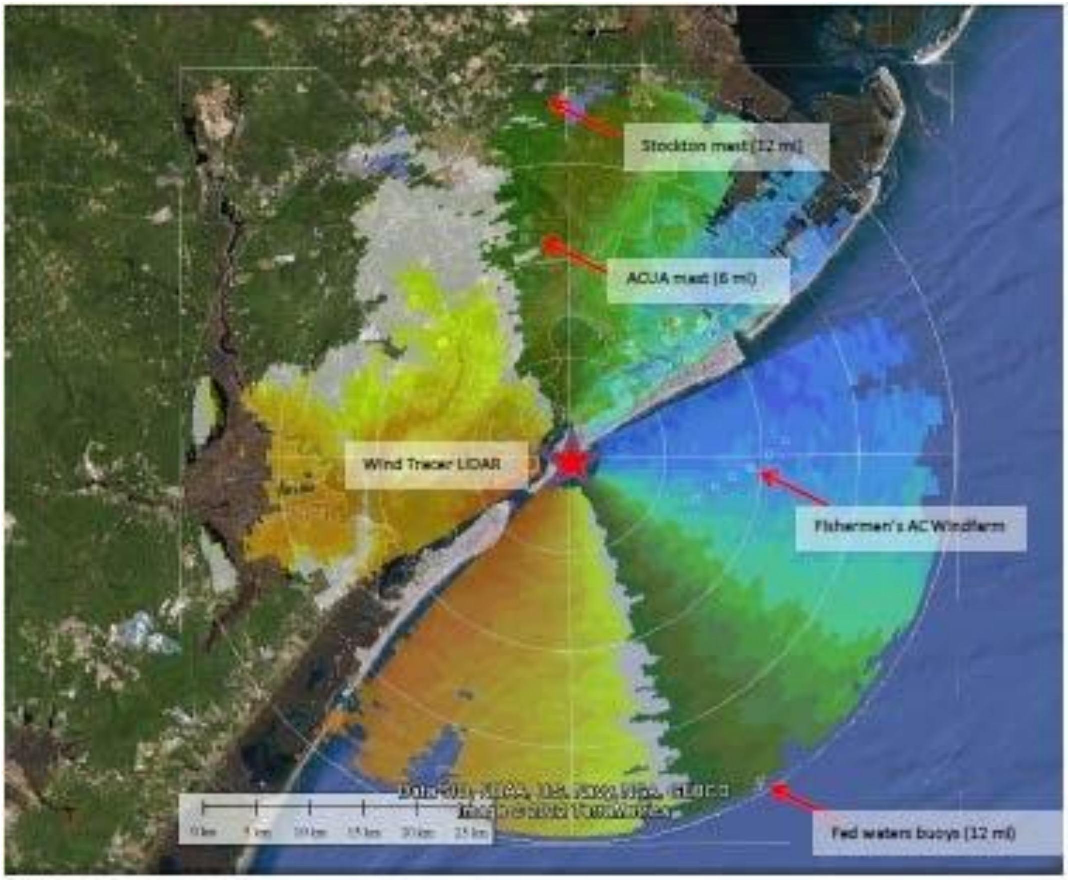


Figure 3: Wind Tracer LIDAR coverage plot showing the locations of the operating instrument platforms and the proposed offshore windfarms

3. Buoy-mounted vertically profiling LIDAR
    a. The AXYS Wind Sentinel fitted with a Blue Scout OSW 150 vertically profiling LIDAR is presently deployed at the 3-mile wind farm site for configuration, calibration, and operation verification by AXYS technicians. The system also includes cup and vane anemometry located 3 m above the deck of the buoy, a downward looking 3-D profiling current meter, and a pitch-roll-heave buoy wave sensor package for wave measurements.
    b. The system has been calibrated and tested for atmospheric and ocean measurements by AXYS technicians over the summer of 2012. Co-located data sets of the Scanning LIDAR and Blue Scout profiler were obtained immediately after the set-up and evaluation phase of the Wind Tracer LIDAR. These data were analyzed to obtain a first look at the data.

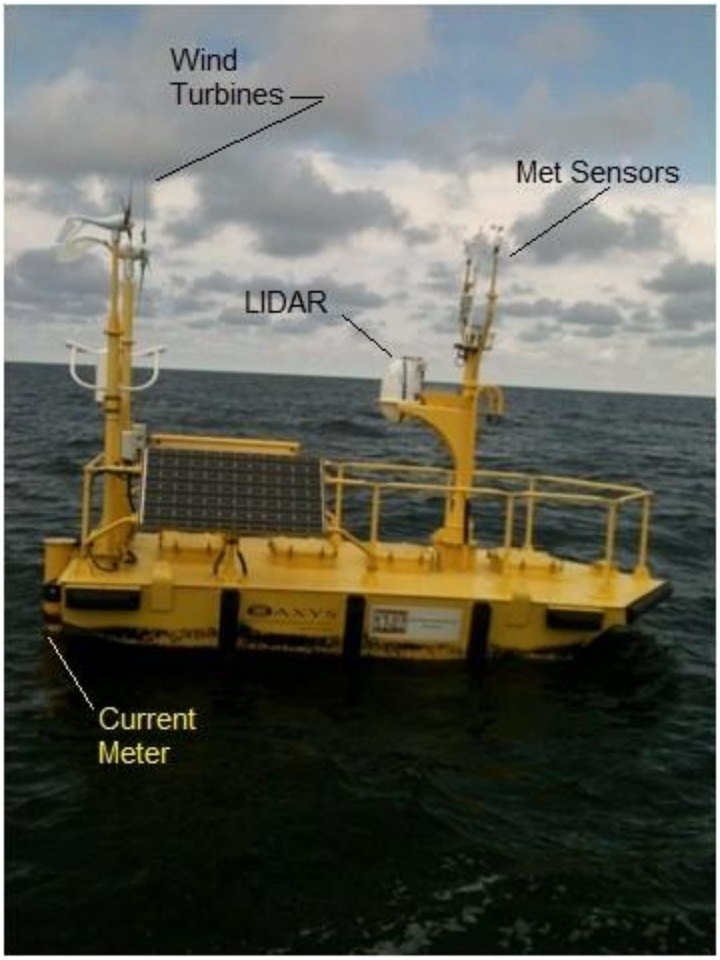


Figure 4: Photo of the AXYS Nomad Buoy showing the location of the instrument packages

Specific objectives

The specific objective of the activities in FY2011-2012 was to inspect and prepare the instruments for the collection of research quality data over the remainder of budget year.

Significant results

1. A few deficiencies were identified on the existing meteorological masts through an inspection by Garrad Hassan technicians, including guy wire tensioning, boom orientation, and wire routing down the mast. Arrangements have been made to correct the identified deficiencies.

2. The 3rd Meteorological tower located 3-miles from the Scanning LIDAR is still awaiting permits from the NJ Department of Environmental Protection. The tower, instruments and

data collection system have been purchased, however, migratory bird concerns have delayed the issuance of the required permits. At this point, it appears that the permit will be denied. The use of a Wind Cube vertically profiling LIDAR or a SODAR, both validated wind measurement systems, are currently being considered as alternative to the Meteorological mast.

3. The Wind Tracer Scanning Doppler LIDAR is installed and operating. Lockheed Martin technicians, under contract with Fishermen's Energy, have installed, calibrated and tested the Wind Tracer System. Presently, scan patterns are being collected over the location of the AXYS buoy located 3 miles east of Absecon inlet.

4. The AXYS Wind Sentinel fitted with a Blue Scout OSW 150 vertically profiling LIDAR is deployed at the 3-mile wind farm site and operating. Co-located data sets of the Scanning LIDAR and Blue Scout profiler were obtained immediately after the set-up and evaluation phase of the Wind Tracer LIDAR. These data were analyzed to obtain a first look at the data. Figure 5 presents a comparison for the processed wind magnitude and direction obtained by the Wind Tracer (y-axis) and Blue Scout (x-axis) at the 110m range gate of the Wind Tracer.

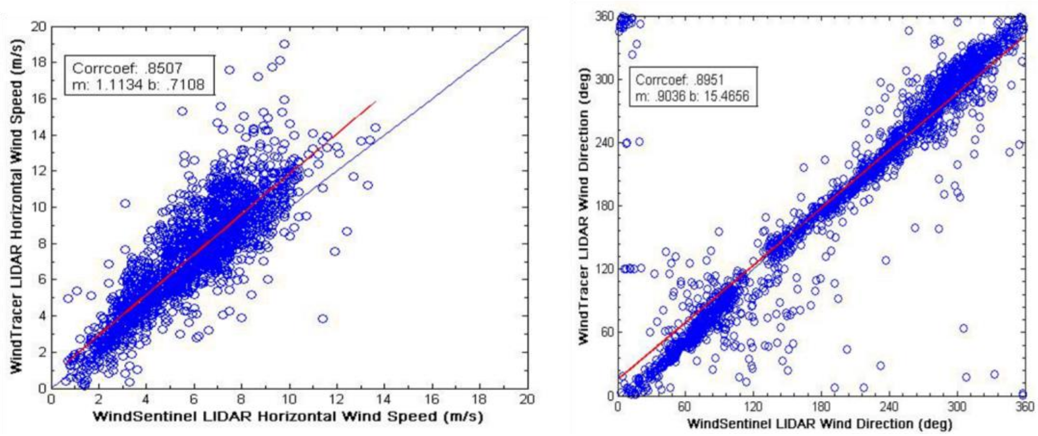


Figure 5

It must be noted that the sampling volumes were not optimized and this is simply a quick look at the data. The plot on the left compares the wind magnitude measured by each instrument over a 14-day period in July 2012. Each sample point is a 10-min average wind speed in m/s. The blue line represents a perfect correlation of the data. Even unoptimized the R^2 fits of the wind speed and wind direction are 0.85 and 0.89, respectively.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 1 outcomes in FY2011-2012 are: (1) the deployment, set-up and calibration of the major research instrumentation (Wind Tracer LIDAR and 2 of the 3 Met Masts); and (2) the development of initial scan patterns and the collection of sample data for preliminary processing.

II. Task 2: Validation Analysis

The collection and processing of the data is a function of site specific measurement requirements. Task 2 in Budget Period 1 focuses on the determination of the optimal profiles of wind speed and direction from the LIDAR radial velocities as a function of azimuth angle and rigorous estimates of the bias and random error of each radial velocity estimate.

Major activities:

In collaboration with Lockheed Martin engineers and GL Garrad Hassan wind energy researchers the major activities in support of task 2 were:

1. The selection of the appropriate scanning LIDAR data collection technique; and
2. The development of a data transfer protocol for the required raw and processed data for validation analysis.

Specific objectives

The specific objective of the activity in FY2011-2012 was to have the data measurement, raw data QA/QC, and transfer protocols in place for use in the validation analysis once the data collection activities begin.

Significant results

1. The “stare” technique has been selected for the collection of validation data between the scanning LIDAR and the met mast anemometers. This technique fixes the scanning LIDAR in both azimuth and elevation angles to measure over collocated sampling volumes of the anemometers mounted to a fixed mast.

2. The data transfer protocol developed starts with the collection of the raw data for both the anemometers and the scanning LIDAR. Once the data are collected for specific sampling periods, the data will be transferred to Lockheed Martine Engineers for initial QA/QC analysis. After processing, the data that meets the quality assurance/control requirements of the instrument will be sent to Garrad Hassan researchers, along with the collocated anemometer measurements, for validation analysis.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 2 outcomes in FY2011-2012 of research are: (1) deployment of the measurement technique for collecting collocated Wind Tracer LIDAR and fixed anemometer data from the 2 met mast; and (2) the development of a data processing and transfer protocol to insure that research quality data is utilized in the scanning LIDAR validation analysis.

II. Task 3: Data Assessment

A detailed analysis of the measurement data from the LIDAR along with comparison of the coastal wind characteristics will be performed by the CO-PIs at NREL and AquaWind LLC. This analysis will evaluate how the scanning LIDAR performance and measurement of the wind characteristics vary with distance from the scanning LIDAR and by atmospheric conditions; using the wind measurements at different distances (6.0, 9.6, and 12 km) from the LIDAR as a reference. The comparative analysis will include, to the extent possible, evaluation of parameters such as wind speed and direction distributions, wind shear, turbulence intensity and their variations by atmospheric conditions, month or season, and time of day.

Major activities:

A meeting of the Project PIs and collaborators was held on August 1, 2012 in the Fishermen's Energy Office in Atlantic City and at which the data assessment requirements were discussed. The data assessment requires validated data to proceed and is therefore reliant upon the completion of tasks 1 and 2. The major activities to address the task 3 objective were:

1. The development of a timeline for budget year one that includes a critical date for the transfer of validated date to NREL and AquaWind for analysis, and
2. The transfer of unvalidated data to NREL and AquaWind for the development of processing techniques.

Specific objectives

The specific objective of the activity in FY2011-2012 was to develop the data assessment protocols and processing routines in preparation for the transfer and analysis of the validated data from task 2.

Significant results

1. The time required to collect and validate the scanning LIDAR and anemometer data was used to develop two timelines; one best-case and one worse-case scenario based on the minimum amount of time NREL researchers would need to assess the validated data (one month minimum before the end of June 2013).

   a. Best-case timeline: Hand off of the validated data to NREL by Jan. 2013
   b. Worse-case timeline: Hand off of the validated data to NREL by March 2013

2. Fishermen's Energy will provide preliminary, unverified data to NREL to work with in advance of the January 2013 data transfer. NREL researchers will use the unvalidated data to assess and optimize the data processing routines to assess the variance of the validated date with varying atmospheric conditions.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 3 outcome in the first quarter of research (Q4 2012) are: (1) the deployment of timelines to insure that all of the Budget Year 1 tasks can be met; and (2) the agreement to transfer unvalidated data for the preparation and assessment of the data processing protocol.

Goal Status: Budget Period 2 (**FY2012-2013**): Fixed scanning LIDAR coastal wind measurement evaluation

The purpose of the FY2012-2013 effort is to collect volumetric wind data with a scanning pulsed Doppler LIDAR to retrieve vector velocities for the validation of coastal scanning LIDAR in comparison to standard anemometer towers located within the coastal zone. Three tasks are being pursued in this budget period: (1) Data collection; (2) Validation Analysis; and (3) Data Assessment.

One focus of the FY2012-2013 research was to finalize the Wind Tracer scan patterns for collecting collocated LIDAR and met mast anemometer data, and to start collecting research quality data for use in the validation analysis of the scanning LIDAR platform. Hurricane Sandy had a major impact on the research effort this quarter. Although no major damage occurred to the research instrumentation or the met masts, regional and local impacts from the storm hindered measurement preparation the week before and three weeks following landfall on October 29, 2013. In late November, the Wind Tracer scanning patterns were finalized and data collection started. Thermal emissions from a heating system roof vent has had an unanticipated impact on the quality of the LIDAR data measured at the location of the 6 and 12 miles met masts, leading to the consideration of contingency plans for data collection.

I. Task 1: Data Collection

The objective of the data collection task is to obtain measurements of scanning pulsed Doppler LIDAR with co-located standard anemometer data over portions of all four seasons and during specific events (e.g., coastal low pressure system passage). These data are necessary to evaluate the performance of the scanning LIDAR with varying atmospheric aerosol levels over broad sampling ranges (5 to 20 km).

Major activities:

Following Hurricane Sandy, renewal of the field measurement campaign began in late November 2013. As of December 31, 2012 that status of the observation network is as follows:

1. Meteorological Masts
    a. The two existing Met Masts have been inspected and approved by Garrad Hassan technicians for obtaining research quality data. The Met Mast instrumentation has been operational since October 2012. Both the Stockton College 50m mast, located 12 miles from scanning LIDAR, and the Atlantic City Utility Authority 50m mast, located 6 miles from scanning LIDAR, are collecting and transmitting data and were operational during Sandy.
    b. The third Met Mast, located 3 miles from the scanning LIDAR, remains in the permit phase. Plans are being considered to substitute for the tower a Wind Cube vertically profiling LIDAR.

2. Wind Tracer Scanning LIDAR
    a. The LIDAR scanning patterns have been finalized for obtaining collocated measurements over the 6 mile and 12 mile anemometers.
    The system operated immediately before Sandy made landfall on October 29, 2012 but local power outages knock out the LIDAR for most of the event.

3. Buoy-mounted vertically profiling LIDAR
    a. Through October the AXYS Wind Sentinel Buoy was located at the 3 mile Federal waters wind farm site. During this time, the Blue Scout vertically profiling LIDAR continued to collect vertical wind profiles that were co-located with Wind Tracer scans over the wind farm site.
    b. The AXYS Wind Sentinel Buoy was unanchored and removed from the water prior to the arrival of Sandy. The buoy remains out of the water and will be redeployed once a heavy lift vessel is available.

Specific objectives

The specific objective of the activities in FY2012-2013 was to initiate the collection of research quality data from the Scanning LIDAR over the sampling volumes of the cup anemometers located on the 6-mile and 12-mile meteorological masts.

Significant results

1. The regional impact of Hurricane Sandy reduced the data collection period in this quarter.

2. The Wind Tracer Scanning Doppler LIDAR is operating and collecting data over the 6-mile and 12-mile meteorological masts. It appears that a heat vent on the roof of the building upon which the LIDAR is deployed is in line with the direction of the meteorological masts

located to the north-northwest of the LIDAR and is having an impact on the data collection effort.

3. The 3rd Meteorological tower located 3-miles from the Scanning LIDAR is still awaiting permits from the NJ Department of Environmental Protection. At this point, plans are underway to deploy a Wind Cube vertically profiling LIDAR located approximately 3 miles west-southwest of the Wind Trace scanning LIDAR to conduct a proof of concept test on the use of a Wind Cube in place of the meteorological mast. The proposed location of the Wind Cube is not in-line with the heat vent.

4. The AXYS Wind Sentinel was removed from the ocean prior to the arrival of Sandy. Plans are underway to redeploy the buoy as soon as possible.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 1 outcomes in the FY2012-2013 period of research are: (1) the initial collection of research quality data from the Wind Trace scanning LIDAR and the cup anemometers located 6 and 12 miles from the LIDAR; and (2) the development of a proof of concept test to evaluate the use of a Wind Cube vertically profiling LIDAR in place of the 3-mile meteorological mast.

II. Task 2: Validation Analysis

The collection and processing of the data is a function of site specific measurement requirements. Task 2 in Budget Period 1 focuses on the determination of the optimal profiles of wind speed and direction from the LIDAR radial velocities as a function of azimuth angle and rigorous estimates of the bias and random error of each radial velocity estimate.

Major activities:

In collaboration with Lockheed Martin engineers and GL Garrad Hassan wind energy researchers the major activities in support of task 2 were the initial analysis of the data collected by the Wind Trace scanning LIDAR and the anemometers located 6 and 12 miles from the LIDAR.

Specific objectives

The specific objective of the activity FY2012-2013 was to begin the validation analysis of the use of the Wind Tracer as a research quality wind measurement platform.

Significant results

Data sets from the met towers and the Wind Tracer were provided to Garrad-Hassan for quality assessment and preliminary analysis. Garrad-Hassan reports that while the met mast time series are complete, the quantity of data received and processed by the Wind Tracer appears to be negatively affected by the presence of the building exhaust plume located adjacent to the Wind Tracer, and along the same azimuth as the met masts. Lockheed Martin engineers are presently evaluating the exhaust plume impacts to data quality and quantity. The potential for terrain interference with the LIDAR beam as it scans to the 50m masts is also being evaluated.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 2 outcomes in the FY2012-2013 period of research are:

Preliminary findings from Garrad-Hassan regarding correlations between the Wind Tracer and the met mast data show that this approach does show promise, however the interferences previously discussed have yet to be more fully evaluated to determine if the meaningful results may be achieved with the with the present configuration. All data collected by the masts and the Wind Tracer will be provided to NREL for analysis during the next reporting period.

II. Task 3: Data Assessment

A detailed analysis of the measurement data from the LIDAR and the met towers along with comparison of the coastal wind characteristics from the different systems will be performed by the CO-PIs at NREL and AquaWind LLC. This analysis will evaluate how the scanning LIDAR performance and measurement of the wind characteristics vary with distance from the scanning LIDAR and by atmospheric conditions; using the wind measurements at different distances (6.0, 9.6, and 12 km) from the LIDAR as a reference. The comparative analysis will include, to the extent possible, evaluation of parameters such as wind speed and direction distributions, wind shear, turbulence intensity and their variations by atmospheric conditions, month or season, and time of day.

Major activities:

The data assessment requires validated data to proceed and is therefore reliant upon the completion of tasks 1 and 2. The major activities to address the task 3 objective focused on the transfer of unvalidated data to NREL and AquaWind for the development of processing techniques.

Specific objectives

The specific objective of the activity in FY2012-2013 was the continued development of the data assessment protocols and processing routines in preparation for the transfer and analysis of the validated data from task 2.

Significant results

1. Due to emerging issues with the amount of research quality data provided by the Wind Tracer, the transfer of valid LIDAR data has been delayed. Presently, the project team is working on transferring valid data by March 2013.

