Assessment of a balloon-borne buoy based measurement system with co-located tower and lidar measurements

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Assessment of a balloon-borne buoy based measurement system with co-located tower and lidar measurements

by

Gregory Thrasher Matson

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Meteorology
Program of Study Committee:
Eugene S. Takle, Major Professor
William Gutowski
R. Ganesh Rajagopalan

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Ames, Iowa
2015

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DEDICATION

I would like to thank my advisor Dr. Eugene Takle for the opportunity I was given with this project. Dr. Gutowski and Dr. Rajagopalan thank you for being on my committee and devoting time to helping me in this process. Thanks to my family and friends for their support throughout this process. Lastly, I would like to thank the best prodigy ever for keeping me motivated and being there with me every step of the way. With the amount of traveling and work I did for this project sometimes it would get overwhelming, but having her around kept me focused and determined.
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ABSTRACT

The development of a balloon-borne buoy based measurement system which aims to find a more cost effective method to be able to characterize offshore winds is assessed. The buoy measurements taken are compared to meteorological tower and Galion lidar data. Data were collected from several field studies located in Iowa, New Mexico, and Texas throughout 2013 and 2014. A look at balloon-borne buoy based wind measurement system that were developed and used in this study will be explained. Findings show that wind speeds correlate well, while wind directions did not correlate as well. An algorithm developed to verify the heights at which the modules were flying at through use of the hypsometric equation will be examined. Spectral analysis is used on data taken during the February 10th field study in the Gulf of Mexico. The study provides an encouraging outlook on assessing offshore winds moving forward, by displaying the ability for the system to operate autonomously for a brief period of time in the Gulf.
1. GENERAL INTRODUCTION

1.1 Background and motivation

The ability to characterize offshore wind resources with the goal to develop a better method to create wind power poses a unique challenge. The marine environment poses difficulty in being able to acquire quality data. The methods currently used to profile onshore wind resources are difficult to deploy in a marine environment. Remote location, hurricanes, salt water, and wave heights are some difficulties that need to be overcome when trying to assess offshore winds.

These methods include the use of a lidar or meteorological tower. A lidar is a remote sensing technology that measures distance by using a laser, which analyzes reflected light. To measure wind speeds, the lidar shoots a laser beam and measures the shift in wavelength of the scattered light collected at the lidar. The velocity of the particles can then be estimated. The most accurate and versatile way to obtain remote measurements is through Doppler lidar (Dunne et al. 2011). This study uses a Galion lidar, which is a laser based wind-profiling device capable of measuring wind speed and direction, which has a unique all-sky scanning capability with a range of up to 4 km.

There are methods already in place that are capable of assessing offshore winds, but these come with flaws. Currently the methods to profile offshore winds involve using standard instrumentation and sensors on fixed meteorological towers as well as lidars, though lidars are very expensive. Prices can vary depending on the height of the meteorological towers used. A 60 m meteorological tower which is used in this study can cost roughly $32k. An offshore lidar costs roughly $1.3 million to purchase, totaling to about $1.95 million after the first year of deployment including maintenance costs.
The high costs using either meteorological or lidars can in turn limit the opportunities to find suitable locations for placements of wind turbines to create wind power. An alternative method will be explored in an effort to find a more cost effective method to be able to characterize offshore winds through the use of a marine-based balloon-borne wind measurement system.

Dari Dexheimer of Anemometry Specialists and Keith von Gruber a contractor, engineered and tested the marine-based balloon-borne wind measurement system. An overview of the entire system will be described in Section 4. This project had myself assist the group while the system were being constructed, take photos for documentation of the project, as well as organizing and preparing the data retrieved from the system during field tests for analysis purposes.

1.2 Thesis organization

Section 3 contains the Introduction where some historical context on past wind measurement systems are given. In Section 4, the balloon-borne buoy based measurement system will be explained in its entirety. Methods will show how the data will be analyzed in Section 5. Section 6 will explain what types of data will be used in this study. In Section 7, results will be provided from the data obtained from different field tests. Section 8 contains an Analysis and interpretation section. Conclusions will then wrap the thesis up in Section 9.
2. INTRODUCTION

The atmospheric boundary layer (ABL) is the part of the troposphere that is directly influenced by the presence of the earth’s surface, and responds to surface forcing (terrain induced flow modification and heat transfer, to name a few) with a time scale of about an hour or less (Stull 1988). Studies have been performed to gain a better understanding of how the boundary layer works. Understanding the ABL and its interaction with the environment can help determine suitable sites for wind turbines.

Funded by IAWIND, this project will explore a different method for in situ measurements involving meteorological variables for wind resource characterization in the lower 120 m of the marine atmospheric boundary layer. The goal of this project is to demonstrate a system capable of obtaining wind measurements continuously throughout the day and overnight hours that replicates the requirements for acquiring wind resource characteristics as required for siting wind turbines in the US. The target site location is off the coast of South Padre Island, TX. In addition to IAWIND, Baryonx and Anemometry Specialists also collaborated for this project.

This project will aim to assess how we can make offshore wind measurements of high enough quality to meet the requirements to secure financing for development of an offshore wind farm, by using a balloon-system operating from a buoy. To determine whether or not offshore wind measurements are high enough quality, an intercomparison between balloon-based wind measurements and Galion lidar/meteorological towers will be examined. Currently, meteorological towers serve as a way to assess boundary layer wind speeds for potential wind development sites by placing anemometers and wind vanes at designated heights of interest. Tilt-up guyed towers can reach up to roughly 100 m. While this method is widely used for onshore, in an offshore environment this method can prove to be expensive. Another goal this
project has is to create a cost effective system which could be widely used in any environment. To be used in any environment, this system will be capable of operating in adverse weather conditions. Here adverse weather conditions include sustaining hurricane force winds (roughly 70 mph).

Another way to take ABL measurements is through use of a tethersonde system. Instrumentation platforms are placed along the tether line from the tethersonde which then can move to different heights. The tethersonde enables the ability to obtain multiple high resolution profiles of the boundary layer. This project is focused on using a tethersonde system which operates on a buoy. There are other platforms which could be used like an oil platform or a barge. But these platforms can difficult to use, oil platforms generally are farther out in the sea which creates difficulty getting to in case something goes wrong. Barges could work as they can be anchored, however since barges typically have schedules for delivering their cargo, obtaining a lot of quality data in a fixed location would be difficult.

The following section examines a brief history of atmospheric measurement systems, offshore wind measurement guidelines needed to site a wind farm, flight module components needed to site a wind farm, and potential problems to overcome.

2.1 History

Wind measurements taken in the atmosphere have been performed for hundreds of years. Kites were the first lifting platform used to take atmospheric measurements. In 1749 Professor Alexander Wilson and his student Thomas Melville of the University of Edinburgh reported the first atmospheric measurements through use of a kite (Balsley et al. 1998). Using a single tether
Wilson and Melville launched a series of paper kites into the atmosphere, with a thermometer attached to each kite tail.

In the early 1930s, kites were seen as an obstruction to the increase in aircraft activity. Balloons provided a cheap and safer alternative for atmospheric measurements. The use of kites to obtain systematic measurements was viewed as expensive compared to new alternative methods (Balsley et al. 1998). While kites are not used in this project, it is important to understand where balloon systems originated. Kites have limitations which is why balloon systems started to be used.

To be able to take measurements of the boundary layer, a lifting platform is needed. There are two types of lifting platforms: kites and aerodynamic balloons. With these two types of lifting platforms there are two different ways to take measurements: the first being profiling, where there is continuous movement up or down at a given height, and parking the kite or balloon at a constant altitude. For this study the modules used to record atmospheric data will be parked at a various heights.

Kites are best suited to fly in conditions where the wind speed is between 7 and 18 m s\(^{-1}\) (Balsley 2008). The kite has a basic rectangular shape with ram-air-filled parafoils (size ranging from 10-20 m\(^2\)). Domina C. Jalbert came up with the parafoil design and patented it in 1966. Jalbert’s invention was based on the idea that an airfoil could be used to hang payloads in the atmosphere both in-flight in addition to stabilizing objects in flight.
2.1.1 Balloon studies

To gain a better understanding as to what balloon systems are capable of, the following studies examined will detail a few of these systems. Some advantages and disadvantages of balloon systems will also be discussed.

Siebert et al. (2003) introduced a tethered balloon system, the Mobile Automatic Position System (MAPS-Y), which took atmospheric measurements in a lifted fog layer. MAPS-Y has the ability to measure static air temperature, humidity, and three dimensional turbulent wind vectors in both cloudless and cloudy sky conditions (Siebert et al. 2003).

The MAPS-Y system is a German based design that used hydrogen to fill the balloon, with a diameter of 6.5 m and 24 m long. The volume of the hydrogen balloon was roughly 400 m$^3$. MAPS-Y can be operated in wind velocities up to 15 m s$^{-1}$. The MAPS-Y system used in Siebert’s study draws similar comparisons to the balloon size dimensions used in this project.

Cvitan et al. (2002) involved the use of a tethered balloon radiosonde to obtain wind speed profile measurements. Wind speed measurements for this study were obtained via a tethered balloon radiosonde and a pilot-balloon system. Tethered balloons were launched every hour when preferred light wind conditions occurred (Cvitan et al. 2002). The pilot-balloons were only used to take measurements when strong winds occurred near the surface. Two four-day time periods were picked to take wind speed measurements in March, 1983 and October, 1984. Wind speed measurements taken by the tethered balloon systems were restricted to 150 m since strong windy conditions sometimes occurred around 150 m. Target heights for our project are 120 m which is hub height for a wind turbine, which is in a similar range as in Cvitan’s study.
Whiteman et al. (2004) conducted an experiment on June 2-4, 2002 that used a tethered balloon system and temperature data loggers. The study area for this experiment was a small enclosed basin in the eastern Alps called Gruenloch Basin. The objective was to determine under what conditions air temperature measurements from sidewalls can provide useful proxies to atmospheric soundings in the free air over the center of enclosed basins (Whiteman et al. 2004). This would be accomplished by comparing temperature profiles from the temperature data loggers to the tethered balloon soundings.

Two TS-3A tethered balloon systems were used in this experiment (TS1 and TS2). These balloon systems were manufactured by Atmospheric Instrumentation, Inc., which is now part of Vaisala, Inc. The tethersonde temperature system had an accuracy of ± 0.5°C. Each tethered balloon system was flown for one night-time period: the TS1 was flown on the first night and TS2 was flown on the second night. Variables measured for this study included temperature, humidity, pressure, wind direction, and wind speed which were sampled from the floor of the basin to altitudes of approximately 200 m (Whiteman et al. 2004). The next studies examined intercomparisons between kites and balloon systems.

