HURRICANE DATA COLLECTION HARDWARE AND SOFTWARE: IMPROVEMENTS, MAINTENANCE AND DEVELOPMENT

By

ROBIN N. WEAVER

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
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This document is dedicated to those who have lost property to windstorms.

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I thank my fiancé, Wade Stephan, for all of his support and patience as I completed my Master of Engineering degree. I thank my parents for their emotional and financial support, without which I never would have made it this far. I thank my sister, Christiana, and the Stephan family, Bruce, Victoria, Bradley, and Laura Burgess, for their emotional support and encouragement as I accomplished my coursework, research and thesis. I also thank my committee for assisting me in completing my thesis, research and degree. Above all, I thank my heavenly father for the strength he has provided me.

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Robin N. Weaver

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Chair: Kurtis R. Gurley
Cochair: Gary R. Consolazio
Major Department: Civil and Coastal Engineering

Every year, billions of dollars are lost in property and economic disruptions due to windstorms. Improved methods to safeguard life and property against these storms can be developed through a realistic assessment of extreme wind behavior, structural response to these winds, and practical solutions to reducing wind damage. Several universities and organizations have started taking field measurements of wind velocity within the ten-meter envelope that most structures reside, and the resulting wind pressure on full-scale residential structures.

The University of Florida, Clemson University, and Florida Institute of Technology comprise the Florida Coastal Monitoring Program (FCMP). The program is sponsored by the Florida Department of Community Affairs and was initiated in 1998. The FCMP goal is to characterize wind-structure interaction in extreme wind conditions through full-scale data collection. Phase one of the project includes the development of portable

towers to collect wind velocity data. Phase two includes measuring wind pressures on the exterior and interior of low-rise homes.

This thesis presents several contributions to improving, maintaining, and developing the FCMP: 1) The maintenance of the portable towers to ensure they are ready for each hurricane season, the design of base plate stabilizers to steady the five-meter aluminum towers during deployment, and the wiring of fifteen coastal homes. 2) The organization and processing of the collected data for all storms from 1999 to 2002. 3) Improving a software program, written at the University of Florida, to view and analyze wind velocity data collected during hurricane landfall. 4) The development of a software program to view and analyze the pressure data collected from instrumented homes. These contributions will help further ongoing efforts to provide the baseline wind behavior information needed to develop cost-effective wind damage mitigation strategies.

CHAPTER 1
INTRODUCTION

Hurricane Devastation

Top hurricane experts from the National Oceanographic and Atmospheric Association (NOAA) predict up to fifteen storms will develop in the Atlantic Ocean during the 2003 hurricane season. On average, the Atlantic hurricane season produces ten tropical storms; however, above-normal activity has been observed during six of the last eight Atlantic hurricane seasons. The prediction calls for eleven to fifteen named storms, with six to nine becoming hurricanes in 2003. In 2002, there were twelve named storms of which four became hurricanes (National Oceanographic and Atmospheric Association [NOAA] 2003a). The rapidly increasing population in coastal areas of the southeastern United States requires improved methods to safeguard life and property against these storms. These methods can be developed through a realistic assessment of structural vulnerability and practical solutions to reducing wind damage. The work in this thesis focuses on the development of software and hardware tools designed to assist in the characterization of extreme wind behavior through the collection and analysis of full-scale wind and pressure data.

Hurricane Development

Hurricanes are formed from a complex of thunderstorms. For thunderstorms to develop into hurricane strength, the ocean and atmospheric conditions must be favorable. The water temperature must be warmer than 26.5 degrees Celsius (81 degrees Fahrenheit). A sea surface map showing water temperatures during a northern hemisphere summer is presented in Figure 1-1. The yellow, orange, and red colors show the location of water temperature warm enough to support hurricane development. Areas in the Gulf of Mexico, Caribbean, and Atlantic Ocean support water temperatures well above the 26 degrees required for hurricanes to develop.

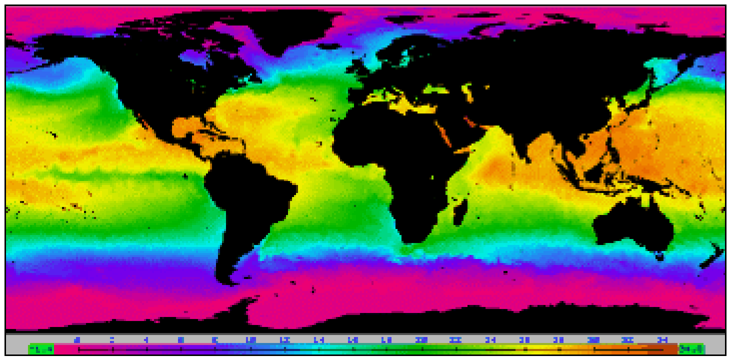


Figure 1-1: Sea Surface Map of Water Temperatures (Office of Satellite Data Processing and Distribution [OSDPD] 2003)

Upper atmospheric winds must be light for a hurricane to develop. The strength of these winds is usually dependant on the amount of wind shear, which is the change in wind speed with elevation. Hurricanes continually gain energy from the release of latent heat as water vapor condenses. The water vapor is a result of heat and moisture rising from the warm ocean water. If the wind shear is too high, the warm air and water vapor surrounding the center of the storm will be displaced. A trough of westerly winds sometimes intrudes into the tropics from middle latitudes, or a ripple in the easterly trade winds, called a tropical wave, moves into the Atlantic Ocean off the coast of Africa. These disturbances, coupled with the Corioles force generated from the spin of the earth, induce a circular inward movement of air within the thunderstorms. This inward movement results in a convergence of air, a drop in pressure, and an increase in the wind speed surrounding the center of convergence. When these winds become strong enough, a tropical depression will develop (Haby 2003). Figure 1-2 shows a group of thunderstorms located in conditions favorable for hurricane development.

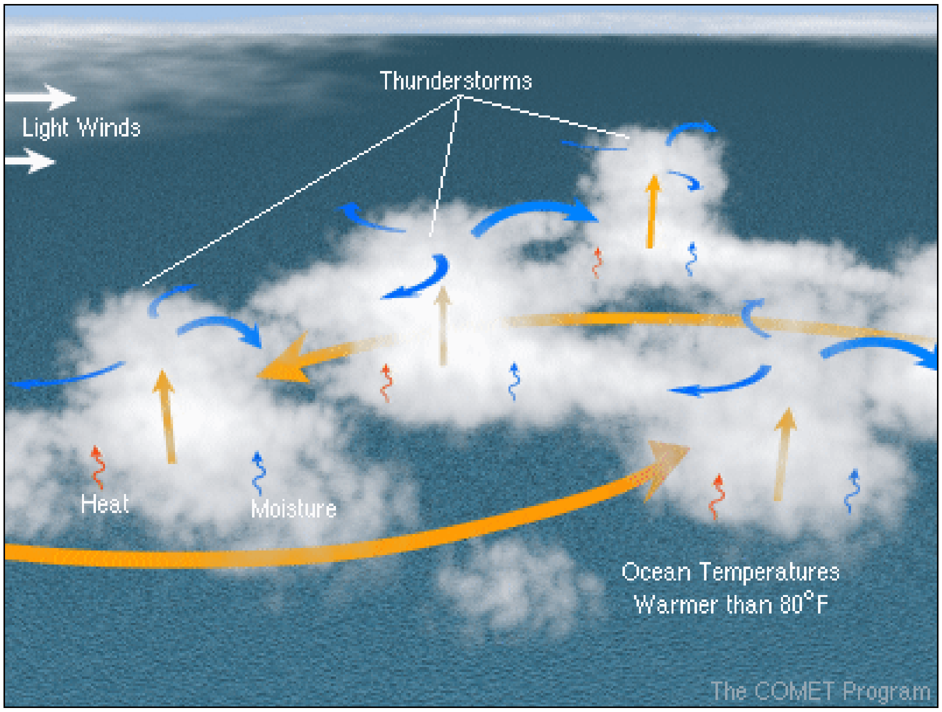


Figure 1-2: Development of a Tropical Storm from Thunderstorms (NOAA 2003b)

Development Stages

The first developmental stage of a hurricane is the tropical depression. This is defined as a collection of thunderstorms with a wind speed greater than 35 mph. The next stage, the tropical storm, has sustained winds of 39-73 mph with pressure greater than 28.94 mmHg. Once the storm attains winds greater than 74 mph and has a pressure less than 28.91 mmHg, it is considered a hurricane. In the 1970s, Herbert Saffir developed a scale to categorize hurricanes by relating the wind speeds to damage inflicted upon structures and vegetation. Robert Simpson then added the expected storm surge due to the hurricane onto Saffir's scale. The Tropical Prediction Center, formerly the National Hurricane Center (NHC), adopted the Saffir-Simpson Scale to relate hurricane intensity and damage potential. The Saffir-Simpson Scale (shown in Appendix

A) indicates probable property damage and evacuation recommendations as well as the maximum sustained winds, minimum pressures, and expected storm surges that are used to delineate each of the five hurricane categories (Simiu and Scanlan 1996).

In the northern hemisphere, hurricanes rotate counterclockwise producing maximum effects in the northeast quadrant of the storm. In this location, wind velocity and storm surge are the largest, and the possibility of tornado formation is the greatest. Storm researchers are most interested in collecting data in this quadrant surrounding the storm and around the eye wall of the storm. As shown in Figure 1-3, the maximum wind speeds are located in the eye wall while the calmest winds are found inside the eye (University of Illinois at Urbana-Champaign [UIUC] 2003). When hurricanes make landfall, they loose their warm water energy source and weaken rapidly. Friction due to the land topography also cause hurricane winds to weaken.

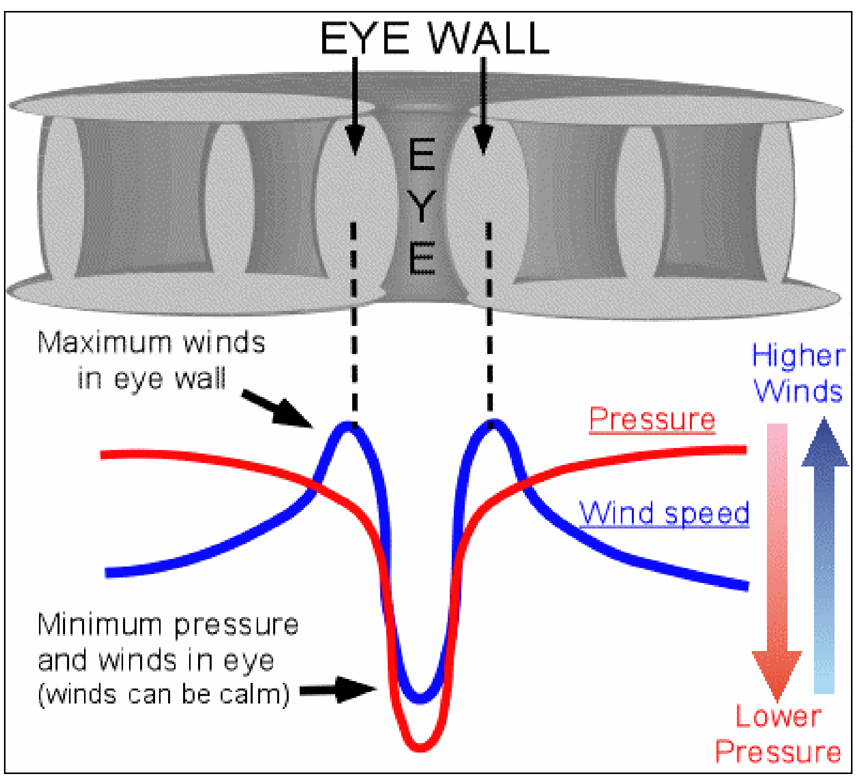


Figure 1-3: Wind and Pressure in Eye Wall (UIUC 2003)

Hurricane Threats

There are many threats associated with a hurricane. Most familiar are the high winds; however, the leading cause of loss of life is actually due to water. Over six thousand people were killed in the Galveston Hurricane of 1900, mainly as a result of the storm surge (The Canadian Hurricane Centre [CHC] 2003). Storm surge is the rapid rise in water level that occurs as a hurricane approaches landfall. This results in destructive inland flooding. Storm surge is due to high onshore winds that push a front of ocean water over land, and also to water that is pulled upward due to the extremely low pressure found near the eye of the storm. The majority of storm surge is usually related to the onshore winds.

Ten to fifteen inches of rain is common although more should be expected if the storm is moving slowly. Tropical Cyclone Denise produced 71.9 inches of rain over a twenty-four hour period in 1996 (CHC 2003). Most coastal regions cannot handle the heavy rains associated with a storm due to slow sloping topography and low elevations. The combination of heavy rains and large storm surges can result in severe flooding of these hurricane prone areas.

Hurricanes are known to produce small tornadoes, which add to the destruction of the already powerful hurricane. As hurricanes make landfall, winds and overall strength dissipate creating a strong vertical shear that allows for the development of tornadoes. Ten percent of deaths associated with hurricanes are due to tornadoes spawned from the storm. Tornadoes, like the hurricane itself, need a heat source. Therefore, more tornadoes spawn from hurricanes in the Gulf of Mexico than the Atlantic Ocean and most occur during the day, near the coast (National Hurricane Center [NHC] 2003).

Hurricane winds cause massive destruction due to the large forces they impart to structures as well as the wind-borne debris. High winds can impose both positive and suction pressure on various portions of a building. These pressures typically increase non-linearly with an increase in wind speed. For positive pressure resulting from head-on winds, the rate of the pressure increase is proportional to the square of the rate of wind speed increase (NHC 2003). Suction pressures due to wind occur on roofs, and side and leeward walls. These pressures are more complicated than a simple square proportion, but also tend to increase in a nonlinear fashion with wind speed. Wind loads used by structural engineers are presented in provisions such as ASCE7. Building dimensions and surrounding topography are used to determine the design pressures due to the maximum wind speed for the geographical location.

The continued development and improvement of accurate models of wind pressure over various building types has been the subject of much research. More recently, full-scale efforts have been initiated to help validate and advance decades of wind tunnel research. The collection, analysis, and dissemination of such full-scale data is the subject of the research presented in this thesis.

Turbulent Wind and Wind Load Characterization

Not long ago, wind load provisions found in building codes were only three or four pages long. Today, the wind load provisions of ASCE7 consist of over fifty pages, reflecting an increased recognition of the complexity of this load type. Current wind load design procedures given in ASCE7 are based on wind tunnels tests performed in the 1970s at the University of Western Ontario. The tests were performed on rectangular structures and the wind behavior was assumed to be stationary and to produce Gaussian wind loads. Stationary behavior requires that the statistics associated with the fluctuating wind characteristics be invariant over time. Gaussian distribution is equivalent to normal distribution where the function defining the process is symmetric about the mean. Records of full-scale wind pressure data often exhibit non-Gaussian behavior and wind speeds are often highly non-stationary in hurricanes and other wind events (Simiu and Scanlan 1996). Small changes in wind direction have also resulted in large changes in pressures in previous full-scale tests (Porterfield and Jones 2003). Given the tremendous damage potential of high winds, improved models of extreme wind behavior are being sought.

Currently, most wind data is based on time averaged wind speeds collected at airport weather stations, or on upper atmospheric measurements. However, the terrain that surrounds a structure has a strong influence on the wind-structure interaction, and most low-rise structures are not located in the open exposure-type terrain characteristic of an airport. This poses a difficulty when extrapolating observed wind phenomena from airports to built up areas where most residential structures are found.

The lower region of the atmospheric layer, where low-rise structures reside, is complicated and advanced models for its behavior do not currently exist (Uematsu and Isyumov 1999). Records of full-scale high wind velocity data exhibit non-stationary behavior that also differs from upper atmospheric conditions (Gurley and Kareem 1997). In order to improve wind models used in wind tunnels and code provisions, and to better understand how wind behaves in the lower boundary layer as it interacts with structures, more in-situ, full-scale testing of structures in high wind conditions is needed. A combination of wind velocity data and the resulting pressures on structures collected at full-scale will be used to improve the characterization of wind behavior.

Several organizations have identified the need for, and initiated, full-scale testing in natural high wind environments. University research teams from Louisiana State University, Florida State University, Texas Tech University (TTU), and Oklahoma University have developed mobile Doppler radar systems to characterize the lower-level atmospheric wind behavior during hurricanes. TTU is also continuing a program to collect wind data during hurricane events using portable towers instrumented with anemometers. TTU towers will provide data within the ten-meter elevation envelope that most structures lie in, but which the Doppler radar cannot reach. Such efforts will help determine the characteristics of turbulent winds as they approach vulnerable structures.

The resultant wind loads on structures are also the subjects of several ongoing studies. John Hopkins University and the University of Illinois have partnered to create the Blue Sky project, discussed later, which collects pressure and wind speed data year-round on a single low-rise coastal structure in Southern Shores, North Carolina. However, a greater variety of more common shapes of houses tested at full-scale is needed in order to better calibrate ongoing wind tunnel studies being performed on a variety of shapes.

TTU is assisting National Institute of Standards and Technology (NIST) with a new initiative to examine wind induced loads on a variety of structures. Wind Engineers at TTU are collecting meteorological and pressure data for a rectangular building located on the TTU campus. Details of the building and tests being performed are discussed in Chapter 2. The building is also being modeled in various wind tunnels to verify wind models and code predictions. However, this structure will never witness a hurricane event. A larger variety of structures need to be examined in natural high wind environments.

The University of Florida, Florida Institute of Technology, and Clemson University have also created a team to study hurricane winds and their effects in structures. This project is titled the Florida Coastal Monitoring Program (FCMP) and was established in 1997 with funding from the Florida Department of Community Affairs and Federal Emergency Management Agency (FEMA). The goal is to collect both hurricane approach wind velocity data and the resultant pressure on structures using portable wind towers and instrumented coastal homes. The results from FCMP full-scale testing will be used to improve wind tunnel testing procedures and to improve code wind load provisions. The FCMP data collection hardware includes four ten-meter towers, sixteen five-meter towers, and twenty-five coastal homes.

The ten-meter towers collect wind speed and direction at five and ten meters as well as ambient pressure, relative humidity, temperature, and rainfall quantities as the storms pass. The five-meter towers were recently added to the program to provide horizontal spatial separation in wind velocity measurements. Up to four five-meter towers may be transported on each ten-meter tower and set up in a radius up to 200 feet from each of the main ten-meter towers during storm landfall. The mobility of the towers makes it possible to collect data in many different locations.

Pressure data is collected on individual homes using up to twenty-eight strategically located pressure sensors on the roof as well as instruments to measure the wind speed, direction, and ambient atmospheric pressure. The twenty-five houses currently under contract with the FCMP represent a wide variety of structural shapes.

Pressure data collected from the homes will be compared to code values to determine if the code values accurately predict wind pressures during extreme wind events. Clemson University is currently building scale models of these homes to test in their wind tunnel. Pressures determined in the wind tunnel will be compared to those resulting from full-scale hurricane tests to improve the methods of testing low-rise structures in the wind tunnels, and to develop more complex wind models to be used in wind tunnel tests.

Thesis Focus

This thesis presents efforts to further develop the FCMP. Contributions include new hardware and software development, database organization and management, and improvements and maintenance of existing project infrastructure.

Goal #1

In the event that an Atlantic or Gulf storm turns to the coast of southeastern United States, the FCMP must be ready to deploy within a day's notice. Team members must be trained and the equipment ready. The towers, data collection instruments, trailers, and vehicles stored at the University of Florida require annual maintenance and preparation for each hurricane season. The tasks in this phase of the thesis include assembly of new equipment, maintenance of existing anemometers, and the installation of instrumentation packages on fifteen homes added to the FCMP across Florida. Details are provided in Chapter 3.

During summer 2002, base plate stabilizers were designed to improve the stability of the new aluminum five-meter towers during erection and deployment off-pavement. Assembly of four towers will be completed summer 2003. Each five- and ten-meter tower has sets of three fixed axis anemometers that collect wind speed and direction data.

These anemometers were serviced in summer 2002, and many of the bearings were replaced.

FCMP is expanding the number of homes available to collect pressure data in the event of a storm. Ten homes in the panhandle of Florida were added to the FCMP as a contribution of this thesis in summer 2001. In summer 2002, an additional five homes along the east coast of Florida were wired in contribution. This brings the total to twenty-five homes ready to collect data for the FCMP in the state of Florida.

Goal #2

FCMP began collecting hurricane data in 1998. Since then, data has been collected for nine storms. For each storm, up to four towers and three homes have been used. When each hurricane season ends, there is still much work to be done.

The tremendous amount of data collected during the storms must be exported from the collection program, organized and labeled for each tower, house and storm, and then processed into a format that may be used by FCMP's software: Wind Data Laboratory (WinDLab). A considerable portion of the thesis work was the re-formatting and organization of all data sets collected since 1999. This includes formatting and organizing data for storms from 1999 through 2002, cataloging tower locations and deployment information, and down-sampling the processed data to a size that may be downloaded from a website by researchers. In formatting the data to be used in WinDLab, bugs were discovered in the program. These errors were corrected and the algorithm was rewritten to drastically reduce the time required to process the data.

Goal #3

A prototype version of WinDLab was developed by former FCMP team member Desiree Cuenca to view and analyze wind velocity data collected by the FCMP (Cuenca

2002). WinDLab provides graphical user interfaces (GUIs) for researchers to examine and analyze wind data records. A major contribution of this thesis to the FCMP is the further development of WinDLab, including making necessary changes to produce a compiled version the software, improving the analysis tools with new algorithms, and making the software faster and easier to use. Many changes had to be made in WinDLab to make it compatible with the down-sampled data as well. Improvements and changes to WinDLab are discussed in detail in Chapter 5.

Goal #4

The final contribution includes the development of new software to analyze data taken with the instrumented houses. This new software will allow users to view and analyze the pressure and meteorological data collected by instrumented homes during hurricane landfall.

WinDLab was created for the analysis of ten-meter portable tower data; it does not allow researchers to analyze data collected from the homes. New software, Wind and House Data Laboratory (WinDLab_H) allows users to examine pressures on the homes in relation to the wind speeds and direction. The software consists of a series of GUIs that allow the user to view time histories of the pressures at various sensor locations on the instrumented homes. A map of the homes, tower, and storm path is provided. In addition, the roof footprint, with the layout of the pressure sensors (taps), is displayed. The correlation between two pressure taps can be calculated as well as the length scales and gust factors of turbulent eddies as they cross over the homes. Such a tool will be useful as we begin to build a database of pressure over different homes from several storms. A detailed description of the analysis tools is provided in Chapter 6.

CHAPTER 2
FULL-SCALE EXTREME WIND DATA COLLECTION

Need for Full-Scale Data

Every year, billions of dollars are lost in property and economic disruptions due to windstorms. In the past two years alone, nine tropical storms and one hurricane made landfall in the United States resulting in fifty-four deaths and over six billion dollars in direct economic damage (NOAA 2003a). Better understanding of wind behavior in windstorms and structural response to these conditions is required to reduce property destruction. In an effort to predict and prevent damage from future storms, researchers are seeking to improve understanding of hurricane wind behavior, and its relation to loads on structures.

Most civil engineering-oriented wind pressure data that exists today was gathered from wind tunnel studies. Proper modeling of the complex turbulent behavior of natural wind in wind tunnels is difficult. Because of this, the wind flow and behavior is commonly assumed to be stationary in the wind tunnel. For wind behavior to be considered stationary, statistical properties, including the mean, standard deviation, and all other higher moments, of the measured wind flow must be invariant with respect to translations in time (Bendat and Piersol 2000). In reality, the behavior of severe winds tends to be non-stationary and turbulent, resulting in rapidly changing pressure structures that are difficult to characterize (Porterfield and Jones 2003). Pressure coefficients given in building codes such as ASCE7 are based on wind tunnel studies that do not explicitly account for the effects of turbulent wind and the resultant loading. Rather, the provisions are intended to envelope the worst-case loading scenarios as observed in wind tunnel studies conducted on several simple rectangular shaped building models. Although most residential structures have more complex shapes than those tested, both in footprint and roofline, little comprehensive research has been done to determine the degree of accuracy when applying the pressures of a rectangular structure to buildings of different shapes and sizes. This is partially due to the presently unsolved inconsistencies that exist when comparing loads at full- and wind tunnel-scales, even on simple shapes.

Before significant progress in extrapolating wind tunnel testing to real structures can be made, extensive full-scale, in-field data sets of natural winds acting on common structural shapes are needed. As referred to in Chapter 1, such efforts are underway at a variety of universities. These efforts can be separated into meteorological studies of the wind field (hurricane wind behavior on a large scale to predict path and intensity), and engineering studies of the ground-level wind field (localized turbulent behavior of approaching wind, and its interaction with structures to produce loads).

Meteorological Data Collection Efforts

Many universities and organizations are currently involved in collecting meteorological data during storm landfall. Florida State University has the Hurricane Hunter, which was initiated during the 2002 hurricane season to study meteorological conditions associated with tropical storms, hurricanes, and tornadoes (Figure 2-1). The meteorological instrumentation is located on a mast that can be extended hydraulically to ten meters. The University of Oklahoma has developed the Doppler on Wheels vehicle to study meteorological data surrounding tornadoes. The Hurricane Hunter and the Doppler on Wheels are similar in appearance and both use remote sensors (radar) to capture meteorological data and wind behavior over a large swept area several hundred meters above the ground (Ray 2003). Such information is useful to researchers developing large-scale hurricane motion models, but not as useful to engineers interested in wind behavior near the ground, where structures reside.

Figure 2-1: Florida State University Hurricane Hunter

Ground-Level Wind and Pressure Data Collection Efforts

Throughout the last decade several universities and organizations have started taking field measurements of wind velocity within the ten-meter envelope that low-rise structures reside, and the resulting wind pressure on full-scale residential structures. Funding for research has been provided from many sources. This includes state agencies such as the Florida Department of Community Affairs (DCA), the Florida Department of Insurance (DOI), and federal agencies such as the National Institute of Standards and Technology (NIST), and the Federal Emergency Management Agency (FEMA). These organizations share a common goal of designing more wind resistant structures and mitigating the effects of extreme wind events.