2. Fishermen’s Energy will provide preliminary, unverified data to NREL to work with in January 2013 for NREL and AquaWind, LLC researchers to use to assess and optimize the data processing routines to assess the variance of the validated date with varying atmospheric conditions.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 3 outcome in FY2012-2013 are: (1) the decision to shift the analysis timeline back to March 2013 to insure that valid data will be assessed; and (2) the continued effort to transfer unvalidated data for the preparation and assessment of the data processing protocol. A second focus in the FY2012-2013 period of research was to: (1) collect wind data from the Wind Tracer scanning LIDAR and collocated LIDAR and met mast anemometer data; and (2) analyze the collected data against instrument standards and accepted quality assurance/quality control measures.

I. Task 1: Data Collection

The objective of the data collection task is to obtain measurements of scanning pulsed Doppler LIDAR with co-located standard anemometer data over portions of all four seasons and during specific events (e.g., coastal low pressure system passage). These data are necessary to evaluate the performance of the scanning LIDAR with varying atmospheric aerosol levels over broad sampling ranges (5 to 20 km).

Major activities:

As of March 31, 2013 that status of the observation network is as follows:

1. Meteorological Masts
    a. Both the Stockton College 50m mast, located 12 miles from scanning LIDAR, and the Atlantic City Utility Authority 50m mast, located 6 miles from scanning LIDAR, are collecting and transmitting data.

    b. The third Met Mast, located 3 miles from the scanning LIDAR, remains in the permit phase. Plans continue to be considered to substitute for the tower a Wind Cube vertically profiling LIDAR. To this end, Fishermen’s Energy, independent of this effort, leased a Wind Cube to conduct a proof of concept analysis. The Wind Cube was located at 39 deg 18' 42.4'' N, 74 deg 35' 22.5'' W, approximately 3 miles WSW of the Wind Tracer Scanning LIDAR. The vertical range gates were set to 50m, 60m, 70m, 80m, 90m, 100m, 120m, 140m, 160m, 180m, and 200m above the instrument. Data was collected over the four week period between Feb. 12, 2013 and March 9, 2013. If desired, these data can be made available for this validation project

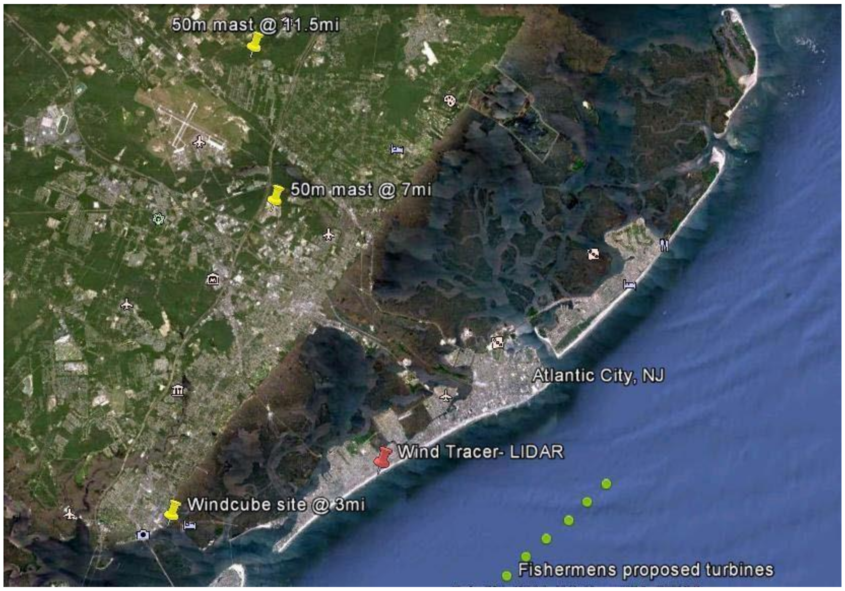


Figure 1. Location map showing position of the Wind Cube relative to the Wind Tracer LIDAR.

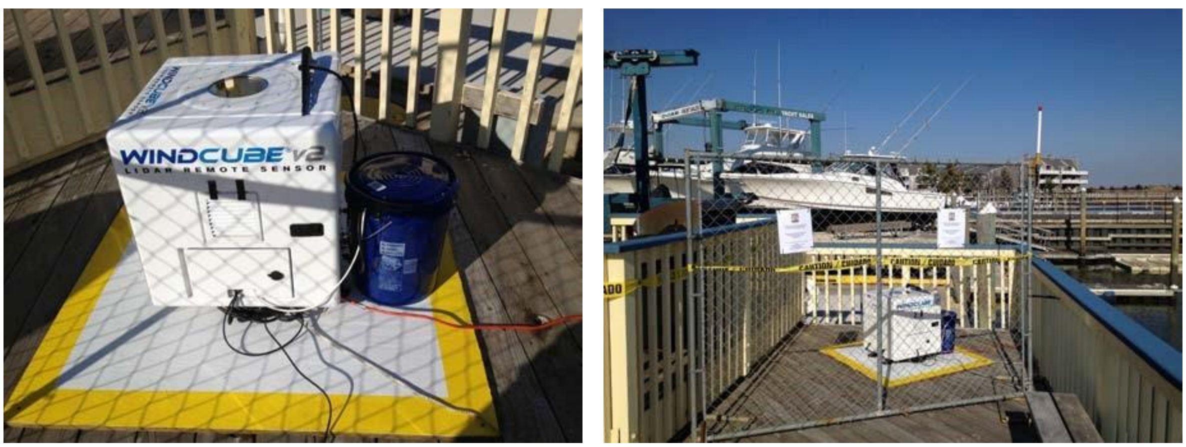


Figure 2. Photographs of the Wind Cube deployment on marina deck.

2. Wind Tracer Scanning LIDAR
    a. The LIDAR scanning patterns have been finalized for obtaining collocated measurements over the 6 mile and 12 mile anemometers. The range cells over the Masts are indicated below.

Figure 3. Wind Tracer LIDAR range Cells and MET mast locations.

For the 4 week sampling period over the wind cube, the wind Tracer was configure to sample for 8 minutes over the Wind Cube and 2 minutes over 360 degrees, repeated every 10 min.

3. Buoy-mounted vertically profiling LIDAR

   a. The buoy remains out of the water and will be redeployed once a heavy lift vessel is available.

Specific objectives

The specific objective of the activities in FY2012-2013 was to continue the collection of research quality data from the Scanning LIDAR over the sampling volumes of the cup anemometers located on the 6-mile and 12-mile meteorological masts.

Significant results

1. The Wind Tracer Scanning Doppler LIDAR is operating and collecting data over the 6-mile and 12-mile meteorological masts. It appears that a heat vent on the roof of the building upon which the LIDAR is deployed continues to have an impact on the data collection effort.

2. The 3rd Meteorological tower located 3-miles from the Scanning LIDAR is still awaiting permits from the NJ Department of Environmental Protection. A Wind Cube vertically profiling LIDAR was deployed by Fishermen's Energy approximately 3 miles west-southwest of the Wind Trace scanning LIDAR to conduct a proof of concept test on the use of a Wind Cube in place of the meteorological mast, at their cost.

3. The AXYS Wind Sentinel was removed from the ocean prior to the arrival of Sandy. Plans are underway to redeploy the buoy as soon as possible.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 1 outcomes in the FY2012-2013 period of research are: (1) the continued collection of research quality data from the Wind Trace scanning LIDAR and the cup anemometers located 6 and 12 miles from the LIDAR; and (2) the proof of concept test to evaluate the use of a Wind Cube vertically profiling LIDAR in place of the 3-mile meteorological mast.

II. Task 2: Validation Analysis

The collection and processing of the data is a function of site specific measurement requirements. Task 2 in FY2012-2013 focuses on the determination of the optimal profiles of wind speed and direction from the LIDAR radial velocities as a function of azimuth angle and rigorous estimates of the bias and random error of each radial velocity estimate.

Major activities:

In collaboration with GL Garrad Hassan wind energy researchers the major activities in support of task 2 was a detailed analysis of the data collected by the Wind Trace scanning LIDAR and the anemometers located 6 and 12 miles from the LIDAR to determine the quality of the collected data.

Specific objectives

The specific objective of the activity in FY2012-2013 was the validation analysis of the use of the Wind Tracer as a research quality wind measurement platform.

Significant results

Data sets from the met towers and the Wind Tracer were provided to Garrad-Hassan for quality assessment and analysis. Garrad Hassan analysts evaluated the estimates of the bias and random error of the Wind Tracer velocity estimates. The validation analysis determined a Mast data recovery rate of 86 % and a LIDAR recovery of 61.5% (Table 1).

	Total Period	Mast	Lidar
# Samples	19988	17215	10589
Coverage (%)	100%	86.1%	61.5%

Table 1

Figure 4 presents the total number of collocated LIDAR and Anemometer data binned by direction. The LIDAR and MET mast anemometer difference is as high as almost 20% in some sectors and correlation is low.

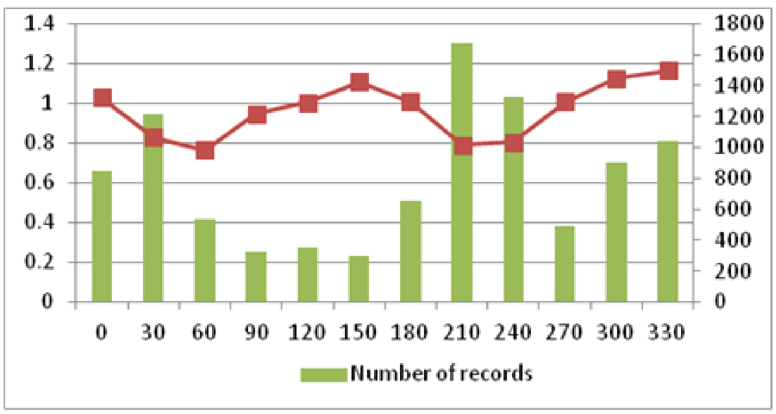


Figure 4.

Figure 5 presents the wind speed coverage over the comparison period. Note that not many samples above 10 m/s.

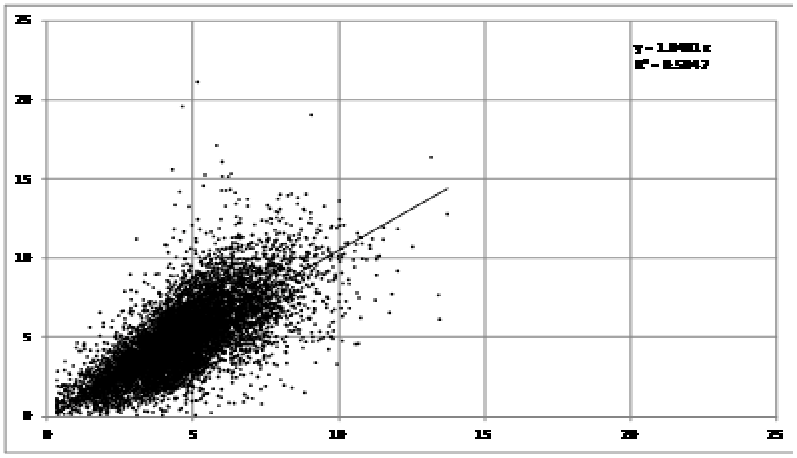


Figure 5. Wind speed correlation between Wind Tracer LIDAR and Mast Anemometers.

A time series comparison of wind direction obtained from the Wind Tracer LIDAR (red) and Mast Anemometers (blue) is presented in Figure 6. Wind Tracer data measured between 300 and 360 degrees from True North show significant variability. This bearing range is in line with the heat vent plume.

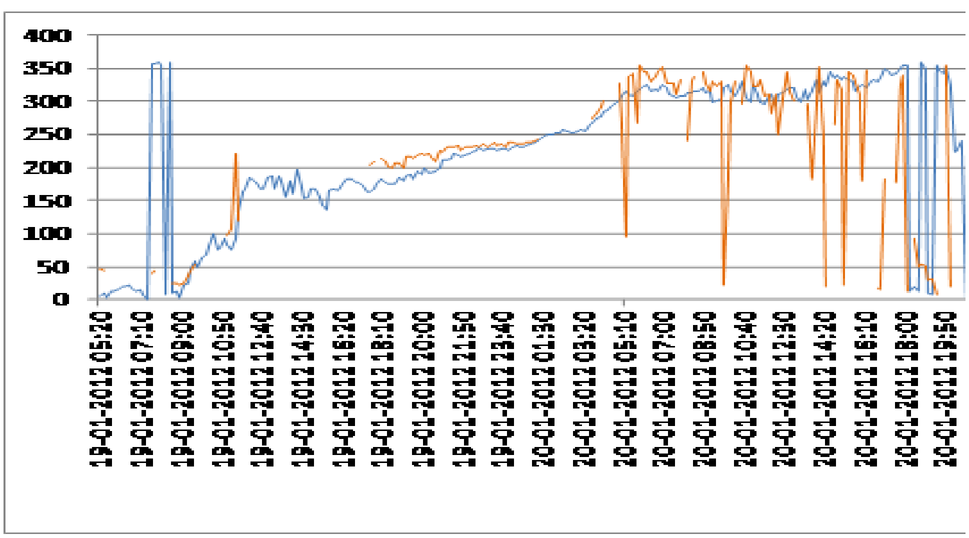


Figure 6. Time series comparison of wind direction between the Wind Tracer LIDAR (red) and the Met Mast Anemometers (blue)

Key outcomes, milestones and other achievements

The key achievements to meeting the task 2 outcomes in the FY2012-2013 period of research are:

Findings from Garrad-Hassan regarding correlations between the Wind Tracer and the met mast data show that this approach does show promise. There is general agreement between the Wind Tracer LIDAR and anemometers but the LIDAR direction is occasionally uncorrelated with the anemometers. Wind Tracer data are of a lower quality between 70-80 degrees and 250 degrees, bearings that are orthogonal to the Wind Tracer range cells. (could be the plume or very low wind speed; needs further investigation to explain).

In general, the analysis show some wind speed and wind direction discrepancies that require additional investigation to explain. Next step would be to discard low wind speeds to focus on wind speeds above, say, 4 m/s and come up with an explanation of the bias as a function of wind sector. All data collected by the masts and the Wind Tracer have been provided to NREL for analysis during the next reporting period.

II. Task 3: Data Assessment

A detailed analysis of the measurement data from the LIDAR and the met towers along with comparison of the coastal wind characteristics from the different systems will be performed by the CO-PIs at NREL and AquaWind LLC. This analysis will evaluate how the scanning LIDAR performance and measurement of the wind characteristics vary with distance from the scanning LIDAR and by atmospheric conditions; using the wind measurements at different distances (6.0, 9.6, and 12 km) from the LIDAR as a reference. The comparative analysis will include, to the extent possible, evaluation of parameters such as wind speed and direction distributions, wind shear, turbulence intensity and their variations by atmospheric conditions, month or season, and time of day.

Major activities:

The data has been transferred to NREL and AquaWind, LLC and is in the process of being analyzed. The results of this analysis will be published by NREL under a separate contract in the future.

Specific objectives

The specific objective of the activity in FY2012-2013 was the transfer of the data to conduct a detailed analysis of the variability between the Wind Tracer LIDAR and the Met Mast anemometers under varying wind speeds and directions.

Significant results

No results at this time.

Key outcomes, milestones and other achievements

The key achievement to meeting the task 3 outcome in the FY2012-2013 **period** of research was the transfer of validated data for the assessment of the quality of the Wind Tracer LIDAR and the Met Mast anemometers under varying atmospheric conditions.

Goal Status: Budget Period 3 (FY2013-2014): Fixed scanning LIDAR coastal wind measurement evaluation

The purpose of the FY2013-2014 effort is to collect volumetric wind data with a scanning pulsed Doppler LIDAR to retrieve vector velocities for the evaluation of coastal scanning LIDAR in comparison to research quality anemometers mounted on two meteorological masts located within the coastal zone. Three tasks are being pursued in this budget period: (1) Data collection; (2) Assessment of data quality; and (3) Evaluation of the performance of the scanning LIDAR for the measurement of research quality wind data in the coastal environment.

The following report summarizes the Phase 1 data collection effort, the quality of the measured data, and the assessment of the Wind Tracer scanning LIDAR data in comparison to the collocated anemometer data. The results of these analyses is used to evaluate the present experimental set-up and assess changes to field measurement program required to isolate natural and anthropogenic generated influence on LIDAR-based wind measurement systems.

I. Task 1: Data Collection

The objective of the data collection task is to obtain measurements of scanning pulsed Doppler LIDAR with co-located standard research quality anemometer data over portions of all four seasons and during specific events (e.g., coastal low pressure system passage). These data are necessary to evaluate the performance of the scanning LIDAR with varying atmospheric conditions over broad sampling ranges (5 to 20 km).

Major activities:

The field evaluation site is centered within a 12 mile radius of Margate, NJ. Margate is located along the southern NJ coast approximately 3 miles southwest of Atlantic City. Prior to the start of the field evaluation of the Scanning LIDAR, Fishermen's Energy (FE) deployed and initiated the operation of the instrument network. The right panel of Figure 1 is a terrain/nautical chart indicating the location of the Scanning LIDAR, two existing 50m meteorological masts operated by Stockton College under contract by Fishermen's Energy, one proposed 60m meteorological mast site located 3 miles from the LIDAR, and the two wind farm sites within which the buoy will be located. The location of Scanning LIDAR is indicated by the orange square on the coast. The 3-mile Meteorological Mast is indicated by the yellow dot to the southwest of the Scanning LIDAR.

The location of the operational 6- and 12-mile meteorological mast are indicated by the yellow dots to the north of the Scanning LIDAR. The 3-mile wind farm site is indicated by the yellow dot located in the center of the figure, due east of the Scanning LIDAR, and the 12-mile site is indicated by the yellow dot in the lower right hand corner of the chart.

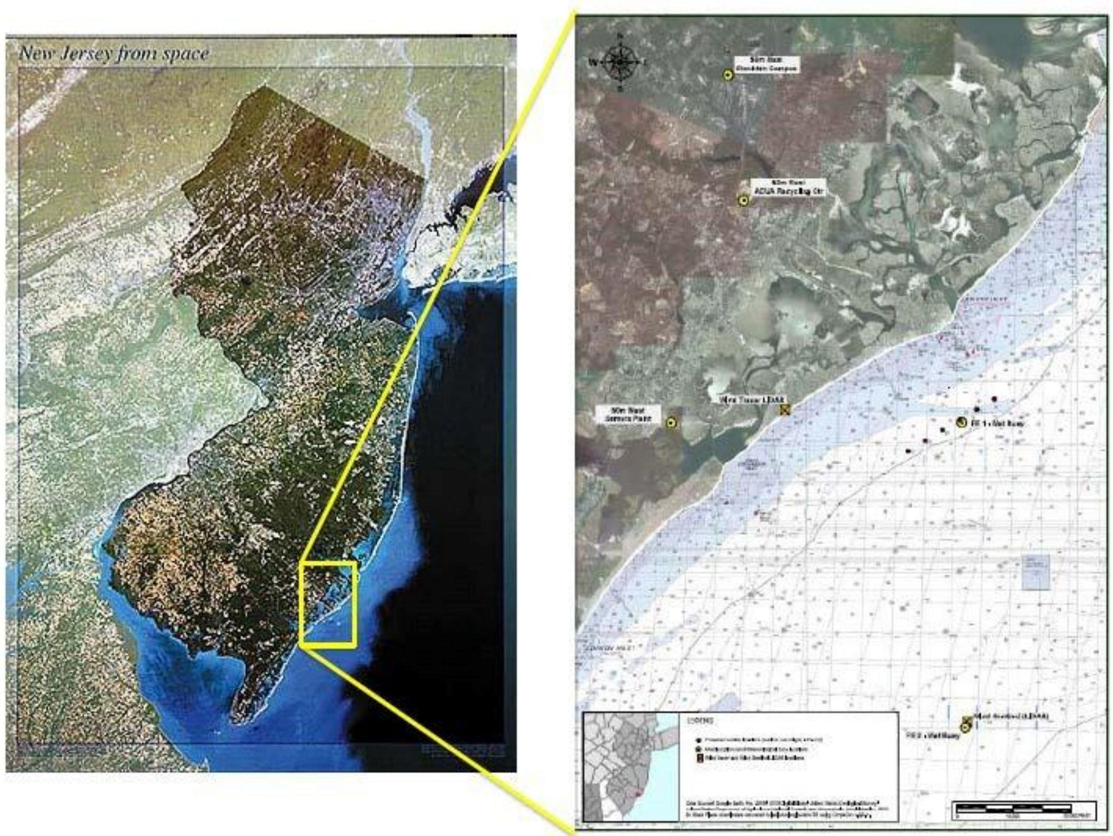


Figure 1: Location Map

The two, 50m masts are NRG XHD TallTowers equipped with 3 NRG Class 1 cup anemometers and 3 Thies First Class anemometers located 30, 40 and 50 m above ground, and 2 NRG #200 wind direction vanes located 35 and 45 m above ground. Both masts utilized the NRG SymphoniePlus data logger to collect data at 1HZ and internally record 10 min average samples of wind speed and direction.