2.1.2 Intercomparison studies

2.1.2.1 Kites

Knapp et al. (1998) used a kite profiling system as well as a high altitude tethered balloon to obtain vertical profiles of temperature, water vapor mixing ratio, and ozone mixing ratio at Ferryland Downs, Newfoundland, Canada. This site was chosen since it is a large, open, not very populated, and flat area of land, which is ideal for launch and recovery purposes (Knapp et al. 1998).
Kites were employed for Knapp’s study since they are a cost effective ways to acquire vertical profiles of the atmosphere. Two types of kites were used in this study, parafoil and flowform. The size of these kites were 5 m$^2$ and 15 m$^2$ for the parafoil and a 10 m$^2$ for the flowform (Knapp et al. 1998). To efficiently profile any variable of interest, the wind speeds must be steady enough to launch and keep the kite system at the designated profiling height. In addition to kites being used in this study, high-altitude tethered balloons provided a way to acquire high density resolved data both vertically and temporally over a specified location (Knapp et al. 1998). Maximum altitudes of 7.6 km were attained using the tethered balloon system, with a rise rate of 2-4 m s$^{-1}$ and no excessive drag on the tether line. Latex meteorological balloons weighing 0.8 or 1.2 kg were used, containing roughly 12.4-16.5 m$^3$ of helium (Knapp et al. 1998). Tethered balloons are able to reach higher vertical altitudes than the kite. Wind conditions can restrict the balloon system by high wind resistance. In this study, observed wind speeds at roughly 5 m s$^{-1}$ showed to be maximum wind speed the balloon system could endure before not gaining much more altitude. In Knapp’s study the tethered balloon system is flown under the same guidelines as the kite system. Since we will be using a tethered balloon system, this study provides some conditions similar to those in which Knapp et al. were able to fly successfully. Some information about lidar were shown as well, since a Galion lidar will be employed in our study.

2.1.2.2 Tethered balloons

Balsley (2008) provided an overview on the Cooperative Institute for Research in Environmental Science (CIRES) tethered lifting system. The tethered lifting system (TLS) has helped improve our understanding of the atmospheric boundary layer through studies focusing on its structure and dynamics. Measurements taken by the TLS are usually from the surface up
to 1-2 km, the boundary layer (Balsley 2008). There are several components that make up the TLS that will be explained in detail, which include the lifting platform, basic meteorological payloads, winch, and a tether-arm-pulley system.

Aerodynamic balloons are used when wind speeds are in the range of 0 to 12 m s\(^{-1}\). These balloons are filled with helium with a total volume ranging from 14 to 22 m\(^3\). The balloon’s maximum altitude is about 1 km; this is due to possible distortional effects caused by barometric pressure decreasing with height. Since balloons are aerodynamic, they have the ability to be adjustable to accommodate certain wind-speed-dependent lift capacities (Balsley 2008).

Attached to the lifting platform is a basic meteorological payload (BMP) which samples the boundary layer. A BMP can take samples of a wide variety of variables of interest like temperature, humidity, pressure, wind speed, and wind direction. In addition to a BMP, there are also turbulence payloads. Turbulence payloads are capable of taking frequency recordings of up to 200-Hz for both temperature and wind speed (Balsley 2008). The turbulence payloads also carry low frequency sensors to sample variables of interest like mean wind speed, wind direction, temperature, and pressure. These instruments include a pitot tube, solid-state temperature sensor, piezoelectric pressure sensor, and a magnetic compass. A payload’s weight used in Balsley’s study is about 5-10 kg, depending on the kite size being used and wind conditions.

To send the lifting platform along with meteorological payloads up into the atmospheric boundary layer, a winch is needed to either raise or lower the lifting platform. There are two different types of spools (heavy or light weight tether) that the tether can be fed through that
depend on the outside conditions. The tether can either be let in or let out at a maximum speed of 2 m s\(^{-1}\) in normal operating conditions.

The TLS system has both advantages and disadvantages. Some advantages include the ability to take atmospheric measurements during both daytime and nighttime, high spatial resolution, ability to operate in remote areas, and the ability to take measurements of more than one variable at a time. Some disadvantages include Federal Aviation Administration (FAA) limitations that can place restrictions on altitudes and time of operation, inability to accurately determine vertical wind speeds, and difficulty to take measurements in adverse weather conditions or in clouds.

Tethered balloon systems provide a reliable way to take ABL measurements. Some advantages of using a balloon system include better resolution, fewer issues taking measurements at true air speed, and a smaller ratio (5:1) compared to a faster flying platform like a helicopter having a larger ratio (20:1) between vertical and horizontal wind speed velocities (Siebert et al. 2003). The versatility and numerous types of payload system options can lead to creative and sufficient ways to gain a better understanding of the ABL. Disadvantages to tethered balloon systems for small-scale measurements include lack of good statistics due to not long enough sampling time periods to ensure statistical significance, and difficulty taking point measurements and deriving area averaged properties (Siebert et al. 2003). Difficulty in getting equipment into remote terrain can prove to be costly as well.

When deciding on a tethersonde system to use for profiling atmospheric measurements, there are many considerations to take into account regarding the sensors. Accuracy, high sensitivity, compatibility, small in size, low power consumption, ability to operate in adverse
conditions, stability, and reliability are qualities that the sensors should possess (Thomas et al. 2005).

2.1.3 Flight in marine environment

Most of the studies discussed in this section examine ABL measurement studies performed onshore. Because this study is focused in a coastal area, it is important to gain an understanding on studies done involving boundary layer measurements in coastal locations.

Gong et al. (2000) analyzed the vertical structure of marine and coastal boundary layer’s effect on ground-level ozone transport in the Canadian South Atlantic region. Tethersonde measurements in Gong’s study ranged from 3 to 400 m above the surface, with a vertical resolution of 5 m. Meteorological parameters measured included: temperature, relative humidity, wind speed, wind direction, and ozone mixing ratio. Resolutions of the meteorological parameters were 0.2 °C, 2%, 0.1 m s\(^{-1}\), 3 °C, and 2 pptv (Gong et al. 2000).

Zhong et al. (2007) used the MM5 numerical model along with tethersonde and radiosonde systems along the southeastern Texas gulf coast to aid in understanding planetary boundary layer (PBL) parameters. The tethersonde system used in this study had a 1 Hz sampling rate, and measured temperature, humidity, wind speed, and wind direction (Zhong et al. 2007). Ten days worth of data in July of 2007 were sampled from the near surface up to 1000 m with a vertical resolution of 5 m. FAA regulations limited the study to 1000 m (Zhong et al. 2007). Data collected during these flights occurred during the ascent periods. The tethersonde system was flown in 2-3 hour flight intervals from 0500 CDT to 2100 CDT (Zhong et al. 2007). After obtaining an understanding on different approaches taken to obtain atmospheric measurements, we will now examine wind measurement guidelines used to site a wind farm.
2.2 Wind measurements needed to site a wind farm

There are certain guidelines that need to be followed when gathering wind data for a prospective wind farm site. These guidelines come from the International Electrotechnical Commission (IEC). The IEC promotes international cooperation on the standardization in the fields of electrical and electrical fields through its international standards, reports, and technical specifications. There are specific guidelines that must be followed when it comes to the measurement frequency (time), period, accuracy, and height.

The IEC states the time the data should be collected continuously at should be a sampling rate of 1 Hz or faster. The data acquisition should store a minimum of these variables which include: 10-minute mean value, standard deviation, maximum value, and minimum value. For the period, the IEC states that the maximum synchronization difference between any two data acquisition systems should be less than 1% of the averaging time. Accuracy of the measurements shall be expressed in terms of measurement uncertainty in Annex E of the IEC61400-12-2. The height for which wind measurements should be obtained is hub height of the wind turbine.

2.3 Flight module components needed to site a wind farm

To obtain wind measurements, a flight module will be used. The specifics of the flight modules used in this study will be explained in more detail in the System Overview section. The IEC provides guidelines when it comes to specific components for the flight modules to ensure the wind data being obtained is of good quality.

When it comes to obtaining wind speed and wind direction data, the IEC states to use a cup, sonic, or propeller anemometer that should be of a class 2.5B or better as defined in the IEC 614DD-12-1:2005. For this study, we will be using a 3-cup anemometer, which will be
explained in more detail in the System Overview section. We will now examine some potential issues.

2.4 Potential problems to overcome

With this type of project, there are a wide variety of obstacles that could occur which would need to be overcome. A few potential problems to overcome will be explained below which include swell, interpolation of data, error analysis of interpolated data, out of plane positioning of cup anemometer rotation, and an algorithm to correct real time data.

2.4.1 Swell

Since the entire system will be in the Gulf of Mexico, the swell induced by the sea would play a role in data acquisition. Swells are surface waves that outrun their generating wind, and radiate across ocean basins (Ardhuin et al. 2009). The reason that swells would cause a problem with the data being collected is that height which the modules are at would constantly be changing. The swell would cause the buoy to rise and fall as waves propagate, and the bigger the wave heights would create a bigger difference in the modules designated height.

2.4.2 Interpolation of data

In addition to the swell being able to alter the height of the modules, wind speeds can also modify the heights. This could be overcome by using multiple modules and interpolate the data and analyze the data at a fixed level. For this project the amount of modules used varied from one to four modules depending on the situation and location the testing was performed at.
2.4.3 Error analysis of interpolated heights

Using interpolated heights can determine data at a fixed level. This study used interpolated heights when multiple modules were in use to observe Power law and Richardson numbers and their values at the various height levels. There will be some degree of uncertainty with those results. An error analysis can be used to see how well the interpolation does. One way this can be done is by having multiple cup anemometers at the same height interval. This allows for a comparison between both, and can potentially give more certainty that the interpolation is providing accurate data.

2.4.4 Out of plane positioning of anemometer cup rotation

The accuracy of wind speed measurements has been subject of numerous studies done in the past few decades, resulting in showing the principal sources of measurement errors (Papadopoulos et al. 2001). Overspeeding and out of plane position of cup anemometer rotation are causes of measurement error.