Texas Tech University

Texas Technological University (TTU) has developed towers to collect in-field hurricane wind data. This program, Wind Engineering Mobile Instrumented Tower Experiment (WEMITE), consists of several portable towers (Figure 2-2). TTU's goal is to collect wind data in an open exposure area in the path of a hurricane as it makes landfall. Horizontal wind speed and direction are measured at ten, twenty and thirty-five feet. Vertical wind speed is measured at ten and thirty-five feet. Relative humidity, barometric pressure, and temperature are also measured. The towers may be collapsed for transport (Figure 2-3) and are stabilized by guy wires that are connected to the tower at the thirty-five foot level and to the ground by earth anchors. All WEMITE data is collected at 10 Hz (Schroeder and Smith 1999).

Figure 2-2: TTU WEMITE Deployed for Hurricane Floyd, Sept 16, 1999

Figure 2-3: TTU WEMITE Collapsed for Transport

In addition to WEMITE, TTU has continued to study pressures on a full-scale heavily instrumented research building located at TTU. The building may be rotated to control the angle from which the natural wind strikes the building. The angle of attack is then duplicated in wind tunnel tests to verify and improve testing techniques. Results from the Texas Tech Building, shown in Figure 2-4, will be used as a standard frame of reference for many wind tunnel studies. Meteorological conditions surrounding the building are monitored by a forty-six meter tower located near the building (Uematsu and Isyumov 1999, Levitan and Mehta 1992). Wind speed and direction are measured by a set of three fixed axis anemometers. A close up of the meteorological data collection instrumentation is shown in Figure 2-5.

Wind tunnels tests on scale-models of the Texas Tech Building have been conducted around the world and the results have been used to improve wind tunnel simulation techniques significantly. However, this building will never experience the effects of a hurricane or tropical storm. Separate efforts are underway to investigate extreme winds on coastal structures.

Figure 2-4: Texas Tech Building

Figure 2-5: Meteorological Instrumentation at the Texas Tech Building

John Hopkins University and University of Illinois

John Hopkins University and the University of Illinois have joined together to instrument the Kern P. Pitts Center, a low-rise structure, to collect wind and wind-induced pressure data on the structure during storms that occur year-round on the Outer Banks of North Carolina. For the project, called Blue Sky, the house was instrumented with multiple pressure sensors and strain gauges to measure wind force and structural response. The home is shown in Figure 2-6. Surface pressures are measured at ten exterior points on the structure using differential pressure sensors. The two-story home is currently being updated with new hardware through the National Institute of Standards and Technology (NIST).

Figure 2-6: Blue Sky Full-Scale Experimental Home

Two meteorological data collection towers are located near the house to measure wind velocity, rainfall, barometric pressure, and temperature. Wind velocity is also measured by a vane anemometer located above the chimney. All data is collected at 25 Hz (Porterfield and Jones 2001).

Florida Coastal Monitoring Program

The University of Florida, Clemson University, and Florida Institute of Technology comprise the Florida Coastal Monitoring Program (FCMP). The project is sponsored by the Florida Department of Community Affairs and was initiated in 1998. The FCMP goal is to collect wind velocity and pressure data on strategically located coastal residences during a hurricane. Phase one of the project includes the development of ten-meter portable towers designed to withstand hurricane force winds and collect wind data as hurricanes make landfall. Phase two of the project includes measuring wind pressures on the exterior and interior of residential low-rise structures. This makes the FCMP unique in its collection of both wind field velocity and structural load data in hurricane conditions.

The FCMP gathered data from its first storm, Georges, in 1998. Since then data has been collected from Dennis, Floyd, and Irene in 1999, Gordon in 2000, Michelle and Gabrielle in 2001, and Isidore and Lili in 2002. University of Florida and Clemson University team members assist with the deployment of the hurricane data collection hardware. The data collected by the FCMP is intended to enhance public knowledge of hurricane wind behavior and will be used by professional and researchers alike to improve home design and building codes.

Ten-Meter Towers

Ten-meter height is a standard reference height used in wind engineering. The ten-meter towers collect wind speed and direction at both five and ten meters. Rainfall, barometric pressure, temperature, and relative humidity are also collected at an elevation of two meters. The towers (Figure 2-7) are built on an 18-foot long trailer and are collapsible so that they may be towed. The towers can be set up with three people in less than thirty minutes, are designed to withstand wind speeds of up to 200 mph, and are stabilized by four outriggers. The tower may be deployed on pavement or earth. Earth screws may be attached to the outriggers for additional overturning strength if the tower is deployed off-pavement. A computer for collecting and storing the data is located in a weather and impact resistant box on the tower (Figure 2-8).

Figure 2-7: Ten-Meter Tower Erected Off-Pavement Prior to Storm Landfall

Figure 2-8: Computer Box on Ten-Meter Tower

<u>Five-Meter Towers</u>

Additional five-meter towers have been designed by students at the University of Florida to be used in conjunction with the ten-meter towers. They will be ready for deployment for the first time in the 2003 hurricane season. The five-meter towers (prototype in Figure 2-9) provide wind speed and direction at the five-meter elevation through the use of three fixed axis anemometers on non-orthogonal axis. The five-meter towers will provide important lateral wind characteristics that cannot be measured with a single tower. Up to four five-meter towers can be used in conjunction with each ten-meter tower. Improvements to the five-meter towers are discussed in Chapter 3. Details about the design of the five-meter tower may be found Hayes (2000) and Cuenca (2002).

Figure 2-9: Five-Meter Tower Prototype Being Tested at Energy Park, Located at the University of Florida

Coastal Homes

The structures being used in the FCMP are single-story homes equipped with pressure sensors and wind resisting retrofits. These retrofits include new roofs, hurricane straps or tie downs, and other improvements that will increase structural resistance to wind loading. The structures represent a variety of shapes and sizes; however, not enough data has currently been collected to reliably quantify pressure coefficients. With continuing effort and better understanding of wind and wind pressure behavior, improvements in approximating these coefficients will be made. The effectiveness of the retrofits will also be examined to determine if they should be used in all homes located in high wind regions.

Collected pressure data will be integrated with the wind velocity data to improve understanding of wind and wind pressure relationships, the pressure forces resulting from extreme wind speeds on the homes, and how the low-rise structures react. The damage to the retrofitted homes is compared to damage of surrounding homes to determine the performance and benefits of the retrofitting chosen. FCMP homes are located along the coastlines of Florida and are spaced about ten miles apart (see Figure 2-10).

University of Florida Contributions to the FCMP

Ten-meter towers

Two ten-meter towers, the five-meter towers and some of the house equipment are stored and maintained at the University of Florida. Every summer, the ten-meter towers, trailers and vehicles require servicing and maintenance. The data collection hardware for the ten-meter towers also requires periodic servicing. A contribution to this thesis work includes ten-meter tower, trailer, and instrumentation maintenance.

Figure 2-10: FCMP Instrumented Homes (Map by World Sites Atlas)

<u>Five-meter towers</u>

The five-meter towers were developed at the University of Florida by former FCMP team member Krista Hayes (Hayes 2000). Former FCMP member Desiree Cuenca improved the existing design by creating an aluminum version which is less expensive to produce and easier to transport and assemble (Cuenca 2002). Stability of the five-meter towers will be improved through the addition of three steel plates to the existing aluminum base plates. The towers and their improvements are discussed in detail in the hardware section, Chapter 3.

Data analysis software

A software program to view the collected hurricane data is being developed at the University of Florida. This software, Wind Data Laboratory (WinDLab), will allow researchers to calculate and view general statistics describing wind characteristics. A prototype for WinDLab was developed by FCMP team member Cuenca and is described in detail in her thesis (Cuenca 2002). Improvements to, and further developments of, WinDLab are a major contribution of this thesis to the FCMP. Contributions include making necessary changes to compile the software, and making the software faster and more user-friendly. Creating a downloadable version that runs independent of the MATLAB environment is one of the major focuses of this thesis, discussed in detail in Chapter 5.

In addition to improving WinDLab, a prototype version of WinDLab was created to view pressure data collected from FCMP homes during hurricane landfall. The house version of WinDLab and its creation and uses will be discussed in detail in Chapter 6 of this thesis.

Database management

A portion of this thesis discusses the updating and management of the entire existing database of wind information collected to date by the FCMP. Significant efforts have updated all files with additional information necessary for proper analysis. These modified data sets will be posted on the project website.

Real-time remote data transmission

In spring 2003, the UF students used FCMP funds to purchase cellular service hardware and laptops that will be used to collect data and summary statistics in real-time during storm landfall. Team members Forrest Masters and Luis Aponte are using Lab

View, a computer program for data acquisition, to create a program that will calculate storm statistics and format the collected data. Then, the data is transmitted via wireless web access and cell phones to a remote location during the storm. This data will help to insure that the equipment does not malfunction, or provide information about a malfunction so that the problem can be addressed as soon as it may be done safely. Real time data collection will allow us to determine the passing of the eye wall and when the storm has slowed down to a safe enough level to return to the equipment. Updates will also be shared with the National Hurricane Center.

FCMP website

A website is being developed to disseminate the data to other researchers and colleagues. The website was developed by undergraduate FCMP team member Jamie J. Farnham at the University of Florida, and is still under construction. The website will provide detailed information about the FCMP and the existing storm database. On the website, researchers can view the storm track, as shown in Figure 2-11, the tower and house locations, and general storm information for each storm the FCMP has collected data. The new version of WinDLab, as well as data files from previous storms, will be provided for download from this website.

Instrumenting coastal homes

The FCMP uses coastal homes to collect in-situ pressure data from low-rise gable-end homes as hurricanes make landfall near them. Wiring the homes consists of installing the wires and data board (Figure 2-12), which are permanently fixed to the house, and checking the installed system to insure the wiring to the pressure sensors and computer will work properly to collect data in the event of storm landfall. The equipment for the homes was developed at Clemson University and FCMP members from the

University of Florida and Clemson University work together to wire new homes each summer.

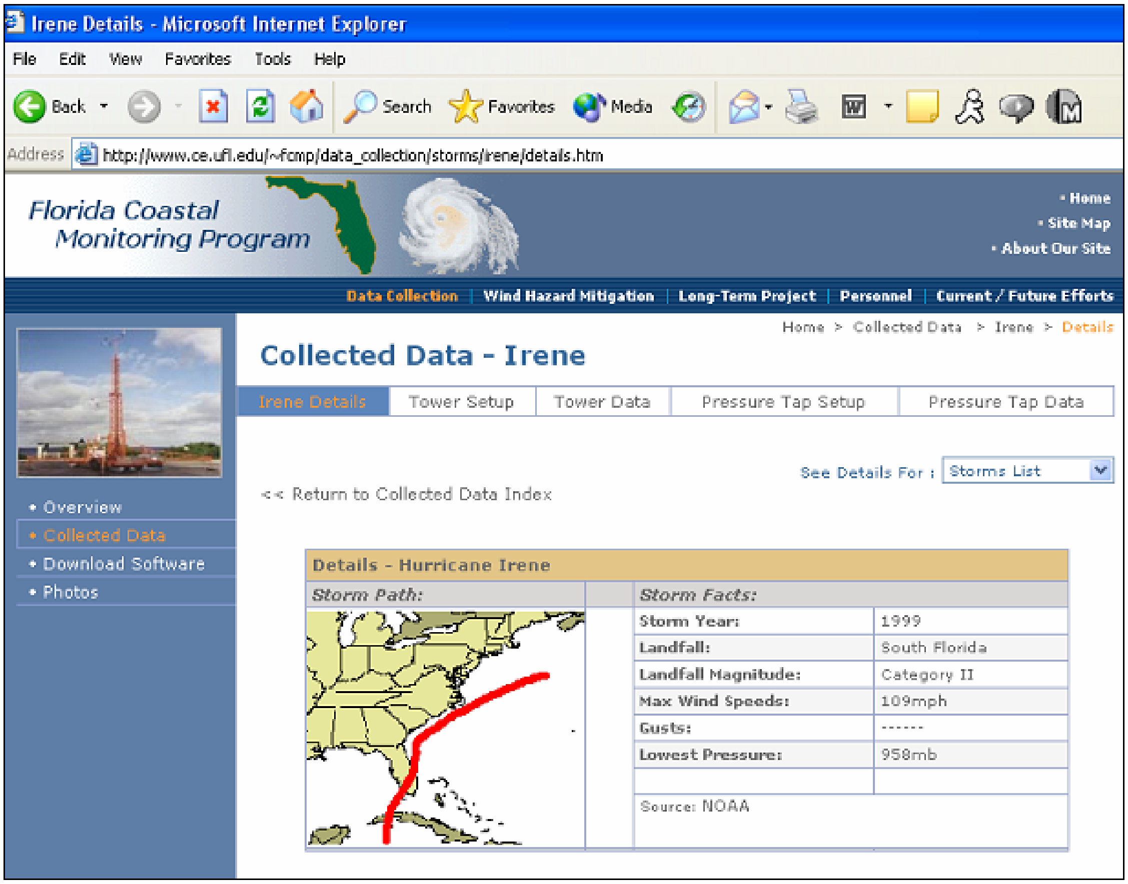


Figure 2-11: FCMP Website Storm Path and Details for Hurricane Irene, 1999

Figure 2-12: Wiring and Checking Data Acquisition Board

Summary of Original Contributions

The FCMP is continually improving and maintaining the existing data collection hardware and analysis software. While the bulk of the overall FCMP activities are documented in this thesis, focus is placed on the original contributions made by the author. A summary of the contributions to be discussed in this thesis include:

Improvements to Five-Meter Towers

- Ordering data collection hardware
- Aiding in design of base plate stabilizers

Maintenance of the Ten-Meter Towers (2001 and 2002)

- Removing rust and painting
- Servicing vehicles and trailers
- Cleaning towers and lubing all moving parts
- Servicing anemometers and replacing bearings

Installation of Coastal Home Hardware (2001 and 2002)

- Wiring ten homes in the panhandle of Florida
- Wiring five homes in central eastern Florida

Deployment

- Tropical Storm Isidore (2002)
- Hurricane Lili (2002)

Organization and Processing of Collected Data

- Correcting and improving data processing software
- Cataloging, organizing and processing data from 1999-2001
- Down-sampling of all existing hurricane data
- Updating all existing files with additional information needed for future analysis

Software Improvements

- Increasing ease of use and efficiency of WinDLab
- Creating a centralized data loading system and user-guide to available data sets
- Making WinDLab compatible with 10 Hz data format
- Creating non-MATLAB dependent executable version

Software Development

- Creating WinDLab_H prototype for analysis of house pressure data
- Creating visualization and analysis tools for wind and pressure data from houses

CHAPTER 3
HURRICANE DATA COLLECTION HARDWARE IMPROVEMENTS, MAINTENANCE AND INSTALLATION

Five-Meter Towers

Florida Coastal Monitoring Program (FCMP) will deploy five-meter towers for the first time in 2003. These additional towers will be used with the ten-meter towers to allow measurement of spatial correlation in the horizontal wind field, thus providing a better understanding of near ground wind behavior (Hayes 2000).

Correlation analysis establishes the degree to which two processes are interrelated. The correlation function relating the two processes is the same as the coherence function when the mean of the processes is removed. The coherence function, $\lambda_{xy}^{2}(f)$, is the ratio of the square of the absolute value of the cross-spectral density function to the product of the auto-spectral density functions of the two processes, $S_{xx}(f)$ and $S_{yy}(f)$ (Equation 3-1). It determines the degree to which one process (*y*) is related to the other (*x*) in a linear sense. The resulting coherence is always between –1 and 1, where –1 and 1 are perfectly correlated and 0 is not correlated.

$$\lambda_{xy}^{2}(f) = \frac{\left|S_{xy}(f)\right|^{2}}{S_{xx}(f) * S_{yy}(f)} \qquad (3\text{-}1)$$

where *f* indicates a function of frequency.

The statistical quantity $\lambda_{xy}^{2}(f)$ can be used to estimate lateral gust size by determining the level of correlation between wind measured at two separate locations. A high correlation indicates that large (wide) gusts are impinging upon both locations, while a low correlation indicates that the gusts are not large enough laterally to span both instruments. It is expected that most gusts span a width from several to dozens of meters.

The four portable ten-meter towers are typically placed several miles apart to maximize coastal coverage. This spacing does not allow any correlations studies between towers, since the same gusts are not impinging upon multiple towers at those separation distances. The only correlation that may be examined from this data consists of the vertical correlation between the five- and ten-meter anemometers on the same tower. The additional five-meter towers will be deployed within several hundred feet of the main towers and connected to the same data acquisition system. The intent is to capture measurements of the same gusts at several separated points, in an effort to quantify the average size of these gusts.

The steel five-meter tower prototype, shown in Figure 3-1, was originally designed and constructed by Hayes (2000) at the University of Florida.

Figure 3-1: Five-Meter Tower Prototype (Hayes 2000)

Former FCMP team member Desiree Cuenca worked with ALUMA Tower Company, Inc. to create a similar five-meter tower constructed of structural aluminum (Cuenca 2002). These towers only weigh sixty-four pounds and rest on a 20” x 24” base plate. The towers are easily attached to the sides of the ten-meter tower trailers for transport (Figure 3-2).

Figure 3-2: Five-Meter Tower Attached to a Main Tower For Transport (Cuenca 2002)

Tower Improvements

Currently, the 20” x 24” aluminum base plate for the five-meter tower is stabilized by shear pins pushed into the earth during assembly. Although easy to assemble and transport, the new towers tend to be top heavy during erection. During deployment, the five-meter towers will need to be erected off-pavement due to the requirement of the earth screws that hold the guy wires in place. Therefore, the inherent instability will be a problem during erection. FCMP team members have designed a set of three base plate extensions to be placed on the base plate prior to the placement of the first tower section. These arms, design shown in Figure 3-3, are three feet long and will provide additional stability during construction as well as additional strength in high wind conditions. Stability and ease of use were considered during the initial design of the arms.

The design of the five-meter towers is complete and most of the hardware required for construction has arrived. The aluminum frame and base plate are delivered from ALUMA Tower Company, Inc. prefabricated. The guy wires, wiring, and instrumentation are installed at the University of Florida. Construction and assembly of four five-meter towers will be completed in summer 2003. These towers will be tested in-field during the 2003 hurricane season.

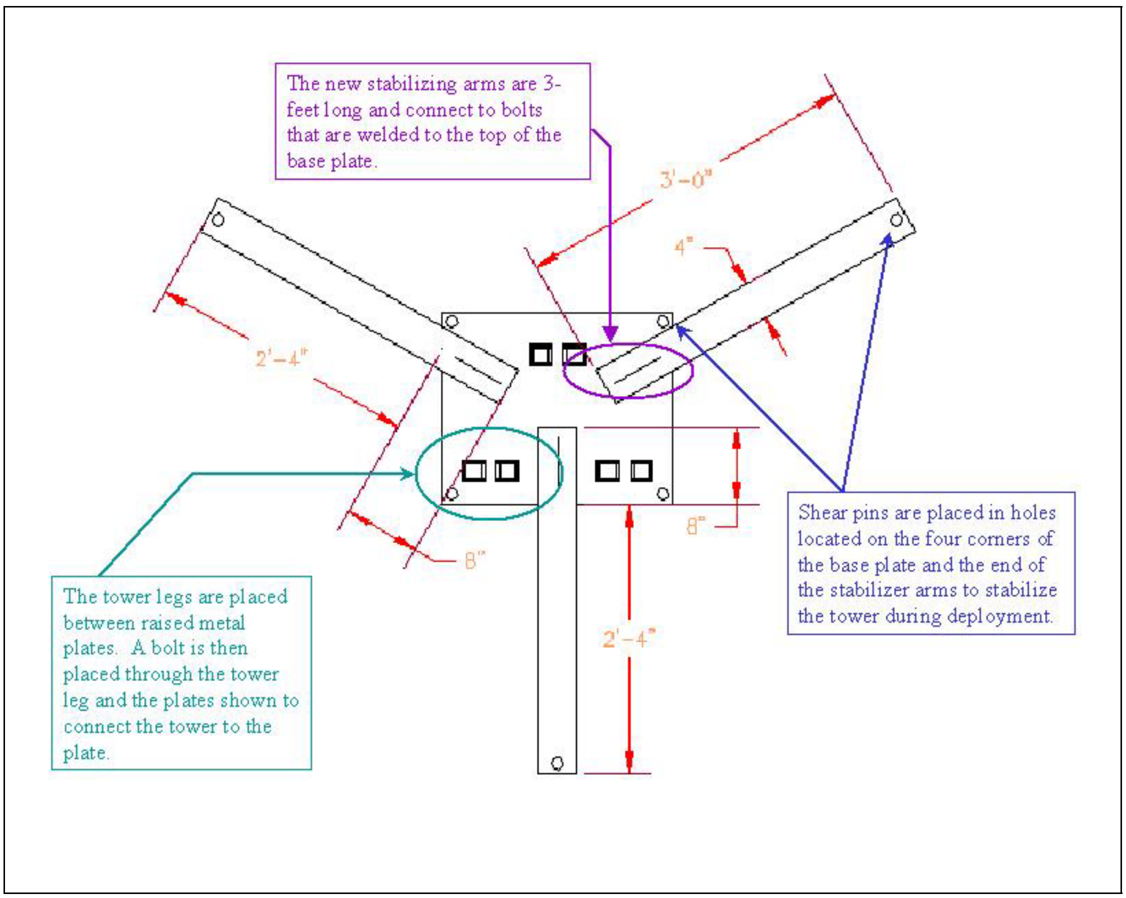


Figure 3-3: Base Plate Stabilizer Design for Five-Meter Towers

Equipment Maintenance

Upkeep of the data collection hardware is an important aspect of being ready to chase a storm at a moment's notice. Routine maintenance of the ten-meter towers and vehicles is critical to prepare for the upcoming hurricane season. Required maintenance includes servicing the trailers and vehicles, lubing and inspecting all parts, and cleaning. The steel towers must be inspected and rust must be removed. Contributions of this thesis include assisting with annual maintenance of the equipment for the 2001 and 2002 hurricane seasons.

The fixed axis anemometers are used in a set of three, located at non-orthogonal directions from one another to prevent occurrence of dead spots in the wind speed and direction data collected (see Figure 3-4). Due to the harsh environmental conditions of the storms, corrosion and rust are inevitable. Therefore, anemometers must be cleaned of rust and corrosion annually, or every few years, depending on usage. Each fixed axis anemometer has two bearing sets, one located at the propeller, and one located at the DC current converter. Corroded or rusted anemometers bearings have increased friction and therefore do not spin at the calibrated rate relating the wind speed to output voltage; they must be replaced.

In summer 2002, maintenance of all anemometers stored at the University of Florida was performed as contribution of this thesis. First, corrosion and rust were removed from, then any bearings that appeared corroded, or rusted or that did not allow the propeller to spin at an acceptable rate, were replaced. The new anemometer bearings are filled with a waterproof grease to extend the bearing life under severe weather conditions. Along with the use of waterproof grease, holes in the anemometer shell surrounding the prop bearings were sealed with silicone. R.M. Young, the manufacturer of the anemometers, verified that these holes are not critical and may be closed for use in harsh or wet environments. All threading and moving parts were cleaned and sprayed with silicone lubricant spray.

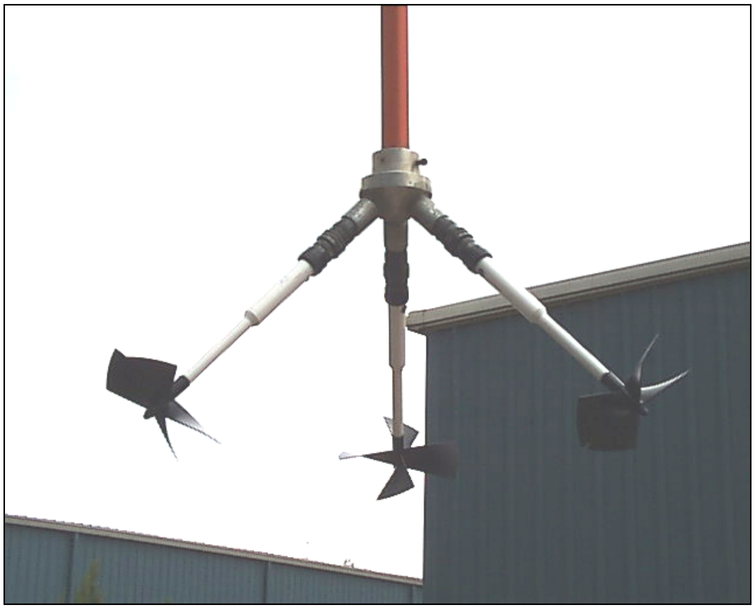


Figure 3-4: Close-Up of the Three Fixed Axis Anemometers

<u>Coastal Homes</u>

The FCMP collects pressure data from low-rise homes as hurricanes make landfall. A total of twenty-five homes in the State of Florida are wired to collect pressure data in event of a storm. A thesis contribution includes participation in the wiring of fifteen of the existing twenty-five FCMP homes. In 2001, ten homes located in the panhandle of Florida between Pensacola and Panama City were wired. In 2002, five more homes between Melbourne and Stuart on the east coast of Florida were also wired. These homes will provide data that will be compared to wind tunnel test data and to wind load code provisions.

FCMP students and faculty install the sensor plugs, data boards, and wiring necessary to collect data. All of the installed wiring is run through CPVC piping under the eave of the house (Figure 3-6) therefore nothing is visible from the front of the home. Pressure sensors are placed inside the attic of the home to determine the internal pressure. Each home is also set up to receive twenty-eight pressure taps on the roof to collect uplift pressure data (Figure 3-7). In addition to the pressure sensors, each home is equipped with its own vane anemometer, ambient pressure sensor, and video camera. Homes are wired during the spring or summer. Once homes are wired, minimal maintenance is required. While wiring a home may take one to two days of hard labor, and many months of planning and renovating, setting up a home to collect data during a storm only requires a matter of hours.