A field inspection of both masts was conducted by engineers from Garrad Hassan at the beginning of the field evaluation in July 2012. The inspection report identified three deficiencies that required correcting prior to the collection of certifiable anemometer wind data. The identified deficiencies were addressed by correcting the orientation of the anemometer booms, increasing the guy wire tension, and correctly wrapping the instrument cables along the mast. By October

2012, both 50m masts were collecting research quality wind data. Hurricane Sandy significantly impacted the region on October 29, 2012, making landfall approximately 10 miles northeast of the Scanning LIDAR in Brigantine, NJ. Although the eye of the storm passed directly over the 50m mast sites, minimum damage was experienced and the instrumentation network was back in operation within a few days after landfall.

Between November 2012 and April 2014 the observation network remained operational with two of the 3 meteorological masts installed and collecting data. The third mast remains unpermitted.

Present Status of the Instrument Network:

1. Meteorological Masts

    a. Both the Stockton College 50m mast, located 12 miles from scanning LIDAR, and the Atlantic City Utility Authority 50m mast, located 6 miles from scanning LIDAR, are collecting and transmitting data research quality wind data.

    b. A permit for the third Meteorological Mast, located 3 miles from the scanning LIDAR has not been obtained.

2. Wind Tracer Scanning LIDAR

    a. The Wind Tracer LIDAR continues to collected data over the 6- and 12-mile meteorological masts in the scanning pattern shown in Figure 2.

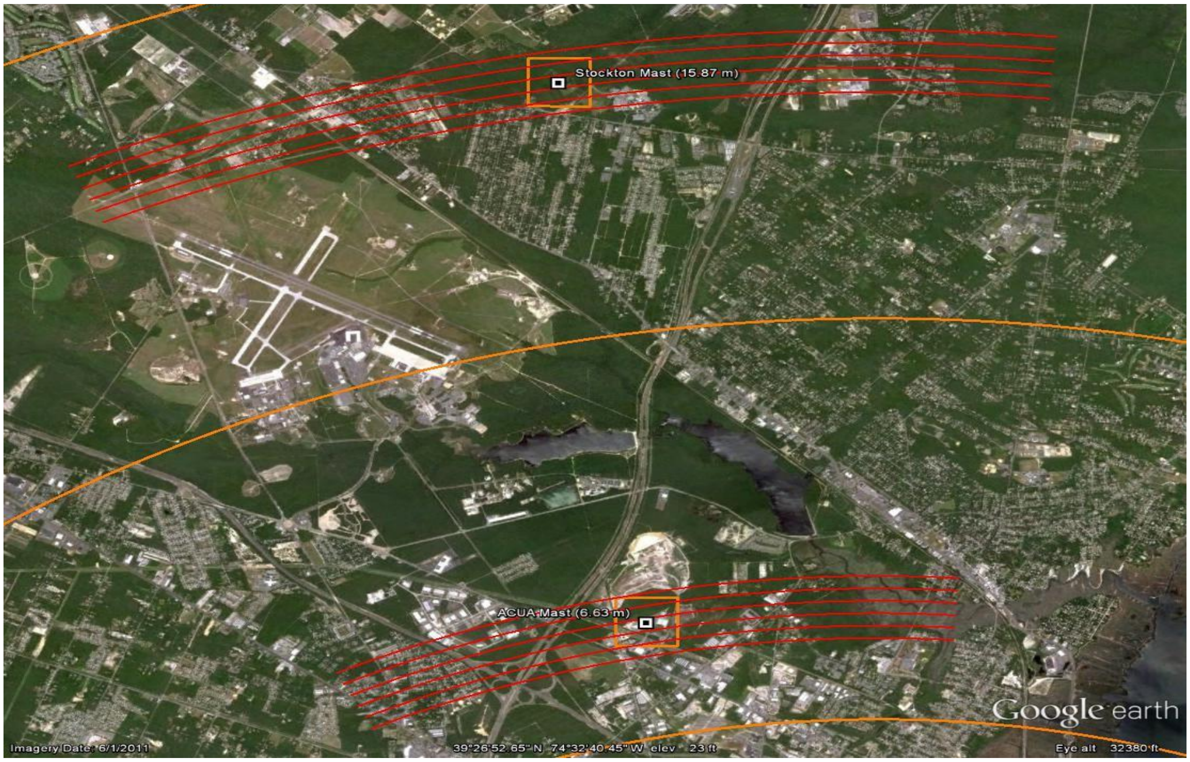


Figure 2. Details of the sector scans used to calculate the wind speed and direction at the ACUA and Stockton masts. Sectors are 30 degrees wide. Range gates are 154.7 m. Data along the arcs are used to estimate the local wind field. Data within the orange boxes (600 m x 600 m) are used to estimate the wind speed and direction at the mast locations. Illustration courtesy Keith Barr, LMCT.

3. Buoy-mounted vertically profiling LIDAR

a. Through October 2012 the AXYS Wind Sentinel Buoy was located at the 3 mile
Federal waters wind farm site. During this time, the Blue Scout vertically profiling LIDAR continued to collect vertical wind profiles that were co-located with Wind Tracer scans over the wind farm site.

b. The AXYS Wind Sentinel Buoy was unanchored and removed from the water prior to the arrival of Hurricane Sandy.

c. The Wind Sentinel buoy was redeployed in spring 2013, 0.5 miles offshore of Absecon Inlet in support of a separate validation study conducted by Fishermen's Energy. The buoy was re-deployed at its location 3 miles offshore of Absecon Inlet by June 2013. The Blue Scout LIDAR on the Wind Sentinel Buoy remains operational

Specific objectives

The objective of this task is to keep the instrumentation network operational to continuously collect research quality anemometer and LIDAR-based wind data. The network, presently consisting of 2 meteorological masts and the Scanning LIDAR have been operating and collecting research quality data from November 2012 through April 2014. Although not part of the Phase 1 data collection effort, the Buoy mounted vertical profiling LIDAR has also been continuously deployed and collecting data from March 2013 through April 2014.

Significant results

1. The Wind Tracer Scanning Doppler LIDAR is operating and collecting data over the 6-mile and 12-mile meteorological masts.

2. The 3rd meteorological mast located 3-miles from the Scanning LIDAR has been determined by the PIs to no longer a viable option due to permit constraints.

3. The AXYS Wind Sentinel is deployed within the 3 mile wind farm location and the Blue Scout Vertically profiling LIDAR continues to collect vertical wind data over the ocean.

Key outcomes, milestones and other achievements

The key achievements to meeting the task 1 outcomes between April 2013 and April 2014 are: (1) the continued collection of data from the Wind Trace scanning LIDAR and research quality data from the cup anemometers located 6 and 12 miles from the LIDAR; and (2) the continued operation of the Wind Sentinel Buoy and the Blue Scout Vertically Profiling LIDAR.
II. Task 2: Data Analysis

The collection and processing of the data is a function of site specific measurement requirements. Task 2 in Budget Period 1 focuses on the determination of the optimal profiles of wind speed and direction from the LIDAR radial velocities as a function of azimuth angle and rigorous estimates of the bias and random error of each radial velocity estimate.

Major activities:

In FY13, wind energy researchers at GL Garrad Hassan, under contract with Fishermen’s Energy, conducted a detailed analysis of the data collected by the Wind Trace scanning LIDAR and the anemometers located 6 and 12 miles from the LIDAR to determine the quality of the collected data.

Specific objectives

The specific objective of the activity was to determine if research quality data at standards acceptable for wind energy research is being collected by both the anemometers and the Scanning LIDAR.

Significant results

The validation analysis determined a Mast data recovery rate of 86 % and a LIDAR recovery of 61.5% over the FY13. It was determined that, in general, good agreement between the Wind Tracer LIDAR and anemometers was obtained. Wind Tracer data are of a lower quality between 70-80 degrees and 250 degrees, bearings that are orthogonal to the Wind Tracer range cells. The analysis also show some wind speed bias to high velocity winds (>10 m/s) and wind direction discrepancies that require additional investigation to explain. A more detailed reanalysis focused on only wind speeds greater than 4 m/s was suggested to further investigate the bias as a function of wind sector.

Key outcomes, milestones and other achievements

The validated data was provided to NREL researchers in FY13 to investigate the data discrepancies identified in the data validation phase. All data collected by the masts and the Wind Tracer were provided to NREL researchers for analysis; the results of which are presented in section III.

III. Task 3: Data Assessment

Major activities:
A detailed analysis of the measurement data from the Scanning LIDAR and the meteorological masts along with comparison of the coastal wind characteristics from the different systems was conducted on the data analyzed by GL Garrad Hassan and provided to co-investigators at NREL and AquaWind LLC. This focus of the analysis was to evaluate the performance of the scanning LIDAR in varying atmospheric conditions and distance from the scanning LIDAR (6.0 and 12 mile ranges).

Specific objectives

The specific objective of the FY2013-2014 activity was to investigate the possible reason for lower quality Wind Tracer data between 70-80 degree and 250 degree bearings with particular focus on the impact of the persistent winter heat plume that is emitted in line with the meteorological masts.

<u>Significant results</u>

NREL researchers and Co-PIs, Andrew Clifton and Dennis Elliott conducted preliminary comparisons of the data validated by GL Garrad Hassan. The data include measurements from the two masts (ACUA and Stockton) and the Lockheed Martin Wind Tracer scanning LIDAR. The overall objective was to evaluate how the data acquired from the LIDAR and masts compare, and how that comparison changes with flow conditions. The ACUA mast is 11,431.7 meters from the Wind Tracer on a bearing of 348.86° and the Stockton mast is approximately 18,200 meters from the Wind Tracer on a bearing of 350.35°.

Derivation of Wind Tracer Speed and Direction

The Wind Tracer LIDAR determines line of sight wind speeds at many different ranges and azimuth angles. This is done by emitting a pulse of laser light, waiting for a time δt and measuring the Doppler shift of the reflected light. This gives the line of sight wind speed (V_{LoS}) at a distance $r = c\delta t/2$, where c is the speed of light. If the wind field at the target area has a speed U and components u, v and w, the line of sight wind speed looking from an azimuth angle θ and elevation from horizontal ϕ is given by:

$$V_{LoS} = U\cos\phi\sin\left(\theta + \sin^{-1}\frac{v}{U}\right) + w\sin\phi$$

The Wind Tracer uses a single laser mounted on a head that rotates around two axes, allowing it to vary the elevation and azimuth with which the wind field is sampled. The magnitude of the line of sight velocity is highest when looking directly into or away from the wind, and lowest when the wind blows perpendicular to the laser beam. This method allows the above equation to be solved, if assumptions are made about the region over which the flow is broadly homogenous.
In the present analysis, the wind speed and wind direction from the Wind Tracer are derived from 30-degree sector scans that include 3 range gates, with 154.7 m between gate centers. Statistics for the meteorological masts are then derived from boxes 600 m by 600 m, centered on the masts. These sectors and the boxes around the masts are visualized in Figure 2 above.

The heights above ground of the Wind Tracer measurement at the two different mast locations are:

- ACUA: 50.6 m and 71.6 m
- Stockton: 61.5 and 90.2 m

ACUA and Stockton Meteorological Mast Instrumentation and Data

A summary and comparison of the instrumentation and data used in the data assessment is provided in Table 1.

Table 1 Heights and types of selected instruments on the ACUA and Stockton towers

Mast	Height	Variable	Device	Data
ACUA	34	Wind direction	NRG #200P wind vane	• 10-minute mean
	48	Wind speed	Thies First Class Anemometer	• 10-minute scalar mean • 10-minute minimum and maximum • 10-minute standard deviation
Stockton	46	Wind direction	NRG #200P wind vane	• 10-minute mean
	50	Wind speed	Thies First Class Anemometer	• 10-minute scalar mean • 10-minute minimum and maximum • 10-minute standard deviation

Wind roses for the ACUA and Stockton masts are plotted in Figure 3 and Figure 5. The most frequent wind directions are in the sectors from south to the west and northwest. Winds from the north and east sectors are less frequent. At both the ACUA and the Stockton masts, turbulence intensities are quite high and average about 20%. The turbulence intensity generally decreases with increasing wind speed before rising again at around 5-7 m/s (Figures 4 and 6). A dependency of turbulence intensity on wind direction can also be observed in the data.

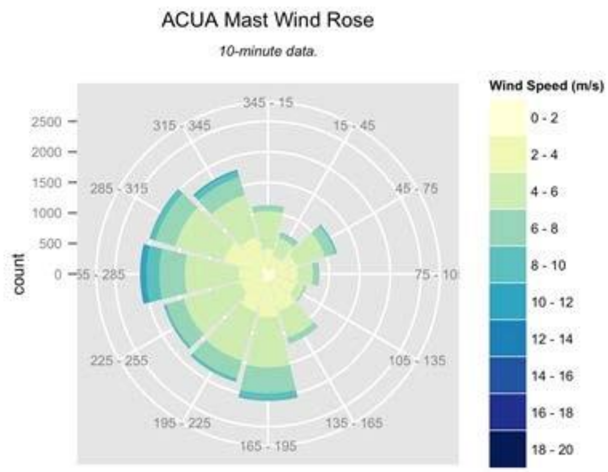


Figure 3. Wind rose showing wind speed and direction frequency from the ACUA mast instrumentation.

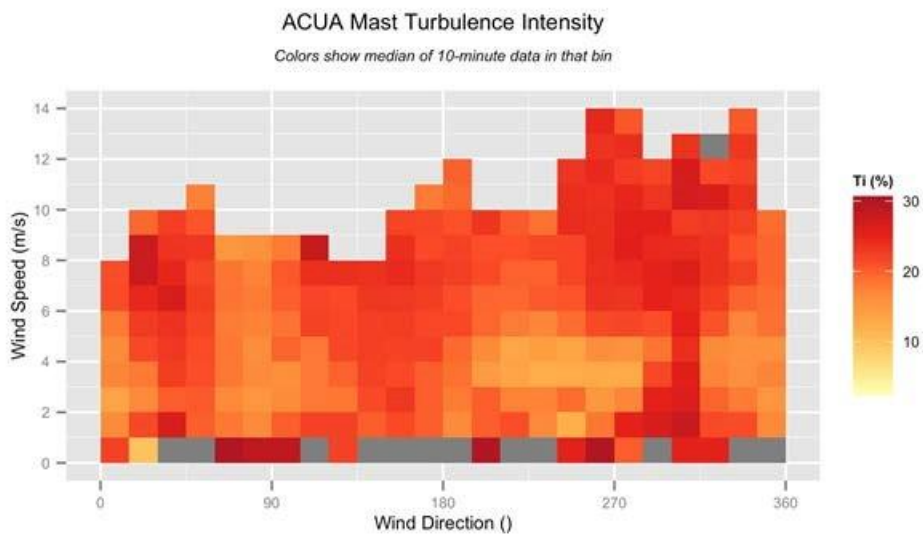


Figure 4. Turbulence intensity versus wind speed and direction from the ACUA mast instrumentation.

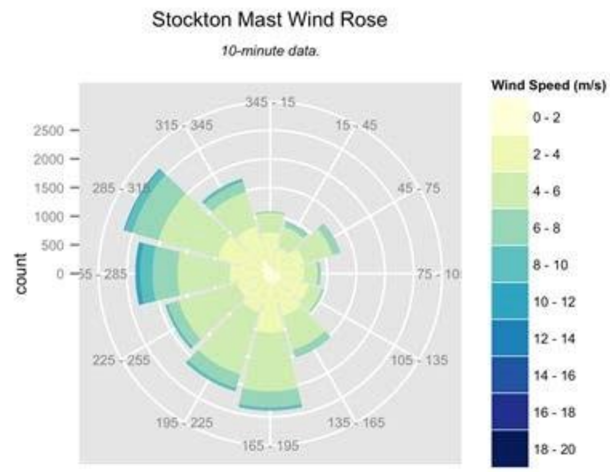


Figure 5. Wind rose showing wind speed and direction frequency from the Stockton mast instrumentation.

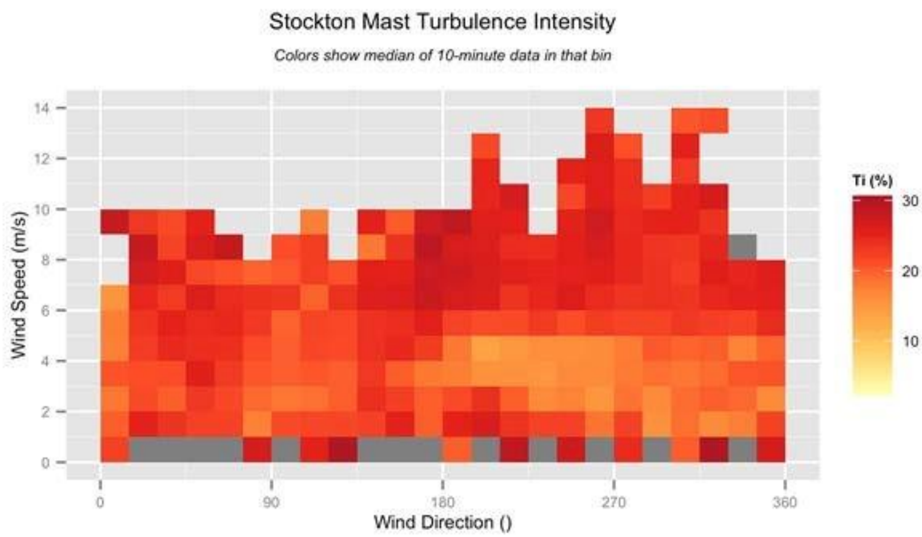


Figure 6. Turbulence intensity versus wind speed and direction from the ACUA mast instrumentation.

Comparison of Mast and LIDAR Data

Availability of mast and Wind Tracer data at the ACUA and Stockton locations is plotted in Figures 7 and 8, respectively. Data availability is quantified as the percentage of valid 10-minute data points from each of the systems in a given time period. In a 30-day month, there should be

4,320 data points. While the masts typically have more than 3,500 data points in a month (~80% availability), there is significantly less Wind Tracer data available at the ACUA (20-60% availability per month) and Stockton (10-15% availability per month) sites.

Although the Stockton site has less data availability than the ACUA site, the lack of other sites at other distances and directions makes it impossible to say if the Wind Tracer availability is a function of distance to target alone, or the combination of distance and wind direction at that distance.

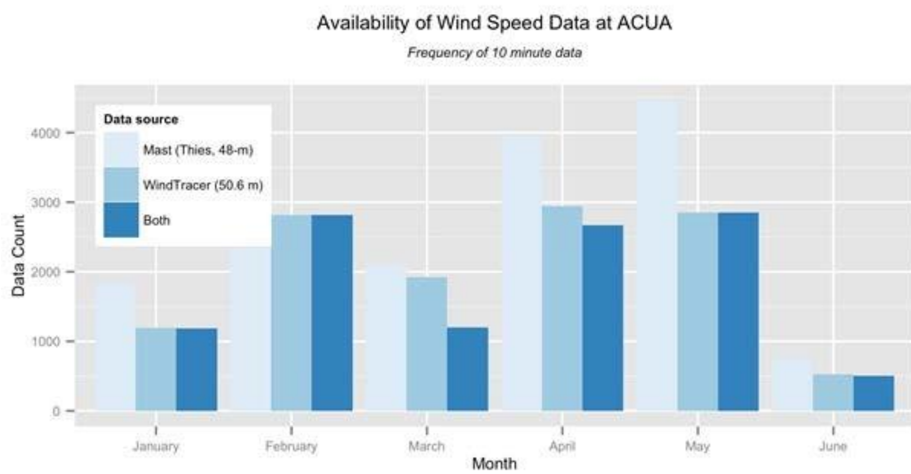


Figure 7. Availability of data at the ACUA site. Counts are given of valid values from the mast, Wind Tracer and when data from both systems are available simultaneously.

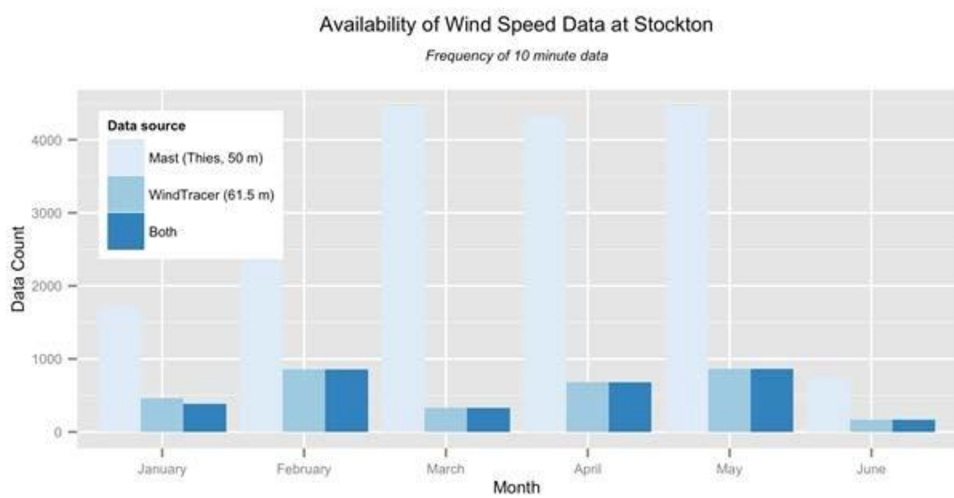


Figure 8. Availability of data at the Stockton site. Counts are given of valid values from the mast, Wind Tracer and when data from both systems are available simultaneously.