Wind speeds can enter the cup anemometer from different directions which can cause an out of plane position. The cup anemometer is used in this study as it is widely used due to its sturdy, simple, reliable, and requires minimal maintenance (Busch and Kristensen 1976). The cup anemometer is preferred for continuous measurements as there is no need for alignment into the wind direction. One disadvantage cup anemometers have is they can overspeed which is caused by a nonlinear response to fluctuating winds (Busch and Kristensen 1976). Cup anemometers respond faster as wind speeds increases, but slower as wind speeds decrease.
2.4.5 Algorithm to correct real time data

For a system to run continuously throughout the day, a large amount of data would be collected. Having to go through the data manually and make adjustments to the height at which the modules are collecting data at, as well as performing interpolations for specific heights would be a daunting task. An algorithm that could do this automatically would save time.

It is important to have reliable and accurate height measurements for the balloon-borne sensors. With the balloon system used in this study, we have two methods to be able to determine the real time height data. First the modules are equipped with a GPS signal which can be used to observe the heights at which the module is being flown at. The GPS samples at 10-Hz with an estimated ± 1-3% accuracy. The second method is to use the Hypsometric equation which can determine the height of the module since we have temperature and pressure measurements taken from each module and from the buoy. The Hypsometric equation will be explained in the Methods section.

With both of these approaches there will be some degree of error, so an error analysis using both methods would need to be examined. We will use percent errors to determine the amount of error in the methods. Having both ways to calculate the heights is good to have in case something goes wrong with the GPS signal or vice versa the pressure data. We will now take a look at the marine-based balloon-borne wind measurement system.
3. SYSTEM OVERVIEW

This section examines and explains the prototype marine-based balloon-borne wind measurement system. The subsections that follow will take a look at each part which makes up the entire system which can be seen in Figure 1.

3.1 Balloon system

The balloon system is made up of several components which will be described below along with photographs. These components include sea anchor, anchor chain, buoy, winch, balloon tether line, power cabling line, lighting and marking system, tethersonde module, balloon, emergency deflation device (EDD), and power system.

3.1.1 Sea anchor

The sea anchor is used to keep the buoy in the permitted location while in the Gulf of Mexico. Without an anchor, the buoy would be free to move about due to the constant wave movement, but also aerodynamic drag forces being exerted on the buoy from the balloon while in flight. The sea anchor is composed of two rail car wheels placed on top of one another weighing 840 kg. Figure 2 below shows sea anchor and anchor chain set up aboard a vessel before being deployed for field testing.

3.1.2 Anchor chain

An anchor chain is needed to serve as the connection between sea anchor and buoy. Two anchor chains that were 19 mm of galvanized steel were used. Galvanized steel were used to protect from rust and corrosion, by coating the steel with zinc. One is 30 m long, and the other is 15 m long totaling 45 m. Two chains were used instead of one for easier maintenance needs, once replacing the anchor chains is required. The 30 m chain lies on the ocean floor which
prevents buildup on the chain, while the 15 m chain is suspended in the water. To connect each chain together, 19 mm galvanized anchor bolt shackles and galvanized pear links were used.

3.1.3 Buoy

The buoy is custom designed by Mooring Systems of Cataumet, MA. This is the base of the tethered balloon system which houses all of the main components for the system. Also located on the buoy includes: three solar panels, a winch, two battery boxes, a marine-grade RF data antenna, two buoy navigation lights, and a satellite alarm monitoring box. Figure 3 shows the buoy fully assembled and in the water.

3.1.4 Winch

To reel in and out the balloon system a winch is needed. The winch used in this study were manufactured by Skydoc weighing 158 kg, had a line pull capacity of 238 kg, and a line retrieval speed of 20 m per minute. Figure 4 displays a winch situated in the back of a truck during field testing near the Sandia Park tower in New Mexico.

3.1.5 Balloon tether line

A tether line is used to suspend meteorological instruments in the air from the balloon to collect data. Figure 5 shows both tether and power cable line together. This line also holds the force of the balloon and tethersonde modules. The spool of tether used in the winch is 182 m long altogether. Since the target height for the balloon to fly is 150 m, 30 m of tether line is left to account for various angles and sudden gusts. The tether line is coated with Urethane spectra braid, which is rated for 1130 kg.

To attach the modules and FAA light to the tether line, a clamp was employed. Two aluminum rods are fastened together through the clamps which are then screwed together via ordinary thumb screws, and then tightened. At the ends of the two aluminum rods, there is an
aluminum pivot block which is used to attach onto the tether line. This pivot block keeps the
tethersonde boom level. Figure 6 shows a close-up view of the aluminum pivot block. The
aluminum pivot block can be tightened and un-tightened which allows for quick attachment and
detachment of the tethersonde booms.

3.1.6 Power cable line

The power cable supplies power throughout the entire system. The power cable feeds
into a series of junction boxes which then supply power to the tethersonde modules and FAA
lighting. In total there are a total of five junction boxes used in this setup. Figure 7 shows what a
junction box looks like. Each junction box has a ferrite installed, which provides protection
should any part of the system be struck by lightning.

3.1.7 Lighting and marking system

To warn aircraft or ocean traffic of the buoy systems location, lights and marking tape are
used on the system. For the daytime, a series of pink or orange marking tape are applied to the
tether line roughly every 15 m. For nighttime a series of lights are applied to the system. Along
the tether line is one light that is attached to the tether line like the tethersonde modules are
attached. Below the bottom of the balloon is an aluminum circular ring which has three separate
lights mounted onto it. Figure 8 shows the aluminum circular ring with lights. Two more lights
are attached on the balloon.

3.1.8 Tethersonde modules

Tethersonde flight modules were employed to collect atmospheric data, manufactured by
Anasphere. These modules received data by being flown in the air attached to a tether line,
suspended in the air by a balloon. The flight modules measured wind speed, wind direction,
temperature, pressure, and relative humidity. Table 1 below provides specifications and
manufacturer for each instrument. Instrumentation used on the tethersonde flight module was manufactured by Renewable NRG Systems.

There are several components that make up a tethersonde these components include: 3-cup anemometers, boom, battery box, line attachment, electronics box, and aerodynamic fins. Figure 9 shows a fully assembled tethersonde flight module.

Once in flight, the modules sent data wirelessly to the power system located on the buoy or base station; which is hooked up to a laptop which can view the data as it comes in. The data receiver connects directly to any standard PC via a 9 pin RS-232 cable, which runs on a 12 VDC power source. The maximum data transmission range is about 3000 m.

3.1.9 Balloon

Two different balloons both spherical in design, but with different size dimensions were used in this study. The different types were a Kingfisher and a Model #25 SkyDoc. The Kingfisher is smaller, and about 3.6 m in diameter with a volume of 11.9 \( \text{m}^3 \), and has a lift of 7.3 kg of lift at calm winds at sea level. The Model #25 SkyDoc is larger about 6.7 m in diameter with a volume of 73.4 \( \text{m}^3 \), and has a lift of 55 kg at calm winds at sea level. Figure 10 displays the Model #25 SkyDoc ready to be moved to the gulf site.

3.1.10 Emergency deflation device

An emergency deflation device (EDD) is used to immediately deflate the balloon should it drift too far away from its assigned GPS position to prevent the balloon escaping or posing a risk to others. One possible risk would involve a shackle breaking, which would result in the balloon flying away. The EDD would burn a small tear into the balloon to allow for the balloon to deflate and fall down to the surface. Figure 11 shows what the EDD looks like.
3.1.11 Power system

The power system is composed of several parts. The entire system is run off of four, twelve volt VDC AGM 176 Ah batteries. There are two battery boxes on the buoy, each containing two batteries. Figure 12 shows one of the battery boxes on the buoy. To keep the batteries charged, there are three solar panels that were attached onto the buoy. Each panel can generate 240 W. There is an electronics box on the buoy where all the power cabling, wiring, switches, and router are located. Figure 13 shows the inside of the electronics box. We will now explore the methods that will be used to analyze the data.
4. METHODS

This section takes a look at the equations and methods used to analyze the data obtained for this study. When examining averages the values can be quite close making it hard to see exactly what is happening. We used the differences between module and either tower or Galion lidar data to get a better look at the data. The Galion lidar which is manufactured by SgurrEnergy which will be explained in the Data section in more detail.

To examine the difference between approximate and exact values, the percent error is found using the follow equation:

\[
\frac{|\text{approximate value} - \text{exact value}|}{|\text{exact value}|} \times 100\%
\]

From the above equation, the module (approximate) data is being compared to tower or Galion lidar (exact) data.

To determine the relationship between two locations wind speeds or wind directions, correlation coefficients are found using the following equation:

\[
\text{Correl}(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}}
\]

Where \(\bar{x}\) and \(\bar{y}\) are the sample means average 1 and average 2. In this case average 1 would be module data and average 2 would be any tower or Galion lidar data.

To examine the relationship between wind speeds at one height and another, the power law is used to get a better idea as to which module heights would be best to use when interpolating 80-m hub height wind speeds. The wind speeds and their heights recorded from the modules are used to then approximate wind speeds at an 80-m hub height for a wind turbine. The equation for the power law can be seen as:

\[
\frac{U_2}{U_1} = \left(\frac{Z_2}{Z_1}\right)^\alpha
\]
Where U is the wind speed (m s\(^{-1}\)), Z is the height (m), and \(\alpha\) is a stability coefficient. To solve for the stability coefficient, the power law can be rewritten as:

\[
\alpha = \frac{\log \left( \frac{U}{Z} \right)}{\log \left( \frac{U_2}{Z_2} \right)}
\]

To investigate whether or not the flow of air is turbulent or not from the data acquired by the modules, the Richardson number is found.

\[
Ri = \frac{g \frac{\partial \theta v}{\partial z}}{\left[ \left( \frac{\partial \bar{u}}{\partial z} \right)^2 + \left( \frac{\partial \bar{v}}{\partial z} \right)^2 \right]^{-\frac{1}{2}}}
\]

To solve for the Richardson number with the data acquired from the modules we use another set of equations. To find the \(u\) and \(v\) components from the cup speed and wind vane measurements we use:

\[
\sin(\theta) = \frac{u}{\text{wspd}} \quad \cos(\theta) = \frac{v}{\text{wspd}}
\]

wspd is the wind speed and \(\theta\) is the wind direction. To find virtual temperature (\(\theta_v\)), we start with finding the saturation vapor pressure (\(e^*\)) using the following equation from Emanuel (Emanuel 1994), which is based on the Clausius-Clapeyron equation.

\[
e^* = 6.112 \exp \left( \frac{17.67 T}{T + 243.5} \right)
\]

\(T\) is temperature, we then multiply \(e^*\) by the relative humidity to get vapor pressure (\(e\)). The mixing ratio (\(r\)) is found next using:

\[
r = \epsilon \left( \frac{e}{p-e} \right)
\]

\(\epsilon\) is the ratio of molecular weight of water vapor to dry air which is a constant of .622, and \(p\) is pressure. Potential temperature (\(\theta\)) is found using
\[ \theta = T \left( \frac{P_0}{P} \right)^{R/c_p} \]

\( P_o \) is a reference pressure usually 1000 mb. \( R \) is the gas constant of air and \( C_p \) is the specific heat capacity at a constant pressure which is a constant of .286. To find virtual temperature for unsaturated air with mixing ratio, the following equation is used

\[ \theta v = \theta * (1 + 0.61 * r) \]

To determine the heights of the modules used in the study, the Hypsometric equation is used. The Hypsometric equation gives

\[ \Delta z = -\frac{(R_d * T_v)}{g} * \ln \left( \frac{p_1}{p_2} \right) \]

Where \( R_d \) is the gas constant of air which is 287 J K\(^{-1}\)\ kg\(^{-1}\), \( T_v \) is the average virtual temperature between two heights, \( g \) is gravity which is 9.81 m s\(^{-2}\), and \( p_1 \) and \( p_2 \) are the module pressures.