Figure 3-6: Existing CPVC System that the Wires from the Sensors are Plugged Into

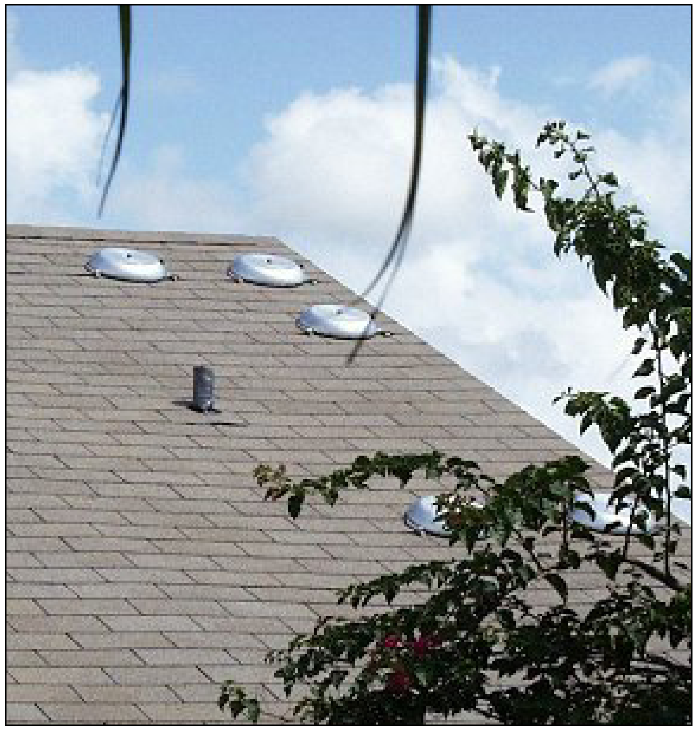


Figure 3-7: Pressure Sensors Installed Before the Storm

Need for Data Analysis Software

This chapter has focused on hardware for data collection. Most of the major hardware systems were developed at Clemson University. The University of Florida was tasked with the role of data analysis, with an emphasis on developing software to view and characterize the wind data.

FCMP has collected wind velocity data from nine storms. The University of Florida has developed software, referred to as WinDLab (Wind Data Laboratory), to analyze the data taken from this FCMP hardware. The prototype developed by Cuenca (2002) proved to be an effective tool for visualization and analysis of wind speed and direction data taken from the towers. Improvements to this software tool are discussed in Chapter 5.

FCMP has now collected house pressure data from three storms. With the number of houses and quantity of house data growing, WinDLab's capabilities are being expanded to include the analysis of the pressure data from the houses. A plan view of each house will be provided, including locations of all the pressure taps. Visualization tools will allow the user to see wind speed and direction, as well as select pairs of pressure tap records to view and analyze. This software will be available online, along with data sets of the house pressure data collected during severe wind events. The development of the software prototype is a major contribution of this thesis and is discussed in detail in Chapter 6.

CHAPTER 4
COLLECTION AND PROCESSING OF DATA

Data Collection

This chapter documents the deployment process in some detail, and summarizes two deployments from the 2002 hurricane season. The organization and processing of the raw data is also discussed as a contribution to the thesis research.

As a tropical storm or hurricane approaches the coast of southeastern United States, the Florida Coastal Monitoring Program (FCMP) tracks the storm with assistance from the National Weather Service and the Hurricane Research Division of NOAA. Data collection hardware is set up as close to the storm's predicted landfall as possible. The ten-meter towers were built on trailers so that they may be towed to a desired location, as shown in Figure 4-1. Portable towers are deployed and coastal homes are instrumented to collect data before the storm makes landfall. After setting up equipment, FCMP team members relocate to a safer area until the storm has passed.

Twelve named storms developed in the Atlantic Ocean during the 2002 hurricane season (NOAA 2003a). Of these storms, only Tropical Storm Isidore and Hurricane Lili approached the United States mainland. The FCMP collected data for both.

Instrumented homes are equipped with anemometers, pressure sensors, cameras and data acquisition computers twenty-four to forty-eight hours before landfall. If possible, a ten-meter tower is deployed near the home to provide correlation with the anemometers located on the roof of the homes. A fully instrumented home is shown in Figure 4-2.

Figure 4-1: Ten-Meter Towers In-Tow

Figure 4-2: Fully Instrumented Home with Ten-Meter Tower, Hurricane Michelle, 2001

Pressure sensors are attached to brackets on the roof with eye bolts, as shown in Figure 4-3, and the number of the sensor is logged in case information regarding the calibration is required. Wind pressures are measured as precise as one-tenth of a pound per square foot by the sensors (Dees and Smith 1999).

Figure 4-3: Attaching Pressure Sensor to Roof Brackets

A computer box (Figure 4-4) is connected to the data acquisition board via a waterproof military connection. Pressure data from the roof, walls and attic is then recorded on the computer hard drive. The house powers data collection equipment. In the event of power loss to the house, the computer has four back up batteries to supply power for the remainder of the storm.

Figure 4-4: Computer Box Used to Store Data During the Storm

In addition to the pressure sensors and anemometers on the roof of each home, pressure sensors are located inside the attic and exterior walls of the home to report internal pressures induced on the structure. A weatherproof video camera on a steel frame, nicknamed the Johnny 5, is placed in the yard of the home to monitor the roof and equipment and to record any damage that occurs to the retrofitted home. In addition to the video camera, the Johnny 5 also contains a pressure sensor to measure a reference pressure away from the house. Wires run from the Johnny 5 to the computer box where the video and pressure data is digitally recorded.

Tropical Storm Isidore

On September 26, 2002 Tropical Storm Isidore struck the coast of Louisiana, not far from the Florida border (Figure 4-5). Several FCMP instrumented houses in the western Panhandle of Florida were in the potential strike zone. Therefore, the team decided to set up near Pensacola, Florida instead of the predicted point of landfall in eastern Louisiana. The strongest winds of a storm are typically located in the northeast quadrant surrounding the storm; therefore, significant wind gusts were experienced at the deployment location.

Three homes were set up to collect pressure data from Tropical Storm Isidore. Three ten-meter towers were also deployed. University of Florida towed two towers to Pensacola and Clemson University towed one tower as well as the equipment for the homes that were instrumented. Two of the towers were set up adjacent to homes and the third was set up near the coastline for an open exposure environment. Figure 4-6 shows a map of the storm path and the locations of the ten-meter towers deployed for Isidore. Towers T0 and T1 were deployed adjacent to homes and T2 was deployed on the shoreline in Gulf Breeze.

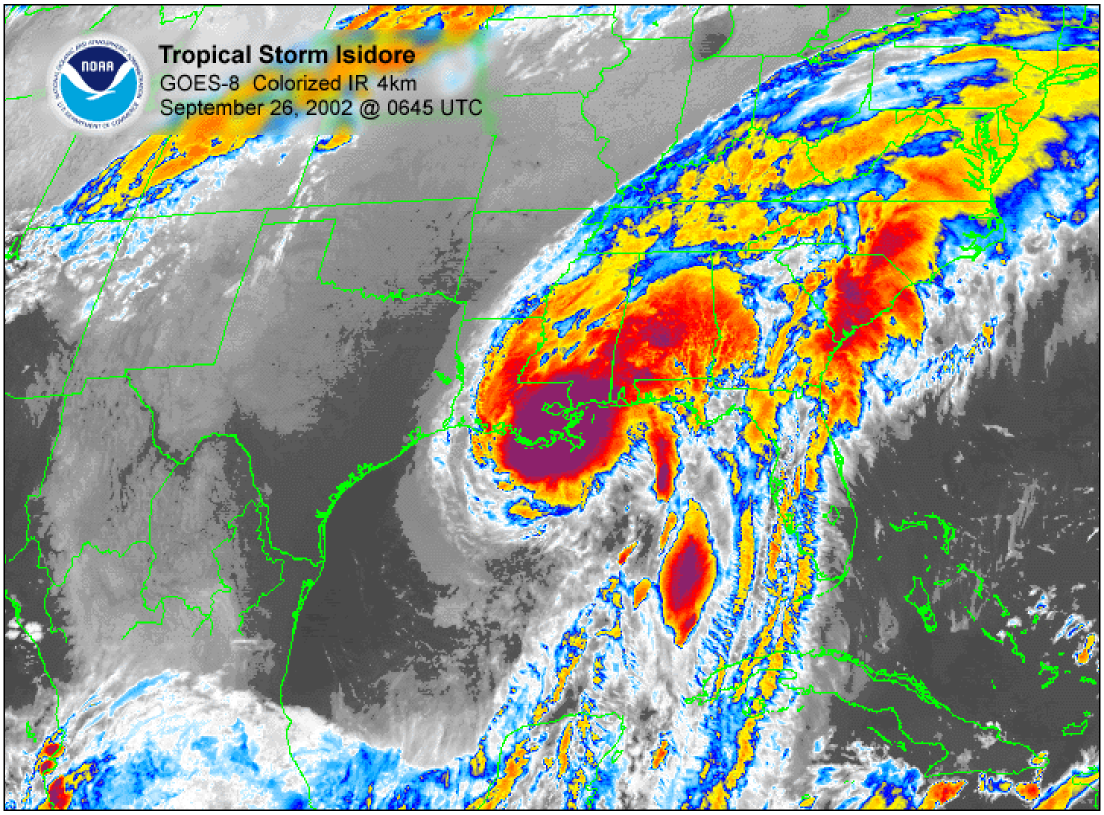


Figure 4-5: Tropical Storm Isidore (NOAA 2003c)

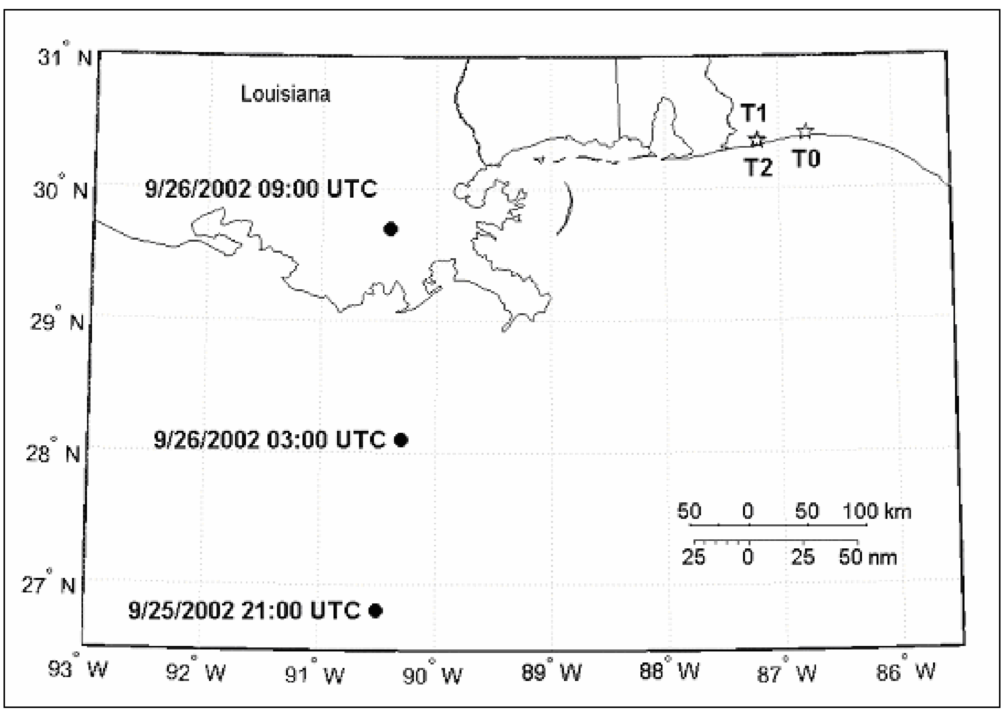


Figure 4-6: Tropical Storm Isidore Storm Path and Tower Locations

Hurricane Lili

FCMP only has homes located in the state of Florida; however, FCMP has traveled as far as North Carolina and Louisiana to collect storm data with the portable towers. On October 3, 2002, Hurricane Lili made landfall in western Louisiana. The FCMP deployed all four ten-meter towers for Hurricane Lili. The towers could not be set up close to shore due to the extremely low elevation in southern Louisiana. The city of New Orleans resides below sea level and is at great risk of flooding when struck by a hurricane or tropical storm. Hurricane Lili (Figure 4-7) was estimated to be a category four as it approached land; however, it lost strength quickly near the coast and was a Category one at landfall. The locations of all four towers deployed and the storm path of Hurricane Lili are shown in Figure 4-8.

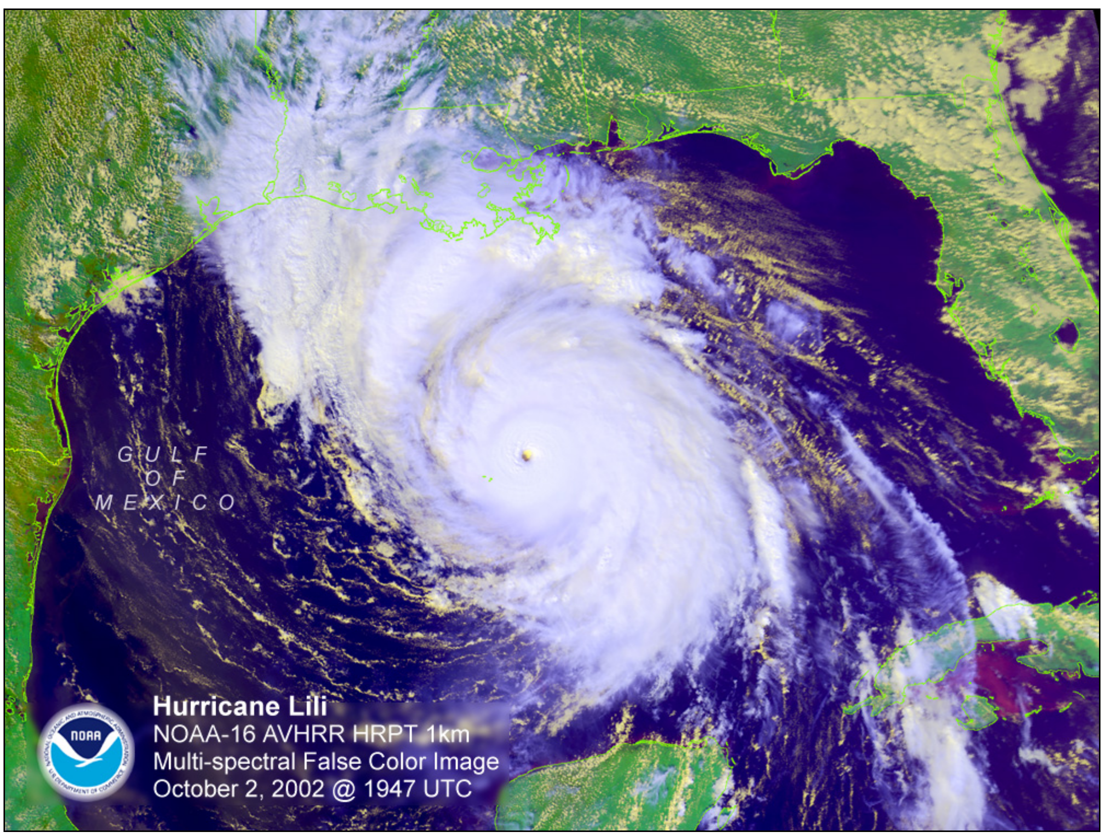


Figure 4-7: Hurricane Lili Before Landfall (NOAA 2003c)

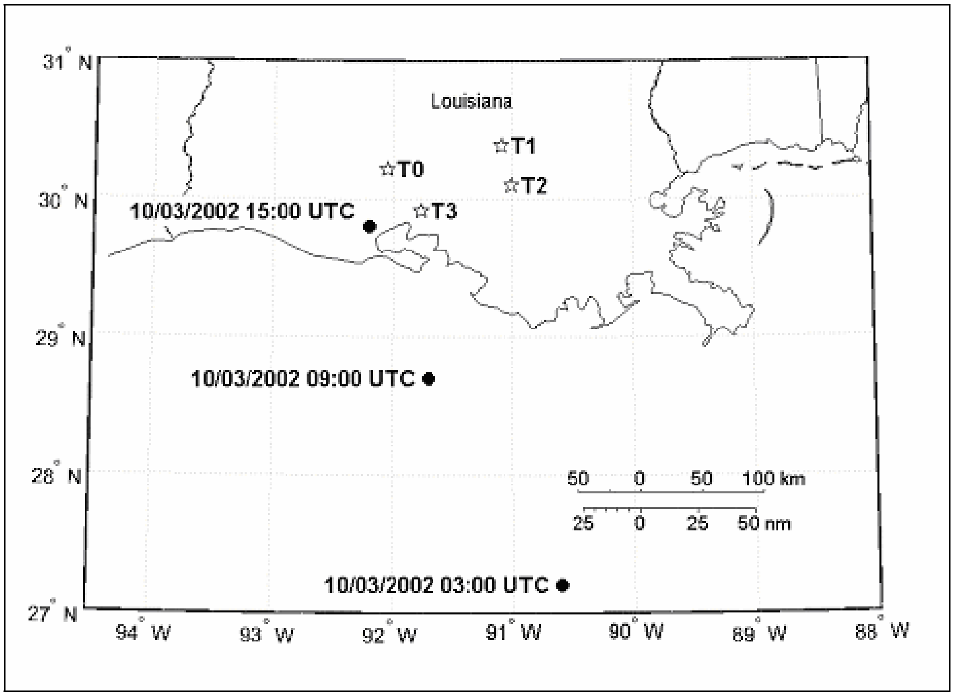


Figure 4-8: Map of Hurricane Lili Path and Tower Deployment Locations

Processing Collected Data

The data collected from the towers and houses must be organized, processed and analyzed with various statistical tools in order to characterize wind field behavior and its interaction with residential structures. This section discusses several developments in these procedures.

The data sets are stored in a compact binary format as they are collected using a C++ program written by FCMP team members at Clemson University. This program is called Tower. Before analysis can take place, the data sets are exported from Tower into individual 15-minute records in an ASCII format. Once exported from Tower, the data is then transformed from ASCII to MATLAB format to compress the data files and to convert them into a form that can be easily accessed and used within the MATLAB environment.

The ten-meter towers have a set of three fixed axis anemometers at five and ten meters. These anemometers, referred to as the gill anemometers, are arranged non-orthogonally to prevent dead spots when the wind changes direction. The wind data exported by Tower is in this non-orthogonal form. Before the wind speed and direction may be displayed in Cartesian coordinates, they must be transformed into u, v, and w orthogonal components. The component of the wind, u, is the horizontal component that is into the wind. The v component is horizontal and perpendicular to the wind and the component w is vertical. The conversion is an iterative process in which the head-on angle of the wind direction must be determined. Once the angle is determined, the direction and speed are computed. Validation of the orthogonalization of the wind components is completed though comparison of the resulting components of the ten meter gill anemometers to those given by the weather monitor (vane anemometer) located at the ten meter elevation.

Several problems arose while using the conversion algorithms. For example, very low wind speeds would lead to singularities in the equations used to orthogonalize the data, preventing convergence. The conversion was also quite time consuming, taking approximately 15-minutes per 15-minute record. The algorithm has been corrected to work-around low-speed induced singularities, and has been altered to make use of MATLAB's vector-operation capabilities to improve efficiency. A single 15-minute file now takes only a few minutes to process rather than 15. Thus, processing many hours of data from up to four towers takes significantly less time than in past seasons.

<u>Organizing Collected Data</u>

FCMP has been collecting data since 1998 and up until recently, no concerted effort to organize the extensive data sets was made. This resulted in a disorganized collection of incomplete data sets, partially stored at Clemson, and partially at UF. For example, several of the tower data sets did not have an associated GPS location recorded, making evaluation of local terrain impossible. As a contribution to this thesis, data from all storms collected in 1999 through 2002 were exported, cataloged, and processed in a uniform manner suitable for analysis with WinDLab. Missing information was filled in when possible. An Excel sheet cataloging important information known about each collection is shown in Appendix B. In addition to the Excel sheet showing storm data collected, an Excel sheet was also created for each storm. Each Excel sheet contains the UTC date and time at which each 15-minute record was written to the hard drive, as well as the GPS location of the tower or house, the operator of the data collection software, a description of the surrounding terrain, and the trailer angle (needed to resolve wind direction).

A MATLAB script file was written to read these Excel sheets and to import and save the GPS location, time and date stamp, and trailer angle information into the original data records. Excel and MATLAB use different reference years and formats for storing dates. Therefore, the algorithm converts the imported Excel date and time to a format usable by MATLAB and stores it as a variable in the original data records. This additional data was used to improve WinDLab's displays and to assist WinDLab users in determining which data files they would like to analyze. Details of the improvements made to the prototype version of WinDLab are provided in Chapter 5.

The wind direction recorded by the Tower data collection software is relative to the trailer itself, not relative to north. The trailer angle must be accounted for when calculating the direction of the wind relative to north. This information is now stored inside each data record. The trailer angle was not taken into account in the prototype version of WinDLab; all wind directions were calculated relative to the trailer. With assistance of other FCMP team members, trailer angles for all storms were calculated. Changes were made to WinDLab to account for the trailer angle.

Data Dissemination and Down-Sampling

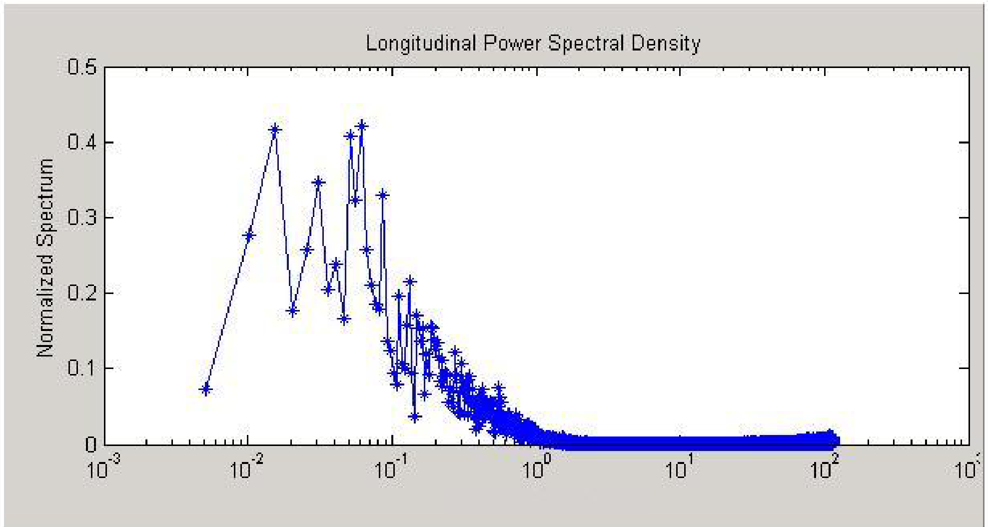
Data collected by the FCMP is intended for public knowledge and for use by researchers seeking to improve structural resistance during extreme wind events. In an effort to share the collected data, both the WinDLab software and the data files collected by the towers and homes will be available for downloading from the FCMP website. Wind data from each tower is collect at 100 Hz during the storm. Each 15-minute wind record is over 11 MB after the data has been exported and processed. These large files take a long time to manipulate and load in WinDLab. In addition, a public web site will offer downloads of the data. Given that users may want to download more than one hundred records for a given storm, downloading the current file size is rather cumbersome.

MATLAB was used to down sample the data using segmental averaging. During the segmental averaging, ten 100 Hz samples were averaged together resulting in a new 10 Hz version. Investigations were conducted to ensure that the important characteristics of the data were not filtered out during this process. Spectral plots show that the significant signal energy lies well below 5 Hz, which is the nyquist cutoff frequency for 10 Hz data. Normalized spectrum plots, created using WinDLab, are shown for the 100 Hz and 10 Hz data formats of Hurricane Lili wind speed data in Figure 4-9. The units on the horizontal axis in these plots are dimensionless reduced frequency (frequency multiplied by a reference height and normalized by mean wind speed). Additionally, the first four statistical moments were compared between 100 Hz data sets and their reduced 10 Hz version, showing no appreciable differences. The results from Tropical Storm Isidore T1 data are presented in Table 4-1. The first ten records (150 minutes) of data were used to calculate the statistics. Therefore, for the purpose of public dissemination of the data sets, the reduced frequency data is acceptable for determining wind characteristics with WinDLab. The new data files are only 1.2 MB per 15-minute record, making download significantly more convenient.

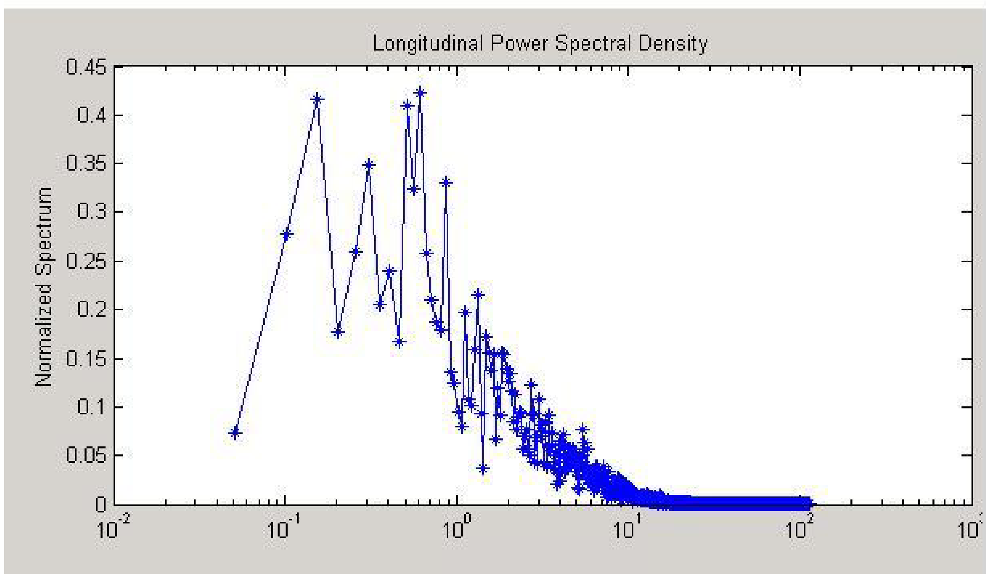
In addition to retrieving data through the web, researchers interested in the data can request a CD containing WinDLab software and data files. Raw data files for an entire storm, collected at 100 Hz, are generally too large to fit on one CD. The down-sampled version of the data, as well as the software will now fit on one CD for easy distribution and operation. Many changes had to be made to WinDLab in order to be able to distribute it to users unfamiliar with MATLAB and for it to operate with the 10 Hz version of the data. These changes are discussed in Chapter 5.