The Wind Tracer provides a snapshot of the wind speed at the ACUA and Stockton site every 10 minutes. In contrast, the ACUA and Stockton mast data loggers sample data every second

and then store the 10-minute mean, minimum and maximum wind speed values, as well as the standard deviation. The 1-second data from the mast instruments are not stored.
Because of the turbulence at the mast locations, the wind speed during a 10-minute period at that site will not be constant. Also, because the Wind Tracer only samples the winds at the site once in that period, it is unlikely that the snapshot Wind Tracer wind speed will show a good agreement with the mean wind speed from the masts. This is important, because mean wind speed is usually required for wind resource assessments.

A comparison of the snapshot Wind Tracer wind speed with the ACUA mast wind speed is shown in Figure 9. Data are grouped according to the wind direction at the ACUA mast, measured by a wind vane at 35 m above ground (data from the 45-m wind vane are bad). Intervals where the mean ACUA 48-m wind speed was less than 3 m/s have been removed. The agreement between the mast and Wind Tracer wind speeds is shown using the gradient of an ordinary least-squares fit to the data (mm) and the coefficient of determination, R^2. There is a visually good agreement between the magnitude of the wind speed reported by the Wind Tracer and the wind speed reported by the ACUA meteorological mast when winds are approximately parallel to the line of sight of the Wind Tracer to the ACUA mast (i.e. from approximately 350° or 170°), although higher wind speeds are typically measured by the Wind Tracer than the mast. Reasonable correlations – considering the scatter - are also seen for other directions. However, when winds at the ACUA site are from sectors centered on 260° or 80° the scatter is increased and there is a worse agreement between the Wind Tracer and ACUA mast data. If the winds at the 35-m level are similar to the winds at 50-m, these sectors are approximately perpendicular to the line of sight of the WindTracer to the ACUA mast. This increased error in estimating the speed of winds that are almost perpendicular to the line of sight of the WindTracer may stem from the low line-of-sight velocity and consequent low Doppler shift when the WindTracer is looking in this direction. Coefficients of determination (R^2) for the data show no obvious dependence on wind direction.

Wind speeds measured by the WindTracer at the Stockton location (Figure 10) are less well correlated with the mast measurements that at ACUA. This can be seen both in the gradient of the fit and in the coefficient of determination for each wind speed sector. Unlike the ACUA data, negative correlations are seen between the WindTracer and mast in some wind directions sectors at Stockton. The lack of data with wind speeds greater than 10 m/s means that data are weighted towards lower wind speeds than ACUA.

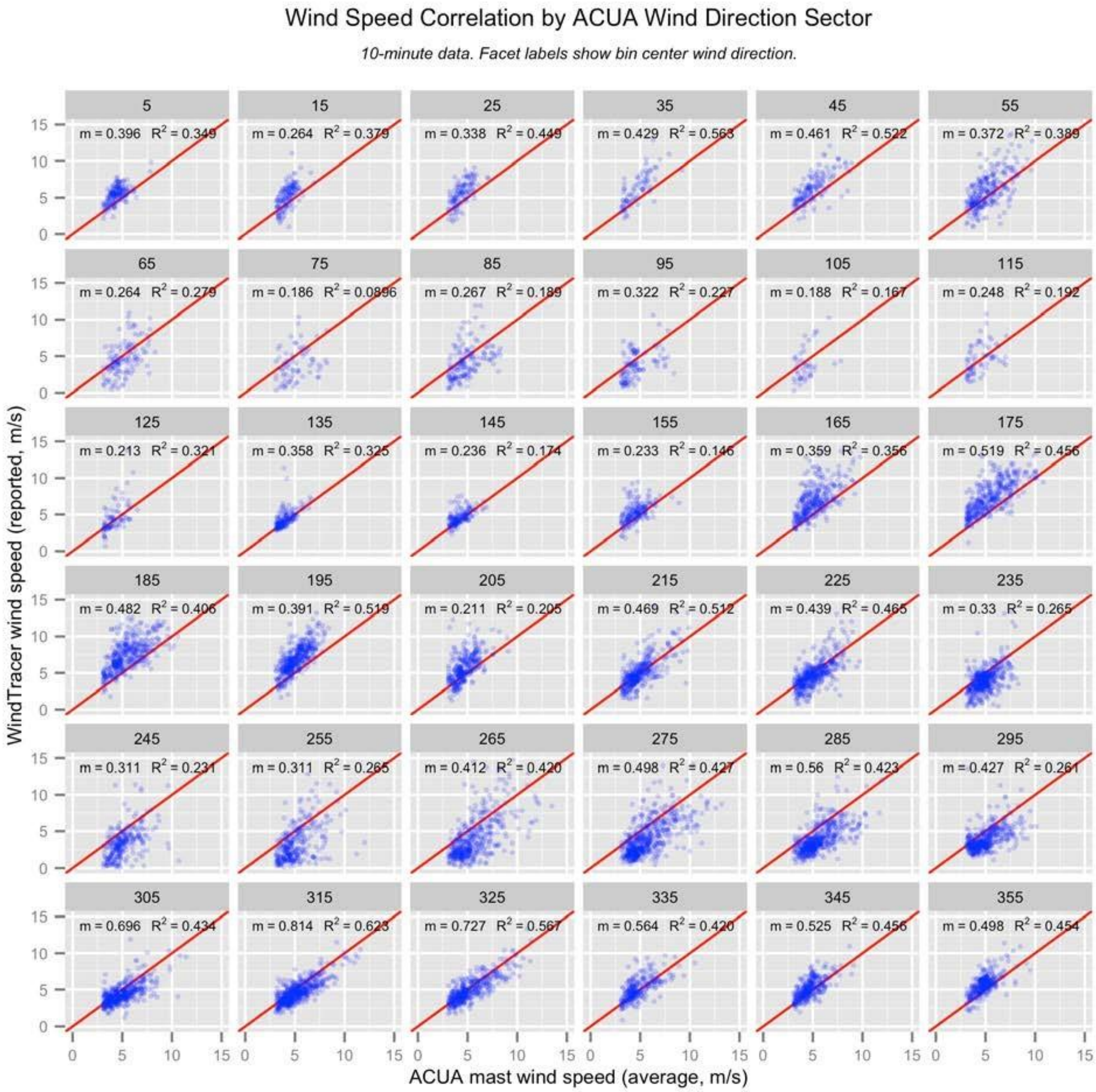


Figure 9. Correlations between ACUA mast and WindTracer wind speed data, grouped by ACUA 35-m wind direction sector. Periods where the wind speed was less than 3 m/s at the ACUA mast have been removed. Plots are annotated with the gradient of an ordinary least-squares fit (mm) and the coefficient of determination, R^2 for that wind sector.

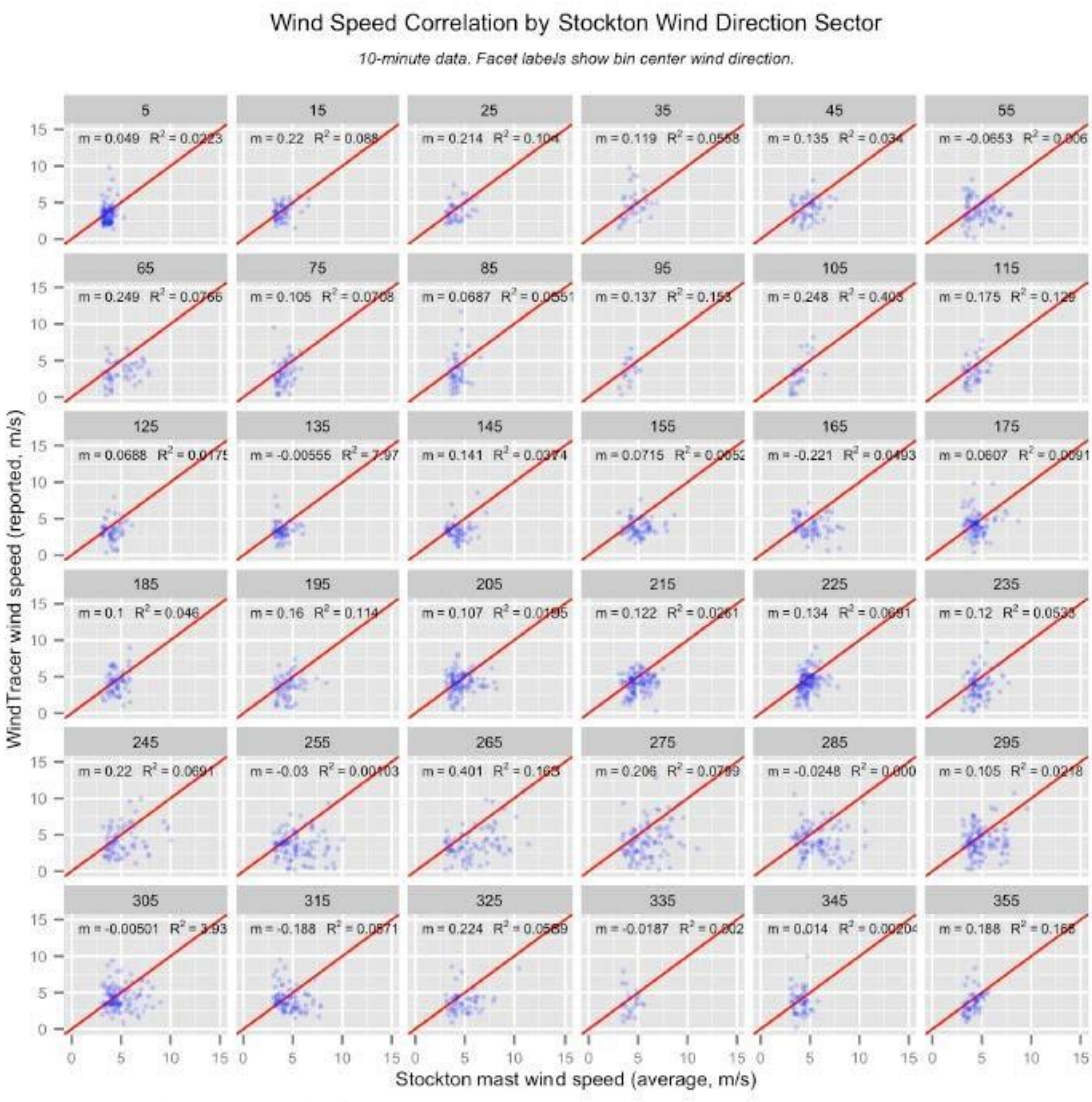


Figure 10. Correlations between Stockton mast and WindTracer wind speed data, grouped by ACUA 46-m wind direction sector. Periods where the wind speed was less than 3 m/s at the Stockton mast have been removed. Plots are annotated with the gradient of an ordinary least-squares fit (mm) and the coefficient of determination, R^2 for that wind sector.

If the WindTracer were measuring at the same height as the instrumentation on the masts, the snapshot wind speed from the WindTracer should be between the maximum and minimum wind speed recorded by the meteorological masts. To compare the WindTracer wind speeds with mast wind speed data, observations are deemed to “Hit” if the WindTracer wind speed is between the minimum and maximum mast wind speed. Data are deemed to “Miss” if the WindTracer wind speed is outside this range. Data are then subset by mast wind direction and wind speed. For each bin, we then define the LIDAR’s measurement hit rate as:

$$hit\_rate = \frac{n(Hit) - n(Miss)}{n(Hit) + n(Miss)}$$

A hit rate of 1 would mean that all measurements by the LIDAR in that bin were hits (in the range of the mast measurements). A hit rate of -1 would mean that all measurements in that bin were misses (outside of the range of the mast measurements). Ideally, the hit rate would be 1 in all bins.

Results for this comparison at the ACUA mast are plotted in Figure 11. The WindTracer shows a higher hit rate at measuring the ACUA wind speeds when there is an offset between the wind direction at ACUA and the azimuth from the WindTracer to ACUA. When winds at the ACUA mast at 34 m are in bins centered from approximately 65° to 95°, and from 245° to 275°, the WindTracer hit rate is reduced, particularly at wind speeds less than 6 m/s. Winds from these directions are approximately perpendicular to the line of sight from the WindTracer location to the ACUA. The hit rate at the Stockton mast (Figure 12) shows similar trends to that seen at ACUA. The hit rate increases when winds are approximately aligned with the line of sight of the LIDAR, and reduces when the LIDAR looks perpendicular to the winds at the Stockton site.

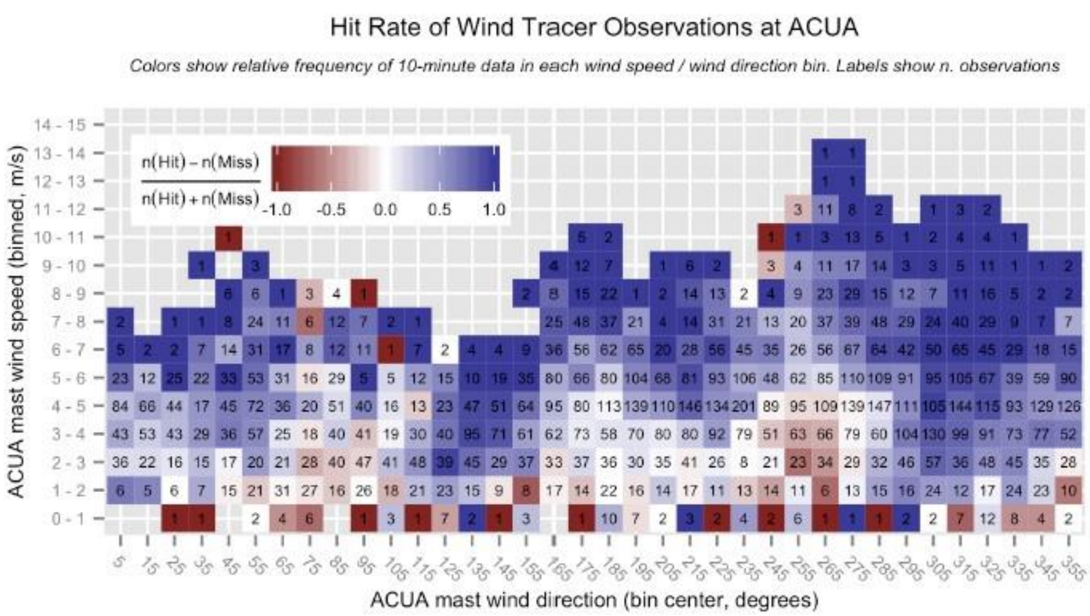


Figure 11. Relative frequencies of WindTracer wind speeds falling within the min-max range of the ACUA mast wind speed data. Data are binned by 35-m ACUA mast wind direction and 48-m mast wind speed.

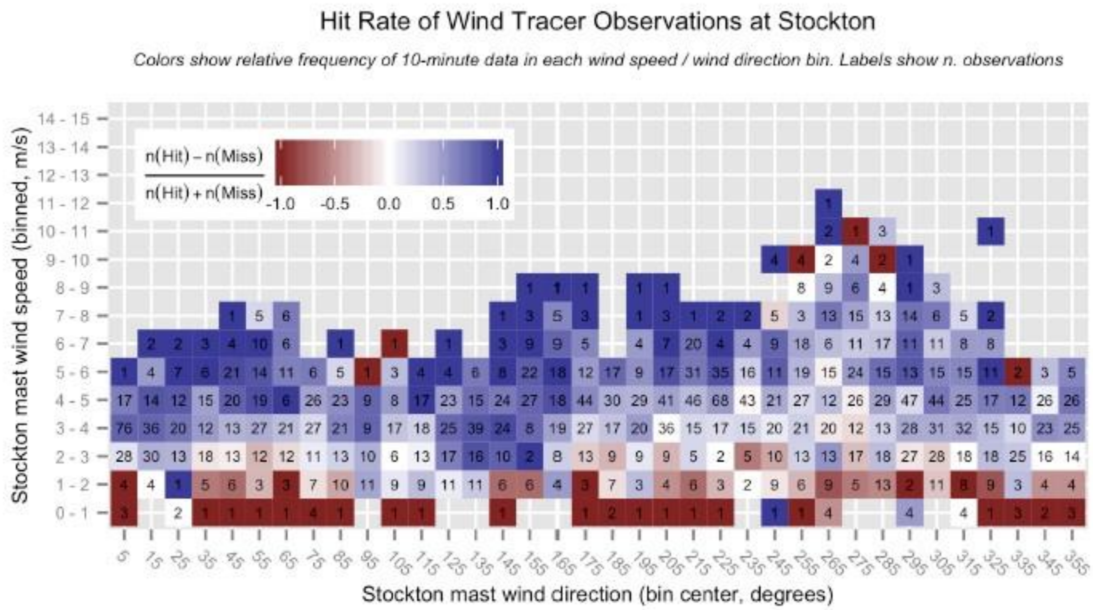


Figure 12. Relative frequencies of WindTracer wind speeds falling within the min-max range of the Stockton mast wind speed data. Data are binned by 36-m Stockton mast wind direction and 50-m mast wind speed.

The WindTracer skill for the complete time series of 10-minute measurements is shown in Figure 13. Because only one pair of measurements are being compared, data are either in or out of range in each 10-minute interval.

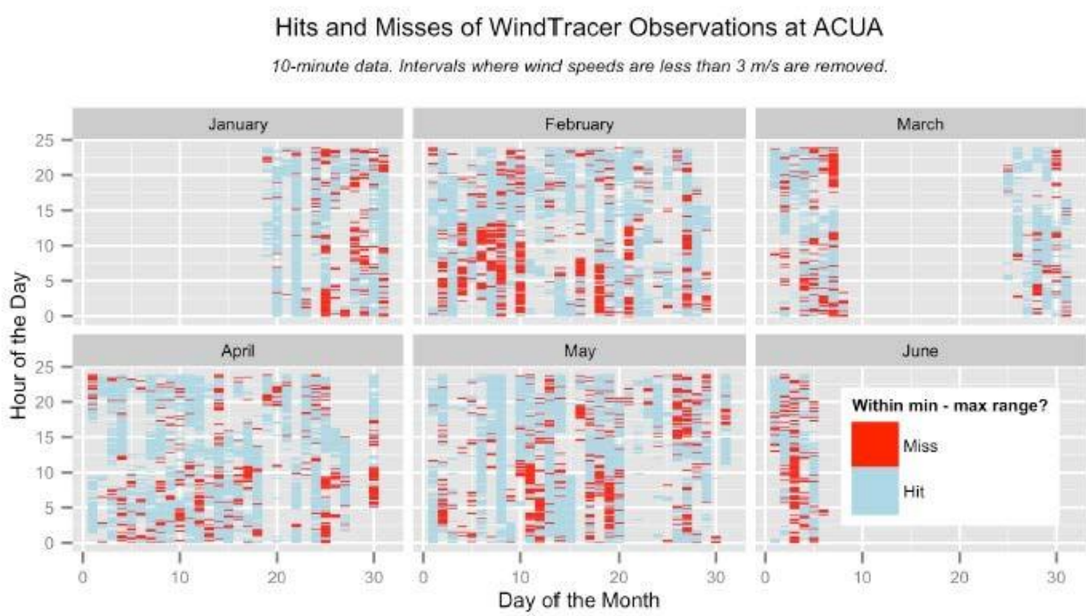


Figure 13. Time series showing when WindTracer wind speeds are within the range given by the ACUA mast wind speed minimum – maximum range.

Previously, it had been suggested that the accuracy of the WindTracer might have been impacted by ground heating between the WindTracer and the masts, or by hot air venting from the building beneath the WindTracer. Figure 13 shows no evidence for diurnal cycles of performance, or of worse performance in the summer or winter months. Therefore, it appears that there is no apparent link between surface heating cooling and building heating and cooling, and the WindTracer performance. However, it should be noted that heating may lead to convection around the LIDAR and thus complete loss of the LIDAR signal, rather than errors compared to the ACUA and Stockton masts. Wind speed distributions for each month for the ACUA and Stockton sites from the masts and WindTracer are plotted in Figure 14 and Figure 15. As the acceptability of the wind speed distribution depends on the use of the data, these are provided for information only.

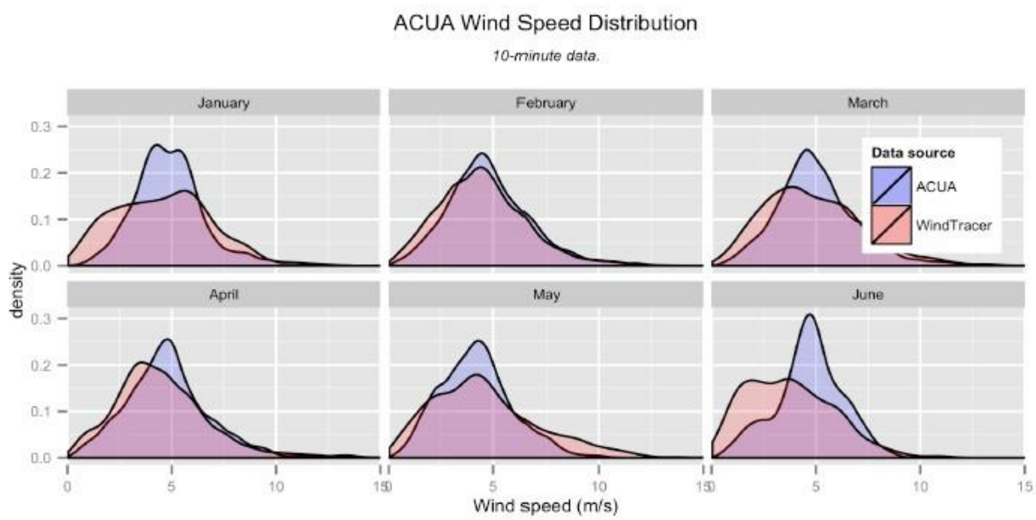


Figure 14. Wind speed distributions at the ACUA site. Data are derived from the ACUA mast 48m anemometer and the WindTracer 50.6-m level.