An alternative form of the Hypsometric equation was used to find the pressures at each module height. The alternative form is as follows

\[ p_1 = e^{-\frac{\Delta z}{(R_d*T_v)} * p_2} \]

Now that we have taken a look at the methods used to analyze the data, we will now explain the different types of data used.
5. DATA

Data for this study came from three different sources which include tower, module, and Galion lidar. Tower and Galion lidar data are both used to compare to module data. Each type of data will be explained in this section.

5.1 Tower data

Meteorological tower data was used in this project to compare the data collected from the modules. There were three meteorological towers used, two in Iowa and one in New Mexico. All tower data collected were in 10 minute averages and instrumentation reported the average, standard deviation, maximum, and minimum for each variable. Wind speed, wind direction, temperature, and barometric pressure were the meteorological variables being sampled.

5.1.1 Iowa tower

Two 50 m meteorological towers were installed about 40 miles to the northeast of Ames, IA. Figure 14 displays the locations of each tower on a map. These meteorological towers were installed, and gathered data from October 2012 thru March 2013. Tables 1 and 2 provide the time periods that both towers were in operation.

There were twelve meteorological instruments which gathered wind speed, wind direction, temperature, and barometric pressure data at various heights. There were six anemometers which sampled wind speeds, which had two anemometers each at three different heights. These heights were 48 m, 32 m, and 10 m. Two wind vanes were used to sample wind direction at heights of 47 m and 10 m. There were two temperature sensors set at 48 m and 3 m. Barometric pressure sensors were setup at 48 m. Tables 3, 4, 5, and 6 display instrumentation details for Holstine and Hill towers.
5.1.2 New Mexico tower

50 m meteorological towers were installed near Sandia Hills, NM which is located about 30 miles to the northeast of Albuquerque, NM. Figure 15 displays the location of the tower on a map. This tower operated and gathered data from November and December of 2013. Table 7 provides a more in-depth look at the data collection time periods.

Similar to the Iowa meteorological towers; wind speed, wind direction, temperature, and barometric pressure data were collected at various heights. There were four anemometers which sampled wind speeds, two at 48.5 m and two at 40 m. Two wind vanes sampled wind directions at 47 m and 34 m. Two temperature sensors were used at 48.5 m and 32 m. Table 8 provides anemometer instrumentation details, and Table 9 provides wind vane and temperature instrumentation details.

5.2 Module data

Data acquired from these modules come from several field tests in various locations. The locations where module data were acquired include near the Holstine meteorological tower in Iowa, the Sandia Park meteorological tower in New Mexico, and around the South Padre Island area in Texas. Figure 16 displays location of module flights on a map. Tables 10, 11, and 12 show the time periods module data were collected and which location.

5.3 Galion lidar data

A Galion lidar from SgurrEnergy was deployed near the South Padre Island site in August 2013, Table 13 displays time periods of received Galion lidar data. There are 3 different range gates with data, these range gates are 4, 9, and 16. The Galion lidar provides a several variables in the dataset which includes: elevation angle, horizontal component of line of sight measurement, horizontal wind speed, average intensity, minimum intensity, measurements
accepted, mean square error, pitch, roll, wind direction, X, Y, and Z. After explaining the different types of data used in this study, we will now examine the results.
6. RESULTS

This section will take a look at how the wind speed and wind direction module data performed when being compared to either tower or Galion lidar data. There were a total of nine field tests using module data which used to compare to either tower or Galion lidar data. The data will be divided up into two sub sections; module data compared to tower data, and module data compared to Galion lidar data. Each field test is classified as a different case. Analysis of module heights is also discussed in this section.

6.1 Module and tower data

Seven field tests spanning eight different days involving comparisons between module data and tower data will be shown in this first sub section. The first case was an exploratory field test in Iowa, while the remaining cases were done near Sandia Park, NM. A series of plots are shown below for each case to show comparisons between module data and tower data. Wind speeds and direction variables are examined in each case. Averages, differences, percent error, and tower vs. module plots with a line of best fit are shown for each case. Correlation coefficients between module and tower data for all of the December field tests are shown in Table 2.

6.1.1 Case 1: March 19 and 20, 2013

Figure 17 shows tower and module average wind speeds, differences, and percent errors. Module and tower data were close in comparison throughout much of the afternoon and evening hours, with the 10 m B tower data having slightly higher wind speeds. Higher wind speed differences occurred around 2000 LST. Human error was likely the cause since the electrical tape which was used to keep the tethersonde fixed at 10 m, lost its adhesiveness due to the frigid
temperatures which caused the module to gradually lower down to the surface. New batteries were placed into the tethersonde and raised it back to its 10 m height so it could run overnight. Shortly after midnight there was an apparent disparity between tower and module data. With the percent errors values were relatively low and show higher errors in relation to larger wind speed differences.

Figure 18 shows a scatter plot with a best line of fit. There appears to be strong correlation shown in these plots, with values for both heights compared to module data having a ratio close to 1.

Figure 19 shows wind direction, differences, and percent errors. The wind directions match up very well up until about 2000 LST. There is a large difference between tower and module data for the remainder of the evening and into the early morning hours. Table 15 shows correlation coefficients found between module data and tower data for wind speed and wind direction. The wind speeds show very high correlation values around .90, while the wind direction shows very little correlation. Percent errors show a similar story, fewer than 20% error until the evening hours. After midnight we see percent errors back to around 20% or less.

6.1.2 Case 2: December 3, 2013

Site observations from this day included mostly cloudy skies. A high pressure system was situated well to the north near the Colorado/New Mexico border. Temperatures for this period were in the 50s.

Figure 20 shows average wind speed and differences. Module and tower data match up fairly well in this period. The module tends to underperform by one to two m s\(^{-1}\) during some time periods. There is apparent disagreement between the two datasets at the beginning and end
of this period, which could be attributed to the ascent and descent time while getting the module situated at a steady height. Figure 21 shows the wind speed percent error. Throughout most of this period the percent errors are relatively low, with higher errors observed during the beginning and end of this time period.

Line of best fit plots can be seen in Figure 22 which shows little correlation between module and tower wind speeds. Figure 23 shows wind direction, differences, and percent errors. There is a pretty big difference between module and tower data. Percent errors for wind direction show very high errors with the wind direction data.

6.1.3 Case 3: December 10, 2013

Mostly cloudy skies were experienced on this day. Wind speeds were relatively calm to start this period before gradually picking up after 1400 LST as the wind direction changed. Temperatures for this period remained in the low 30s.

Figure 24 shows average wind speed and wind speed differences. Module and tower data matched up very well in this period. Differences ran ±0.5 m s⁻¹ for much of this period. Towards the end of this period around 1500 LST, the module began to underperform before matching up again to end the period.

Figure 25 shows the wind speed percent error. Percent error values for this period tended to stay at or below 50% for both heights. The 40-m shows some percent errors reaching close to 60%. This could be attributed to the height of the module, as it is suspended in the air shifts in wind direction which can be seen in Figure 27 could raise or lower the modules height for brief period of time. Wind directions were off by a large margin again and the tower anemometers
detected a wind shift at different times around 1520 LST. Wind direction percent errors for the most part are very high throughout the period.

Figure 26 shows the line of best fit, which shows the tower and module wind speed data correlates well with values close to one. 48 m has values closer to one while 40 m are a bit higher by a few tenths.

6.1.4 Case 4: December 11, 2013

Clear skies occurred on this day. Wind speeds were calm for most of the period before slightly picking up. Temperatures for this period started in the upper 30s before ending in the lower 40s.

Figure 28 shows tower and module average wind speed and their differences. The early period the module shows to be about 1 m s\(^{-1}\) off, before matching up very well around 1500 LST and on. Percent errors showed in Figure 29 shows similar features as in the wind speed averages. Higher errors early on followed by lower errors later in the period.

Figure 30 shows some correlation between the datasets, with the 40-m tower data having slightly higher values in the equation of best fit. Figure 31 shows wind directions, differences, and percent errors. The tower data had some differences to start the period before lining up together. An interesting note here is that the module data appears to have captured the 34 m wind direction by about 30 minutes late. There is a large disparity in the differences between tower and module wind direction. For much of the period, percent errors were well above 50%, with some moments of lower errors at 1450 LST and 1600 LST.
6.1.5 Case 5: December 12, 2013

Overcast skies were observed during this period, as a stationary front pushed eastward. Temperatures remained in the upper 30s.

Figure 32 shows wind speeds and their differences. Module wind speeds changed from being slower or faster than tower wind speed’s for much of the first half. For most of this period module data came within ±1 m s⁻¹. There were about an hour of missing module data in the early afternoon, which were caused by loss of power from the tethersonde as the batteries ran out. The system had to be brought down to replace the batteries, and then sent the system back up. Figure 33 shows wind speed percent errors. The first half of this time period the percent errors are quite high, but shortly after noon the percent errors were quite low before the tethersonde lost power.