Table 4-1: Comparison of First Four Central Moments for Isidore Data

	100 Hz	**10 Hz**	**Percent Difference**
Mean	7.2618	7.2618	0.00
Standard Deviation	4.1141	4.0497	1.57
Skewness	0.99471	1.0414	4.48
Kurtosis	3.9913	4.0469	1.37



Hurricane Lili Tower T1 Records 1-4 at 100 Hz Frequency



Hurricane Lili Tower T1 Records 1-4 at 10 Hz Frequency

Figure 4-9: Normalized Spectrum Plots Created Using WinDLab

CHAPTER 5
TOWER WINDLAB SOFTWARE IMPROVEMENTS

Development of Wind Data Analysis Software

The software to collect and export the data collected during storm landfall, referred to as Tower, will only allow the user to view individual 15-minute data records, and does not contain the statistical analysis tools required to characterize wind behavior. The companion software written to collect pressure data from the houses, referred to as House, allows the user to view the pressure data collected for each tap for individual 15-minute records, again with no statistical analysis tools. In order to fully analyze wind and pressure data, researchers need to be able to examine the behavior over long periods of time.

A data analysis program, Wind Data Laboratory (WinDLab), has been developed at the University of Florida to accommodate users wishing to view statistics and perform analysis of the wind records recorded by the FCMP. Former FCMP member Desiree Cuenca developed a prototype version of WinDLab using the MATLAB 6.0 platform (Cuenca 2002). MATLAB was chosen to create WinDLab due to its combination of high performance computation abilities and visualization tools.

The graphical user interfaces (GUIs) in WinDLab were created using GUIDE, a GUI toolbox provided by MATLAB. GUIDE provides a simplified means to create a GUI and its corresponding source code file. Pre-programmed GUI objects, called *uicontrol* objects, are available for selection in GUIDE. *Uicontrol* objects include edit, check, and text boxes, pushbuttons, sliders, radio buttons, toggle buttons, popup menus, frames, and list boxes. These objects may be arranged on a layout grid without having to program the location and description of each tool in the GUI. Within GUIDE, *uicontrol* objects can be sized, colored, and titled. These properties, and all others describing the visualization of the objects, are called handles.

GUIDE creates a base script file that contains callbacks to each of the objects. The callbacks are arranged in a switchyard fashion with one per *uicontrol* object. The creator places command code after the callbacks for each object. These commands are unlimited and may include changes to the *uicontrol* object handles, changes to other *uicontrol* objects handles, performing a calculation, and plotting information. The *uicontrol* object will perform the commands after the user interacts with the *uicontrol* on the GUI (Hanselman and Littlefield 2001). One handle property for each *uicontrol* object is reserved for passing data between different *uicontrol* objects. This handle, "UserData", is useful for passing wind data between *uicontrols* and GUIs.

Wind Data Laboratory

WinDLab provides researchers with an interactive tool to analyze wind data collected at ground level during high wind events. The Main Control window is the first GUI of WinDLab. This window provides access to the help files and the analysis tools available in WinDLab. Figure 5-1 shows the Main Control window for the prototype version of WinDLab.

As a contribution of this thesis, several significant improvements were made to the prototype version of WinDLab. These include a more convenient data selection interface, adding 10 Hz data compatibility to the 100 Hz existing structure, the addition of intermediate messages to users waiting for data loading or computation, simplification of numerous analysis tools, improvements to algorithm efficiency to increase speed, and the creation of a stand-alone executable version for dissemination of the tool to non-MATLAB users. The new version will be referred to as WinDLab, Version 3. Help files for WinDLab, Version 3, are provided in Appendix C. Another contribution of this thesis is the creation of a companion version of WinDLab to visualize and analyze data collected from the instrumented houses. This work will be discussed in Chapter 6.

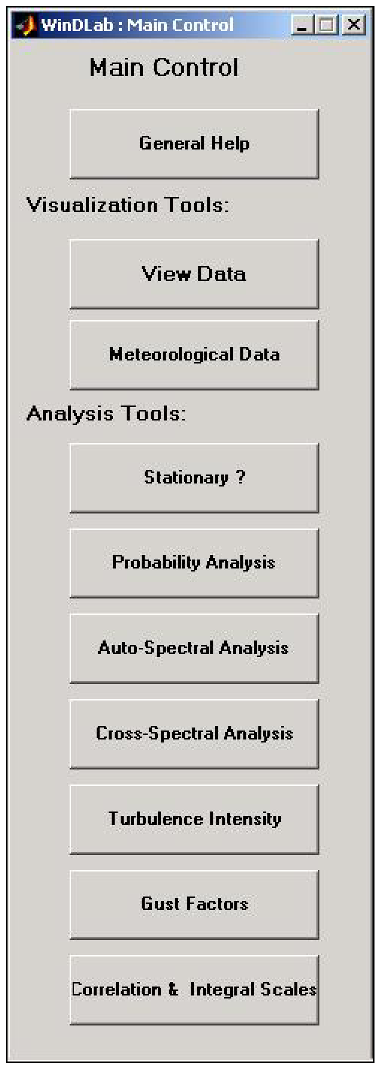


Figure 5-1: Main Control for WinDLab Prototype (from Cuenca 2002)

Before discussion of the improvements, a brief description of the analysis tools available in WinDLab will be presented. More detailed explanations of the analysis tools are available in Cuenca's thesis, *Hurricane Data Collection Hardware and Analysis*

Software, or the WinDLab help files (Cuenca 2002). The subsections below address the individual buttons shown in Figure 5-1.

Data Visualization Tools

The View Data window allows the user to view the wind speed and direction of the loaded data records. The user may choose to plot the data from one anemometer at a time, or from multiple anemometers to compare them. Wind data may be viewed at the original sampling rate, or the user can choose to view plots of the 1-, 3-, or 10-second averaged gusts. In addition, basic statistics of the data are calculated and displayed for the anemometer chosen by the user. The statistics calculated include the maximum and mean speed for all data loaded, and the maximum wind speed for 1-, 3-, and 10-second averages. The time, in minutes, from the start of the loaded data at which these statistics occur is also displayed.

The Meteorological Data window provides an overview of the environmental data sets loaded. The data shown is collected at 100 Hz at an elevation of two meters. Data displayed includes wind speed, temperature, relative humidity, atmospheric pressure, and rainfall.

Data Analysis Tools

Wind is commonly assumed to be stationary and the analysis tools in WinDLab are based on this assumption. Validation or rejection of this assumption for the loaded data is provided in the Stationarity window. Strict definition of stationary requires that all central moments, performed across multiple ensembles of data, do not vary with time. This calculation of statistics is not feasible for hurricane wind data since there is only one ensemble for each record.

Instead, a Stationarity check is performed in WinDLab by examining the variation in the statistical characteristics and performing a *reverse arrangement test*. Weakly stationary is defined as the first two moments being invariant in time, and is typically measured by looking at a plot of mean and standard deviation measured sequentially over small segments of time. If no trends are observed in the first or second moments as a function of time, then the data is considered weakly stationary. The Stationarity window consists of plots of mean wind speed per minute, standard deviation per minute, and turbulence intensity (coefficient of variation) per minute. The mean value is plotted as a straight line though each plot. The slope of the line should be approximately zero for stationary data since the central moments of stationary data do not vary with time. A *reverse arrangement test* is also performed on the data. This test tracks the number of fluctuations in the data. The *reverse arrangement test* is believed to provide a good view of the stationarity of the data (Bendat and Piersol 2000).

Probability distribution is important in describing wind behavior and may be used to determine the likelihood of an extreme gust. The Probability Analysis window provides a histogram of the wind speed, plots of various probability density functions (PDFs) as well as the first four moments of the data. The third central moment normalized by variance to the 3/2 power, coefficient of skewness (Equation 5-1), and fourth central moment normalized by variance squared, coefficient of kurtosis (Equation 5-2), describe the general shape (asymmetry and slenderness) of the PDF. For Gaussian data, skewness equals zero and kurtosis is equal to three.

$$\text{Coefficient of Skewness} = \gamma_3 = \frac{E\left[\left(v - \mu_v\right)^3\right]}{{\sigma_v}^3} \qquad \text{Equation 5-1}$$

$$\text{Coefficient of Kurtosis} = \gamma_4 = \frac{E\left[(\nu - \mu_\nu)^4\right]}{\sigma_\nu^{\ 4}} \qquad \text{Equation 5-2}$$

Where E [ ] is the expectation operator (taking an average)

$\sigma_\nu = \sqrt{VAR}$ (VAR = variance, the mean square value of ν about its mean)

μ_ν = the mean value of ν

A histogram of the data is plotted in the top window and the user may select from various PDFs to overlay and compare to the data. The chosen PDF is also plotted on a logarithmic scale below the histogram for a closer view of the tail ends of the curves. PDF models available include Gaussian, Beta, Mean-shifted Rayleigh, Type-1 Largest Value, and Lognormal distributions. A goodness-of-fit test is performed for each function and is compared to the goodness-of-fit of a Gaussian distribution probability density function. The goodness-of-fit tests performed include the Kolmogorov-Smirnov and the Mean Square Error.

The power spectral density function (PSD) of a random variable is the distribution of energy with respect to frequency. It is a measure of the variable's memory (the dependence of its current value on values from previous times). For wind, most energy is located in the low frequency range, which is commonly close to the natural frequency of tall buildings. This is important because it can induce resonance and promote structural damage. Many models have been created to describe the PSD of wind. In the Auto Spectral Analysis window of WinDLab, five models (Harris, Kaimal, Davenport, Karman, and Solari) are provided for comparison with an empirical PSD created using the Fast Fourier Transform. The user may select the number of segments into which the data should be divided into prior to calculating the empirical PSD. The mean square error for each model is also provided.

The Cross-Spectral Analysis window of WinDLab plots the cross-spectral density magnitude and phase, and coherence between two anemometers. The analysis presents the amount of linear correlation between the anemometers. In this window, the user can compute the correlation and coherence between two anemometer locations on the ten-meter tower. This will assist in determining the vertical size of gusts to which the ten-meter towers are exposed. The window also has the capability to calculate correlation and coherence between two five-meter towers (as discussed in Chapter 3) and a five and ten-meter tower. This will add to the understanding of near-ground wind behavior and will also aid in determining the horizontal size of gusts.

Turbulence intensity represents the magnitude of the wind velocity fluctuation compared to the mean wind speed. It is determined the same way as the coefficient of variation in statistics, by dividing the standard deviation by the mean for a given time period. Turbulence intensities are very sensitive to the duration times used to calculate them and tend to converge as the duration time increases. In WinDLab, 1-second, 3-second, 30-second, 1-minute, 2-minute, 5-minute, and 10-minute durations are available for user selection.

Gust factors help to quantify the dynamics of wind fluctuations about the mean and the load amplification introduced by the building dynamics during wind loading. Traditionally, structures are designed for wind loads provided through building codes. Most codes provide a static wind load that is then multiplied by a gust factor (Zhou, Kareem, and Gu 1999). The gust factor is the ratio between the peak and average wind speeds over a given time duration, and thus express the size of the largest gusts with respect to the mean. Loaded data records are divided into 1-, 2-, 5-, 10-, 15-, or 30-minute duration times and the wind speeds are recalculated into 1-, 3-, 5-, 10-, and 30-second gusts. The user can select which combination of duration and averaging time they would like to use to calculate the gust factors. Three plots are provided: 1) individual plots of gust factors for each averaging time with the mean gust factor for the entire record, 2) gust factor versus duration time for the selected averaging time, and 3) gust factor versus averaging time for the selected duration. Three empirical models of gust factors, Durst, Cook, and Krayer and Marshall, may be plotted in the gust factor versus averaging time plot as well.

The Correlation and Integral Scales window performs calculations of autocorrelation functions and integral scales. The integral length scale is a measure of the longitudinal size of turbulent eddies, in units of meters. These eddies are related to the level of spatial correlation of wind gusts across a structure. This window provides plots of the wind speed and the autocorrelation function estimate for 5-, 15-, and 30-minute time intervals. The plot in figure 5-2 was created using the new WinDLab, Version 3. The bottom graph is a new addition, which shows the calculated integral scales for each hour of data loaded. This window also reports the overall averaged integral scales for 5-, 15- and 30-minute time intervals is the lower boxed region on the left side of the window. This value is the mean of the integral scales calculated for each time segment.

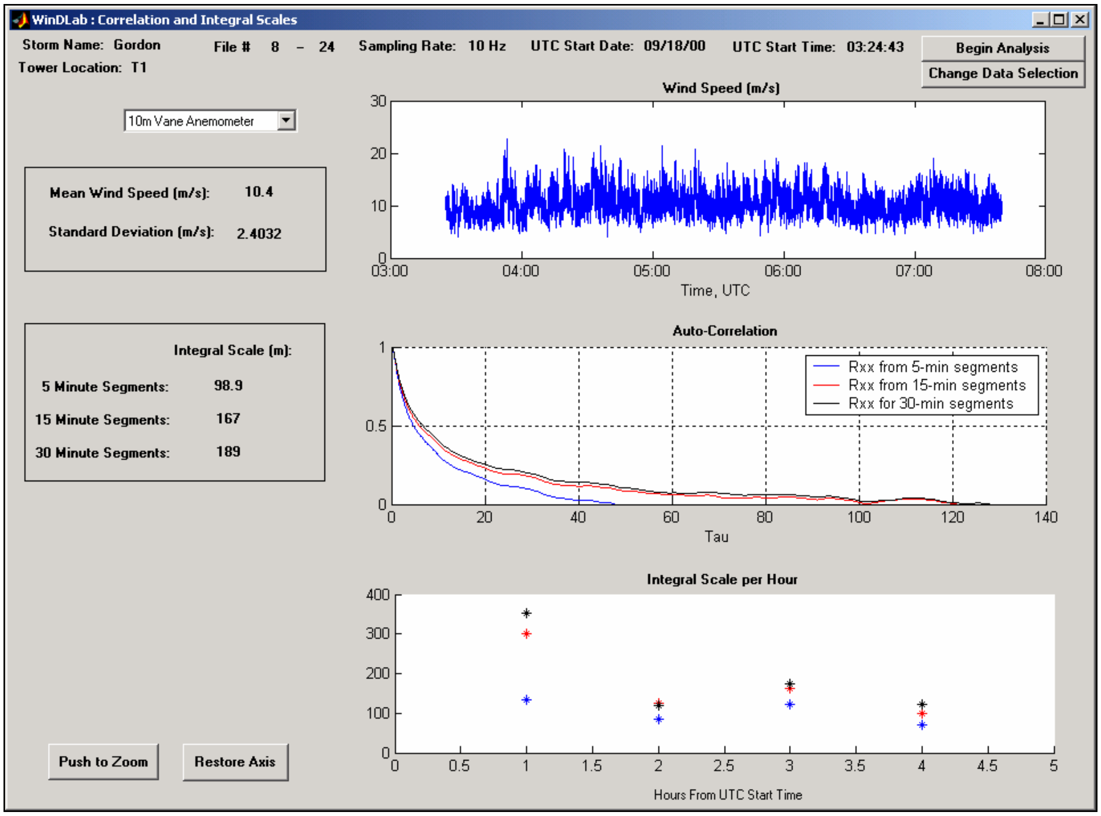


Figure 5-2: Correlation and Integral Scales Window in WinDLab (Version 3)

Improvements to WinDLab

Improvements to the prototype version of WinDLab include: making WinDLab easier to use, the addition of intermediate messages to users waiting for data loading or computation, the addition of time and date stamps to the original data and WinDLab displays, creating a compiled version of the software for dissemination to non-MATLAB users, making the software compatible with the reduced 10 Hz data, and algorithm speed and efficiency improvements. Many of the improvements and changes to WinDLab are discussed in detail below. Before the data sets exported from Tower can be used in WinDLab they must still be processed as was explained in the data collection and processing chapter of this thesis (Chapter 4). Changes to the prototype and compilation of version 3 were completed with MATLAB 6.5 and MATLAB compiler 3.0.

Loading Data

To get started using WinDLab, users must first select the data files that they would like to view and/or analyze using WinDLab. In the prototype version, the data files to be analyzed had to be reselected and reloaded for each analysis window. If the previous analysis window was closed, there would not be a record of which files had been loaded. In addition, the prototype version of WinDLab required the user to input the storm name and tower number in a specific format that is compatible with MATLAB. The user was not informed of the data sets available and the naming system can be confusing to someone unfamiliar with FCMP data cataloging procedures. Loading multiple records can take from a minute, to a half an hour, or more, depending greatly on the number of records loaded and the computer being used. For example, to run a visualization, spectral analysis, and probability analysis, the data of interest would need to be loaded three separate times. When viewing more than one hour of data, the loading process would be time consuming.

FCMP has collected data from nine storms and the list continues to grow every year. To be a practical tool, WinDLab needs to be able to provide the user with some guide as to the type of data available (storm names, location of the towers relative to storm landfall, time frame of available records, etc.). In the WinDLab, Version 3, users may select the files that they want to analyze from the new Load Data window (Figure 5-3). Pull down menus with the names of the storms and toggle buttons for each tower used in that storm are provided along with a map of the tower locations and storm path. A table on the right side of the window provides information on the time frame and number of data files available for each tower in the selected storm. The maps provided on the "Load Data" window were created with MATLAB's mapping toolbox, and include the tower locations and the storm track. GPS coordinates of the storm track were obtained from NOAA. FCMP team members recorded the GPS coordinates of the towers during deployment.

The user is thus guided through the selection of data, and no longer needs any a prior knowledge of the available storms and data files. Once loaded, the data is passed through the handles structure of the main control GUI to each analysis window, removing the need to load data again for each new analysis window. Finally, a pop-up type window was added to indicate the progress while loading data. This is helpful when loading many files, which can take several minutes.

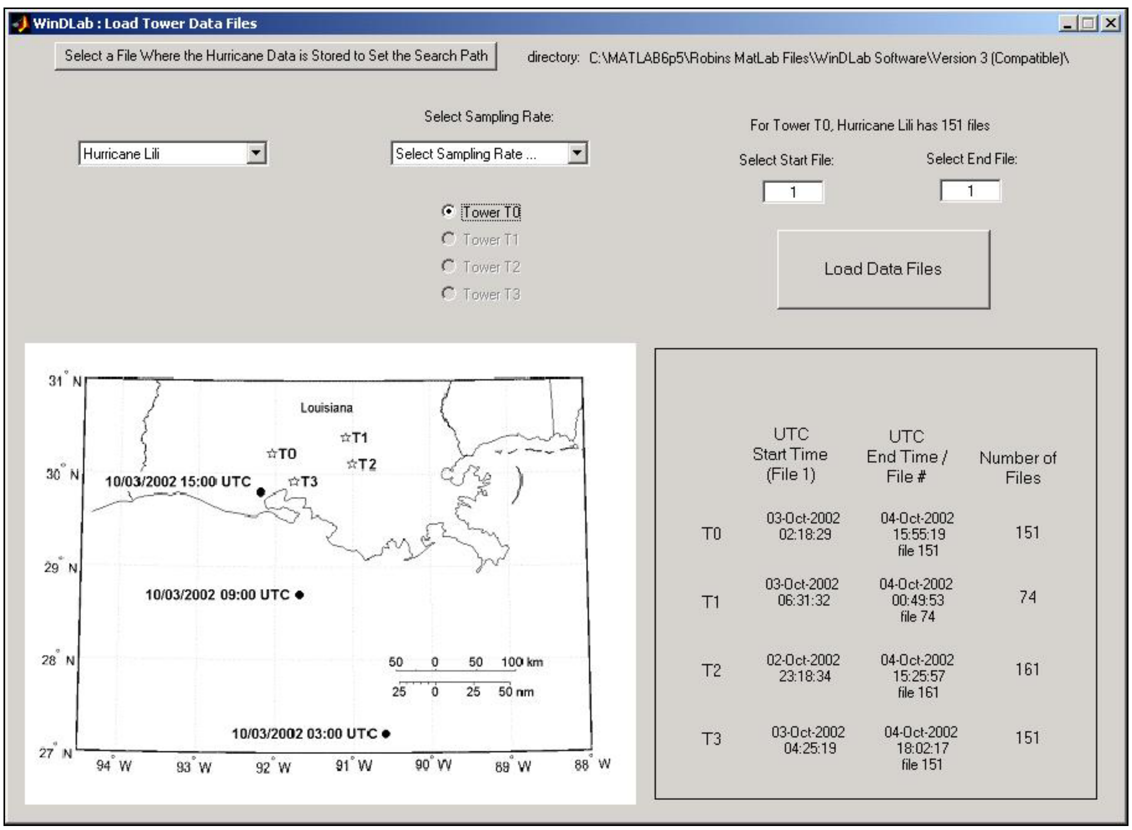


Figure 5-3: New Load Data Window in WinDLab, Version 3

When WinDLab is initiated, the main control GUI is the first to appear. At this point, the user can only select to load data files or view the help files. All other analysis windows are disabled. After the data files have been selected and loaded, the visualization tools and analysis tools become available for the loaded data files. The new Main Control window of WinDLab is shown in Figure 5-4 both before and after the data is loaded. The arrows show the progression of steps available to the user. The circles indicate the visualization and analysis tools available to the user after the data is loaded. The visualization tools allow users to view wind velocity and meteorological data, as described above. The analysis tools include test of stationarity, probability analysis, auto-spectral and cross-spectral analysis, and the calculation of turbulence intensities, gust factors, correlation, and integral scales.

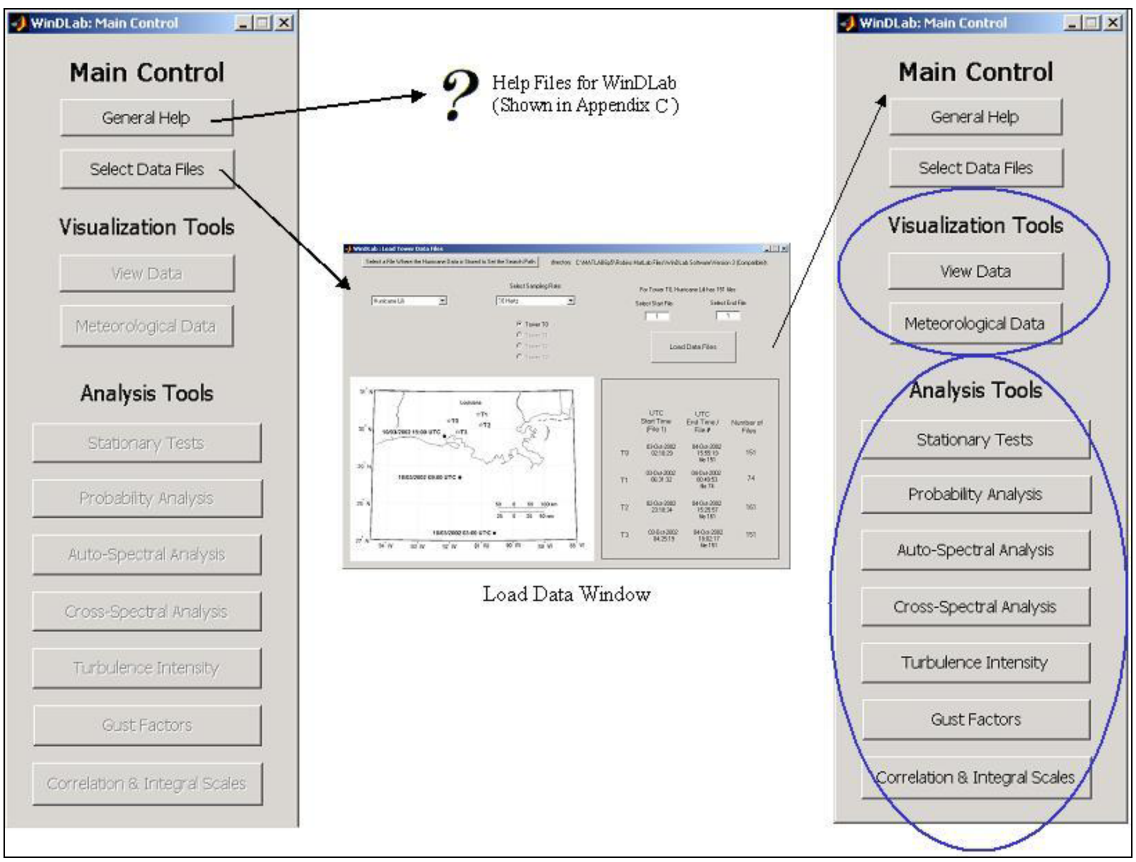


Figure 5-4: Main Control of WinDLab Before and After Loading Data

Ten Hertz Compatibility

The prototype WinDLab was created for the 100 Hz raw data files. Each 15-minute record is about 12 MB once it has been formatted for use in WinDLab. Even with increased standard capacity of computers and the availability of CDs and DVDs, these data files can quickly fill the storage space on a personal computer. Note in Figure 5-3 that there are between 74 and 161 15-minute files for each of the four towers deployed in Hurricane Lili. These files take a long time to download from the FCMP website and to load into WinDLab. Most fluctuations in wind energy and behavior occur at frequencies well below 10 Hz. With this knowledge it was determined that a lower frequency version of our data may be used without a loss of resolution in important wind characteristics. Many changes had to be made within WinDLab in order for it to operate properly with both the original 100 Hz data and the 10 Hz down-sampled data. The user is able to select which data size they would like to use for analysis in WinDLab when they select the data from the Load Data window (shown previously in Figure 5-3).