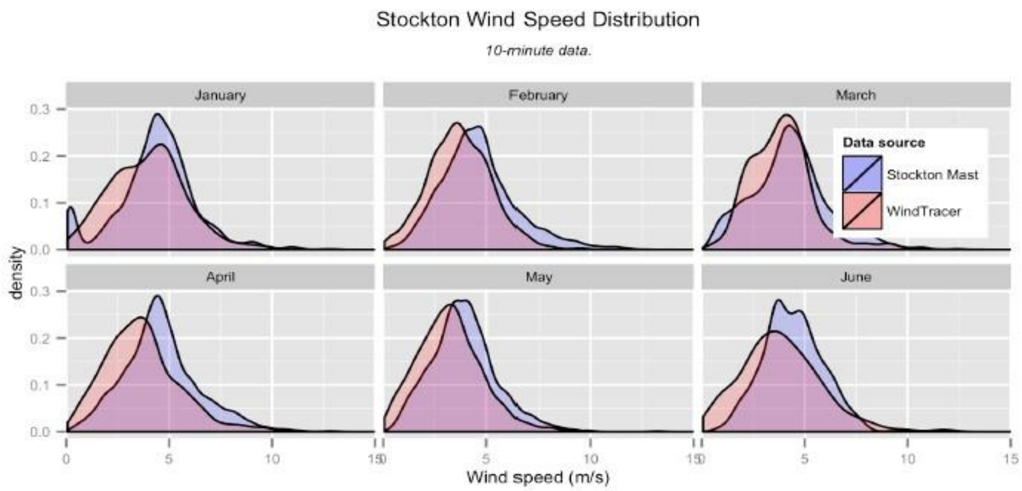


Figure 15. Wind speed distributions at the Stockton site. Data are derived from the Stockton mast 50-m anemometer and the WindTracer 61.5-m level.

As with the wind speed, the wind direction from the WindTracer is not directly comparable to the wind directions from the ACUA and Stockton masts because of the short visit time. However, no other data are available to verify the WindTracer performance. The mast data do not include maximum or minimum wind directions, as those values are meaningless. Instead, the wind directions can only be compared directly. A comparison of the WindTracer wind direction with the ACUA mast 35-m wind direction is shown in Figure 16. Intervals where the mean ACUA 48-m wind speed was less than 3 m/s have been removed. The wind direction reported by the WindTracer roughly agrees with the ACUA wind direction. Empty bands are seen in the WindTracer wind direction data in the ranges 73° to 83° and 258° to 264°. These empty bands suggest that WindTracer data had already been removed in sectors where the winds are approximately ±5° from perpendicular to the line of sight.

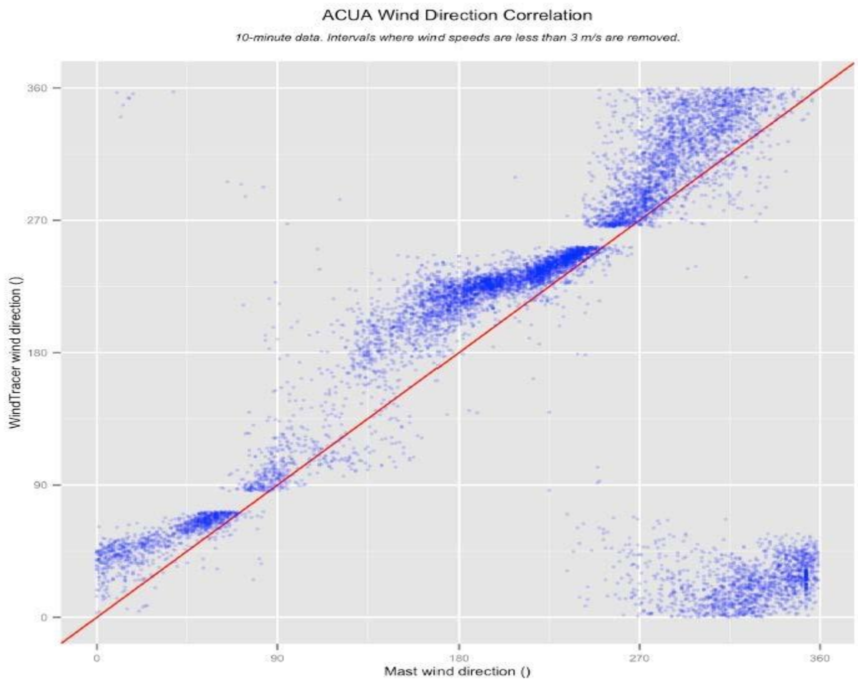


Figure 16. Correlation between ACUA mast 35-m wind direction and WindTracer 50.6-m wind direction data. Periods when the wind speed was less than 3 m/s at the 48-m level on the ACUA mast have been removed.

A comparison of the WindTracer wind direction with the Stockton mast 46-m wind direction is shown in Figure 11. The correlation between wind directions from the WindTracer and the Stockton tower is much reduced compared to the ACUA location.

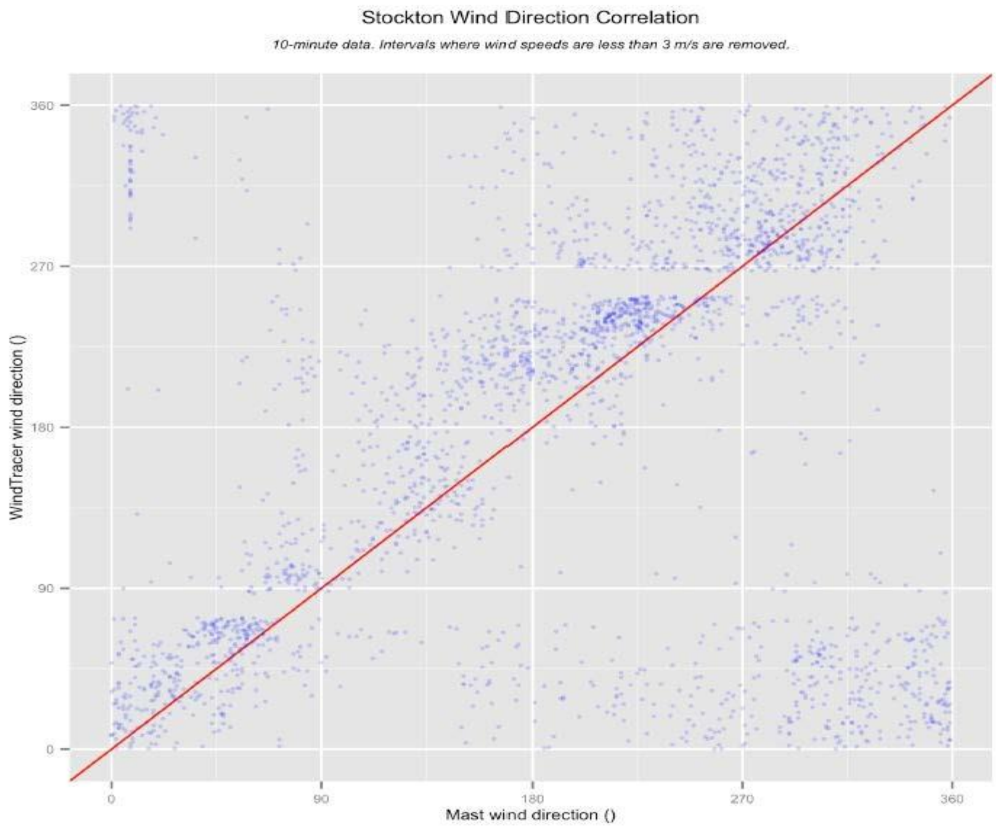


Figure 17. Correlation between Stockton mast 46-m wind direction and WindTracer 61.5-m wind direction data. Periods when the wind speed was less than 3 m/s at the 48-m level on the Stockton mast have been removed.

Error in the WindTracer direction compared to the ACUA mast appears largest when the winds at the ACUA mast are directly parallel to the azimuth angle from the WindTracer to the ACUA mast. However, the wind direction data from the ACUA and Stockton masts also includes the effects of the mast structure shadowing the vane. At the ACUA mast, the wind vanes are on the north side of the mast (6°). At the Stockton mast, the wind vanes are on the North side of the mast (8°). From experience, this would lead to greatest errors when the winds are from the south side of the mast, as is seen in Figure 16 and Figure 17. Removing this effect is very difficult without a second wind vane at the same height

Key outcomes, milestones and other achievements

A first series of measurements by a long-range WindTracer scanning LIDAR at two meteorological masts have been analyzed and compared. An accurate and unequivocal comparison of the LIDAR and mast data is difficult because of the quality of the data that are available from the masts and their locations. However, results suggest that the LIDAR is capable of measuring realistic wind data at distances up to 12 miles in favorable conditions. Specific concerns over the configuration of the instrumentation, data collection and data quality, include:

- Non-uniformity of the landscape around each meteorological mast may be leading to locally high spatial variation in the flow, such that the WindTracer measurements cannot capture conditions local to the mast.
- Cup anemometers at the ACUA mast are at a different level (48 m) to the WindTracer measurement (50.6) in a region where there may be high shear induced by the forestry to the north and south of the mast.
- Low availability of concurrent data from the Stockton mast and the WindTracer does not allow evaluation of the accuracy of the WindTracer at longer ranges.
- Averaging of the measured wind speeds and wind direction on the mast loggers prevents us from comparing the mast and WindTracer data at the same instant in time.
- No evidence for diurnal or seasonal cycles of performance makes it difficult to draw an apparent link between surface heating cooling or building heating and cooling, and the WindTracer performance.
- The existence of a heat plume located on a bearing of approximately 350 degrees TN emanating from the building on which the LIDAR is mounted is in-line with the existing meteorological towers, possibly creating localized scintillation of the laser pulses.

This preliminary analysis suggests that under favorable conditions (such as short range to target, homogenous flow, and winds near to the line of sight) the WindTracer data are within the range of the mast measurements. However, as wind speeds drop, ranges increase, and flows are perpendicular to the line of sight, the agreement between the WindTracer and the masts reduces. We note that with the current instrumentation and data, we cannot distinguish between effects that are very local to the mast, such as anemometer shadowing or wind direction changes with height, and poor LIDAR measurements.

Goal Status: Budget Period 4 (FY2014-2015): Fixed scanning LIDAR coastal wind measurement evaluation

The purpose of the FY2014-2015 effort is to collect volumetric wind data with a scanning pulsed Doppler LIDAR to retrieve vector velocities for the evaluation of coastal scanning LIDAR in comparison to research quality anemometers mounted on two meteorological masts located within the coastal zone. Collocated LIDAR derived winds and meteorological tower data at the 6 and 12 mile mast were collected between October 2012 and June 2013. A quality assurance analysis of the collected data, conducted by DNV-GL (formerly GL-Garrad Hassan), determined an Anemometer recover rate of 86% and a LIDAR recovery rate of 61.5%. Wind bearings orthogonal to the LIDAR beam at the Meteorological Masts (70-80° and 250-260°) were determined to be of low quality, as expected.

A preliminary comparisons of the data validated by DNV-GL was conducted. A comparison of wind speed data collected by the LIDAR and the anemometers at the 6 mile (ACUA) mast showed visually good agreement between the magnitude of the wind speed reported by the WindTracer (manufactured by Lockheed Martin Coherent Technologies) and the wind speed reported by the ACUA meteorological mast when winds are approximately parallel to the line of sight of the WindTracer to the ACUA mast (i.e. from approximately 350° or 170°). However, higher wind speeds are typically measured by the WindTracer than the mast. Reasonable correlations were also seen for other directions, except when winds at the ACUA site are from sectors centered on 260° or 80°. This increased error in estimating the speed of winds that are almost perpendicular to the line of sight of the WindTracer stem from the low line-of-sight velocity and consequent low Doppler shift when the WindTracer is looking in this direction. Coefficients of determination (R^2) for the data show no obvious dependence on wind direction. Wind speeds measured by the WindTracer at the 12 mile (Stockton) location were less well correlated with the mast measurements than at ACUA. Unlike the ACUA data, negative correlations were found between the WindTracer and mast in some wind directions sectors at Stockton.

The analysis of the collected data revealed no evidence for diurnal cycles of performance, or of worse performance in the summer or winter months. Therefore, it appears that there is no apparent link between surface heating cooling and building heating and cooling, and the WindTracer performance within the validated data. However, it is noted that heating may lead to convection around the LIDAR and thus complete loss of the LIDAR signal, leading to the observed low return of valid WindTracer data. An accurate and unequivocal comparison of the LIDAR and mast data is difficult because of the quality of the data that are available from the masts and their locations. However, results suggest that the LIDAR is capable of measuring realistic wind data at distances up to 12 miles in favorable conditions.

The poor quality of the data collected by both the anemometers located on the meteorological masts and the WindTracer Scanning LIDAR necessitated a change in both the instrumentation configuration and the sampling methods for both the anemometers and the LIDAR. Over the course of a year (April 2013 to April 2014), a number of options were pursued and evaluated in an effort to reconfigure the instrumentation network to; (1) reduce the influence of landscape generated turbulence on anemometer measurements, (2) remove the influence of the heat vent on the WindTracer LIDAR measurements, and (3) improve the temporal and spatial resolution of the collocated anemometer and LIDAR data.

The Phase 1 data collection and analysis effort has been changed to evaluate the influence of the existing heat plume on the measurement quality of the WindTracer LIDAR and, in a broader sense, evaluate its performance in an urban coastal environment. Assessment of the influence of the heat plume on the LIDAR measurements began in March of 2014 through the continuous monitoring of the plume air temperature. In October 2014, the ACUA mast was fitted with a Campbell Scientific CR1000 logger capable of recording and storing data at 1Hz, allowing for the comparison of the mast and WindTracer data at the same instant in time. A second CR1000 is being procured to upgrade the Stockton mast with similar 1Hz data collection capability. Brand new, MeasNet calibrated Thies Clima First Class anemometers will be installed on both masts in mid February 2015.

Concurrent with the heat plume analysis, the siting for a 3rd 60 meter mast located on a bearing of ~275° from the LIDAR location is being pursued. If permitted, the 60m mast will be equipped with 3 NRG Class 1 cup anemometers and 3 Thies First Class anemometers and 2 NRG #200 wind direction vanes. The anemometers will be placed in co-located pairs on opposite sides of the mast at elevations of roughly 40, 50 and 60 m above ground (same configuration as the existing masts with exception of higher elevations). The wind direction vanes will be located 45 and 55 m above ground. A Campbell Scientific CR1000 data logger will measure and store the recorded wind measurements at a frequency of 1 Hz.

The following report summarizes the heat plume monitoring and the continued assessment of the WindTracer scanning LIDAR data in comparison to the collocated anemometer data. The results of these analyses are used to evaluate the capability of detecting heat plume venting and possible correlation with low WindTracer LIDAR data returns.

I. Task 1: Data Collection

The objective of the data collection task is to monitor the venting of the heat plume located on the building as well as continue to obtain measurements of scanning pulsed Doppler LIDAR with co-located standard research quality anemometer data.

Major activities:

The field evaluation site is centered within a 12 mile radius of Margate, NJ. Margate is located along the southern NJ coast approximately 3 miles southwest of Atlantic City. Prior to the start of the field evaluation of the Scanning LIDAR, Fishermen's Energy (FE) deployed and initiated the operation of the instrument network. Figure 1 indicates the location of the Scanning LIDAR, two existing 50m meteorological masts operated by Stockton College under contract by Fishermen's Energy and the proposed location of a third 60m meteorological mast site located 10.2 miles WNW of the LIDAR. The location of Scanning LIDAR is indicated by the blue circle on the coast. Both of the operational 50m masts are located NNW of the LIDAR; one at a range of 7.2 miles (ACUA mast) and the other at 11.4 mile (Stockton mast).

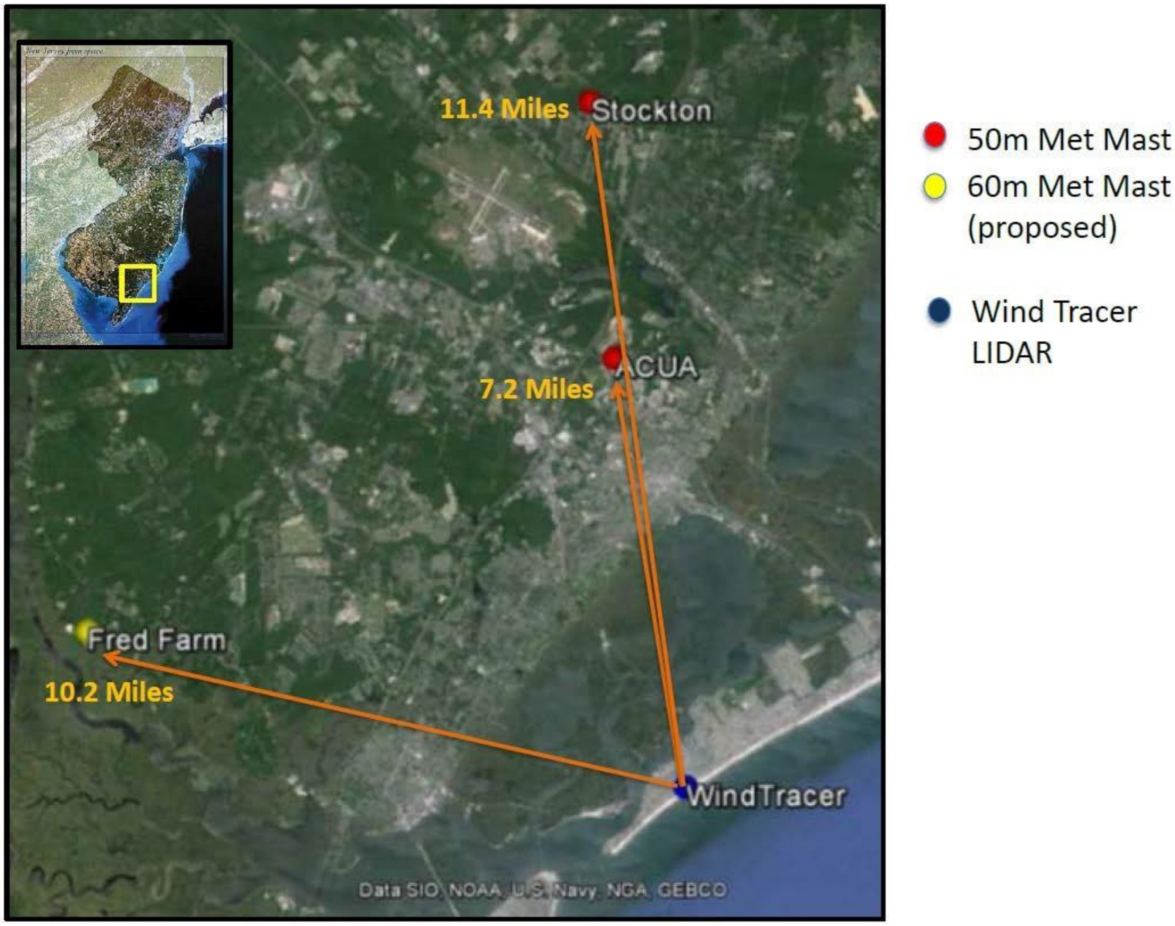


Figure 1: Location Map

The two, 50m masts are NRG XHD TallTowers equipped with 3 NRG Class 1 cup anemometers and 3 Thies First Class anemometers located roughly 30, 40 and 50 m above ground, and 2 NRG #200 wind direction vanes located 35 and 45 m above ground. Both masts initially utilized NRG SymphoniePlus data logger to collect data at 1HZ and internally record 10 min average samples of wind speed and direction. In October of 2014, the 6 mile tower was upgraded with a Campbell Scientific CR1000 logger capable of recording and storing data at 1Hz, allowing for the comparison of the mast and WindTracer data at the same instant in time. A second CR1000 is being sought to upgrade the Stockton mast with similar 1Hz data collection capability.

The LIDAR is installed 168ft above Mean Sea Level on top of an apartment building located immediately landward of the Margate, NJ shoreline at Latitude 39º 19´ 10.86" and Longitude 74º 30´ 47.25" (Figure 2). The LIDAR collects volumetric data over the two existing 50 meter masts on an approximate bearing of 350 degrees TN (Figure 3).

Figure 2. Location of WindTracer LIDAR on top of the elevator shaft of the Margate Towers Condominium Building in Margate, NJ.

Figure 3. Depiction of the approximate LIDAR sampling volume at the ACUA and Stockton meteorological masts.