Lines of best fit plots shown in Figure 34 display low correlation between the data sets, and low values around .26. Wind direction, differences, and percent errors are shown in Figure 35; there were quite a large disparity between the datasets. Large differences between the data sets can also be shown with the percent errors.

6.1.7 Case 6: December 18, 2013

Mostly cloudy skies were experienced in this period. Temperatures were in the lower 50s. Figure 36 shows wind speeds and difference for module and tower data. For much of this period the module had higher wind speeds about 1 m s⁻¹ in difference compared to tower data. Towards the end of the period the module were delayed in capturing the rise in wind speeds that the tower data recorded. Percent errors for this period are shown in Figure 37. The 40-m tower data percent errors differ and show higher percent errors compared to the 48-m tower data.
Figure 38 shows lines of best fit plots for this period. Overall there were low amounts of correlation between module and tower wind speeds. The 40-m tower data yields slightly higher correlations as compared to the 48-m tower data.

Figure 39 shows wind direction, differences, and percent errors. Quite a large disparity is seen here and the percent errors. There were a few low percent errors which resulted in the wind direction matching up during a few times in this period.

6.1.8 Case 7: December 19, 2013

Mostly cloudy skies were seen to start this period before becoming partly cloudy. Temperatures ranged from the upper 40s to lower 50s.

Figure 40 shows wind speeds and their differences. For this period the module and tower data matched up fairly well. In the early afternoon around 1300 LST the module data over performed by about 1 to 2 m s\(^{-1}\), but for much of the period the differences stayed between -1 to 1 m s\(^{-1}\). Percent errors showed in Figure 41 shows pretty common spikes in errors mainly below 50%. The 40-m anemometers differences are greater than the 48-m differences.

Figure 42 shows line of best fit plots. Overall there was some correlation between tower and module data, with most values ranging in the low to mid 50’s.

Wind direction, differences, and percent errors are shown in Figure 43. Large disparities are shown throughout much of the period. Percent errors for wind directions show the large disparity with percent errors over 50% for much of this period.
6.2 Module and Galion lidar data

Two field tests involving comparisons between module and Galion lidar data will be shown in this section. There are three different range gates (RG) used in comparing to module data. The heights for each are as follows; RG4 is 47.9 m, RG9 is 101.2 m, and RG16 is 175.7 m.

The first two cases September 8th and November 15-16 were tested at the South Padre Island site. A series of plots are shown below for each case to show comparisons between module data and Galion lidar data. Wind speeds and direction variables are examined in each case. Averages, differences, percent error, tower vs. module plots with a line of best fit, power law alpha values, and Richardson number plots are shown for each case.

6.2.1 Case 8: September 8, 2013

This case used three modules and the heights sampled include 50 m, 70 m, and 90 m. The heights are based on the average altitudes for each module. Figures 44, 45, and 46 show wind speeds and their differences. For the first part of this period, the 50-m data is noticeably low which could be caused by the module still being on the ground and not being at the target height. For much of the period the modules come within 1-2 m s\(^{-1}\) of the Galion lidar. In the second part of the period after 1330 LST the RG4 and RG9 50-m and 70-m module wind speeds outperform the 90-m slightly. For RG16 the 90-m module data slightly does better at capturing the Galion lidar wind speed data.

When looking at the wind speed percent errors in Figure 47, the 90-m module shows very high percent errors for each RG. Higher percent errors are shown in the early period for all RG’s, but after 1300 LST the percent errors drop below 40\% for the rest of the period for RG4 and RG9. Looking at line of best fit plots in Figure 48, 49, and 50, there is a low correlation between
50-m module wind speeds and Galion lidar wind speeds. Higher correlations with 70-m module wind speeds were observed for RG4 and RG9, and the correlation were lower with RG16. The 90-m module wind speeds see a fair amount of correlation between RG4 and RG9, there is a small amount of correlation with RG16.

Figures 51, 52, and 53 show module wind direction compare to Galion lidar wind direction. The 70-m and 90-m module wind direction matches up fairly well to Galion lidar data. The 50-m module wind direction is off by a wide margin in the first half of this period before matching up with the Galion lidar wind direction.

Wind direction percent errors are shown in Figure 54. Aside from the large percent errors in the first half of the period for the 50 m module, all three modules show percent errors below 50% for each range gate.

Figure 55 shows power law alpha values. Higher alpha values are observed in the first part of the period, with alpha values ranging from -.20 to .20 after 1330 LST. Richardson numbers are plotted in Figure 56. This daytime period shows turbulent flow throughout the period for all module heights. The air is primarily in an unstable stratification at all module heights.

Table 17 shows correlation coefficients between module data and Galion lidar data. The wind speed and RG4 show highest correlations. For wind directions the 70-m module heights show fair amount of correlation with all three range gates, with the other heights showing lower or no correlation at all.
6.2.2 Case 9: November 15-16, 2013

For this case, two modules were used at heights of 60 m and 100 m. The heights are based on the average altitudes for each module. There are some periods of missing data, in the early part of this period, the system had to be powered down to correct some lighting issues which took about two hours to fix and get the system back up and running. The data towards the end of the period ended abruptly as the carabiner ring which connected the balloon and tether wire together, somehow broke resulting in the balloon getting carried away which ultimately disappeared.

Figures 57, 58, and 59 show module wind speeds and their differences compared to each Galion lidar RG. For all three range gates shown the 60-m module data matches up fairly well, with the RG4 data showing differences consistently around 0 m s\(^{-1}\) for most of the period. RG16 shows the largest amount of differences with values at some points around -3 m s\(^{-1}\).

Figure 60 shows wind speed percent errors. The 100-m module data shows consistently higher errors throughout the period, while the 60-m module data shows lower errors. RG4 shows some higher percent errors to start the period before falling to below 20%. RG9 shows the lowest percent errors throughout the entire period ranging from 30% and below. RG16 shows percent errors hovering around 20% before dropping.

Figure 61 and 62 show lines of best fit plots for both modules and each range gate. The 60-m data shows very strong correlation between module and Galion lidar. The 100-m data shows very low correlation between module and Galion lidar.

Wind directions and their differences for each module and range gate are shown in Figures 63, 64, and 65. Each range gate shows large differences between module data. Percent
errors in Figure 66 also show the disparity between module and Galion lidar with very high percent errors.

Figure 67 shows power law alpha values for the module data. Alpha values are shown to be quite low. Richardson numbers are plotted in Figure 68. This period shows a noisy signature. The air does not become entirely stable as the \( R_i \) approaches 0.5. The period between 2330 to 1240 LST shows the flow becoming strongly stable, however it is short lived and drops down to near-neutral followed by unstable shortly after.

Correlation coefficients for wind speed and wind direction are shown in Table 18 between module and Galion lidar data. Little correlation is shown in the 60-m module data, but there is some correlation with the 100-m module data. When it comes to wind directions, there appears to be some high correlation values for the 100-m module data. Module heights and wind measurements will now be examined.

6.3 Offshore measurements

6.3.1 Deployment of the buoy-based system

On February 9\textsuperscript{th} 2014, a boat operated by the University of Texas at Brownsville was commissioned to tow the buoy-based system to the offshore site. The offshore site is located roughly five miles west of the South Padre site which can be seen in Figure 16. Figure 69 shows a picture of the boat used to tow the system out to the offshore site. We departed from the marina around 1200 LST, there were overcast skies with temperatures in the 50s, winds were between 5-10 knots out of the NNE, and wave heights were between 1-3 feet.
It took roughly five hours to get the buoy-based system out to the site, which was not anticipated. The reason it took so long to get to the site was keeping the buoy system level as it was being towed. Figure 70 shows an image of what we wanted to avoid which is the buoy being tilted and submerging parts of the system. To keep it level and avoid the buoy from tilting and submerging parts on the buoy in sea water, the boat traveled at a speed of less than a knot.

Upon reaching the site, the first thing that was done was to deploy the anchor. Figure 71 shows the setup of the anchor and chain. The anchor was positioned at the end of the boat on a sheet of plywood that extended over the edge of the boat. Under the plywood were two 2x4’s. The plywood was used as a base for the anchor to sit on to avoid damaging the boat, and the two 2x4’s were used to catapult the anchor off of the boat and slide down into the water. Everything was tied down and setup so that once we arrived to the site, one cut of the rope binding the 2x4’s down would catapult the anchor into the water. The anchor chain was snaked out for a smooth deployment on one side of the deck. The anchor deployment went very smoothly. Due to issues with the lighting system and lack of daylight, we could not begin to collect data. We decided to leave the system and return the next day to begin collecting data.

On February 10th 2014, we left the marina around 1000 LST to head back to the offshore site to begin data collection. Upon reaching the site, issues with the lighting system remained and so we decided to launch the system and collect data during the day. We could not collect any data after sunset without a working lighting system.

We began attaching modules and raising the system into the air shortly after 1100 LST. Figure 72 shows the setup of the modules on the deck of the boat. To get the modules onto the tether line, we had to moore to the buoy. Once we were moored to the buoy someone had to get
onto the buoy and physically attach the modules onto the tether line. We had to continuously watch and make sure the solar panels would not hit the side of the boat due to waves. The balloon was then raised as modules were being attached at heights of 9 m, 40.7 m, 75.9 m, and 90.5 m.

Once the balloon was raised to approximately 100 m, the boat was unmoored from the buoy and the balloon-based measurement system was operating by itself collecting data powered by the solar panels. Figure 73 shows the balloon system employed and collecting data.

6.3.2 Data

Data being measured for this period include module wind speed, wind direction, temperature, and pressure. Buoy temperature and pressure data were also being collected. Data collection ran from 1100 LST to 1430 LST on February 10th 2014. During this time there were partly cloudy skies, temperatures were in the 60s, with winds out of the SSE between 5-10 knots, and wave heights of 1-3 feet. The following sections provide analyses of data acquired during this period.

6.3.3 Measurement of module height

Two methods of obtaining heights are examined which include the module GPS and analysis of module pressure data by use of the hypsometric equation. When first applying the hypsometric equation, there were noticeable differences between calculated heights and GPS heights. Some of the module pressures that were recorded were unrealistic, such as a module recording 1050 mb and the buoy recording 1014 mb. Modules three and four recorded very high pressures, while pressures for modules one and two were not as high.
This prompted the use of a bias correction on each of the modules to correct the unrealistic values which would then give us better height values that matched up better with the GPS heights. The modules began collecting data at 1110 LST. A 10-minute period between 1200 - 1210 LST had missing data. To perform the bias correction we used the 1210 LST time period because there were no missing data after this time. Furthermore during the first hour while the modules were running we were attaching and raising the modules up into the air. So by 1210 LST the entire system was collecting data and the modules were all suspended in the air along the tether line.