Common Features and Changes Made to Each Window

Each analysis window now displays the storm and tower selected by the user, the data files selected, the time and date of the first data record, and the sampling rate of the data selected. In the previous version, the user had to re-input the storm and tower information in this location, and then reload the data files. Now the data is passed through the handles structure so the time required to reload the data files is eliminated. Each window contains a “Display Data” or “Begin Analysis” button that instantly gathers the loaded data from the main control GUI handle structure. Adjacent to the display of the loaded data is the option to change the loaded data selection. If this button is pushed, the user is returned to the Load Data window of WinDLab. A comparison of the display provided by each version is presented in Figure 5-5. The top display shows the "File Prefix" the user had to enter for the prototype version. WinDLab now determines this prefix from the user's selections of storm and tower made on the Load Data window. The number of files available for each tower is shown on the Load Data window of WinDLab. The user selects which files they would like to view before loading the data.

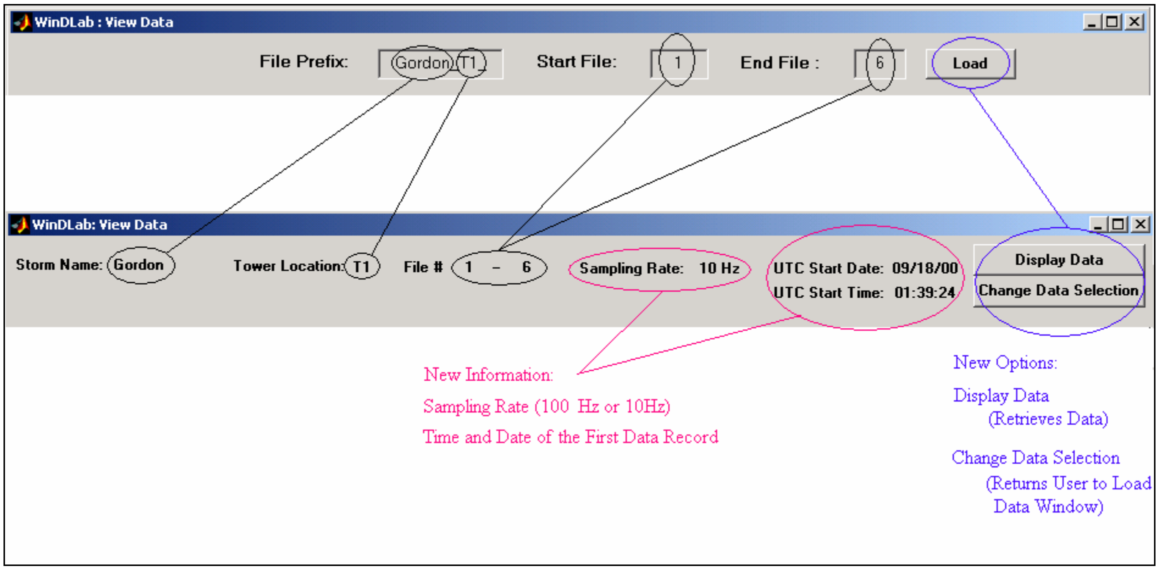


Figure 5-5: Comparison of Display of Loaded Data in WinDLab. Top: Prototype Display. Bottom: WinDLab, Version 3.

Increased Usability

The prototype of WinDLab was very functional for users familiar with its capabilities and restrictions. However, it was determined that new users were expected to know too much about the data and how to use WinDLab. Now the user is guided through each window. Handle properties of the *uicontrols* are used to gray out and disable analysis tools until the user has loaded the data into the window and provided information necessary for analysis. Warning dialogs have been added to warn users if they did not supply all the information needed to operate an analysis tool. In addition, moving wait bars were added to inform the user that WinDLab was still performing the requested calculations. To improve the look of WinDLab, the background of drop-down menus and edit boxes were changed to white to reflect the coloring scheme of Microsoft Windows.

Most windows are equipped with zoom capabilities. The zoom function has been improved in the new version such that the user may zoom by dragging a box over the section they want to see more closely. The original axis is restored with the push of a button. In the prototype, the values on the axis that the user wanted to zoom into had to be entered manually. The alteration of the zoom command made the analysis windows less crowded and easier to use. The View Data windows with the old zoom edit boxes and the new push button zoom capability are shown in Figure 5-6 and 5-7, respectively. The View Data window shows the wind speed and direction. The direction is shown as N, E, S, and W; therefore, the numerical values for the original zoom function were difficult to determine. With the new system, the user can drag a box over the area they would like to view more closely; they no longer have to estimate the values to enter.

Other noticeable changes between the windows in Figure 5-6 and 5-7 include the x-axis of the plot windows and the wind direction. In Figure 5-6, the prototype, the x-axis only shows the amount of time past, using the beginning of the loaded data as the zero-reference. The new x-axis (Figure 5-7) reflects the actual time the data was collected, and the addition of the date to the top of the window completes the information on exactly when the data being analyzed occurred. This addition was made possible by the database management portion of the work. As described in Chapter 4, the appropriate time and date stamps were added to each of the existing files.

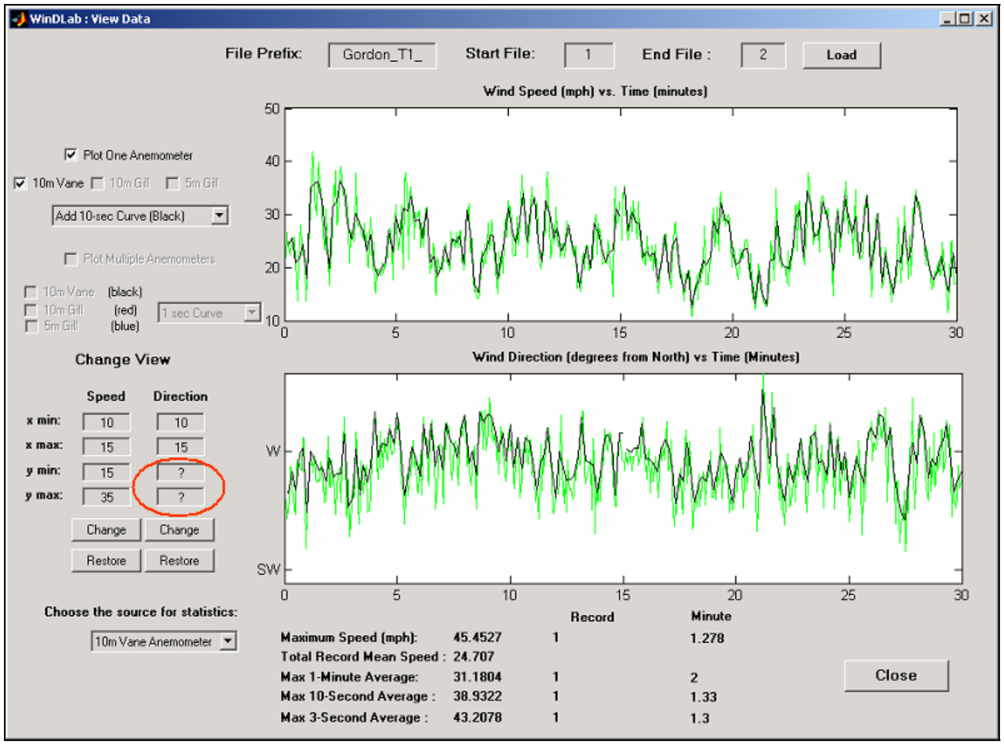


Figure 5-6: View Data Window for WinDLab Prototype Version with Edit Zoom Boxes

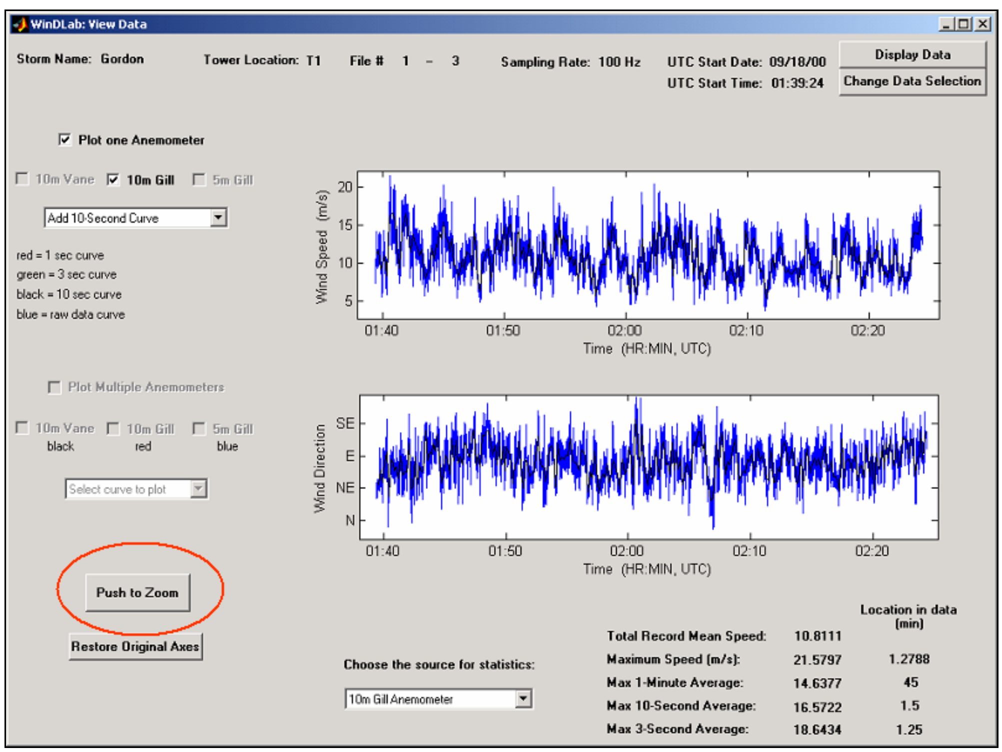


Figure 5-7: New View Data Window for WinDLab, Version 3. with Dragging Mouse Zoom Capability.

The difference in the wind direction between the windows in Figure 5-6 and 5-7 is due to the correction of the trailer angle from the prototype version. The angle shown in Figure 5-6 is actually with respect to the trailer (not north). Figure 5-7 shows the direction with respect to north.

Compilation of WinDLab

The prototype version of WinDLan can only be run using a MATLAB platform. Although powerful, MATLAB is expensive, and not every potentially interested researcher will own a license. MATLAB 6.0 or more current must be used to run the GUIs contained in WinDLab. MATLAB offers a compiler that will allow GUIs or codes written in MATLAB to be used without the presence of a MATLAB platform. Compilation of WinDLab creates a stand-alone application that is self-contained and therefore can be packaged and distributed via a CD or our project web site. MATLAB Compiler 3.0 was used to create a MATLAB independent version of WinDLab. Many changes had to be made within WinDLab before it could be successfully compiled. The examples provided below are not a comprehensive listing of the upgrades made in the 3.0 version of WinDLab, but give some indication of the work needed to convert the original version to an executable.

Compiler Limitations and Work-Arounds

Many MATLAB functions are not supported in the stand-alone applications created by MATLAB Compiler 3.0. Limitations and restrictions are presented in the MATLAB Compiler User's Guide (MATLAB Compiler 2002). Most functions listed in the User's Guide were not used in the creation of WinDLab, or they were easily substituted. However, many limitations not presented in the User's Guide were discovered during the compilation of WinDLab. These limitations were determined through trials of compiling the individual GUIs of WinDLab. Determining limitations and creating methods to work around them was an iterative and lengthy process.

MATLAB allows users to establish a search path to locate data files on a computer. This path can be used to allow WinDLab access to the data files without the user having to place them in the same directory as WinDLab. This path is not accessible within the stand-alone version. WinDLab and the FCMP data files will be available for downloading from the FCMP website. The placement of these data files on each individual machine is unknown and, therefore, cannot be pre-programmed into WinDLab. MATLAB provides a command *uigetfile* that allows the user to search for a data file on their computer. This command is typically used to load a data file; however, it can also be used to return the path name and file name of the data file. On the Load Data window, the user is asked to locate a file within the same directory as the hurricane data files. When the user presses "open", the path to the data files is stored within the GUI. WinDLab then uses the path to load the data files selected by the user.

MATLAB uses the *load* command to load data files. WinDLab users can load any number of FCMP data files into WinDLab as long as they are sequential. A character string that represents the file name is created based on the storm and tower selected by the user and the files they have selected. The character string cannot be used directly after the *load* command. The command *eval* must be used in conjunction with load command and the character string. However, the compiler will not allow the use of this combination. The *load* command must be combined into one character string which contains the file name before using *eval*. The new Load Data window creates the proper character string, combines it with the path to the directory, and then evaluates the string as a command.

Another limitation that was discovered is that MATLAB Compiler does not allow the use of multiple legends in GUIs. This was a common occurrence throughout WinDLab. Figures 5-8 and 5-9 show the Gust Factor window of the prototype and version 3 of WinDLab, respectively. The need for multiple legends in the compiled version was handled through the creation of stationary legends.

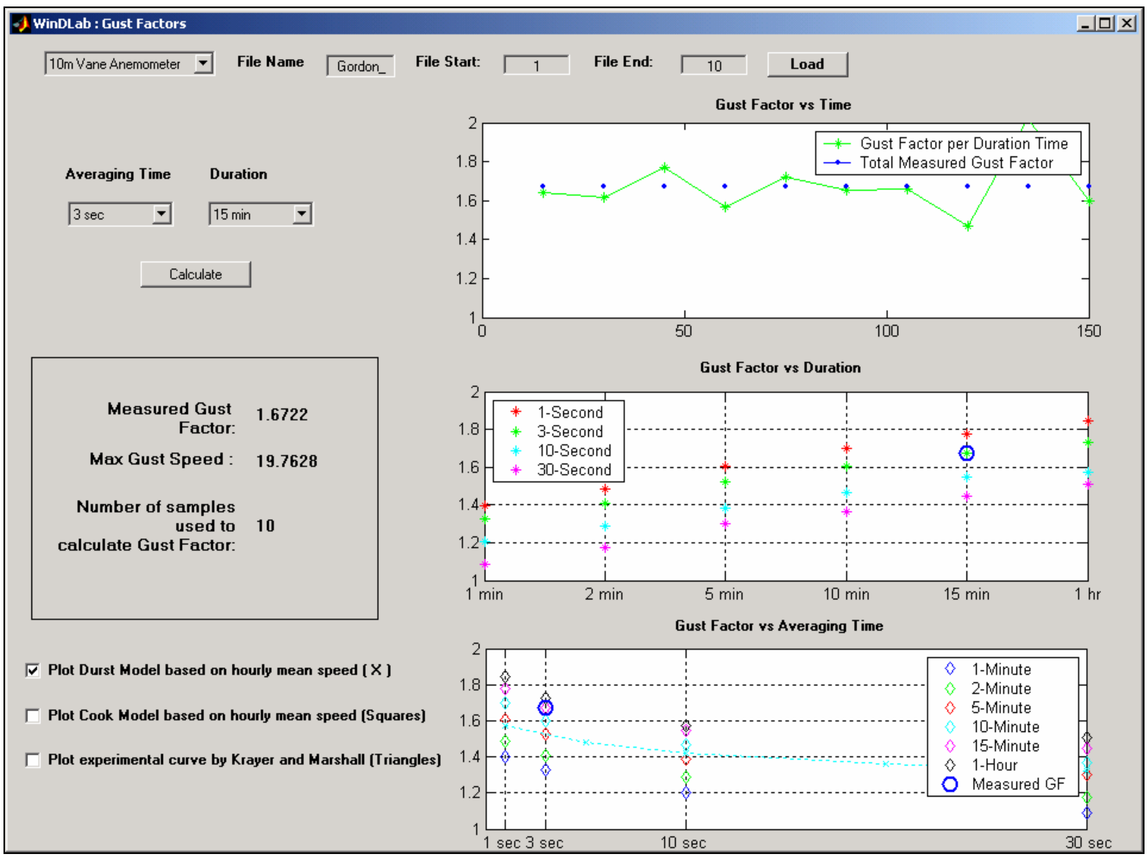


Figure 5-8: Prototype Gust Factor Window (Cuenca 2002)

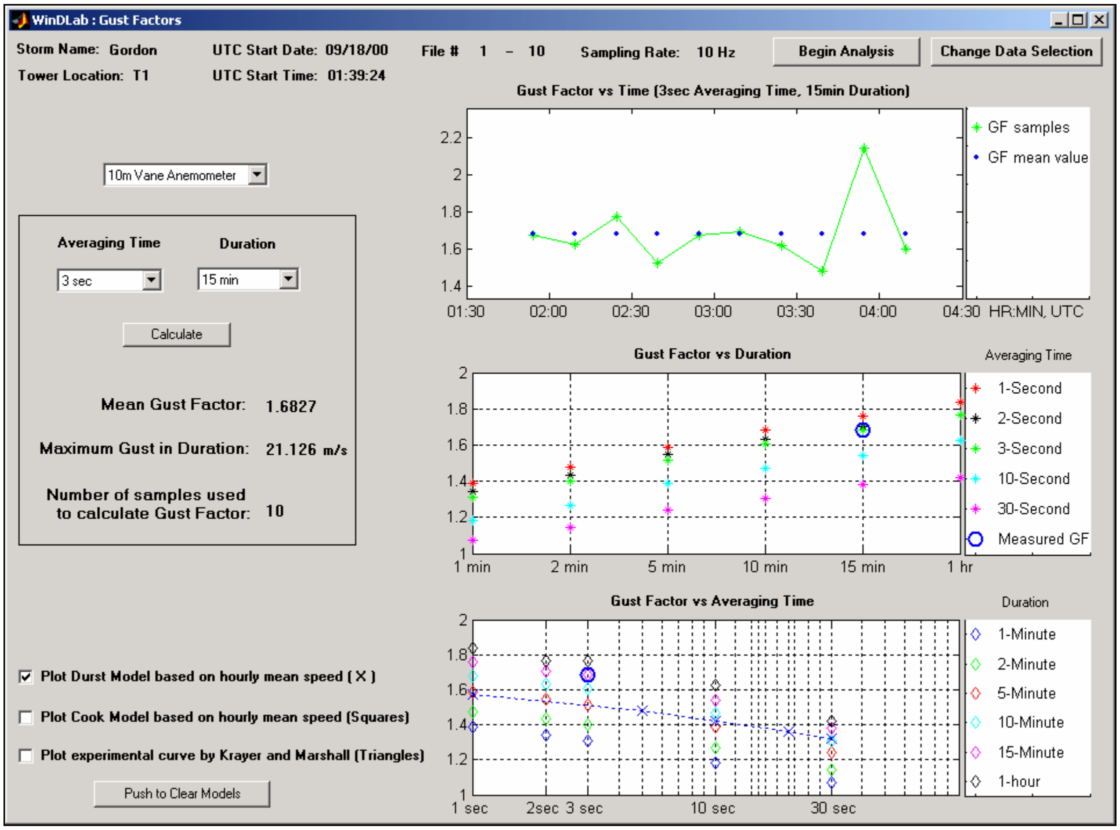


Figure 5-9: Gust Factor Window with Stationary Legends (WinDLab, Version 3)

<u>WinDLab for the House Pressure Data</u>

WinDLab, as presented so far, has been developed to work with the wind velocity data collected from the portable towers. A companion tool to allow analysis and visualization of the pressure data collected from the houses was developed as a contribution of this thesis. The new software is titled WinDLab_H for House Wind Data Laboratory and is described in Chapter 6.

CHAPTER 6
HOUSE WINDLAB SOFTWARE DEVELOPMENT

Introduction

An extension to WinDLab has been developed to analyze the pressure data collected by the FCMP homes. This software, Wind and House Data Laboratory (WinDLab_H) allows users to view the pressures on the instrumented homes in relation to the wind speeds and direction and provides a comprehensive tool for performing analysis on pressures collected from low-rise homes during hurricane and tropical storm landfall. The reduction and analysis of pressure data is significantly more complex than for the wind velocity data from the towers. Clemson and UF researchers have been developing algorithms in tandem to translate the pressure data from its raw form to a form useful for analysis within WinDLab_H. WinDLab_H was created using MATLAB 6.5 and the GUI creation tool, GUIDE, provided by MATLAB. The development of WinDLab_H is a major contribution to this thesis, and the subject of this chapter.

The layout and operation of WinDLab_H is based on WinDLab; therefore, the user does not have to learn a completely new program. WinDLab_H is divided into 3 major components: Data selection and loading, data visualization, and data analysis. The visualization tools for WinDLab_H have been expanded and are different than those available in WinDLab. The new visualization tools include:

- Viewing wind speed and direction in relation to the house
- Viewing the wind speed and the pressures at two pressure tap locations
- Viewing the pressure coefficients as calculated from in-field data collection

- Viewing the pressure coefficients as calculated using ASCE7
- Viewing the pressure coefficients as calculated from wind tunnel tests conducted by Clemson University (in progress)

The analysis tools available in WinDLab_H are the same as those available in WinDLab. These tools may be easily altered to better-fit wind pressure behavior in future versions of WinDLab_H. Analysis tools currently available include:

- Stationarity check
- Probability analysis
- Auto-spectral analysis
- Cross-spectral analysis
- Calculation of turbulence intensity
- Calculation of gust factors
- Viewing correlation and integral scales

Data Selection and Loading

WinDLab_H has a central loading window that operates similarly to the Load Data window provided in WinDLab, Version 3. For each storm, a map with the locations of the homes instrumented is provided, along with the storm track. These maps also provide a view of where the portable towers were deployed so the user can access the accompanying tower data using WinDLab if desired. The maps are being created using the same MATLAB mapping software used to create the tower maps. If no house data was collected for the storm collected, the statement "No House Data Collected for this Storm" replaces the map. For each storm used to collect data, a placeholder map was integrated into WinDLab_H (Figure 6-1). The placeholder maps are marked in the script file; therefore, the finished maps can be easily installed once they are created. A map with the locations of all homes that are wired to accept instrumentation is also available from the Load House Data window. When the user presses the "View Map of All FCMP Homes", a separate window showing the map provided in Figure 2-10 is opened.

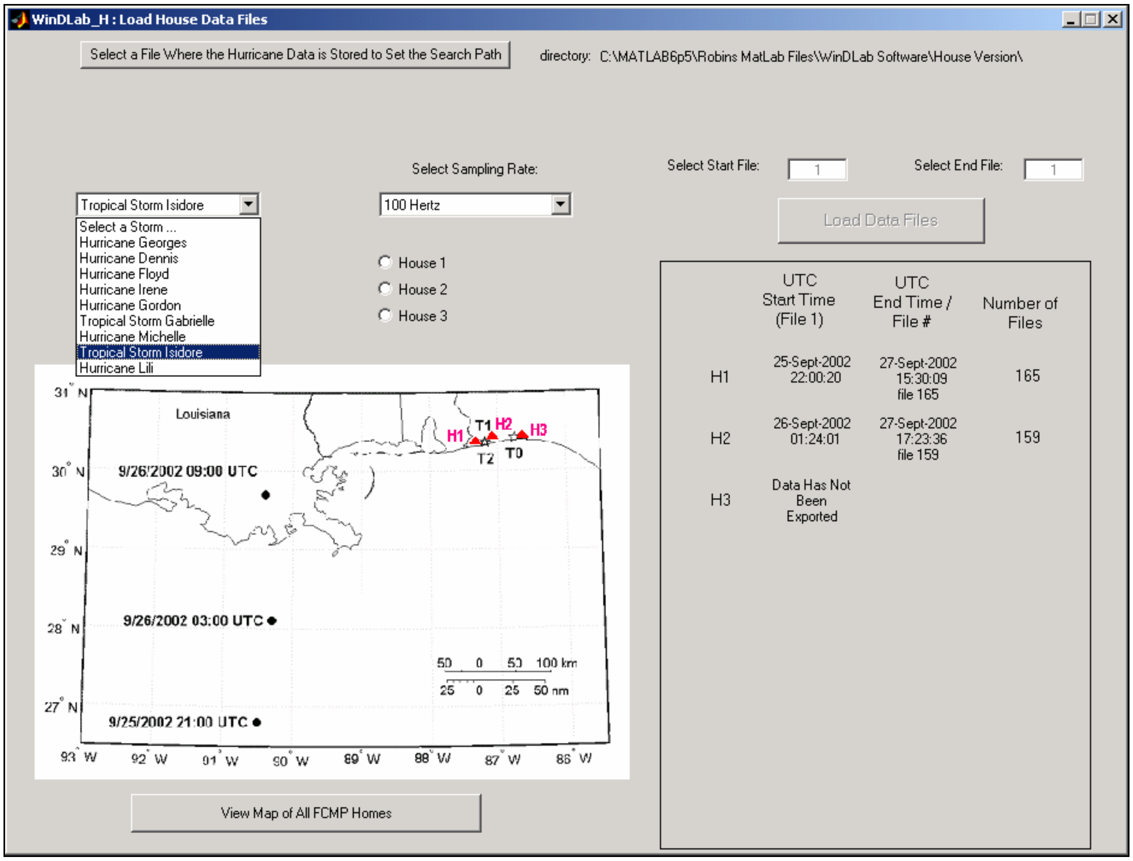


Figure 6-1: Selection of Tropical Storm Isidore from the Load House Data Window

When a house is selected, a layout of the roof and pressure taps is opened in a separate window. An example roof layout figure is shown in Figure 6-2. Clemson University is in the process of creating these layouts for the actual FCMP homes. The user may keep this window open for future reference when choosing which tap(s) from the house to analyze.

Main Control

The Main Control window (Figure 6-3) provides the user with a way to view and access the visualization and analysis tools available in WinDLab_H. This window contains pushbuttons that open the help files, the Load House Data window, the five new visualization windows, and the seven analysis windows. To start using WinDLab_H, users must first select the data files that they would like to view and analyze. This can be achieved by pushing the “Select Data Files” button. This will take the user to the Load House Data window described in Figure 6-1. The visualization and analysis buttons are only accessible after loading the data, as was the case for WinDLab, Version 3, described in Chapter 5.