The WindTracer LIDAR is housed in a 6ft x 6ft x 6ft instrument shed containing the electronics, computer, power supply and laser. The LIDAR emerges from the instrument shed through the rotational scanner at one corner of the container. The shed is supported by a metal I-beam foundation that is connected to the structural bearing beams of the building.
(Figure 4).

Figure 4. WindTracer instrument shed located on top of Margate Towers Condominiums

The portion of the building containing the elevator shaft equipment also houses additional mechanical equipment required to supply the building with water, heat and air conditioning, and includes a chimney for venting heat from the building through the roof of the elevator shaft. The chimney opening is located approximately 7ft NW of the northwest corner of the WindTracer instrument shed, immediately below the rotational scanner (Figure 5). The location of the chimney heat vent is approximately 6ft below and in-line with the LIDAR scanner on a bearing of 350° TN; in-line with the sampling volumes over the ACUA and Stockton masts (Figure 6).

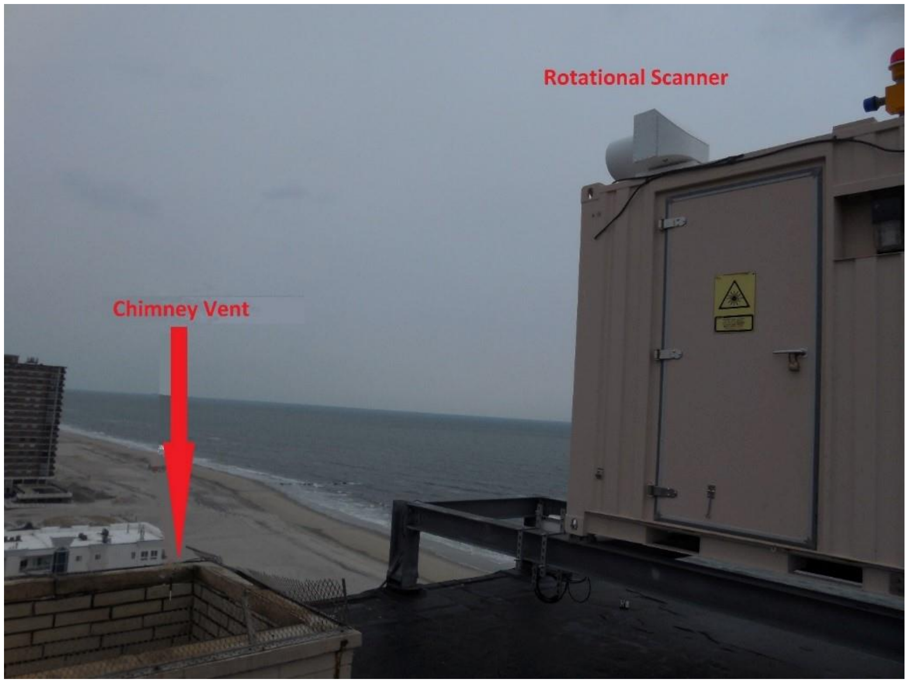


Figure 5. Location of chimney heat vent relative to WindTracer instrument shed and rotational scanner.

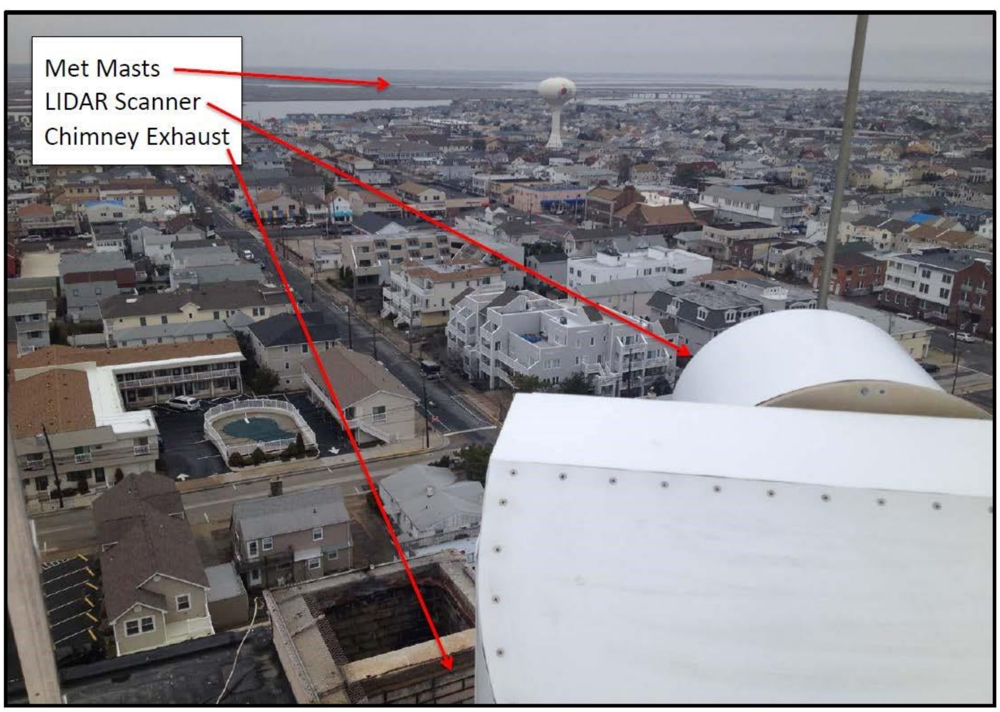


Figure 6. View from scanner looking over chimney heat vent toward meteorological masts on a bearing of 350° TN.

To determine if the heat plume vented by the chimney has an effect on the quality of the data returned by the WindTracer LIDAR, a monitoring system consisting of an ambient temperature probe, a heat vent temperature probe, and a cup and vane anemometer was placed on the roof in March 2014. The ambient temperature probe and cup and vane anemometer are attached to the southeast corner of the support beams and the vent temperature probe is attached to the eastern side of the chimney (Figures 7 and 8).

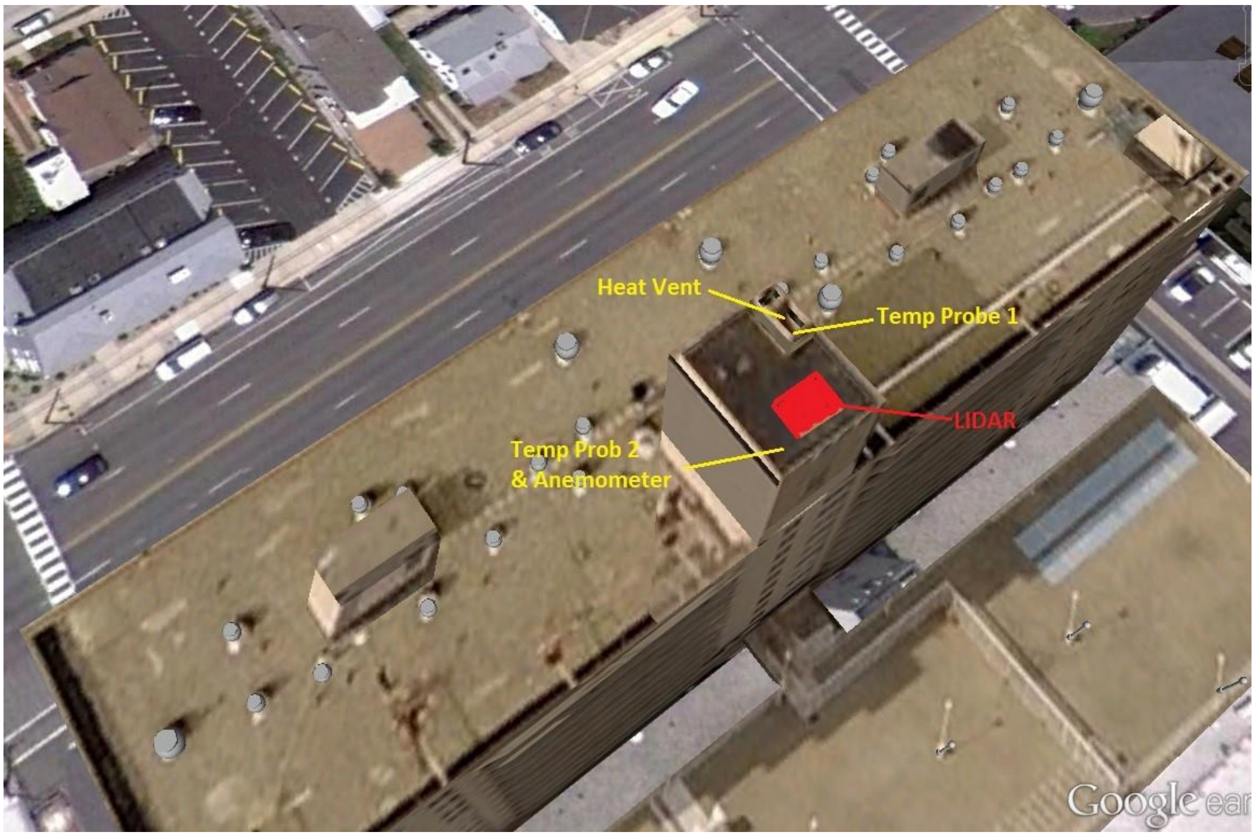


Figure 7. Plan view of elevator shaft roof indicating the location of the WindTracer shed, chimney heat vent, and temperature monitoring probes.

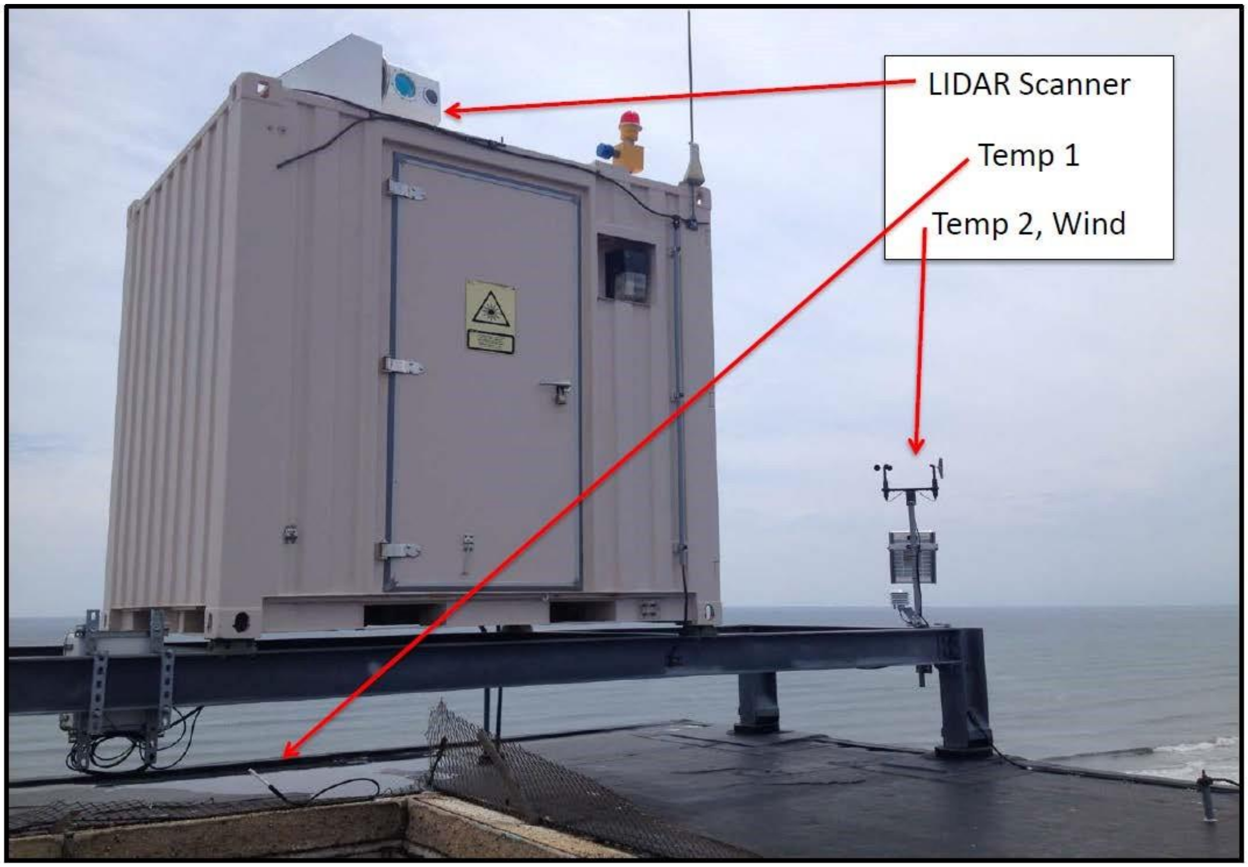


Figure 8. View of the heat plume monitoring system components located on the roof of the elevator shaft building looking toward the south. Note that the heat vent temperature probe (Temp 1) is unshielded.

II. Task 2: Plume Data Collection and Analysis

The plume monitoring system started collecting data on March 25, 2014 and has operated continuously through December 2014. The system records the average, minimum, maximum and standard deviation of the exhaust vent temperatures at one minute intervals and the ambient temperature at 5 minute intervals. The roof top anemometer records five minute averages and standard deviations of the wind speed and wind direction. Here we analyze the ability of the monitoring system to detect plume venting events and identify any periodicities in the data.

<u>Significant results</u>

Figure 9 presents a 7-day time series of the temperature and wind speed data collected by the plume monitoring system and the corresponding wind speed data from the ACUA anemometer and the collocated WindTracer LIDAR wind speed located at an elevation of 48m. The temperature data is plotted on the lower panel of Figure 9. The ambient temperature is represented by the green line (Temp2) and the temperature at the vent is represented by the blue line (Temp1). The ambient temperature show a strong diurnal pattern of gradual warming during the day and cooling at night over the first 3 days of the record. From Julian day 160 to 163, the ambient temperature becomes more constant with no evidence of the daily diurnal pattern. The temperature probe at the heat vent shows a similar diurnal heating and cooling pattern over the first 3-days of the record but measures a slightly higher mean temperature. High frequency oscillations are evident in the vent temperature measurements. Such higher frequency oscillations are not present in the ambient temperature record. The high frequency oscillations are generated by the chimney venting heat at an almost constant frequency.

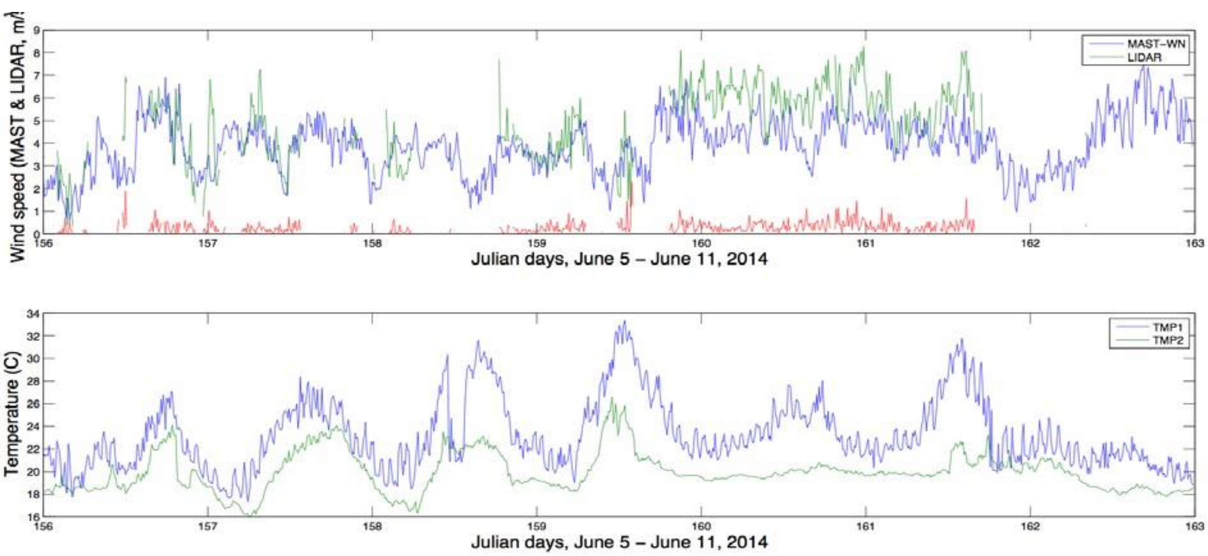


Figure 9. Top panel: Wind speed measured by the ACUA 48m anemometer (blue line) and the WindTracer LIDAR derived wind speed (green line) at the ACUA 48m anemometer. Bottom panel: Ambient air temperature (green line) and vent air temperature (blue line) measured by the roof top plume monitoring system. The red line is the standard deviation of the LIDAR measurements.

The top panel of Figure 9 presents the wind speed data collected by the 48m anemometer on the ACUA mast (blue line) and the WindTracer calculated wind speed (green line) from the sampling volume containing the ACUA 48m anemometer. Over the first 3-days of strong diurnal heating and cooling, the WindTracer returns significantly less data than the cup anemometer. This is evident in the multiple breaks in the record of the standard deviation of the WindTracer wind speed (red line). Wind speeds over the initial 3 days show a slight semi-diurnal pattern with an average wind speed of between 3 and 4 m/s. Steadier, sustained winds of 4 to 6 m/s occur between Julian Day 160 to 162, WindTracer wind speed data returns are much more consistent over this 2 day period. However, the data indicates that the WindTracer overestimates the wind speed measured by the cup anemometer.

To investigate the variable diurnal temperature signal recorded by the plume monitoring system, data from the National Weather Service's weather observation station KACY, located at the Atlantic City International airport was obtained to provide local weather conditions. Station KACY is located 2.25 miles northwest of the ACUA mast (Figure 10).

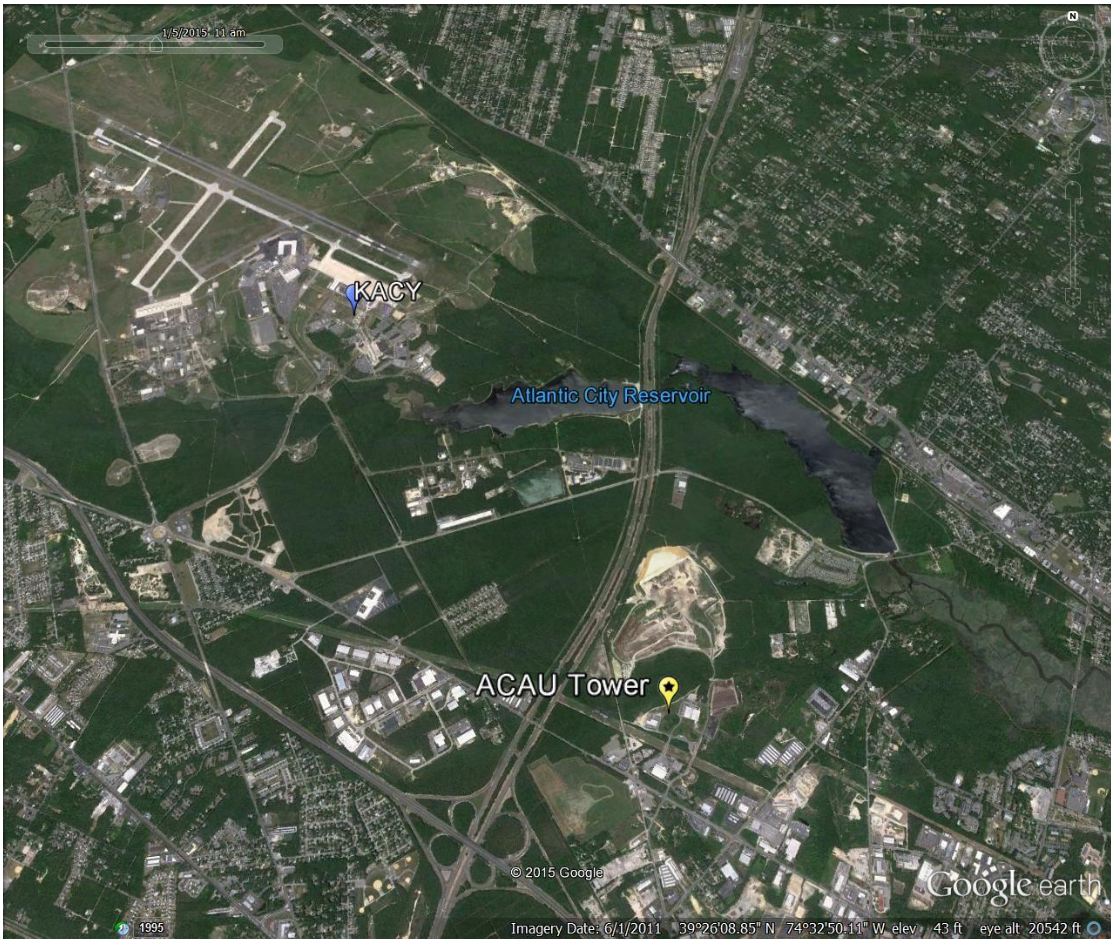


Figure 10. Location of the KACY weather observation station relative to the ACUA mast.