We assumed that the GPS was accurately measuring height and that the module temperature sensors were measuring accurately at 1210 LST. We then used the GPS heights from 1210 LST with the Hypsometric equation to calculate the actual pressure for each module. These calculated pressures are then compared to the module pressure measurements to determine each module bias.

Figure 74 shows the GPS heights (top), heights calculated from the Hypsometric equation (middle), and percent errors (bottom). With the GPS heights, H1 refer to the module 1 height which was the first module attached to the tether line. Then H2, H3, and H4 follow with H4 being module 4 the last module attached to the tether line during deployment. At 1410 module 4 erroneously reports a higher height than module 3. This could be due to an error in the data being sent from the module to the base station on the buoy.

The heights calculated from the Hypsometric equation are shown in the middle plot. H12 refers to the distance between module 1 and 2, and then H23, H34, and H4b referring to the other modules. H4b refers to the distance between module 4 and the buoy. The heights found using the
Hypsometric equation are higher than the GPS heights. There appears to be a bump in the heights at 1310. This might be attributed to a gust of wind which pushed the balloon horizontally which then increases the height distance.

With the percent errors, the first hour of data collection will show very high percent errors due to the modules being attached to the tether line and raised up into the atmosphere. H12 and H34 both have percent errors around 50% or below for much of the period after 1210 LST. H23 has high percent errors starting at 1210 LST but gradually decreases towards the end of the period. H4B has percent errors spike at 1310 LST, but runs relatively high for the entire period.

The GPS provided good data, however we lack strong evidence to confirm the heights due to malfunctions to the pressure sensors. Human error can be attributed to the pressure sensor errors. During the preparation phase the modules motherboards which contain all of the sensors were waterproofed, however it is likely that a part got covered which shouldn’t have which lead to the pressure sensors reading unrealistic values. Since the waterproofing of the motherboards caused an issue with the pressure sensors, it is possible that the temperature sensors could also have been corrupted by the waterproofing of the motherboards.

**6.3.4 Analysis of module wind measurements**

During the February 10\textsuperscript{th} launch of the buoy system in the Gulf of Mexico, 1-s wind speed data were gathered. To examine what the frequencies within the data set would look like, a spectral analysis was used. Spectral analysis is a tool used to describe the scales of energy within the wind speed and the inter-connection between low energy and high energy information. The process of creating the spectral analysis will be explained below.
Before a spectral analysis is performed, the data must be detrended. Detrending the data removes the trend from the data, which allows for analysis of the fluctuations in the data set about the trend. Detrending forces its mean to zero and reduces the overall variation.

A Fourier analysis will be used to convert the time to a frequency. A Fourier analysis splits arbitrary signals into waves. So we will use the Fast Fourier Transform (FFT). The FFT resolves a time waveform into its sinusoidal components, and creates the frequency spectrum of the data from the time domain data. The FFT allows for the estimation of component frequencies in data from a discrete set of values sampled at a fixed rate. Should a frequency have a high amplitude, the turbulent eddies associated with the frequency will contribute to the turbulence kinetic energy. If we have \( N \) data points, then the highest frequency that can be resolved in a Fourier analysis is the Nyquist Frequency. The Nyquist Frequency is \( \frac{N}{2} \) (Stull, 1988).

After the FFT is performed, smoothing methods were used to remove periodic components from the data set while maintaining the main trend. Without using a smoothing method, the plots looked very noisy which can be hard to interpret. The goal of smoothing is to reduce the amount of noise while maintaining the signals shape. The normalizing frequency used is \( \frac{fz}{U} \) where \( f \) is the frequency, \( z \) is the height, and \( U \) is the wind speed.

Figure 75 below shows a comparison between a non-smoothed and smoothed plot. The left plot’s signal is hard to interpret with all the noise, while the right plot shows a much smoother signal which has the smoothing method applied. A moving average filter is used to determine the degree of smooth applied to the data. The default smooth value is three, so from
that default value we raised the value until the signal was less noisy and maintained the overall
shape by not smoothing too much out. The span used in this study is 50.

The 1-s data for the modules had frequent missing data gaps, so the entire period was not
used. Three spectra from the February 10th 1-s data were analyzed, when the buoy system was
launched in the Gulf of Mexico. Of the four modules launched modules F66E8C (highest) and
F7127D (lowest) were used. These time periods analyzed were chosen based on having no
missing gaps in the data set, as the other two modules had consistent missing data each minute.

The time periods used include a 20 minute time period from 1114-11:34 LST, a 10
minute time period from 1153-1203 LST, and a 7 minute time period from 1423-1430 LST.
During this time period party cloudy skies were observed before about an hour of clear skies
from 1145-1245 LST. The clouds rolled back in shortly after that. Synoptically there was a low
approaching from the west and a cold front to the north.

Figure 76 below shows the module F66E8C spectra’s for each time period, and Figure 77
shows module F7127D’s spectra. We see a similar trend in both Figures where in part a where
we can see a spike in the frequency towards the end of the spectrum that appears lower in part b,
and even lower in part c. So as the day progresses the spike is less and less. Module F66E8C
which is the higher module in elevation shows higher intensities, while the lower module has
lower intensities. With these plots we could be seeing a change in the boundary layer, from a
mixed boundary layer in the late morning to a stable boundary layer in the early afternoon.

The 1-Hz data might not be high enough resolution to capture the higher spectrals of
turbulence, which means with these plots we only see some of the energy scales in the boundary
layer. Since we are not seeing the entire energy scale, there is a lack of a curve on the high end
of the spectrum. Figure 78 below shows a range of resolution frequencies showing the same plot. As the resolution frequency is increased, the ability to see the finer details of the signal is lost.

In order to see if this is the case or not, we next looked at a piece of 1-s data from the New Mexico field tests. These field tests used the buoy system in order to test the equipment before deploying the whole system into the Gulf of Mexico. A 20 minute time period (1230–1250 LST) of 1-s data was used from a field test done on December 10, 2013. Clear skies were observed, and light winds recorded from the module.

Figure 79 below shows the spectral analysis of this time period. An overall similar shape is seen as compared to the February 10th spectrums. One difference though is that the left side of the spectra is curved, where the spectrums from the February 10th were flat. The 1-Hz data still shows that it might not be high enough resolution.

We then took some 1-s data from the crop wind energy experiment (CWEX) data, a 20 minute period was used to create a spectral analysis. We chose the same time period that was used with the previous New Mexico spectra (1230–1250 LST), and also that had similar synoptic settings which for both cases had light winds and clear skies. Figure 80 below shows the spectral analysis of the CWEX data. This spectrum looks quite different compared to the previous spectrums. The power spectral density is much higher throughout the spectra compared to the buoy power spectral densities. This could be due to the higher surface roughness, since it is during the summer and corn growing season. A higher surface roughness would create more turbulence. Compared to the previous plots over the sea where the buoy was placed, there would be low surface roughness and low turbulence.
Even though the CWEX spectra and buoy spectra show different shapes, by using the CWEX data we can hope to better understand the buoy data. The CWEX spectra shows quite a bit of fluctuation in the flow field which is shown by its erratic shape compared to the buoy spectra. The peaks in the FFT can help show us which frequencies are contributing to the turbulence near the rough (corn field) surface. The higher frequencies found in this spectra seen around a frequency of $10^{-2}$ correspond to small scale turbulence, and the lower frequencies seen near a frequency of $10^{-1}$ result in large scale turbulence.

Looking at the buoy spectra we can see that there are peaks of higher frequencies which can be seen around a frequency of 1 and 3, with module F66E8C having higher peak intensities as it is further away from the surface. These peaks which are less in intensity when compared to the CWEX spectra are a result of small and large scale turbulences. With the surface being smooth as it is over water, we see less turbulence as the amplitudes of the peak frequencies are lower when compared to the CWEX spectra. The peaks in the FFT can help show us which frequencies are contributing to the turbulence generated similarly found in the CWEX spectra.
7. ANALYSIS AND INTERPRETATION

The goal of this project aimed to demonstrate a system capable of obtaining wind measurements continuously throughout the day and overnight hours, which would replicate the requirements for acquiring wind resource characteristics for siting a wind turbine in the US. While the project did not fully achieve its original goals significant progress was made in getting the system to operate autonomously in the Gulf of Mexico for a brief period of time. In particular, the quality of data was not at the standard of onshore data, and secondly time and funds did not allow exploration of the automated balloon-filling process.

The system as a whole used in this study provides a concept that can be used going forward. However there were numerous troubleshooting once the system deployed into the Gulf that should be examined and looked into for future deployments. Addressing these would ideally make future deployments easier and safer.

Once everything was installed onto the buoy, there was limited space to maneuver. This made it difficult and dangerous when someone had to be on the buoy. The possibility of having a buoy with a larger surface area should be looked at which would allow more space for someone to work while on the buoy deploying the modules for data collection. For the deployment in February 2014, one person had to stand on the battery boxes and maintain balance due to constant wave motion to get the modules attached onto the tether line. With more space to work with would allow for not only safer conditions, but also easier ability to get the system launched successfully.

For the most part the system worked well, aside from the lighting system. The lighting system which is vital to be able to run at night, gave problems on more than one occasion. This
led to some setbacks and the inability to obtain data in long durations particularly in the overnight hours. Looking into a different lighting system would be worth examining in future endeavors.

The winch and tether line installed on the buoy worked very well and never showed much of an issue. There needs to be some thought into how to get the entire system out to the gulf without wear and tear being applied to the tether line. During February 2014 deployment as the system was being prepped to be flown during the day, observations of abrasions on the tether line were noticed. These abrasions were likely a result of towing the system out to the Gulf site.

The solar panels installed on the buoy worked well, initially four solar panels were to be installed onto the buoy. This proved to make it impossible for someone to be able to get on the buoy to attach modules onto the tether line while sending the system up into the atmosphere. The size of the solar panels made it very difficult to maneuver around on the buoy. In the February 2014 deployment, only three solar panels were installed on the buoy instead of the original four. Having fewer solar panels should be examined which would allow more space to work while deploying the system, or taking a look into a different kind of solar panel smaller in size would make it easier to operate on the buoy during deployment. An issue came around during the February 2014 deployment where the solar panels would hit the side of the vessel, because we had to tie up to the buoy for someone to get on and attach modules onto the tether line for data collection.