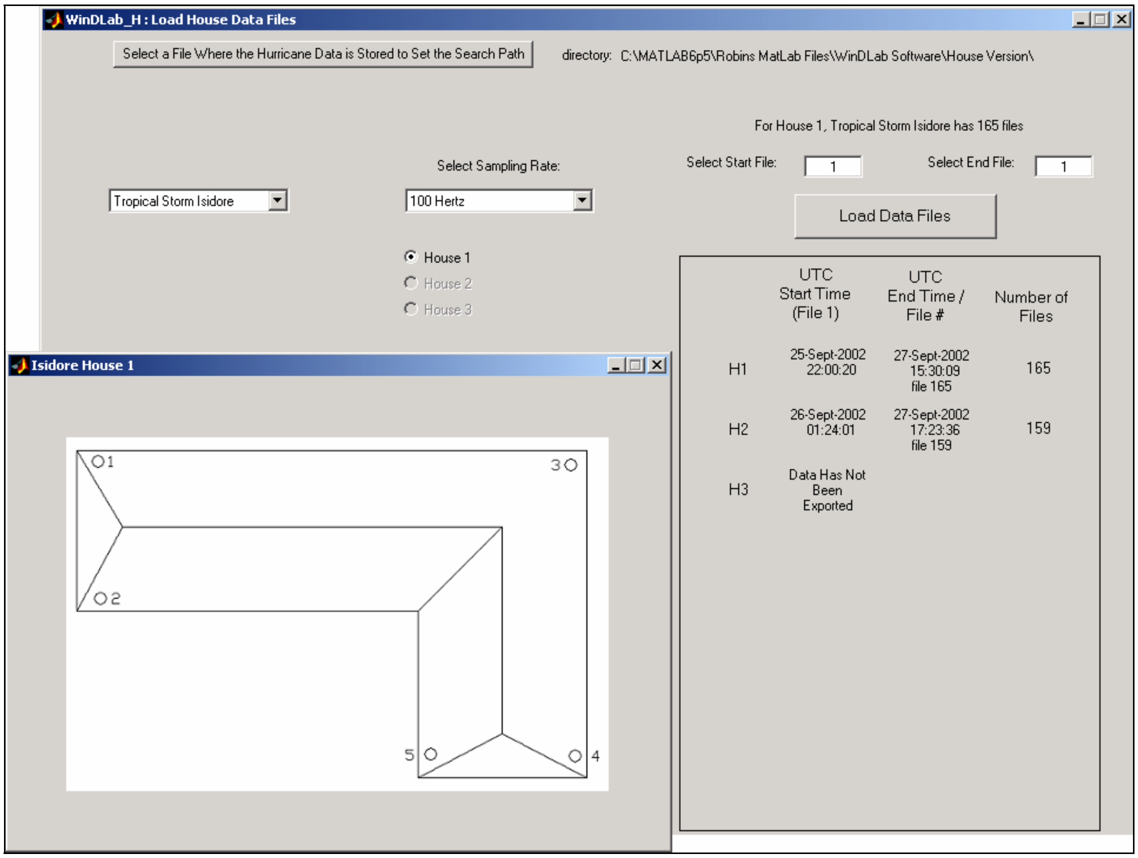


Figure 6-2: Example Roof Geometry and Pressure Tap Layout Resulting from Selection of House 1 on the Load House Data Window

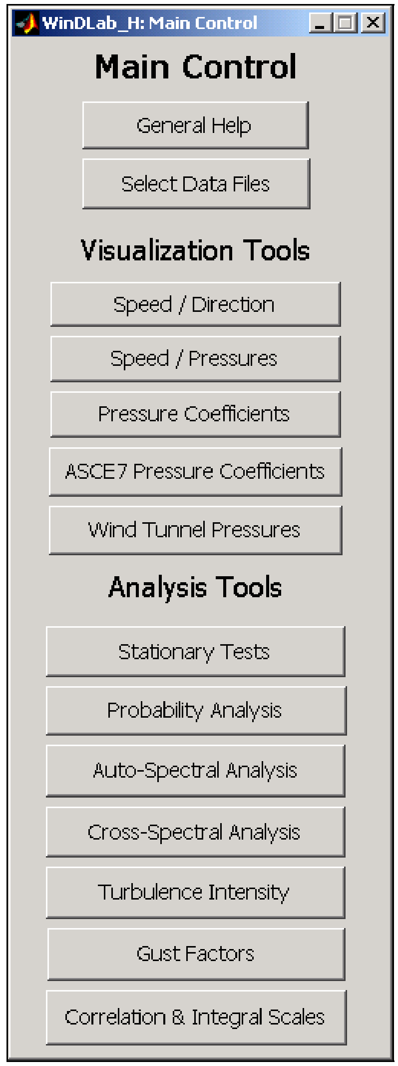


Figure 6-3: WinDLab_H Main Control Window

<u>Pressure Selection</u>

Atmospheric pressure is measured at a remote location using a pressure sensor located on the Johnny 5 video camera set up in the yard of the house. The pressure sensors used on the instrumented homes measure absolute pressure. An absolute pressure is the total pressure acting at the location of the pressure tap and includes the forces due to the atmosphere and the local wind. The atmospheric pressure is the pressure due to the weight of the earth's atmosphere. This pressure varies with hurricane passing. Most windows in WinDLab_H allow the user to select between viewing the pressures in absolute or relative pressure, where relative pressure is simply the absolute minus the atmospheric pressure. This relative pressure is the pressure 'felt' by the house at the location of the pressure tap.

Wind Speed and Direction

Each home is instrumented with one or two anemometers. These anemometers are cup anemometers, and therefore report the speed and direction in a 2-D (horizontal) environment. The house data record used to develop WinDLab_H was equipped with one anemometer. Wind velocity data collected from the ten-meter towers will be used to characterize the wind behavior near the home as it interacts with the structure, and the cup anemometer on the house will be used as the local reference velocity. This reference velocity will be used in conjunction with relative pressure to estimate the pressure coefficient, discussed in a later section of this chapter.

Exporting and Processing Data

House data is stored in a compact binary format as it is collected using House, a C++ based software code written at Clemson for use with FCMP equipment. Before analysis can take place, these sets are first exported into individual fifteen-minute files in an ASCII format. The data is then transformed from ASCII to MATLAB format to compress the data files and to convert them into a form that can be easily accessed and used within the MATLAB environment. House data is recorded in vector format with thirty-two or thirty-four columns. The columns include:

- The time step, in fractions of a second (1)
- The reference pressure, from the Johnny 5 (2)
- Twenty-eight channels of pressure data (3-30)
- Direction from each anemometer (31, and 32 if two anemometers)
- Speed from each anemometer (33, and 34 if two anemometers)

Individual columns of the exported data array are saved as descriptive variables within each fifteen-minute record. WinDLab_H uses these variable names to access the pressure and wind velocity data within the loaded data files.

The exported data is in volts, measured between zero and ten. Clemson University is currently developing algorithms to convert the data into the corresponding engineering units for wind speed and direction, and absolute and atmospheric pressures. Note that the examples of the various windows in this chapter display the data in volts and not engineering units. This is easily corrected once Clemson has finalized the data processing procedures.

Visualization and Analysis Tools

Following are descriptions of the visualization and analysis tools available in WinDLab_H. All values shown are from Tropical Storm Isidore, 2002. For Isidore, three homes were instrumented to collect data. The pressure data from House 1 and House 2 have been exported. Data files from Isidore, House 1, have been converted to MATLAB format and were used in the development of WinDLab_H.

Visualization Tools

WinDLab_H contains five windows that allow users to view the pressure and wind data collected by the homes (refer to Figure 6-3). The last three of the five visualization tool buttons: “Pressure Coefficients”, “ASCE7 Pressure Coefficients”, and “Wind Tunnel Pressures” buttons open GUI windows that display the distribution of pressure coefficients on the roof as calculated from the full-scale data, ASCE7 wind load provisions, and the Clemson wind tunnel, respectively.

Pressure coefficients, C_p, are used to calculate design pressures on structures for a given wind velocity. This coefficient is a ratio of the relative pressure at a given location with the square of velocity (Equation 6-1).

$$C_p = \frac{p - p_o}{\frac{1}{2} \cdot \rho \cdot V^2} \qquad \text{Equation 6-1}$$

where p is the absolute pressure (roof pressure transducer)

p_o is the atmospheric reference pressure (Johnny 5)

ρ is the density of air

V is the mean reference wind velocity (roof anemometer)

The “Pressure Coefficients” visualization window is intended to display the C_p on the FCMP houses as measured full-scale. The “ASCE7 Pressure Coefficients” window is intended to provide a view of the C_p on the house as specified in the ASCE 7-98 provisions. The “Wind Tunnel Pressures” window is intended to provide the C_p on the house as measured in the Clemson wind tunnel. Thus, these 3 windows together would contrast code loads with measured full-scale and wind tunnel loads for the same house. These windows are still under development. The UF team is awaiting additional information from Clemson (FCMP house schematics, data processing algorithms, and wind tunnel results) before they can be completed.

The first two of the five visualization tool buttons: the “Speed / Direction” and “Speed / Pressure” visualization buttons open the Wind Speed and Direction and Wind Speed and House Pressures windows. The wind speeds and directions used in these windows are from the first roof anemometer data recorded. The wind speeds and direction are presented in volts. However, the wind directions were multiplied by 36 to convert them to degrees. These two visualization windows have been completed, with details to follow.

<u>Wind speed and direction</u>

The Wind Speed and Direction window provides an active compass to view the wind direction with respect to the house. This window is accessed from the "Speed / Direction" button on the Main Control. The wind speed and wind direction are plotted in separate windows with a slider bar between them (Figure 6-4). Users can move the slider bar to view the direction corresponding to that time on a compass placed above the house roof layout using their mouse. After the slider is moved, and the mouse button is released, a line showing the selected location is plotted on both the wind speed and wind direction windows, and an arrow corresponding to the direction is placed on the compass. Figure 6-5 shows the wind direction plot zoomed in to verify that the compass direction matches the direction for the location chosen. The compass and the house layout are oriented north so that they may be easily compared. The mechanics of the wind loading can change dramatically at a point on the roof as a function of direction. This feature allows the user to quickly locate segments of data that may represent, for example, a flow regime change from separation to re-attachment zone, producing very different kinds of loading on the roof.

Pressure values may also increase or decrease significantly with changes in wind direction. Hurricanes rotate counterclockwise in the northern hemisphere. As the storm approaches land, winds generally flow east to west. If the storm passes to the west of the home, this direction will change to a south to north then west to east flow as the hurricane passes by. Users can use this window along with the Wind Speed and House Pressures window (next) to view variations in the pressures as the wind direction changes.

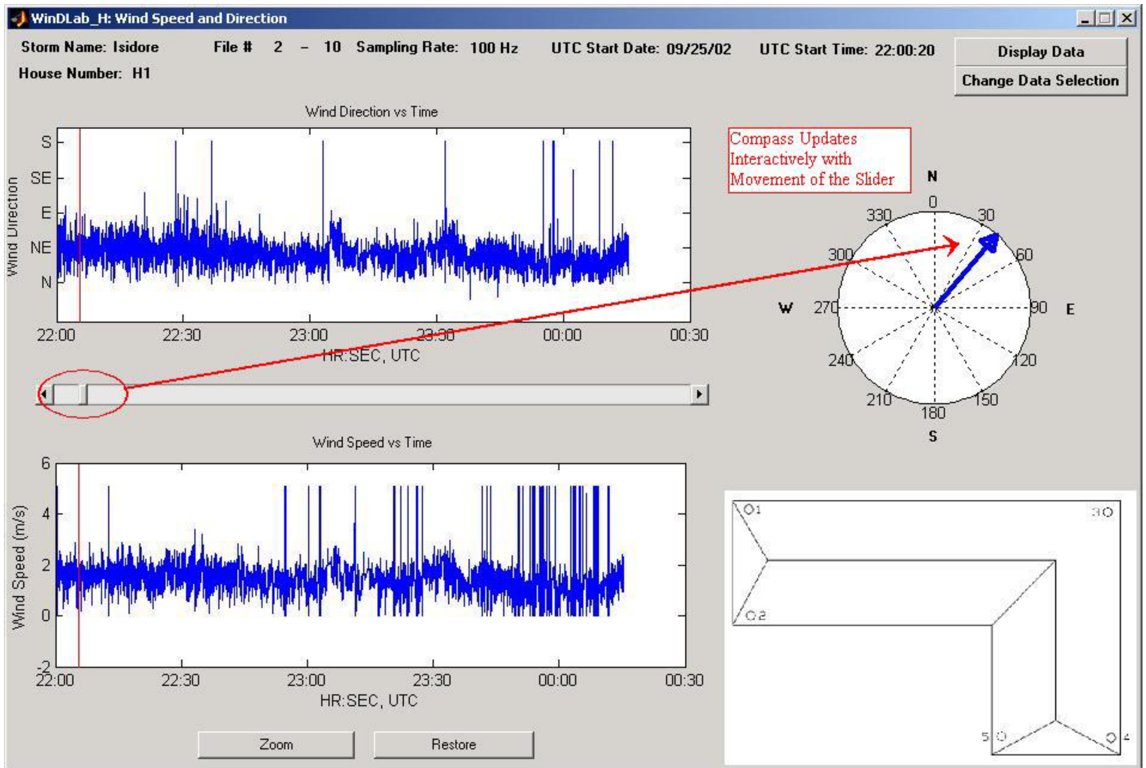


Figure 6-4: Wind Speed and Direction Window in WinDLab_H

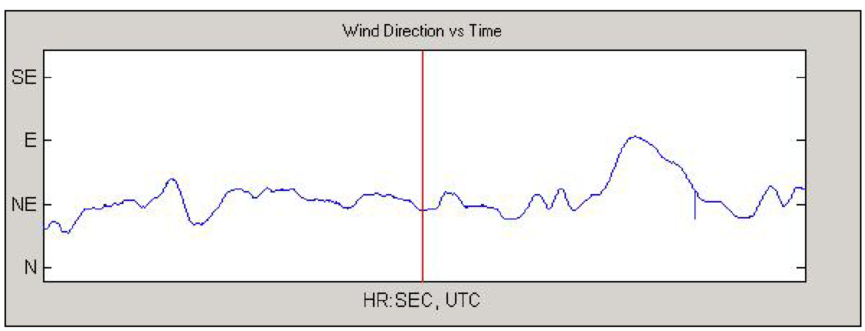


Figure 6-5: Zoom View of Wind Direction Plot

<u>Wind speed and house pressures</u>

The Wind Speed and House Pressures window contains three plots and a layout of the pressure sensors. It may be accessed by pushing the “Speed / Pressure” button on the Main Control. The top plot displays the wind speed from the anemometer and the bottom plots display the pressures from individual pressure taps (see Figure 6-6). The users may select the pressure taps they would like to view from drop-down menus located next to each of the plots. The pressures can be plotted as absolute or relative. In addition to the pressure plots, the correlation coefficient between the two pressure taps is calculated and presented. The correlation coefficient, ρ_{xy}, will lie between –1 and +1 and is calculated as the ratio of the covariance to the product of the standard deviation of the two processes (Equation 6-1).

$$\rho_{xy} = \frac{C_{xy}}{\sigma_x \sigma_y} \qquad \text{Equation 6-1}$$

Where $C_{xy} = E\left[\left(x(t) - \mu_x\right)\left(y(t) - \mu_y\right)\right]$

σ_x and σ_y are the standard deviations of x and y

μ_x and μ_y are the mean values of x and y

E [ ] is the expectation operator (taking an average)

t is time

The correlation coefficient describes the linear dependence between the taps in the analysis, where 0 indicated no dependence, 1 is perfect dependence, and -1 is anti-dependence. This will aid in determining if different pressure taps experienced the same impinging gusts, and in quantifying the average size of these gusts. The layout of the taps is provided for quick reference of numbering.

<u>Analysis Tools</u>

The analysis tools available in WinDLab_H are the same as WinDLab, Version 3; therefore, the analysis tools are not described in detail. Rather, the following sections describe how these tools may be used to interpret the pressure data. Each window, and the changes made to the window, are also described briefly in this section.

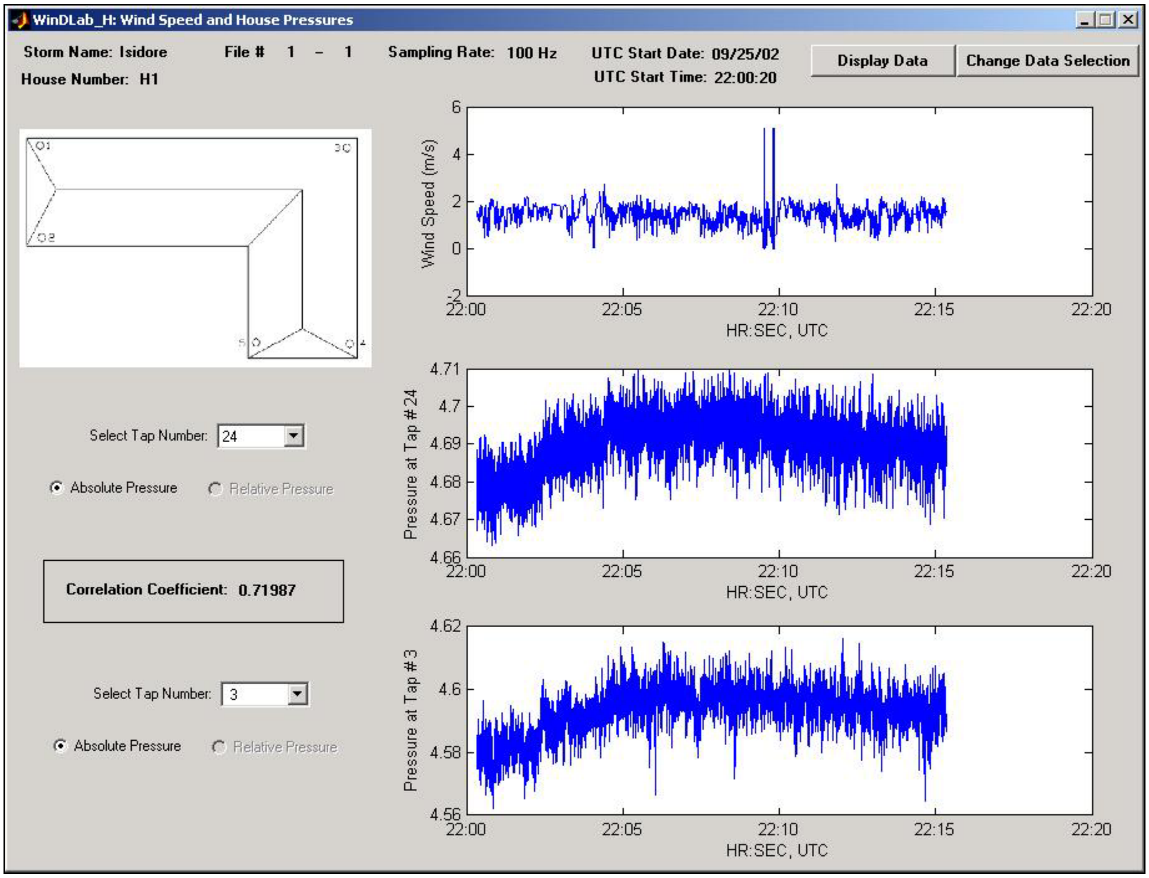


Figure 6-6: Wind Speed and House Pressure Window in WinDLab_H

<u>Stationary tests</u>

The Stationarity window (Figure 6-7) is the first analysis tool available in WinDLab_H, since the use and applicability of the other analysis tools depend on the degree of stationarity of the data. Full-scale pressure data on low-rise structures is often non-stationary. Turbulent eddies that occur as wind interacts with a structure result in non-stationary pressure data characteristics. Changes in mean wind speed, direction, and energy also lead to non-stationary behavior.

Weak sense stationary behavior, as described in Chapter 5 of this thesis, requires that the first and second statistical moments do not vary significantly with time. This window presents plots of the mean pressure, the standard deviation of the pressure, and the turbulence intensity as well as the slope of each plot. If no large variations are present in the data the slope will be approximately zero, and the data can be considered weakly stationary. The data shown in Figure 6-7 is in volts. All voltage values reported by House are between zero and ten.

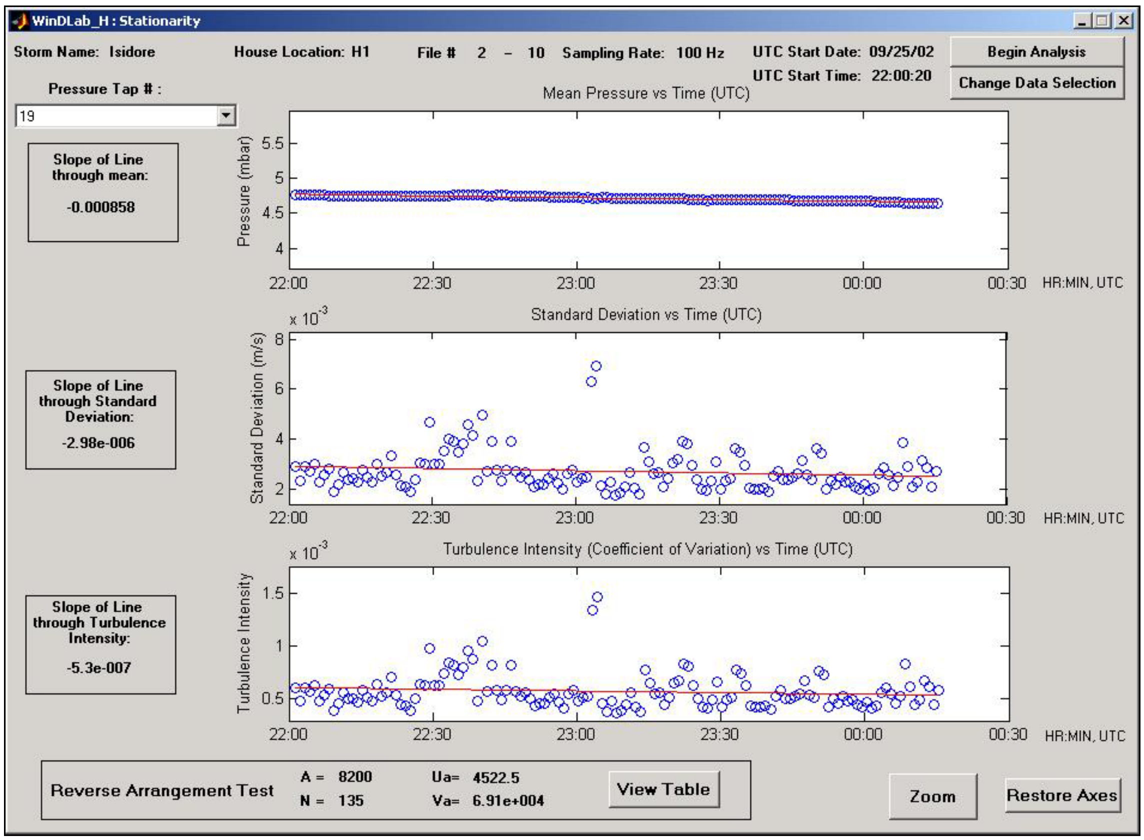


Figure 6-7: Stationarity Window

<u>Probability analysis</u>

As described in Chapter 5, the probability distribution function (PDF) describes the probability of an occurrence of a range of values of a random variable. For the pressure data, the PDF describes the probability that a pressure of a certain magnitude will occur within the loaded data records. Currently, the PDF models available in WinDLab_H are the same as WinDLab, Version 3. Most of these models are more applicable to wind speed, not pressures. Therefore, these models are expected to change in future versions of WinDLab_H. The window also reports the first four central moments of the loaded data. These statistics will be used to better characterize pressure behavior in extreme wind events.

The display generated in the probability analysis window considers both wind speed and local pressure. The “Display Data” button retrieves the loaded data from the Main Control handle structure and plots a histogram of the wind speed from the roof anemometer with a Gaussian fit (Figure 6-8). This plot provides users with a display of the wind speed behavior associated with the wind pressure data they are about to analyze. This window is not meant to provide details about the wind; therefore, the first four central moments are not calculated for the wind speed and no other fits may be applied to the wind speed. This plot is removed when a pressure tap is chosen.

When a pressure tap and PDF model are selected from a pull-down menu, the histogram of the pressure data and the model are plotted in the top window. Figure 6-9 shows the histogram of the pressure data from tap 22 on Isidore House 1. This record shows multi-modal distribution behavior that is quite intriguing. Once the pressure data is converted from volts to pressures, the relative difference of the peaks can be computed and the fluctuations of the wind speed and direction should be compared to further investigate this unusual behavior.