Figure 11 presents a week long time series of wind velocity data measured by the WindTracer and ACUA 48m cup anemometer, the ambient and heat vent temperature measured on the roof adjacent to the WindTracer, and the temperature and cloud cover data measured at the Atlantic City airport weather station. Significant cloud cover was measured by the KACY station over the first two days of the record; June 26 and 27. The roof top measurements of the ambient air and heat vent temperatures track closely to each other, however the heat vent temperature is slightly higher (~ 2°C) than the ambient temperature. The KACY station measured no cloud cover from June 28 and 29. Over this two day period, the roof top temperatures show a diurnal pattern of heating and cooling, however during the peak temperatures of the day, the heat vent temperature is almost 10°C higher than the ambient roof top temperature.

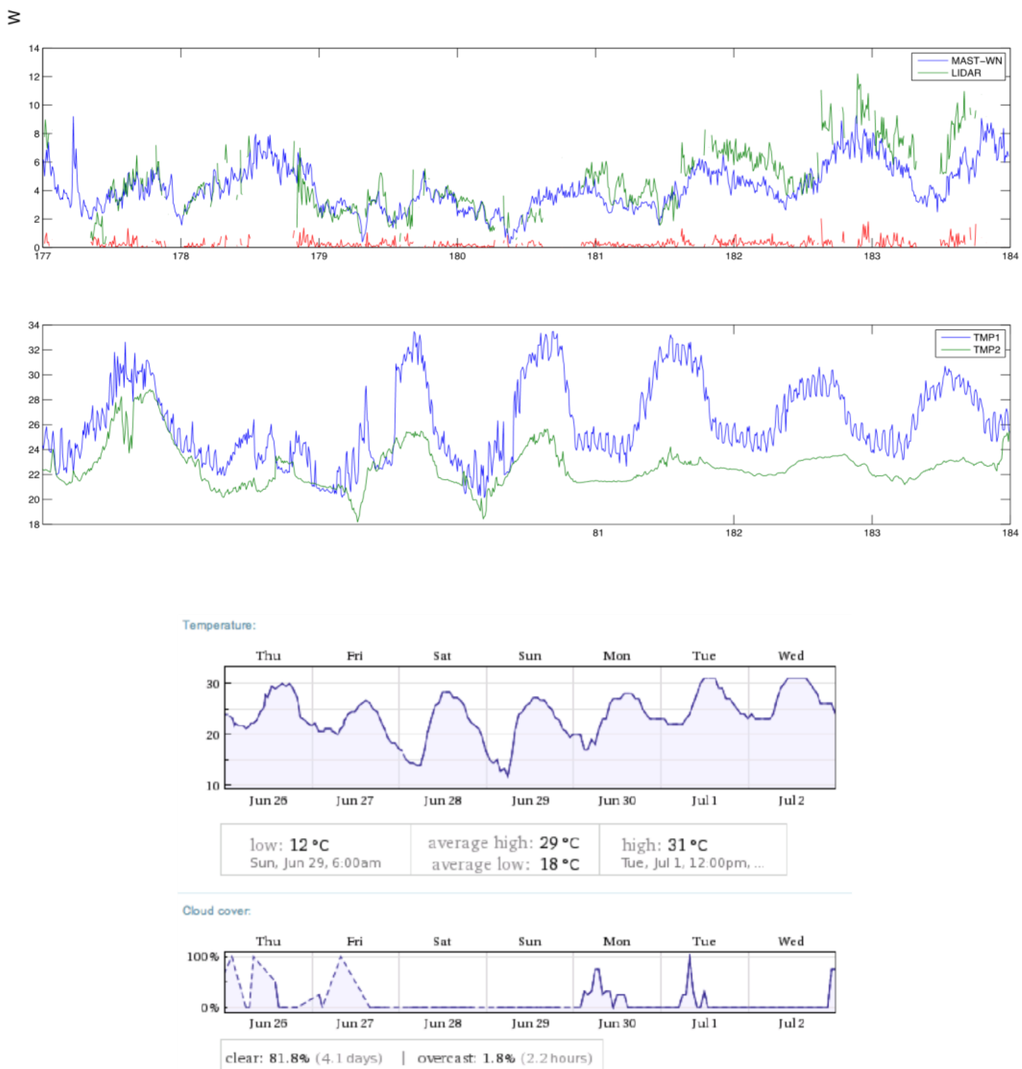


Figure 11. Wind velocity measured by the WindTracer and ACUA 48m cup anemometer (top), ambient and heat vent temperature (middle), and temperature and cloud cover data measured at the KACY weather station (bottom). Measurements span the time period between June 25 and July 2, 2014.

The measured temperature variation is due to the lack of shielding of the vent temperature probe from incident solar radiation. The ambient temperature probe is covered by a radiation shield (see Figure 8).

Cloud cover returns on June 30th and July 1st. The ambient temperature becomes much more constant over the last three days of the record. The vent temperature probe still shows strong diurnal heating over the same time period as a result of the incident solar radiation. The KACY temperature data show increasingly warm temperatures over the same time period that are on average 5°C warmer than the ambient temperature on the roof. A review of the wind data from the roof indicates a shift in wind from the WSW to the S between June 30 and July 2, creating a sea breeze along the coast that most likely does not reach the KACY site located 10 miles inland form the coast. Throughout the record, the high frequency oscillations generated by the chimney vent remain present in the temperature record recorded by the vent probe. This indicates that the heat plume can be detected regardless of the high ambient temperatures.

There are nine gaps in the WindTracer data collected over the 7 day time period, the largest of which extended for 7 hours. There is no apparent relationship between cloud cover and WindTracer data returns. As wind speeds gradually increase over the last 3 days of the record, the WindTracer does measure slightly higher wind speeds than the ACUA 48m anemometer.

The continuous time series of roof top ambient air temperature, vent temperature, ACUA 48m anemometer wind speed, and the WindTracer wind speed at the ACUA 48m anemometer, collected between April 25th and September 7th, 2014, were processed through a Fast Fourier Transform (FFT) to assess the frequency distribution of cyclical patterns in the data. Gaps in the WindTracer data set were filled by linear interpolation between adjacent wind speed measurements. The result of the FFT analysis is plotted in Figure 12. All four of the time series show a strong spike at a period of 24 hours, indicating a strong diurnal fluctuation in temperature and wind speed. A second, much smaller spike occurs in all four records at a period of 12 hours indicating weaker semi-diurnal oscillations in wind and temperature. The roof top temperature sensors show evidence of a higher frequency oscillation centered on a period of 8 hours. Finally, there is a single oscillation that only appears in the heat vent temperature record centered on a period of 1 hour. This unique frequency oscillation is the cyclical venting of heat form the building through the chimney.

Figure 13 presents a nine day snap shot of the recorded data and frequency distribution of the roof top temperature data and WindTracer wind speed located at the ACUA 48m anemometer. The top panel presents the time series data. The low amplitude high-frequency oscillations in the heat vent temperature probe are clearly evident in the time series plot in panel a. The heat vent probe also captures the larger amplitude diurnal oscillations that are present in eight of the nine days in the record. The shielded ambient temperature probe captures the diurnal oscillation on only two of the nine days. Due to the unshielded measurements taken by the heat vent temperature probe, it is expected that a significantly greater amplitude will appear in the frequency distribution for the Temp1 signal than the Temp2 (ambient) signal. Comparing the amplitudes in the frequency distributions presented in Figure 13, panels b - d, it is evident that the high-frequency oscillations only appear in the vent temperature signal (panel b). The small amplitude is a result of the low amplitude oscillation in the temperature signal. The results of the analysis does show that the plume monitoring system is capable of detecting the presence and duration of each venting cycle.

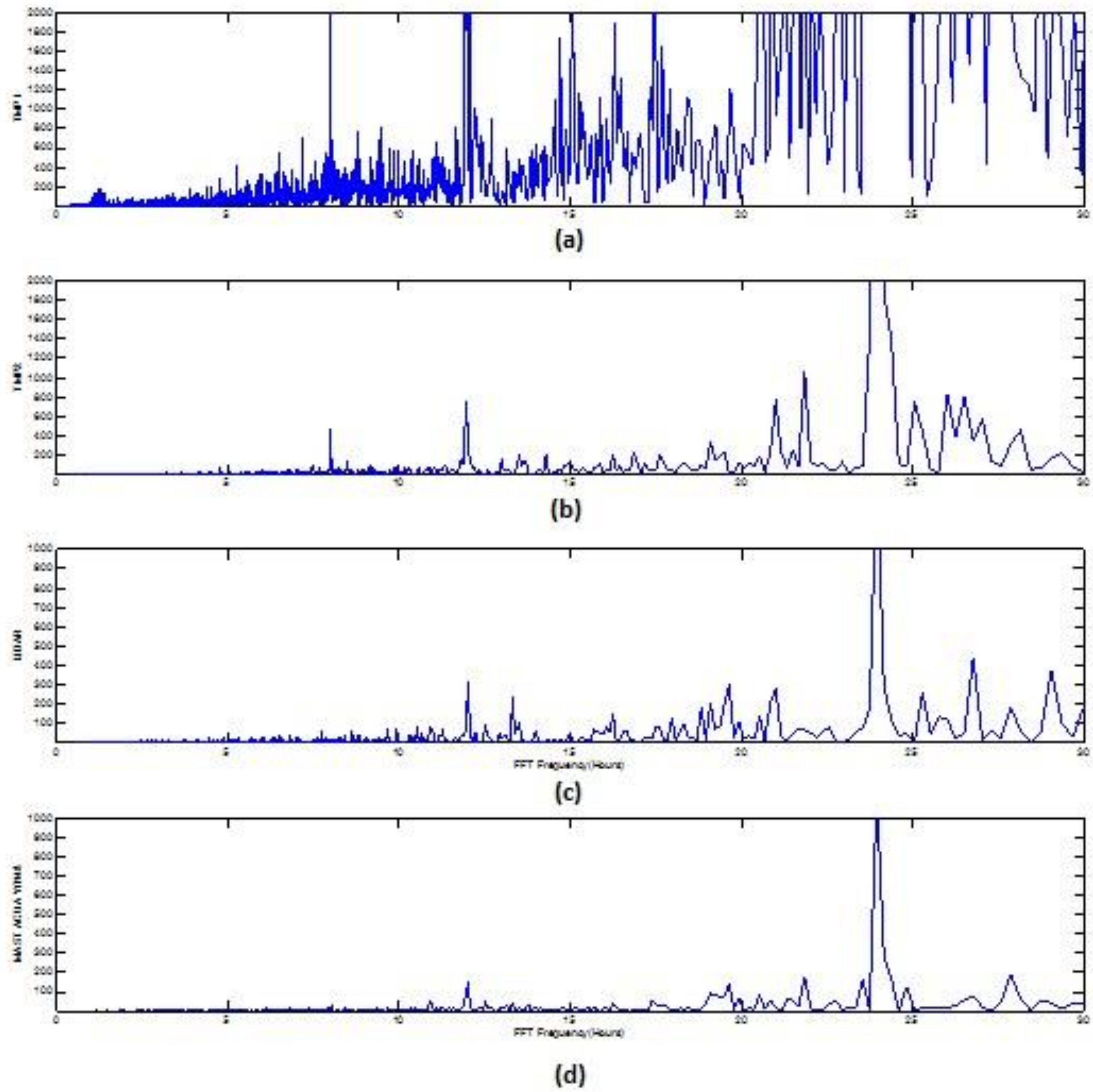


Figure 12. Frequency variation of (a) exhaust vent temperature, (b) ambient roof top air temperature, (c) WindTracer wind speed at the ACUA 48m anemometer, and (d) the ACUA 48m anemometer.

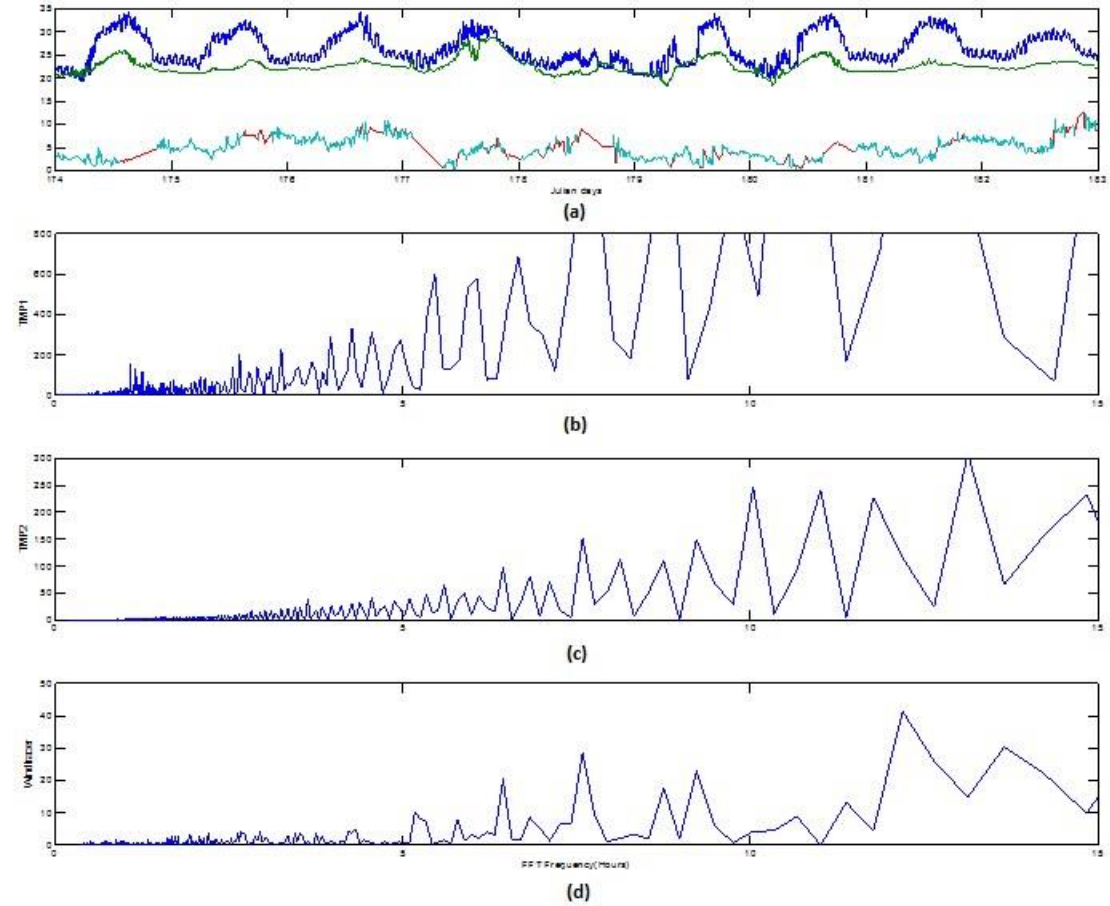


Figure 13. Frequency analysis of a nine day segment of roof top temperature data and WindTracer wind speed located at the ACUA 48m anemometer: (a) Time series of heat vent temperature probe (blue line), ambient air temperature (green line), and WindTracer wind speed (aqua line); (b) frequency distribution of heat vent temperature; (c) frequency distribution of roof top ambient air temperature; and (d) frequency distribution of WindTracer wind speed. Red lines in panel (a) are linear interpolations between WindTracer data points.

<u>Key outcomes, milestones and other achievements</u>

A heat vent plume monitoring system was deployed on the roof adjacent to the WindTracer LIDAR. Data collection started on March 25, 2014. The system is operating continuously, collecting the average, minimum, maximum and standard deviation of the exhaust vent temperatures at one minute intervals and the ambient temperature at 5 minute intervals. An analysis of 135 days of data collected by the plume monitoring system, wind speed data from the ACUA 48m cup anemometer, and the WindTracer LIDAR wind speed at the ACUA 48m bin has been completed. The analysis confirms that the plume monitoring system is capable of capturing the time and duration of each venting episode, in both clear and overcast conditions. A frequency analysis of the periodic signals in each data set indicates that there is no apparent correlation between chimney heat plume venting and the number and quality of WindTracer data returns.

There is also no apparent relationship between WindTracer data returns and clear or overcast sky conditions.

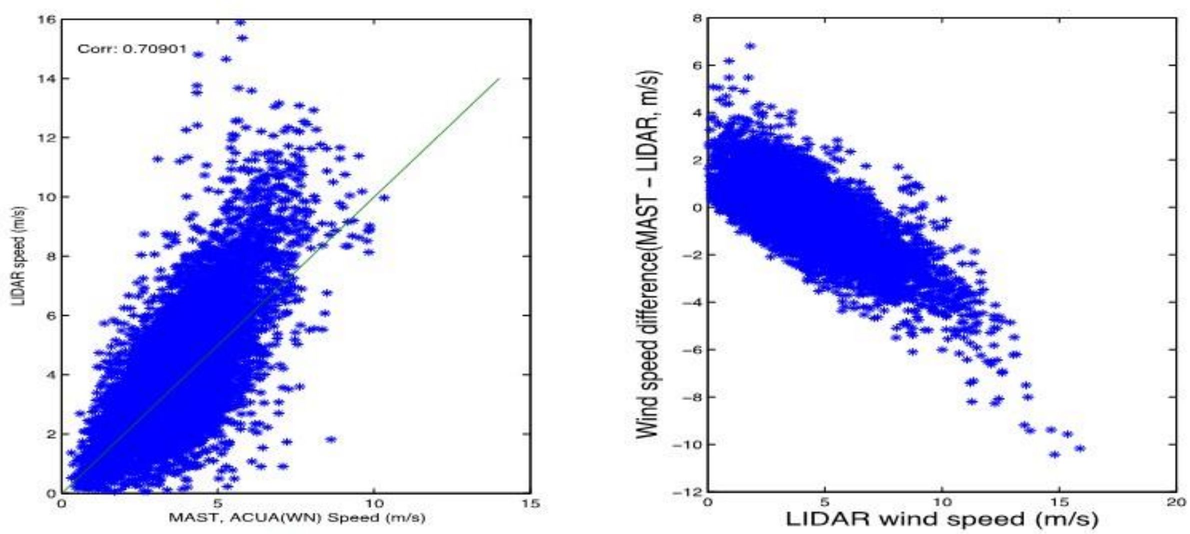
III. Task 3: Data Assessment

<u>Major activities:</u>

A comparative analysis of the wind data measured by the scanning LIDAR and the ACUA meteorological masts was conducted to determine the possible influence of the heat plume on the quality of the comparison. The objective is to evaluate the performance of the scanning LIDAR under increasingly greater temperature difference between the heat vent temperature probe and the ambient air temperature.

<u>Significant results</u>

A comparison of the WindTracer wind speed with the ACUA 48m mast wind speed is shown in Figure 14. The coefficient of determination, R^2, between the WindTracer and ACUA anemometer over the 135 day record was 0.71 (Figure 14a). Visually, the WindTracer wind speeds appear to correlate well with the anemometer data for wind speeds less than 4 m/s. As the wind speed measured by the LIDAR increases, the WindTracer overestimates the anemometer measured wind speed. The overestimation increases with increasing wind speed measured by the WindTracer (Figure 14b).



(a) (b)

Figure 14. (a) Correlations between ACUA 48m cup anemometer and WindTracer wind speed data, and (b) Wind speed difference between mast and WindTracer relative to WindTracer wind speed.

Figure 15 presents the correlations between ACUA 48m cup anemometer and WindTracer wind speed as a function of the temperature difference between the heat vent and the ambient air temperature. The majority of the temperature data falls within a temperature difference range of between 0 to 5 °C and 5 to 10 °C (top two plots in Figure 15). The WindTracer and ACUA 48m cup anemometer are correlated with R^2 values of 0.66 and 0.73, respectively. Larger temperature differences[1], ranging between 10 to 15 °C and 15 to 20 °C, show correlations similar to the lower temperature difference ranges. It should be noted that higher wind speeds appear to be correlated with lower vent and ambient air temperatures. This could be the result of the unshielded temperature probe at the vent measuring higher temperatures on clear, fair weather days. The calculated R^2 wind speed correlations of between 0.66 and 0.80 over a temperature difference range of 0 to 30 °C, indicates that the heat plume vented from the roof has very little influence on the wind speed correlations between the WindTracer and ACUA 48m anemometer.