While the data was limited, most of the case studies analyzed in this study showed that the module wind speeds correlated well with tower or Galion lidar data. The case study done in
Iowa wind speeds match up very well, and aside from the possible human error in the late hours. Several cases done in New Mexico showed similar findings that the wind speeds correlated well.

Both the Iowa and New Mexico field studies allowed for the use of multiple sensors on tower heights which can also be used to examine how the sensors on the towers worked together. For the wind speeds, the heights having multiple sensors were very close in comparison with each other with both the Iowa and New Mexico field studies.

Wind directions were a different story however as there were vast differences between module and tower data. But when examining the differences between the multiple sensors at the same heights, the wind speeds were very close in comparison. The large difference between module and tower wind directions is probably due to the electronics box on the tethersonde rotating due to wind speeds. The addition of an aluminum block to prevent the electronics box from rotating should improve the difference between module and tower.

The cases in Texas showed positive results as well, however with some malfunctions the data is hard to interpret fully. Similar trends are found as well, where the wind speeds between the module and Galion lidar correlate fairly well. Wind directions did not correlate well.

It would have been encouraging as well to see the wind directions correlate as well as the wind speeds did, however with the adjustment of adding an aluminum block to the modules which would disallow the modules from rotating as much while suspended in the air.

When it comes to the data used from the deployment in the Gulf of Mexico in February, 2014. There were time constraints and deployment hazards which did not allow for a full problem diagnosis in real time. With the limited data acquired we made an attempt to gain as
much knowledge as possible about the system problem. So we performed an experiment on the
data that was acquired.
8. CONCLUSION

Overall, the development of a marine-based balloon-borne wind measurement system is an arduous task. While the data obtained was not as long in duration as we would have liked, this project has shown that an offshore wind measurement system can be created.

From the data we were able to obtain, it is encouraging to see that the wind speeds showed high correlation between the buoy system and either tower or Galion lidar data. Wind directions did not perform as well, but with the addition of a small aluminum block to prevent the module electronics compartment from rotating we would expect to see better results.

Should this process be done again or having the chance now to look back on the procedures that were done, there are some areas that would be adjusted. First and foremost with the large size of balloon being used and the amount of work that was done was overwhelming at times, the addition of more people available to help would speed up the process. Also having more people available with the large balloon launches would help ensure the balloon launches were successful and safer. Having more people would also help in overseeing the balloon system is operating as it should, being in such a remote area this can be hard to do. With more people then shifts could be created to monitor the system more efficiently.

As far as the buoy goes, it was a very complex system and little room to operate on the buoy when it was in deployment. Exploring the possibility of having a slightly larger buoy would help make maneuvering around on the buoy easier as there would be more space. Having someone attach modules onto the tether line while in the Gulf with constant wave motion was an arduous task.
The ability to obtain wind measurements offshore for the purpose of determining whether or not a site is suitable for wind farm placements is a very important task going forward. The ability to have the system run on its own for a brief period during the day is an encouraging accomplishment. This project will hopefully be able to help others in their endeavors should they go about a similar process.
9. ACKNOWLEDGEMENTS

Funds supporting this project were provided primarily by the Iowa Alliance for Wind Innovation and Novel Development (IAWIND) from the University of Iowa under a contract from the Iowa Department of Economic Development. Additional support was provided by Baryonyx Corporation under a contract from the Department of Energy; Anemometry Specialists, Inc.; and the National Science Foundation under the State of Iowa EPSCoR Grant 1101284.
10. REFERENCES


## 11. TABLES

Table 1: Specifications for each instrument used on the tethersonde module.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Method</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Range</th>
</tr>
</thead>
</table>
| GPS        | 22 channel tracking receiver| speed 0.05 ms\(^{-1}\)  
headling 0.1\(^{\circ}\)  
lst/ion 0.0001 min  
altitude 0.1 m | 10 Hz timing |             |
| Pressure   | MEMS                        | 0.1 mb            | 0.5 mb   | 0 – 1100 mb |
| Relative Humidity | Capacitive              | 0.10%            | 3%       | 0 – 100%   |
| Temperature| Semiconductor               | 0.125°C          | 0.5°C    | -55 to +125°C |
| Wind Speed | NRG #40C anemometer         | 0.1 ms\(^{-1}\)  
(whichever is greater) | 1 ms\(^{-1}\) or 5% | 0 – 59 ms\(^{-1}\) |
| Wind Direction | 2-axis magnetometer      | 1\(^{\circ}\)    | 2\(^{\circ}\) | 0 - 359\(^{\circ}\) |

Table 2: Time period of data collection from the Holstine tower in Iowa.

<table>
<thead>
<tr>
<th>Holstine, IA</th>
<th>Month</th>
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<td>November</td>
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<td></td>
<td>December</td>
<td>12/1/2012 1200 LST</td>
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<tr>
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<td>1/31/2013 2350 LST</td>
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<td>February</td>
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<td>2/28/2013 2350 LST</td>
</tr>
<tr>
<td></td>
<td>March</td>
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<td>3/20/2013 0650 LST</td>
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Table 3: Time period of data collection from the Hill tower in Iowa.

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<td>11/30/2012 2350 LST</td>
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<td>December</td>
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<td>February</td>
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**Table 4:** Provides anemometer specifications used on the Holstine meteorological tower in Iowa.

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**Table 5:** Provides wind vane, temperature, and pressure specifications used on the Holstine meteorological tower in Iowa.

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Table 6: Provides anemometer specifications used on the Hill meteorological tower in Iowa.

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Table 7: Provides wind vane, temperature, and pressure specifications used on the Hill meteorological tower in Iowa.

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Table 8: Time period of data collection from the Sandia Park tower in New Mexico.

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<td></td>
<td>December</td>
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Table 9: Provides anemometer specifications used on the Sandia Hills meteorological tower.

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<td>0.18</td>
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Table 10: Provides wind vane and temperature specifications used on the Sandia Hills meteorological tower.

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Table 11: Module data time periods near the Holstine tower in Iowa.

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<th>Iowa Data</th>
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</tr>
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Table 12: Module data time periods near the Sandia tower in New Mexico.

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<thead>
<tr>
<th>New Mexico Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
</tr>
<tr>
<td>December</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Table 13: Module data time period near South Padre Island, Texas.

<table>
<thead>
<tr>
<th>Month</th>
<th>Module ID</th>
<th>Location</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>F666B1/F713B5/F7127D</td>
<td>South Padre Site</td>
<td>10/31/2013</td>
<td>10/31/2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1940 LST</td>
<td>2050 LST</td>
</tr>
<tr>
<td>November</td>
<td>F666B1/F7127D</td>
<td>South Padre Site</td>
<td>11/15/2013</td>
<td>11/16/2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1350 LST</td>
<td>0250 LST</td>
</tr>
<tr>
<td>February</td>
<td>F7127D/F66E8C/F68EED/F666B1</td>
<td>Marina (Port Isabel)</td>
<td>2/9/2014</td>
<td>2/9/2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0600 LST</td>
<td>0920 LST</td>
</tr>
<tr>
<td></td>
<td>F7127D/F66E8C/F68EED/F666B1</td>
<td>Gulf</td>
<td>2/10/2014</td>
<td>2/10/2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1110 LST</td>
<td>1440 LST</td>
</tr>
</tbody>
</table>

Table 14: Galion Lidar data time periods obtained.

<table>
<thead>
<tr>
<th>Month</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>8/7/2013</td>
<td>8/31/2013</td>
</tr>
<tr>
<td></td>
<td>0520 LST</td>
<td>1700 LST</td>
</tr>
<tr>
<td>September</td>
<td>9/1/2013</td>
<td>9/30/2013</td>
</tr>
<tr>
<td></td>
<td>0000 LST</td>
<td>2350 LST</td>
</tr>
<tr>
<td>October</td>
<td>10/1/2013</td>
<td>10/30/2013</td>
</tr>
<tr>
<td></td>
<td>0000 LST</td>
<td>2350 LST</td>
</tr>
<tr>
<td>November</td>
<td>11/1/2013</td>
<td>11/30/2013</td>
</tr>
<tr>
<td></td>
<td>0840 LST</td>
<td>1520 LST</td>
</tr>
<tr>
<td>December</td>
<td>12/1/2013</td>
<td>12/31/2013</td>
</tr>
<tr>
<td></td>
<td>0740 LST</td>
<td>2350 LST</td>
</tr>
<tr>
<td>January</td>
<td>1/1/2014</td>
<td>1/31/2014</td>
</tr>
<tr>
<td></td>
<td>0000 LST</td>
<td>2350 LST</td>
</tr>
<tr>
<td>February</td>
<td>2/1/2014</td>
<td>2/8/2014</td>
</tr>
<tr>
<td></td>
<td>0000 LST</td>
<td>2350 LST</td>
</tr>
</tbody>
</table>

Table 15: Wind Speed and Wind Direction correlation coefficients between module and tower data for the Iowa field study in March 2013.

<table>
<thead>
<tr>
<th>Date</th>
<th>WSpd</th>
<th>WDir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 19/20</td>
<td>0.9146</td>
<td>0.9081</td>
</tr>
<tr>
<td></td>
<td>-0.52058</td>
<td></td>
</tr>
</tbody>
</table>

Table 16: Wind Speed and Wind Direction correlation coefficients between module and Galion lidar data for a field test on South Padre Island, TX in September 2013.

<table>
<thead>
<tr>
<th>Date</th>
<th>Module Height</th>
<th>WSpd</th>
<th>WDir</th>
<th>WDir</th>
<th>WDir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 8</td>
<td>50 m</td>
<td>0.8406</td>
<td>0.6130</td>
<td>-0.0346</td>
<td>-0.1515</td>
</tr>
<tr>
<td></td>
<td>70 m</td>
<td>0.6881</td>
<td>0.4580</td>
<td>0.0833</td>
<td>0.5630</td>
</tr>
<tr>
<td></td>
<td>90 m</td>
<td>0.6328</td>
<td>0.5080</td>
<td>0.2260</td>
<td>0.3906</td>
</tr>
</tbody>
</table>
Table 17: Wind Speed and Wind Direction correlation coefficients between module and Galion lidar data for a field test on South Padre Island, TX in November 2013.