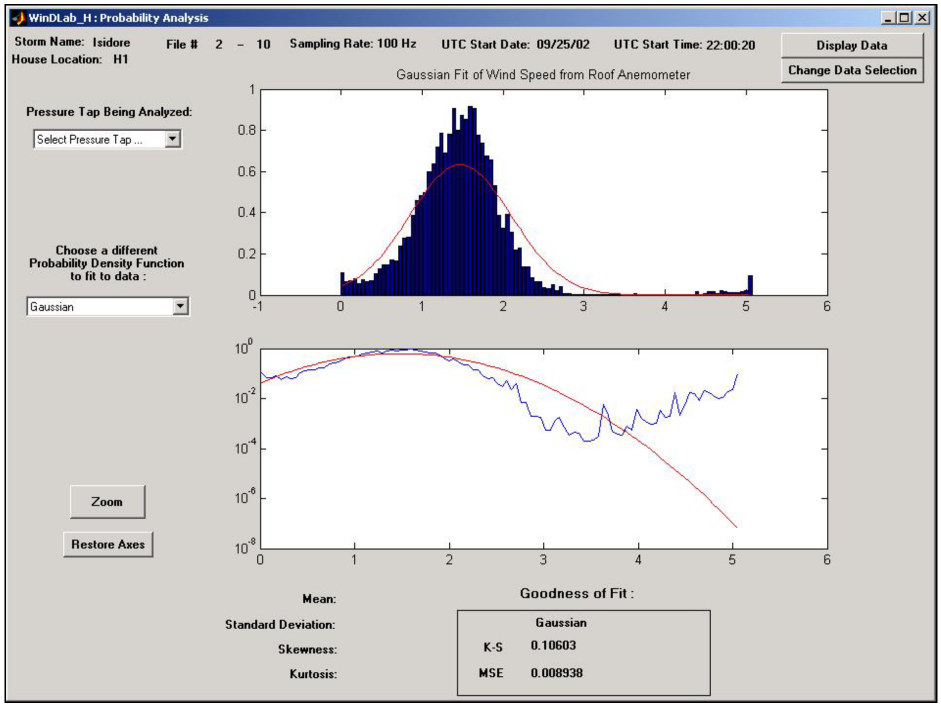


Figure 6-8: Gaussian Fit of Wind Speed from Roof Anemometer

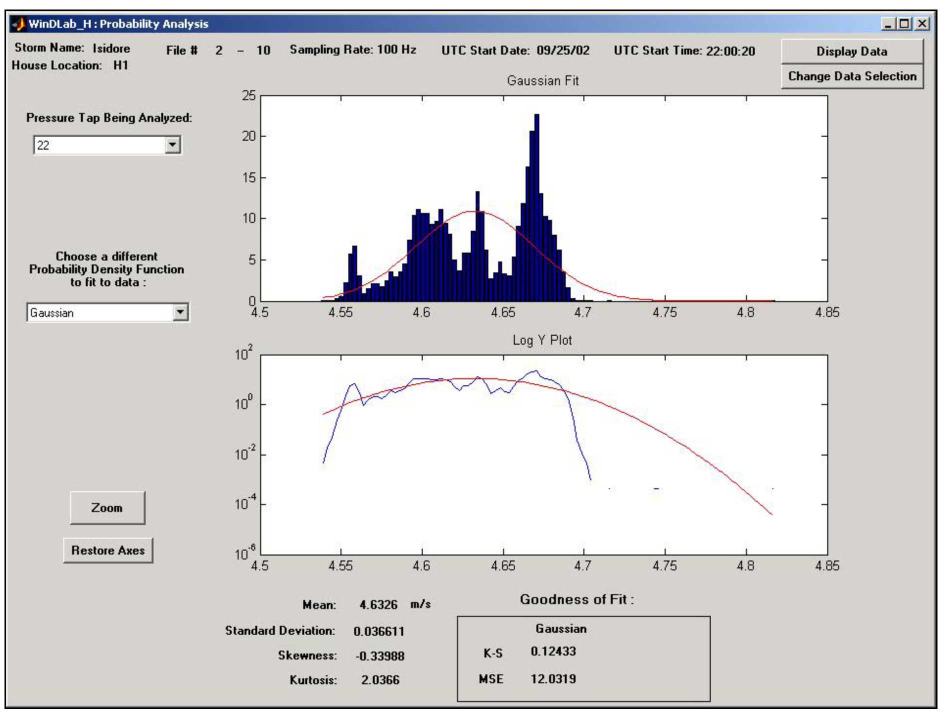


Figure 6-9: Probability Analysis Window

Auto-spectral analysis

The Auto-Spectral Analysis window computes the distribution of variance with frequency, or the power spectral density (PSD) function. Variance is related to the amount of energy in the system; therefore a plot of the PSD allows the user to visually determine at which frequency most energy in the process occurs. Figure 6-10 show the PSD for the pressure data from tap 1. A future version of WinDLab_H will contain empirical models of pressure PSD for comparison.

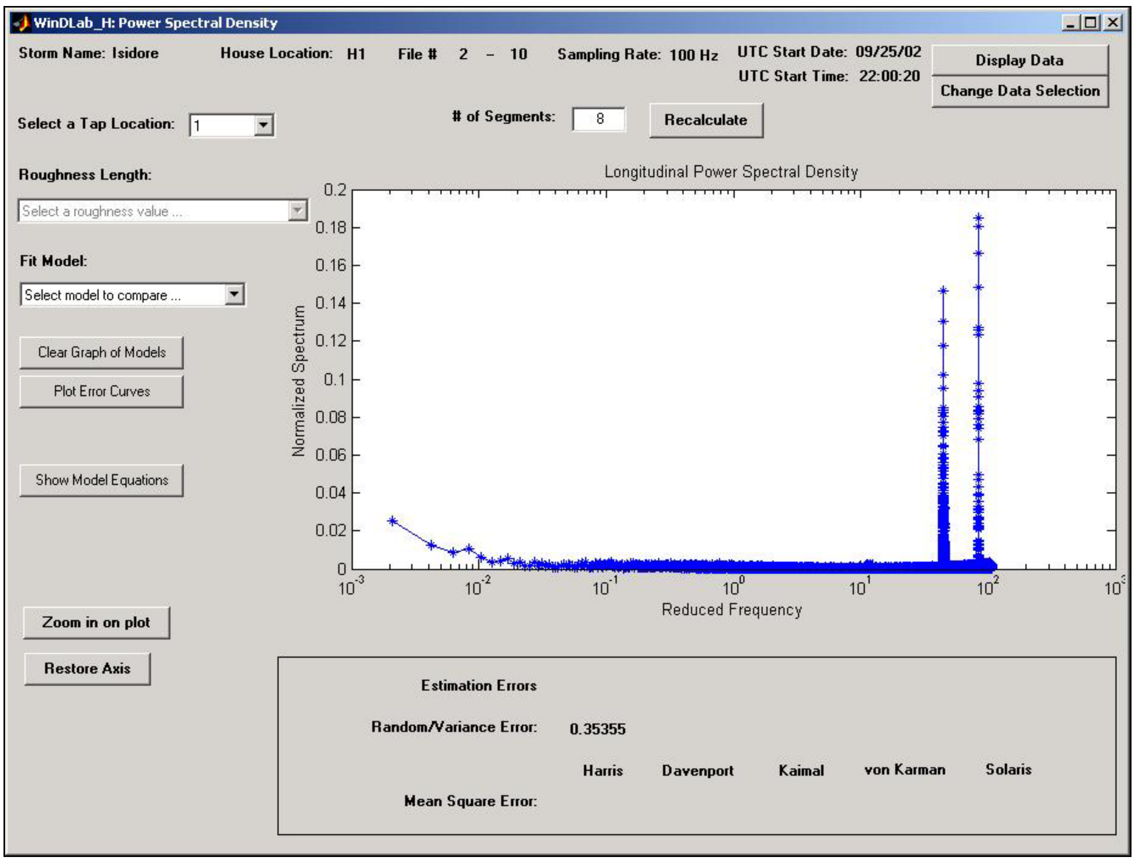


Figure 6-10: Power Spectral Density Window (Auto-Spectral Analysis)

Cross-spectral analysis

The Cross-Spectral Analysis window calculates the cross-spectral density magnitude and phase, and coherence (Figure 6-11). The coherence function was presented in Chapter 3, Equation 3-1, of this thesis and describes the degree of correlation between two processes. This window calculates the coherence between the two taps selected by the user (taps 11 and 18 in this example). The user may select the number of ensembles to divide the data record into before using the Fast Fourier Transform to calculate the cross-spectral density function. The correlation coefficient is calculated from Equation 6-1 and is displayed in the lower left of the window. In this example, taps 11 and 18 are very strongly correlated, as indicated by a coherence of 1.0 from the 10 to 100 Hz range, and the correlation coefficient of almost 1.0. This suggests that the taps are very close to each other and experiencing the same gusts. When Clemson delivers the schematics of tap locations for the house under analysis, this can be investigated further.

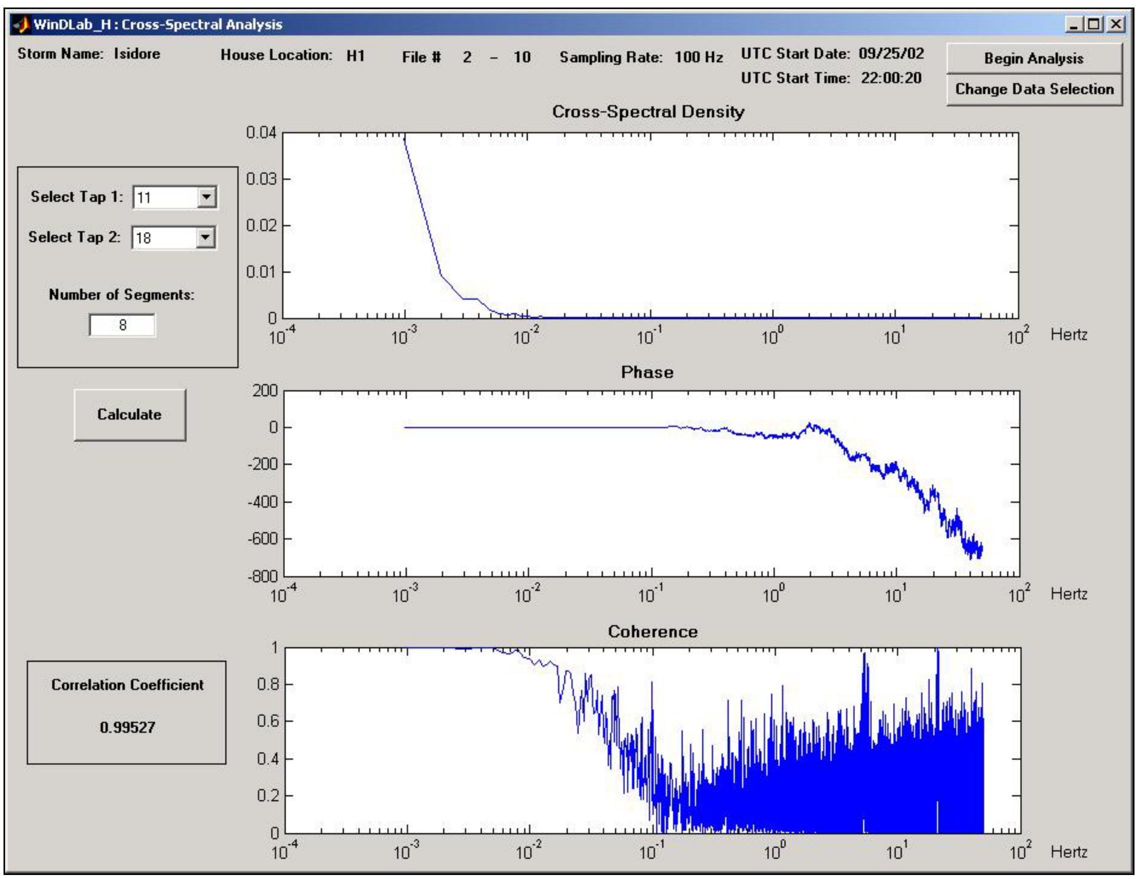


Figure 6-11: Cross-Spectral Analysis Window

Turbulence intensity

Turbulence intensity describes the average fluctuation of a process in ratio with its mean. Turbulence intensity, I , is calculated similarly to the coefficient of variation and is equal to the ratio of the standard deviation to the mean (Equation 6-2).

$$I = \frac{\sigma}{\overline{U}} \qquad \text{Equation 6-2}$$

where σ = standard deviation of the pressure

$\overline{U}$ = the mean pressure value

The turbulence intensities in WinDLab_H are calculated for the pressures on the tap selected by the user. This window operates the same as the WinDLab, Version 3, Turbulence Intensity window for the wind velocity data. Figure 6-12 provides an example of the analysis of tap 15. When the volts are converted to engineering units, this window will be significant when quantifying the uncertainty associated with measurements of the pressure coefficient. That is, a mean pressure coefficient must be viewed in light of the magnitude of the fluctuations about that mean value, which is what this window provides.

Gust factors

Gust factors, as described in Chapter 5, account for peak fluctuations in wind speed. The measured gust factor is the peak value divided by the mean (Equation 6-3) over a given duration.

$$G = \frac{u_{\max}}{\overline{U}} \qquad \text{Equation 6-3}$$

where $u_{\max}$ is the maximum pressure

$\overline{U}$ is the mean pressure

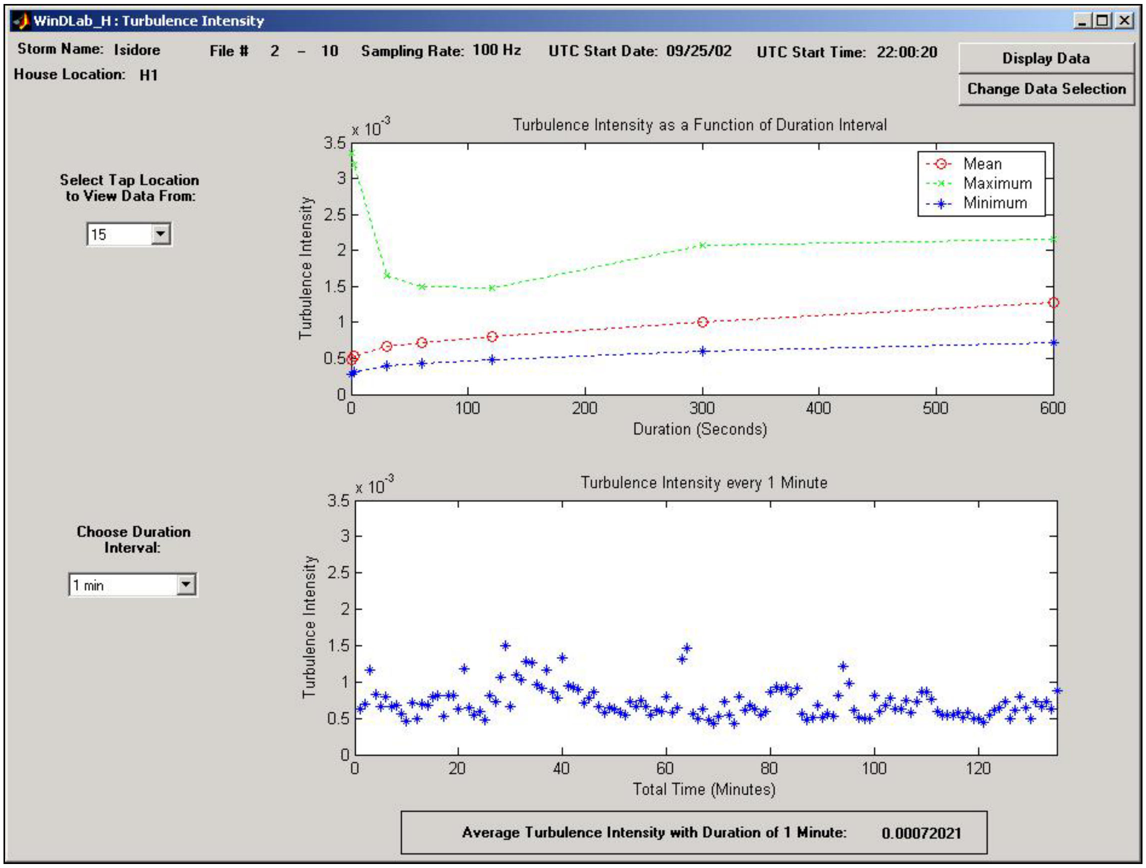


Figure 6-12: Turbulence Intensity Window

WinDLab_H averages the pressures acting on the chosen tap location to the selected averaging time (100, 10, 1, 0.1 Hz) and then determines the mean and peak pressures for the duration selected (1, 3, 5, 10 minutes). Gust factors, G, are more typically associated with wind speed. They are not as commonly applied to wind pressures, but do speak to the physical behavior of peak gust levels relative to the mean. Figure 6-13 presents the Gust Factor window for WinDLab_H. Again the use of the raw data in voltage form renders the results rather meaningless. Once the conversions to engineering units are made available from Clemson, this window will provide a view of likely bursts of pressure. This, as was the case for turbulence intensity, is useful for associating error with pressure coefficient measurements.

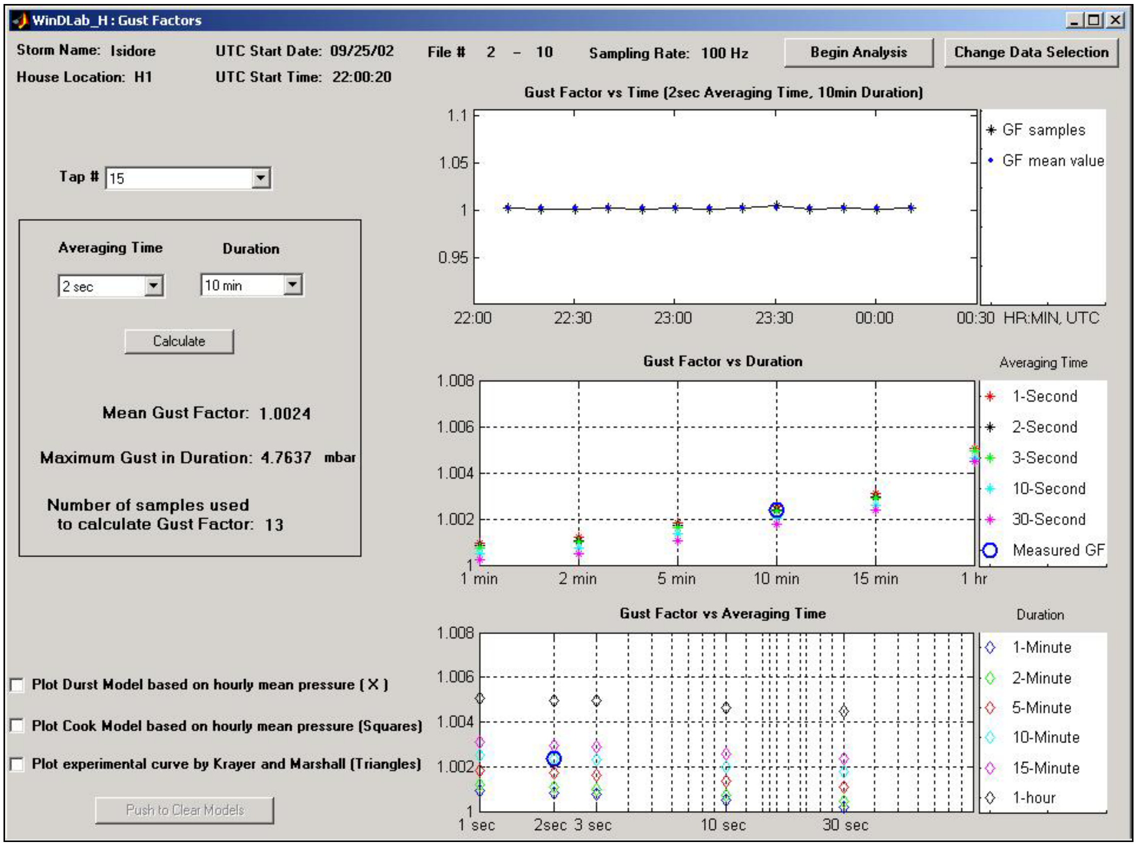


Figure 6-13: Gust Factors Window

<u>Correlation and integral scales</u>

The Correlation and Integral Scales window (Figure 6-14) will allow the calculation of the size of the turbulent eddies that pass over the home. The integral scales, or length, of the eddies are calculated as described in Chapter 5, and in Cuenca (2002). The integral scales calculated from the pressure taps will be compared to those estimated from the five- and ten-meter towers located near the home to determine if the characteristics of the eddies change as they flow over the approach terrain to the home.

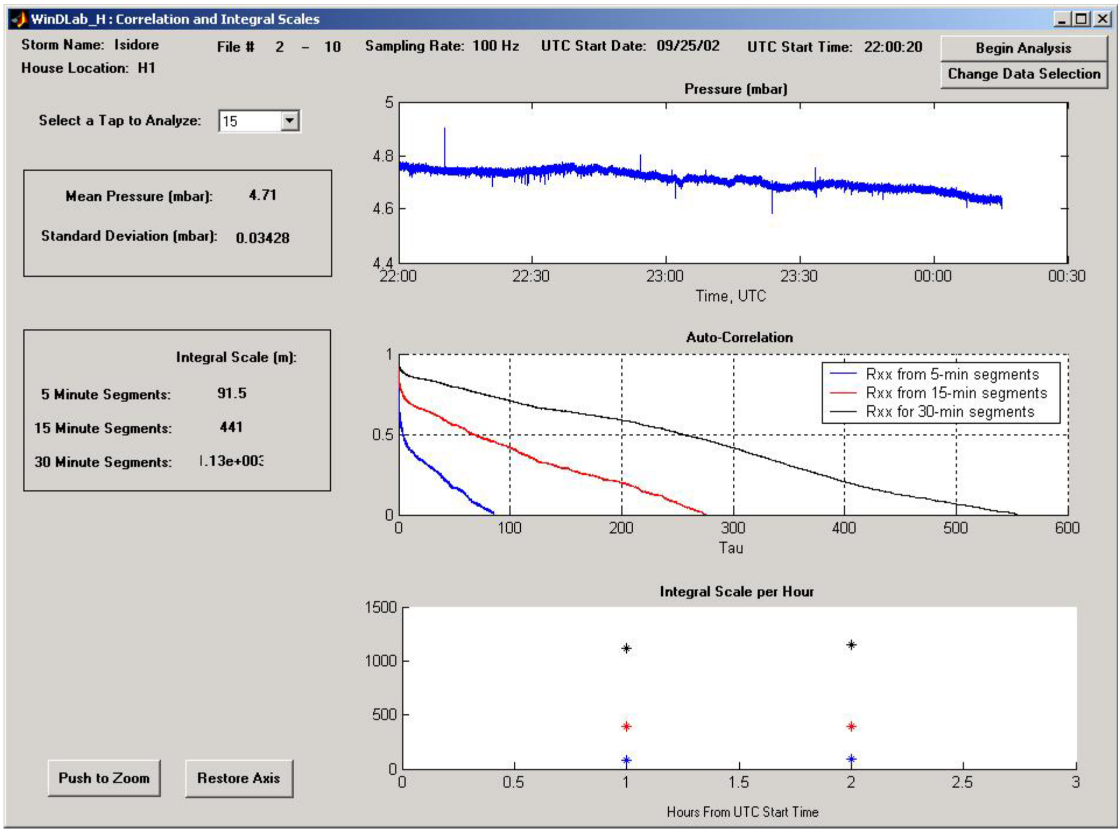


Figure 6-14: Correlation and Integral Scales Window

Summary

WindLab_H will be a powerful tool for viewing and analyzing pressure data collected on full-scale coastal homes during extreme wind events. Once Clemson University and the University of Florida complete the algorithms to convert the voltage output to engineering units, users will be able to observe important pressure characteristics and pressure coefficients that result when hurricanes make landfall. The determined characteristics and coefficients will then be used to improve wind pressure models and wind load code provisions. WinDLab_H was created such that it is compatible with MATLAB Complier 3.0 and will available, with the house data, from the FCMP website.

CHAPTER 7
SUMMARY AND RECOMMENDATIONS

The FCMP uses portable towers and instrumented coastal homes to measure full-scale wind and pressure data during hurricane landfall in an effort to better understand and characterize the wind and pressure behavior during extreme wind events. This thesis provides contributions to improving and maintaining the FCMP, as described below. In addition, recommendations of methods to further improve the FCMP are provided in this chapter.

Hardware Improvements, Maintenance and Installation Summary

Five-Meter Tower Improvements

The five-meter tower prototype was designed at the University of Florida by Hayes (2000). Cuenca improved the design by creating an aluminum version that is lighter and easier to transport (Cuenca 2002). Base plate stabilizers were designed to steady the towers during deployment off-pavement or in high wind conditions. These plates are 3-feet long and are connected to the base plate with bolts and to the earth using shear pins (refer to Figure 3-3). The plates are easily manufactured and installed during deployment.

Data Collection Hardware Maintenance

Two ten-meter towers are stored at the University of Florida. These towers are maintained and serviced annually. Summer 2001 and 2002, routine maintenance of the towers was performed. Summer 2002, the fixed axis (gill) anemometers were serviced and many of the bearings were replaced.

Coastal Homes Hardware Installation

The FCMP has twenty-five wired homes in the State of Florida. A contribution of this thesis is the wiring of fifteen of these homes. Summer 2001, ten homes in the Panhandle of Florida were wired and in summer 2002, five homes in East-Central Florida were wired. Wiring the homes takes several days and includes the placement of the sensor plugs, the CPVC conduit, and the data acquisition box. During deployment, wired homes can be instrumented in a couple of hours.

Collection and Processing of Data Summary

Data Collection

The FCMP collected data for Tropical Storm Isidore and Hurricane Lili in the 2002 hurricane season. During deployment, the ten-meter towers are erected close to the shoreline or in the vicinity of an instrumented home before landfall.

The FCMP instrumented three homes in the Panhandle of Florida for Tropical Storm Isidore. Two ten-meter towers were deployed in the vicinity of homes and a third was deployed near the coastline. A map of the storm track and towers deployed was provided in Figure 4-6.

Hurricane Lili made landfall in Louisiana. The FCMP deployed all four towers. The towers could not be deployed near the coastline; however, a large area was covered by the towers, as was shown in Figure 4-8.

Data Processing

The FCMP has been collecting data since the 1998 hurricane season. Until now, the recorded data had not been cataloged and much of the deployment details were missing. An Excel sheet cataloging the collected data and deployment details was created and the missing information has been recorded into the original data records.

Wind velocity data for all storms from 1999 to 2002 have been exported, processed and down sampled as was described in Chapter 4. Additional information was added to each file to provide exact time, date and location information. This information is used by the updated WinDLab software.

Summary of Tower WinDLab Improvements

WinDLab provides an extensive tool for the visualization and analysis of the wind velocity data collected by the FCMP. The analysis tools available aid researchers, experts and the general public in characterizing wind behavior in extreme wind events. Improvements to WinDLab include making producing a stand-alone version, making the software more efficient and easier to use, and making it compatible with both the 10 Hz and 100 Hz data formats.

WinDLab, Version 3, provides the user with information about available data records using the new Load Data window. This window provides maps of the storm track and tower locations, and allows user to decide what data they would like to load into WinDLab using a series of pull-down menus. The date and time the data was collected along with the number of data files available are also provided. After the data sets are loaded, they do not need to be loaded for each tool. Instead, they are passed through the handles structure of the GUIs.