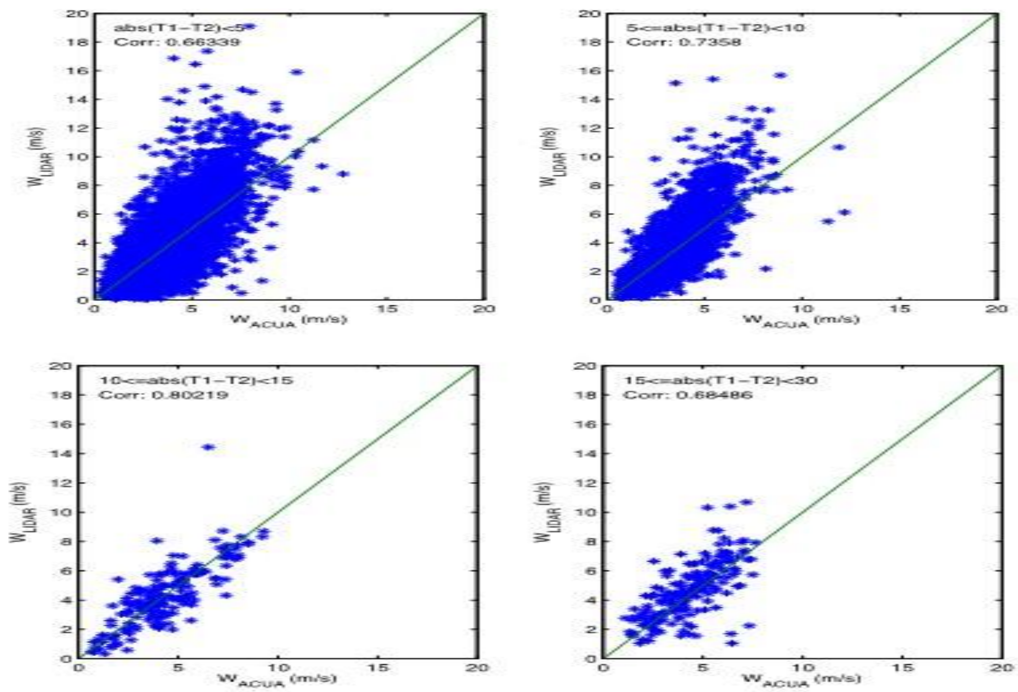


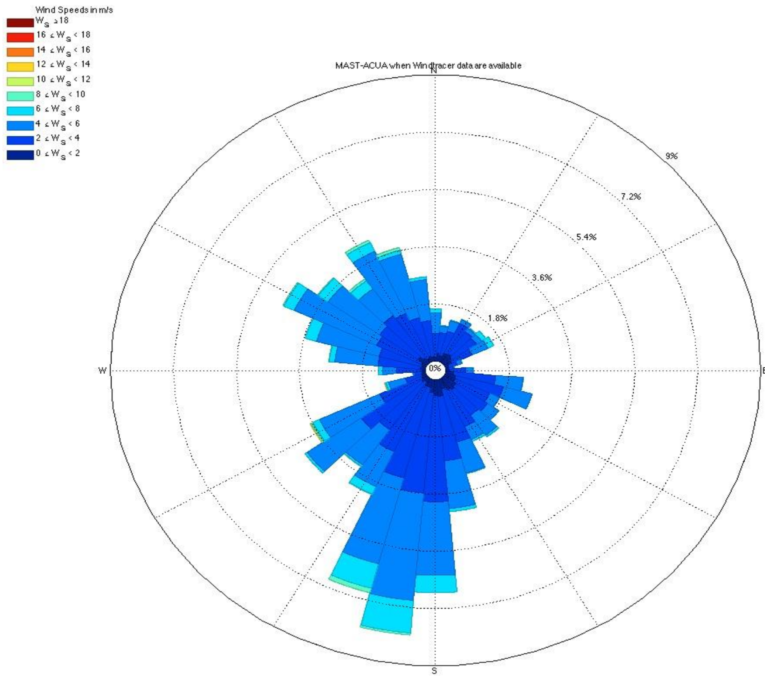
Figure 15. Correlations between ACUA 48m cup anemometer and WindTracer wind speed as a function of temperature difference between the heat vent (T1) and the ambient air temperature (T2).

[1] The large temperature differences are a result of unshielded temperature measurements obtained by the heat vent probe.

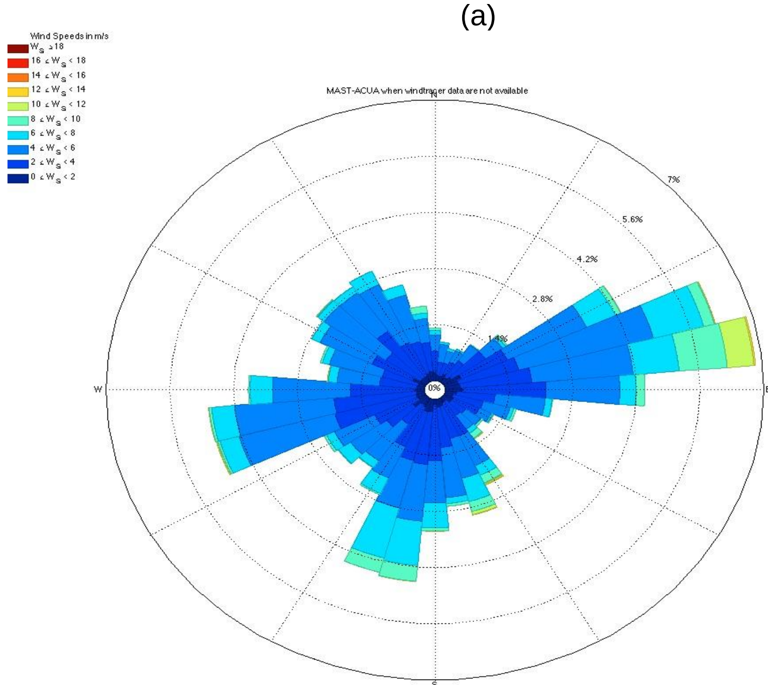
Figure 16 and 17 present the directional dependence of the collected WindTracer data at the ACUA mast. The top plot in Figure 16 shows the wind speeds and directions collected by the ACUA 48m cup when corresponding WindTracer data is available. A noticeable gap is present centered on 80° and 260°. Figure 16b shows the wind speed and directions collected by the ACUA 48m cup anemometer when WindTracer data is not available. WindTracer data is predominantly unavailable from directions centered on 80° and 260°, although data is unavailable from almost all directions, but at a much less frequent rate. As previously determined during the 1st year of data collection, there is good agreement between the magnitude of the wind speed reported by the WindTracer and the wind speed reported by the ACUA meteorological mast when winds are approximately parallel to the line of sight of the
WindTracer to the ACUA mast (i.e. from approximately 350° or 170°), although higher wind speeds are typically measured by the WindTracer than the mast. Reasonable correlations – considering the scatter - are also seen for other directions. However, when winds at the ACUA site are from sectors centered on 260° or 80° the scatter is increased and there is a worse agreement between the WindTracer and ACUA mast data.

Figure 17 presents the available WindTracer data over the 135 day data record. Winds measured by the WindTracer are centered primarily from 220° and 345°. Significantly higher wind speeds were measured from the SSW. Comparing Figure 17 to Figure 16a, it is evident that the recorded mast directions are shifted approximately 30 degrees to the south and peak wind speeds in the SSW quadrant are 2 to 8 m/s lower that the WindTracer wind speeds.

The relative error in WindTracer wind speed as compared to the ACUA 48m anemometer is presented as a function of wind direction measured at the ACUA mast and by the WindTracer in Figure 18. Wind direction data from the ACUA mast indicates that wind speeds are underestimated by the WindTracer centered on 80° and 260°. The WindTracer wind direction plot shows that the LIDAR does not measure data for winds centered on 80° and 260°. Significant overestimates of wind speed are present in the WindTracer data immediately adjacent to the wind direction bands with no data. Winds from the 80° and 260° sectors are approximately perpendicular to the line of sight of the WindTracer to the ACUA mast. The increased error in estimating the speed of winds that are almost perpendicular to the line of sight of the WindTracer may stem from the low line-of-sight velocity and consequent low Doppler shift when the WindTracer is looking in this direction. Filtering the data to remove wind directions between 40° and 120°, and between 220° and 300°, should remove the most significant overestimates of WindTracer wind speed.



(a)



(
b
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Figure 16. (a) ACUA 48m cup anemometer data collected when WindTracer data is available, and (b) ACUA 48m cup anemometer data collected when WindTracer data is not available.

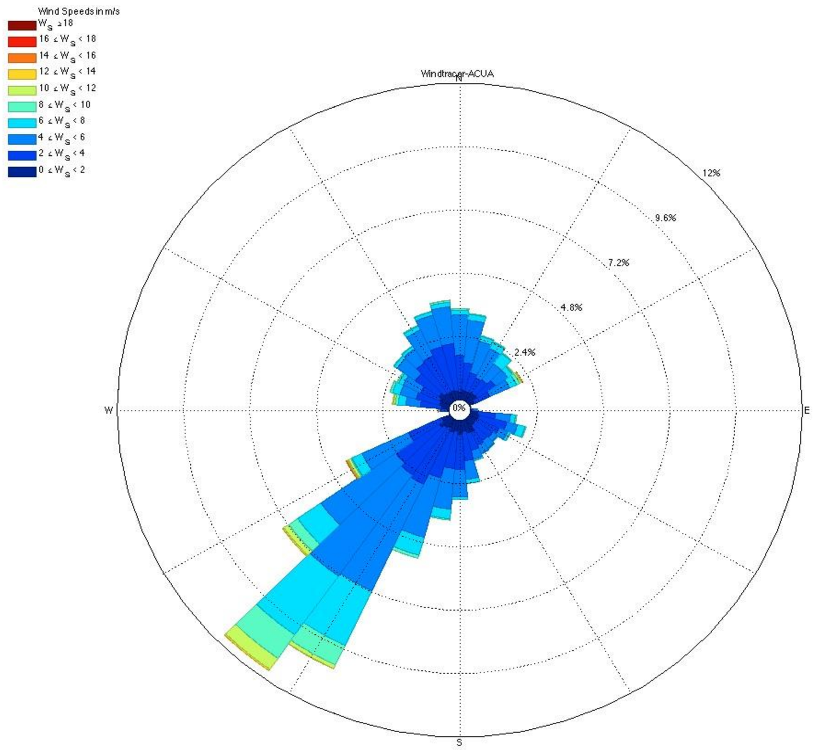

Figure 17. Wind speed and direction distribution measured by the WindTracer over the 135 day period between April 25 and September 7, 2014.

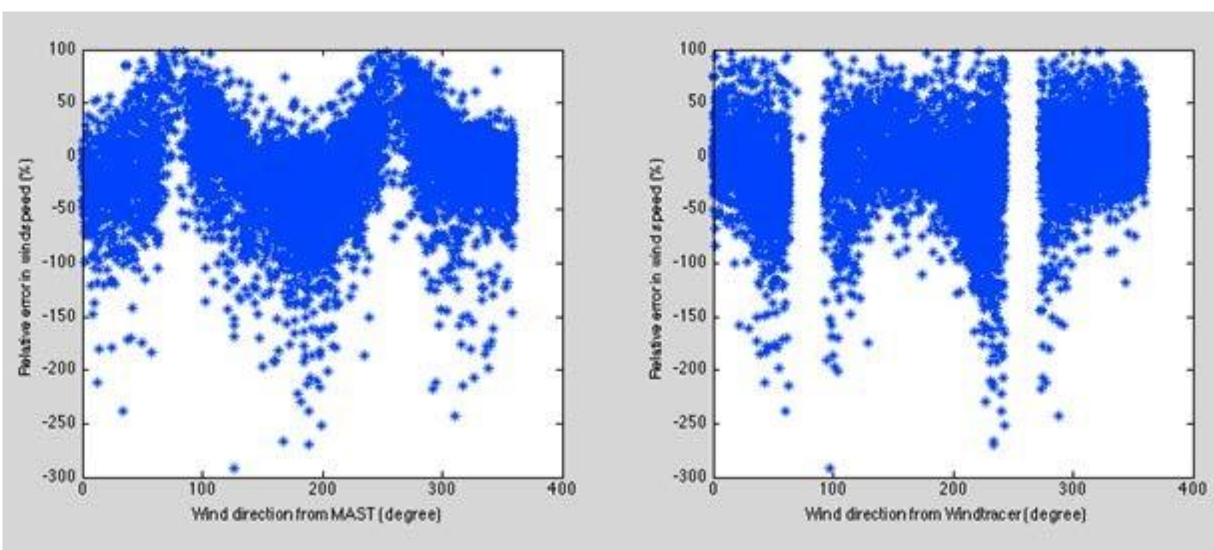

Figure 18. Relative error in WindTracer wind speed versus ACUA 48m anemometer as a function of wind direction measured at the ACUA mast (left), and by the WindTracer (right).

Key outcomes, milestones and other achievements

A comparison of the WindTracer wind speed with the ACUA 48m mast wind speed determined that as the wind speed measured by the LIDAR increases, the WindTracer overestimates the anemometer measured wind speed, and that the overestimation increases with increasing wind speed measured by the WindTracer. An analysis of the correlations between ACUA 48m cup anemometer and WindTracer wind speed as a function of the temperature difference between the heat vent and the ambient air temperature determined that the heat plume vented from the roof has no influence on the wind speed correlations between the WindTracer and ACUA 48m anemometer. An analysis of the wind direction dependence of the collected WindTracer data at the ACUA mast confirms the prior finding that wind propagating perpendicular to the line of sight of the WindTracer to the ACUA mast (68° - 92° and 248° - 276°) cannot be measured by the WindTracer. Significant overestimation of wind speeds in the directional sidebands adjacent to the windows of missing data indicates that the ability of the LIDAR to measure winds traveling orthogonal to the beam direction covers a wider range of wind directions.

CONCLUSION

This heat vent plume analysis suggests that there is no influence of the heat plume on WindTracer wind speed and direction measurements. Comparisons between the WindTracer and the ACUA 48m anemometer continue to show that under favorable conditions (such as short range to target, homogenous flow, and winds near to the line of sight) the WindTracer data are within the range of the mast measurements. However, as wind speeds drop and flows become perpendicular to the line of sight, the agreement between the WindTracer and the masts reduces. The present analysis indicates that the ability of the LIDAR to measure winds traveling orthogonal to the beam direction covers a wider range of wind directions than those that the WindTracer cannot directly measure.

The data analysis indicated that the sampling frequency of the cup anemometers and the wind vanes on the ACUA and Stockton meteorological masts is not optimal. Prior to December 2014, both mast sampled wind speed and direction at 1Hz but due to logger limitations only 10 minute average samples were recorded. The scanning configuration of the WindTracer only allows the LIDAR to sample over the meteorological masts for a few seconds in each 10 minute scan. The discontinuity in sampling is responsible for a certain percentage of poor correlations between the WindTracer and mast wind speeds.

In October 2014, the existing Symphonie logger at the ACUA mast was replaced with a Campbell Scientific CR1000 data logger capable of sampling and storing data at a frequency of 1Hz (Figure 19). This immediately improved the temporal resolution of the collected anemometer and wind vane data (Figure 20). The present configuration allows for the collection of 3600 data points per hour from each instrument (4 cup anemometers and 2 wind vanes). In December 2014, Fishermen’s Energy and Lockheed Martin Coherent Technologies personnel reconfigured the WindTracer scanning pattern to improve the quantity and quality of wind measurements at the mast sites. During each 10 minute scan, 7 of the 10 minutes are dedicated to both masts (and two offshore areas of interest to Fishermen's as potential wind energy sites). In that 7 minutes, the masts are scanned 4 times for approximately 35 seconds (followed by a scan of the two offshore sites) spread evenly throughout the 7 minutes. The last 3 of the 10 minutes is dedicated to a 360° regional scan (Fishermen's has executed a 360° since the WindTracer was commissioned) which also yields wind measurements at the mast sites. This increased amount of scan time at the masts coupled with a slower scan speed of 1 degree per second (resulting in a 2° wide product beam) is designed to improve data return rates and quality of data.

The new mast sampling configuration and the revised WindTracer scanning pattern has been operating since December 4, 2014. The collected data will be analyzed over the next quarter to evaluate improvements, if any, in the ACUA 48m anemometer and WindTracer wind speed correlations.

Figure 19. Campbell Scientific CR1000 logger installed at the ACUA mast

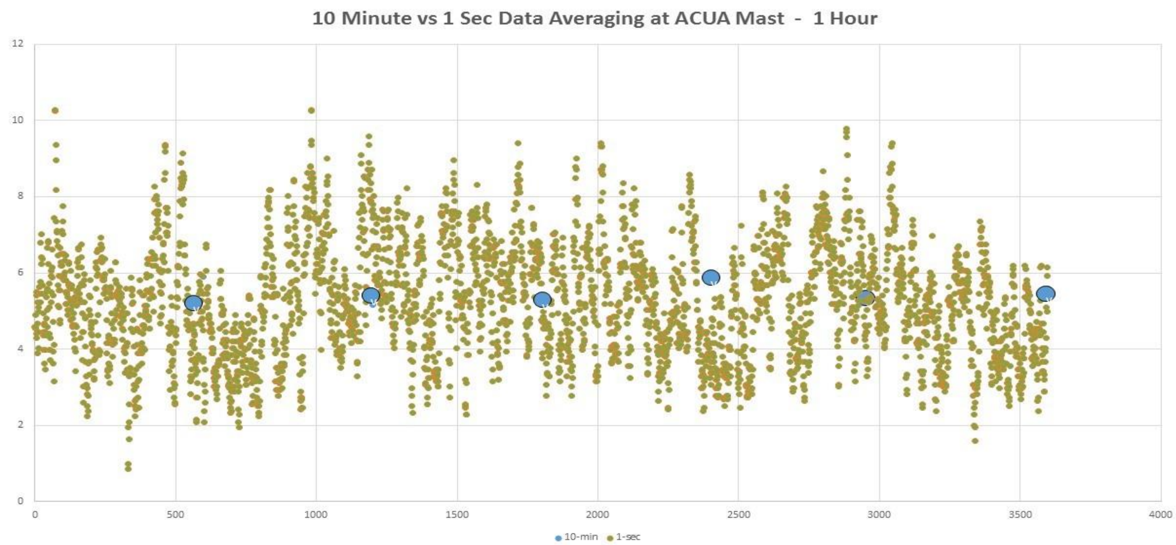

Figure 20. Time series plot of 1Hz wind measurements (green dots) and 10 minute average wind speed measurement (blue dots) showing the improved data collection capability at the ACUA mast.

CHANGES / PROBLEMS

Emerging Issues:

The upgraded sampling capacity of the ACUA logger and the revised WindTracer scanning pattern will allow for an improved evaluation of the capability of the WindTracer to accurately measure wind speed and direction at a range of 7.2 miles, 48m above ground. Improved measurements capability at multiple ranges from the WindTracer is still an issue. To address this, the PIs are actively working toward acquiring a 2nd CR1000 to replace the existing Symphonie logger on the Stockton mast and continue to pursue permits for the erection of a third mast to be located 10.2 miles WNW of the WindTracer.

1. Instrumenting the Stockton meteorological masts to reduce uncertainty.

The initial data analysis indicated that the instrumentation configuration on the Stockton meteorological masts is not optimal. It is proposed to replace the existing Symphonie data logger with a CR1000 capable of storing 1Hz data from cups and vanes to improve the data available for comparison with the WindTracer.

2. Erecting a new 60-m meteorological masts at a location unaligned with the heat vent.

Fishermen's Energy continues to pursue a permit to install a new 60-m tower. A terrain and line of sight analysis was completed and a number of highly probable mast sites were identified (Figure 21). Farm 3 is presently being considered for the installation of a temporary 60-m meteorological mast. Lease agreements with the landowner and a no impact statement from US Fish & Wildlife Service have been obtained. In October 2014, and approval letter form the FAA was issued. Presently, Fishermen's Energy is discussing the development of a permit application with Egg Harbor Township, NJ.

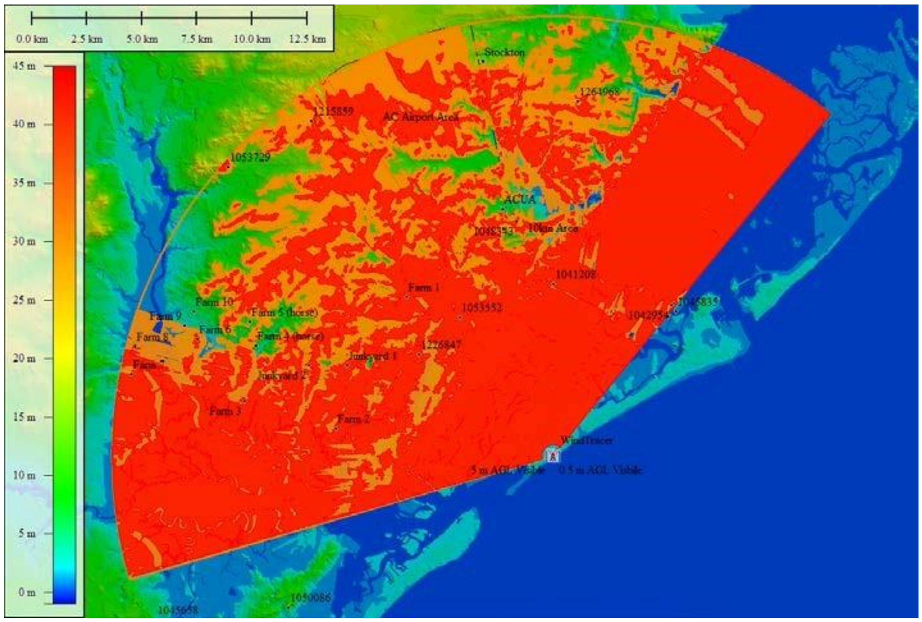

Figure 21. Terrain and line-of-sight analysis. Red and orange areas indicate unobstructed line-of-sight relative to the WindTracer.

Goal Status: Budget Period 5 (**January 1, 2016 to April 1, 2016**): Data Analysis
Plans during this period consisted of the collection of 3 months of WindTracer and ACUA mast wind data at the 48m anemometer to determine if the increased temporal resolution of wind data improves the wind speed correlation between the cup anemometer and the LIDAR. Data was sent to NREL for analysis and final reporting.