<table>
<thead>
<tr>
<th>Date</th>
<th>Module Height</th>
<th>WSpd</th>
<th>WDir</th>
<th>WDir</th>
<th>WDir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 15-16</td>
<td>60 m</td>
<td>-0.0958</td>
<td>-0.5093</td>
<td>-0.4356</td>
<td>-0.2168</td>
</tr>
<tr>
<td></td>
<td>100 m</td>
<td>0.2230</td>
<td>0.4764</td>
<td>0.5404</td>
<td>0.7277</td>
</tr>
</tbody>
</table>

Table 18: Wind Speed and Wind Direction correlation coefficients between Module data and various tower heights for the New Mexico field studies in December 2013.

<table>
<thead>
<tr>
<th>Date</th>
<th>WSpd</th>
<th>WDir</th>
<th>WDir</th>
<th>WDir</th>
<th>WDir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 3</td>
<td>0.0639</td>
<td>0.0812</td>
<td>0.0797</td>
<td>0.1159</td>
<td>0.0331</td>
</tr>
<tr>
<td>Dec 10</td>
<td>0.8986</td>
<td>0.9017</td>
<td>0.8275</td>
<td>0.9254</td>
<td>-0.6882</td>
</tr>
<tr>
<td>Dec 11</td>
<td>0.8655</td>
<td>0.8407</td>
<td>0.8761</td>
<td>0.8492</td>
<td>-0.5873</td>
</tr>
<tr>
<td>Dec 12</td>
<td>0.667</td>
<td>0.6491</td>
<td>0.6532</td>
<td>0.6407</td>
<td>-0.211</td>
</tr>
<tr>
<td>Dec 18</td>
<td>0.7856</td>
<td>0.7705</td>
<td>0.8458</td>
<td>0.8177</td>
<td>-0.1616</td>
</tr>
<tr>
<td>Dec 19</td>
<td>0.8182</td>
<td>0.8158</td>
<td>0.8089</td>
<td>0.813</td>
<td>-0.304</td>
</tr>
</tbody>
</table>
12. FIGURES

Figure 1: Sketch of entire system and its components.

Figure 2: Image showing sea anchor (upper left) and anchor chain (right) aboard the vessel before deployment to gulf site on February 9th, 2014 (Photo by G. Matson).
Figure 3: Image showing the buoy fully assembled with a) solar panel, b) battery box, c) marine-grade RF data antenna, d) buoy navigation lights, and e) satellite alarm monitoring box (Photo by G. Matson).

Figure 4: Image showing the winch in the back of a pickup truck during field testing near Sandia Park, New Mexico in December 2013 (Photo by G. Matson).
Figure 5: Image showing tether (left) and power cable (right) lines (Photo by G. Matson).

Figure 6: Aluminum pivot block which is used to attach tethersonde modules onto the tether line (Photo by G. Matson).
Figure 7: A junction box used to supply power to tethersonde modules (Photo by G. Matson).

Figure 8: Image showing a circular ring with three lights, part of the lighting system (Photo by G. Matson).
Figure 9: Display of a fully assembled tethersonde flight module including several components: a) 3-cup anemometer, b) boom, c) battery box, d) line attachment, e) electronics box, and f) aerodynamic fins (Photo by G. Matson).

Figure 10: Aerostat balloon ready for field testing, taken at the marina in Port Isabel, TX (Photo by G. Matson).
Figure 11: Image of the Emergency Deflation Device (EDD), which is attached onto the balloon (Photo by G. Matson).

Figure 12: Photo of one of the two battery boxes which powers the entire system (Photo by G. Matson).
Figure 13: Photo of the inside of the electronics box containing power cabling and wires for the entire system (Photo by G. Matson).

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Figure 15: Map displaying location of meteorological tower located in New Mexico.

Figure 16: Map displaying location of module launch sites located in Texas.
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Figure 18: March 19-20, 2013 line of best fit using least squares between module data (x-axis) and tower data (y-axis).
Figure 19: March 19-20, 2013 tower and module average wind direction (top), differences (middle), and percent errors (bottom).

Figure 20: December 3, 2013 tower 48 m and 40 m wind speeds compared to module wind speed (top), and their differences (bottom).
Figure 21: December 3, 2013 percent errors for each tower 48 m (top) and 40 m (bottom) wind speed compared to module wind speed.

Figure 22: December 3, 2013 line of best fit using least squares between module data (x-axis) and tower data (y-axis). Top two plots use 48 m tower data and bottom two plots use 40 m tower data.
Figure 23: December 3, 2013 tower 48 m and 34 m wind directions compared to module wind direction (top), differences (middle), and percent errors (bottom).

Figure 24: December 10, 2013 tower 48 m and 40 m wind speeds compared to module wind speed (top), and (bottom) their differences.
Figure 25: December 10, 2013 percent errors for each tower 48 m (top) and 40 m (bottom) wind speed compared to module wind speed.

Figure 26: December 10, 2013 line of best fit using least squares between module data (x-axis) and tower data (y-axis). Top two plots use 48 m tower data and bottom two plots use 40 m tower data.
Figure 27: December 10, 2013 tower 48 m and 34 m wind directions compared to module wind direction (top), differences (middle), and percent errors (bottom).

Figure 28: December 11, 2013 tower 48 m and 40 m wind speeds compared to module wind speed (top), and their differences (bottom).
Figure 29: December 11, 2013 percent errors for each tower 48 m (top) and 40 m (bottom) wind speed compared to module wind speed.

Figure 30: December 11, 2013 line of best fit using least squares between module data (x-axis) and tower data (y-axis). Top two plots use 48 m tower data and bottom two plots use 40 m tower data.
Figure 31: December 11, 2013 tower 48 m and 34 m wind directions compared to module wind direction (top), differences (middle), and percent errors (bottom).

Figure 32: December 12, 2013 tower 48 m and 40 m wind speeds compared to module wind speed (top), and their differences (bottom).
Figure 33: December 12, 2013 percent errors for each tower 48 m (top) and 40 m (bottom) wind speed compared to module wind speed.

Figure 34: December 12, 2013 line of best fit using least squares between module data (x-axis) and tower data (y-axis). Top two plots use 48 m tower data and bottom two plots use 40 m tower data.
Figure 35: December 12, 2013 tower 48 m and 34 m wind directions compared to module wind direction (top), differences (middle), and percent errors (bottom).

Figure 36: December 18, 2013 tower 48 m and 40 m wind speeds compared to module wind speed (top), and their differences (bottom).
Figure 37: December 18, 2013 percent errors for each tower 48 m (top) and 40 m (bottom) wind speed compared to module wind speed.

Figure 38: December 18, 2013, line of best fit using least squares between module data (x-axis) and tower data (y-axis). Top two plots use 48 m tower data and bottom two plots use 40 m tower data.
Figure 39: December 18, 2013 (top) tower 48 m and 34 m wind directions compared to module wind direction (top), and their differences (bottom).

Figure 40: December 19, 2013 (top) tower 48 m and 40 m wind speeds compared to module wind speed, and (bottom) their differences.
Figure 41: December 19, 2013 percent errors for each tower 48 m (top) and 40 m (bottom) wind speed compared to module wind speed.

Figure 42: December 19, 2013 line of best fit using least squares between module data (x-axis) and tower data (y-axis). Top two plots use 48 m tower data and bottom two plots use 40 m tower data.
Figure 43: December 19, 2013 (top) tower 48 m and 34 m wind directions compared to module wind direction, differences (middle), and percent errors (bottom).

Figure 44: September 8, 2013 each of the three modules and Galion lidar RG4 average wind speed and their differences.
Figure 45: September 8, 2013 each of the three modules and Galion lidar RG9 average wind speed and their differences.

Figure 46: September 8, 2013 each of the three modules and Galion lidar RG16 average wind speed and their differences.
Figure 47: September 8, 2013 wind speed percent errors for each module and Galion lidar range gate.

Figure 48: September 8, line of best fit using least squares between 50 m module data (x-axis) and Galion lidar data (y-axis). Top left shows RG4, top right shows RG9, and bottom left shows RG16.
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Figure 50: September 8, line of best fit using least squares between 90 m module data (x-axis) and Galion lidar data (y-axis). Top left shows RG4, top right shows RG9, and bottom left shows RG16.
Figure 51: September 8, 2013 each of the three modules and Galion lidar RG4 average wind direction and their differences.

Figure 52: September 8, 2013 each of the three modules and Galion lidar RG9 average wind direction and their differences.
Figure 53: September 8, 2013 each of the three modules and Galion lidar RG16 average wind direction and their differences.

Figure 54: September 8, 2013 wind direction percent errors for each module and Galion lidar range gate.
**Figure 55:** September 8, 2013 Power law alpha values.

**Figure 56:** September 8, 2013 Richardson numbers.
Figure 57: November 15-16, 2013 each of the three modules and Galion lidar RG4 average wind speed and their differences.

Figure 58: November 15-16, 2013 each of the three modules and Galion lidar RG9 average wind speed and their differences.
Figure 59: November 15-16, 2013 each of the three modules and Galion lidar RG16 average wind speed and their differences.

Figure 60: November 15-16, 2013 wind speed percent errors for each module and Galion lidar range gate.
Figure 61: November 15-16, 2013 line of best fit using least squares between 60 m module data (x-axis) and Galion lidar data (y-axis). Top left shows RG4, top right shows RG9, and bottom left shows RG16.

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**Figure 63:** November 15-16, 2013 each of the two modules and Galion lidar RG4 average wind direction and their differences.

**Figure 64:** November 15-16, 2013 each of the two modules and Galion lidar RG9 average wind direction and their differences.
Figure 65: November 15-16, 2013 each of the two modules and Galion lidar RG16 average wind direction and their differences.

Figure 66: November 15-16, 2013 wind direction percent errors for each module and Galion lidar range gate.
**Figure 67:** November 15-16, 2013 Power law alpha values.

**Figure 68:** November 15-16, 2013 Richardson numbers.
Figure 69: Image of the boat used to tow the buoy-based system to the offshore site in the Gulf of Mexico (Photo by G. Matson).

Figure 70: Image showing the buoy being towed out to the offshore site (Photo by G. Matson).
Figure 71: Image showing the anchor deployment Setup (Photo by G. Matson).

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Figure 76: Module F66E8C spectral analysis from the February 10th, 2014. a) 20 minute data, b) 10 minute data, and c) 7 minute data.
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Figure 79: Module F7127D spectral analysis from December 10\textsuperscript{th}, 2013.

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