WinDLab now uses the additional deployment information that was stored in the data records to plot the analyzed data versus the actual time the data was collected, in UTC, and to correct for the trailer angle when plotting the wind direction.

Summary of House WindLab Development

A companion tool for WinDLab was created to view and analyze the pressure data collected on full-scale coastal homes. This software, WinDLab_H provides a tool to help characterize the complex behavior of wind flowing over a structure. In addition, tools are provided to help quantify the degree to which wind code provisions accurately describe the pressures that result from extreme wind events.

Two visualization windows were created to view the changes in wind speed, direction, and resulting pressures on full-scale homes as hurricanes make landfall. The Wind Speed and Pressure window calculates the correlation coefficient between the selected pressure taps. The Wind Speed and Direction window provides an interactive compass that is updated by a slider bar between plots of the wind speed and direction with time.

The Load House Data window provides maps of the home and tower locations, and the pressure data records available for each storm. This window provides two additional windows, a picture with the layout and numbering of the taps, and a map of all twenty-five wired homes.

Conclusions and Recommendations

Tremendous damage results from windstorms every year. The FCMP was established by the Florida Department of Community Affairs to assist in understanding the complex behavior that results when wind and structures interaction in the lower boundary layer. The software provided through this thesis supplies the tools necessary to characterize the complex behavior of wind and pressure as they interact with low-rise coastal homes. Recommendations for improvements to each of the software tools are provided in the following sections.

Tower Wind Data Laboratory

WinDLab software is ready to be used by researchers and the general public; however, improvements and maintenance will be required. Each hurricane season the

Load Data window will need to be updated to include the new storm. The tower data will need to be processed and the pull-down menus and toggle buttons updated to reflect the new available data. In addition, summary statistics for each storm should be made available from the FCMP website and the Load Data window. With this information, users can determine which of the hundreds of available data files are of interest to them before downloading the data or loading the data in WinDLab.

House Wind Data Laboratory

The house data files for past storms must be processed before use in WinDLab_H. This should be completed upon determining the conversion factors for the pressure and anemometer data from Clemson University. Once the data is processed, the analysis tools available in WinDLab_H should be altered to reflect the behavior of the pressures.

The power spectral density models used in the Auto-Spectral Analysis window (shown in Figure 6-10) and the probability density function models used in the Probability Analysis window (shown in Figure 6-9) need to be changed to appropriate empirical models for pressure.

APPENDIX A
SAFFIR-SIMPSON HURRICANE INTENSITY SCALE

Category	Sustained Winds	Minimum Pressure	Damage Description and Storm Surge
Category 1	74-95 mph (64-83 kt)	less than or equal to 980 mb.	Damage primarily to shrubbery, trees, foliage, and unanchored mobile homes. Some damage to poorly constructed signs. Coastal roads inundated. Minor pier damage. Small craft with exposed anchorage torn from moorings. No significant damage to other structures.
			Storm surge of 3-5 feet
Category 2	96-110 mph (84-96 kt)	981-965 mb.	Considerable damage to shrubbery and tree foliage, some trees blown down. Major damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some damage to roofs, windows, and doors. Coastal roads may be cut by high water 2 to 3 hours before the storm arrives. Considerable damage to piers. Marina's flooded. Small craft with unprotected anchorage torn from moorings. Evacuation of the coastline and other low-lying areas may be necessary. No major damage to buildings.
			Storm surge of 6-8 feet
Category 3	111-130 mph (97-113 kt)	964-945 mb.	Foliage torn from trees, large trees blown down. Mobile homes destroyed. All poorly constructed signs blown down. Some damage to roofs, windows, and doors. Some structural damage to small buildings. Serious flooding along coastline. Small structures on coast destroyed, larger structures damaged by wave action. Low-level areas (5 feet and less above sea level) flooded inland 8 miles or farther. Coastal roads may be cut by high water 3 to 5 hours before the storm arrives. Evacuation of low-lying coastline area possibly required.
			Storm surge of 9-12 feet

Category	Sustained Winds	Minimum Pressure	Damage Description and Storm Surge
Category 4	131-155 mph (114-135 kt)	944-920 mb.	Most all shrubs and trees blown down. All signs blown down. Extensive damage to roofs, windows, and doors, roofs on small homes destroyed. Complete destruction of most all mobile homes. Major damage to coastline structures due to flooding, wave action, and floating debris. Low-level areas (10 feet or less above sea level) flooded inland 6 miles or farther. Coastal roads cut by high water 3 to 5 hours before the storm center arrives. Major erosion of beaches. Major evacuation of low-lying coastline area, and low ground up to 2 mile inland required.
			Storm surge of 13-18 feet
Category 5	Greater than 155 mph (135 kt)	less than 920 mb.	All shrubs and trees blown down. All signs blown down. Complete failure of roofs on residences and most industrial buildings. Extensive shattering of glass windows and doors. Severe and extensive damage to doors. Some complete building failure, smaller buildings overturned or blown away. Complete destruction of mobile homes. Major damage to structures less than 15 above sea level due to flooding, wave action, and floating debris. Coastal roads inundated by high water 3 to 5 hours before the storm center arrives, cutting off all evacuation routes. Massive evacuation of entire population in low-lying areas within 5 to 10 miles of coastline.
			Storm surge over 18 feet

REFERENCE:
National Hurricane Center (2003). The Saffir-Simpson Hurricane Scale. Retrieved April 14, 2003, from http://www.nhc.noaa.gov/aboutsshs.shtml

APPENDIX B
FCMP STORM DATA ON FILE

Storm Data on File with Clemson University and University of Florida

Data Collection Start and End Times

Storm Name	Tower No	Start Date	Start Time	End Date	End Time
Georges	T0	September 27, 1998	-	-	-
Dennis	T0	August 29, 1999	21:16:25	August 30, 1999	11:03:22
Dennis	T1	August 29, 1999	22:05:54	August 30, 1999	18:53:57
Dennis	T2	August 30, 1999	4:58:14	August 30, 1999	17:15:05
Dennis	T3	August 30, 1999	12:43:34	August 30, 1999	21:30:32
Floyd	T3	September 14, 1999	19:27:16	September 15, 1999	13:00:28
Irene	T0	October 16, 1999	7:33:16	October 16, 1999	17:50:08
Irene	T0	October 17, 1999	21:43:16	October 18, 1999	14:46:28
Irene	T1	October 16, 1999	5:07:00	October 16, 1999	16:39:06
Irene	T1	October 17, 1999	21:06:37	October 18, 1999	14:24:47
Irene	T3	October 16, 1999	8:19:49	October 16, 1999	8:04:46
Irene	T3	October 17, 1999	17:33:58	October 18, 1999	14:52:30
Gordon	T0	September 17, 2000	18:03:38	September 18, 2000	12:06:55
Gordon	T1	September 18, 2000	1:39:24	September 18, 2000	21:12:55
Gordon	T2	September 17, 2000	15:20:36	September 18, 2000	8:38:51
Gordon	T3	September 17, 2000	17:29:57	September 18, 2000	12:48:29
Gabrielle	T1	September 14, 2001	8:57:44	September 14, 2001	11:58:17
Michelle	T1	November 3, 2001	22:10:47	November 5, 2001	19:34:04
Isidore	T0	September 26, 2002	0:53:58	September 27, 2002	16:01:06
Isidore	T1	September 26, 2002	19:20:39	September 27, 2002	13:39:00
Isidore	T2	September 25, 2002	20:44:07	September 27, 2002	13:21:34
Lili	T0	October 3, 2002	2:18:29	October 4, 2002	15:55:19
Lili	T1	October 3, 2002	6:31:32	October 4, 2002	0:49:53
Lili	T2	October 2, 2002	23:18:34	October 4, 2002	15:25L57
Lili	T3	October 3, 2002	4:25:19	October 4, 2002	18:02:17

Storm Data on File with Clemson University and University of Florida

Data Collection Location

Storm Name	Tower No	Location	GPS Lat	GPS Long	GPS Source
Georges	T0	-	-	-	-
Dennis	T0	Kure Beach, NC	33° 57' 0"	77° 56' 0"	N.A. Aprox
Dennis	T1	Wrightsville Beach, NC	34° 12' 51"	77° 48' 16"	Exact
Dennis	T2	Topsail, NC	34° 22' 0"	77° 37' 0"	N.A. Aprox
Dennis	T3	Emerald Isle, NC	34° 40' 0"	76° 56' 0"	N.A. Aprox
Floyd	T3	Vero Beach, FL	27° 38' 0"	80° 24' 0"	N.A. Aprox
Irene	T0	Melbourne, FL	28° 3' 51"	80° 37' 28"	Exact
Irene	T0	Wilmington, NC	34° 9' 4"	77° 51' 54"	Exact
Irene	T1	Melburne, Fl	28° 4' 7"	80° 33' 25"	Aproximate
Irene	T1	Wilmington, NC	34° 9' 7"	77° 52' 6"	Exact
Irene	T3	Melbourne, FL	28° 4' 18"	80° 35' 59"	Exact
Irene	T3	Wilmington, NC	34° 8' 57"	77° 51' 36"	Exact
Gordon	T0	Dunedin, FL	28° 2' 59"	82° 46' 56"	Exact
Gordon	T1	Port Richey, FL	28° 17' 7"	82° 43' 56"	Aproximate
Gordon	T2	Port Richey, FL	28° 17' 7"	82° 43' 29"	Aproximate
Gordon	T3	Dunedin, FL	28° 3' 41"	82° 49' 44"	Exact
Gabrielle	T1	Venice Beach, FL	27° 6' 0"	82° 27' 0"	Exact
Michelle	T1	Homestead, Fl	25° 29' 3"	80° 27' 0"	Exact
Isidore	T0	Mary Esther, FL	30° 24' 37"	86° 45' 11"	Exact
Isidore	T1	Gulf Breeze, FL	30° 21' 41"	87° 11' 25"	Exact
Isidore	T2	Gulf Breeze, FL	30° 21' 8"	87° 10' 25"	Exact
Lili	T0	Lafayette, LA	30° 12' 53"	92° 2' 41"	Exact
Lili	T1	Balton Rouge, LA	30° 22' 58"	91° 5' 32"	Exact
Lili	T2	Donaldsville, LA	30° 5' 44"	91° 0' 23"	Exact
Lili	T3	Lydia, LA	29° 54' 50"	91° 45' 35"	Exact

APPENDIX C
WINDLAB, VERSION 3 HELP FILES

SECTION 1

GENERAL INFORMATION

1.1 Program Overview

This software was developed to view and analyze the data collected by the Florida Coastal Monitoring Program's (FCMP) instrumentation network. The newly developed software provides a comprehensive Graphical User Interface (GUI) to analyze the data collected by the FCMP instruments. It allows users to visualize wind data records, view statistics, view energy distribution, perform probability analysis, calculate gust factors, calculate turbulence intensities, calculate integral length scales, and view correlation functions.

1.2 Required Data Format

The data to be analyzed by this software needs to be contained in MATLAB readable files (**.mat). The data must also be processed by the batch processing files provided with the software. Data provided with the software CD and downloaded from the FCMP website does not need to be processed. It is ready to be used in the GUI. (For more information on processing see section 1.3)

1.3 Batch Processing

Batch processing MATLAB files are provided with the software. First, the data files must be exported from the Tower software used to collect the data. The data is exported as ASCII format (**.dat) in fifteen-minute segments. The MATLAB script file "conv_data.m" reads the ASCII data files and rewrites the data to a **.mat format so it can be easily read within the MATLAB environment.

The next step in the batch processing is the orthogonalization of the anemometer data. The fixed axis (gill) anemometers located on the towers are not oriented in traditional orthogonal directions. The second batch processing file, "correct_gills.m", reads the data created by "conv_data.m", and transforms the gill anemometer data into orthogonal components.

During this second batch processing step, the file prefix name is assigned. The prefix includes the storm name and the tower number, both followed by underscores.

Once these two batch processing steps have been completed, the data files are in the format required for the GUI to work appropriately.

1.4 Common Properties for All Windows

Storm and Tower Information

The storm name and tower number of the data loaded is displayed along the top of each analysis window. The storm name corresponds to the file name prefix that was assigned to the record during batch processing. For example, if the data set is named Irene_T1_1 ... Irene_T1_20, “Irene” will appear after the storm name text. The tower location is the number of the tower that collected the data records selected. This is designated as T0, T1, T2, or T3. The tower number was assigned to each record during batch processing.

File Numbers

These are the number of the first and last data records loaded. For example, if records Irene_T1_5 to Irene_T1_8 were loaded into WinDLab, “5-8” will appear after the “file #” text. This would mean that a total of four files (Irene_T1_5, Irene_T1_6, Irene_T1_7 and Irene_T1_8) were loaded.

UTC Time

The time and date (in UTC) of the first data collected inside the first record loaded is provided at the top of each window. This is the time and day at which data collection began for the records loaded.

Data Source

Wind speed data is collected by three sources on each ten-meter tower. These include a 10-meter vane anemometer, a 10-meter gill anemometer, and a 5-meter gill anemometer. For most windows, with the exception of "Meteorological Data", the user has the option to decide the source of the data to be analyzed.

SECTION 2

"VIEW DATA"

2.1 Window Overview

The "View Data" window provides the user with the ability to view the wind speed and direction of the loaded data. The ability to simultaneously compare the data from different anemometers, and the ability to view the basic statistics of the wind records loaded are also provided.

The top plot in the GUI figure is the wind speed plot in meters per second. The bottom plot is the direction of the wind (with respect to North).

2.2 GUI Tools

"Plot One Anemometer" Checkbox

Check this box to view the data from one anemometer only.

"Plot Multiple Anemometers" Checkbox

Check this box to view and compare the data from two anemometers at the same time.

10-meter Vane, 10-meter Gill, 5-meter Gill Checkboxes

These checkboxes allow the user to choose the source of the data. Source choices include the 10-meter vane anemometer, the 10-meter gill anemometer, and the 5-meter gill anemometer.

When the "One anemometer" checkbox is checked, only one of the anemometer checkboxes can be selected at a time. To change the anemometer selection, the user must first unselect the checkbox.

When the "multiple anemometer" checkbox is selected, at least two of these checkboxes must be checked. All three anemometers may be viewed simultaneously with this option as well.

"Add / Replace Curves" Drop-Down Menu

One of the choices from this drop-down menu must be selected in order to activate the plot command. The GUI has the ability to plot the data decimated to 1-second, 3-second, or 10 second averaging times. Additionally, the raw data may be added to the previous plot or used to replace the plot.

The Add Curve selections adds the chosen plot to the current plot.

The Replace curve option clears the current graph and plots the selected graph.

Add / Replace are only available for the single anemometer plots. The multiple anemometer selections always replace the existing plot.

Zoom / Restore

Pushing the "zoom" button will allow the user to zoom into a specified area of either plot. Zooming is achieved by dragging a box that is created when the user clicks and holds the left mouse button. The "restore axis" button restores both plots to their original axis.

2.3 Statistics

The GUI provides basic statistics of the loaded data. These statistics are calculated from the anemometer source chosen by the user in the drop-down menu at the bottom of the window. The statistics provided include the total mean wind speed from the entire length of the records loaded, the maximum speed of the total record, the maximum 1-minute, 3-second, and 1-second averages, as well as the time at which these maximums occurred. Time provided is the number of minutes from the start of the loaded data records.

SECTION 3

"PROBABILITY ANALYSIS"

3.1 Window Overview

The probability analysis window provides the user with an empirical probability density function (PDF) for the chosen set of data, as well as plots of specific probability distribution functions to compare with the data.

Both plots in the figure are probability density distributions, but the bottom plot is plotted in log-scale to better view the end (tail) behavior.

3.2 GUI Tools

Plotting a Probability Density Model

The drop-down menu on the left hand side of the window allows the user to select a probability density model. This model will be plotted on top of the calculated (empirical) PDF. The empirical and model PDFs are then compared by the Mean Square Error (MSE) and Kolmogorov-Smirnov (K-S) goodness of fit tests.

Zoom / Restore

Pushing the "zoom" button will allow the user to zoom into a specified area of either plot. Zooming is achieved by dragging a box that is created when the user clicks and holds the left mouse button. The "restore axis" button restores both plots to their original axis.

3.3 Statistics Reported

The GUI reports the first four statistical moments calculated from the loaded data records. These moments are the mean, standard deviation, skewness and kurtosis.

3.4 Goodness of Fit Tests

Two types of "Goodness of Fit" tests are performed. These tests compare the closeness of the measured data (empirical) PDF to the chosen PDF model. Tests performed are the K-S and the MSE.

SECTION 4

"AUTO-SPECTRAL ANALYSIS"

4.1 Window Overview

This figure allows the user to plot a power spectral density (PSD) estimate of the specified data, and compare it to existing power spectral models. The anemometer source of the data must be chosen from a pull-down menu located on the upper left of the window. The plot updates automatically when a new source is chosen.

4.2 GUI Tools

Number of Segments

The number of segments is the number of ensembles the data will be broken up into before calculating the Fast Fourier transform for the spectral density calculation. The default value for this is 8, but the user can change the number. If the user changes the number, the "recalculate" button must be pressed to recalculate the power spectral density.

"Recalculate" Button

This button recalculates the power spectral density estimate for the number of segments entered in the "# of Segments" edit text box. Press this button if the number of segments has been changed.

Roughness Length

The roughness coefficient takes into account the effects of terrain roughness and topography. Only the von Karman and Solaris models take into account the roughness length. For these models, the user must select the appropriate roughness length from the drop-down menu to match the conditions at the location the data was collected. The drop-down menu is disabled for all other models.

Fit Model

This drop-down menu allows the user to choose an existing power spectral model to plot on top of the PSD estimate. The models will plot on top of each other until the "Clear Models" button is pressed. Models available include Harris, Davenport, Kaimal, von Karman, and Solaris (from Eurocode I).

"Clear Graphs of Models" Button

This button clears the graph of the models, and restores the plot of the PSD estimate only. This button will also clear the error curves.

“Plot Error Curves”

This button allows the user to plot the power spectral density estimate plus and minus the variance error. To clear the graph of the error curves use the “Clear Graphs of Models” button.

Error Estimates

The GUI reports two types of errors, the variance error and the mean squared error. The variance error is only dependant of the number of segments used to calculate the PSD estimate. The mean squared error compares the calculated PSD estimate to the chosen models.

Zoom / Restore

Pushing the “zoom” button will allow the user to zoom into a specified area of either plot. Zooming is achieved by dragging a box that is created when the user clicks and holds the left mouse button. The “restore axis” button restores both plots to their original axis.

SECTION 5

"CROSS-SPECTRAL ANALYSIS"

5.1 Window Overview

This window allows the user to view the cross-spectral density estimate of two anemometers for the data records loaded. Additionally, the phase and coherence between the anemometers is calculated and plotted. The user has the option of which to anemometers to compare, and the number of segments to be used for the cross-spectral calculations.

NOTE: The "Begin Analysis" button only retrieves the loaded data records. No plots are produced until the sources of the anemometers to be compared are chosen and the "Calculate" button is pressed.

5.2 GUI Tools

Number of Segments

The "number of segments" is the number of ensembles the data will be broken up into before using the Fast Fourier transform to calculate the spectral density. If this number is changed, the user must press the calculate button to recalculate the cross-spectral density function.

Anemometer Checkboxes

Two of these checkboxes must be selected for the cross-spectral density calculations. Once the two data sources are chosen, the user must press the "Calculate" button.

"Calculate" Button

After selecting two anemometer sources this button must be pressed for the calculations to be performed and the results plotted. If the data sources are changed, this button must be pressed again for recalculation.

Correlation Coefficient

The GUI reports the calculated correlation coefficient for the chosen data sources.

SECTION 6

"TURBULENCE INTENSITY"

6.1 Window Overview

The Turbulence Intensity GUI reports the calculated turbulence intensities for different averaging times. It also allows the user to plot a time history of turbulence intensity based on a selected averaging time. The user has the option to choose the anemometer location of the data to be analyzed.

NOTE: The "Display Data" button retrieves the loaded data records and plots the turbulence intensities for the 10-meter vane anemometer. All plots update automatically when the anemometer source is changed.

6.2 GUI Tools

Turbulence Intensity as a Function of Duration Interval

This plot shows the total turbulence intensity as a function of duration interval. This plot does not changed based on the user's choice of duration time for the bottom plot. The green plot shows the maximum turbulence intensity calculated for each corresponding duration interval; the red plot shows the mean turbulence intensity calculated for each corresponding duration interval; and the blue plot shows the minimum turbulence intensity calculated for each duration time. The duration times shown are 1-second, 3-second, 30-second, 1-minute, 2-minute, 5-minute, and 10-minute.

Turbulence Intensity for Each Duration Time Interval

The user must choose the length of the time period over which the turbulence intensity is calculated. This plot shows the turbulence intensities calculated as a function of time for the length of the records being analyzed.

Average Turbulence Intensity

The GUI reports back the average turbulence intensity for the duration interval chosen. This value is calculated for the entire length of the record being analyzed, and is the same value that is plotted as a circle in the top plot.

SECTION 7

"GUST FACTORS"

7.1 Window Overview

The Gust Factor GUI window calculates the gust factors for a chosen averaging time and duration. The user must select the anemometer source of the loaded data, the averaging time, and the duration before calculating the gust factors. Anemometer choices include the 10-meter vane anemometer, 10-meter gill anemometer, or 5-meter gill anemometer.

NOTE: The "Begin Analysis" button only retrieves the loaded data records. Gust factors will not be calculated until the "Calculate" button is pushed.

7.2 GUI Tools

Averaging Time

The averaging time is the length of time over which the wind speed data is being averaged to produce the peak values. An averaging time must be chosen before pressing the "Calculate" button. If a different averaging time is desired after a given calculation, it must be chosen, and the "Calculate" button must be pushed again for recalculation of the gust factors.

Duration

The duration is the length of the time segment over which the mean value is being calculated. The user has the option of 1-minute, 2-minute, 5-minute, 10-minute, 15-minute, and 1-hour duration times. A duration time must be chosen before the "Calculate" button is pushed. If a different duration time is desired after a given calculation, it must be chosen, and the "Calculate" button must be pushed again for recalculation of the gust factors. Gust factor for 1-hour duration will only be calculated if four or more data records are loaded.

"Calculate" Button

This button must be pushed after the averaging time and duration times are chosen for any calculations or plotting to occur.

Measured Gust Factor

The GUI reports the average measured gust factor. This is the mean of the gust factors calculated using the specified averaging time and duration for the entire length of the records being analyzed.

Max Gust Speed

The GUI calculates and reports the maximum gust corresponding to the chosen averaging time.

Number of Points Used to Calculate Gust Factor

The GUI reports back the total number of data points used to calculate the average measured gust factor. This is equivalent to the number of points used to calculate the mean.

Gust Factor vs. Time

This is a plot of gust factor versus time based on the chosen averaging time and duration. The blue dotted line is the total measured gust factor.

Gust Factor vs. Duration Plot

This is a plot of the calculated gust factor as a function of the duration time. This plot does not change based on the user options, but is re-plotted each time the “Calculate” button is pushed.

Gust Factor vs. Averaging Time Plot

This is a plot of the calculated gust factors as a function of the averaging time. This plot does not change based on the user selections, but is re-plotted each time the “Calculate” button is pressed. Note that the one-hour duration plot is only available if four or more data files are loaded.

Durst Model

The “Plot Durst Model” checkbox, when selected, plot the Durst model for gust factors. This model is based on one-hour mean wind speeds. Once plotted, this model can only be removed by pressing the “Clear Models” button.

Cook Model

The “Plot Cook Model” checkbox, when selected, plots the Cook model for gust factors. This model is based on one-hour mean wind speeds. Once plotted, this model can only be removed by pressing the “Clear Models” button.

Krayer and Marshall Model

The “Plot Krayer and Marshall Model” checkbox, when selected, plots the Krayer and Marshall experimental curve for gust factors. This model is based on one-hour mean wind speeds. Once plotted, this model can only be removed by pressing the “Clear Models” button.

SECTION 8

"CORRELATION AND INTEGRAL SCALES"

8.1 Window Overview

The Correlation and Integral Scales window calculates the autocorrelation function and corresponding integral scales for the wind records loaded. It also displays the wind data at a 3-second resolution and reports the mean wind speed.

8.2 GUI Tools

Wind Speed Plot

This is a plot of the wind speed record with respect to time, sampled at a 3-second interval.

Zoom / Restore

Pushing the "zoom" button will allow the user to zoom into a specified area of either plot. Zooming is achieved by dragging a box that is created when the user clicks and holds the left mouse button. The "restore axis" button restores both plots to their original axis.

Mean Wind Speed, Standard Deviation and Turbulence Intensity

The GUI reports the mean wind speed from the entire length of the record in meters per second and the standard deviation for the entire length of the record.

Auto-Correlation Plot

This is a plot of the autocorrelation function estimate for the loaded data records. The plot displays the average of the autocorrelation functions for 5-minute, 15-minute, and 30-minute time intervals. The autocorrelation function estimate is only calculated for 30-minute intervals if two or more data records are loaded.

Integral Scale Plot

This is a plot of the calculated integral scales for each hour of data loaded. For this plot, the mean wind speed for an hour of data is used to calculate the integral scales. The integral scale is plotted for 5-minute, 15-minute, and 30-minute time intervals.

Integral Scale

The GUI reports the overall integral scales for 5-minute, 15-minute and 30-minute time intervals. This number is the mean of the integral scales calculated for each time segment, and is reported in meters. For a 30-minute time interval to be possible, at least two data files must be loaded.

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BIOGRAPHICAL SKETCH

Robin Weaver was born on November 27th, 1978, in Watertown, New York, to Donald and Carol Weaver. At the age of six months she moved to Louisiana and then continued to Niceville, Florida, when she was four. After graduating in the top ten percent of her class at Niceville High School in 1997, Robin moved to Gainesville, Florida, to attend the University of Florida. At the university, Robin participated in the University Scholars Program as she completed her combined bachelor's and master's degree in civil engineering with an emphasis in structures. Throughout her undergraduate and graduate degrees she participated in a hurricane data collection and analysis research project. Upon graduation from the University of Florida in August 2003, Robin will begin working for a structural engineering firm in Fort Myers, Florida.